DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

ν_μ

arXiv:1512.06148, 1601.02984, 1601.05471, 1601.05823

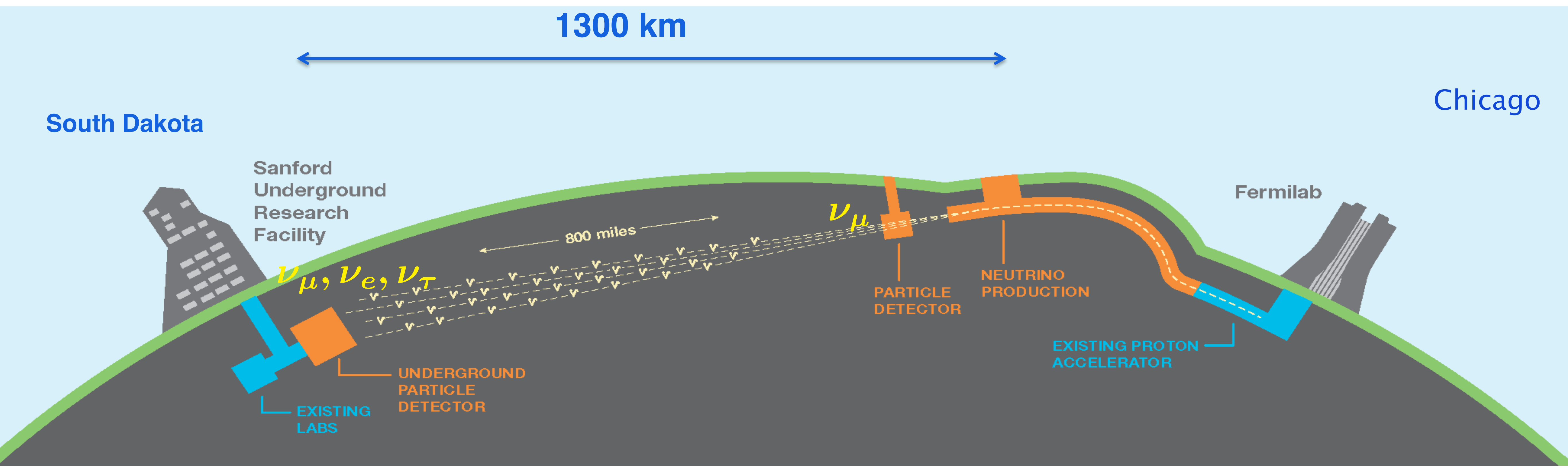
Stephen Parke - Fermilab
for DUNE Collaboration

ν_μ, ν_e, ν_τ

856 collaborators 149 Institutions 29 Nations

What is DUNE/LBNF ?

- **DUNE/LBNF will consist of**
  - **An intense (1-2 MW) neutrino beam from Fermilab**
  - **A massive (70 kton) deep underground LAr Detector South Dakota**
  - **A large Near Detector at Fermilab**
  - **A large International Collaboration (~1000 scientist)**



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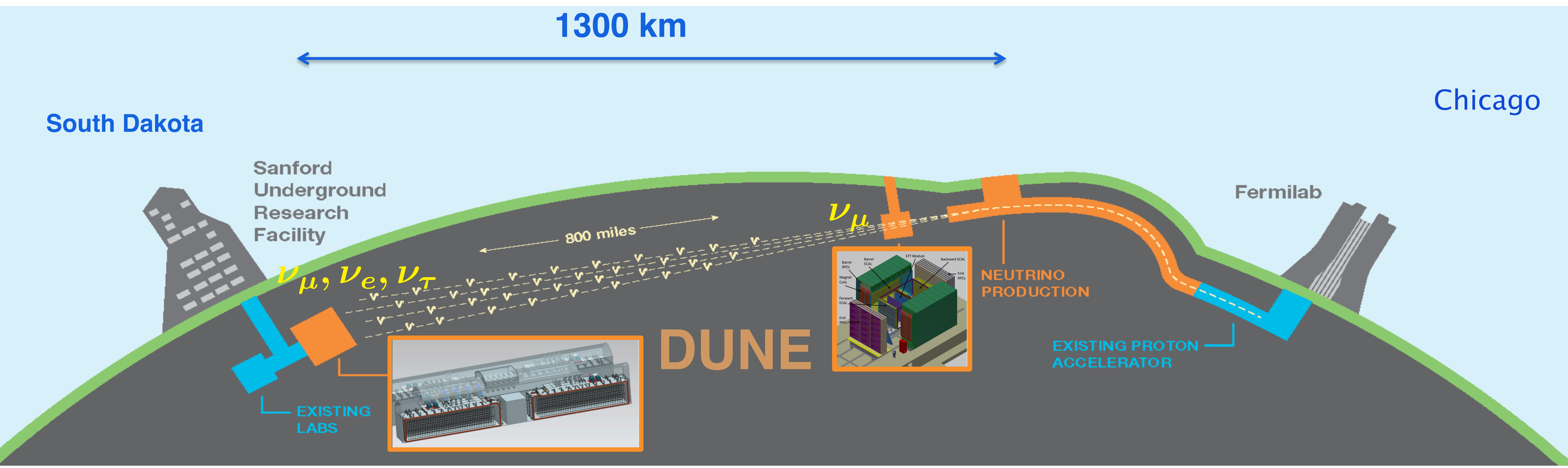
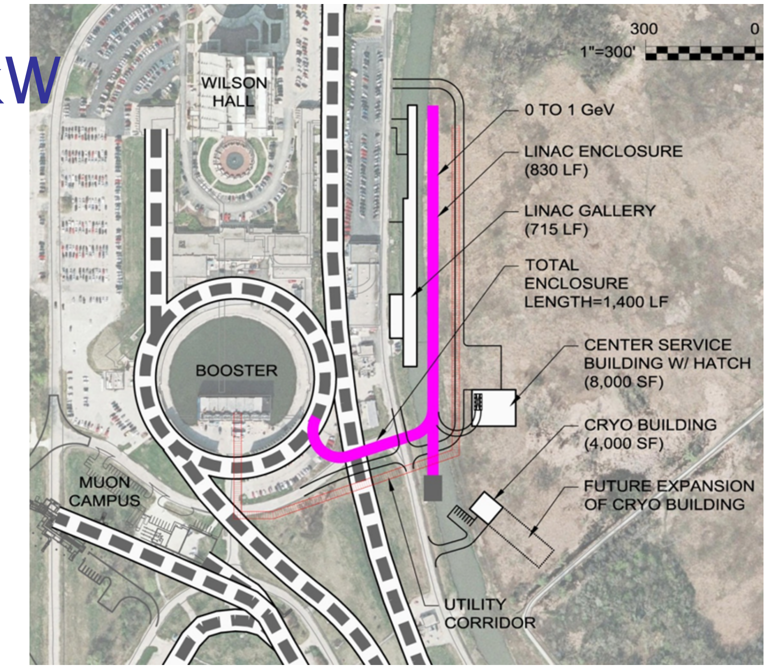


LBNF and PIP-II

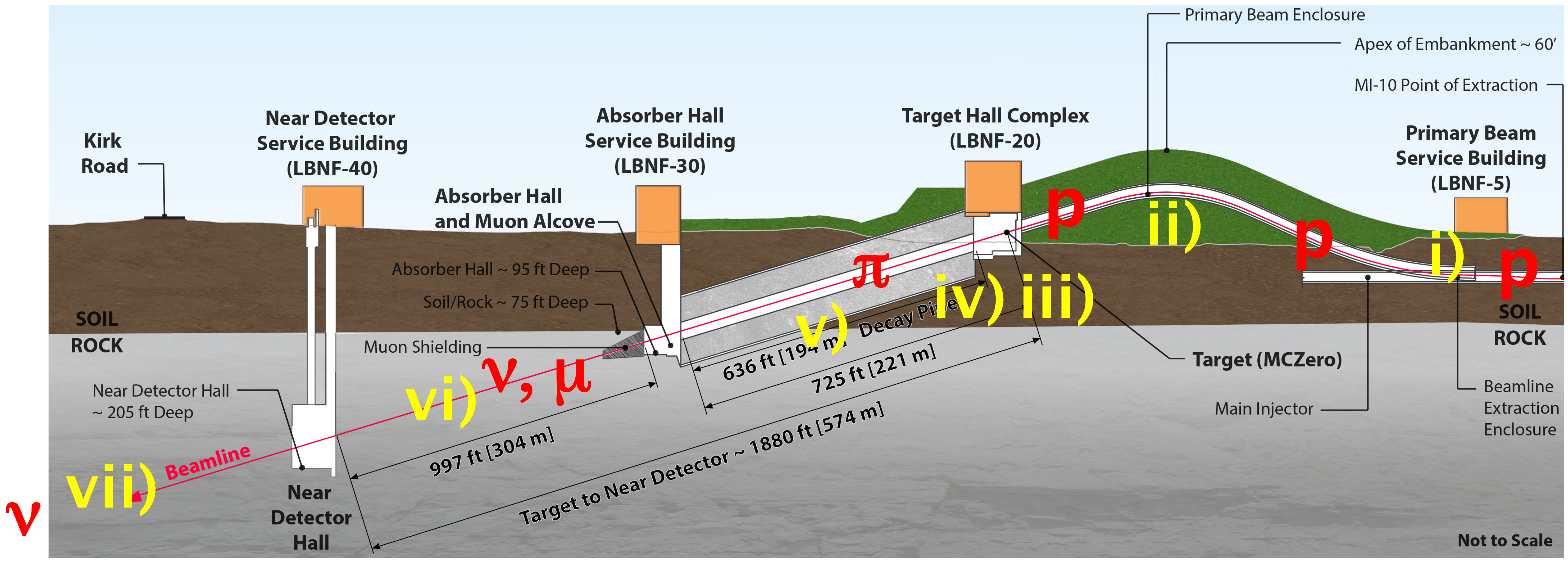
- **In beam-based long-baseline neutrino physics:**
  - § **beam power drives the sensitivity**

- **LBNF will be the world's most intense high-energy ν beam**
  - § **1.2 MW from day one**
    - • NuMI (MINOS) <400 kW
    - • NuMI (NOVA) ultimately 700 kW
  - § **upgradable to 2.4 MW**
- **Requires PIP-II** (proton-improvement plan)
  - § **major** upgrade of FNAL accelerator infrastructure
  - § Replace existing 400 MeV LINAC with 800 MeV SC LINAC



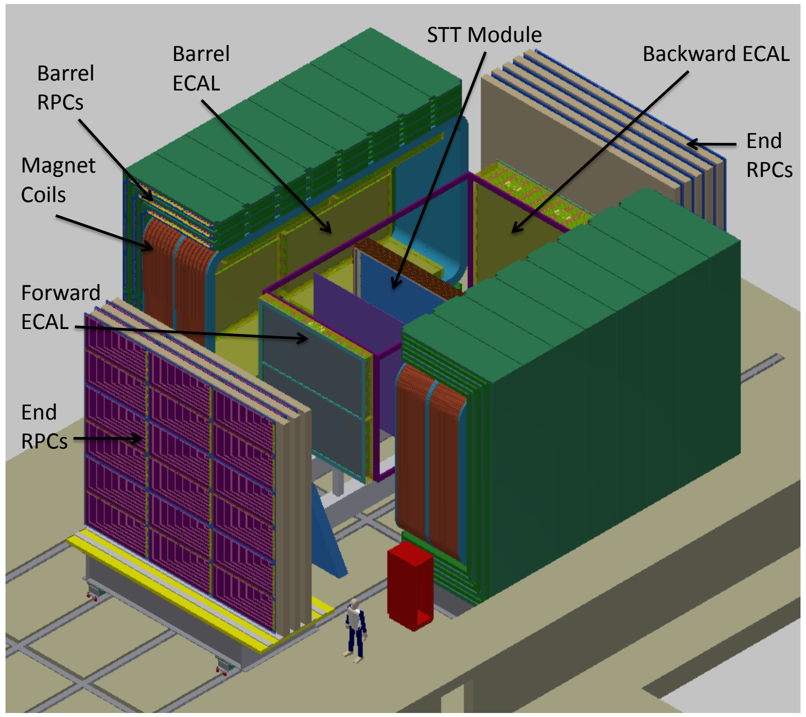
The LBNF Neutrino Beam

- 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) For neutrino/antineutrino beam focus positive/negative pions/kaons
- v) Allow them to decay, e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$
- vi) Absorb remaining charged particles in rock
- vii) Left with a "collimated" ν_μ beam



DUNE ND (in brief)

CDR design is the NOMAD-inspired FGT (Fine Grain Tracker)



- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - RPC-based muon tracking systems
- **Other options being studied**
- **The Near Detector provides:**
  - Constraints on cross sections and the neutrino flux
  - Sterile neutrino search
  - A rich self-contained non-oscillation neutrino physics program

Will result in unprecedented samples of ν interactions

- **>100 million** interactions over a wide range of energies:
  - strong constraints on systematics
  - the ND samples will represent a huge scientific opportunity

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850ft level (~1.5km underground)

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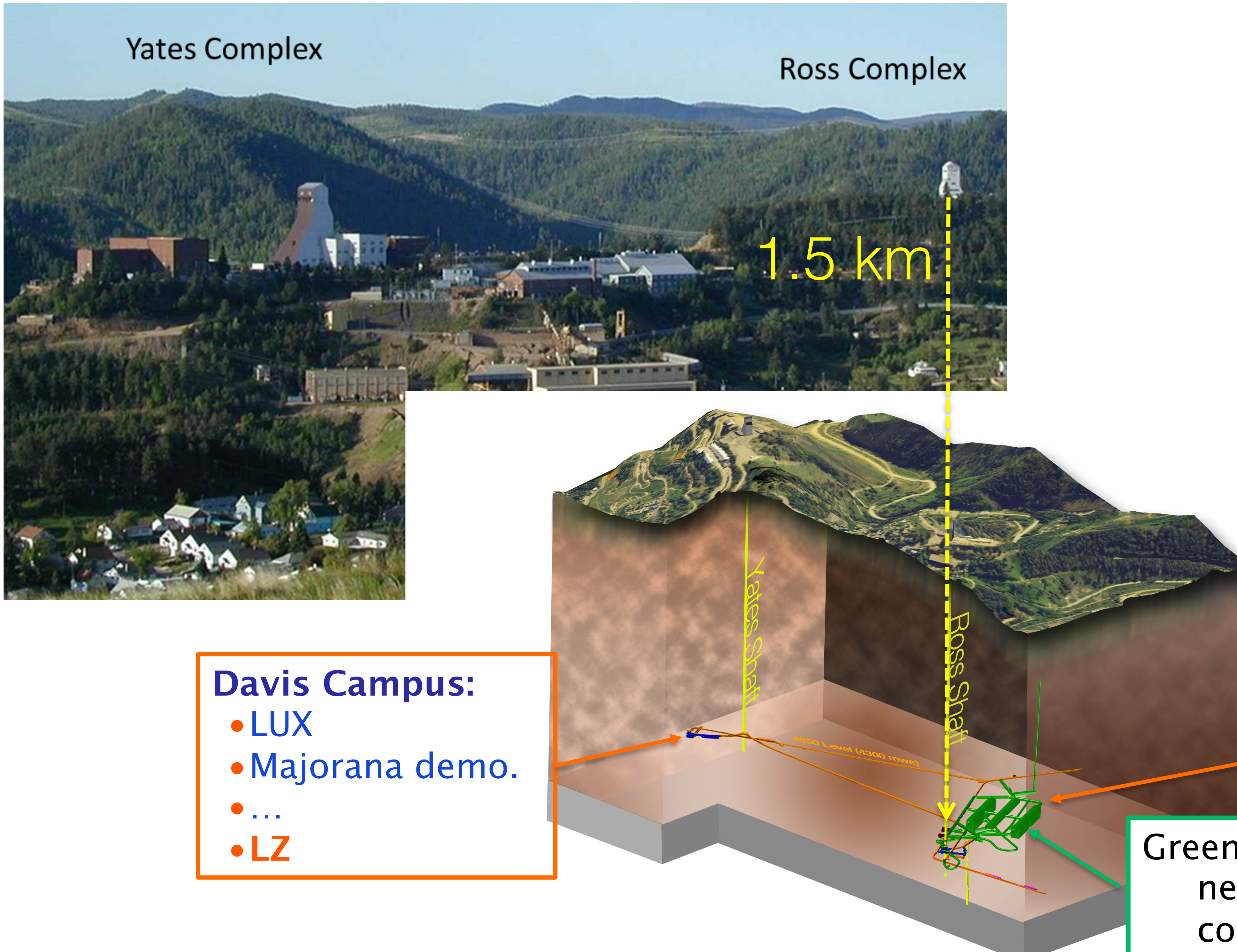

Davis Campus:
- LUX
- Majorana demo.
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

