An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

Alec Habig, for the DUNE collaboration

EPS-HEP 2015, Vienna

Friday, July 24, 2015

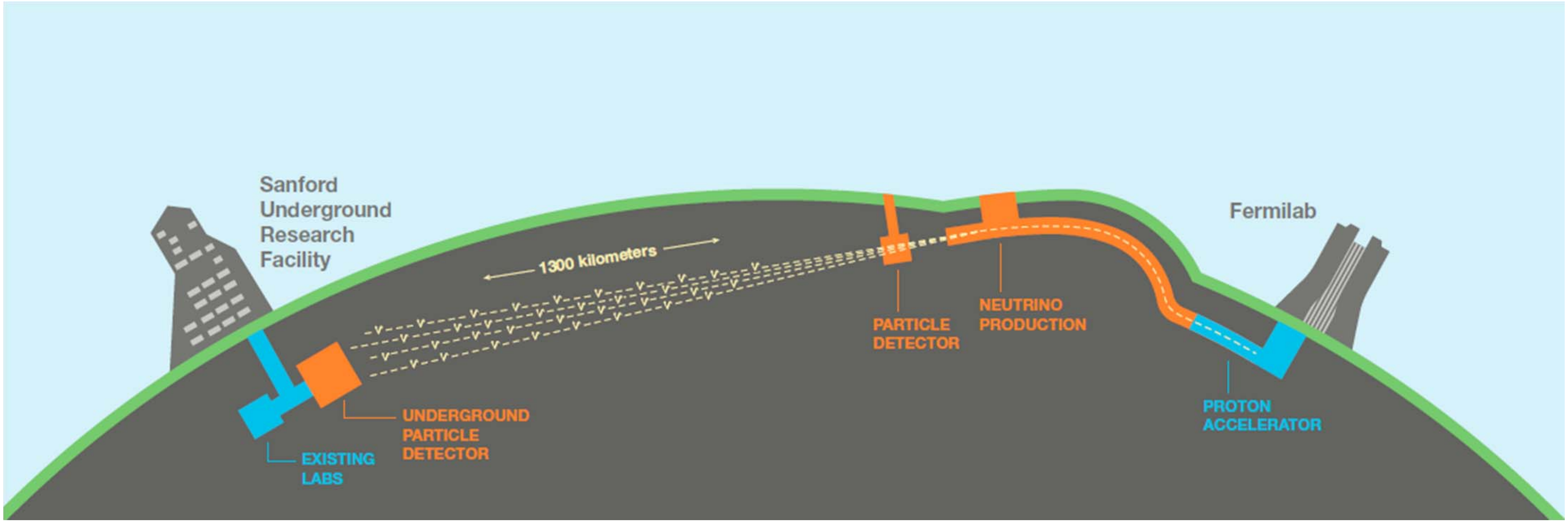
The Deep Underground Neutrino Experiment collaboration is 750 scientists from 150 institutions in 23 countries

Who Are We?

- The collaborations formerly known as LBNE and LBNO, with some new participants
  - Mark Thomson (Cambridge) and André Rubbia (ETH Zurich) are our spokesfolk
  - First collaboration meeting was last April, new Conceptual Design Report (CDR) and "CD1 refresh" passed last week
  - Shared DoE and international funding, CERN involvement
- The beam and infrastructure are now known as Long-Baseline Neutrino Facility (LBNF)

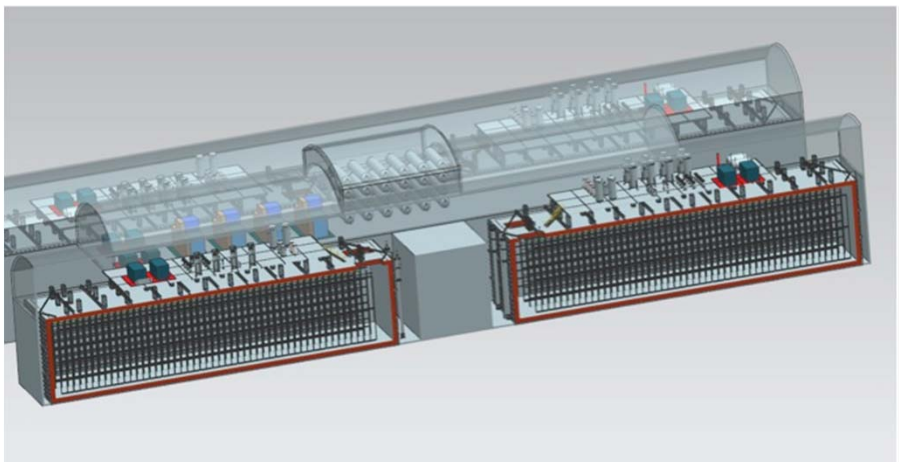
What Will We Do?

- Build a large (40 kt) liquid argon TPC on the 4850' level of the Sanford Underground Lab in the Homestake Mine, and bask in a new, intense neutrino beam from Fermilab
  - Longer baseline, more intense, tunable energy

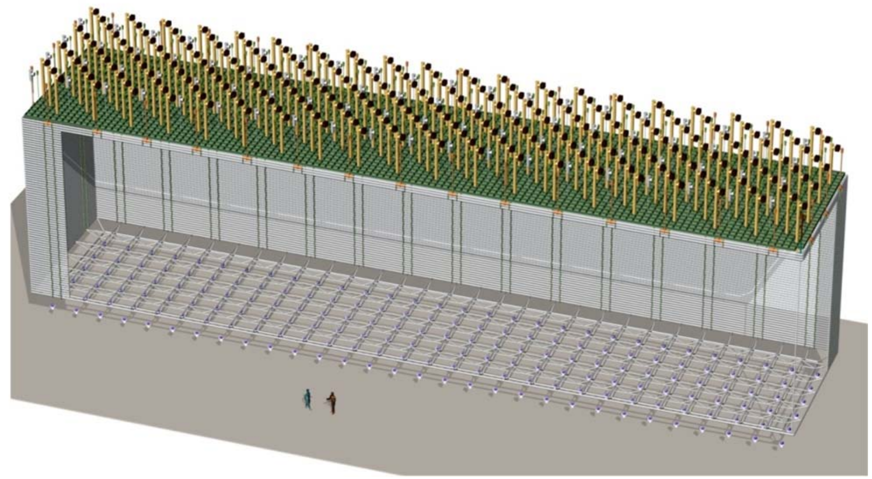


With What?

