LONG-BASELINE NEUTRINO MEASUREMENTS

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Lepton/Photon
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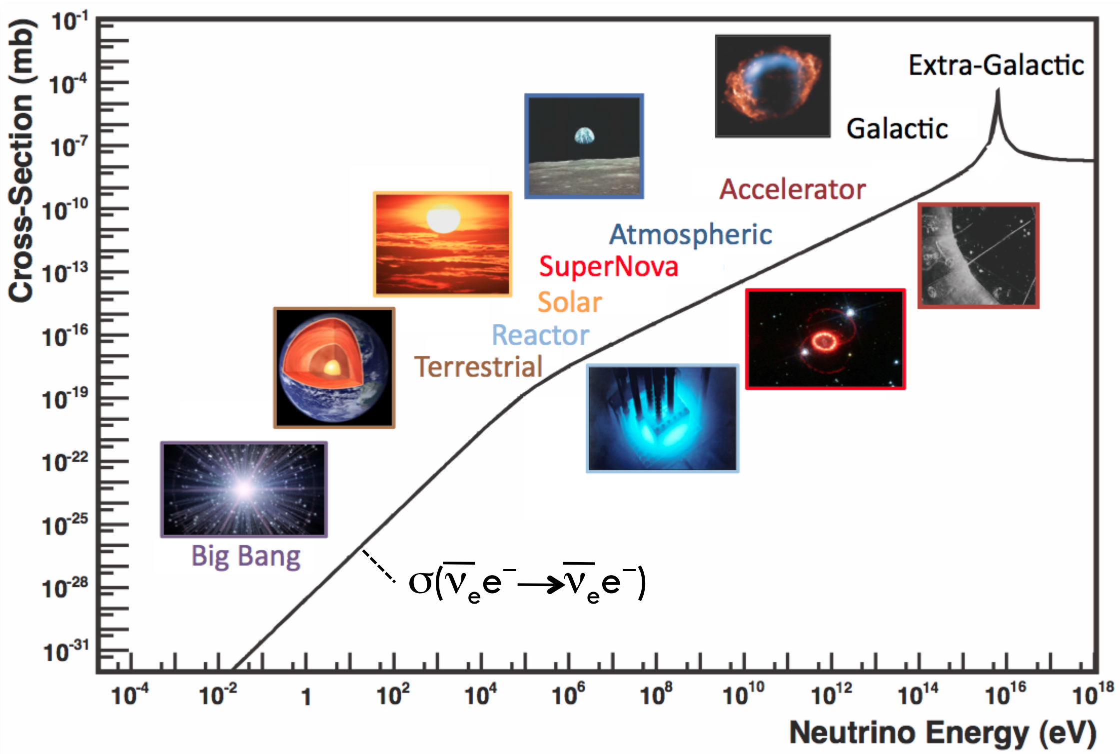
- what's new?
- with an emphasis on accelator-based neutrino experiments

Neutrinos Sources

- neutrinos are one of the most abundant particles in the universe and we are fortunate that there are many sources of neutrinos

- span an enormous energy range (MeV to PeV)



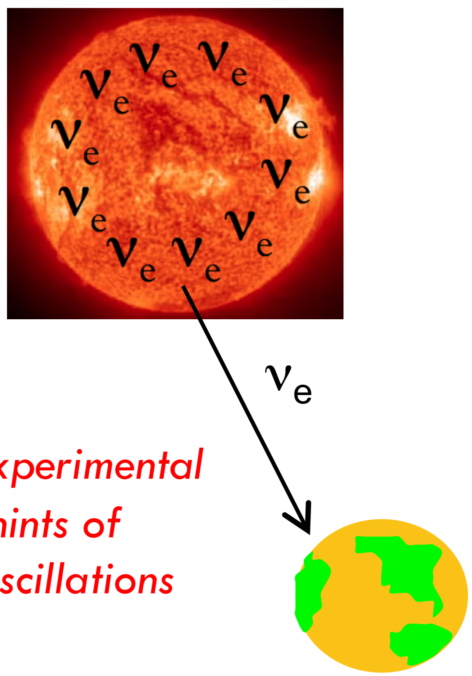
(Formaggio, Zeller, Rev. Mod. Phys. 84, 3, 2012)

- we have gotten a lot of info this way
- we have used many of these sources to make major discoveries

Neutrino Oscillations

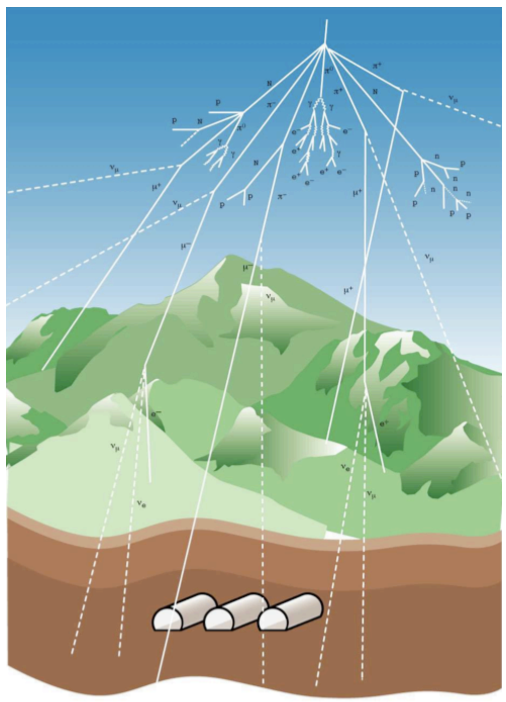
- the discovery that ν's can change from one type to another came from two rather unexpected sources (ultimate long-baseline ν experiments)

Solar Neutrinos



1st experimental hints of ν oscillations

Atmospheric Neutrinos

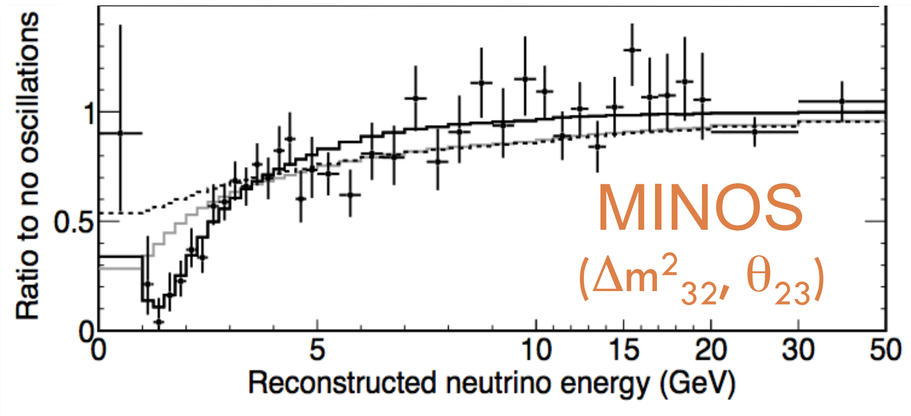


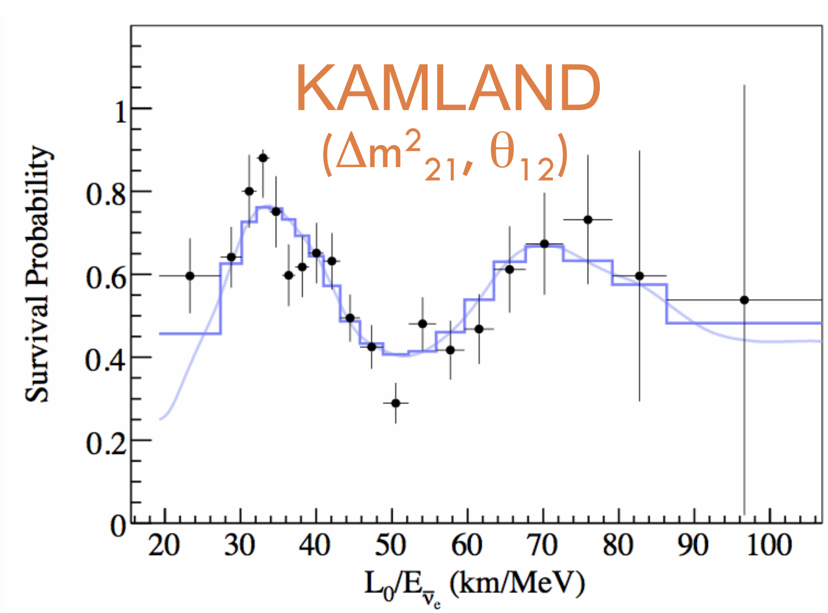
- amplitude: determined by a mixing matrix (θ_{12}, θ_{23}, θ_{13})
- wavelength: determined by mass^2 differences (Δm^2_{21}, Δm^2_{32})
- also depends on L, E_ν

- together these determine the survival probability of a given neutrino

Accelerator & Reactor Neutrinos

4





- while the first indications were observed in astrophysical sources, we have also tested in carefully controlled experiments

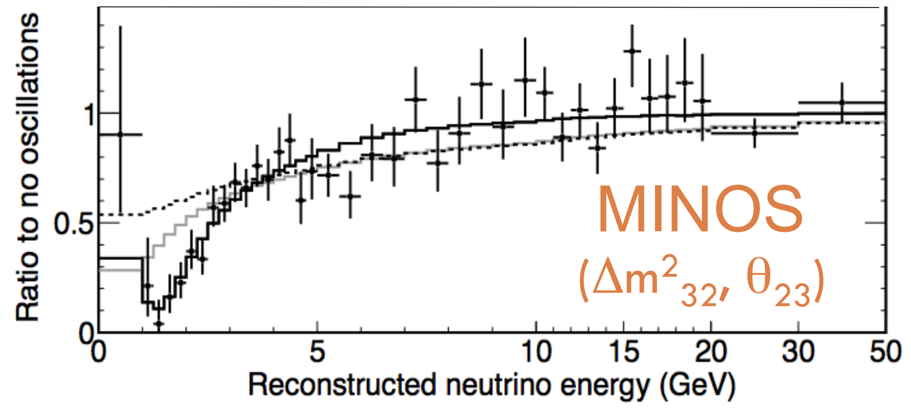
  - *particle accelerators*
  - *nuclear reactors*

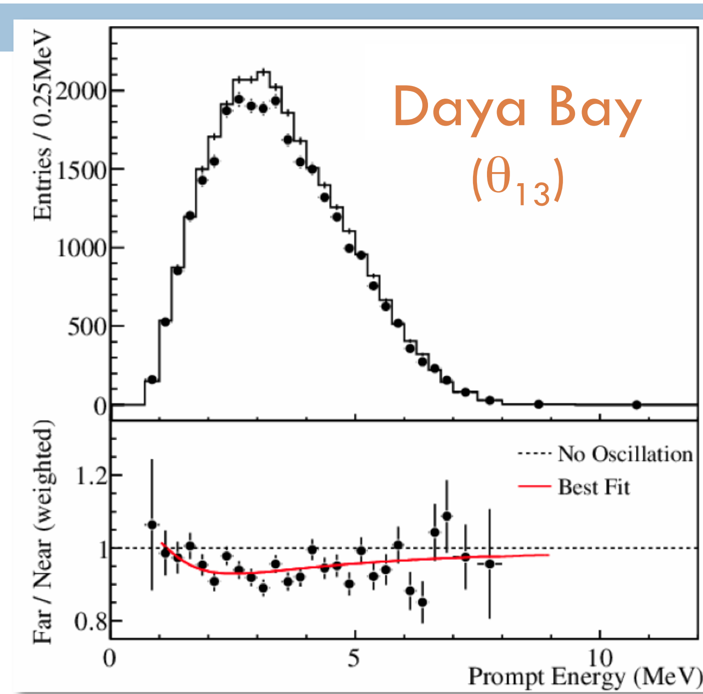
- fixed L, well-known E_ν

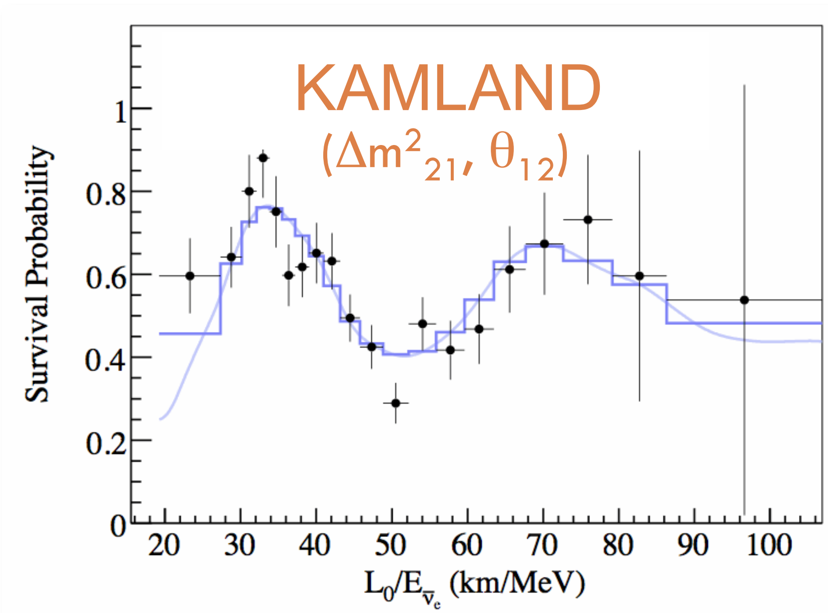
- have played a crucial role in the confirmation of the neutrino oscillation phenomenon

together, these test our theoretical framework

Accelerator & Reactor Neutrinos







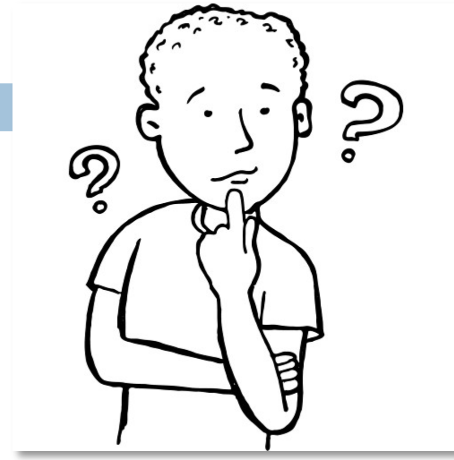
- all three mixing angles have now been measured!
- how does this change things?

$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (stat) \pm 0.005\ (sys)$

An et al., Chin. Phys. C37, 011001 (2013)

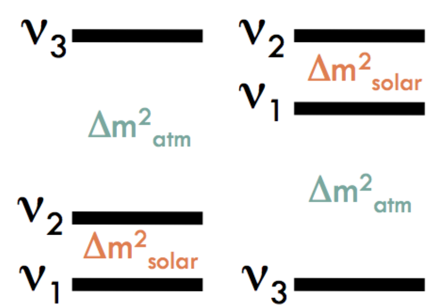
Next Challenges

what does it all mean?



- *establishing such a relatively large value of θ_{13} opens up some very exciting possibilities for long-baseline ν oscillation experiments …*

  - is our 3ν picture correct or is there more to the story? *(NSI, ν_S, …)*
  - what is the ordering of the ν masses? *(implications for GUTs, $0\nu\beta\beta$)*
  - is CP violated in the neutrino sector? *(violation of a fundamental symmetry, δ_{CP} unknown)*



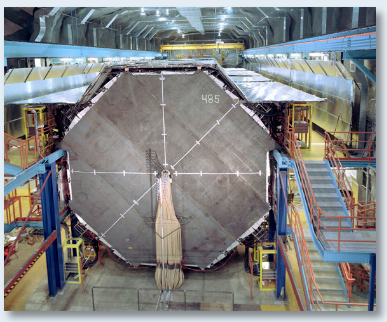
controlled by θ_{13}

- new data from ν experiments aim to address these important questions

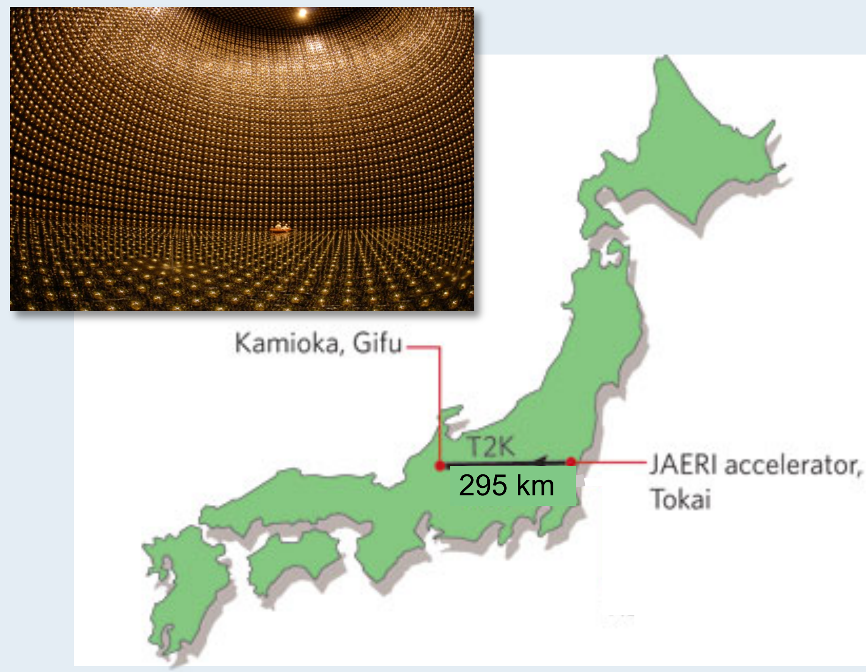
where are we in this experimental quest?