Green =
new excavation
commences in 2017

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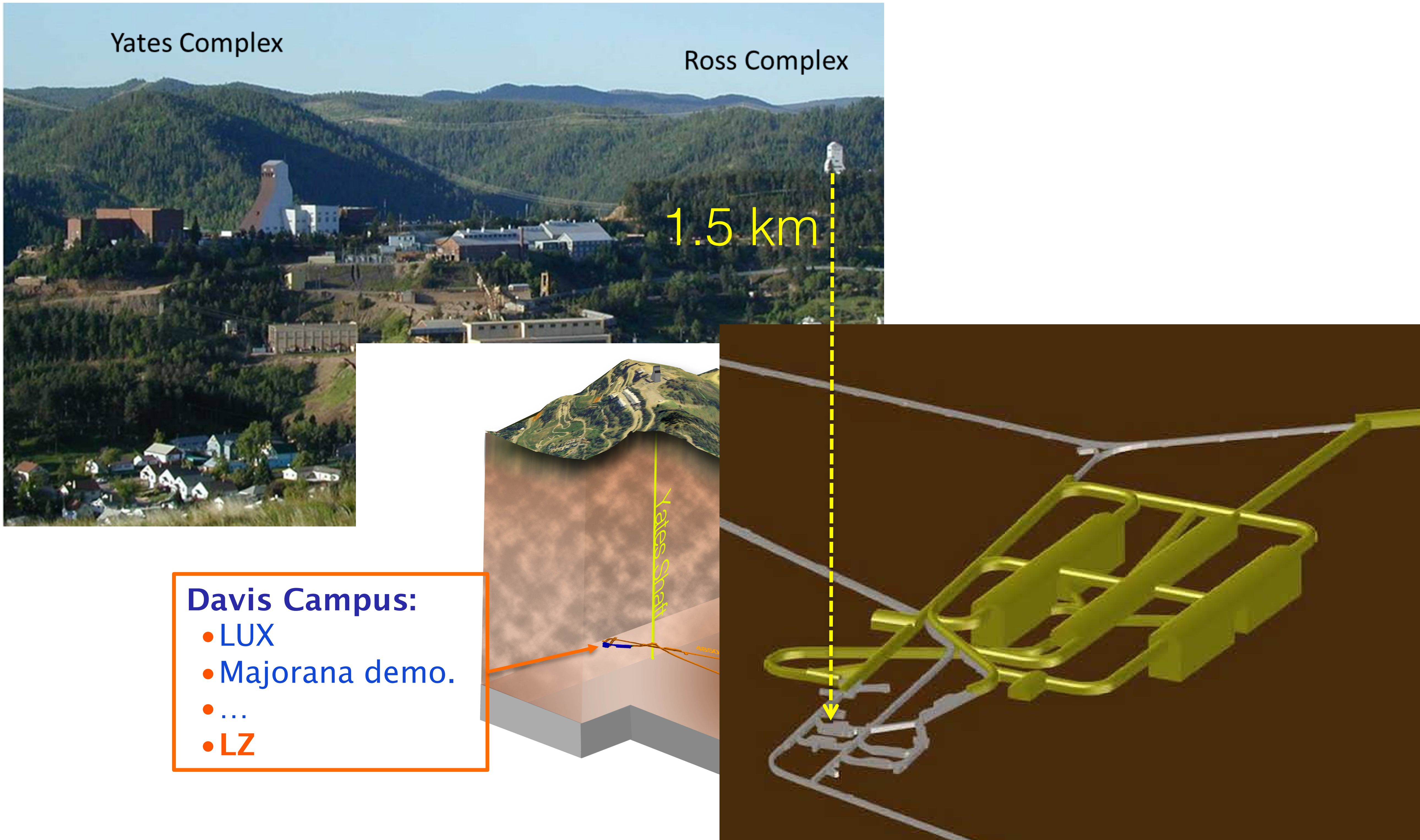
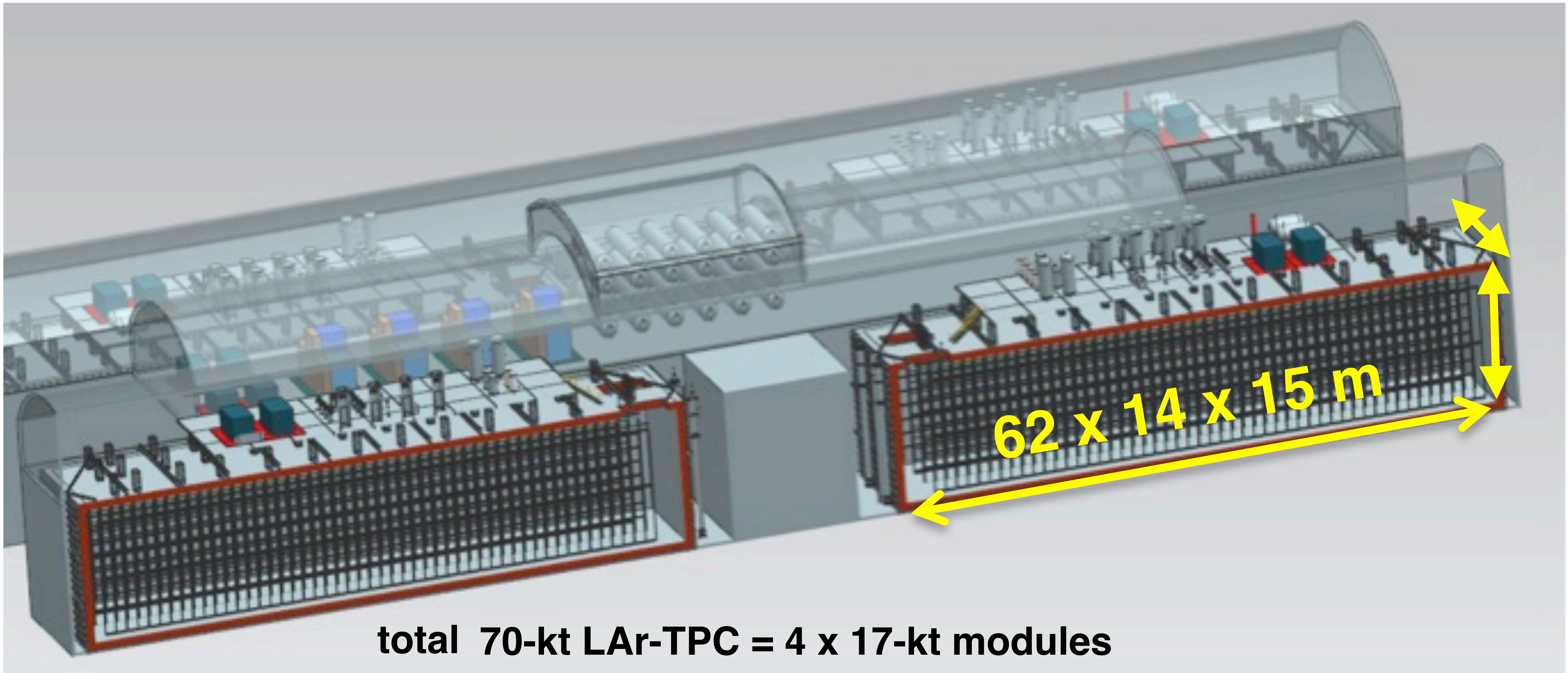
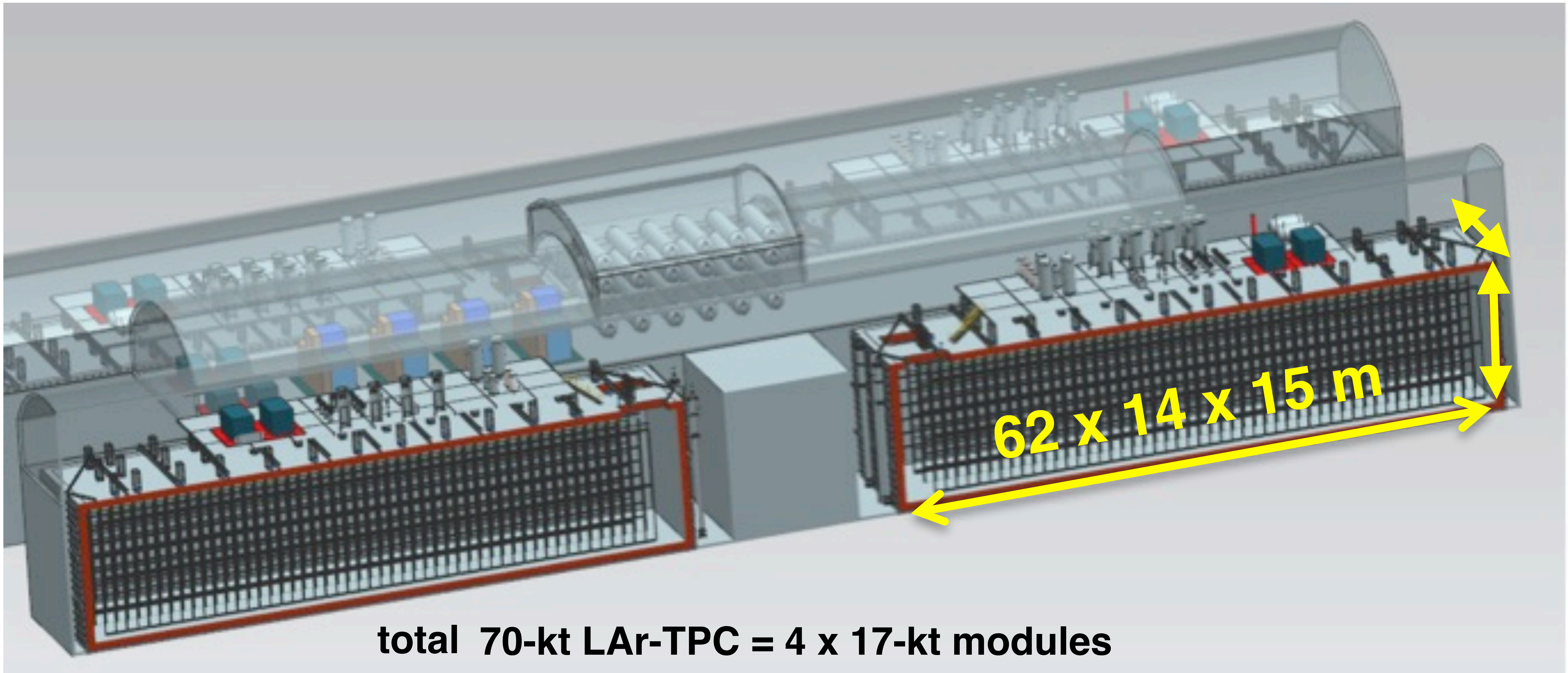




Fiducial = 4 x 10 kt



Fiducial = 4 x 10 kt

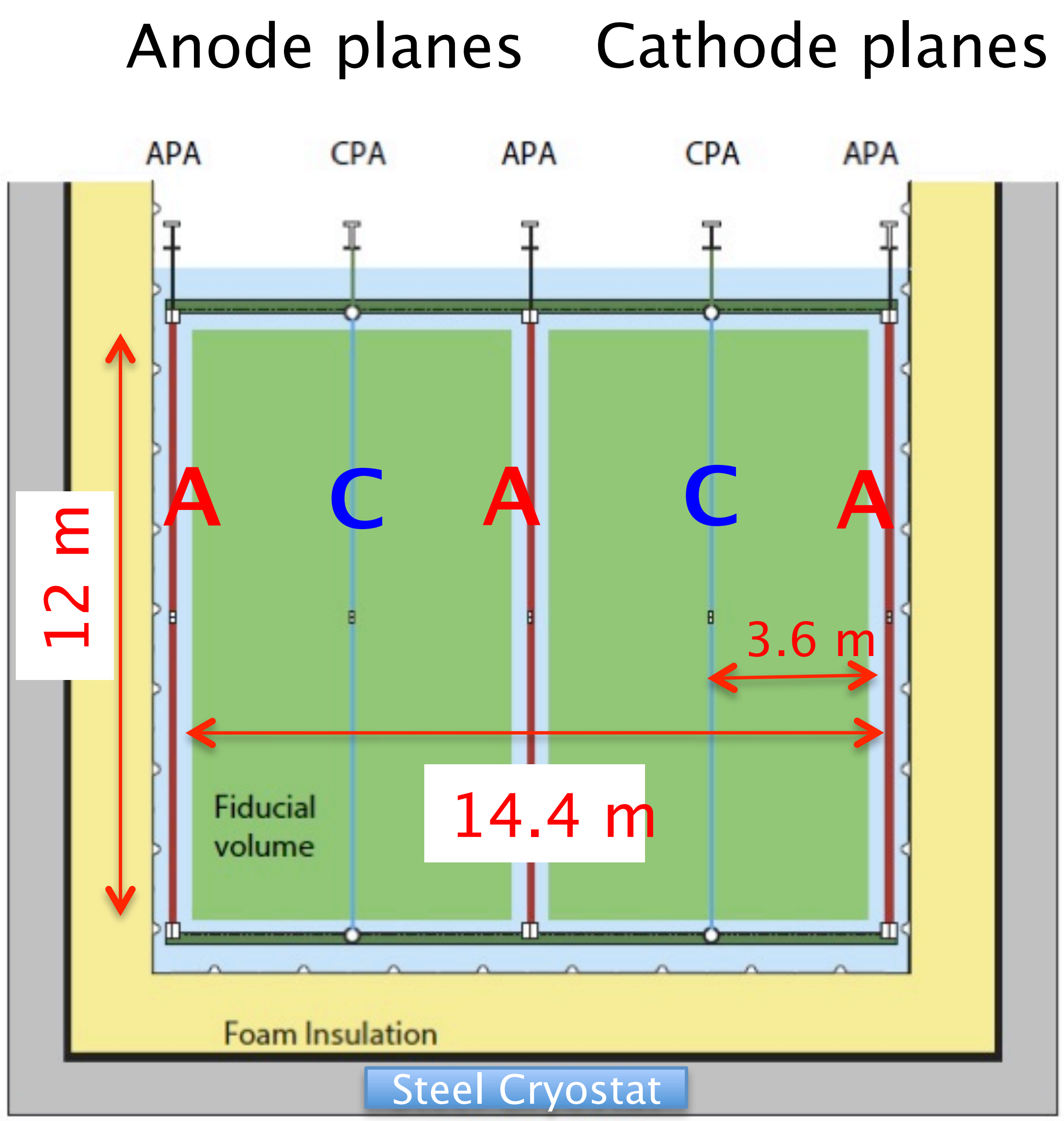
Ar from $\sim \mathbf{10}\ \mathrm{km}^{\mathbf{3}}$ of air

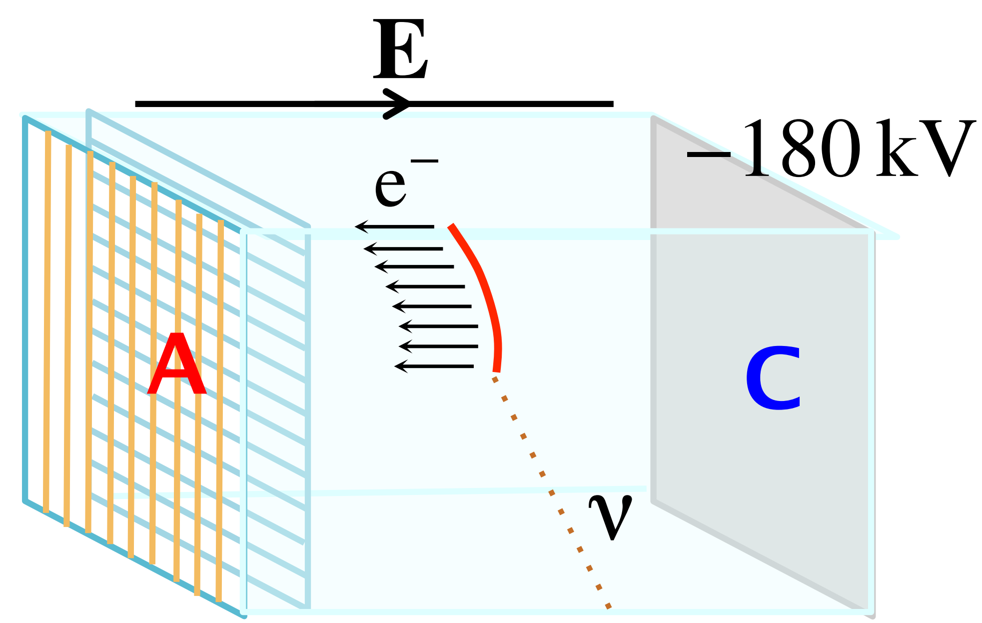
$= 300\mathrm{m} \times$ Area of Fermilab site ($30\ \mathrm{km}^2$)

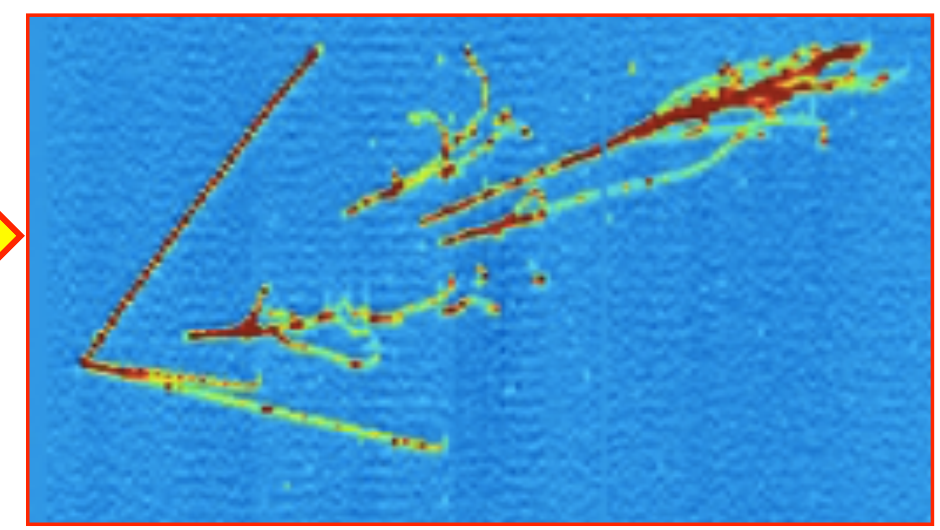
Liquid Argon TPC Basics

e.g. a **modular** implementation of Single-Phase TPC

- Record ionization in LAr volume ⇨ 3D image







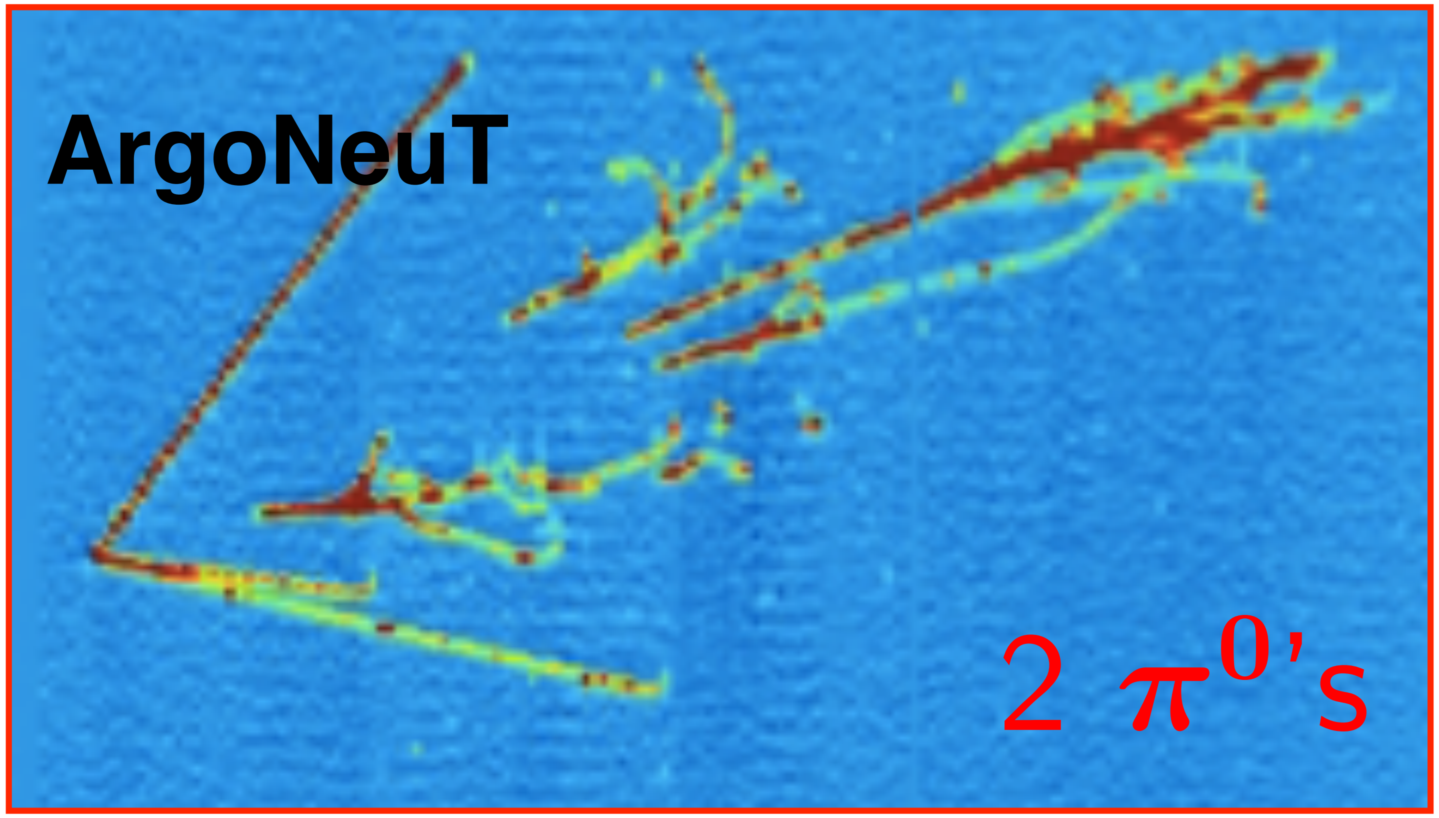
3 planes in DUNE

Staged Approach to 40 kt (fiducial)

Layout at the Sanford Underground Research Facility

- **Four chambers hosting four independent 10-kt FD modules**
  - Gives flexibility for staging & evolution of LAr-TPC technology design
    - Assume four **identical** cryostats: 15.1 (W) x 14.0 (H) x 62 (L) m^3
    - Assume the four 10-kt modules will be similar but **not identical**
- **Collaboration considering two LAr readout technologies**
  - Single-Phase (Ionization read out in the Liquid Ar)
    - Demonstrated by ICARUS, ArgoNut & MicroBooNE
    - Forms basis of first 10-kt detector
  - Dual-Phase (Ionization amplified and readout out in Gas phase)
    - Pioneered by WA105 (protoDUNE-DP)
    - Option for second and/or subsequent detector modules
  - Large-scale prototyping going in parallel at CERN: protoDUNE–SP & protoDUNE-DP

Events:



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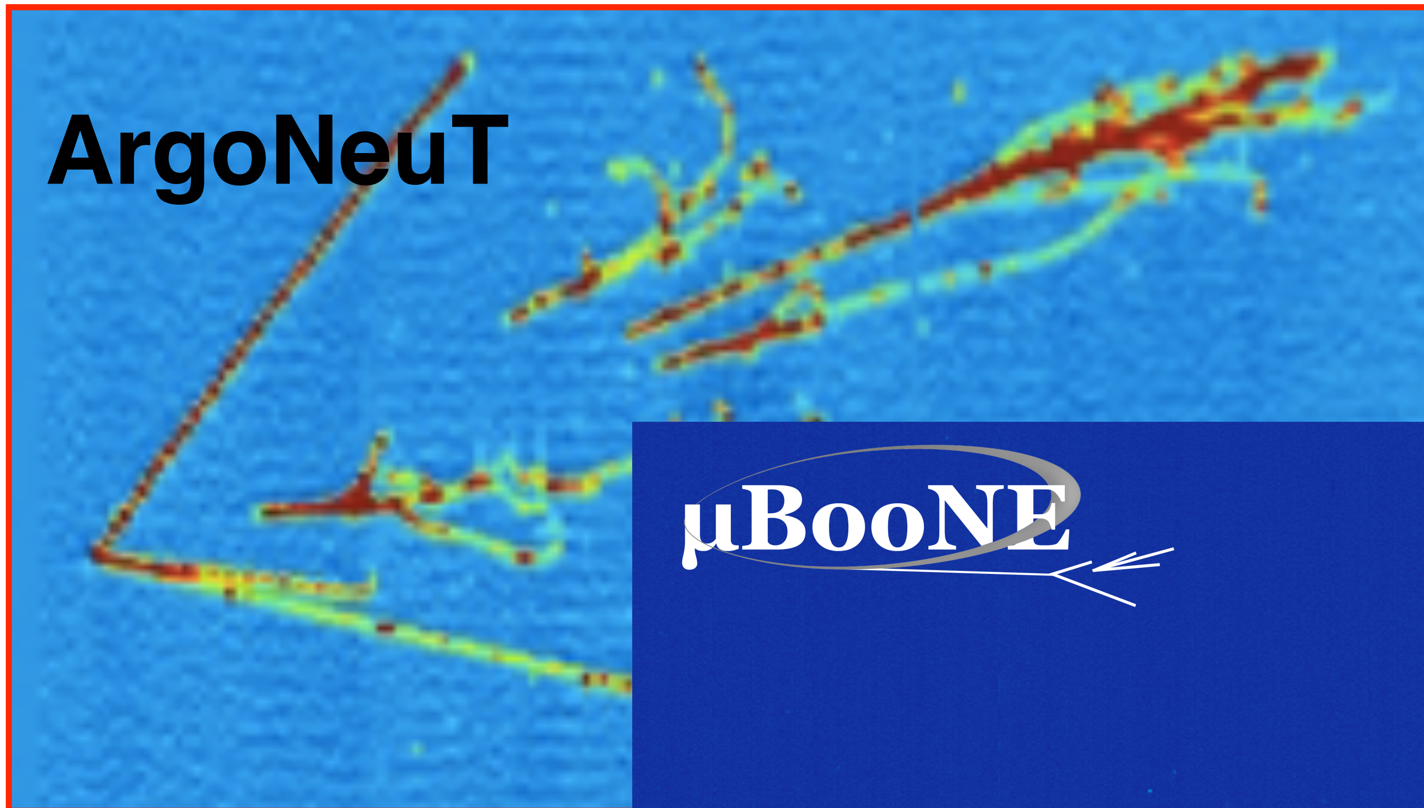
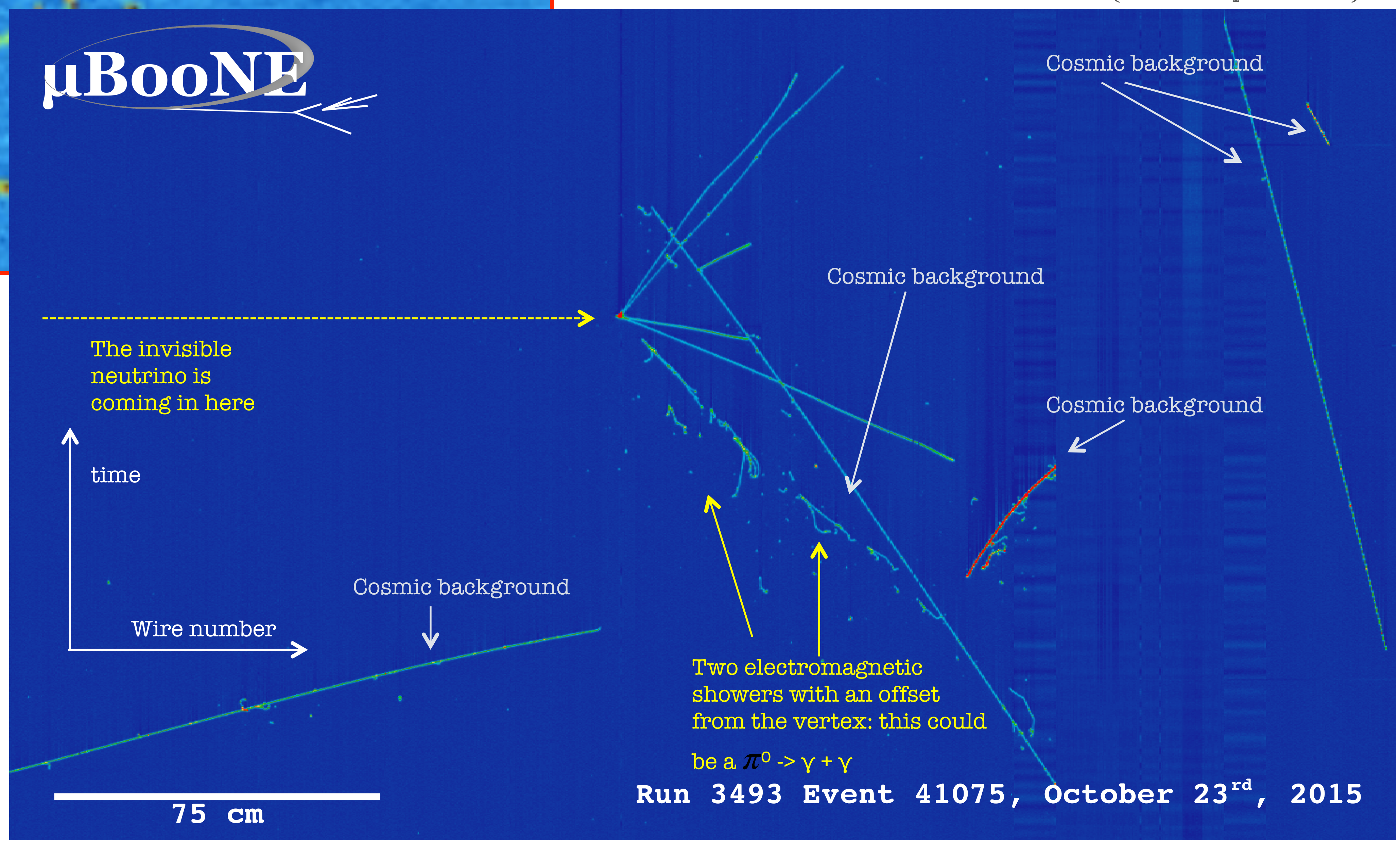


(collection plane view)



Physics of DUNE:

- **Neutrino Mass & Mixing Physics**
  - Stringent test of the 3 Neutrino paradigm
  - CP Violation, Mass Ordering, Dominant Flavor of ν_3, ...
- **Proton Decay**
  - especially $p \rightarrow K \nu$
- **SuperNova Neutrinos**
  - ν_e flux from core-collapse in Milky Way
- **Surprises !**
  - NSI, sterile ν, Lorentz Violation, ν decay, decoherent, ...

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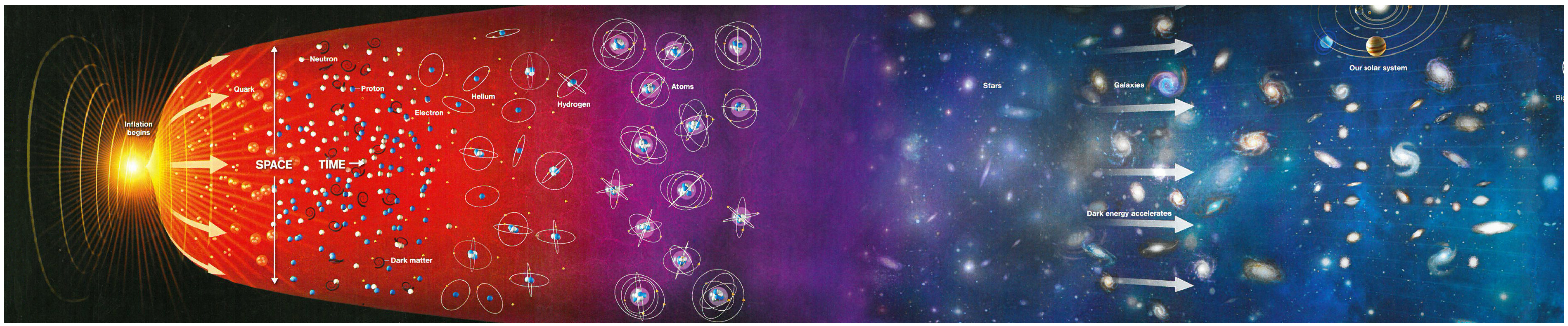
CP Violation:

DUNE will address big questions in science, e.g.

- **The matter-antimatter asymmetry in the Universe**
  - **CP Violation** in the leptonic sector



- **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: best bet to how this happened through "leptogenesis"

Observation of Neutrino Mass implies New Physics

- Right Handed Neutrino + Lepton # Conservation (Dirac)

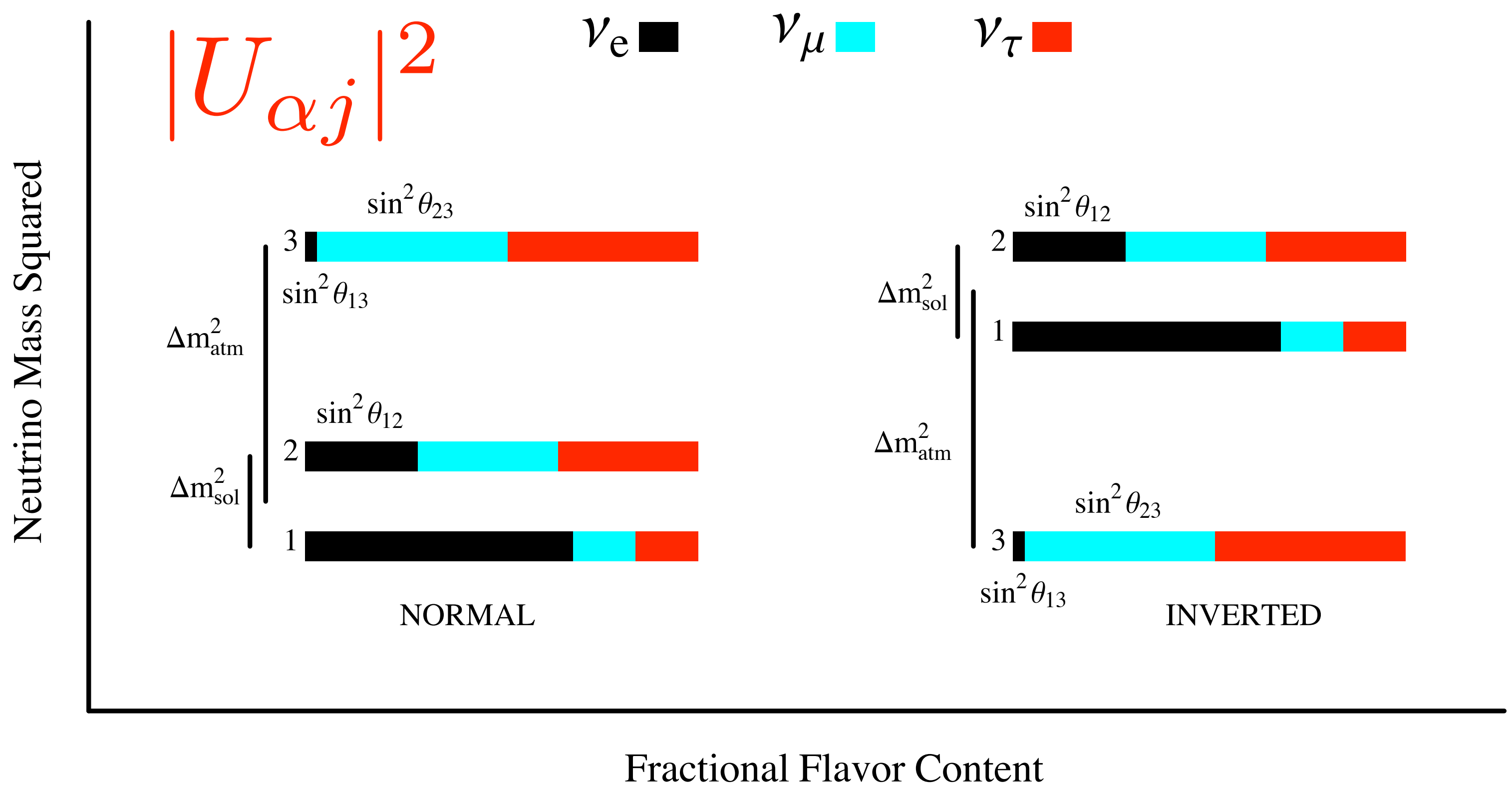
  - OR

- New Interactions: (LH)^2 (Majorana)

- WHAT IS THE MASS SCALE OF THE NEW PHYSICS?

Flavor Content of Mass Eigenstates:

- Labeling massive neutrinos: $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$



O. Mena & SP
hep-ph/0312131

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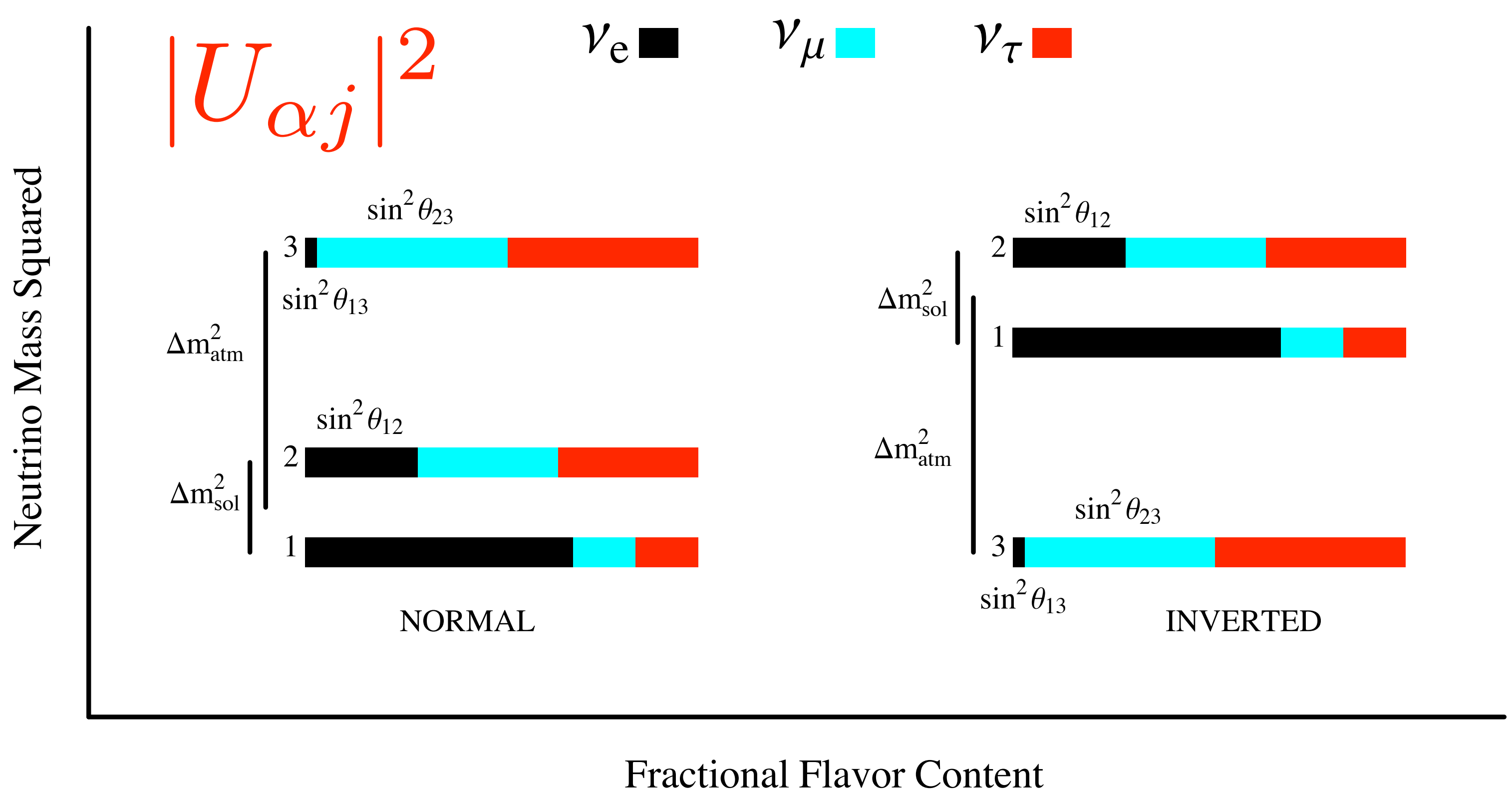

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$$\boldsymbol{\delta m^2_{sol} = +7.6 \times 10^{-5}}\ \mathrm{eV}^2$$

$$|\boldsymbol{\delta m^2_{atm}}| = \mathbf{2.4 \times 10^{-3}}\ \mathrm{eV}^2$$

$$\sqrt{\delta m^2_{atm}} = 0.05\ \mathrm{eV} < \sum m_{\nu_i} < 0.5\ \mathrm{eV}.$$

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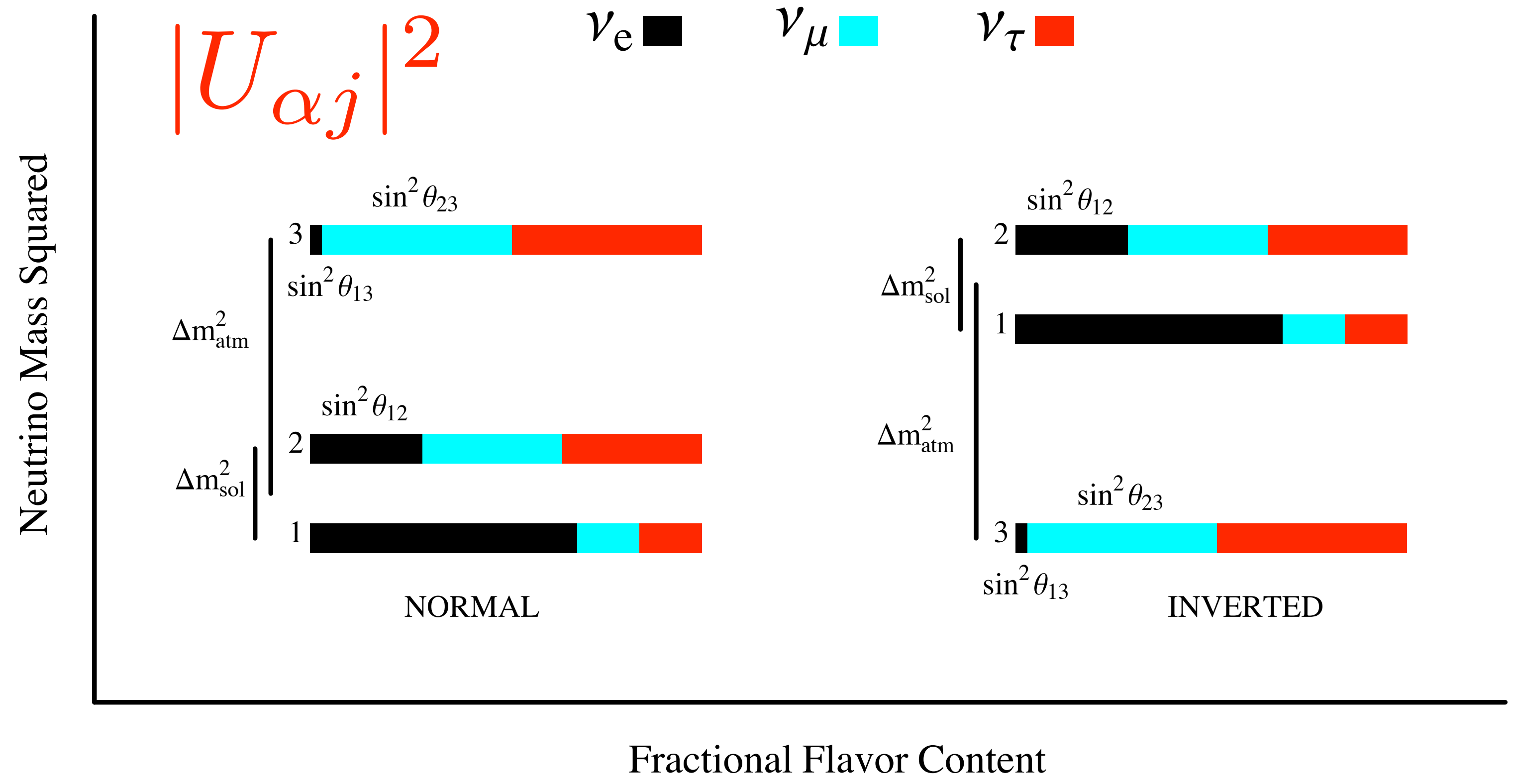

