Probing Neutrino Masses and Mixings with Accelerator (and Reactor) Neutrinos

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IceCube Invites Particle Astrophysics
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Current Major Neutrino Questions

- What are their masses?
  - Neutrinos have extremely tiny masses. Why?
  - But important contributors to how the universe works.
- Are there more than three types of neutrinos (electron, muon, and tau neutrino)?
  - Could there be new "sterile" type neutrino partners?
  - Are these "sterile" neutrinos the reason that neutrinos are different?
- Neutrinos can change from one type to another
  - What is the pattern (and explanation) of these mixings?
  - Is there CP violation in the mixing?
    Could this hold the key to the "matter-antimatter" asymmetry in the universe?
- Are neutrinos a new type of matter particle where the particle and antiparticle are the same? (Are neutrinos Majorana fermions?)

Outline

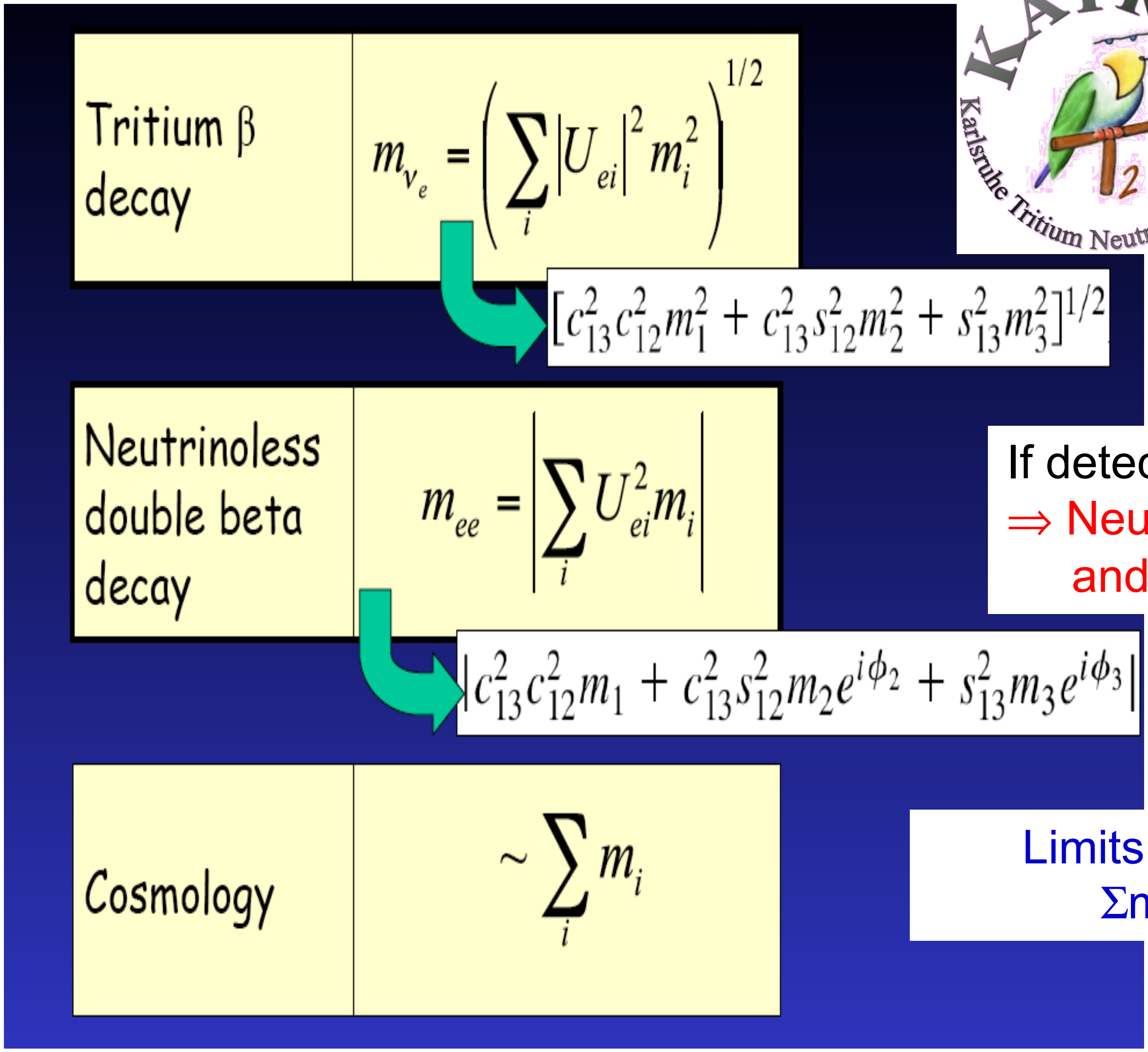
- Introduction to Neutrino Mass and Mixing

- Neutrino Oscillations among ν_e, ν_μ, and ν_τ
  - The “Hunt” for the Little Mixing Angle θ_{13}
  - Plans and Prospects for Measuring CP Violation

- Possible Oscillations to Sterile Neutrinos
  - Current Hints and Anomalies
  - Ideas for Future Searches

- Conclusion

Absolute Mass Scale Determinations



Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei}\rvert^2 m_i^2\right)^{1/2}$
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$
Cosmology	$\sim \sum_i m_i$

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

KATRIN
Karlsruhe Tritium Neutrino Experiment

Current limit (Mainz):
$m_\nu < 2.2$ eV @ 95% CL
KATRIN Sensitivity:
$m_\nu < 0.2$ eV @ 90% CL

If detect 0ν2β decay
⇒ Neutrinos are Majoranna particles
and information on m_ν at 0.1eV scale

Limits sum of neutrino masses:
$\Sigma m\nu < \sim 0.7\,eV$

Neutrino Oscillations

The observation of neutrino oscillations where one type of neutrino can change (oscillate) into another type implies:

1. Neutrinos have mass

and

2. Lepton number (electron, muon, tau) is not conserved
   ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

- The phenomena comes about because the mass and flavor states are different as parameterized by a mixing matrix

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- Two types of oscillation searches: $P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$
  - *Appearance Experiment:*
    Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Need to know the backgrounds
  - *Disappearance Experiment:*
    Look for a change in $\nu_{e/\mu}$ flux as a function of L and E
    - Need to know the flux/and cross sections

Oscillations Parameterized by 3x3 Unitary Mixing Matrix

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

$$\begin{pmatrix} Flavor \\ Eigenstate \end{pmatrix} = (Mixing\ Matrix) \begin{pmatrix} Mass \\ Eigenstate \end{pmatrix}$$

Three mass splittings: $\Delta m_{12}^2 = m_1^2 - m_2^2$, $\Delta m_{23}^2 = m_2^2 - m_3^2$, $\Delta m_{31}^2 = m_3^2 - m_1^2$

But only two are independent since only three masses

If $\delta \neq 0$, then have CP violation $\Rightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

solar atmospheric

Current Measurements: $\Delta m_{12}^2 = 8 \times 10^{-5}\ \text{eV}^2$, $\Delta m_{13}^2 \approx \Delta m_{23}^2 = 2.5 \times 10^{-3}\ \text{eV}^2$

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

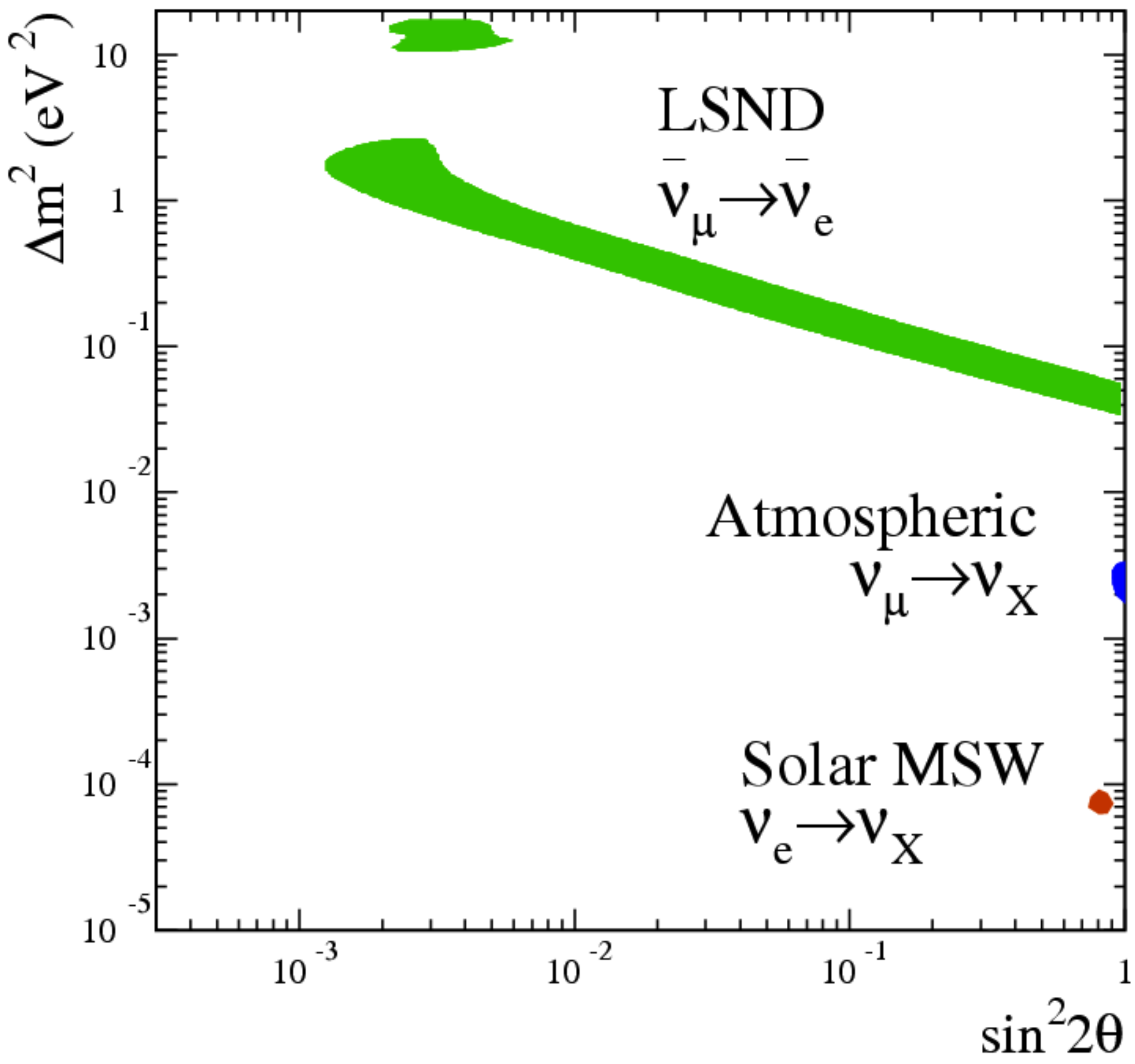
3-mixing angles

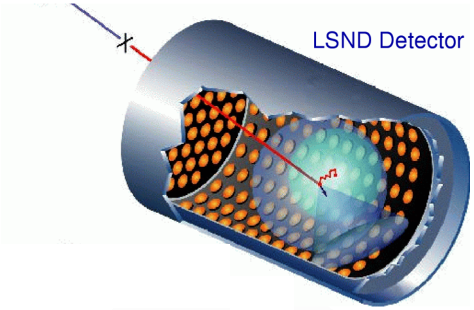
Solar: $\theta_{12} \sim 33°$

"Little mixing angle, θ_{13} "
$\sin^2 2\theta_{13} < 0.14$ at 90% CL
(or $\theta_{13} < 11°$) and δ = ??