Accelerator Neutrinos

- **MINOS** (U.S.)
  - *735 km baseline, on-axis*
  - *120 GeV protons, FNAL*
  - *2005 – 2012 (MINOS+ to follow)*



- **T2K** (Japan)
  - *295 km baseline, off-axis*
  - *30 GeV protons, JPARC*
  - *2010 – present*

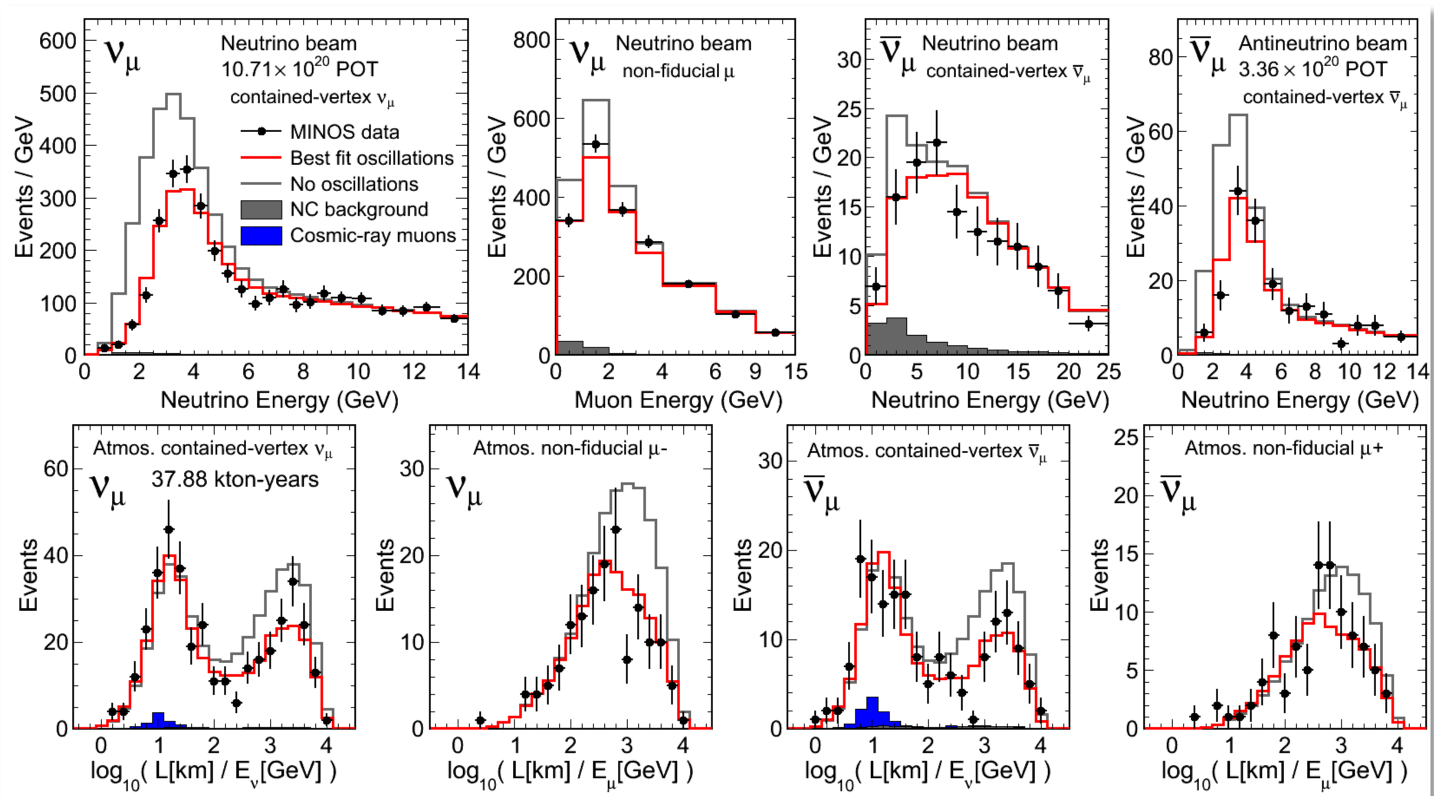


- both ν_μ <u>disappearance</u> & ν_e <u>appearance</u>

ν_μ Disappearance

- **MINOS** - all data sets (accelerator, atmospheric, both ν_μ and $\overline{\nu}_\mu$) combined for final disappearance measurements

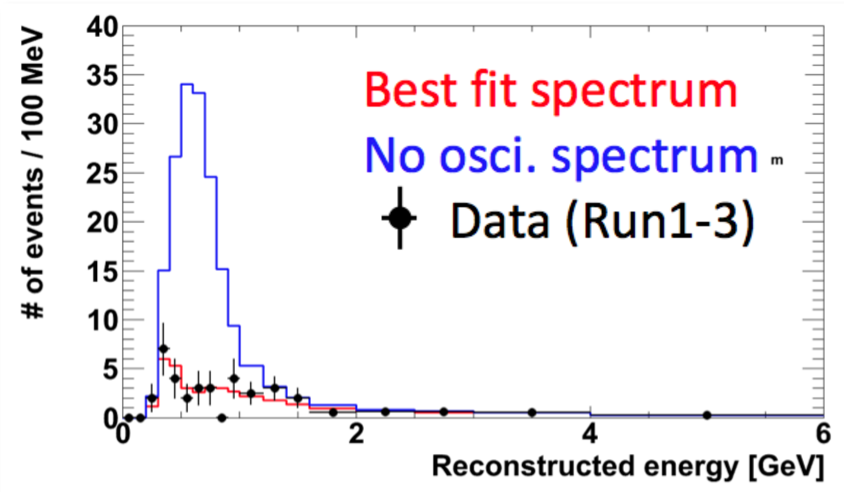
shows how this data all works together & the power of these combinations

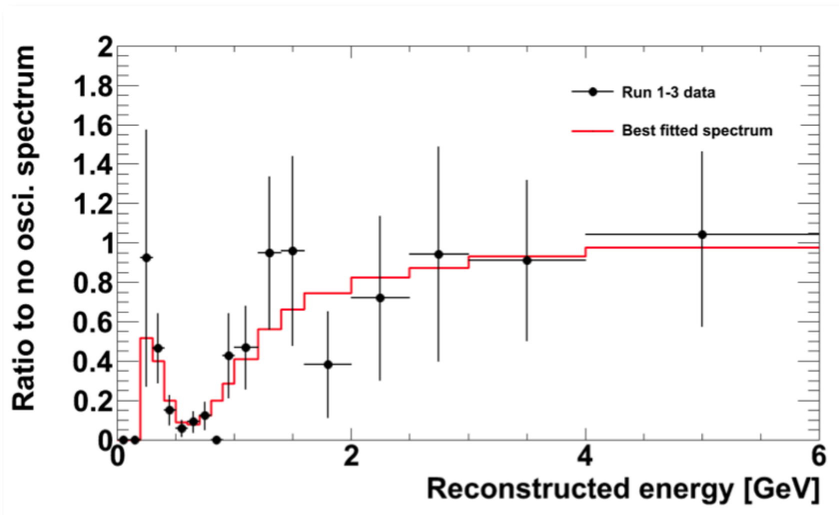


(Adamson et al., arXiv:1304.6335)

measure of ν oscillations over a large range of baselines

ν_μ Disappearance





- **T2K**

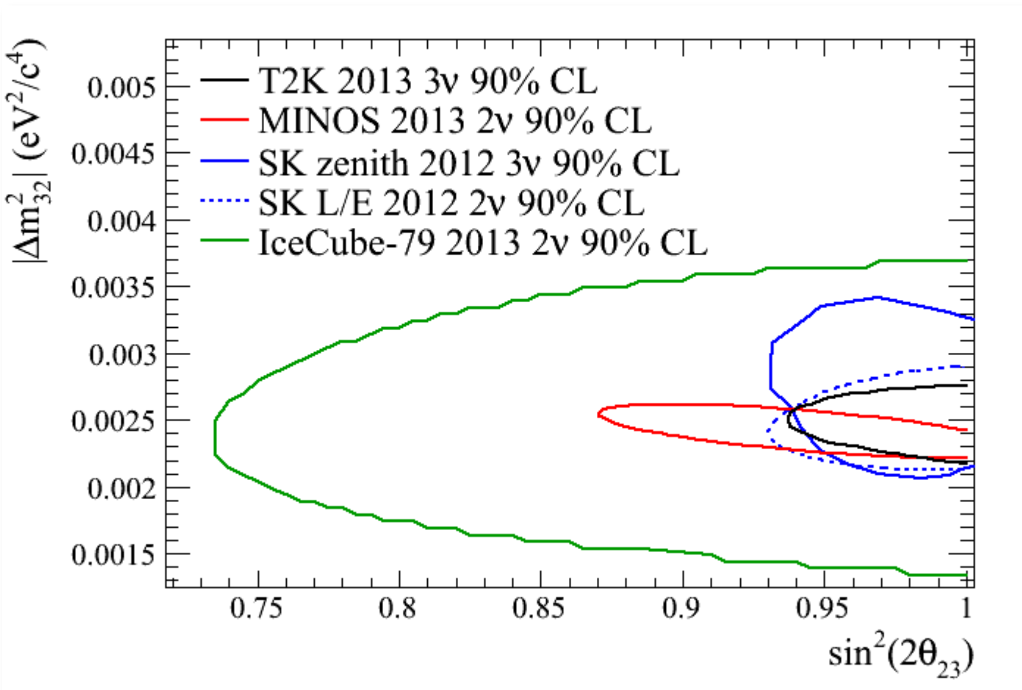
  - observes almost a complete disappearance of muon neutrinos

    (expect 205 events in the absence of oscillations, 58 observed)

  - really seeing the power of the L/E choice

  - unlike quark mixing, we see large effects in neutrinos

ν_μ Disappearance



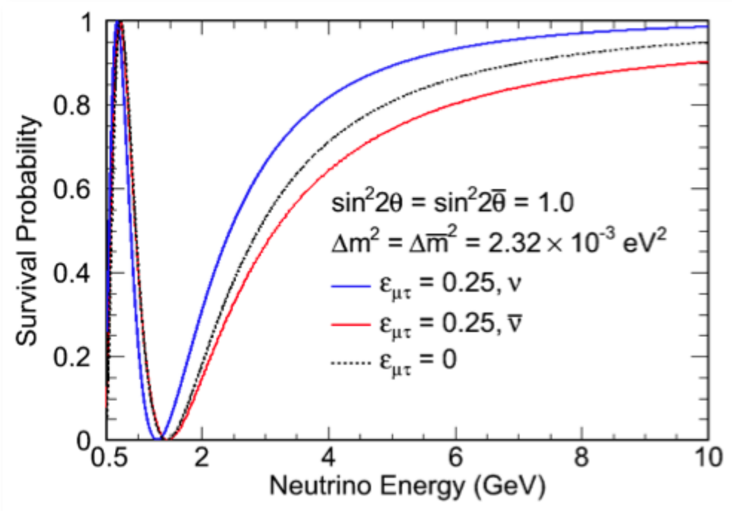
- accelerator neutrinos:
  - **MINOS** most precise Δm^2_{32}
    - * *important for reactor θ_{13}*
  - **T2K** most precise θ_{23}
    - * *is θ_{23} maximal?* some tension
- atmospheric neutrinos:
  - ***Super-K***
  - *ANTARES*
  - ***IceCube***
    (*measured at x10 higher E_ν*)

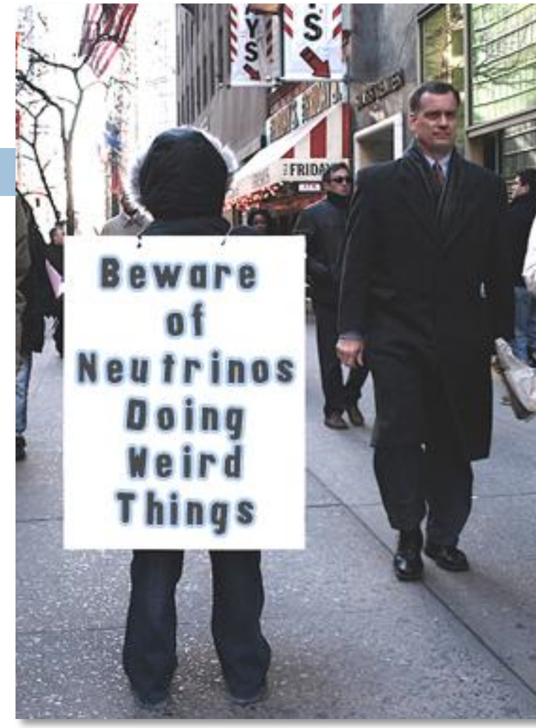
Darren Grant's talk

- crucial to improve our knowledge of θ_{23} as it appears with θ_{13} in long-baseline ν oscillation probabilities (impacts MH, $\not{C}\not{P}$)

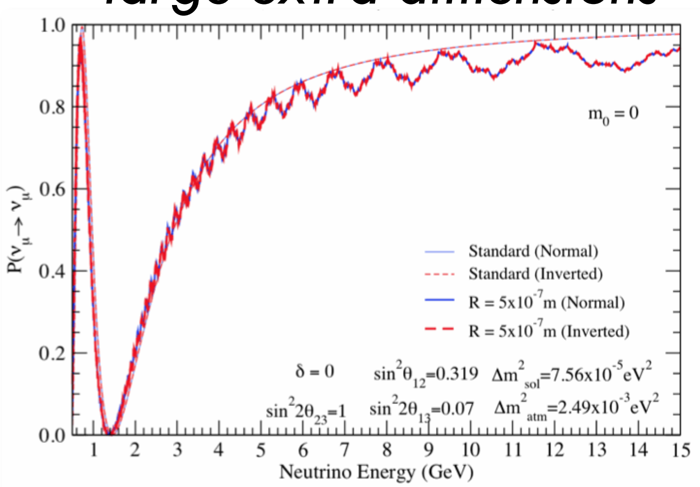
MINOS+

non-standard interactions





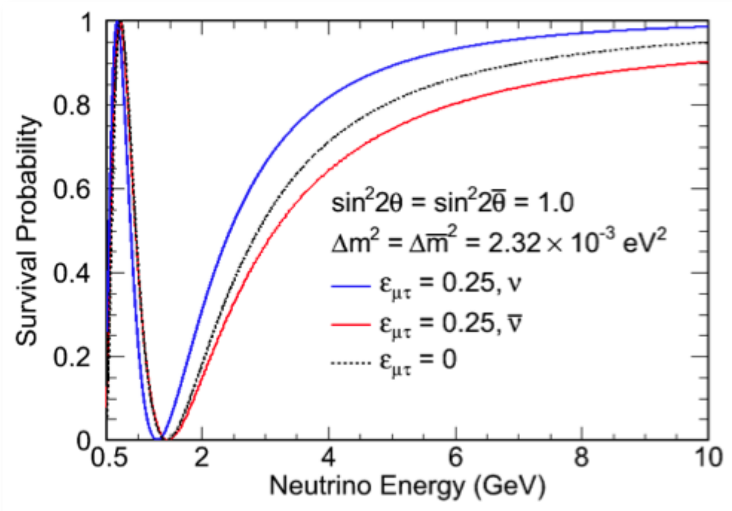
large extra dimensions

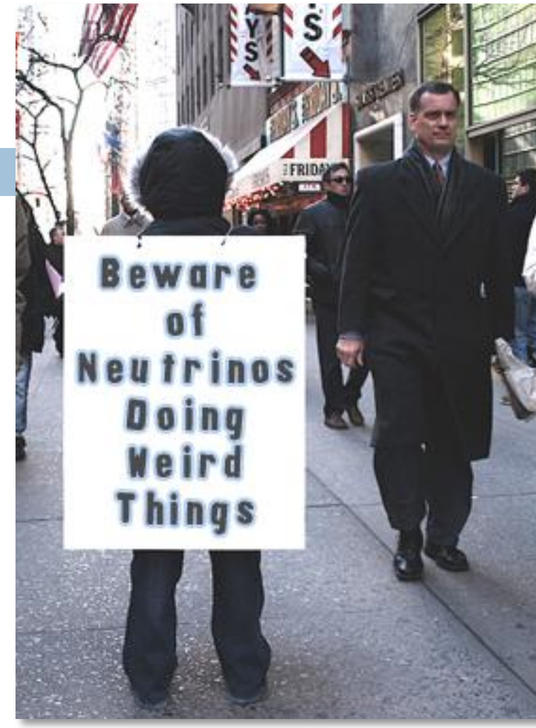


- will run in NOvA beam
  (2 higher beam energy than MINOS)
- look for new physics in previously unexplored regions
- expect ~3,000 events/year

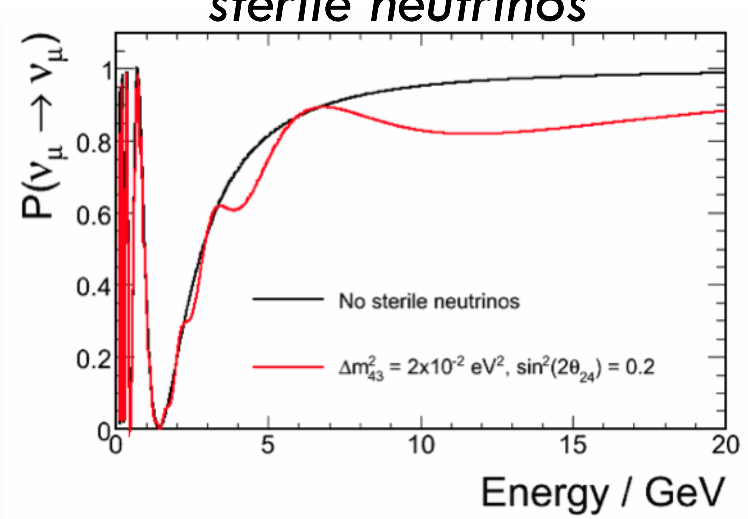
MINOS+

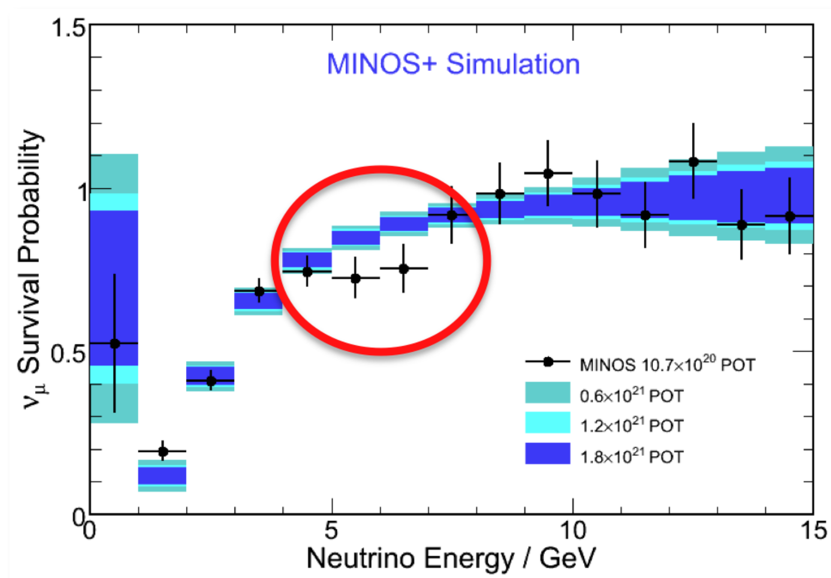
non-standard interactions





sterile neutrinos





MINOS+

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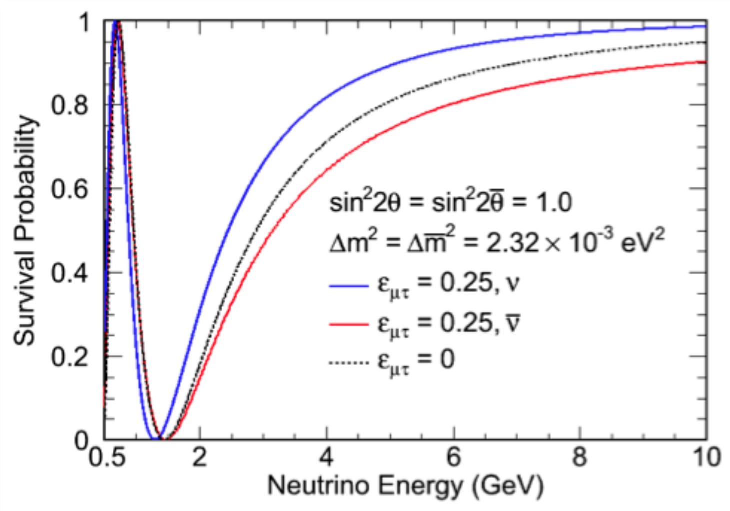