- Staged10 kt LArTPC modules at Homestake



Two 10kt Single-phase modules
ala ICARUS
Gaining experience with LARIAT, MicroBoone, CAPTAIN, SBND at FNAL
First module reference design

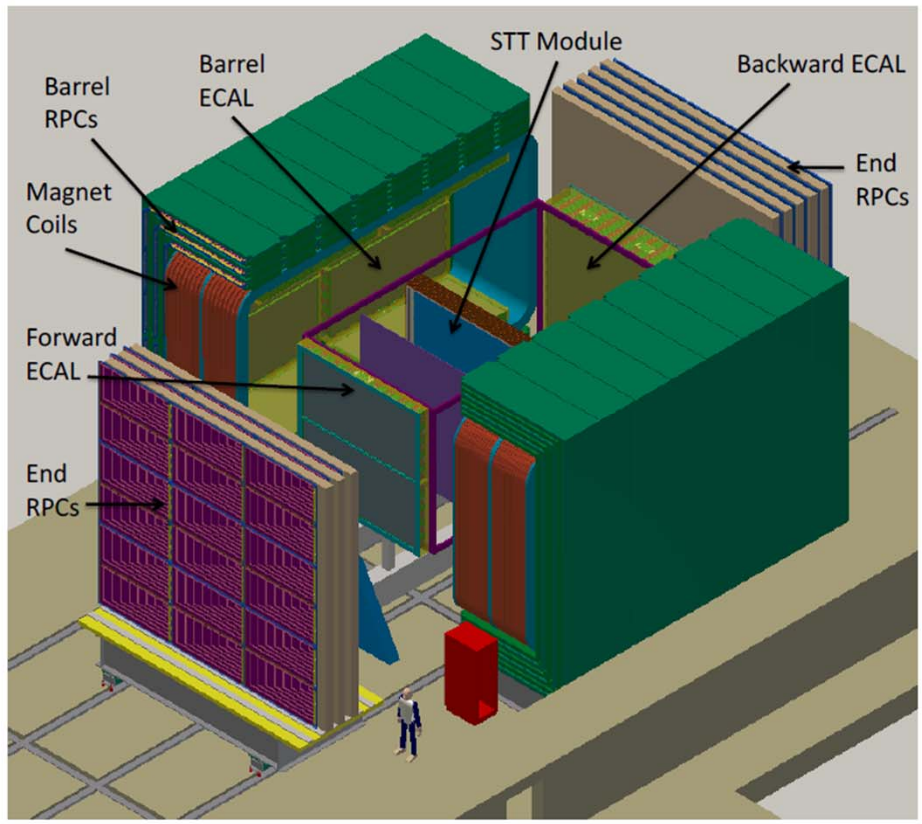


Dual-phase design catches ionization in gas above liquid
Prototyping with WA105 at CERN
Later modules could use this mode

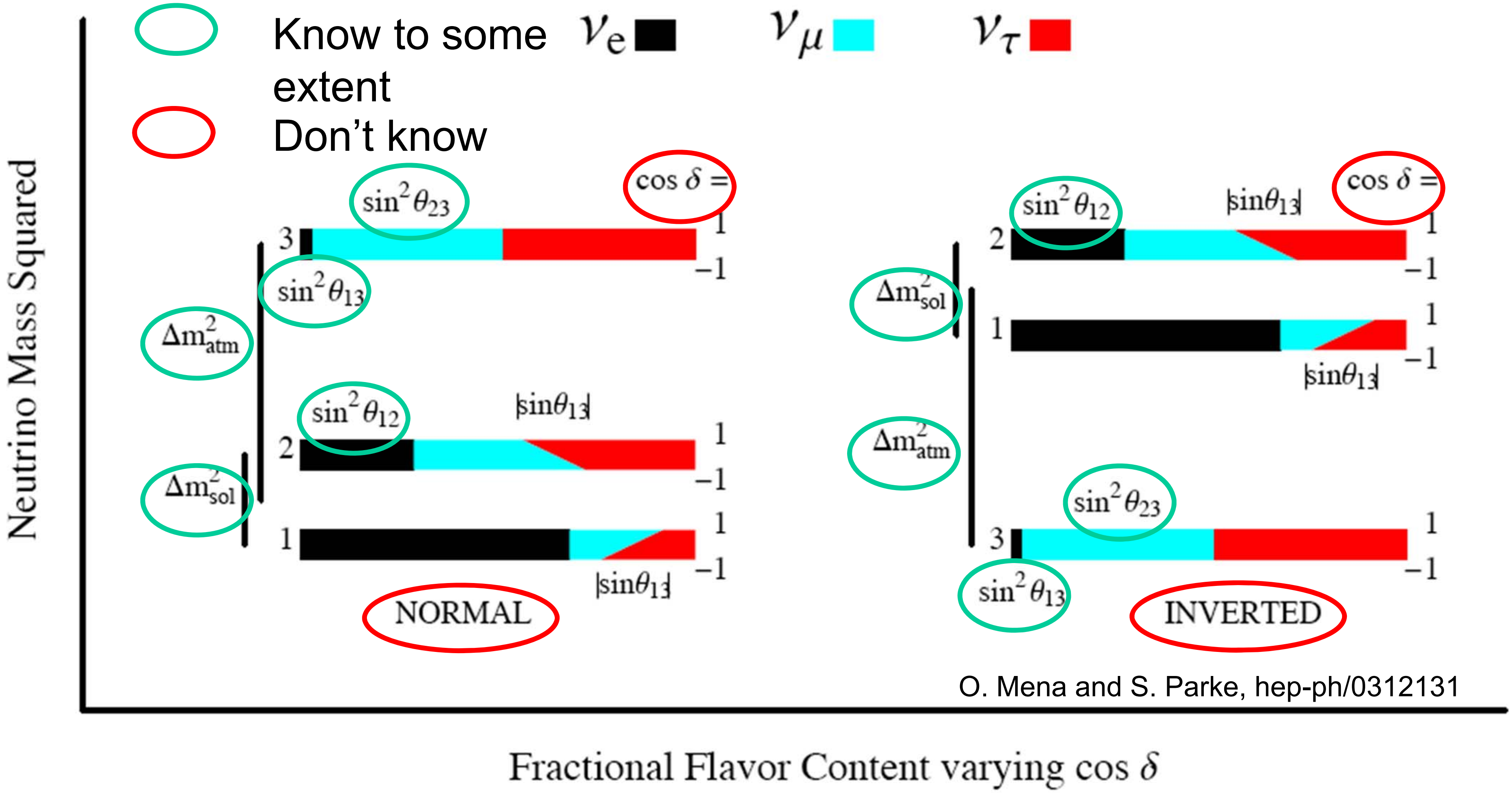
- Final goal is 40kt total Far Detector mass