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$$\sin^2\theta_{23} \sim \frac{1}{2}$$

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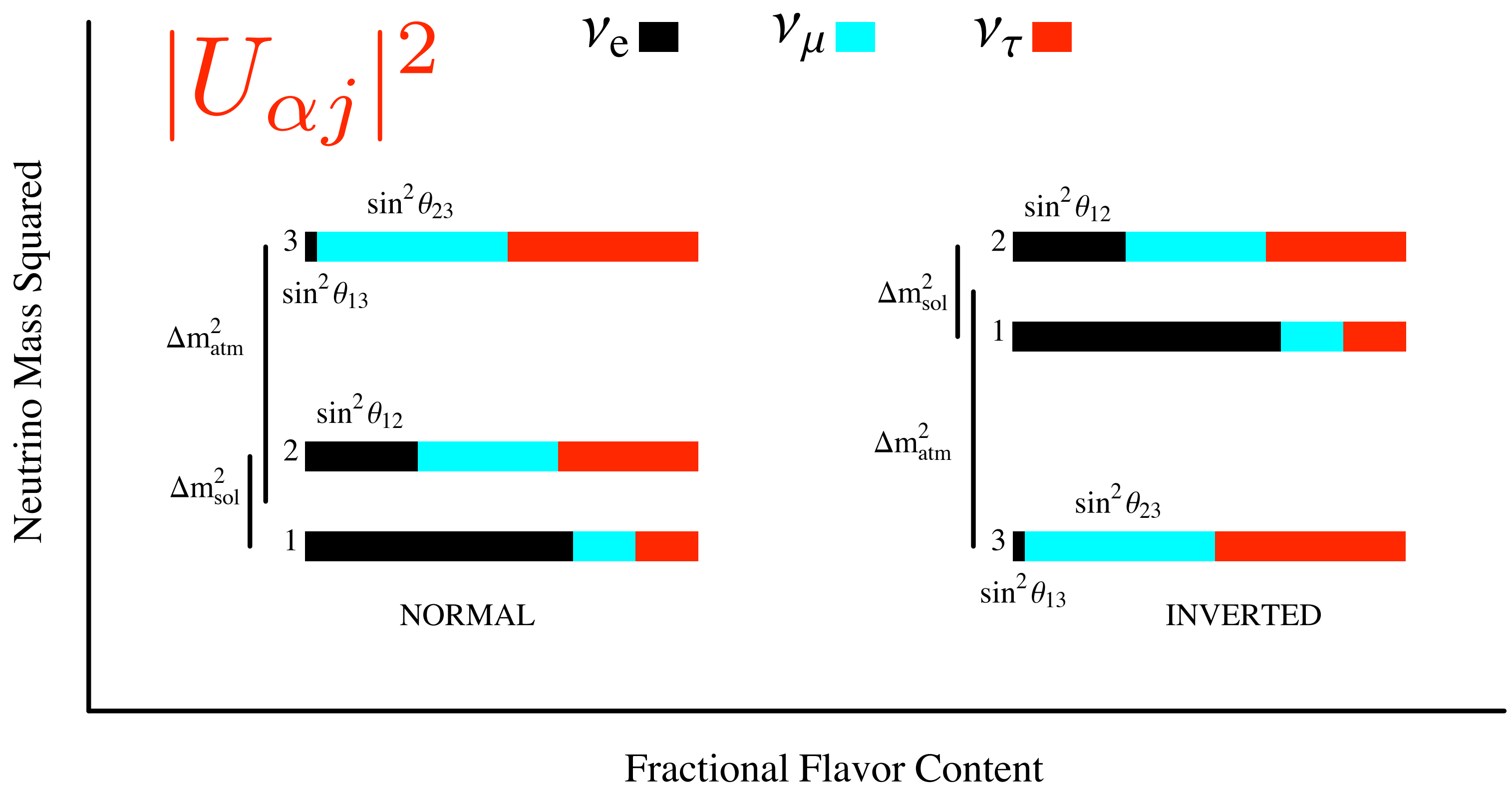

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$$0 \leq \delta < 2\pi$$

The Three Important Questions:

- Is there CP Violation
- Mass Ordering
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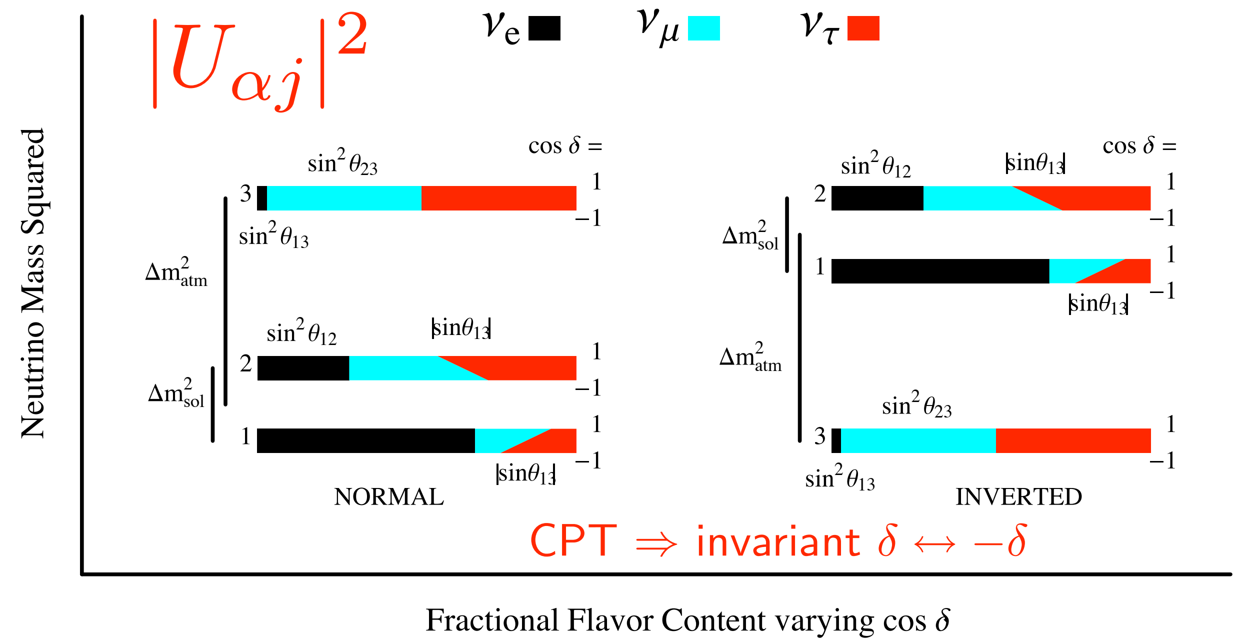

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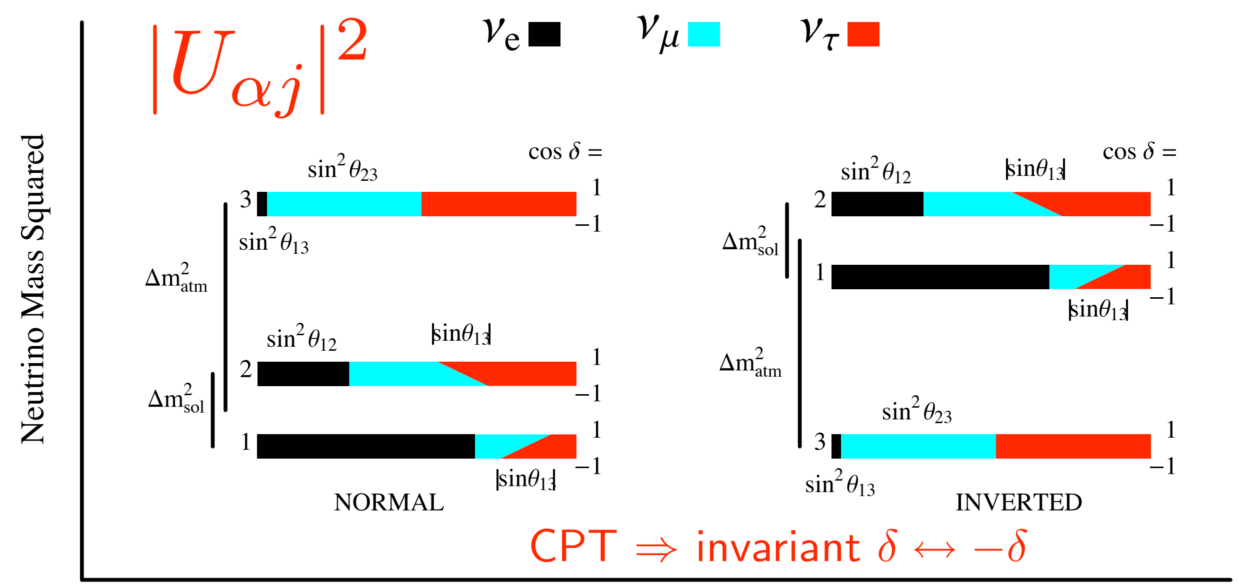

Fractional Flavor Content varying cos δ

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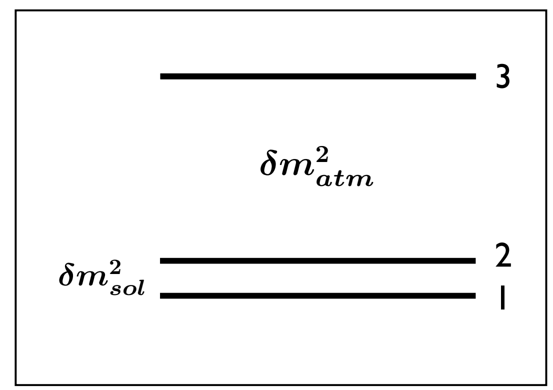
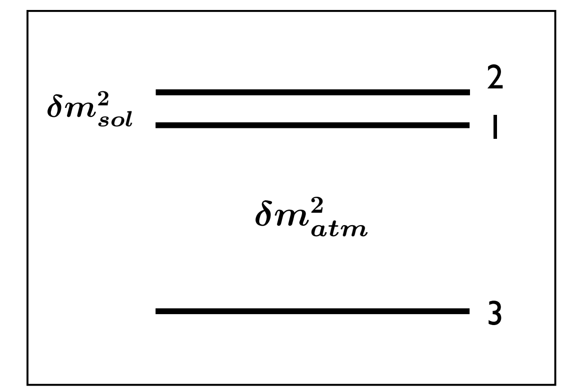
- Mass Ordering



OR



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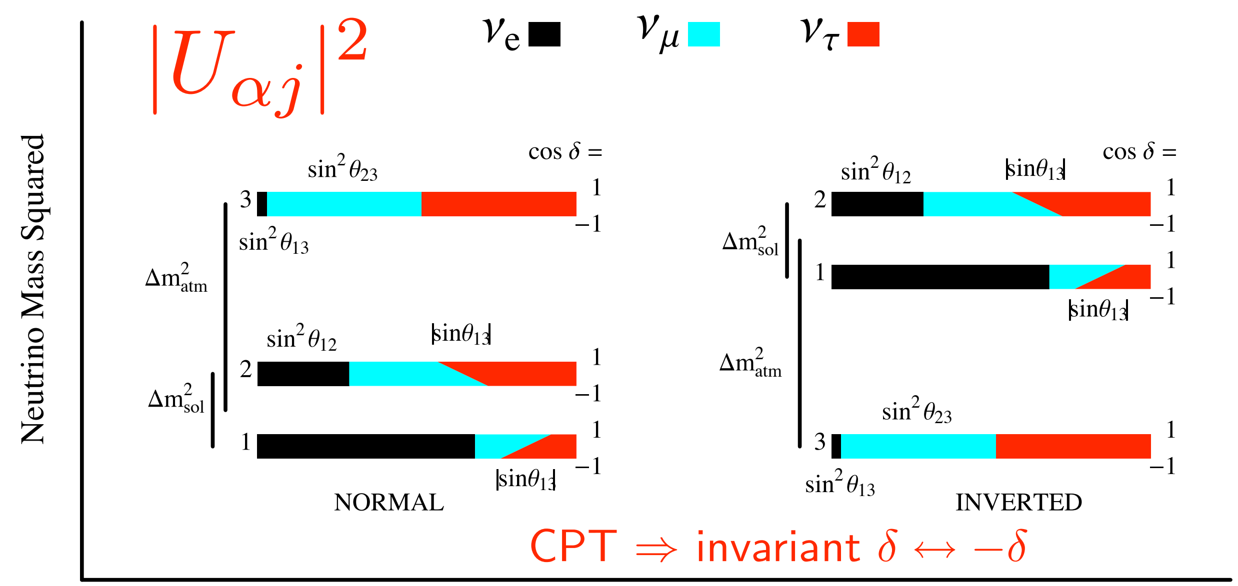

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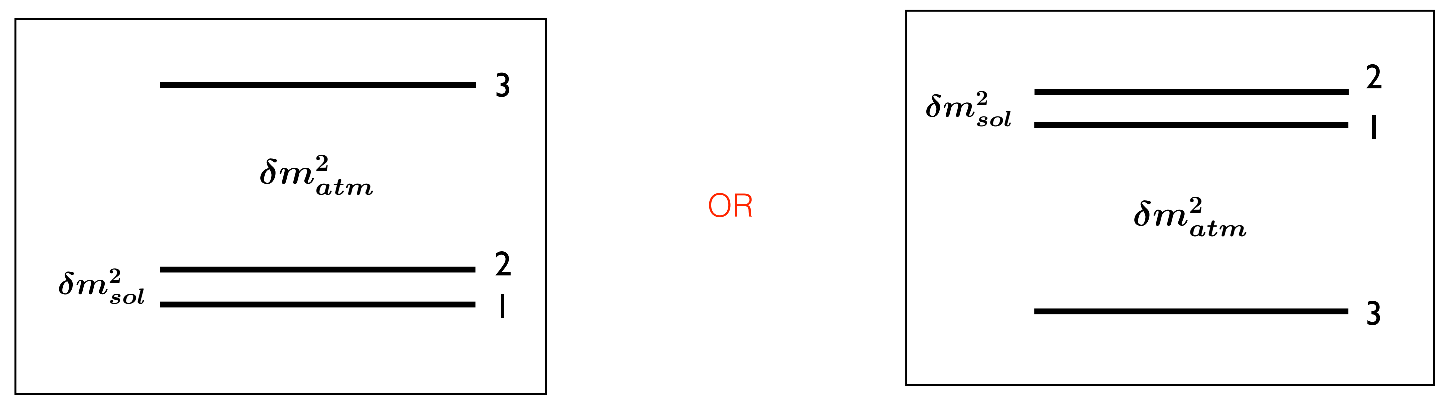
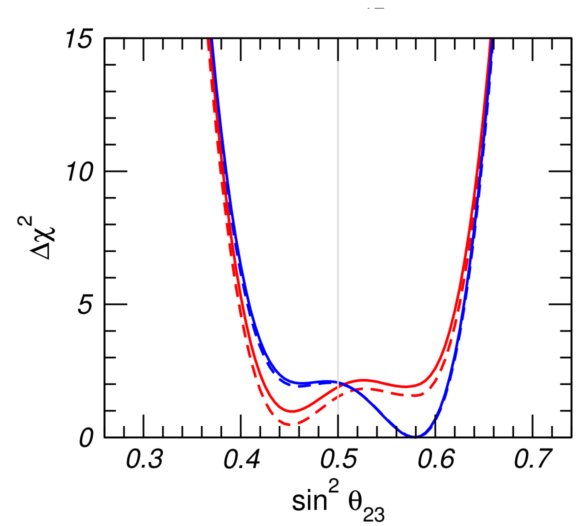
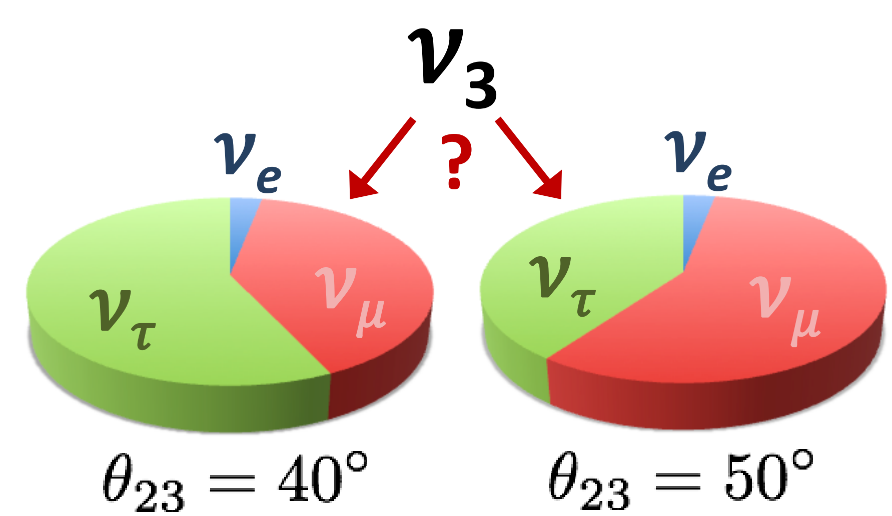


- Dominant Flavor Content of ν_3

θ_{23} octant ?





nueutrino SM Physics Channels:

Appearance: $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$

Disappearance: $\nu_\mu \to \nu_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_\mu$

In Matter: $\nu_\mu \longrightarrow \nu_e$

$$P_{\mu\to e} \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{sol}}|^2$$

where $\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{31}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}$