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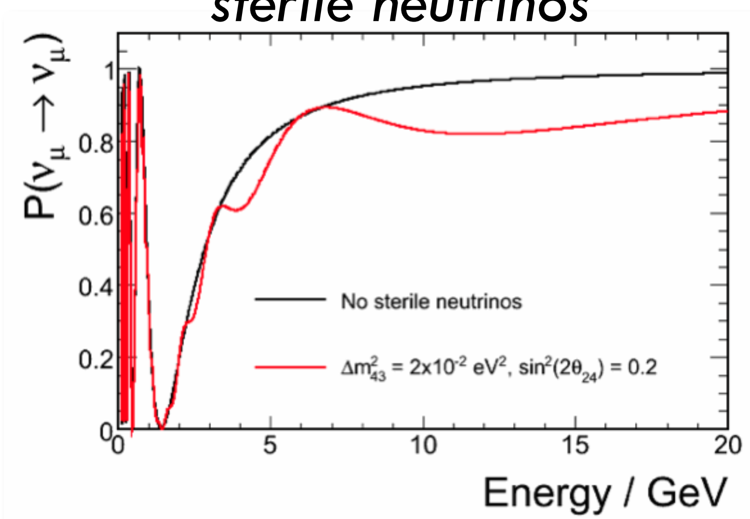
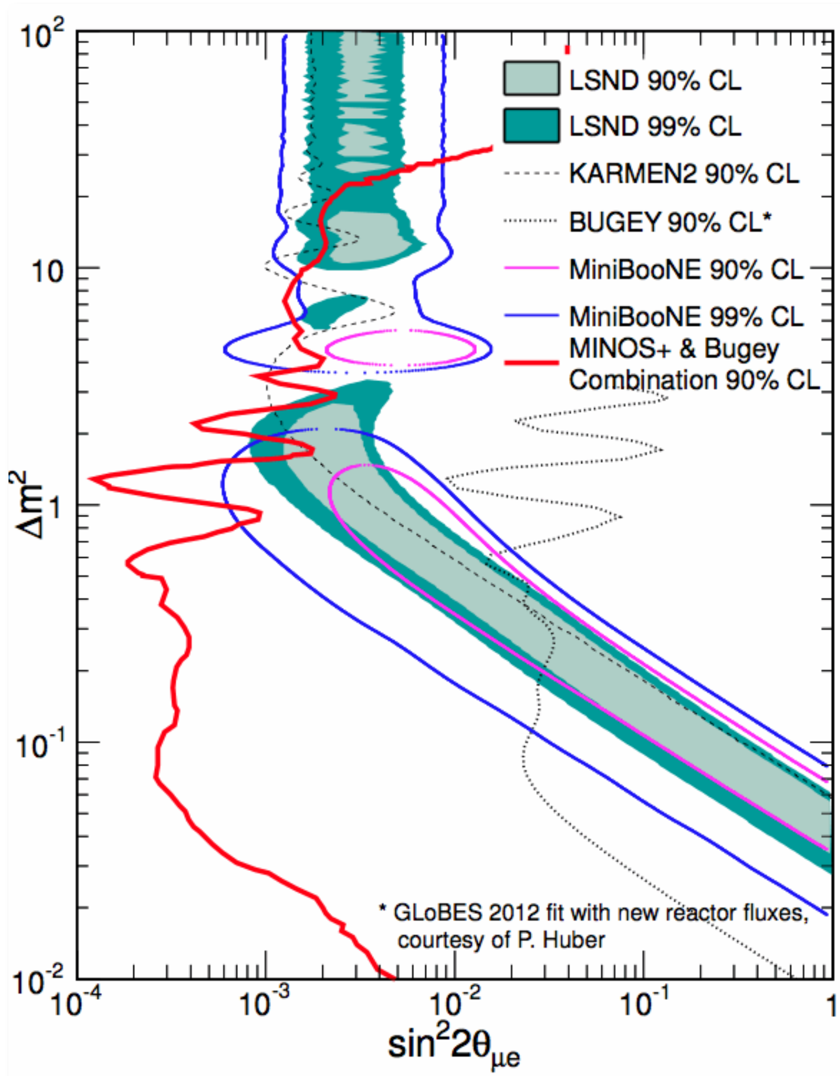
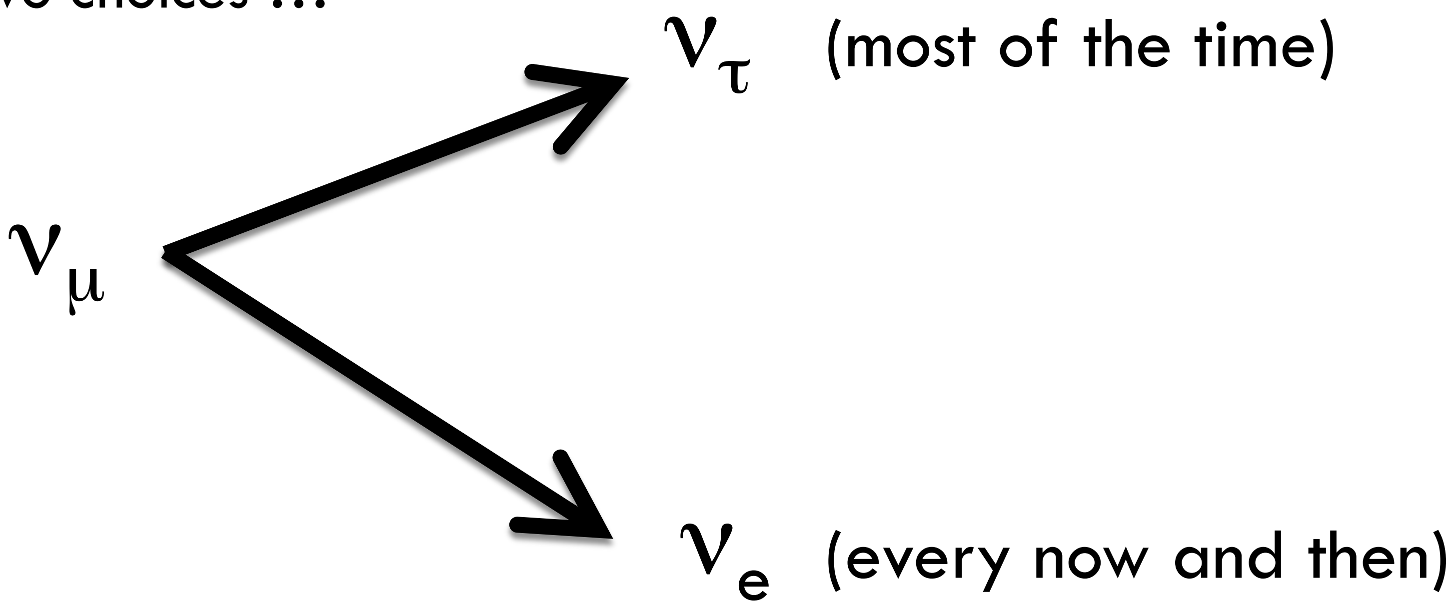




What Are They Disappearing To?

the ν_μ has two choices …



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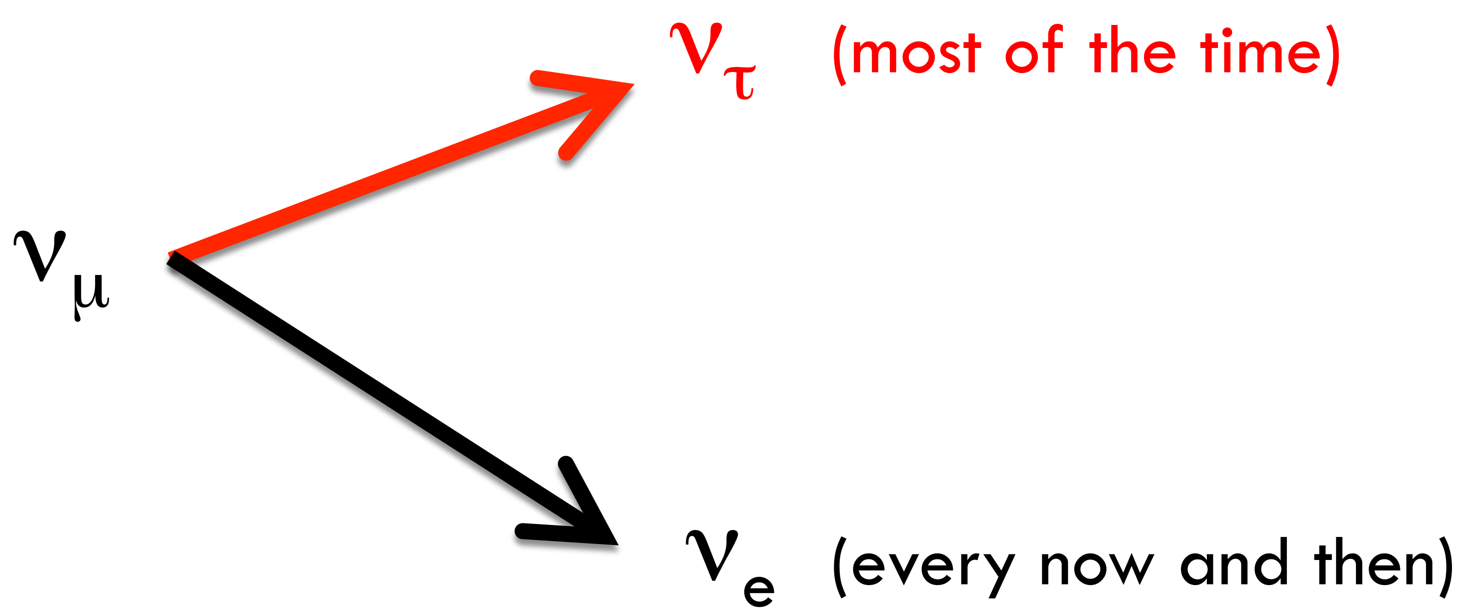
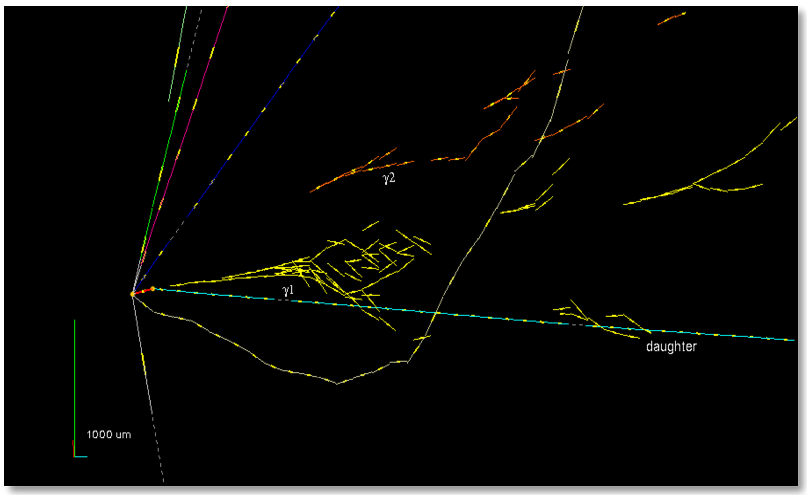
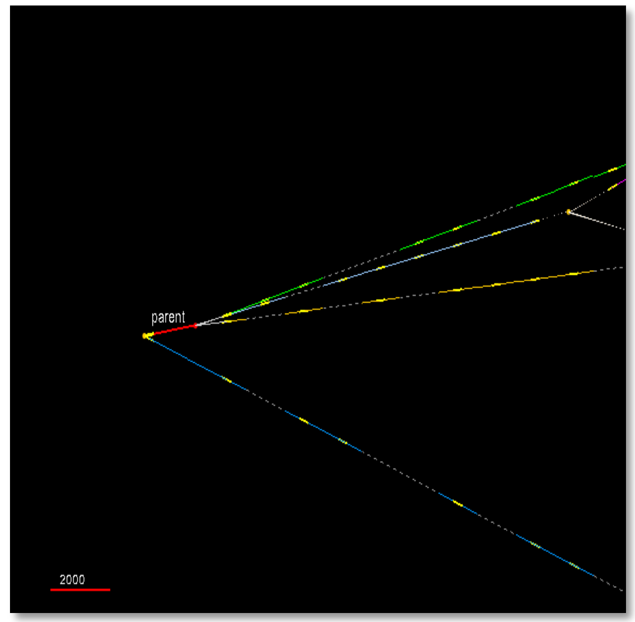


- want to confirm the hypothesis that $\nu_\mu \rightarrow \nu_\tau$ is the cause of the disappearance effect seen in atmospheric & accelerator-based ν's
- need an experiment capable of detecting short-lived τ's

Long-Baseline $\nu_\mu \rightarrow \nu_\tau$

- 400 GeV proton from CERN SPS to produce beam above ν_τ threshold
- emulsion to detect τ decay

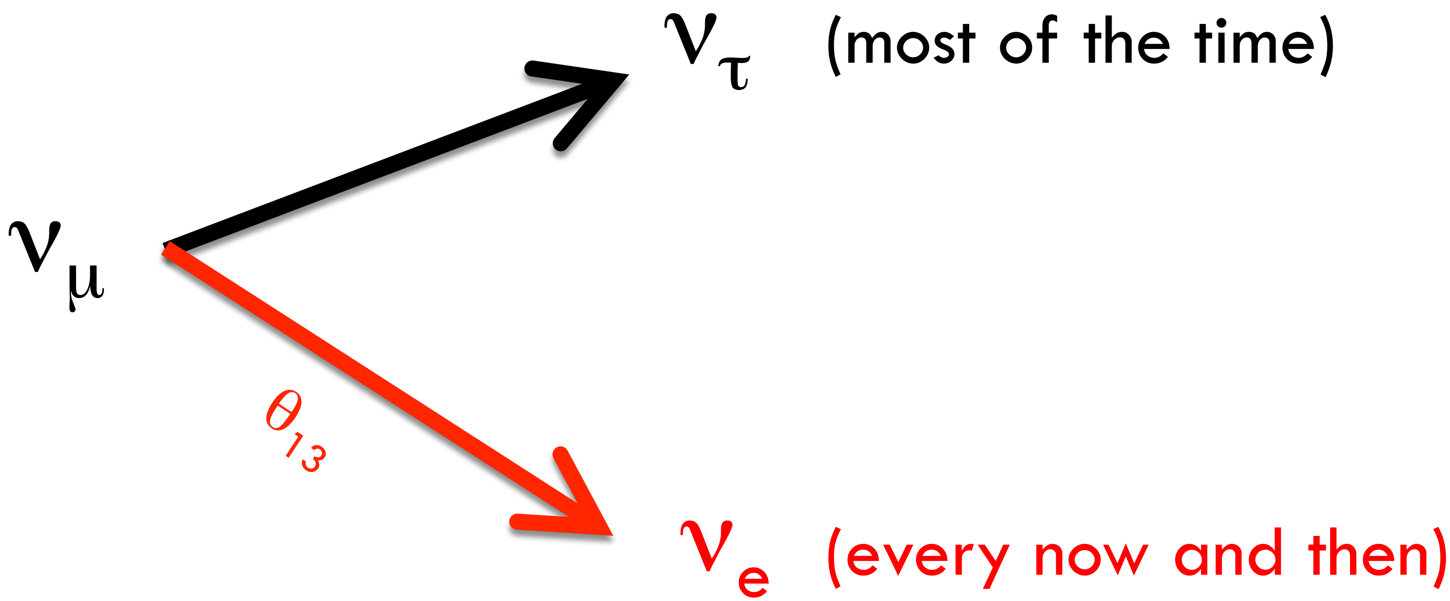




OPERA

- March 2013: OPERA reported observation of a third ν_τ candidate
- strong evidence (3.8σ) for ν_τ appearance also observed in the Super-K atmospheric data *(Abe et al., PRL 110, 181802 (2013))*

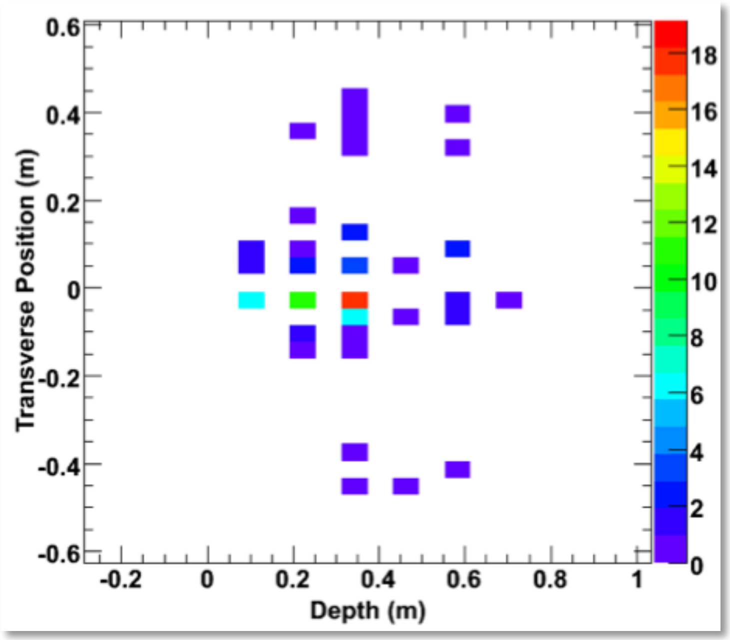
What Are They Disappearing To?