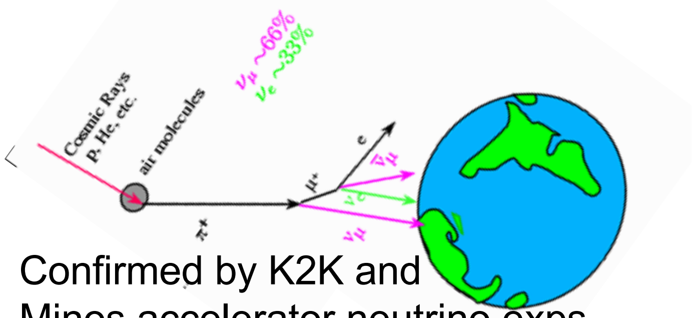
Atmospheric: $\theta_{23} \sim 45°$

Current Oscillation Summary

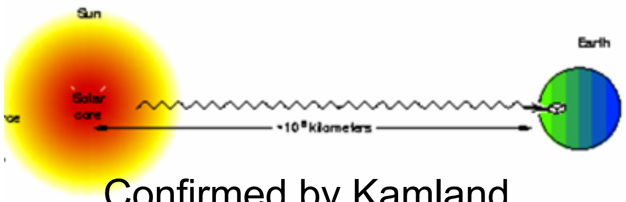




New MiniBooNE $\bar{\nu}_\mu$ consistent



Confirmed by K2K and
Minos accelerator neutrino exps



Confirmed by Kamland
reactor neutrino exp

Manmade Neutrino Sources and Beams

- Pion decay-at-rest beams
- Pion decay-in-flight beams
- Nuclear power reactors

Present and Near-term Program

- High energy radioactive beams ⇒ “Beta Beams”
- Muon storage rings ⇒ “Neutrino Factories”

Future Ideas

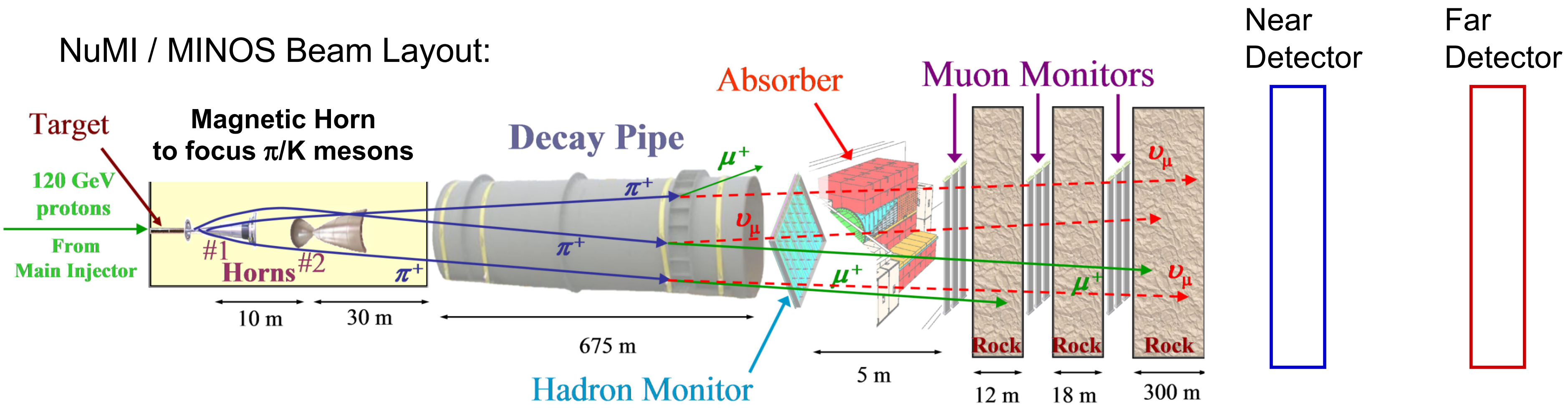
Recent Accelerator $\nu_\mu \rightarrow \nu_\tau$ Measurements: MINOS, OPERA, ICARUS

- Use Pion Decay-in-Flight Beam
  - Produce pions and kaons from accelerator protons (8 – 800 GeV)
  - Focus mesons towards detector for higher efficiency
  - Fairly pure beam of ν_μ or $\bar{\nu}_\mu$ neutrinos depending whether you focus π^+ or π^- mesons.
  - Few percent ν_e backgrounds
  - Best to use a near detector to measure flux and background
    ⇒ MINOS and most new experiments have near detector

$$\pi^+ \left(\text{or } K^+\right) \rightarrow \mu^+ \nu_\mu$$

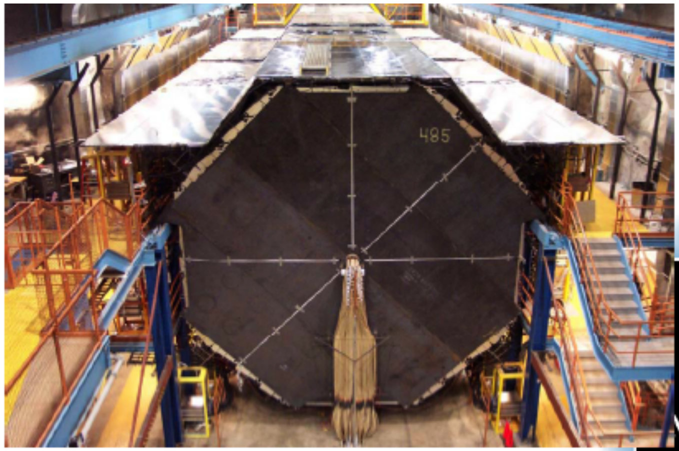
$$\pi^- \left(\text{or } K^-\right) \rightarrow \mu^- \bar{\nu}_\mu$$

NuMI / MINOS Beam Layout:



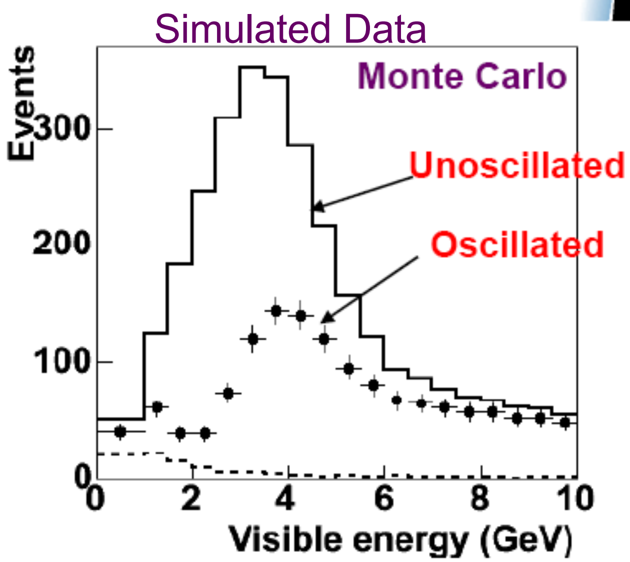
MINOS Accelerator Oscillation Experiment at Fermilab