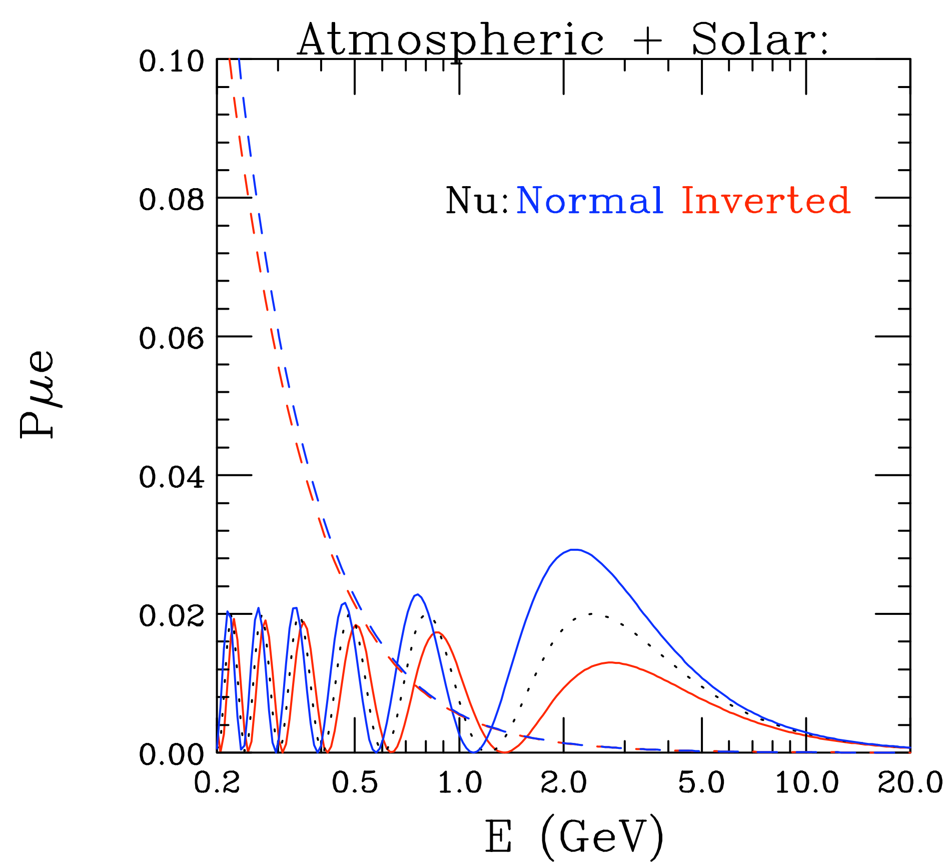
and $\sqrt{P_{sol}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$

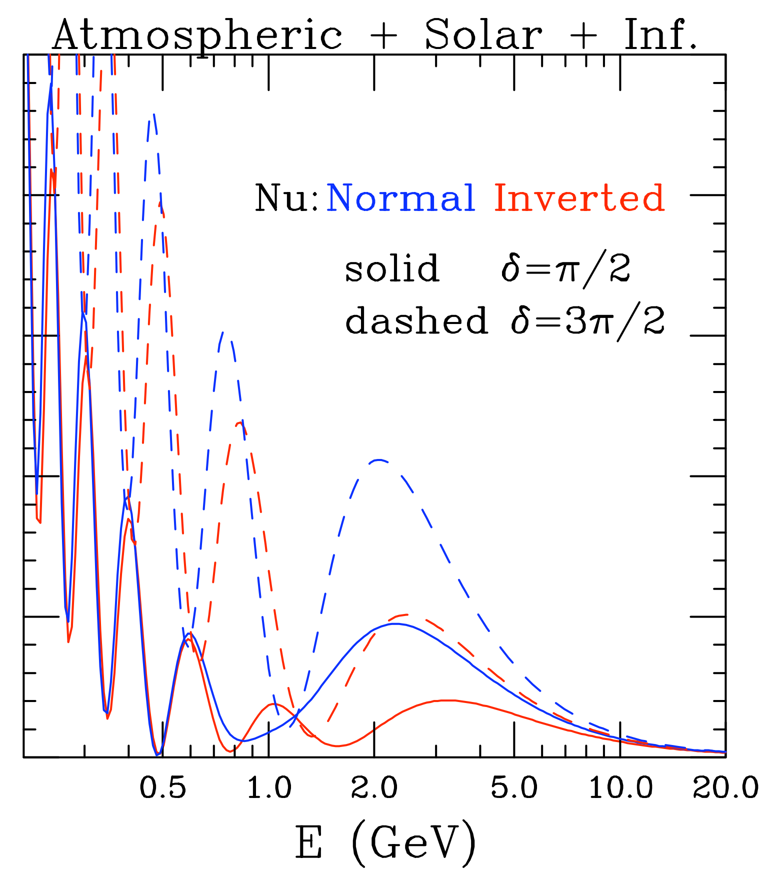
Cervera etal
hep-ph/0002108

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1},$$

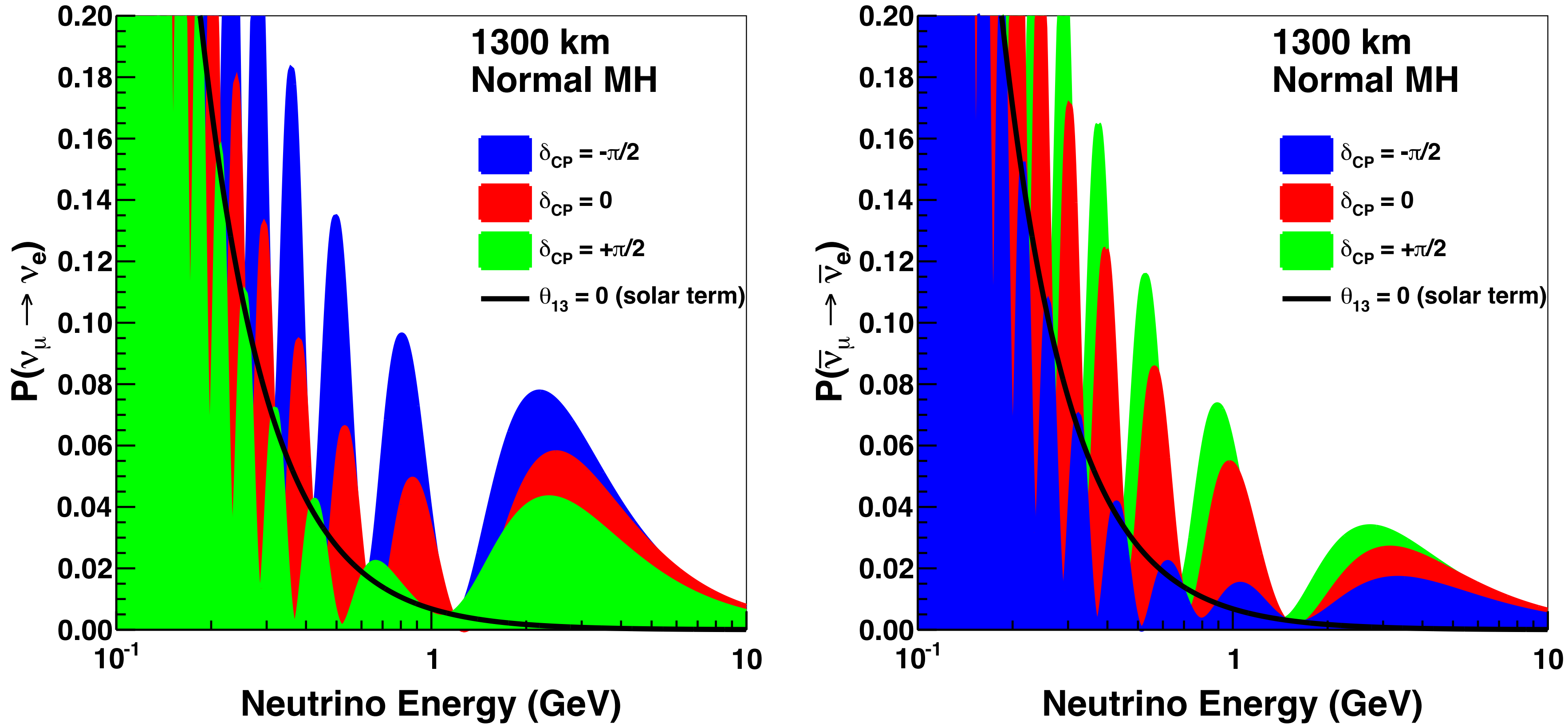
Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$

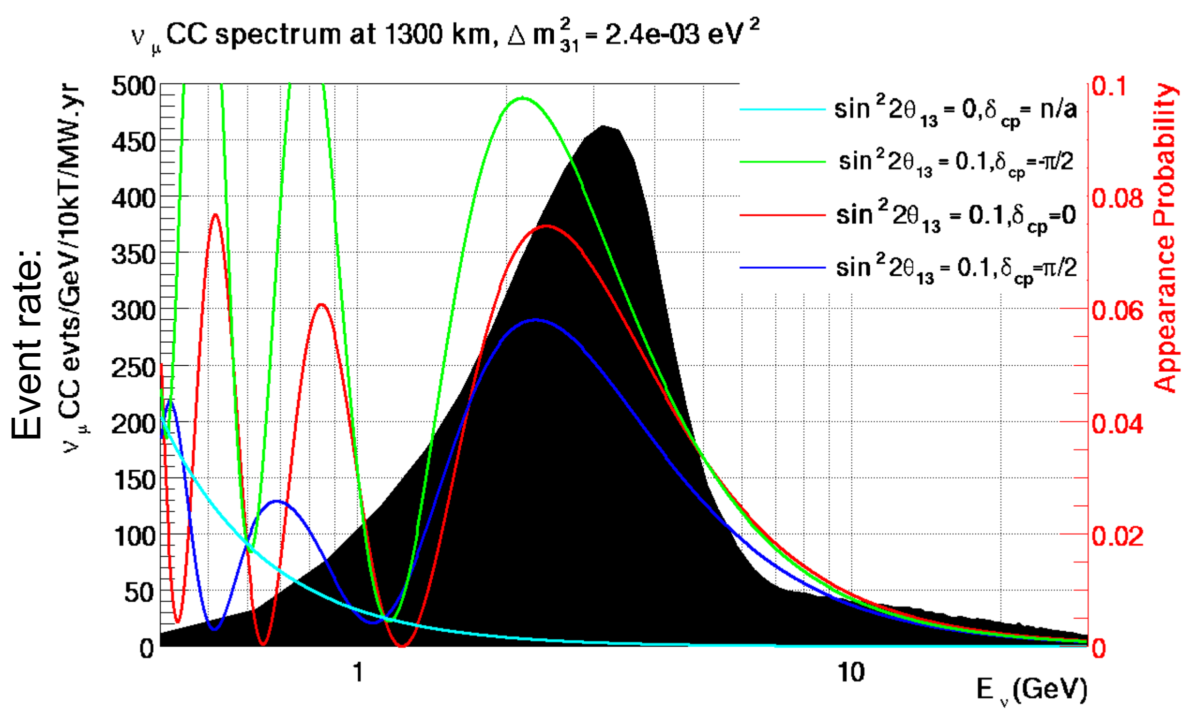




$$\boxed{P_{\mu\to e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32}\pm\delta) + P_{sol}}$$

only CPV


1300 km
Normal MH
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\delta_{CP} = +\pi/2$
$\theta_{13} = 0$ (solar term)
$P(\nu_\mu \to \nu_e)$
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
Neutrino Energy (GeV)

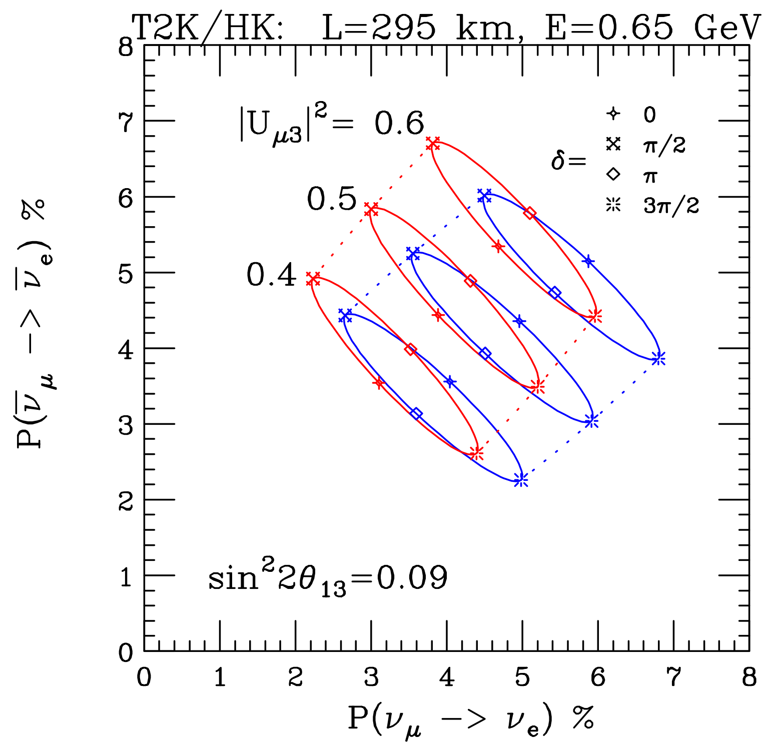

ν_μ CC spectrum at 1300 km, $\Delta m^2_{31} = 2.4\text{e-}03\ eV^2$
Event rate:
ν_μ CC evts/GeV/10kT/MW.yr
$\sin^2 2\theta_{13} = 0, \delta_{cp} =$ n/a
$\sin^2 2\theta_{13} = 0.1, \delta_{cp} = -\pi/2$
$\sin^2 2\theta_{13} = 0.1, \delta_{cp} = 0$
$\sin^2 2\theta_{13} = 0.1, \delta_{cp} = \pi/2$
Appearance Probability
E_ν (GeV)

Correlations between Neutrino and Antineutrino nu_e Appearance

Minakata & Nunokawa
hep-ph/010805

Normal Ordering — **Inverted Ordering**

T2K/HK



$\nu_\mu \rightarrow \nu_\mu$ gives:

$$\sin^2 2\theta_{\mu\mu} \equiv 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = 0.96 \; - \; 1.00$$

$|U_{\mu 3}|^2 \leftrightarrow (1 - |U_{\mu 3}|^2)$ degeneracy !

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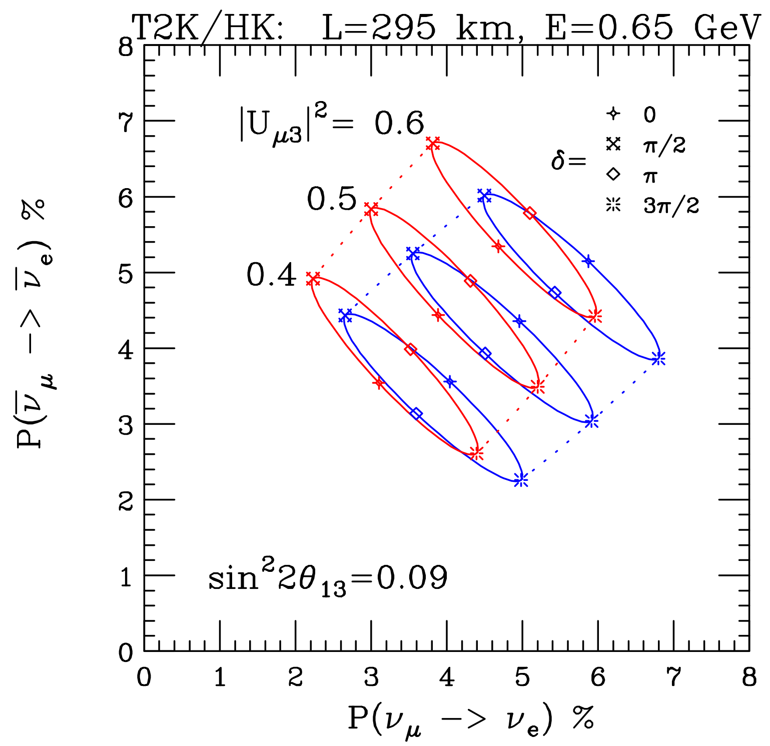
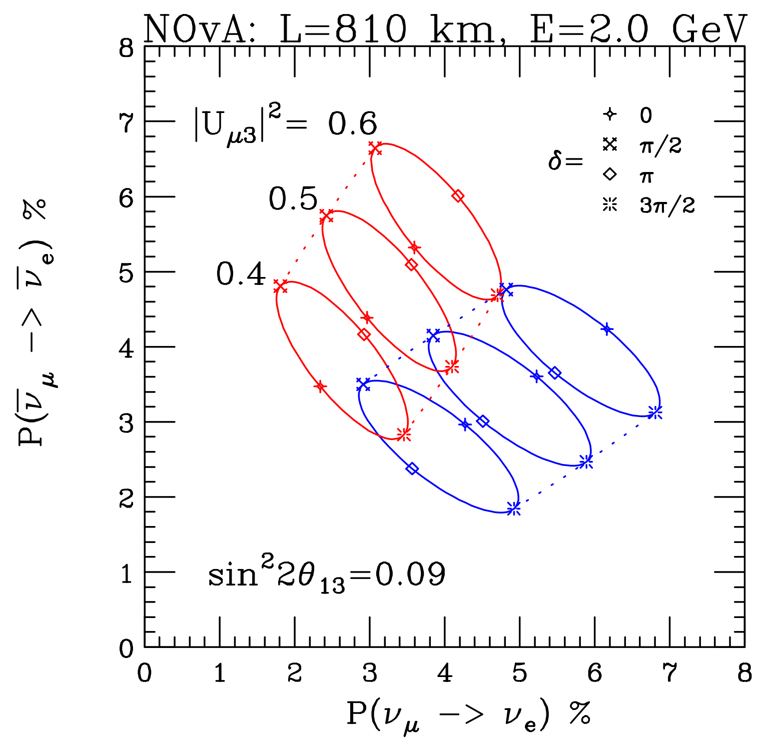


NOvA



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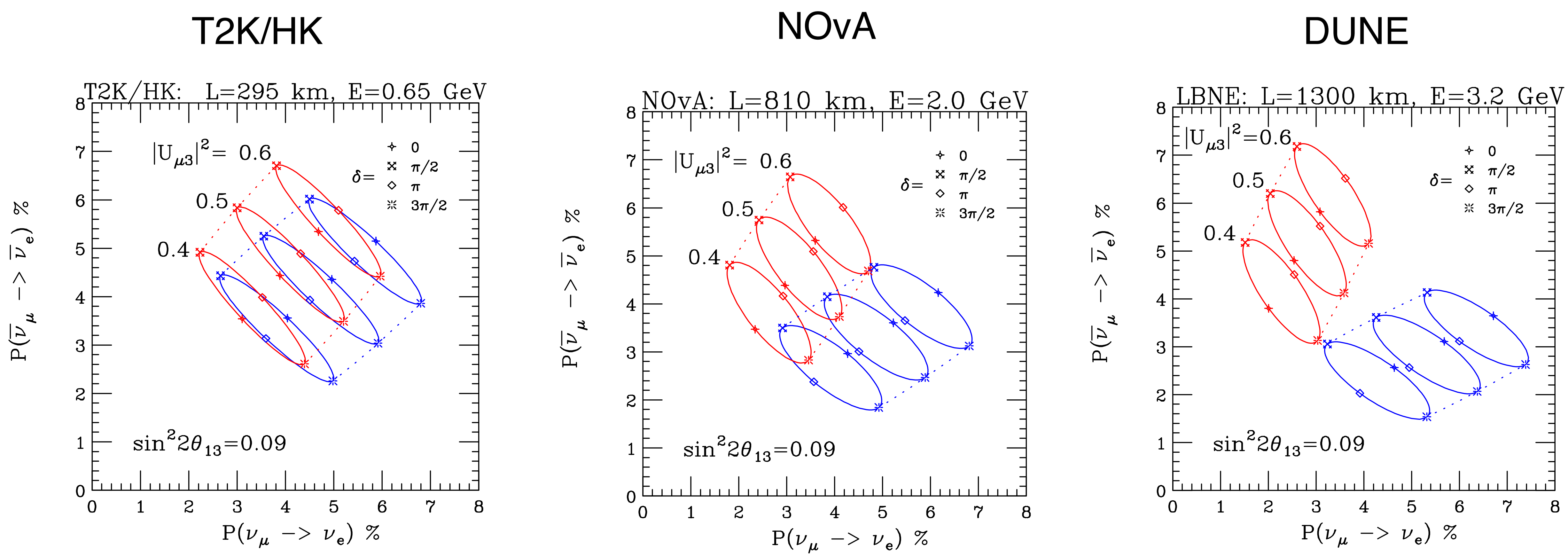