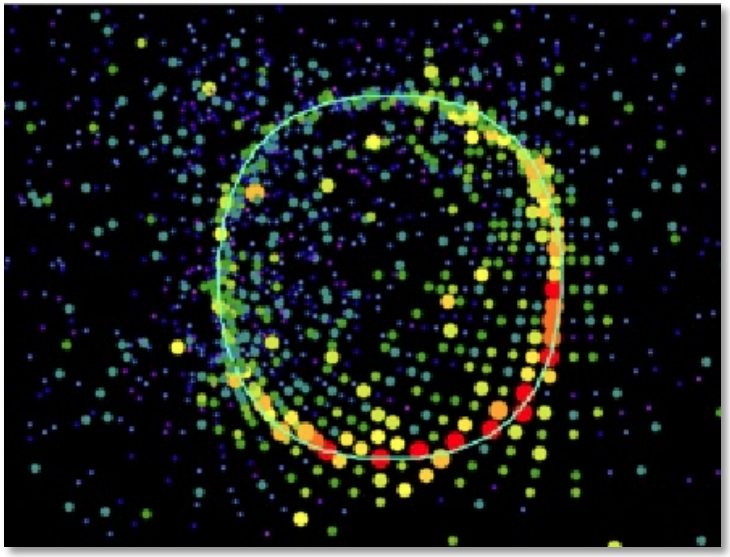
- measurements of subdominant $\nu_\mu \rightarrow \nu_e$ are of great importance because they are very sensitive to mass hierarchy and CP violation

ν_e Appearance

- **MINOS**



- **T2K**

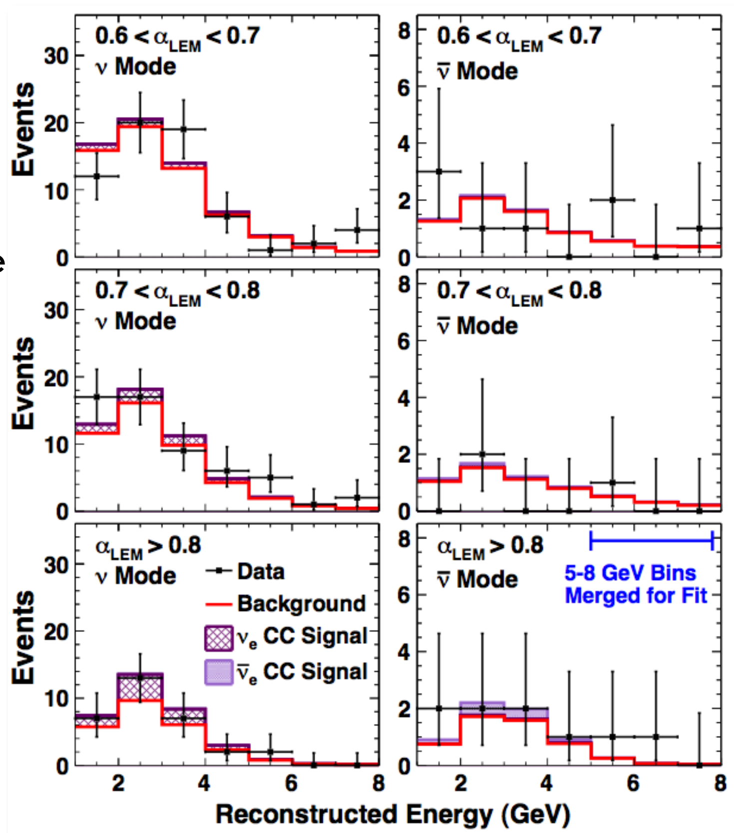


electron neutrino candidate
events in both detectors

ν_e Appearance

- **MINOS**

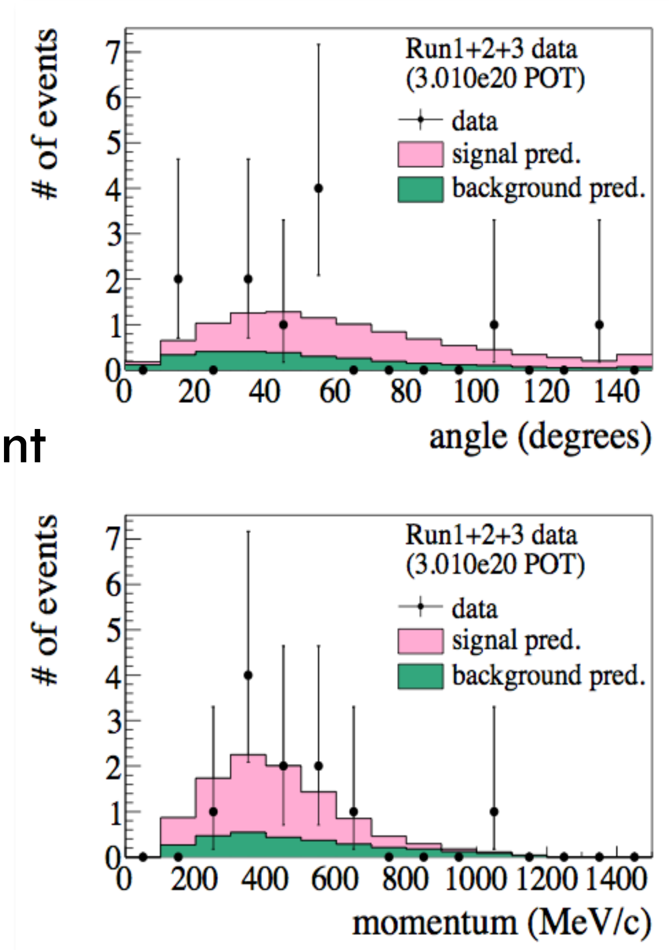
both
ν_e & $\overline{\nu}_e$
data



(Adamson et al., PRL 110, 171801 (2013))

- **T2K**

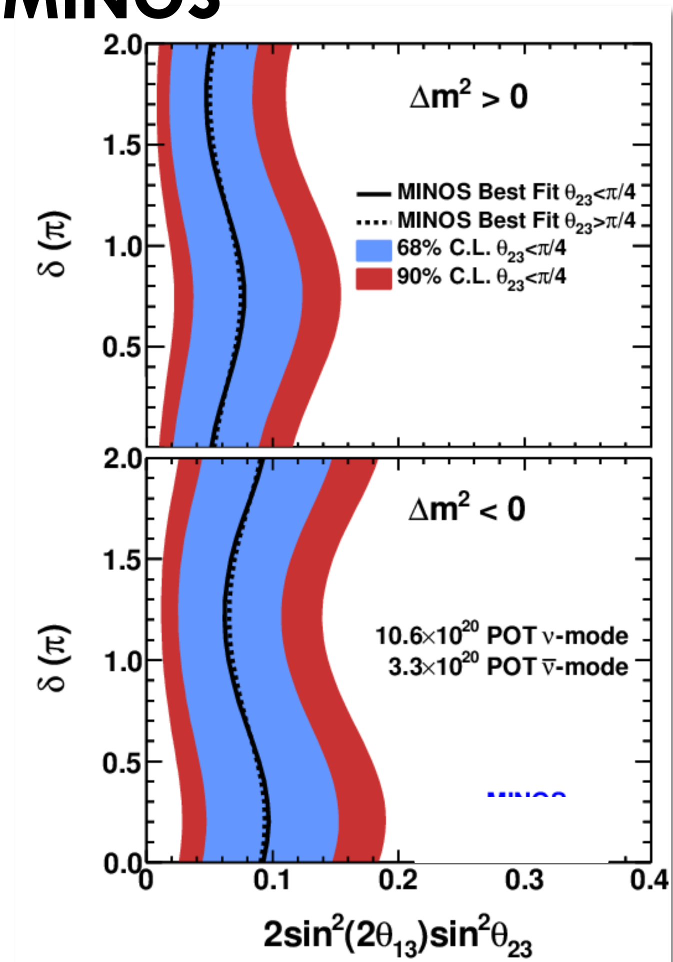
3.1σ excess consistent with $\nu_\mu \rightarrow \nu_e$



(Abe et al., arXiv:1304.0841)

ν_e Appearance Allowed Regions

- **MINOS**



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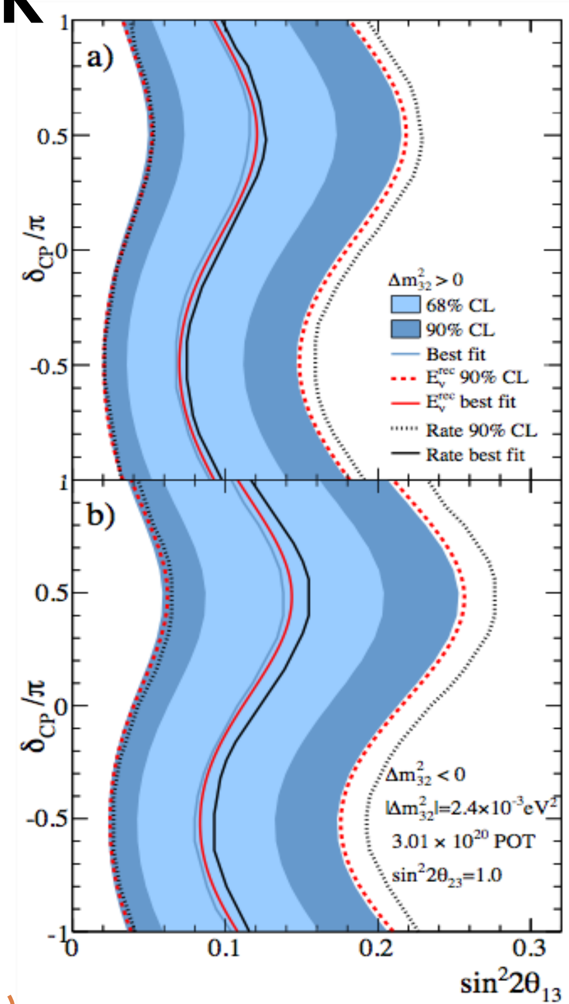

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- consistent with each other and new reactor results
- very powerful cross check

3-Flavor Mixing Picture

- probability of $\nu_\mu \rightarrow \nu_e$ (and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) over long distances:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim \quad & \sin^2 2\theta_{13} && \times \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\
& -\alpha \sin 2\theta_{13} && \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \sin 2\theta_{13} && \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha^2 && \times \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}
\end{aligned}
$$

$$
\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}
$$

- gives a measure of several very important things:

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  - δ_{CP} and CP violation
    (appears in combination with $\sin2\theta_{13}$, $\sin2\theta_{12}$, $\sin2\theta_{23}$)

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  - neutrino mass hierarchy (through matter effects)

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  - δ_{CP} and CP violation
    (appears in combination with $\sin 2\theta_{13}$, $\sin 2\theta_{12}$, $\sin 2\theta_{23}$)
  - neutrino mass hierarchy (through matter effects)
  - θ_{23} octant (which tells us about the nature of ν_3)

effects are all entangled

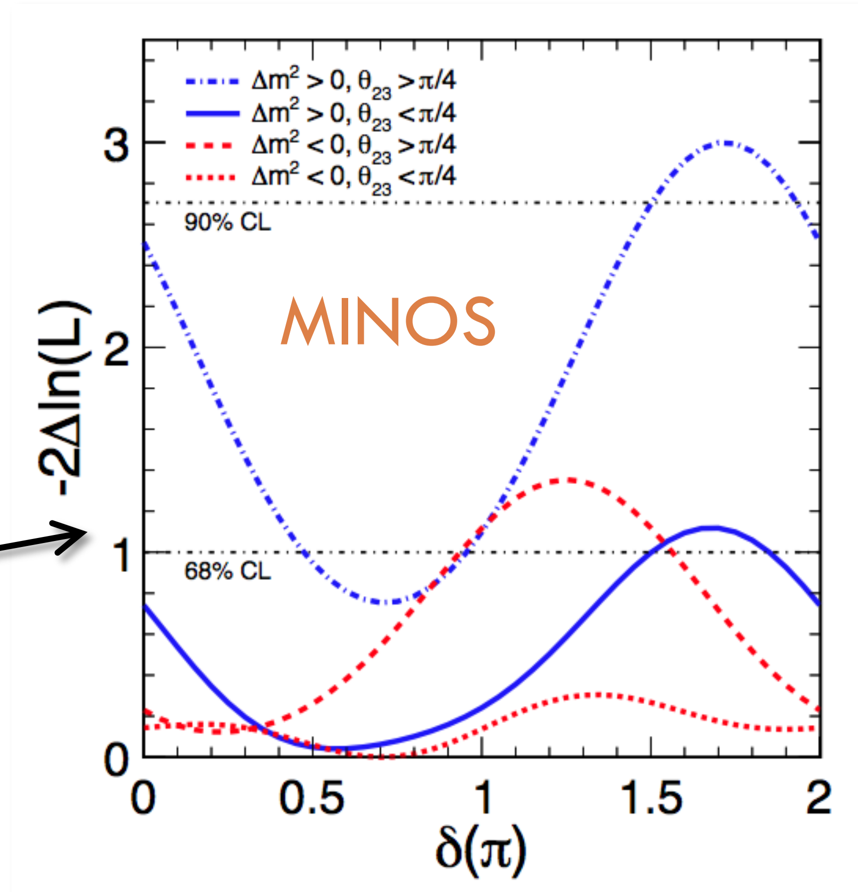
First Attempt at This

- using <u>accelerator-based</u> $\nu_\mu \rightarrow \nu_e$ data which has unique sensitivity to δ_{CP}, mass hierarchy, θ_{23} octant

- combined with <u>reactor</u> θ_{13} results

- shows how this data will be used in the future

  - *this is the concept behind the future accelerator-based long-baseline ν program*

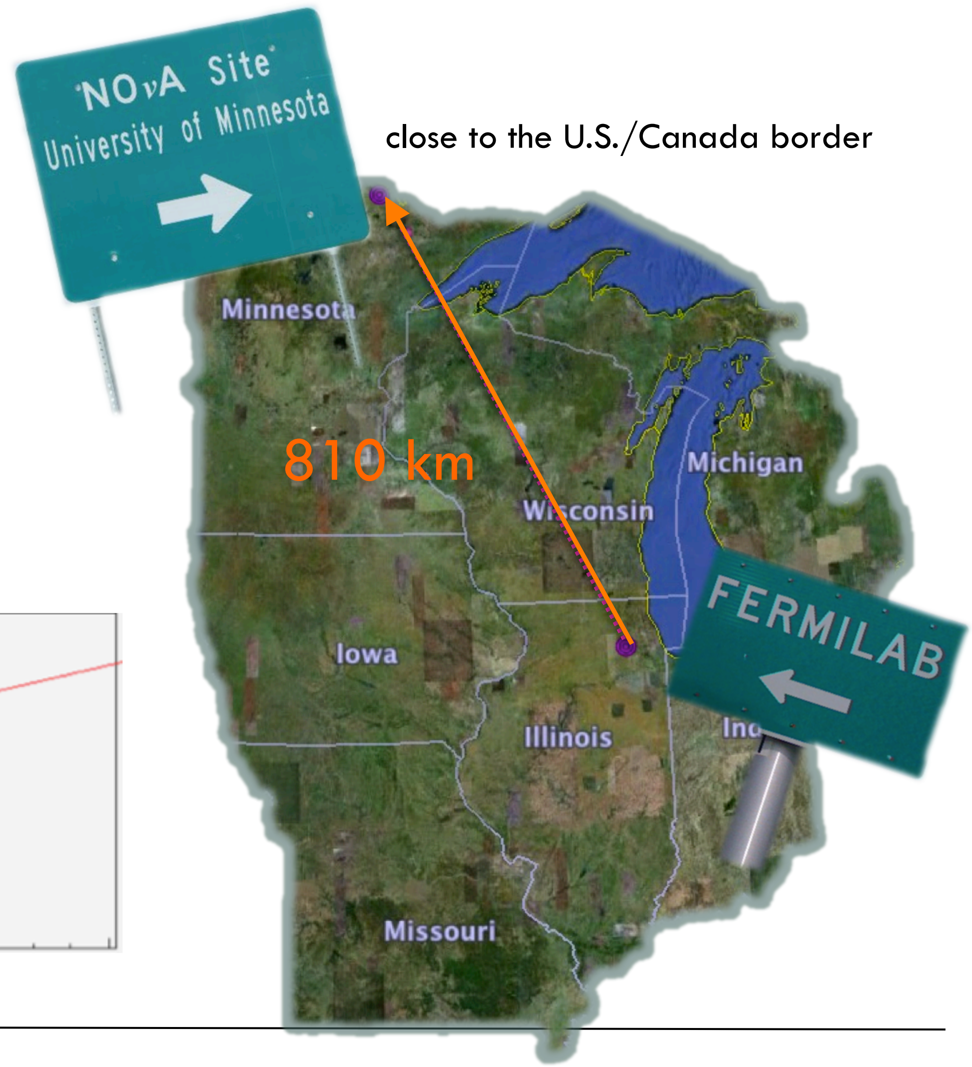


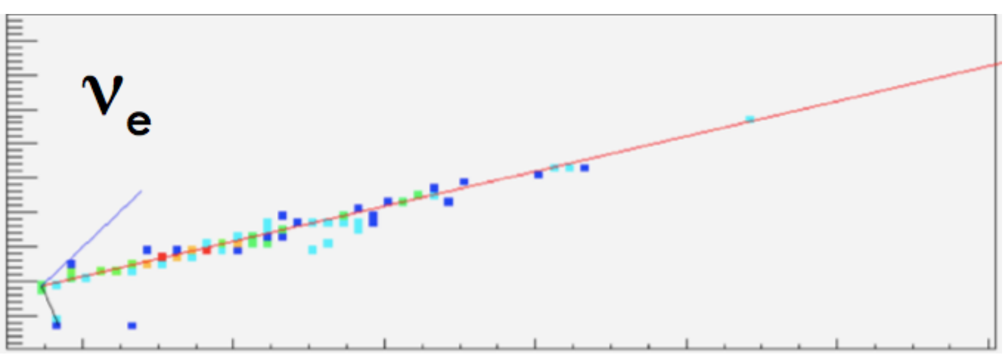
(Adamson et al., PRL 110, 171801 (2013))

- physics handles are there and we are starting to use those handles

NOvA

- 2^{nd} generation long-baseline ν oscillation experiment coming online soon
  - will study $\nu_\mu \rightarrow \nu_e$ add $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions over a distance of 810 km using an off-axis, narrow beam
  - world's most intense accelerator based ν beam (700 kW)