With What?

- Near Detector near the beam source at FNAL
  - Precisely measure pre-oscillation ν beam spectra and flavor
  - Reference design is fine-grained straw tube tracker
  - Calorimeters, 0.6T magnet
  - Will also do neutrino interaction physics



Why?



Stephen Parke's famous visualization of things, as annotated by Gary Feldman

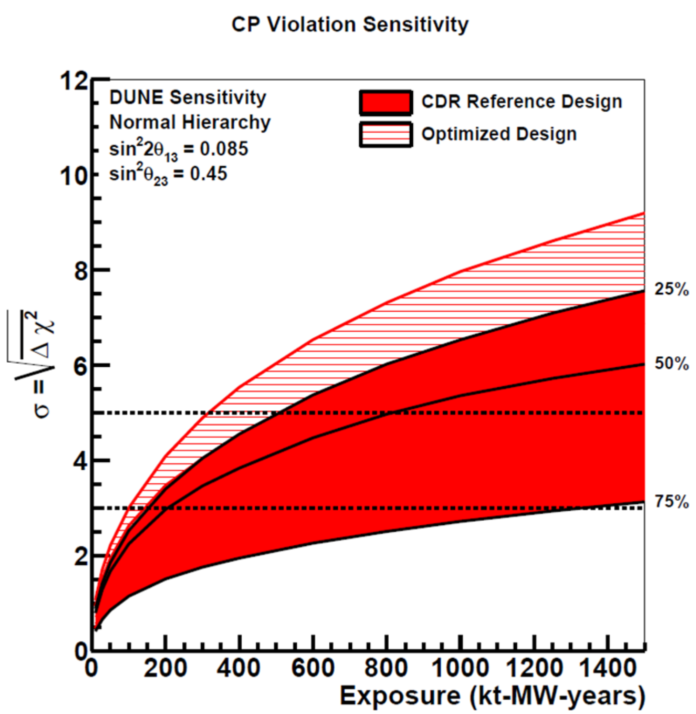
So What Might We Learn?

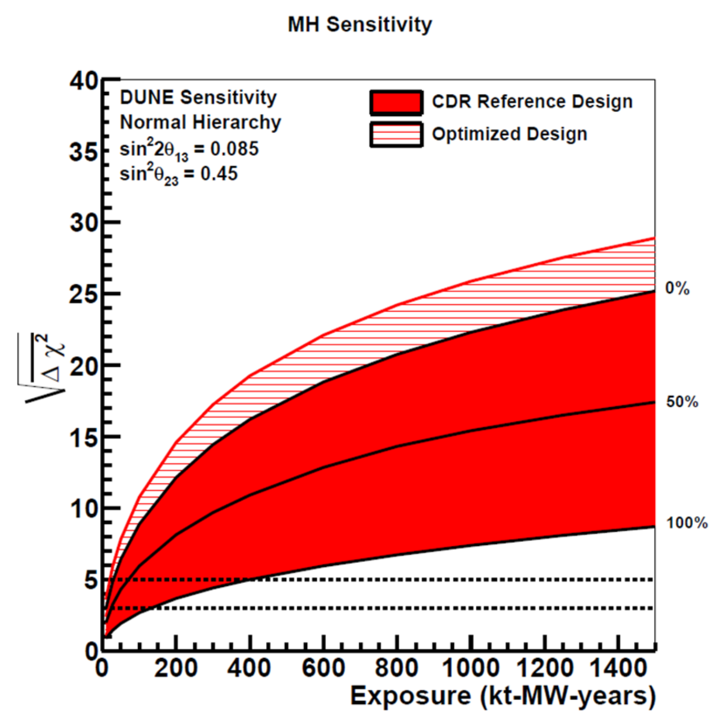
- Does the ν_3 mass state have a ν_e component?
  - Is $\theta_{13} \neq 0$? YES! (*without which nothing else works*)
- Is there CP violation in the lepton sector?
  - Is $\delta_{CP} \neq 0$?
- Is the ν_3 mass state more massive than ν_1 and ν_2 (*normal hierarchy*) or less massive (*inverted hierarchy*)?
  - Absolute mass values need β and $\beta\beta$ decay experiments to nail down
- Does the ν_3 mass state have a larger ν_μ or ν_τ component?
  - Is $\theta_{23} \neq \pi/4$?