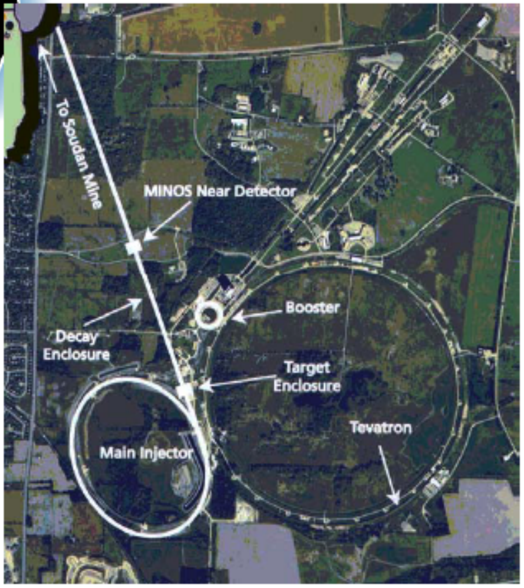
A,Habig, July 2



5.4 kton MINOS far detector

1 kton near detector

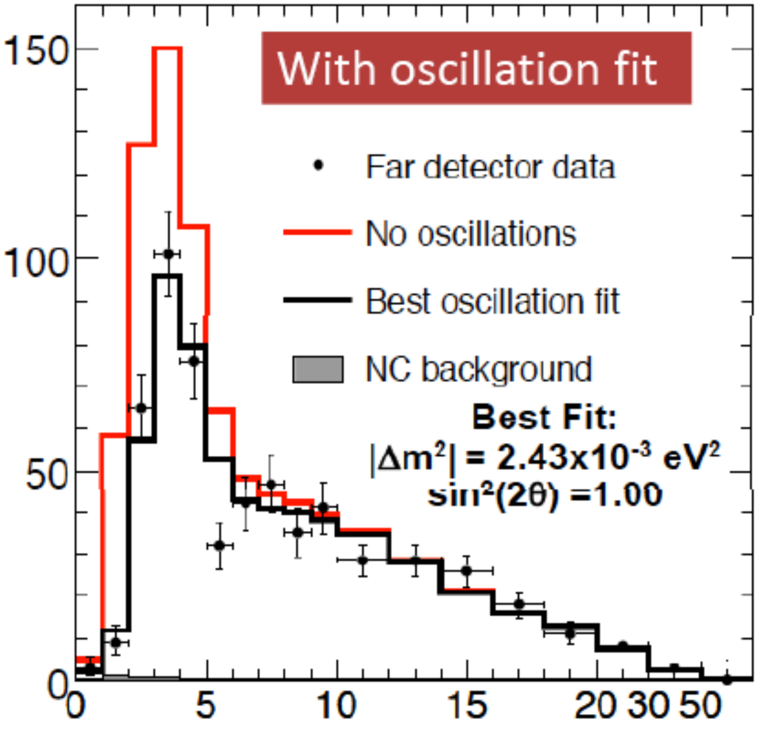




NuMI
beam line

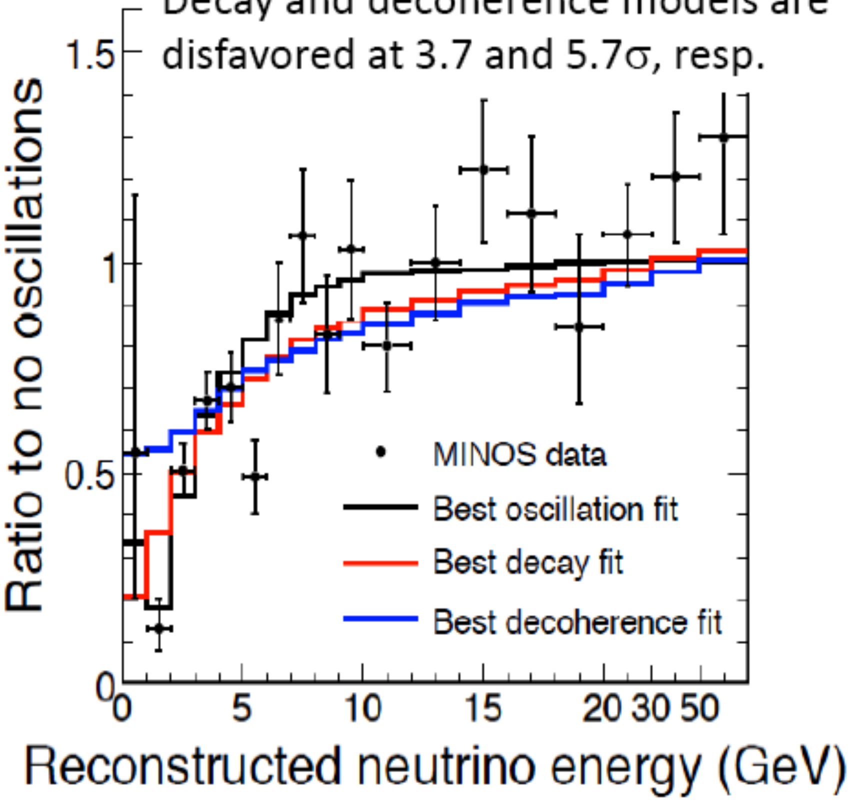
MINOS ν_μ Disappearance Results

848 CC ν_μ candidates ←→ 1065±60(syst) no-osc. prediction



With oscillation fit

Best Fit:
$|\Delta m^2| = 2.43\times10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\theta) = 1.00$



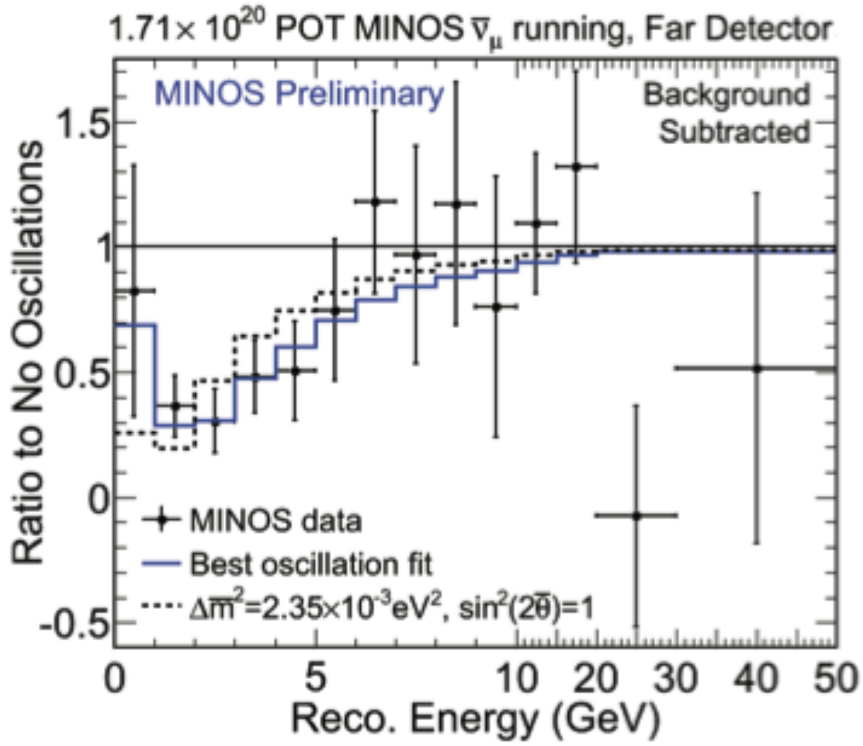
Decay and decoherence models are disfavored at 3.7 and 5.7σ, resp.

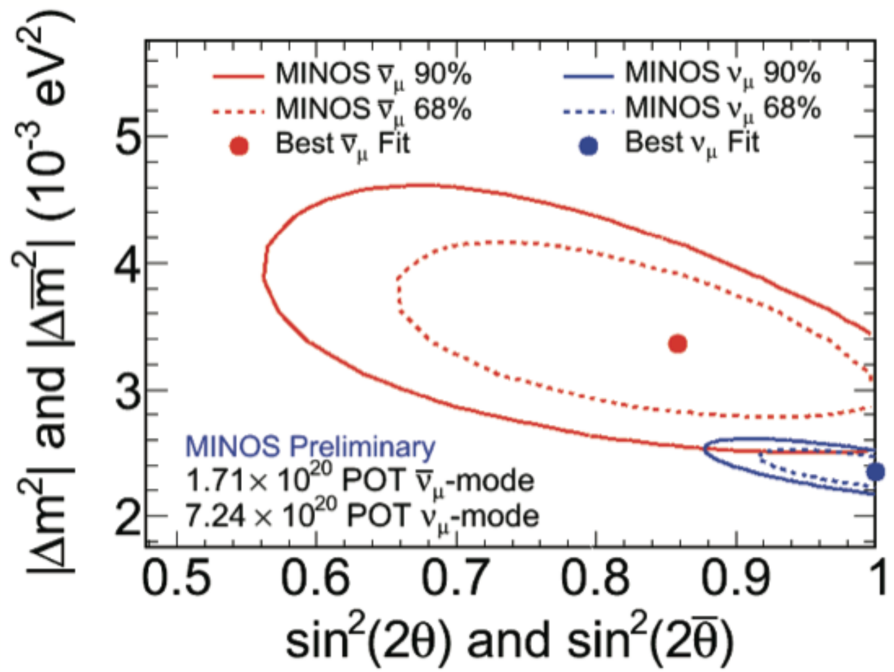
$$\Delta m^2_{23} = 2.43 \pm 0.13 \times 10^{-3}\,\mathrm{eV}^2$$

(5% accuracy, MINOS)

PRL 101 (2008) 131802
(hep-ex/0806.2273)

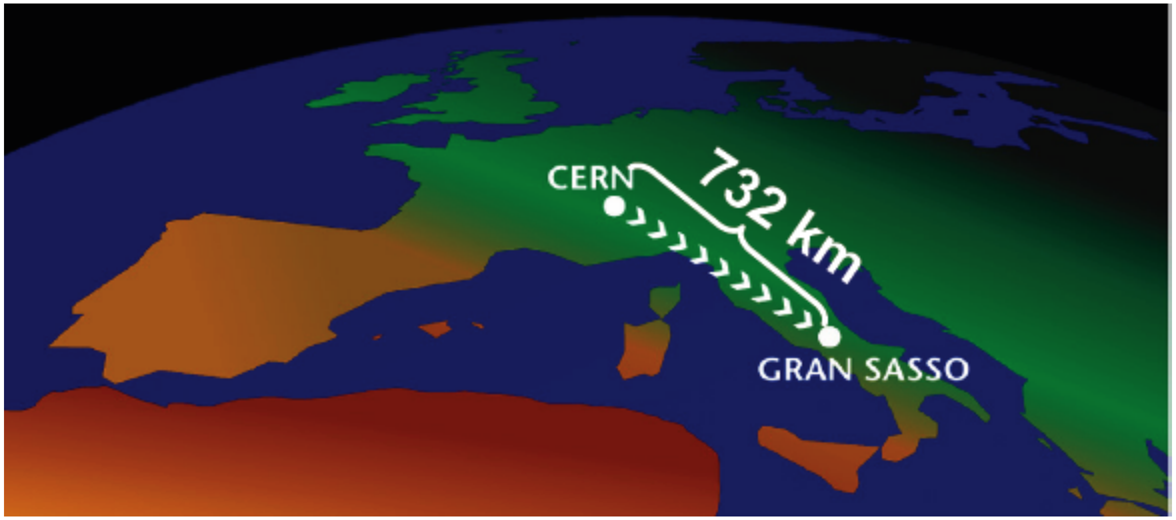
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in $\bar{\nu}$ Mode Somewhat Inconsistent with ν Mode ⇒ CPT Violation?