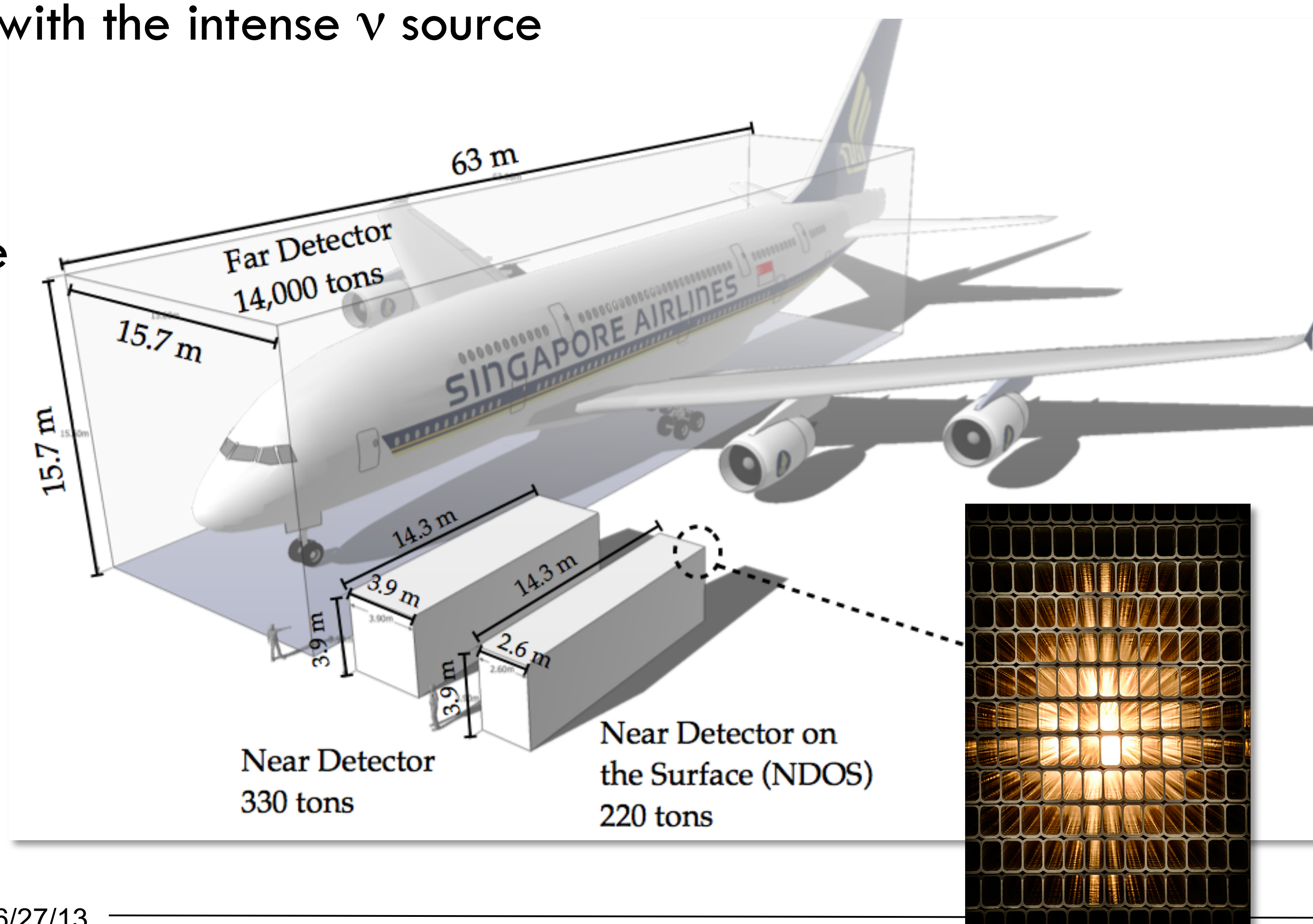


NOvA Detectors

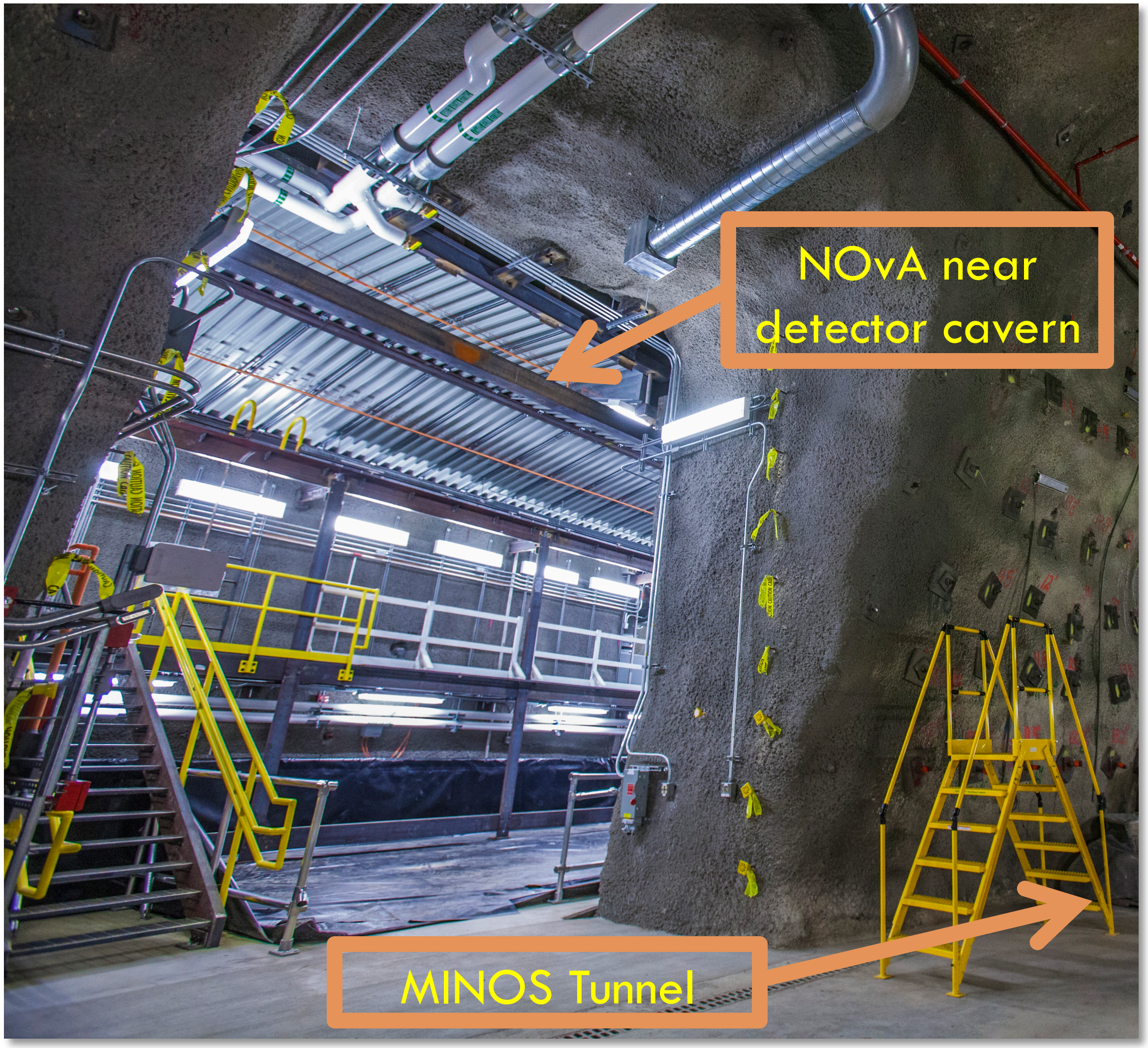
- as we’ve seen, the ν_e signals are small so need a massive detector to go along with the intense ν source

- 14 kton totally active liquid scintillator calorimeter

“largest plastic structure ever built”



Near Detector



- NOvA near detector cavern completed
- near detector assembly starts this month
- goal: ½ of near detector complete by end of year

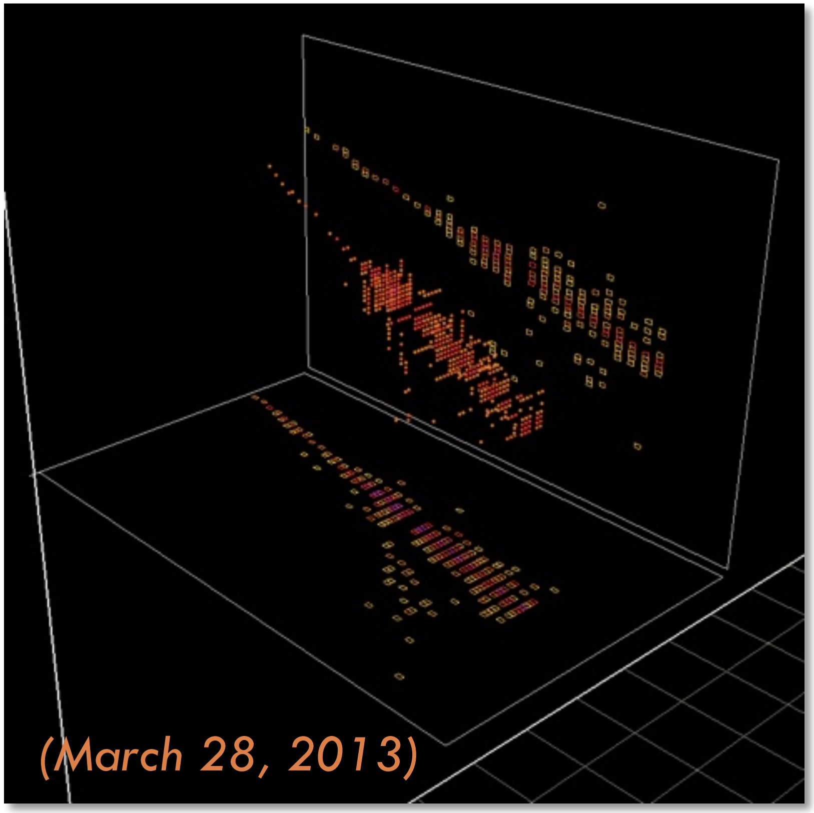
Far Detector

- site at Ash River was completed last year
- NOvA is in steady production mode getting this detector built
  - *54% of the blocks have been installed*
  - *33% of the detector has been filled*
  - *1.4 kton instrumented*

(status as of June 24, 2013)

Ready for Neutrino Beam!

- 3D image of a cosmic ray in instrumented portion of the NOvA far detector



Ready for Neutrino Beam!

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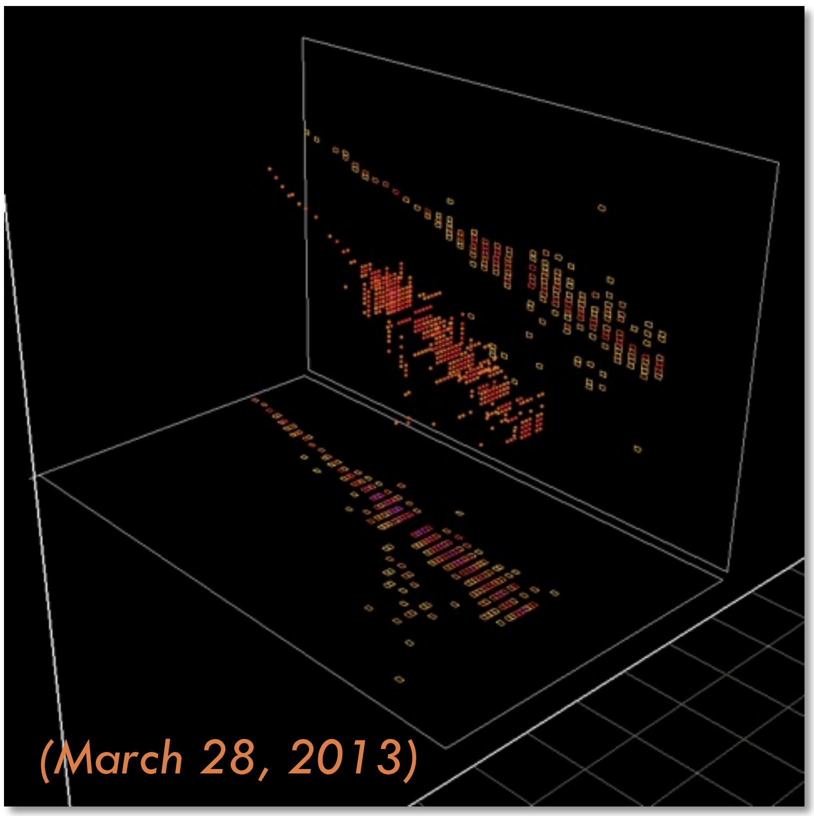
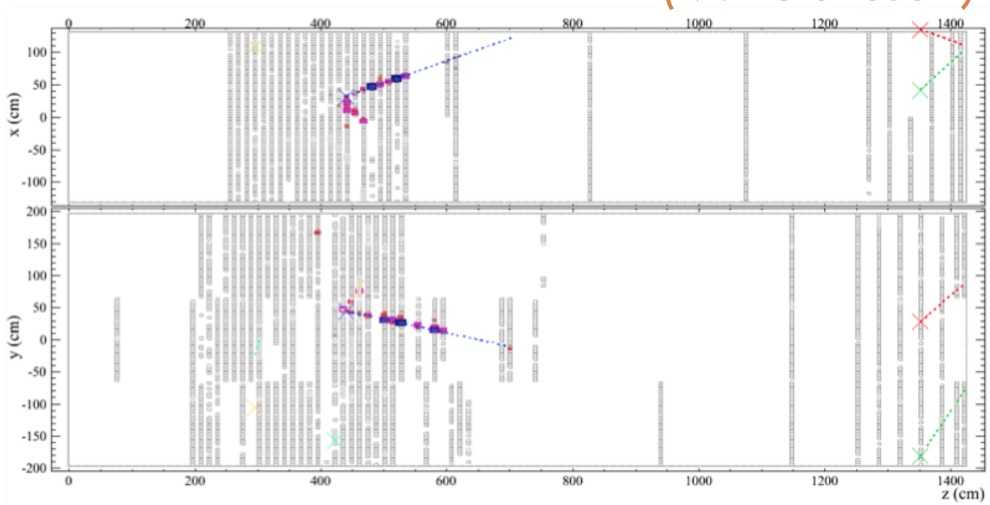
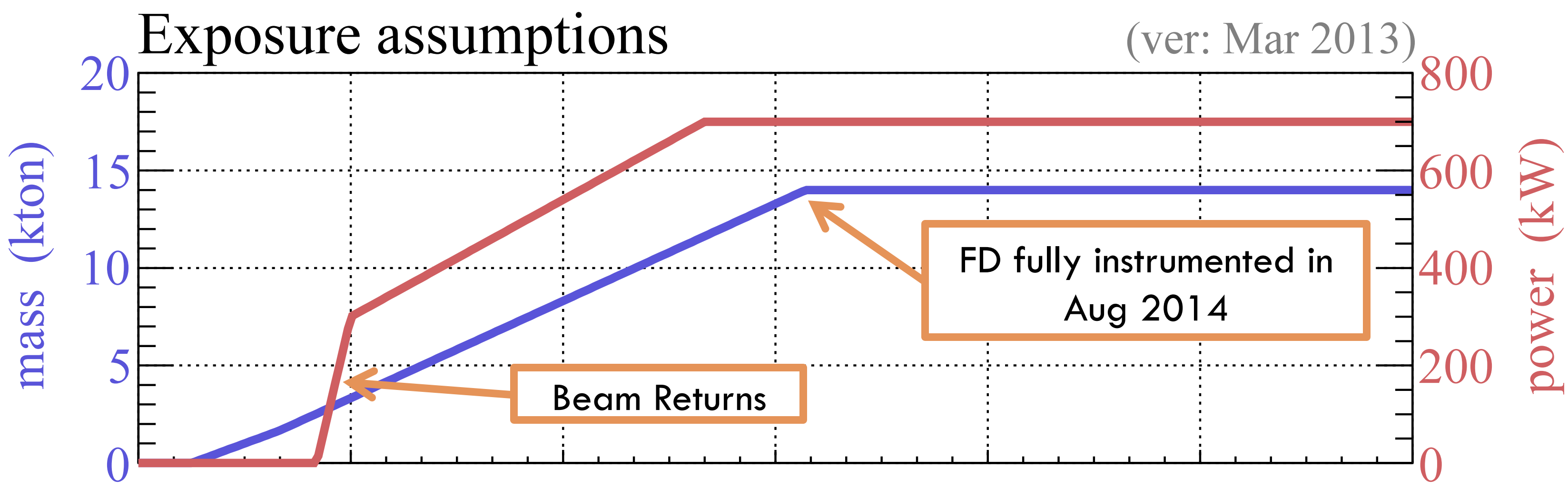


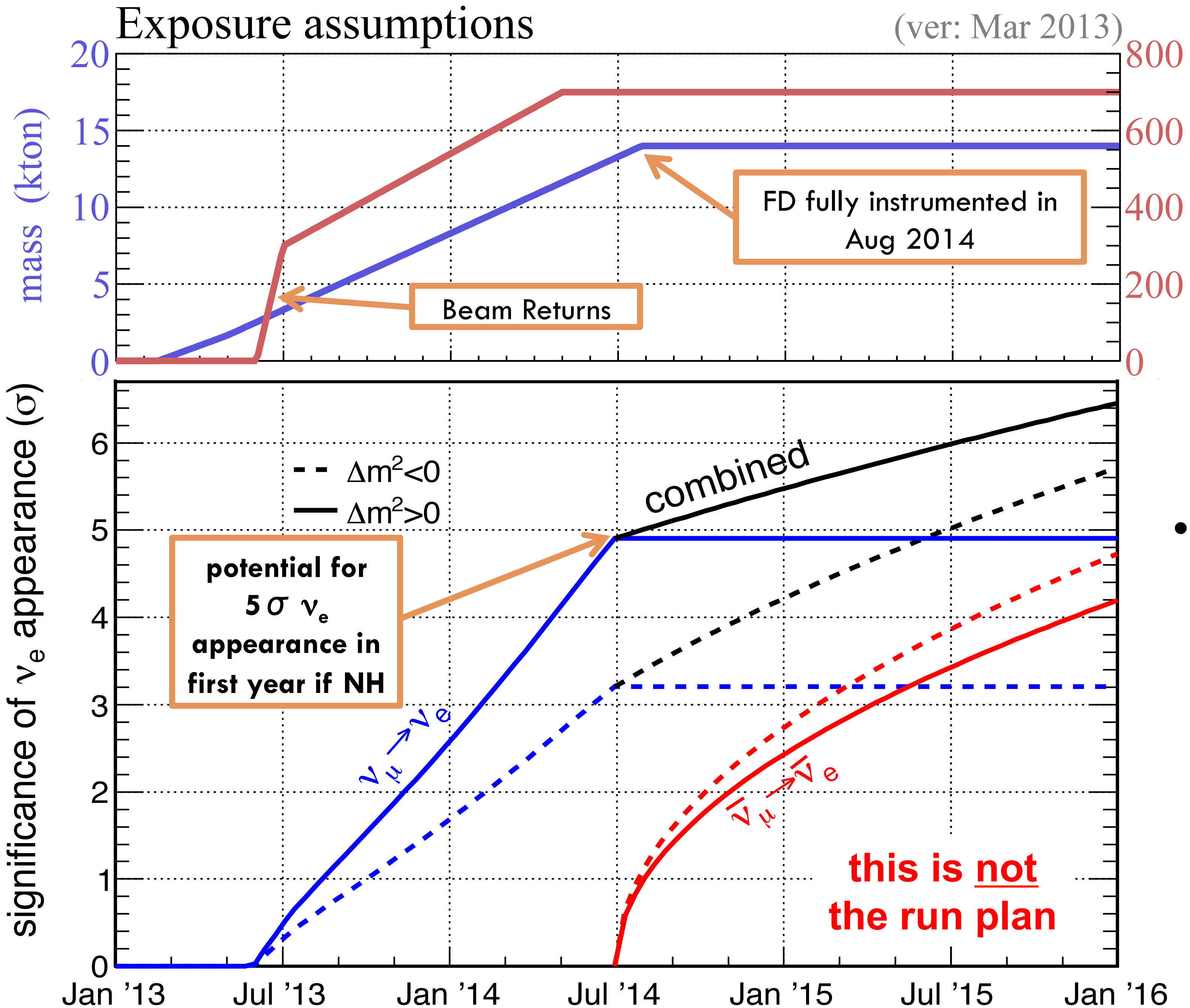
(M. Betancourt)



- also, extracting 1st physics from the Near Detector On Surface (NDOS)

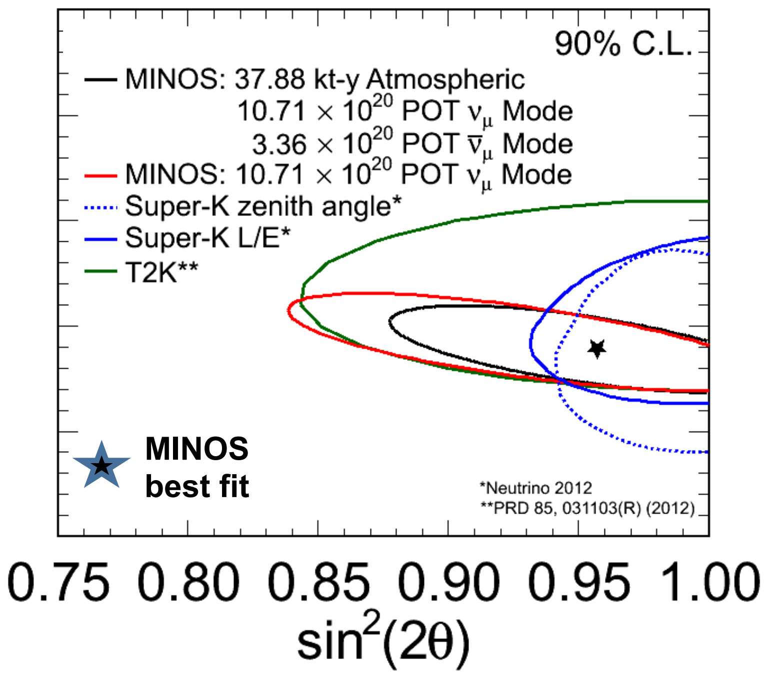


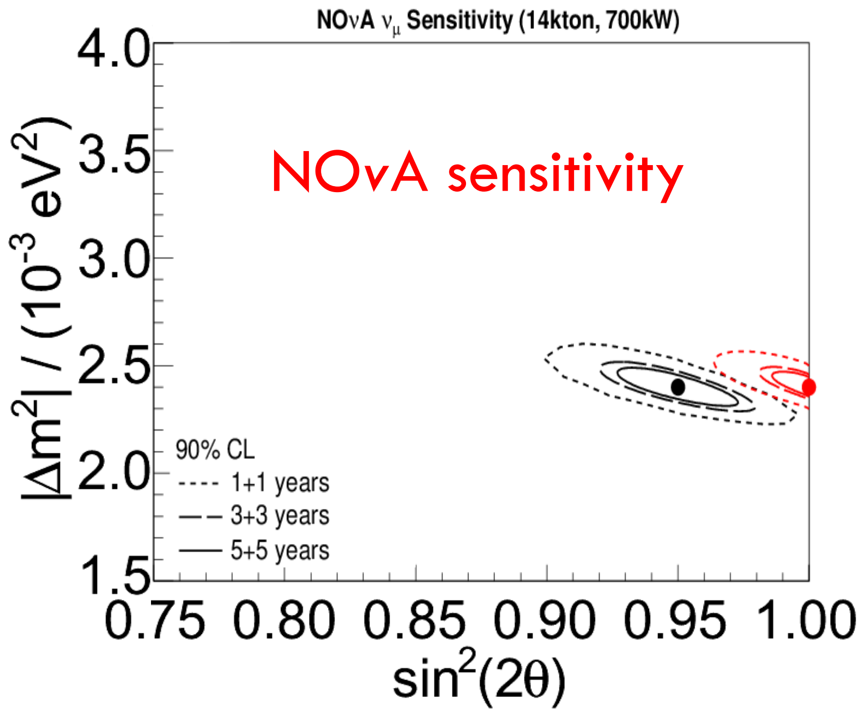
- first ν beam expected in a few weeks!