In my biased opinion, that's 1.5 of the remaining fundamental 2 things we don't yet know about the standard model (θ_{13}, Higgs mass were #3, #4)

How Well?

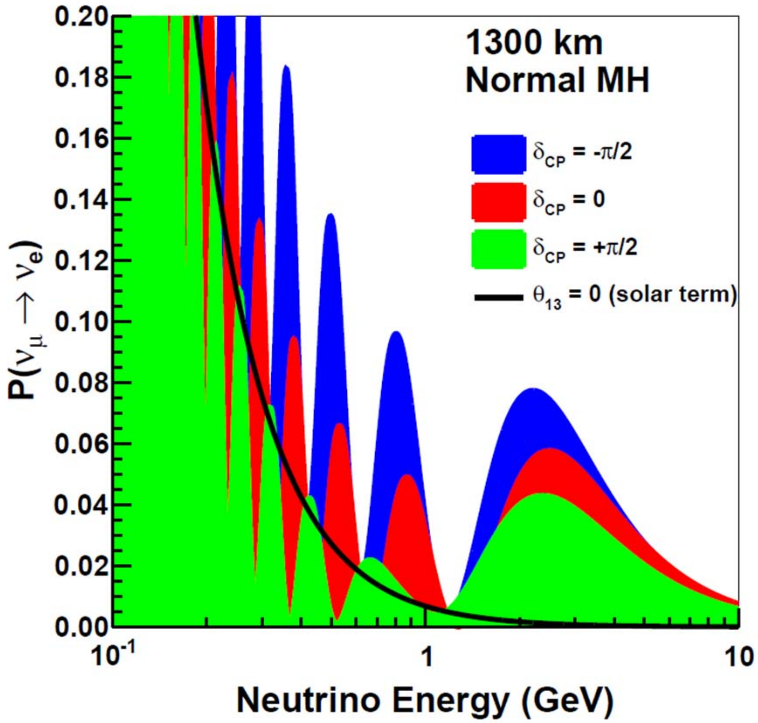
- Primary goal: precision measurement of neutrino oscillation parameters
  - 3σ sensitivity to δ_{CP} for 75% of the possible values of δ_{CP} after 850-1300 kt-MW-years
  - 5σ sensitivity neutrino mass hierarchy for all possible values of δ_{CP} after 400 kt-MW-years

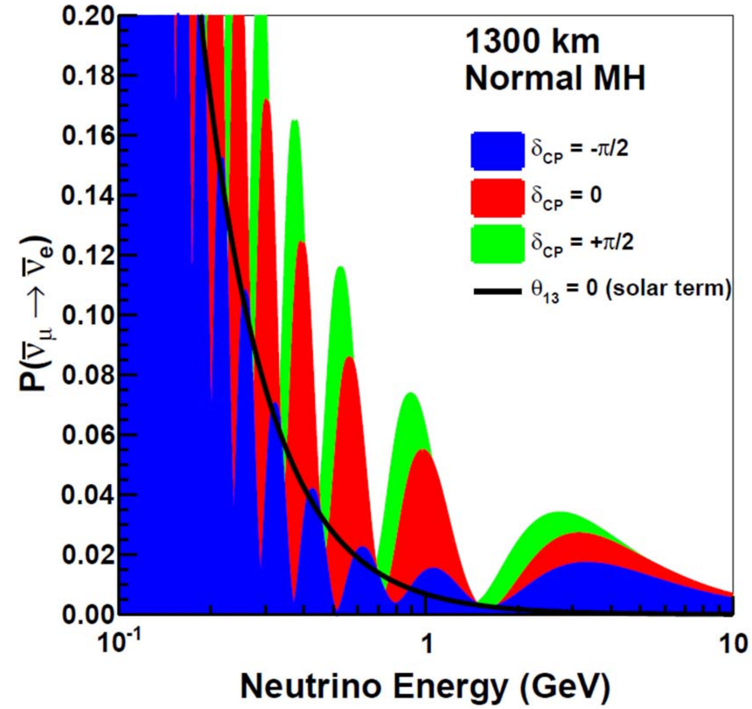




What's the Signal?