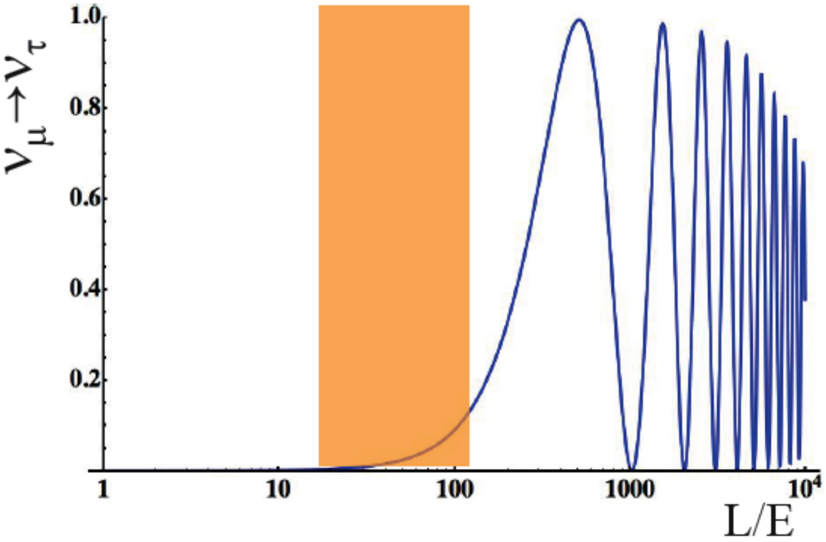


$$\chi^2_{\mathrm{CPT}} - \chi^2_{\cancel{\mathrm{CPT}}} = 5.6\ (2.4\sigma)$$

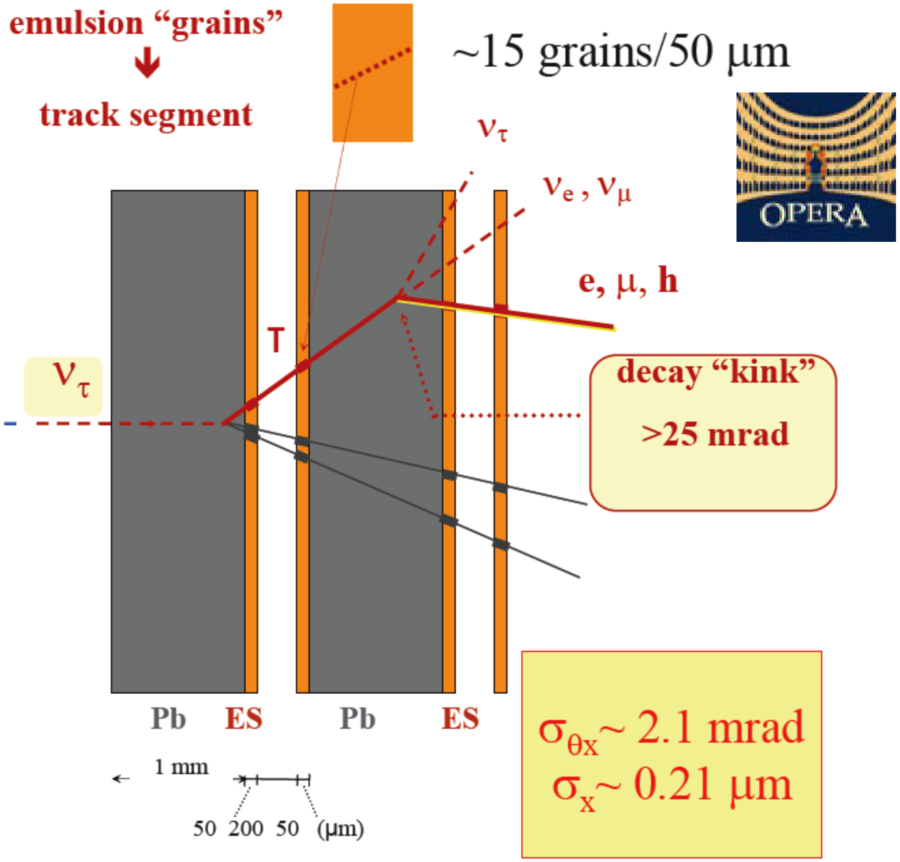
OPERA and ICARUS: ν_τ Appearance Search



- Uses 400 GeV protons to produce neutrino beam $\langle E_\nu \rangle \approx$ 17 GeV
- $\langle E_\nu \rangle$ above threshold to produce τ leptons from ν_τ
- $\langle L/E \rangle \approx 43$ so oscillation probability for Δm^2_{atm} is small



OPERA: Nuclear Emulsion plus Lead

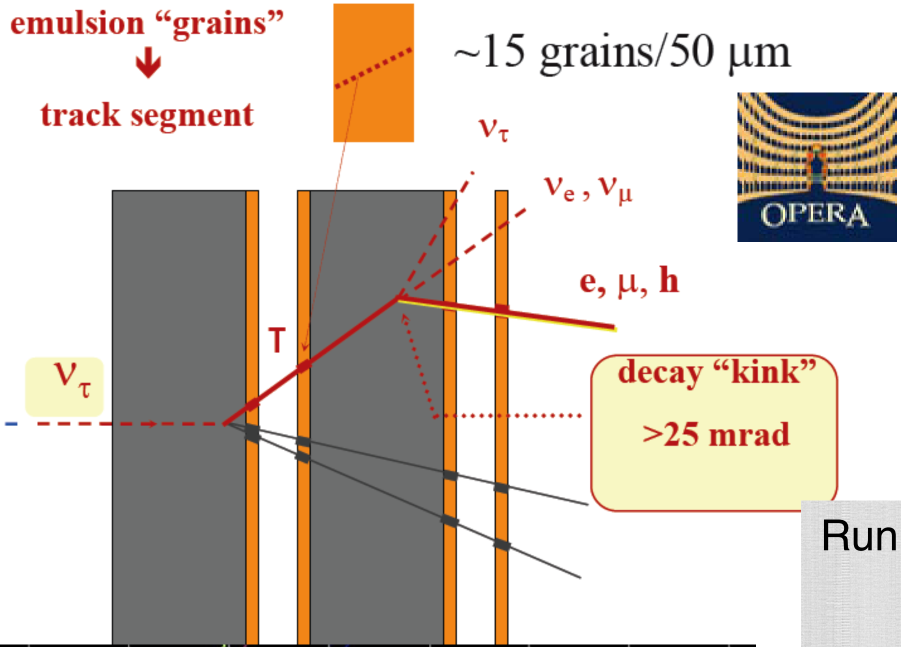


- Scintillator Strips isolate emulsion brick with an event
- Robot then picks out brick to be scanned.
- Currently running since 2007
- Expect about 15 ν_τ events in 5 years

ICARUS: Liquid Argon TPC 600 Tons

- Will use kinematic reconstruction to isolate ν_τ-events.

OPERA: Nuclear Emulsion plus Lead



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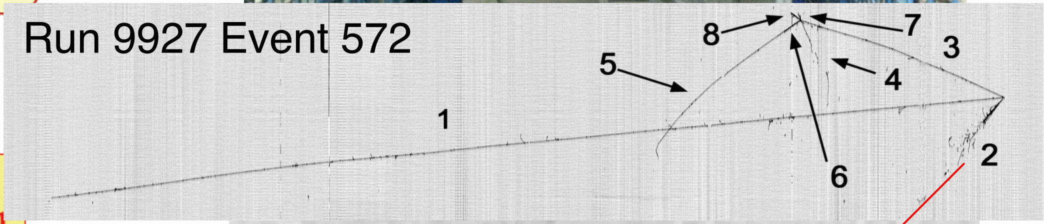
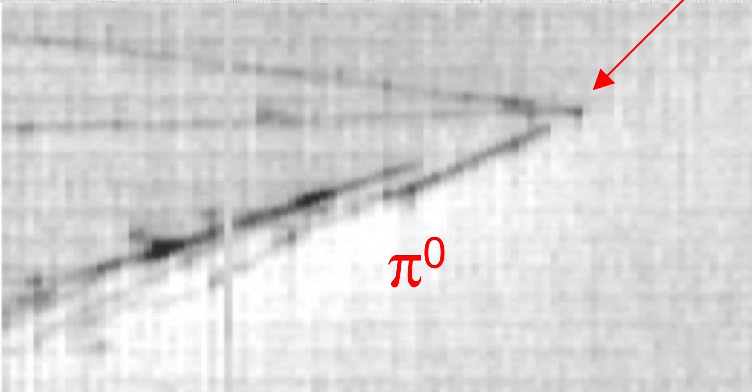
ICARUS: Liquid Argon TPC 600 Tons





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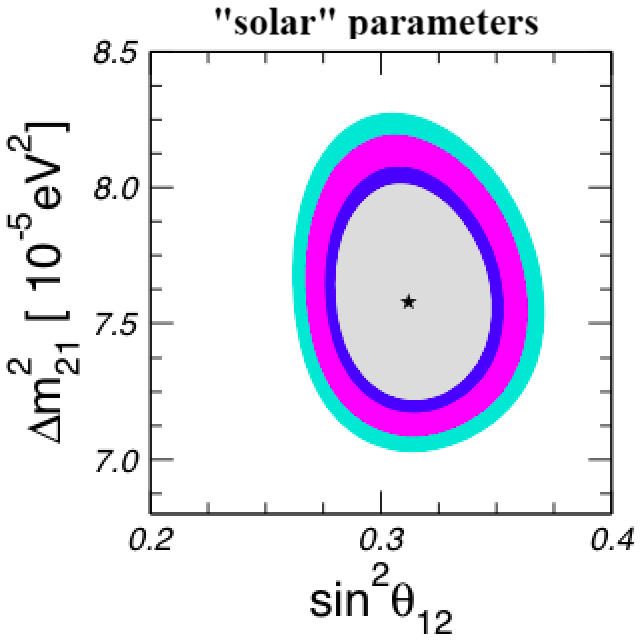
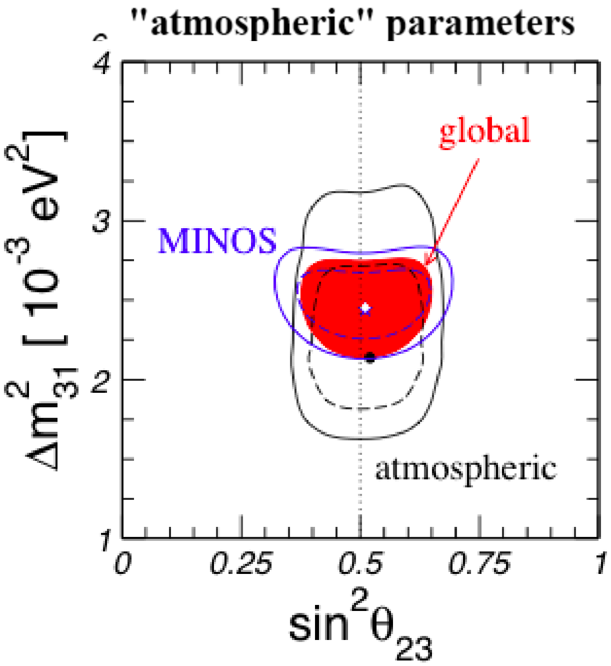
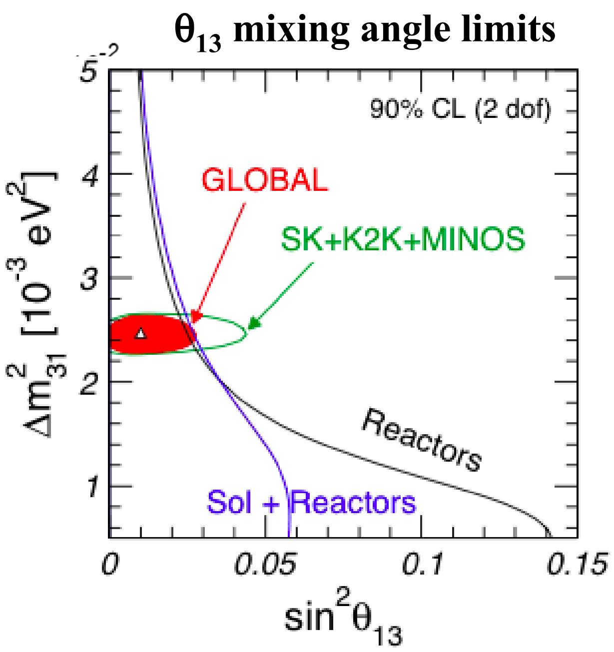
Current Global Fits to Solar, Atmospheric, Accelerator, and Reactor Data