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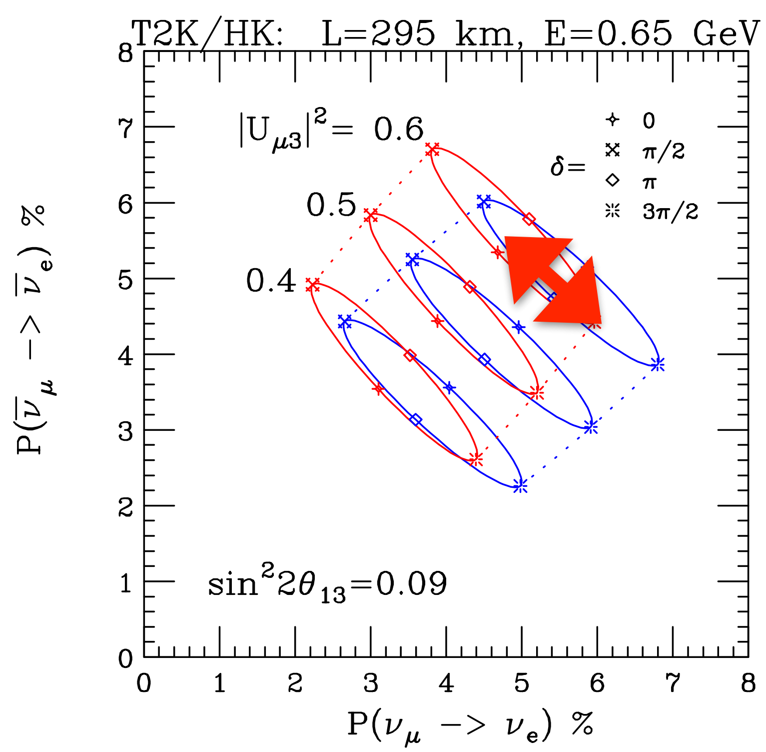

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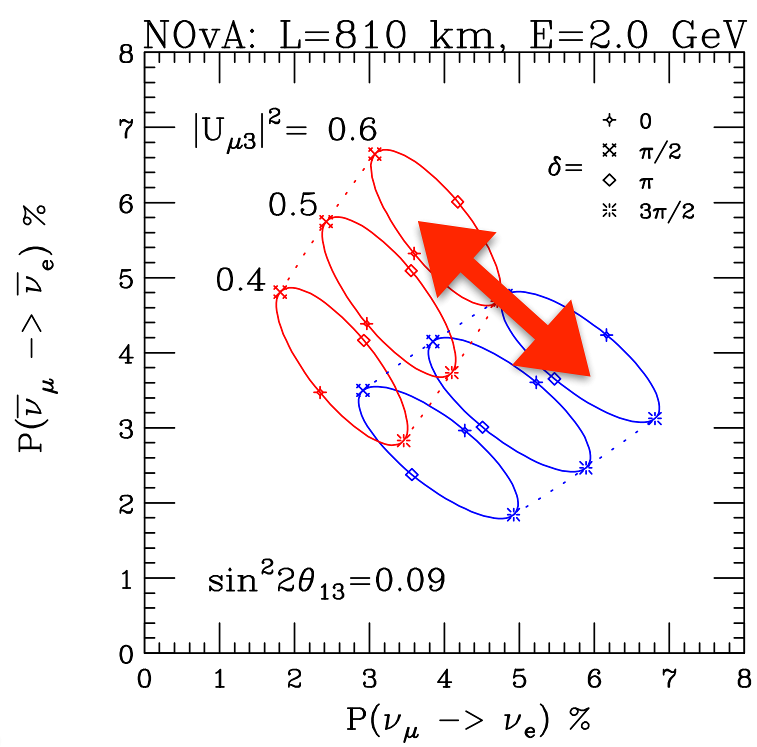
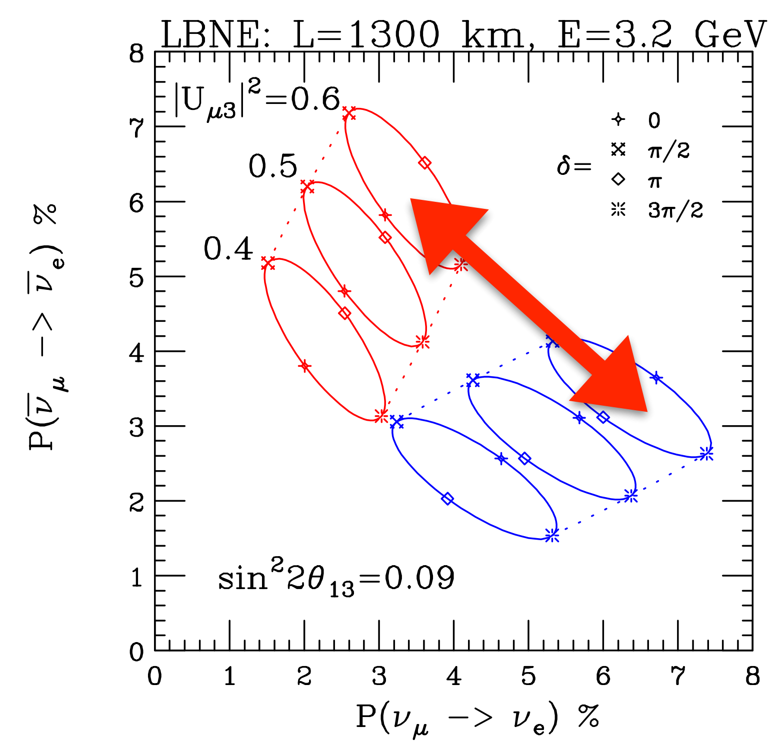


DUNE



$\propto \rho L \ \sin^2 \theta_{23}$

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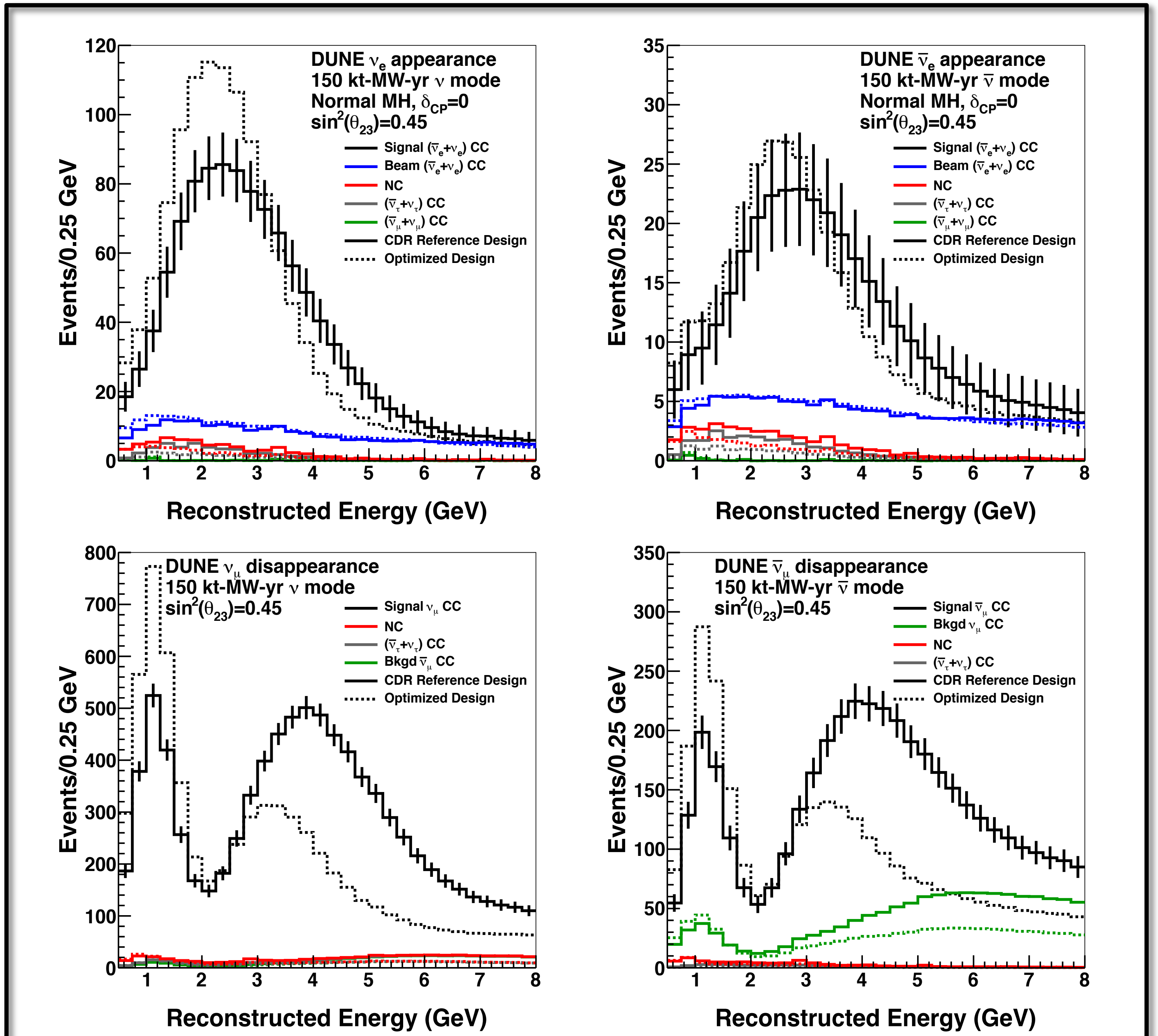
Sensitivity Calculations:

Appearance: $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$

DUNE CDR:

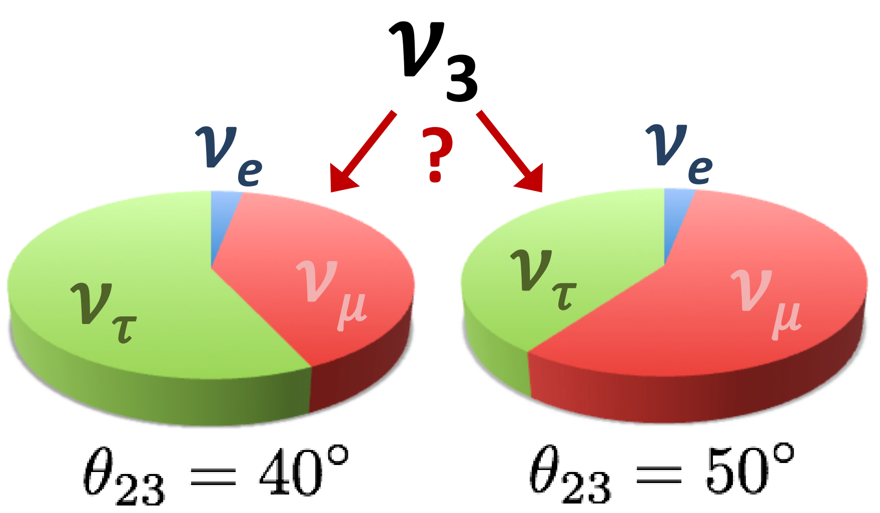


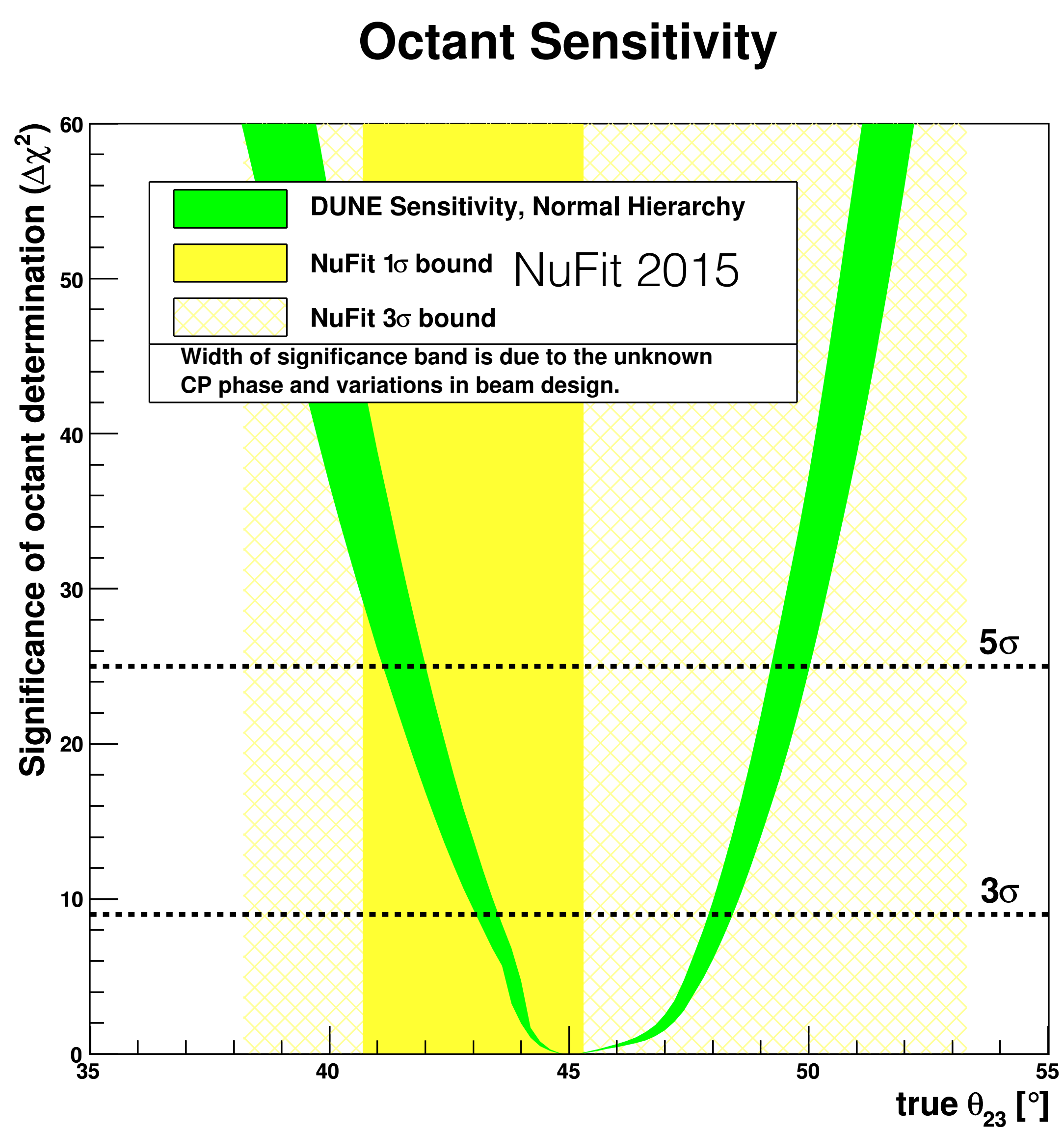
- GLoBES-based fit to four FD samples
- Two neutrino beam line designs considered
- GENIE event generator
- Reconstructed spectra predicted using detector response parameterized at the single particle level
- Simple systematics treatment
- GLoBES configurations to be made public soon

Disappearance: $\nu_\mu \to \nu_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_\mu$

Dominant Flavor of Nu_3

~ 40 ktons x 2 MW x 10 years



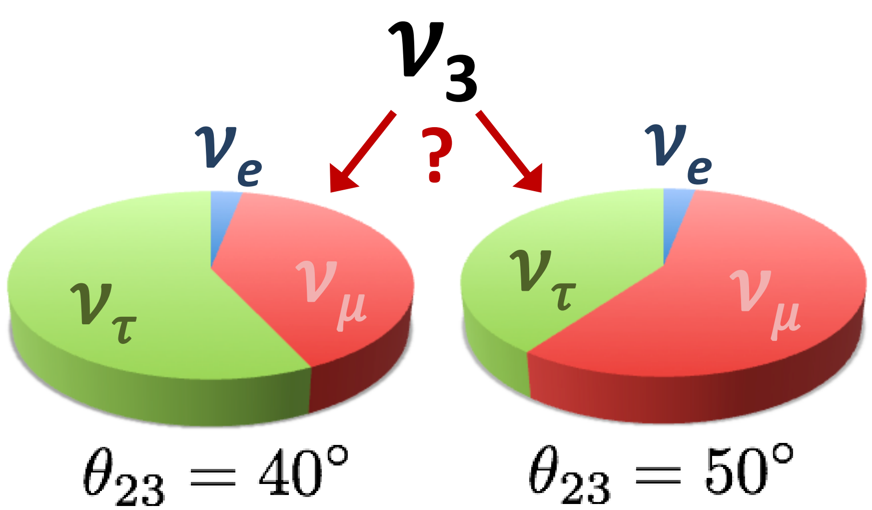


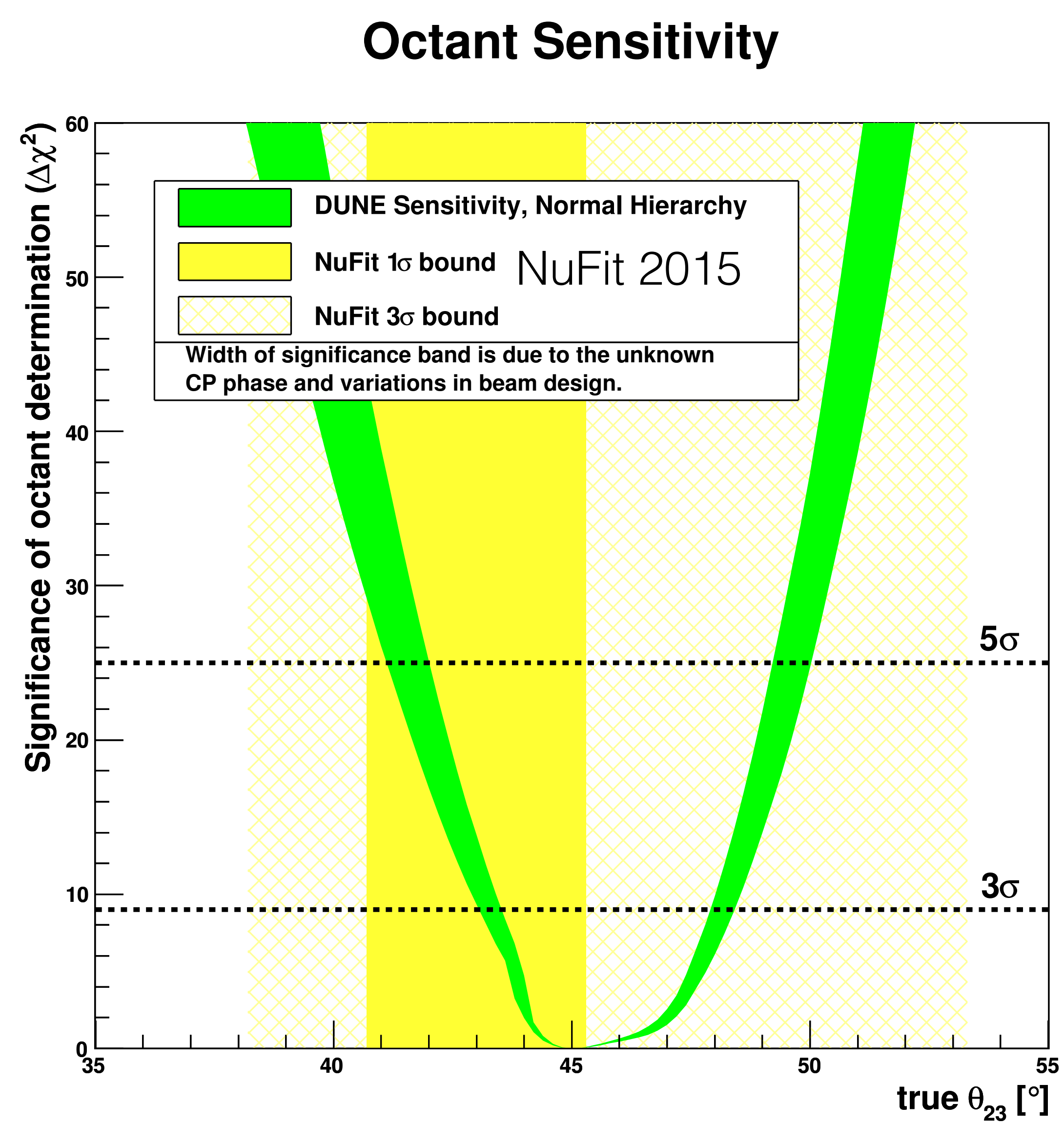
$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\,[1 - P(\bar{\nu}_e \to \bar{\nu}_e)]$$