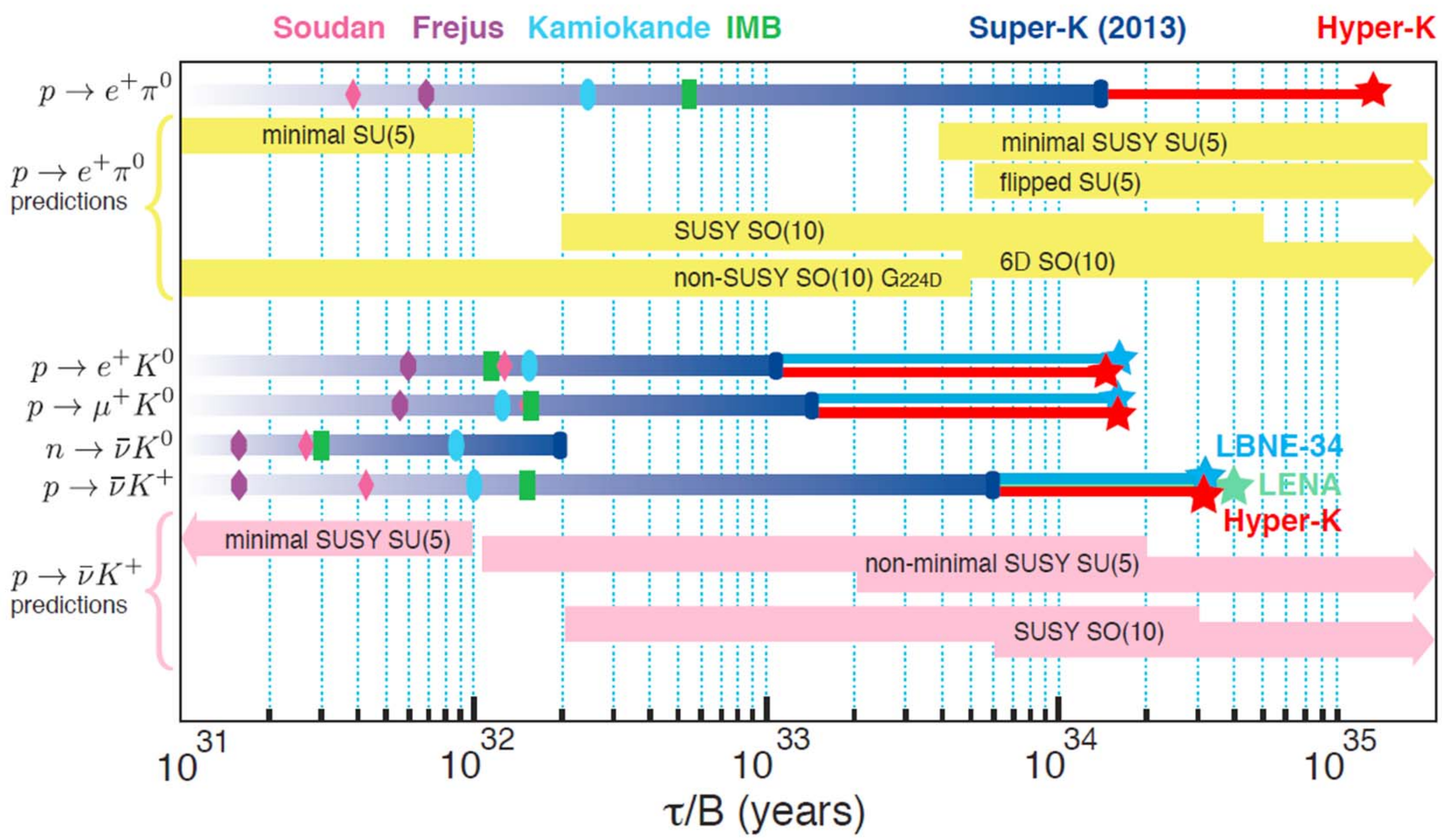
- Measure probability of $\nu_\mu \rightarrow \nu_e$ oscillation for both neutrinos and antineutrinos
  - Compare to expectations for different δ_{CP}, mass hierarchies





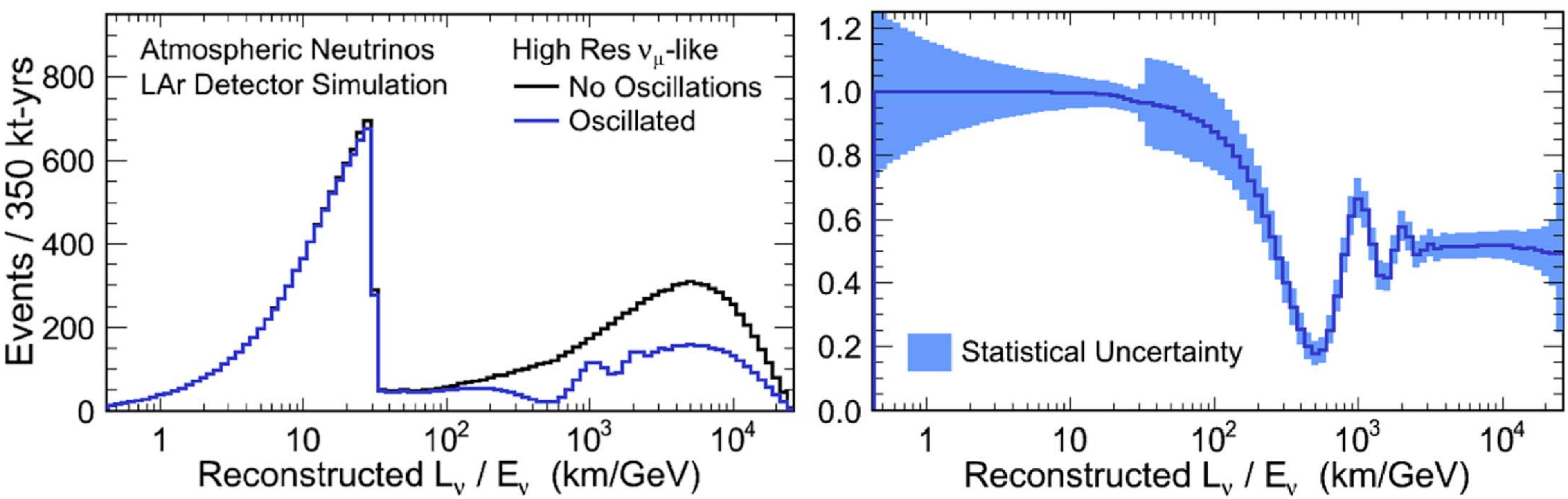
Proton Decay

- GUTs predict protons are unstable at very long lifetimes, beyond what we have probed so far
- A LArTPC has the spatial resolution for good efficiency on popular modes involving Kaons