"solar" parameters

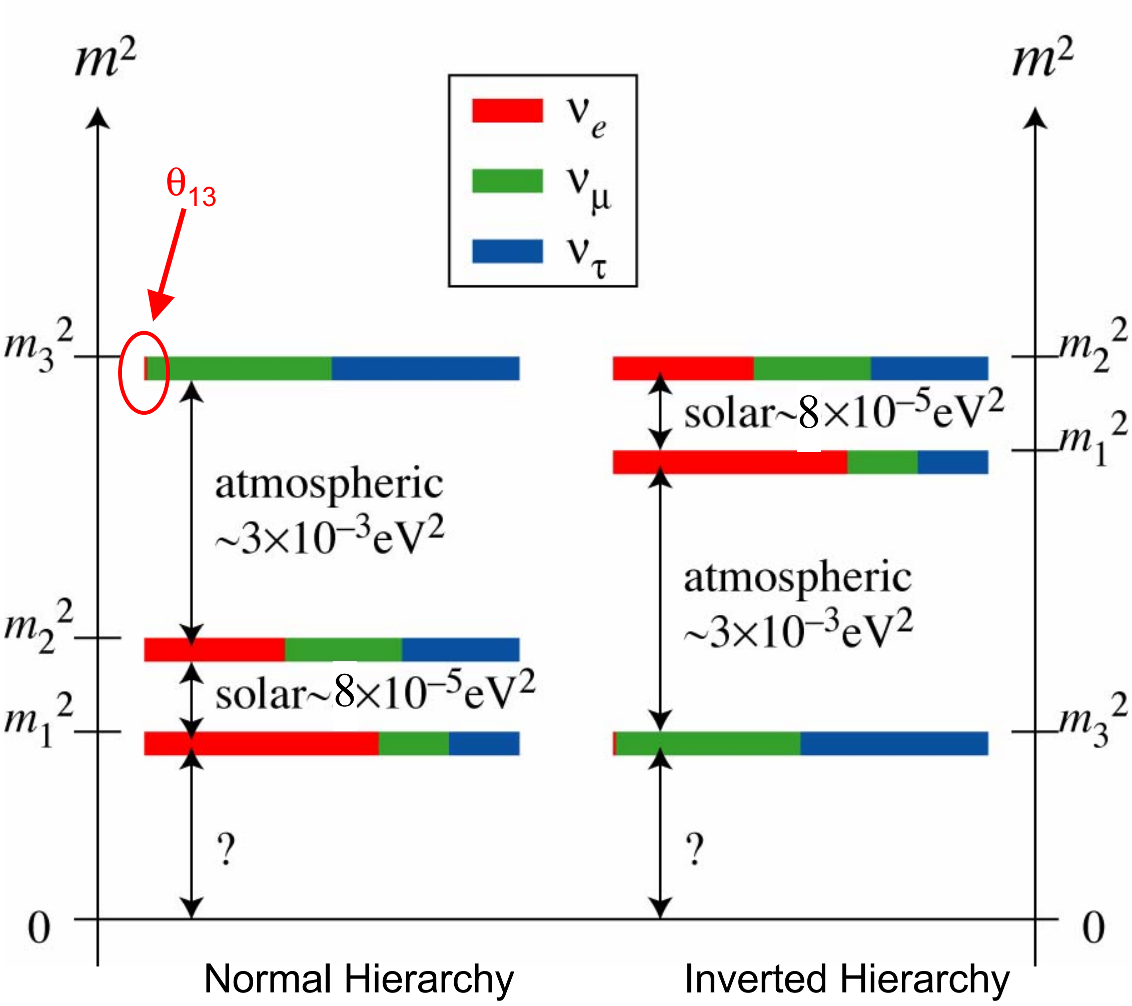

"atmospheric" parameters


θ_{13} mixing angle limits

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.59^{+0.20}_{-0.18}$	7.24–7.99	7.09–8.19
Δm^2_{31} [10^{-3}eV^2]	2.45 ± 0.09 $-(2.34^{+0.10}_{-0.09})$	$2.28 - 2.64$ $-(2.17 - 2.54)$	$2.18 - 2.73$ $-(2.08 - 2.64)$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$	0.28–0.35	0.27–0.36
$\sin^2\theta_{23}$	0.51 ± 0.06 0.52 ± 0.06	0.41–0.61 0.42–0.61	0.39–0.64
$\sin^2\theta_{13}$	$0.010^{+0.009}_{-0.006}$ $0.013^{+0.009}_{-0.007}$	≤ 0.027 ≤ 0.031	≤ 0.035 ≤ 0.039

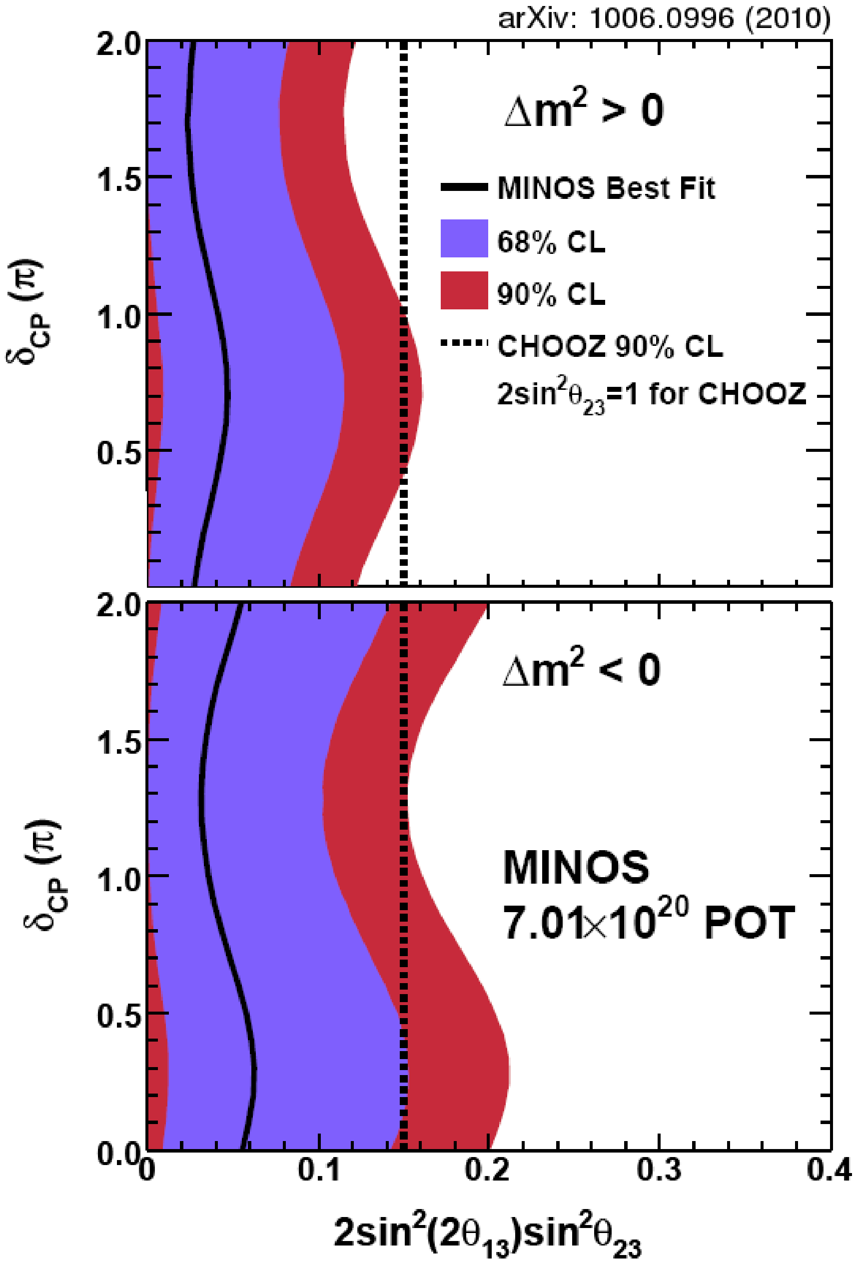
Big Questions in (3x3) Neutrino Mixing

1. What is ν_e component in the ν_3 mass eigenstate? ⇒ The size of the “little mixing angle”, θ_{13} ?
   - Only know $\theta_{13}<11^0$
2. What is the mass hierarchy?
   - Is the solar pair the least massive or not?
3. Do neutrinos exhibit CP violation, i.e. is $\delta \neq 0$?



The Search for the “Little Mixing Angle” (θ_{13})

MINOS and CHOOZ Experimental Limits on θ_{13}



Global Fits:

$\sin^2 2\theta_{13} < 0.12 @ 95\% CL$

Experimental Methods to Measure the "Little Mixing Angle", θ_{13}

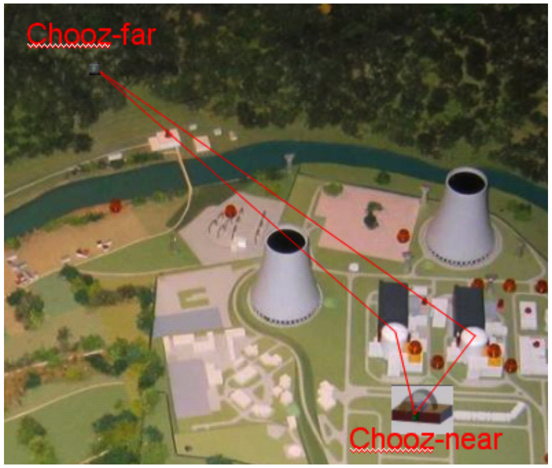
- Long-Baseline Accelerators: Appearance ($\nu_\mu \to \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - – Look for appearance of ν_e in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
L = 810 km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \to \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - – Look for a change in $\bar{\nu}_e$ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
L = 1100 m



Long-Baseline Accelerator Appearance Experiments

- Oscillation probability complicated and dependent not only on θ_{13} but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2) "Matter Effects"
  3. Size of $\sin^2\theta_{23}$

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) &= 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \;(1 - 2S_{13}^2)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
&+4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
&-8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \;(1 - 2S_{13}^2)
\end{aligned}
$$

⇒ ***These extra dependencies are both a "curse" and a "blessing"***

Reactor Disappearance Experiments

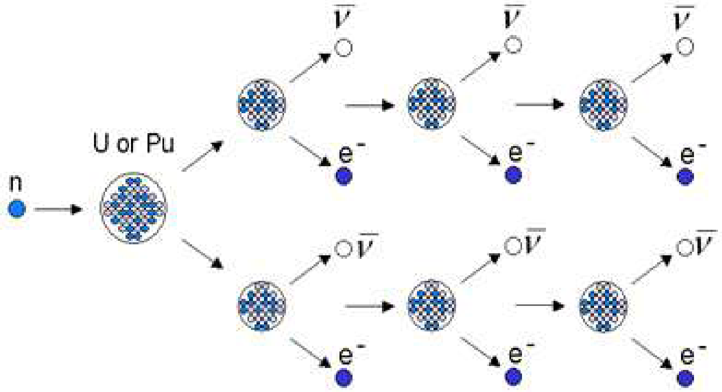
- Reactor disappearance measurements provide a straight forward method to measure θ_{13} with no dependence on matter effects and CP violation