- first ν beam expected in a few weeks!

NOvA ν_μ Disappearance

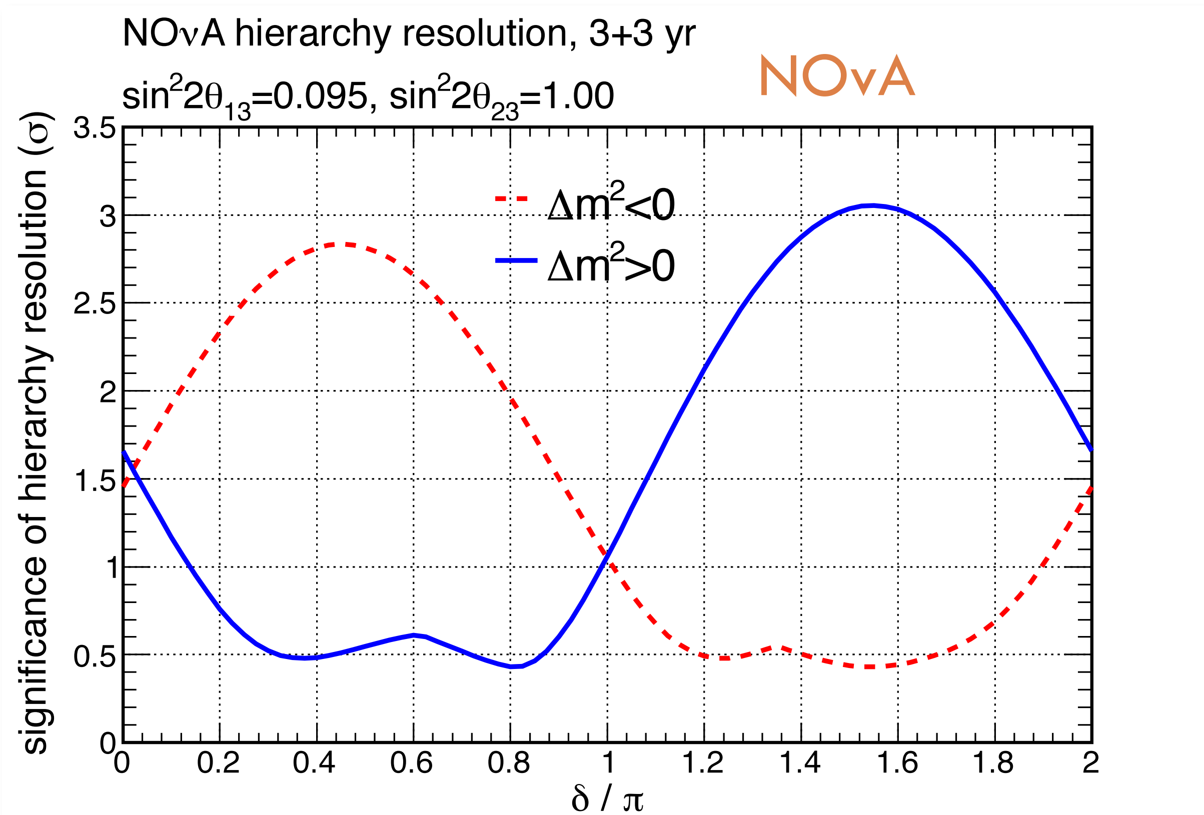




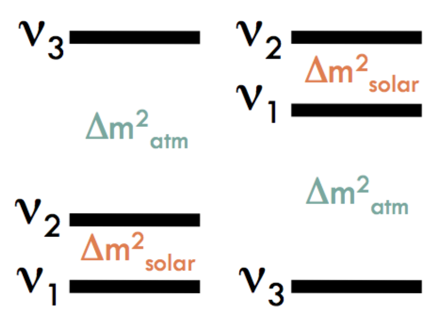
- few-% measurements of Δm^2_{32}, $\sin^2 2\theta_{23}$ for ν's and $\overline{\nu}$'s separately
- is $\sin^2 2\theta_{23}$ maximal? improved precision on θ_{23} is also important for future $\not{C}P$ searches

NOvA ν_e Appearance

- resolving the neutrino mass hierarchy



- will get the world's best look at this in a hurry



NOvA ν_e Appearance

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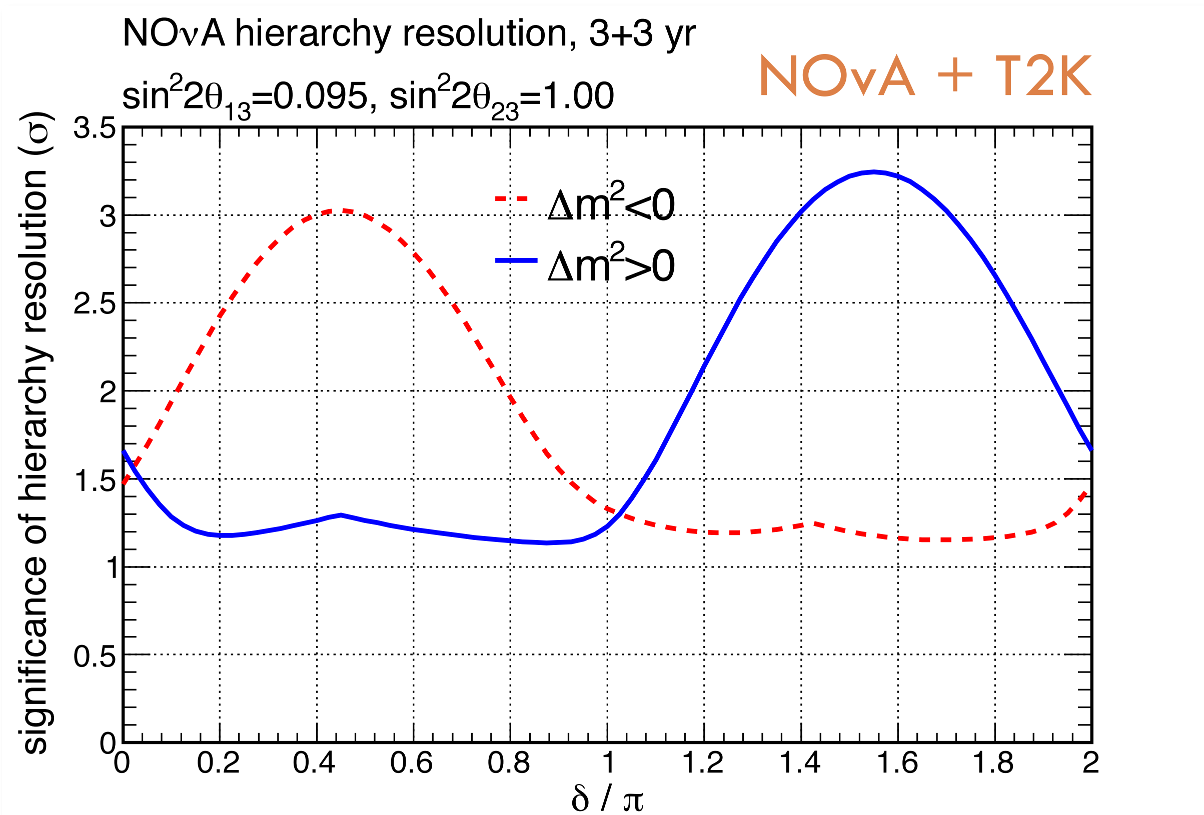

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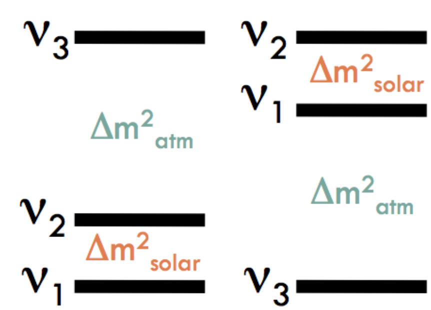
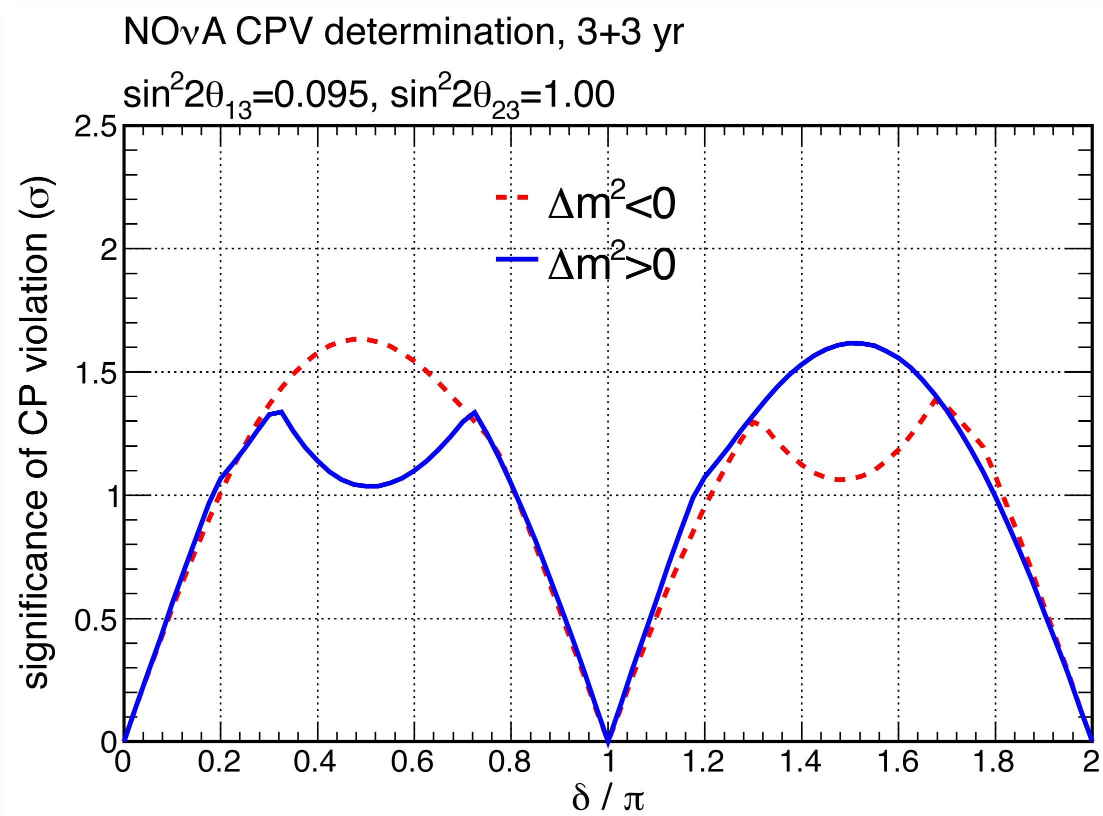


- T2K data is very important in combination!

- also, some new ideas for measuring this with atmospheric & reactor ν's

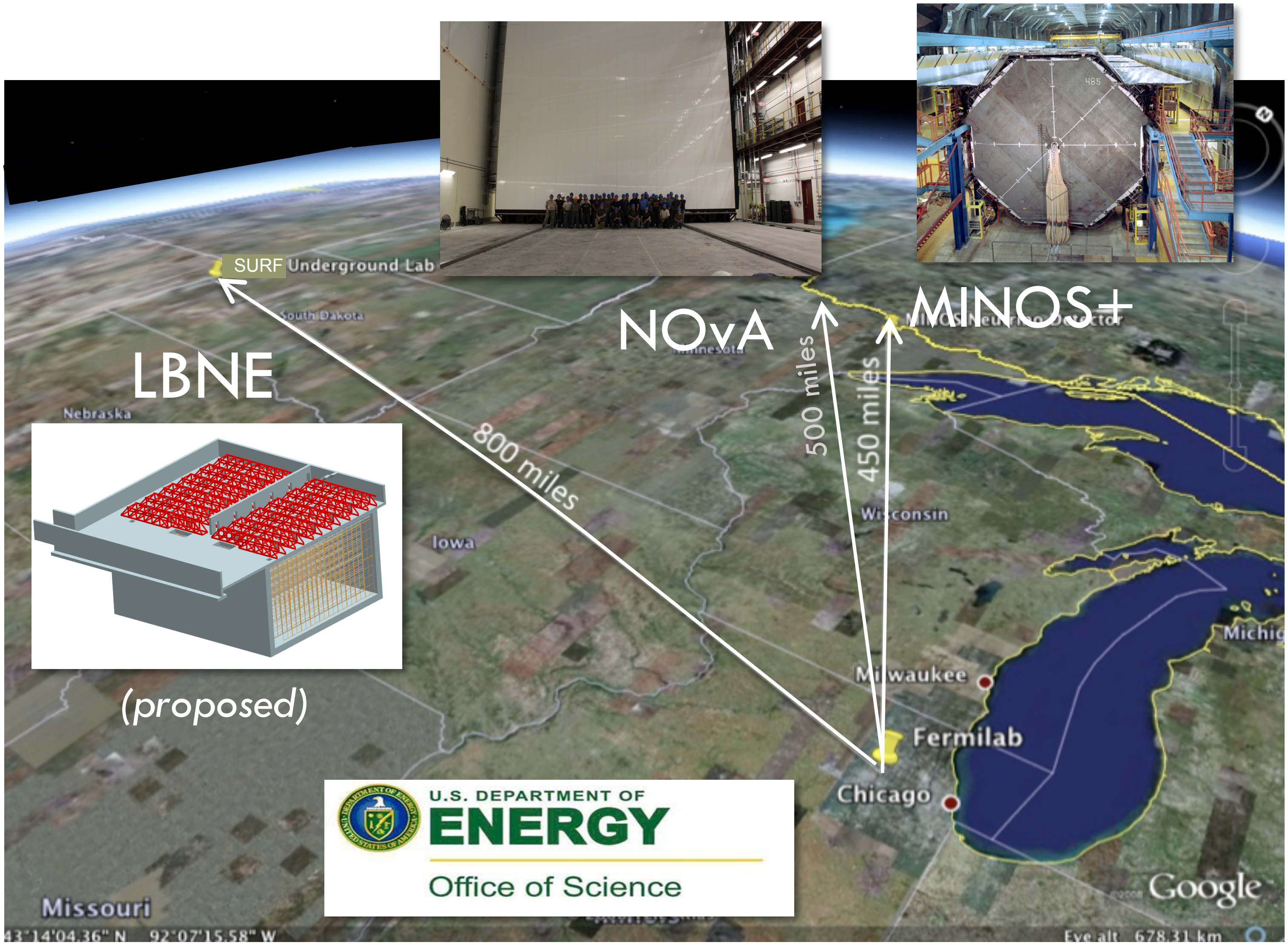
NOvA ν_e Appearance



- may even get a first glimpse at $\not{C}$P if we're lucky

- while new data from both NOvA and T2K are highly anticipated, we know it will be difficult discover $\not{C}$P with current generation experiments

What's Next?



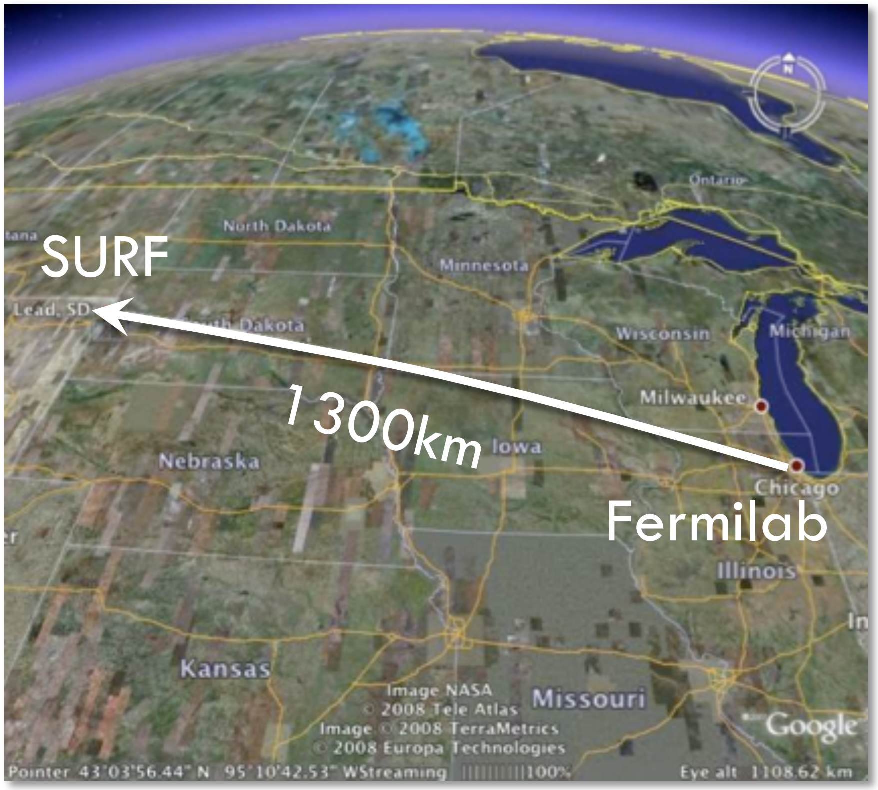
- T2K
- OPERA
- MINOS+
- NOvA

an example, in the U.S.:

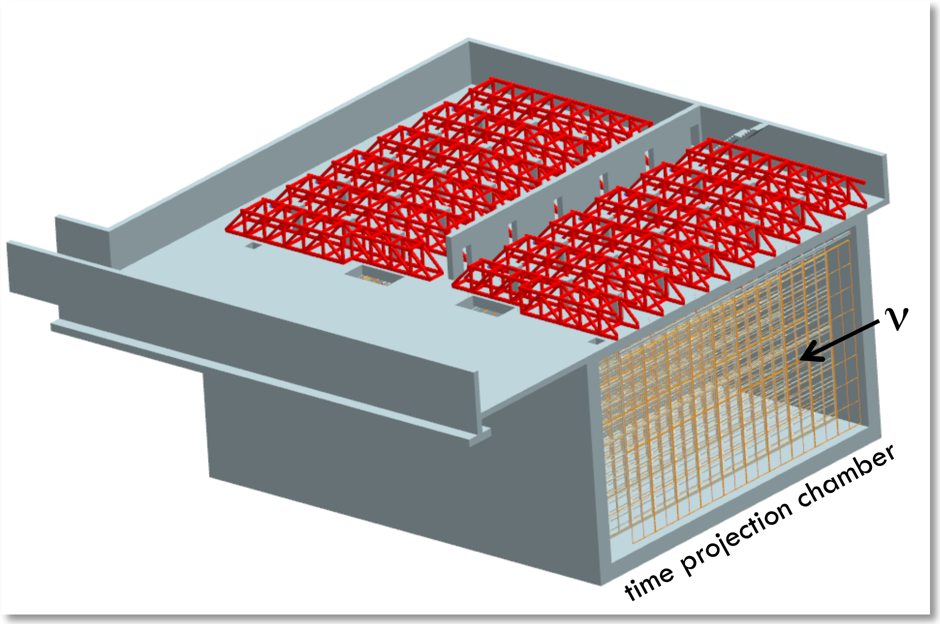
- LBNE

(see also Shiozawa's talk)