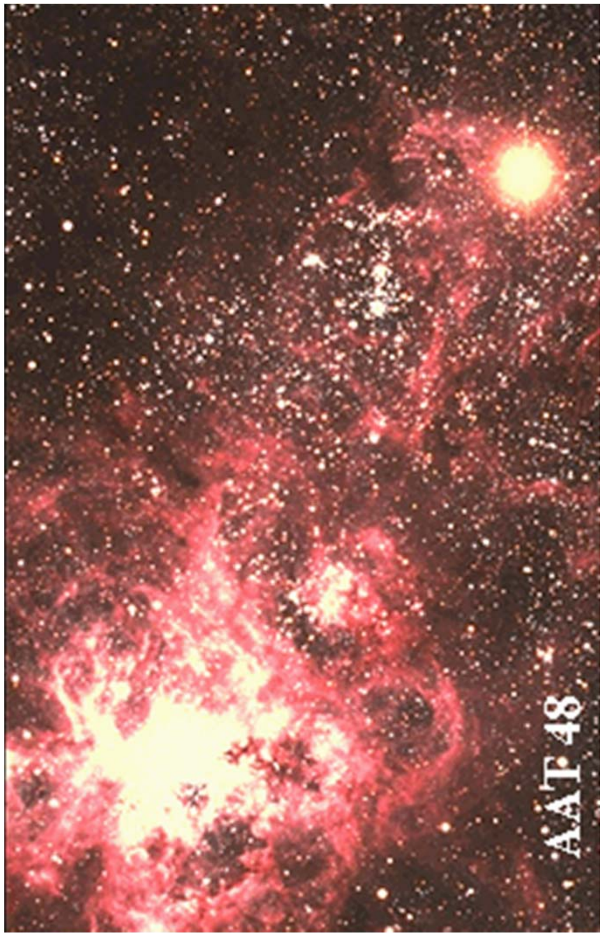
Atmospheric ν

- Neutrinos from cosmic ray interactions in the atmosphere probe a wide range of oscillation parameter space, complementary to the more intense (but narrow band) LBNF beam



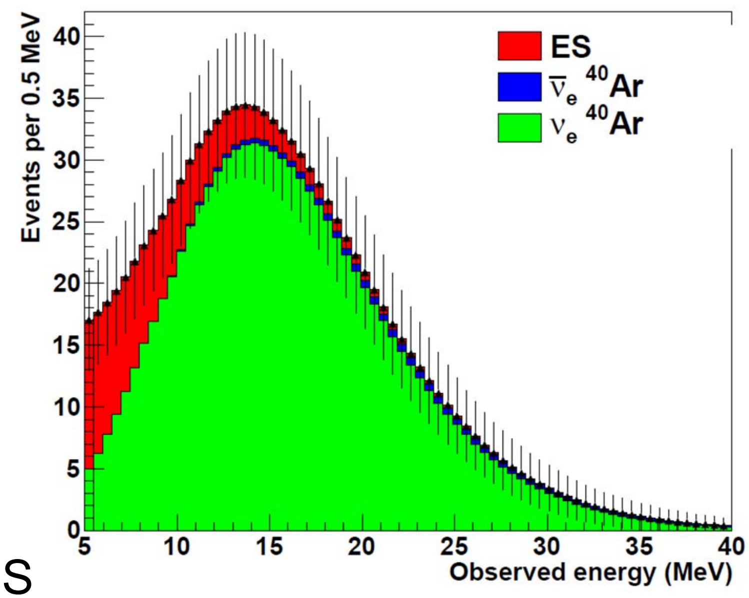
Supernovae ν

- Core-collapse supernova release 99% of their binding energy in a blast of neutrinos (*1% in as kinetic energy, only 0.1% as light!*)
  - Observing this in 1987 revolutionized two fields
- The next time it happens (*in our galaxy*) we want a complete picture
  - Both for astrophysics and particle physics
  - Observing that density of neutrinos in detail will shed light on neutrino properties via collective effects not possible to probe in a lab



All the flavors

- Existing experiments would mostly see anti-electron neutrinos
  - Super-K, IceCube: mostly anti-electron neutrinos
  - LVD, NOvA, Kamland, Daya Bay, Borexino: anti-electron neutrinos and NC (all flavor)
  - HALO: electron neutrinos, but is small
- Measuring all flavors paints the complete picture needed to extract all the results