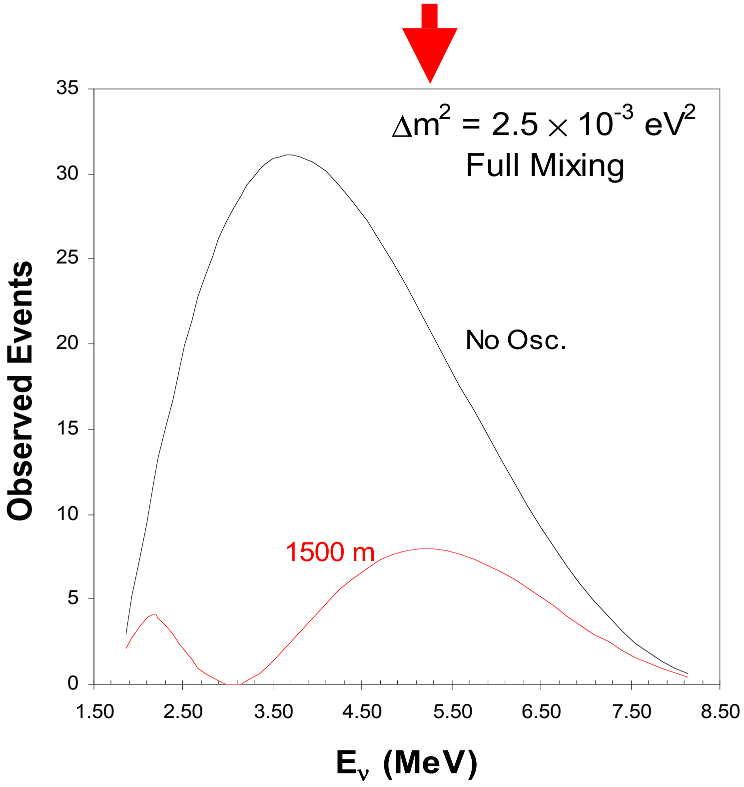
$$
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{13}^2 L}{4E} + \textit{ small terms}
$$

Reactor Neutrino Experiments

Reactor Measurements of θ_{13}

- Nuclear reactors are very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L near 1500 m

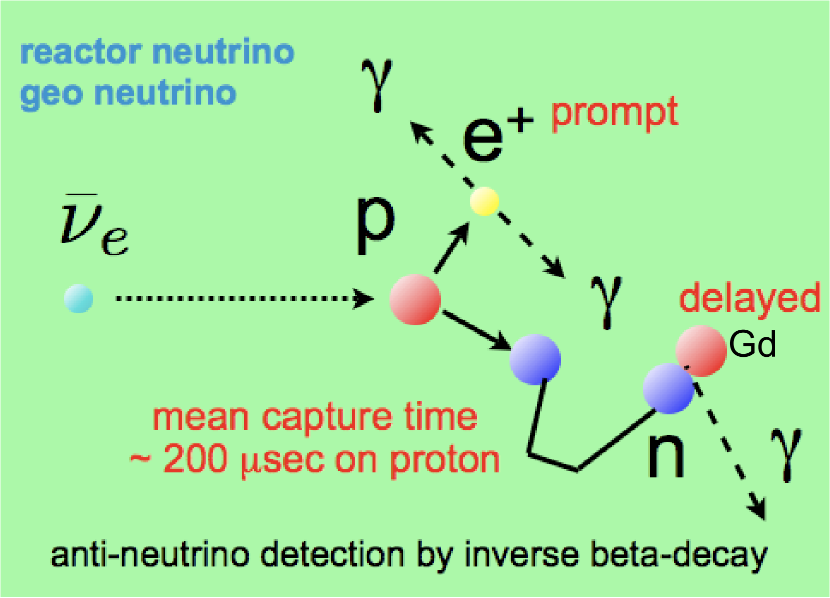




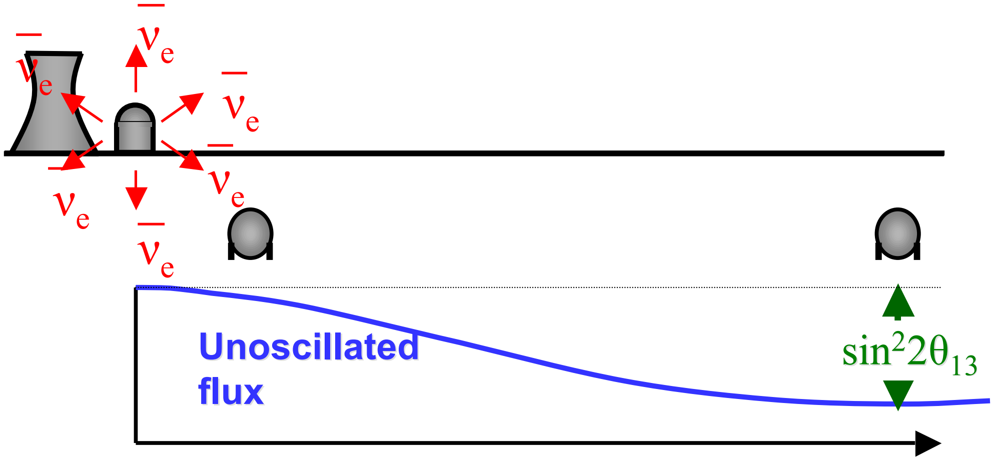
- Disappearance Measurement:
  Look for small rate deviation from 1/r^2 measured at near and far baselines
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector

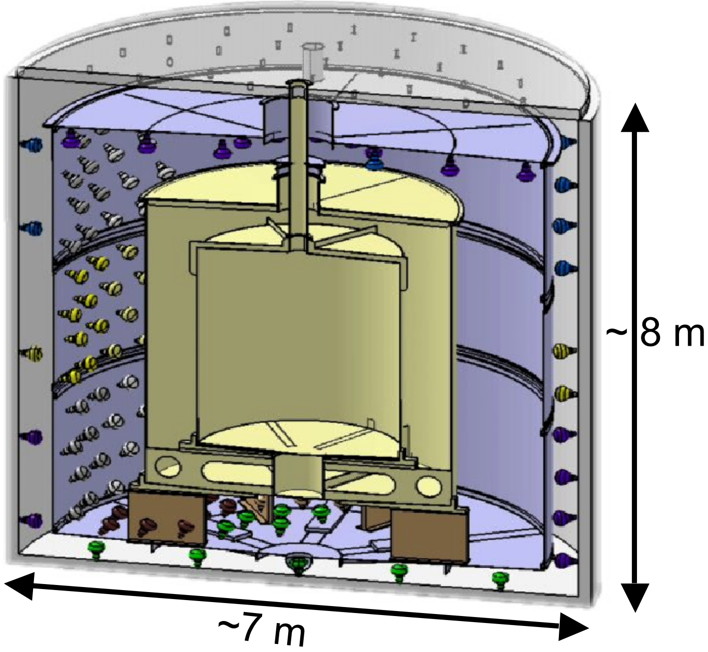
How to do better than previous CHOOZ reactor experiment?

- ⇒ Better detectors with reduced systematic uncertainties
- ⇒ Larger detectors
- ⇒ Reduce and control backgrounds
- ⇒ Use Near/Far Detectors