LBNE



- ingredients for success:
- optimized baseline
  - *1300km is ideal for this physics*
- Liquid Argon TPC
  - *very low bkgs, high ε over broad E_ν*
  - *goal: 34 kton fiducial volume*



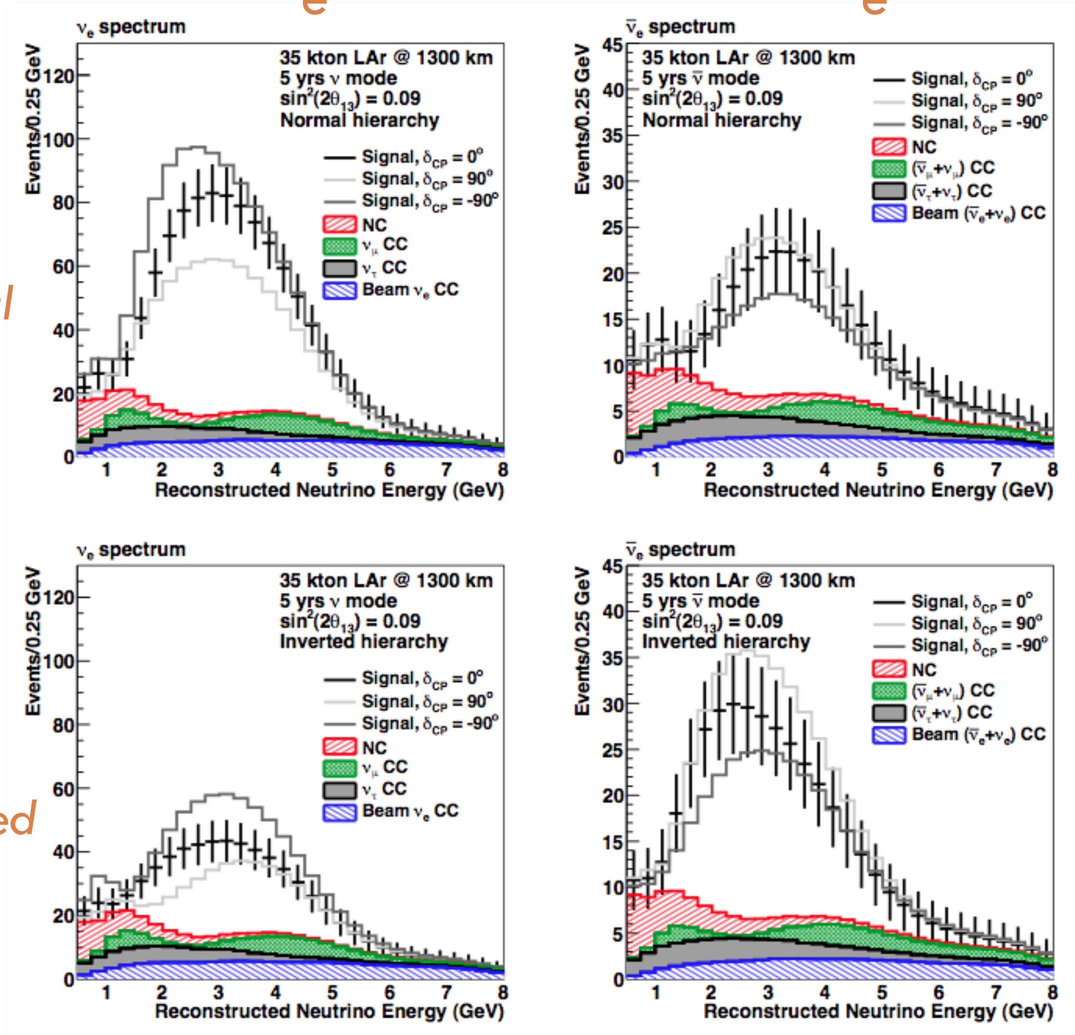
- broad band beam (ν, $\bar{\nu}$)
  - *want to measure the spectrum of ν's across largest possible dynamic range*
  - *700 kW beam initially, 2.3MW capable*

ν_e Appearance Signals in 35 kton

ν_e | $\bar{\nu}_e$

normal

inverted

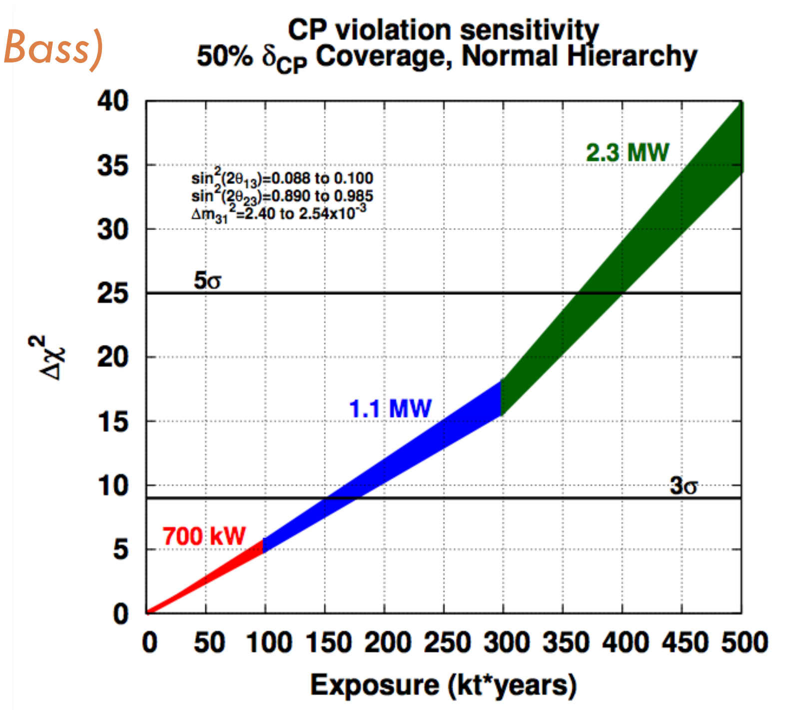


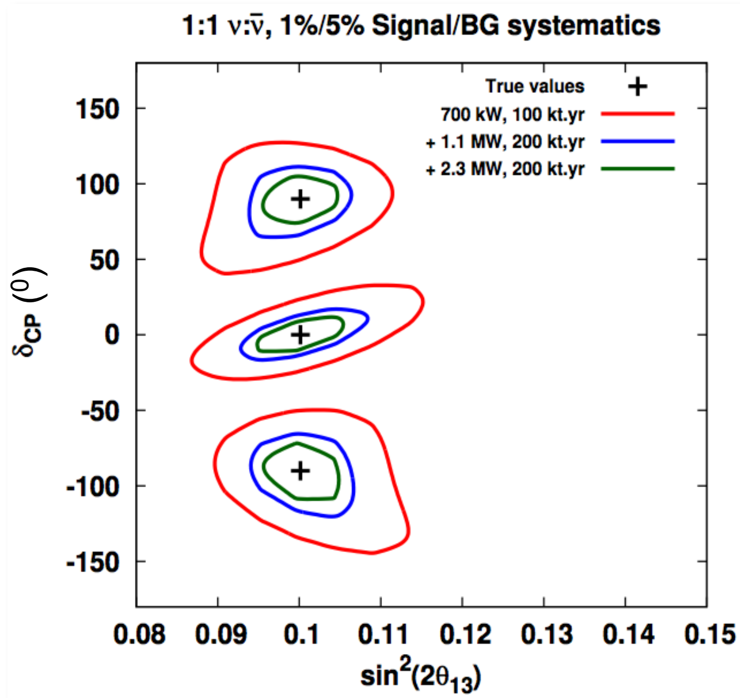
- observe spectral distortions *(peaks & valleys)*
- also looking to see if $\nu,\bar{\nu}$ behave differently *(direct evidence for ~~CP~~)*

(L. Whitehead)

LBNE Physics Goals

(M. Bass)





- measurements of $\not{CP}$ and ν mass hierarchy with using same ν source
- precision tests of 3ν mixing
- large underground detectors can also probe physics not accessible in any other way *(proton decay, supernova burst ν's, atmospheric ν's)*

Plans for LBNE

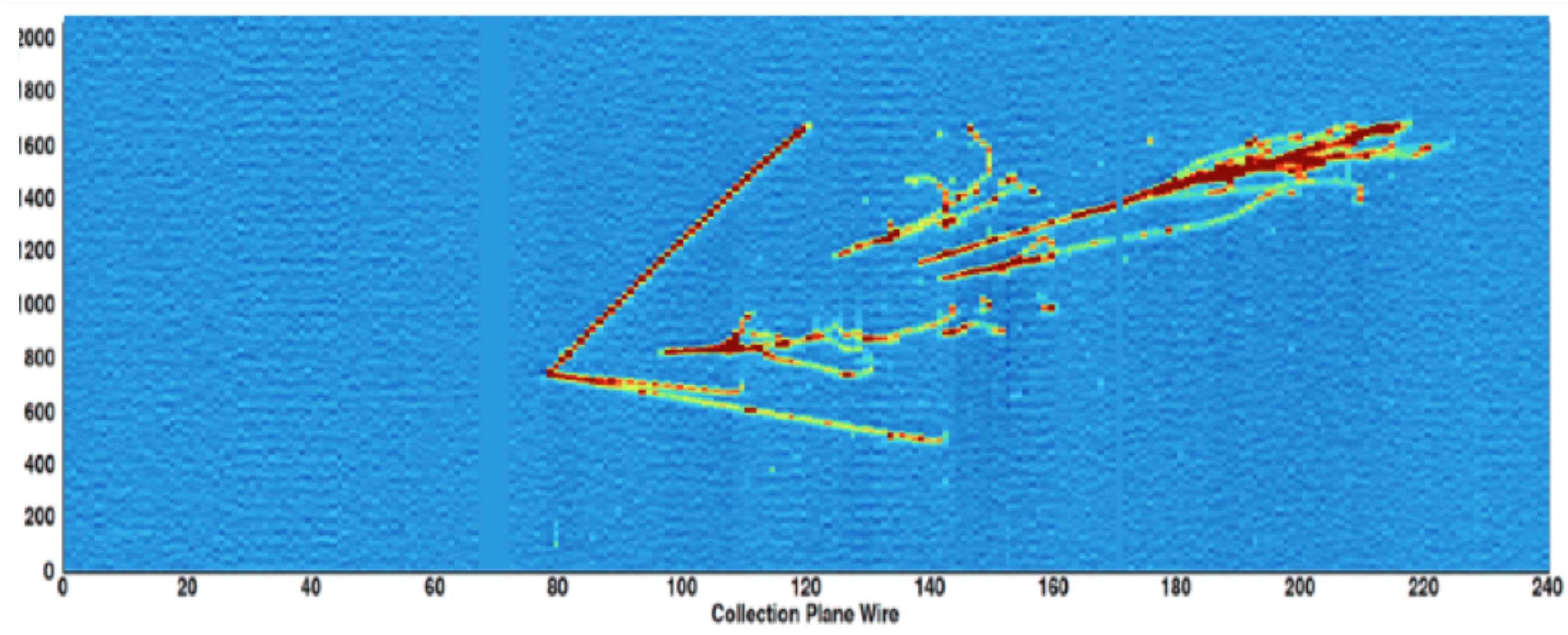
- LBNE has initial approval from the DOE to begin this program
  - *initial approval is for a 10kton far detector on the surface but this can be changed before the project baseline is finalized*
  - *actively seeking foreign partners to expand the scope of this first phase*
- many discussions with potential non-U.S. partners
  - *in discussions: India, U.K., ICARUS/INFN, Brazil, LAGUNA-LBNO*
  - *preliminary discussions: CERN, Dubna*
  - *hoping to initiate discussions with: Japan, China, additional countries in the Americas, Asia, and Europe*
- recently, the leadership of LBNE and LAGUNA-LBNO have begun exploring the possibility of a combined collaboration

… very positive developments!

Liquid Argon TPCs

- we are also excited about the detector technology
- below is an actual ν event from the ArgoNeuT detector *(from Fermilab NuMI neutrino exposure in 2009-2010)*

ν ⟶



(mm scale resolution)

- these detectors are a very powerful tool

MicroBooNE

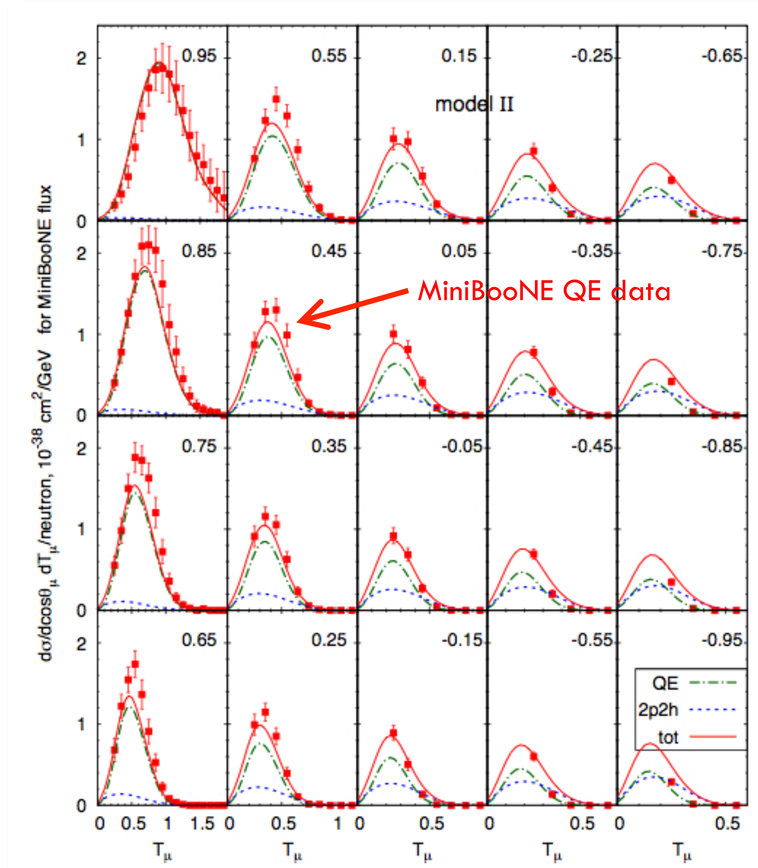
- idea is to start out small to gain some experience
- in the U.S., we are building MicroBooNE now – data-taking in 2014

170 ton LAr TPC
(size of a school bus)

- also, 35 ton LBNE prototype
- in Europe, ICARUS (600 ton LAr TPC) has been running since 2010

Neutrino Scattering

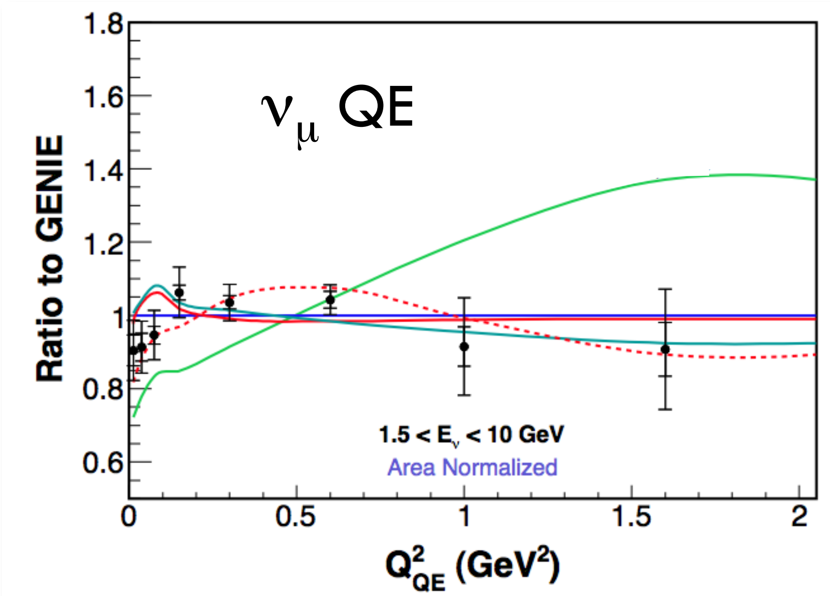
- this program requires better neutrino cross section measurements
  - large θ_{13} makes $\not{C}\!P$ harder (CP asymmetry ~ $1/\sin\theta_{13}$)
  - evidence from a variety of ν data that the underlying nuclear physics is far more complex that we thought *(ex: MiniBooNE data)*
- new data crucial to help sort out these issues



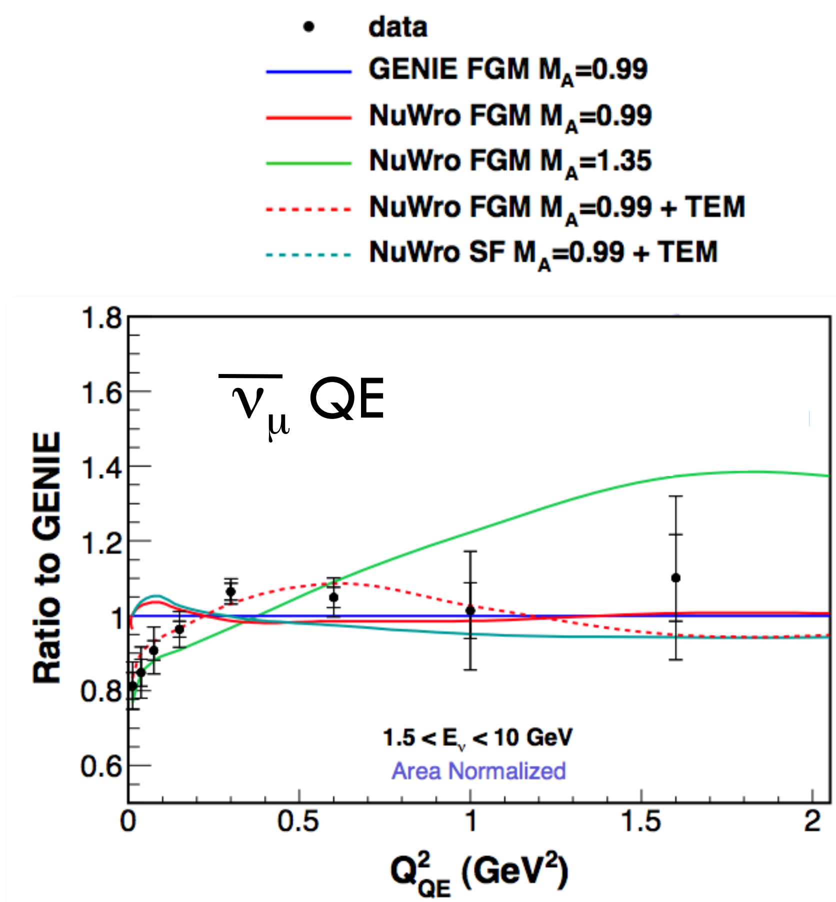
one of many examples

Lalakulich, Gallmeister, Mosel, arXiv:1203.2935

- MINERνA helping sort out whether the effects seen in lower energy ν experiments are related to the axial form factor or nuclear effects