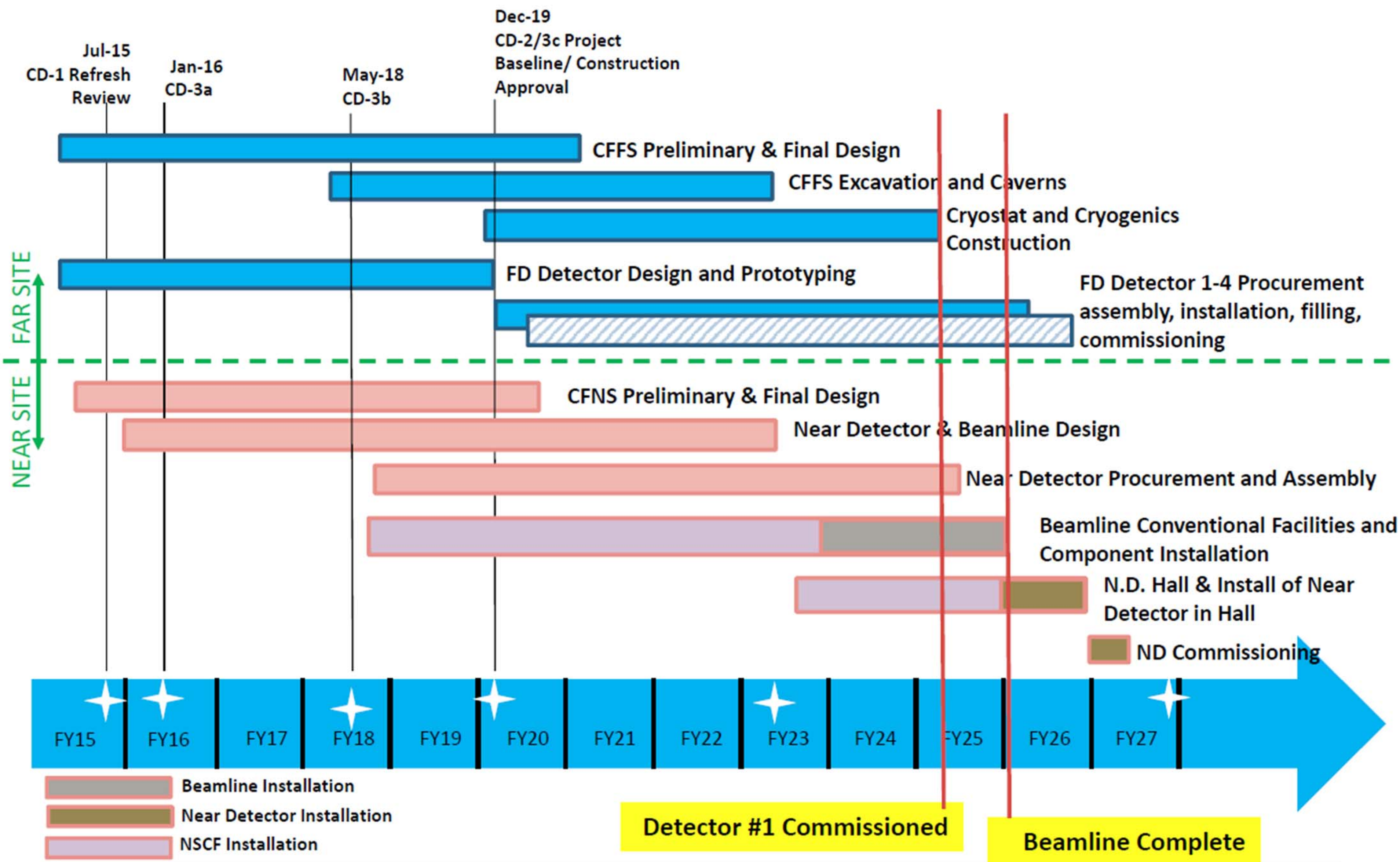


Garching flux seen in DUNE
as calculated by SNoWGLoBES

Other topics…

- We'll have 40kt of high resolution detector deep underground, an intense beam, and a fine-grained near Detector! Can probe many more things:
  - Neutrino interaction physics
  - Indirect dark matter searches
  - Cosmic ray physics
  - Lorentz and CPT violation, extra dimensions
  - Non-standard interactions, sterile neutrinos
- Exploring potential of lower energy neutrino studies:
  - Solar neutrinos
  - Diffuse supernova neutrino background

LBNF/ DUNE Schedule Summary Overview



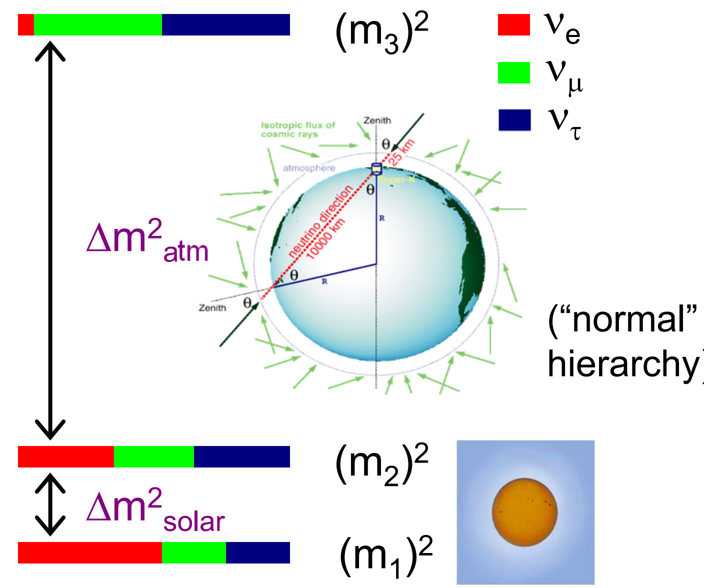
Summary

- While existing long-baseline experiments (T2K, NOvA) might give us hints of δ_{CP} and neutrino mass hierarchy, DUNE is designed to cover most of parameters space with discovery sensitivity
- DUNE will greatly enhance the world's ability to decipher Supernova neutrinos and search for nucleon decay
- Project has a busy but doable schedule and new international cooperation

Backups

Why?