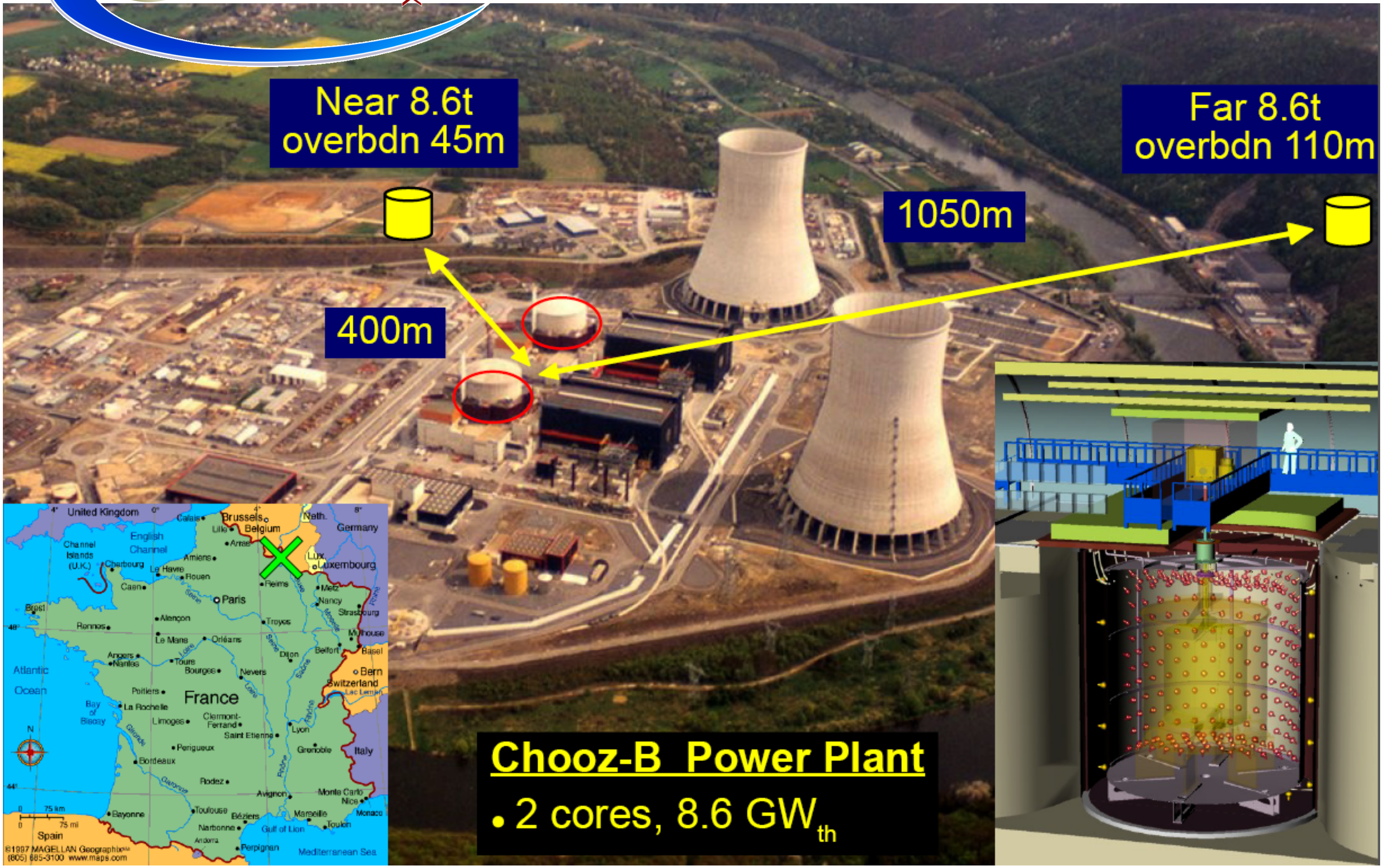


anti-neutrino detection by inverse beta-decay



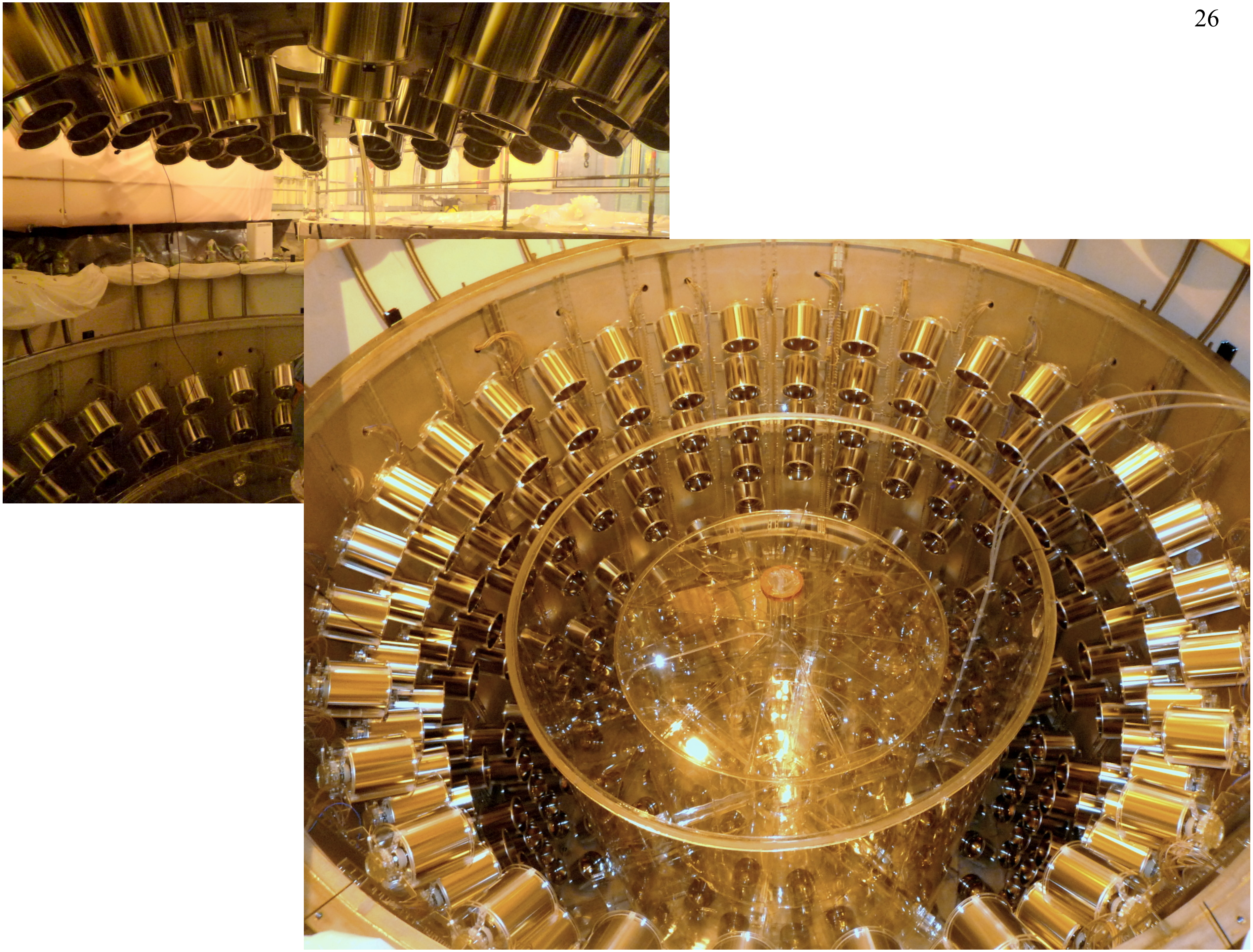


Double Chooz Reactor Experiment in Ardennes, France

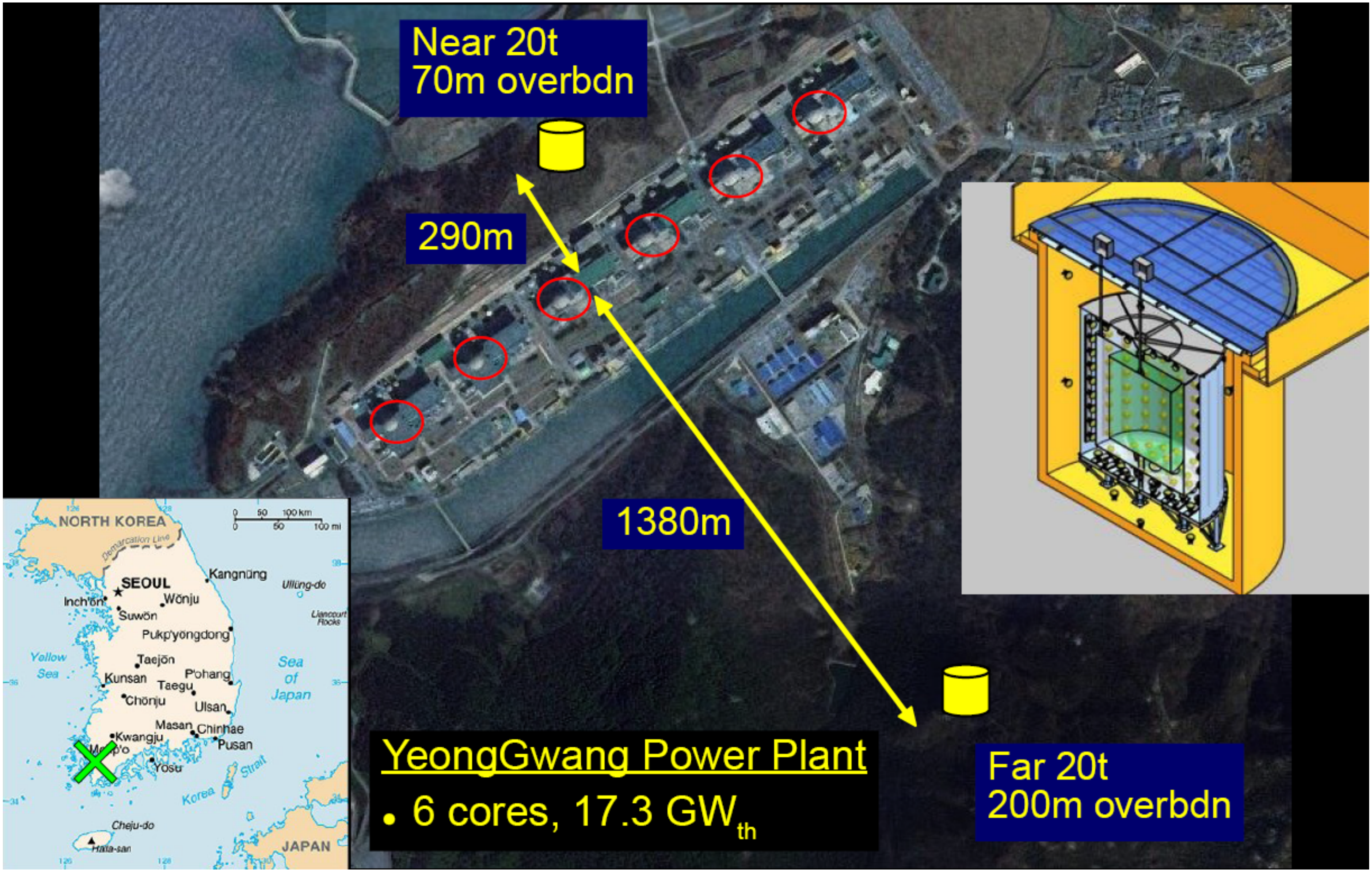


Chooz-B Power Plant

- 2 cores, 8.6 GW_{th}



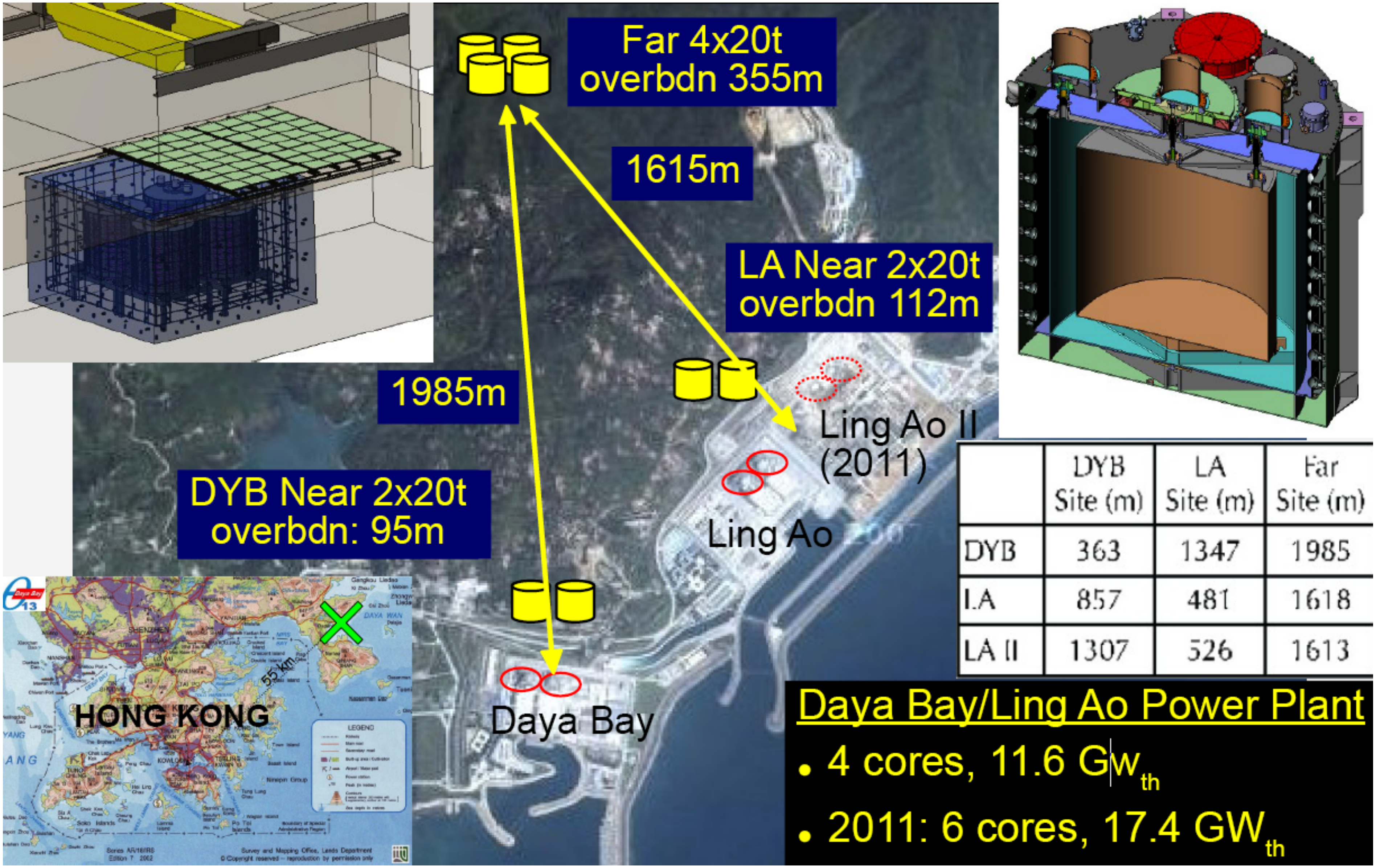
Reactor Experiment for Neutrino Oscillations at YoungGwang in Korea