(Fiorentini et al., arXiv:1305.2243
Fields et al., arXiv:1305.2234)

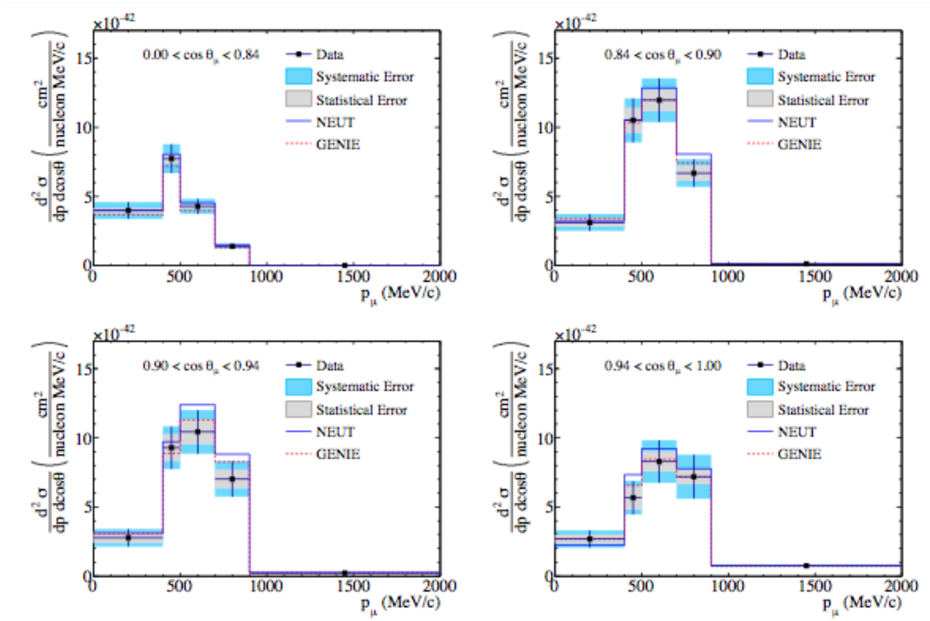


- MINERνA data on multiple nuclear targets will also be highly valuable

Also New This Year

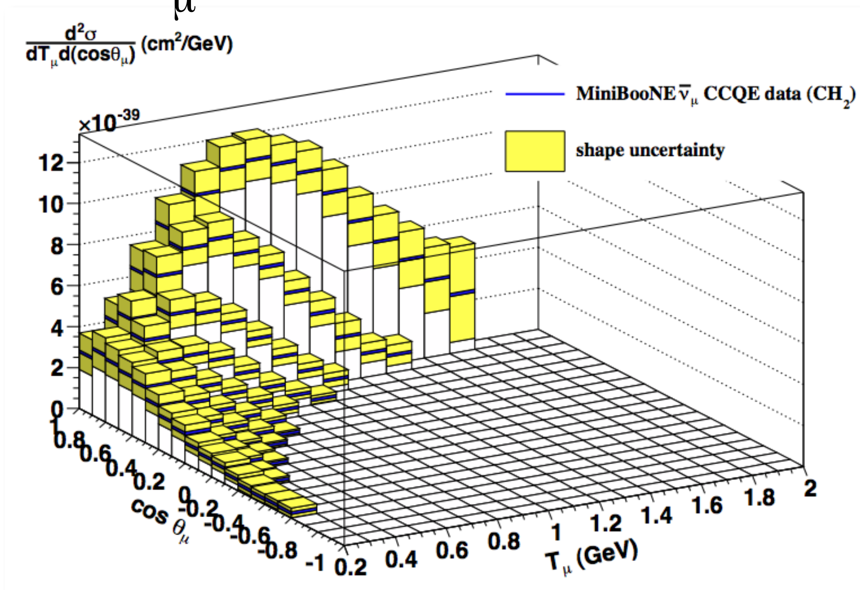
ν_μ CC inclusive scattering results from T2K

(much more to come!)



(K. Abe et al., arXiv:1302.4908)

$\overline{\nu}_\mu$ QE from MiniBooNE



(A. Aguilar-Arevalo et al., arXiv:1301.7067)

- improved σ_ν measurements are necessary and important

Conclusions

- data from a variety of ν sources have all worked together to construct our current model of neutrino mixing *(solar, atmospheric, accelerator, reactor)*

- **accelerator-based long-baseline** neutrino experiments continue to play a very important role …

  - measurements of ν_μ **disappearance** provide the most stringent constraints on atmospheric oscillations; also, $\nu_\mu \rightarrow \nu_\tau$ detection

  - observations of ν_e **appearance** consistent with new reactor results

- next, experiments will exploit non-zero θ_{13} to rigorously test this picture, measure the ν mass hierarchy, and search for CP violation

  - *these experiments promise a rich program with the sensitivity to make fundamental discoveries*

… this is an exciting time!

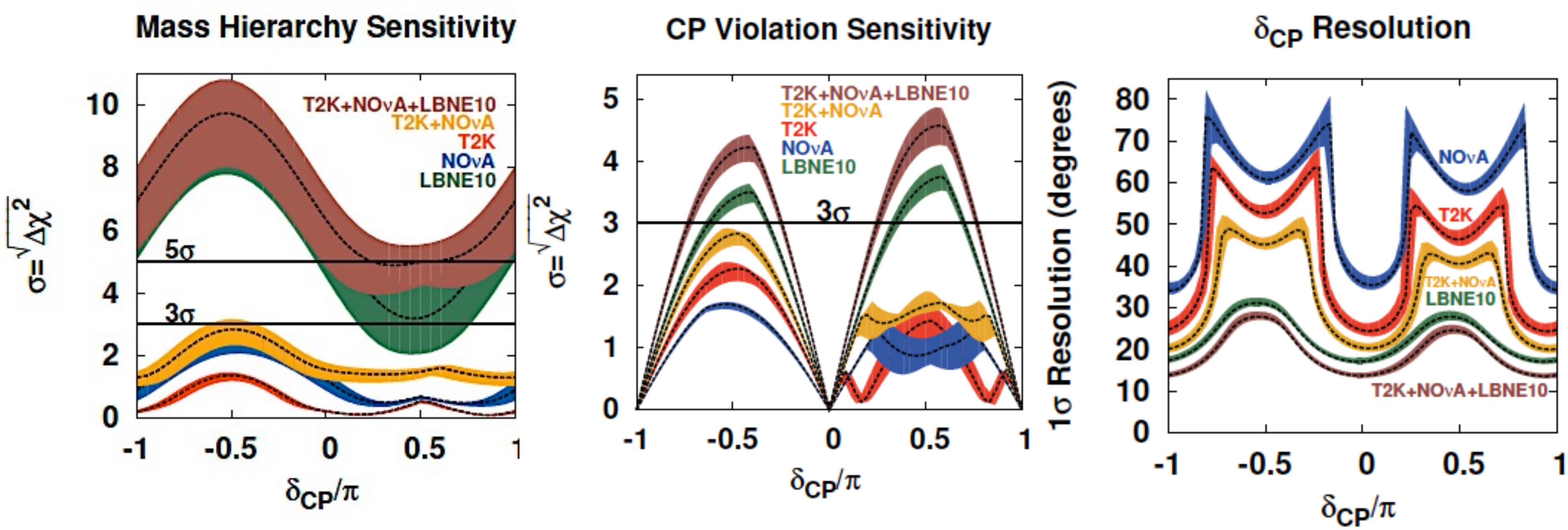
Backups

SURF Today


Majorana detector assembly room: December 2012
The Little X in the Davis Campus (main entrance to the left, secondary access to the right): October 2012
Entrance to the Davis Campus, looking south: May 2012
Majorana Electroforming Laboratory: November 2011
Davis Cavern (Top deck of the LUX experiment, looking north: July 2012
13
South Dakota Science and Technology Authority
Lead, South Dakota
Majorana Demonstrator/Transition Cavern after outfitting: May 2012

LBNE 10kton

- LBNE10 does much better than full program for existing experiments



Bands: 1s variations of θ_{13}, θ_{23}, Δm_{31}^2 (Fogli *et al.* arXiv:1205.5254v3)

T2K 750 kW x 5 yr ν

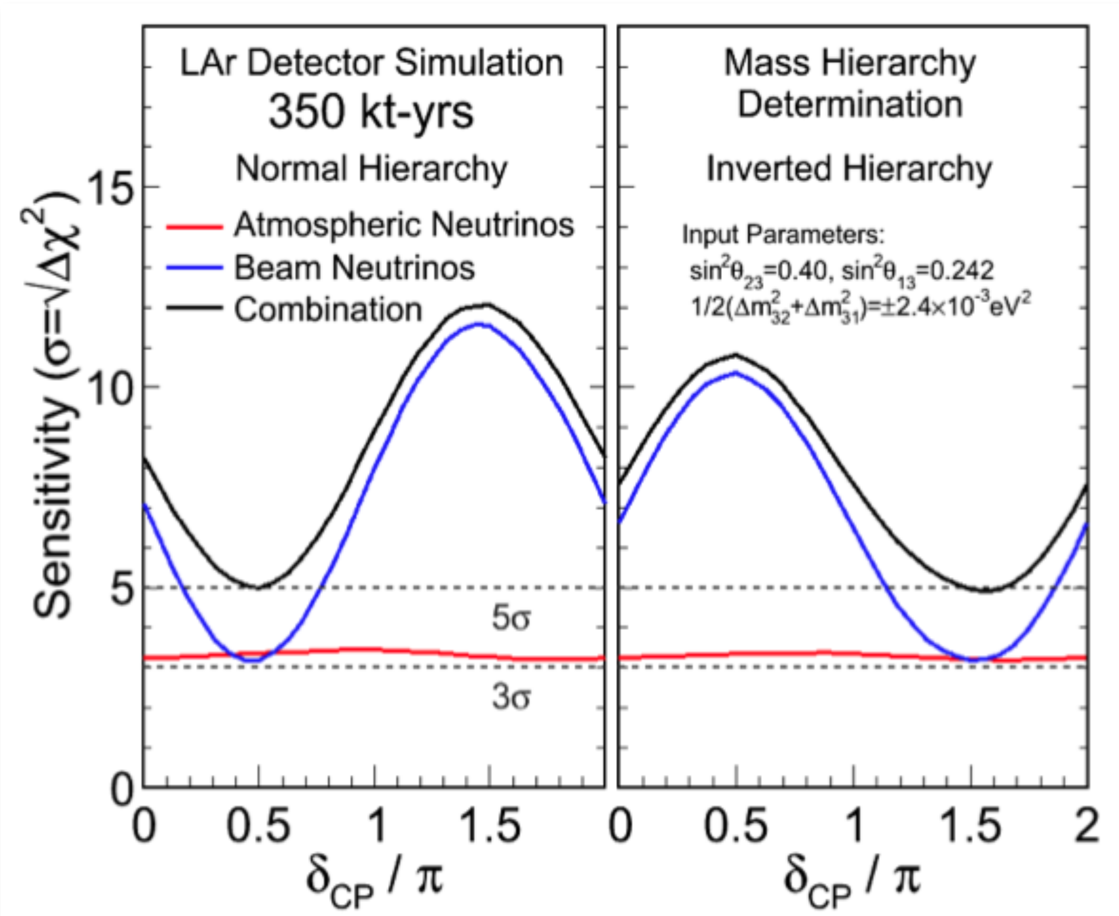
NOνA 700 kW x (3 yr ν + 3 yr $\bar{\nu}$)

LBNE10 (80 GeV*) 700 kW x (5 yr ν + 5 yr $\bar{\nu}$)

* improved over CDR 2012 120 GeV MI proton beam

(M. Bass)

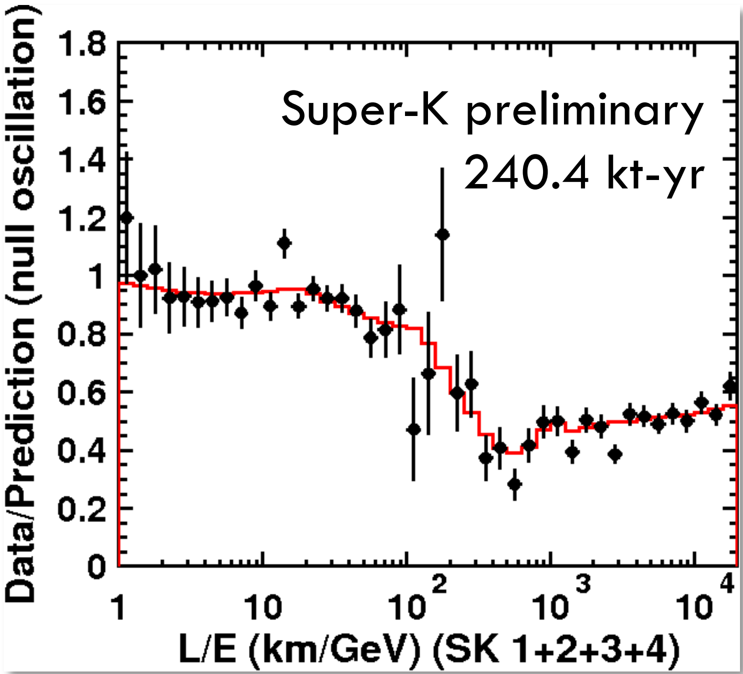
Mass Hierarchy in LBNE

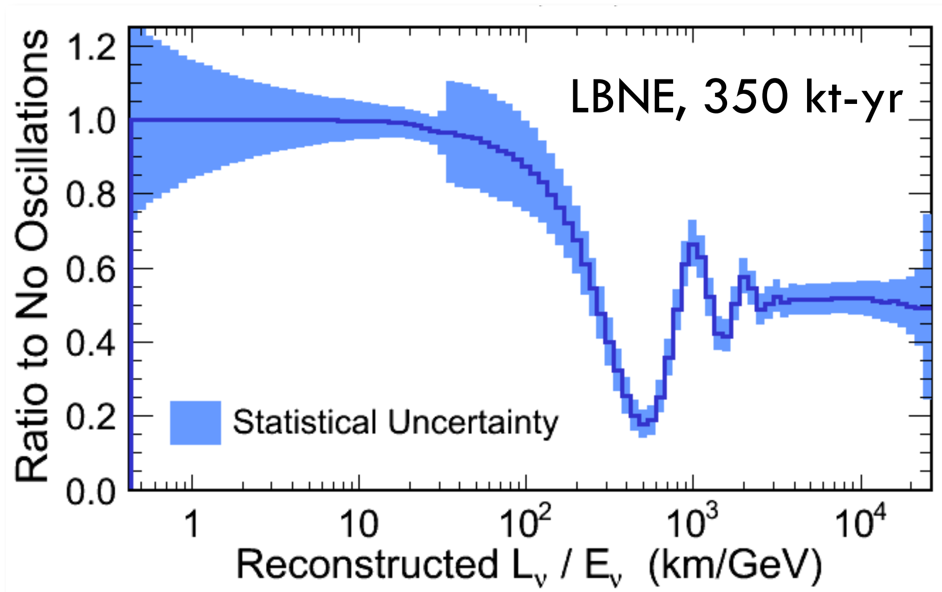


(A. Blake, H. Gallagher)

- combining information from accelerator and atmospheric neutrinos

Atmospheric Neutrinos



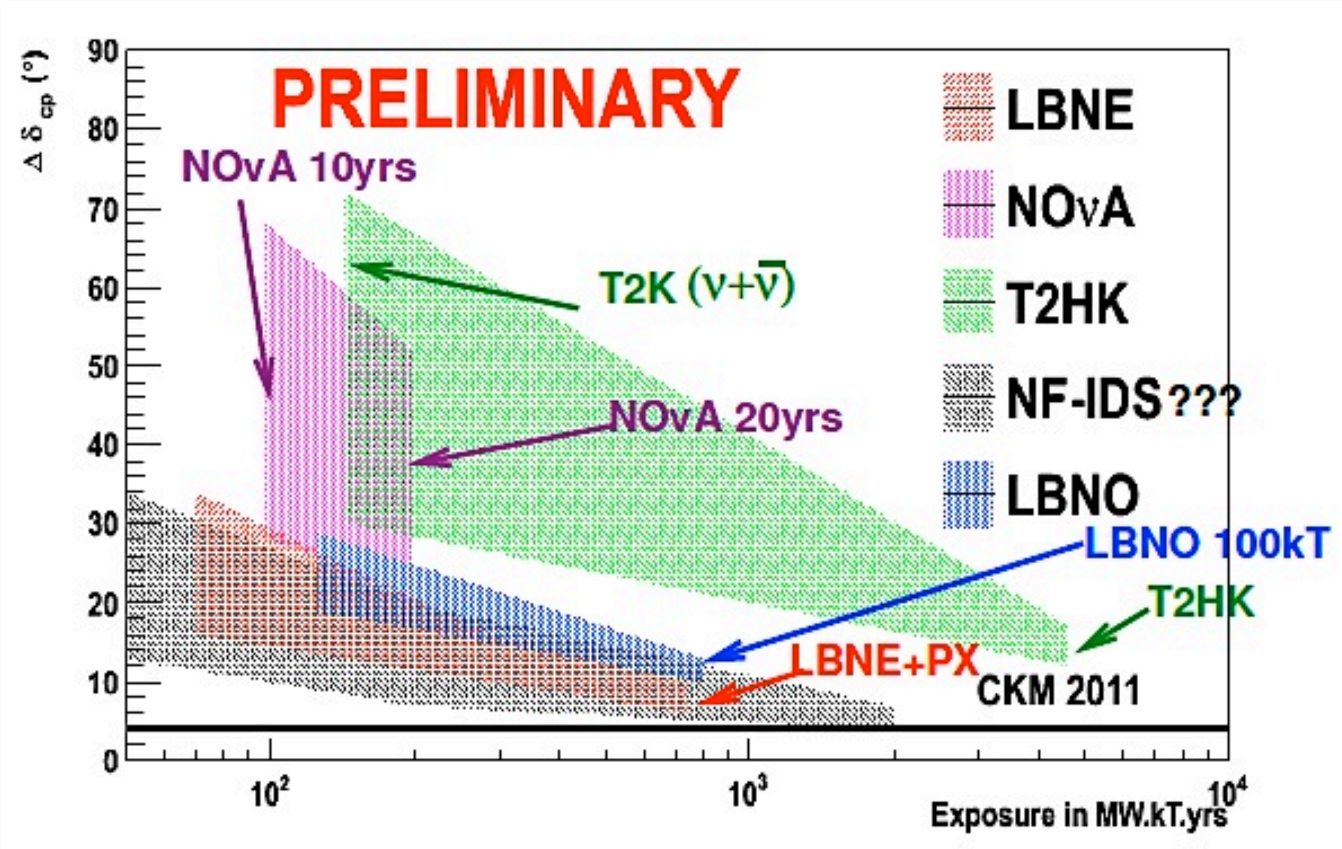


(A. Blake, hep-ex/1208.2899)

- spectacular signature – multiple oscillation dips visible!

Global Program

- how well can we measure δ_{CP}?



(M. Bishai)