- ν are leptons, interact only weakly
  - interact as flavor eigenstates $\{\nu_e, \nu_\mu, \nu_\tau\}$
  - but propagate as mass eigenstates $\{\nu_1, \nu_2, \nu_3\}$
- Different m's make mass states slide in and out of phase as they travel
  - So a ν created as one flavor might be detected as another later



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

$$\sin^2(2\theta_{23}) \equiv 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$$

Useful Approximations:

ν_μ Disappearance (2 flavors):

$P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta_{23} \sin^2(1.27 \Delta m^2_{32} L/E)$

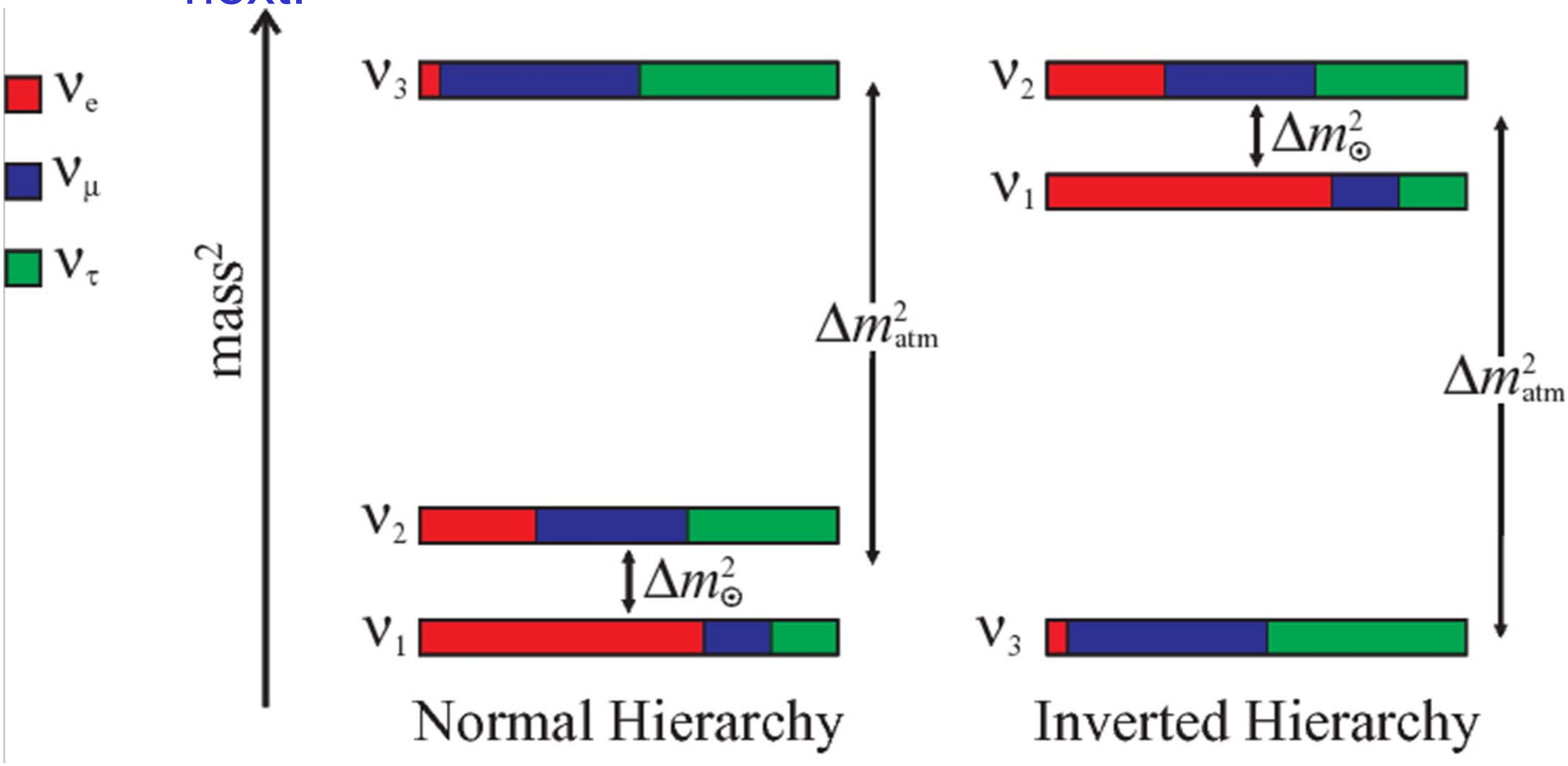
ν_e Appearance:

$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27 \Delta m^2_{31} L/E)$

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

Mass Hierarchy

- Unlike quarks and the other leptons, we do not even know which ν is more massive than the next!



ν_e appearance

- We will start off with few ν_e in a beam of ν_μ and see if more ν_e pop up after some L/E
  - This isn't simply the converse of the reactor case which measures ν_e disappearance and thus θ_{13}
- Back to the oscillation approximations we use for ν_μ disappearance:
  - Note that while experimentally θ_{23} is close to $\pi/4$, if it's not exactly $\pi/4$ we can't tell if it's > or <
  - And that "≈" wipes away a lot more terms which result from multiplying out the mixing matrix properly

<u>Useful Approximations:</u>

ν_μ Disappearance (2 flavors):

$$P(\nu_\mu \to \nu_x) = \sin^2 2\theta_{23} \sin^2(1.27\Delta m^2_{32} L/E)$$

ν_e Appearance:

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E)$$

Where L, E are experimentally optimized and θ_{23}, θ_{13}, Δm^2_{32} are to be determined

ν_e appearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$\overset{(+)}{-}\; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$+\; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ $\Delta = \Delta m^2_{31} L/(4E)$ $A = \overset{(-)}{+} G_f n_e L/(\sqrt{2}\Delta)$

Thanks to Greg Pawloski for typesetting this beast!

- Note there are θ_{23} terms that are not squared, introducing sensitivity to $\theta_{23} > \pi/4$ or $< \pi/4$
- CP-violating δ is present
- Matter effects are in there, differ in sign for ν and anti-ν, so a comparison could allow sorting out the mass hierarchy
- But if θ_{13} is near zero, we learn nothing (all terms$\rightarrow$0)