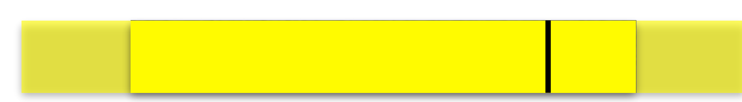
Long Baseline @VOM Reactors

Dominant Flavor of Nu_3

~ 40 ktons x 2 MW x 10 years





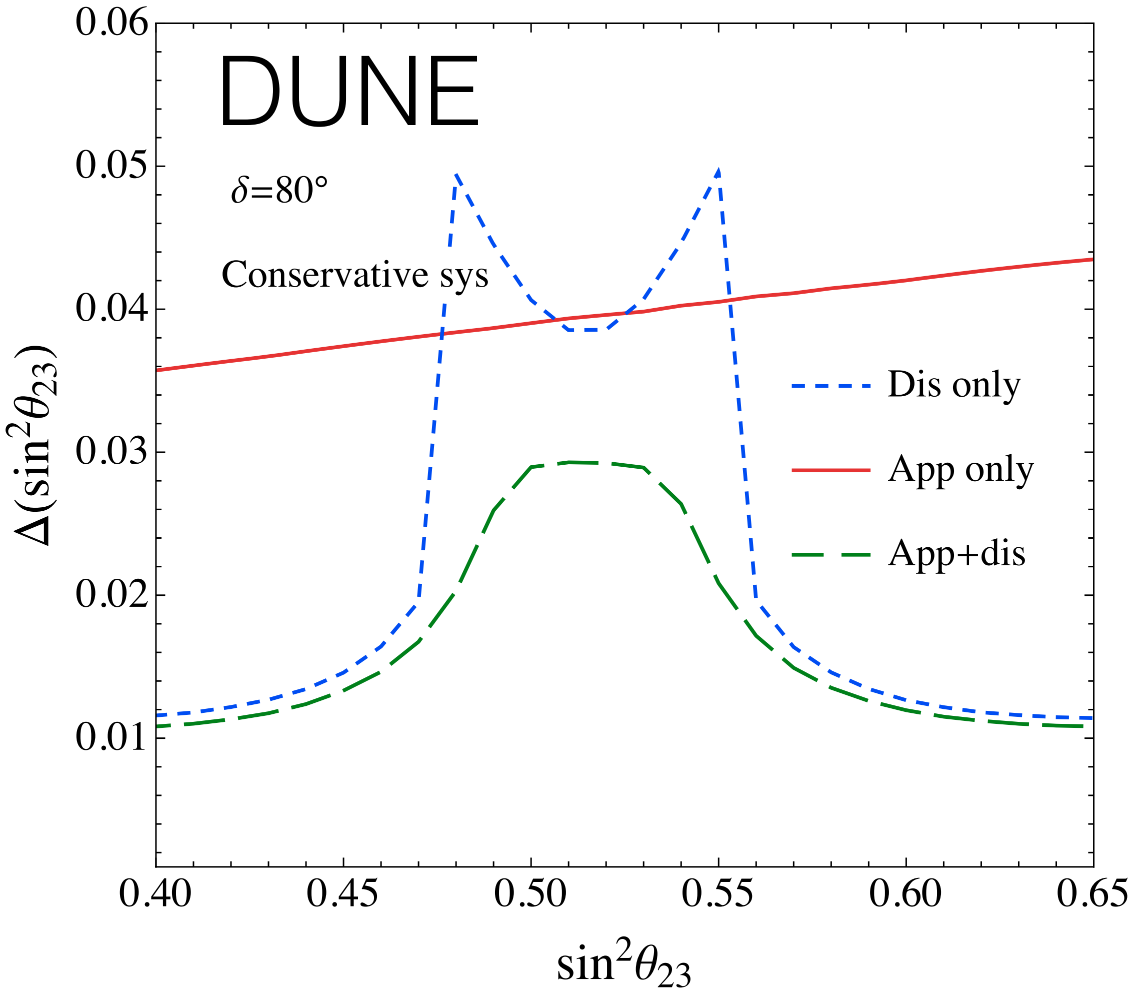


NuFit 2016

$$P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx 2\sin^2\theta_{23}\,[1 - P(\bar{\nu}_e \to \bar{\nu}_e)]$$

Long Baseline @VOM Reactors

Disappearance v Appearance for: θ_{23}



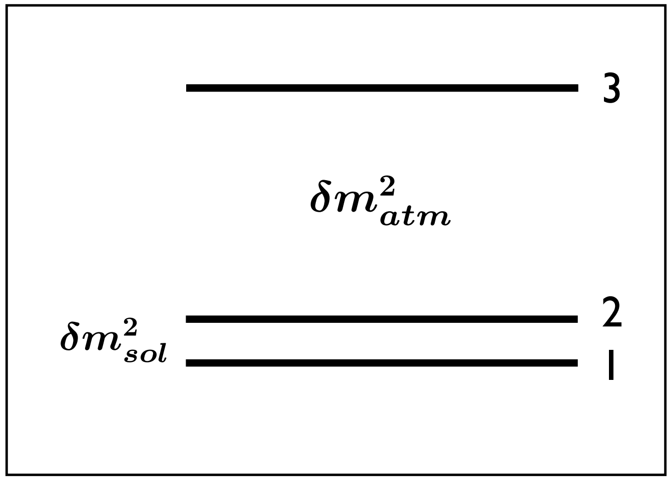
Appearance

Disappearance

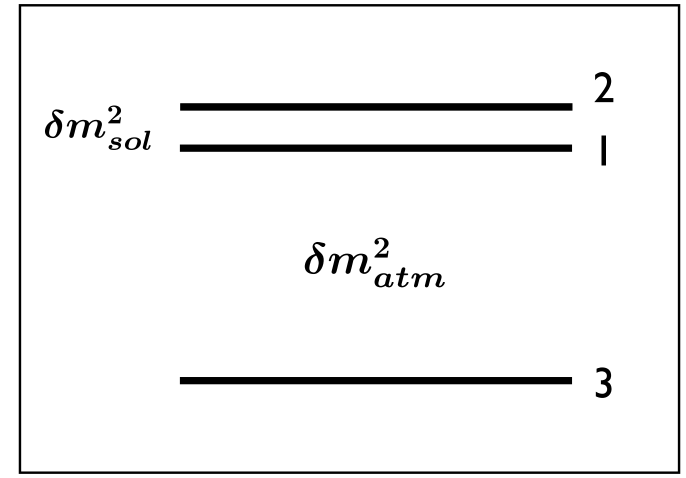
Combined

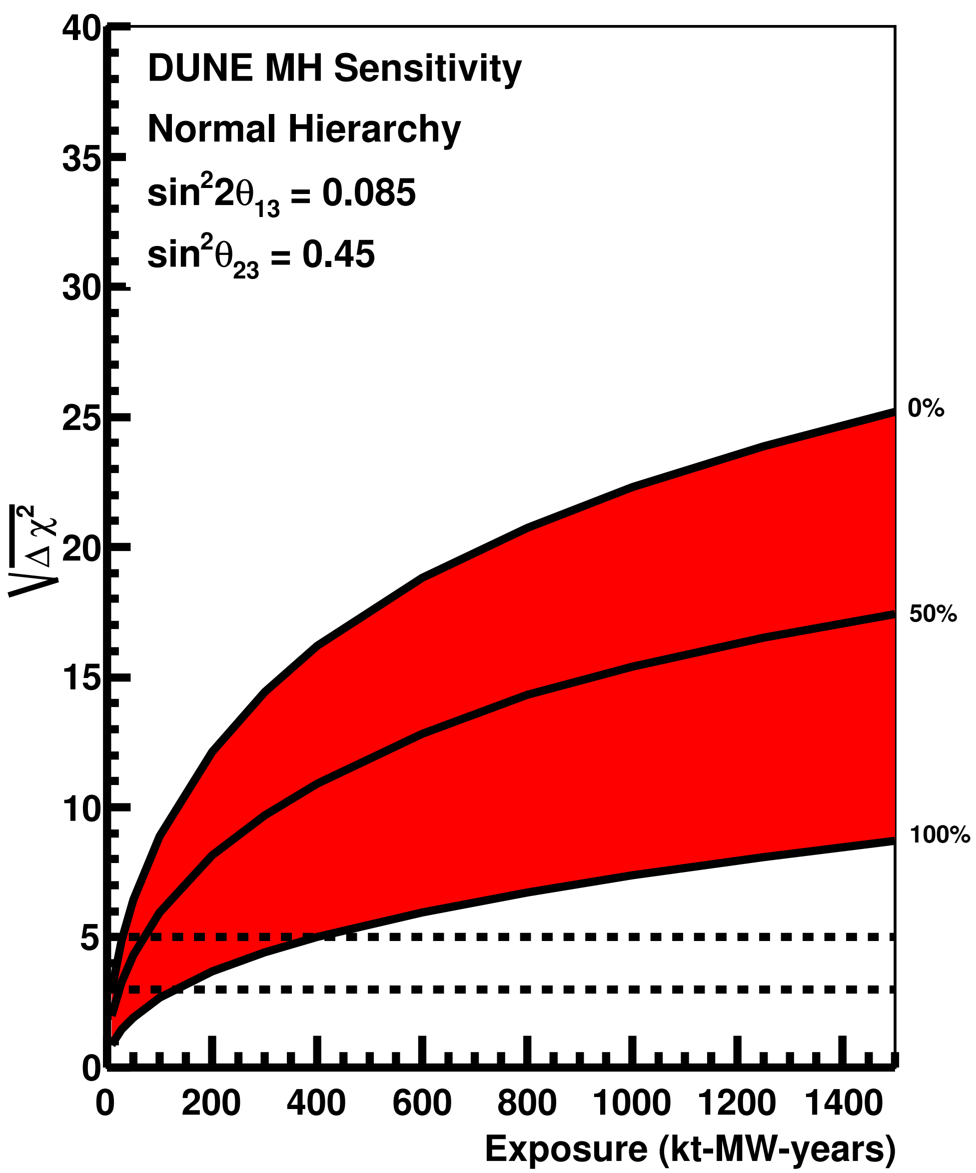
Minakata, Parke 1303.6178; Coloma, Minakata, Parke 1406.2551

Mass Ordering:

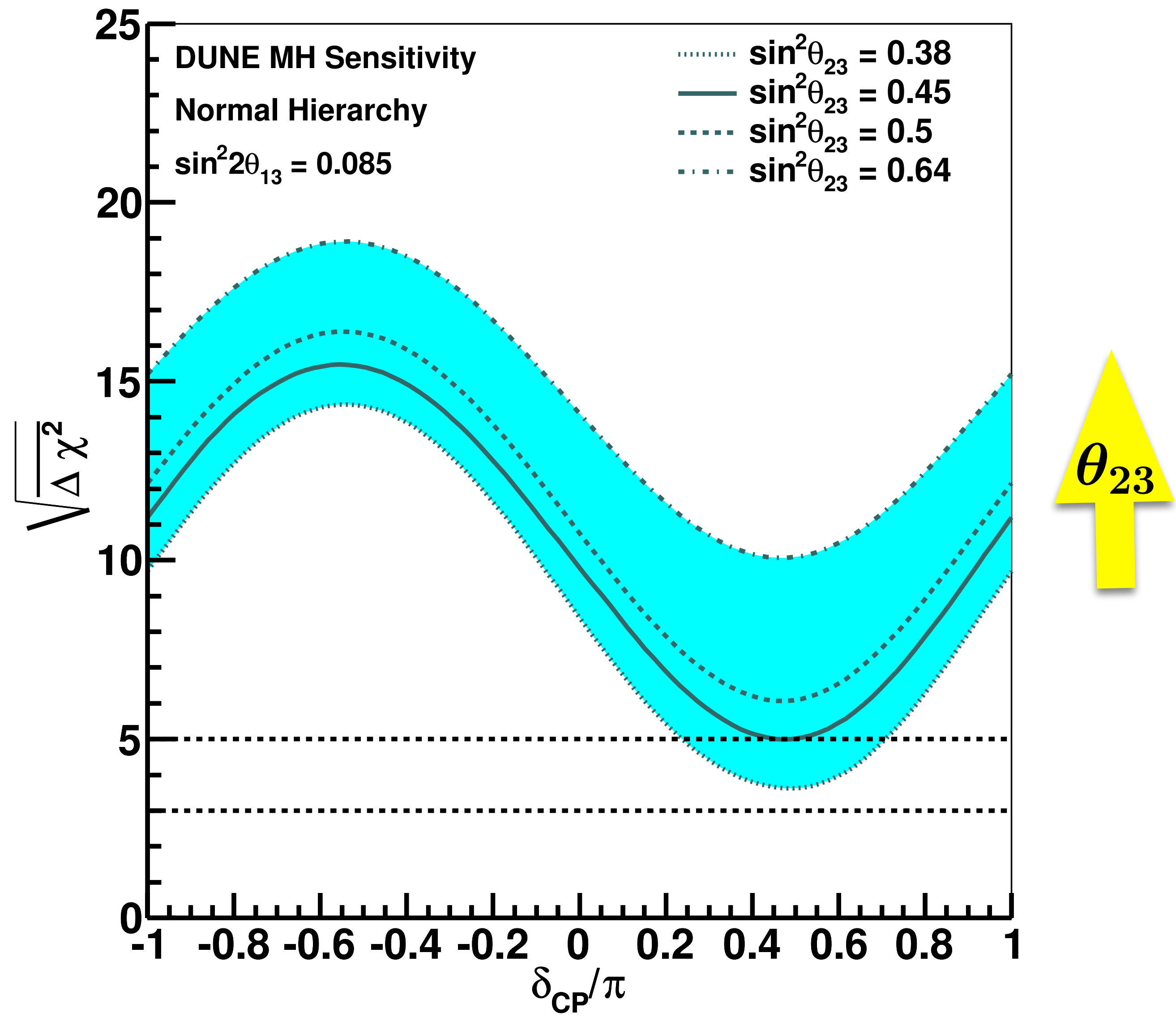


OR





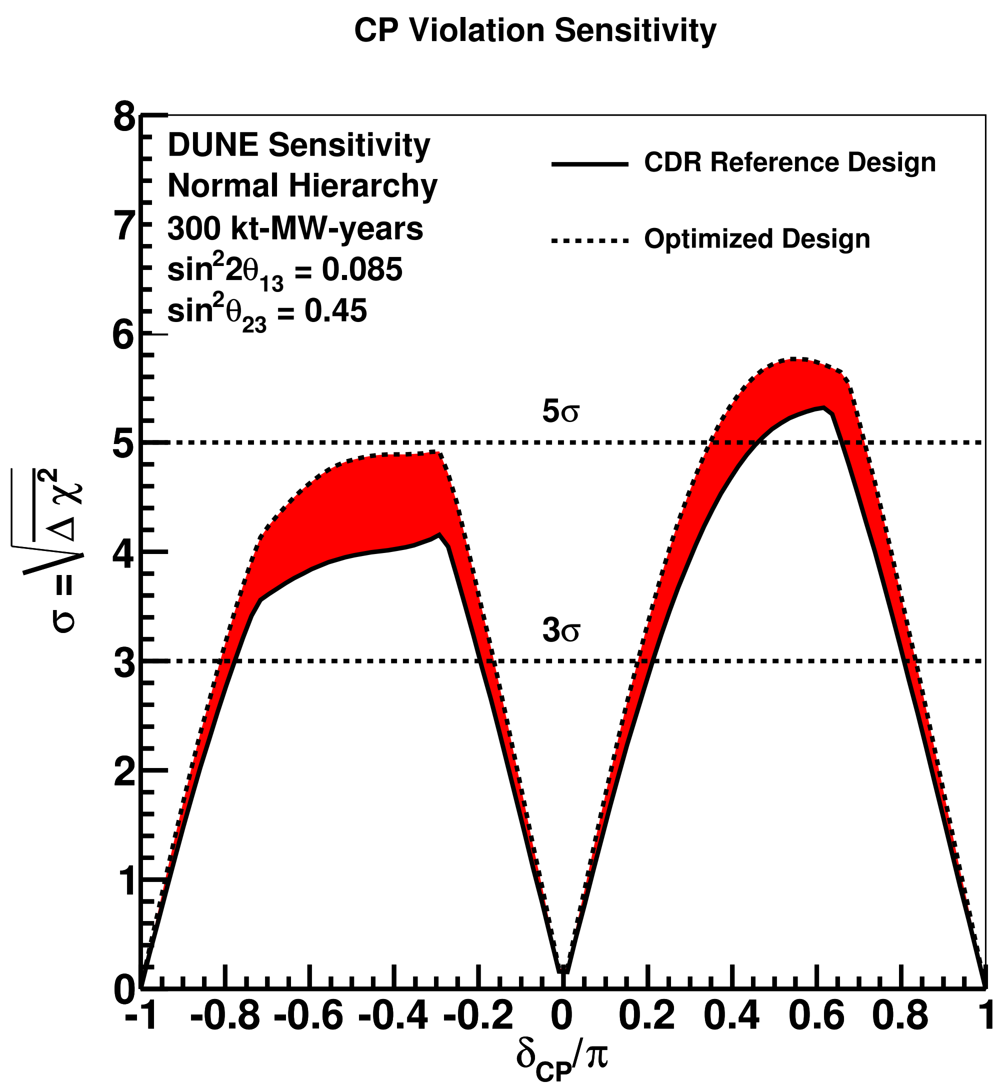
Mass Hierarchy Sensitivity

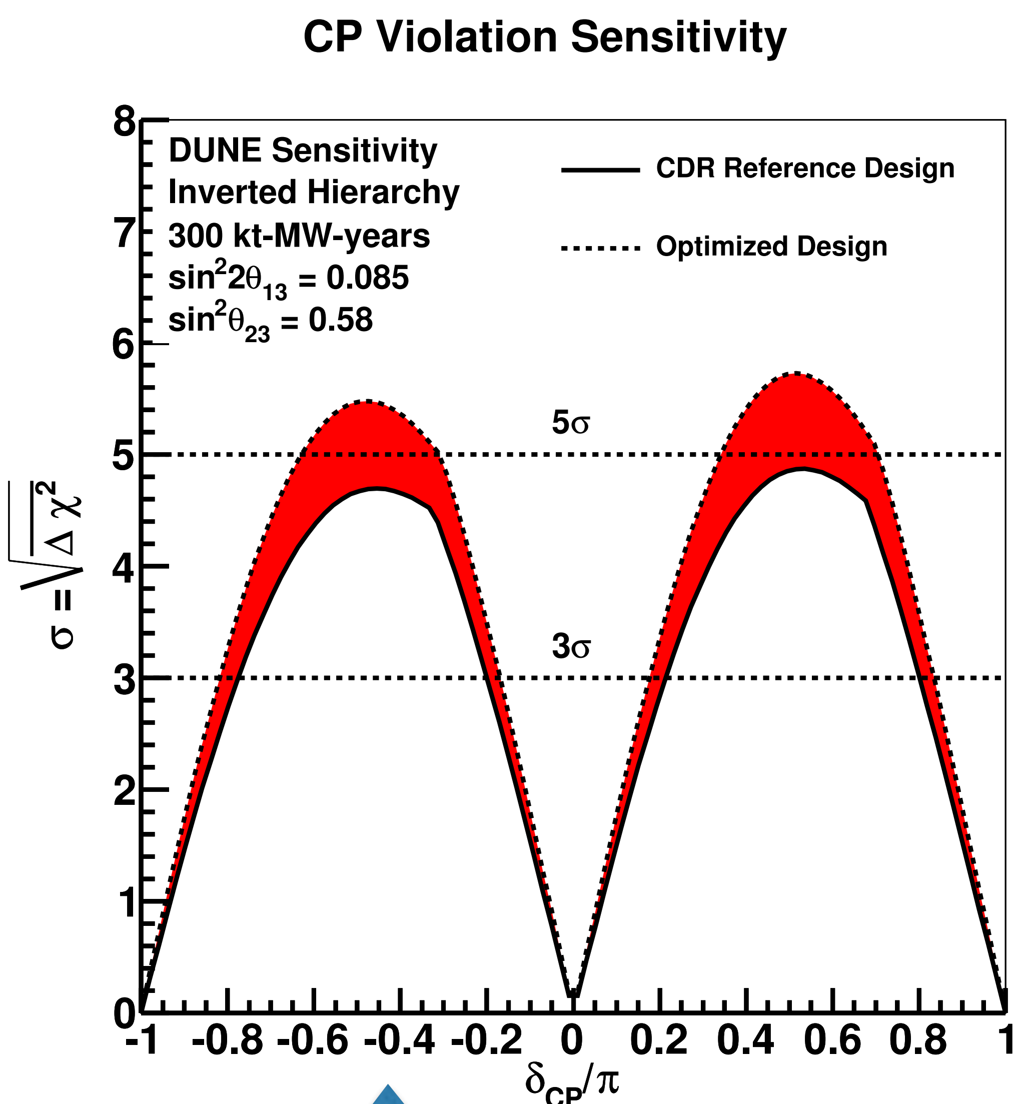


CP Violation:

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

in vacuum

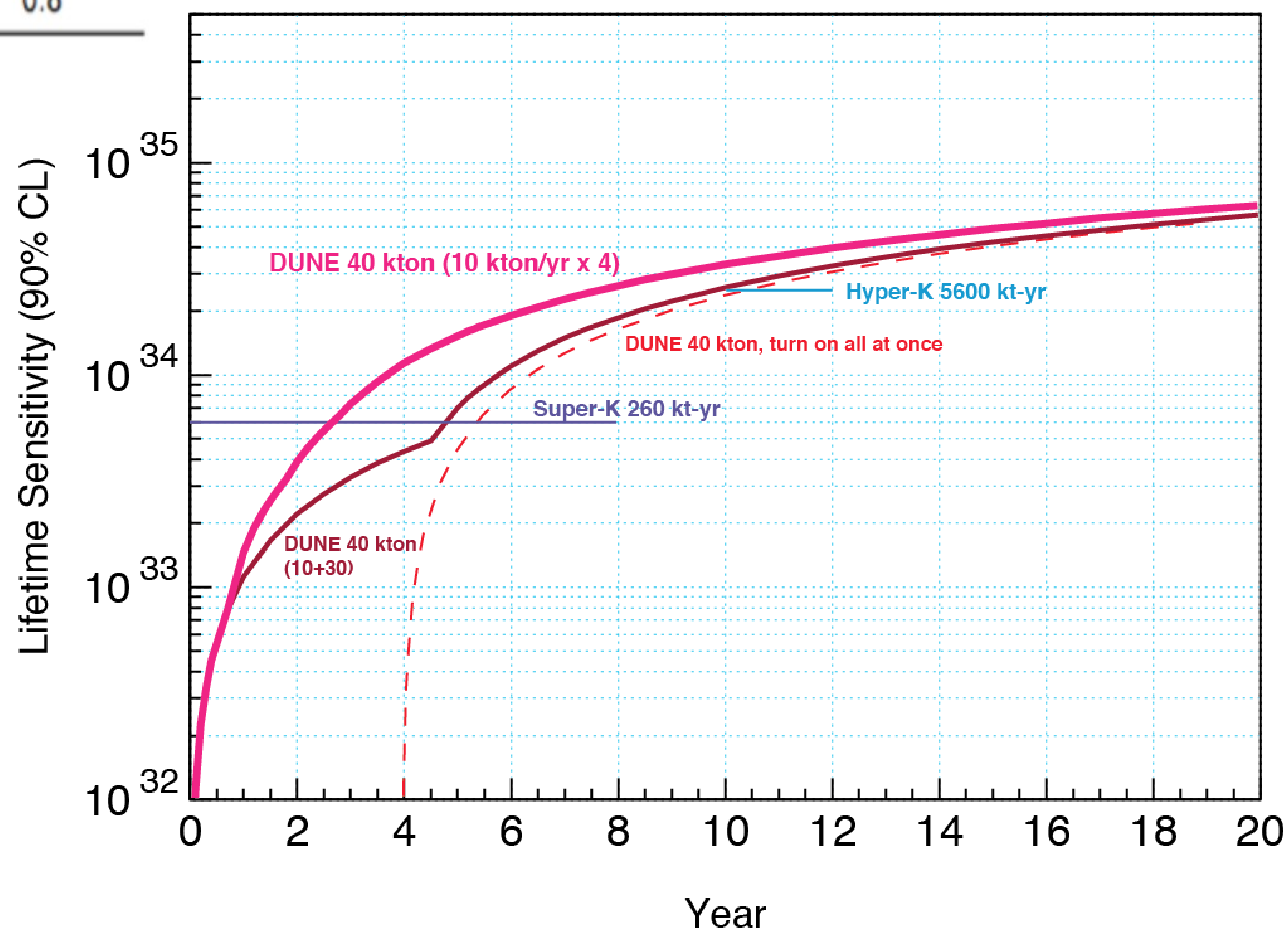




Proton Decay:

Decay Mode	Water Cherenkov Efficiency	Water Cherenkov Background	Liquid Argon TPC Efficiency	Liquid Argon TPC 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

Sensitivity to $p \to K^+ + \overline{\nu}$

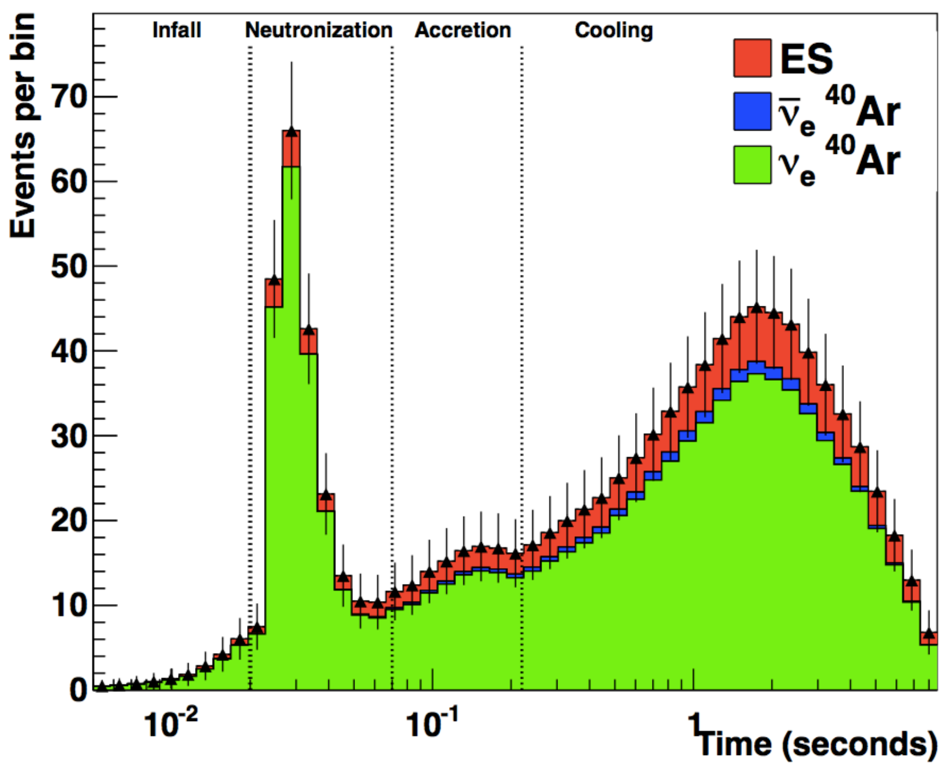


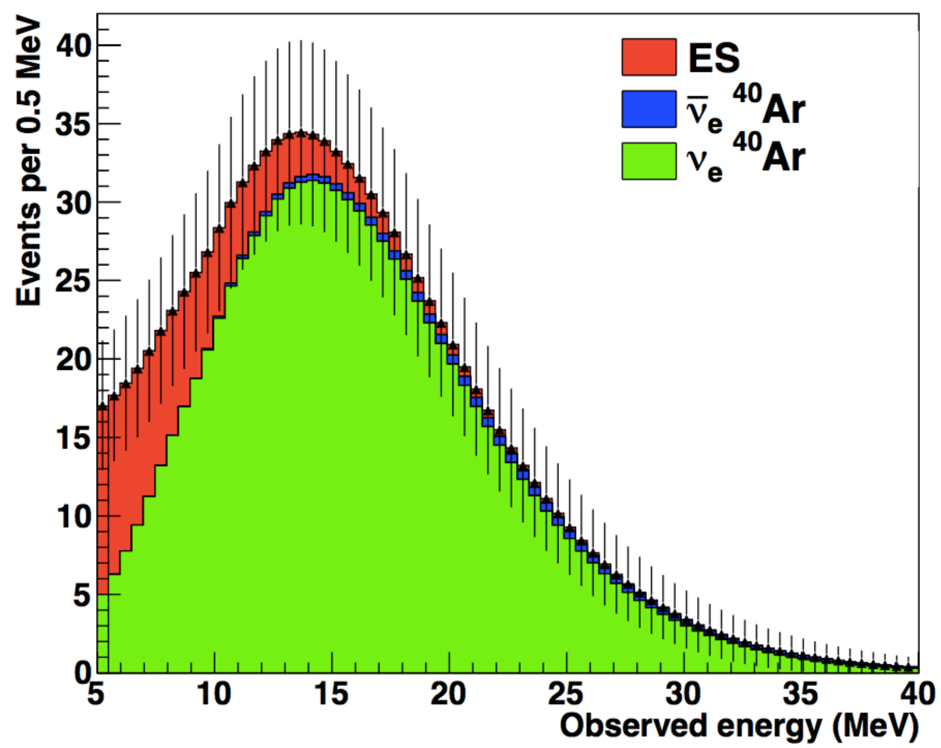
SuperNova Neutrinos:

- LAr detectors are mainly sensitive to ν_e via: $\boldsymbol{\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*}$
- Sensitivity to neutronization burst
- Sensitivity to mass hierarchy
- Complementarity to other detector technologies (mostly $\bar{\nu}_e$ sensitivity)

Flavor composition as a function of time

Energy spectra integrated over time



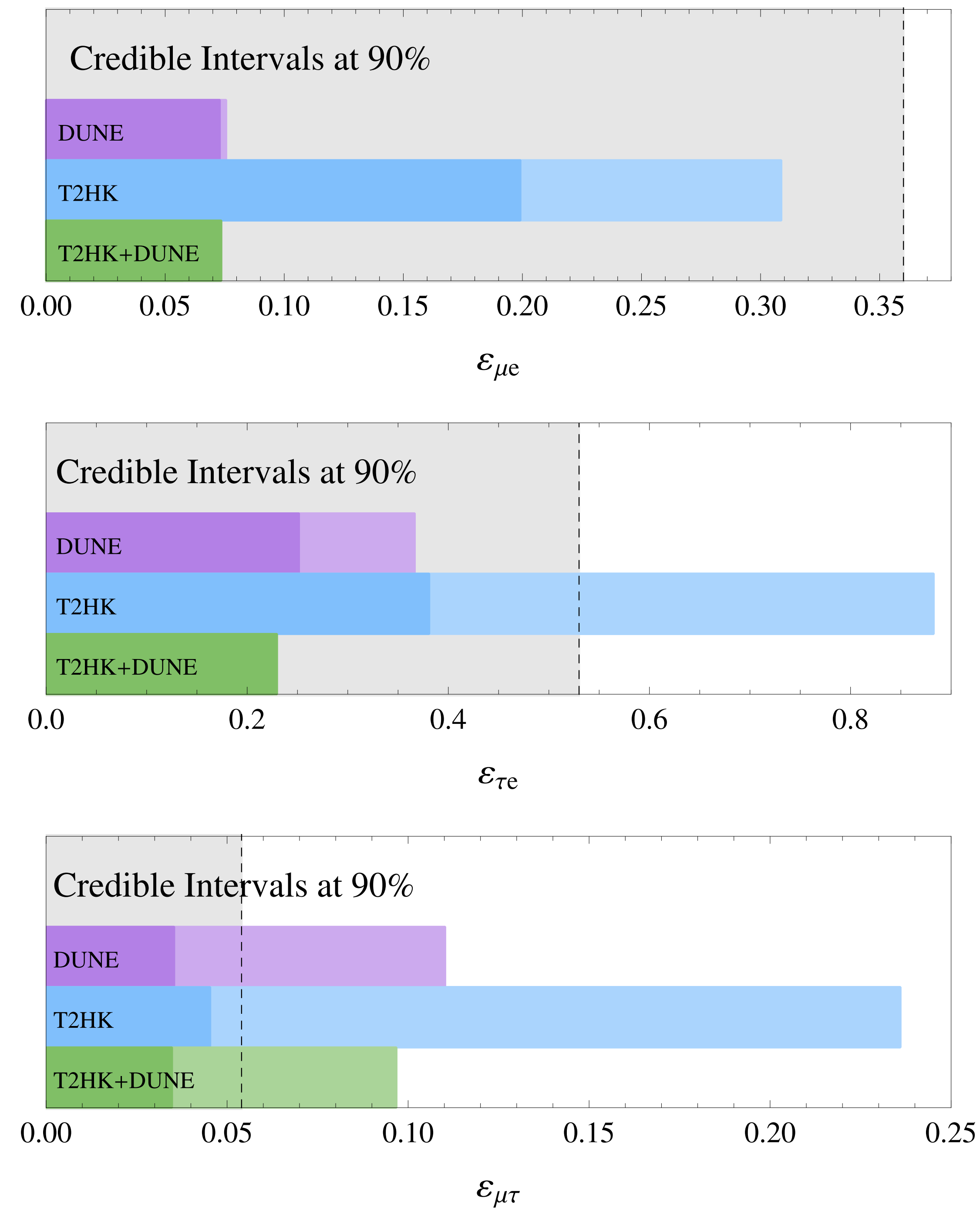


For 40 kton @ 10 kpc,
Garching model
(no oscillations)

Surprises: Non-Standard Interactions

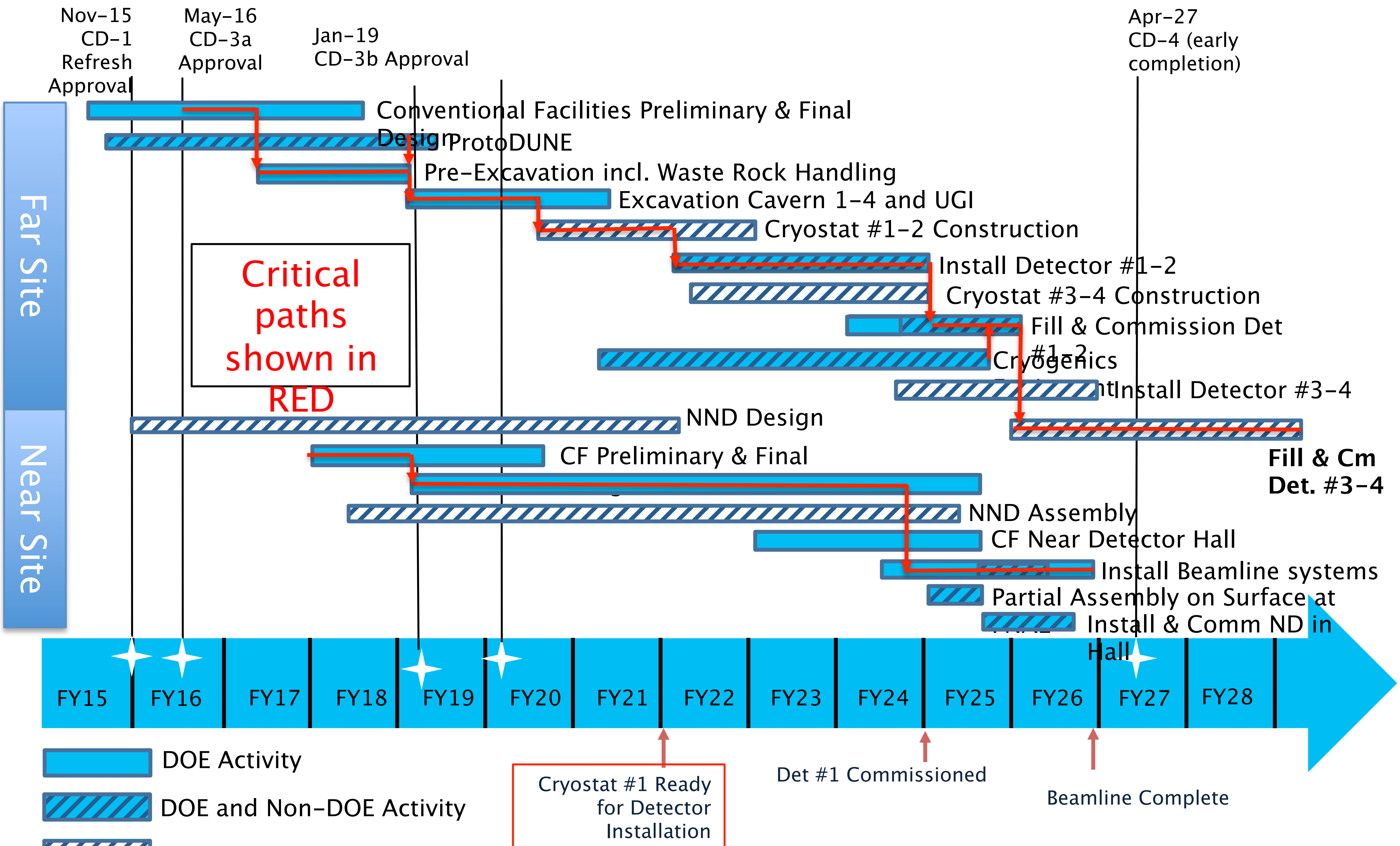
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta_{21} & 0\\ 0 & 0 & \Delta_{31}\end{pmatrix}U^\dagger + A\begin{pmatrix}1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau}\\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau}\\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau}\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

NSI



P.Coloma
arXiv:1511.06357

Schedule



67 27/4/2016 Mark Thomson I DUNE

Summary:

DUNE is a large (70 kton) LAr underground (1.5km) detector exposed to an intense (1-2 MW) Neutrino beam from Fermilab (1300km)

Summary:

ν_μ

DUNE is a large (70 kton) LAr underground (1.5km) detector exposed to an intense (1-2 MW) Neutrino beam from Fermilab (1300km)

Appearance: $\nu_\mu \to \nu_e \quad \bar{\nu}_\mu \to \bar{\nu}_e$ Disappearance: $\nu_\mu \to \nu_\mu \quad \bar{\nu}_\mu \to \bar{\nu}_\mu$

ν_μ, ν_e, ν_τ

Summary:

ν_μ

DUNE is a large (70 kton) LAr underground (1.5km) detector exposed to an intense (1-2 MW) Neutrino beam from Fermilab (1300km)

Appearance: $\nu_\mu \rightarrow \nu_e \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Disappearance: $\nu_\mu \rightarrow \nu_\mu \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

- Perform Stringent tests of the 3 neutrino paradigm
- Determine the size of CP Violation in Nu Sector
- Determine Neutrino Mass Ordering
- Determine which flavor Dominates nu_3
- Broad Physics program including Nucleon Decay & SuperNova Neutrinos
- Surprises: NSI, sterile neutrinos, Nu Decay, Decoherence, Lorentz Violation,…….

ν_μ, ν_e, ν_τ

thanks to:

DUNE Collaborators

especially:

Mark Thomson
Elizabeth Worcester
Jen Raaf
Katie Scholberg
Andrzej Szelc
Jon Paley