YeongGwang Power Plant

- 6 cores, 17.3 GW_{th}

Daya Bay Experiment



Far 4x20t
overbdn 355m

1615m

LA Near 2x20t
overbdn 112m

1985m

Ling Ao II
(2011)

Ling Ao

DYB Near 2x20t
overbdn: 95m

Daya Bay

	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

Daya Bay/Ling Ao Power Plant

- 4 cores, 11.6 GW$_{th}$
- 2011: 6 cores, 17.4 GW$_{th}$

Expected Sensitivities

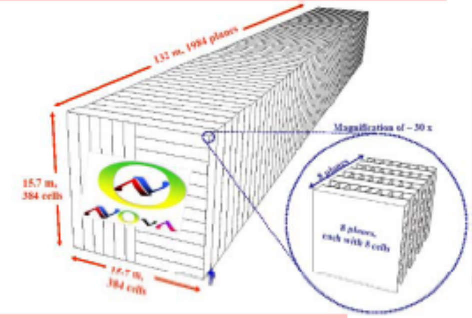
Expt	σ_{stat} [%]	σ_{syst} rel. [%]	$\sin^2 2\theta_{13}$ > (90% CL)
Double Chooz	0.5	0.6	0.03
RENO	0.3	0.5	0.02
Daya Bay	0.2	0.4	0.01

Longbaseline ν_e Appearance Experiments

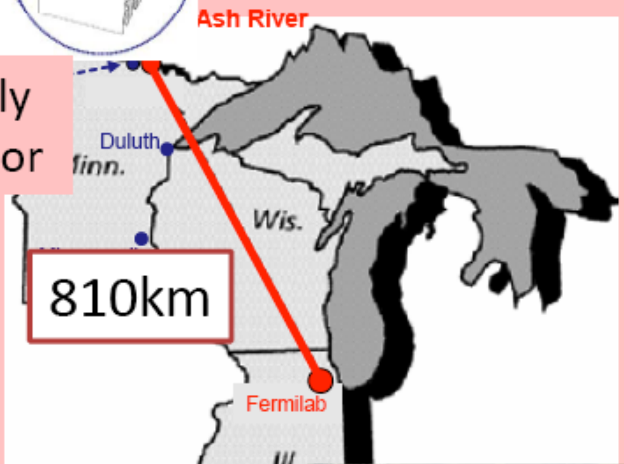
Longbaseline Experiment: T2K and Nova

Improved Beams and Near/Far Detectors
Much Higher Intensity

NOνA
(~2013 -)



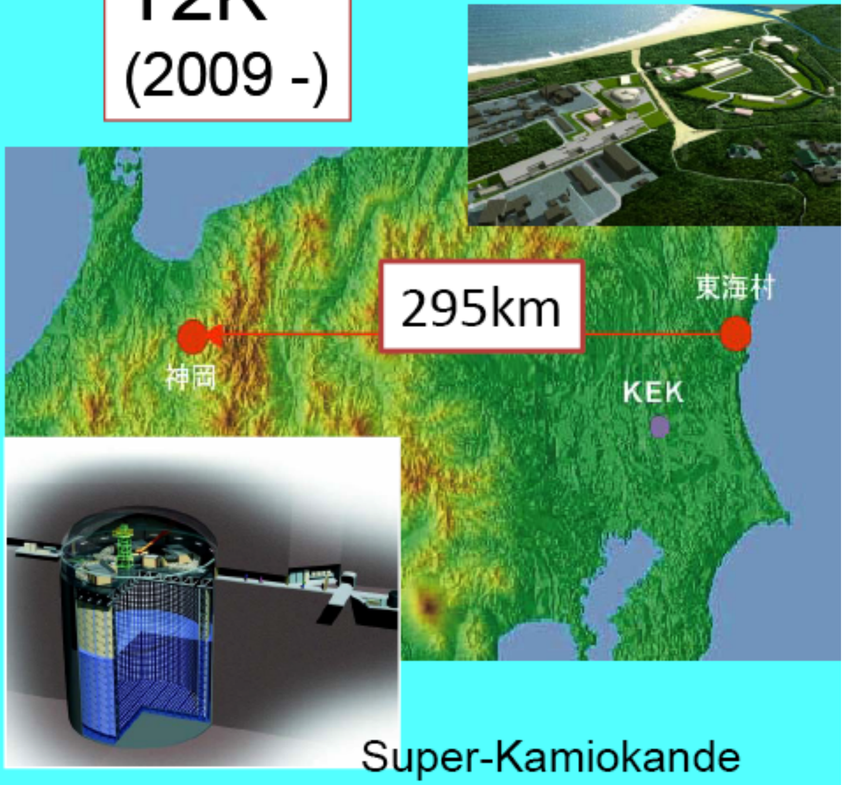
15 kton totally active detector



NuMI beam intensity upgrade to 700 kW

T2K
(2009 -)

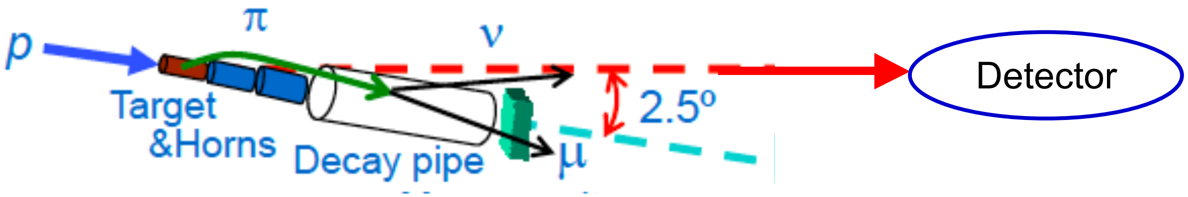
J-PARC
(750kW design)

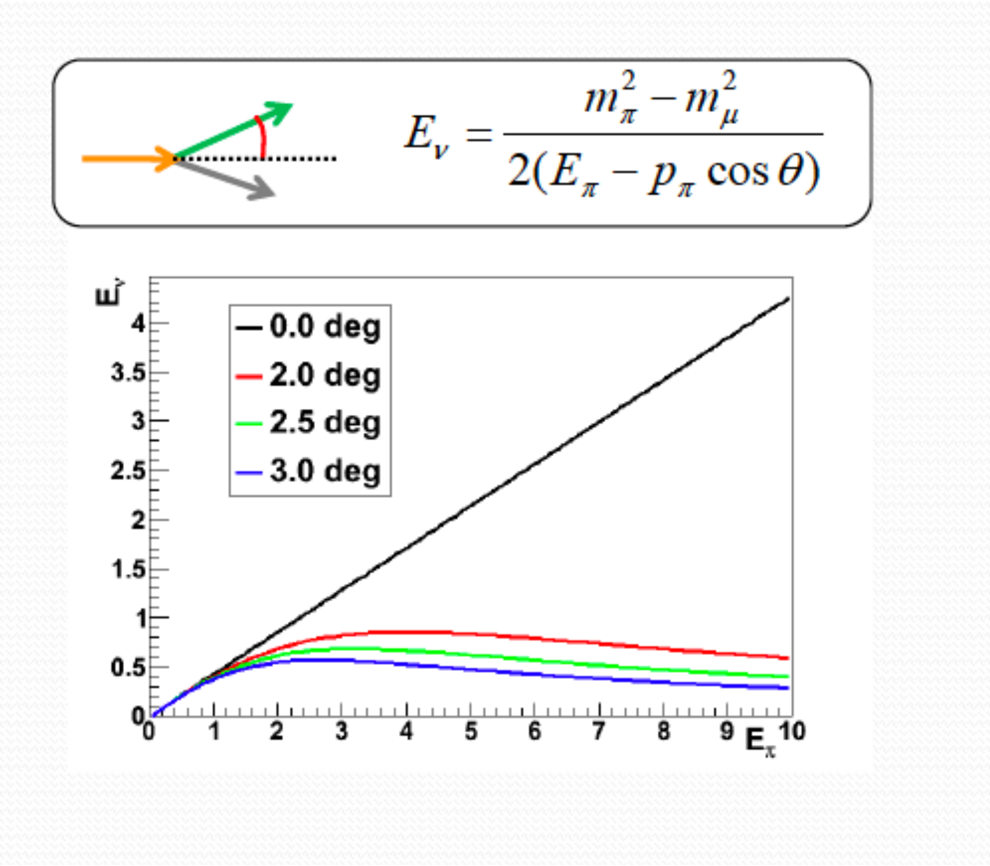


Super-Kamiokande
(22.5 kton fid. vol)

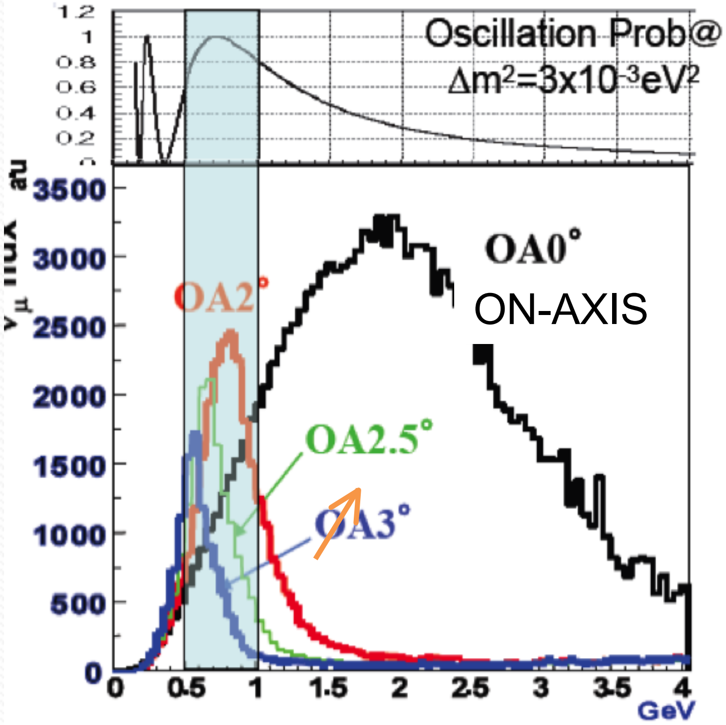
T2K and Nova Use Off-axis Neutrino Beam

- Want to maximize neutrino flux at the appearance probability peak
- Narrow spectrum to reduce backgrounds from high energy processes



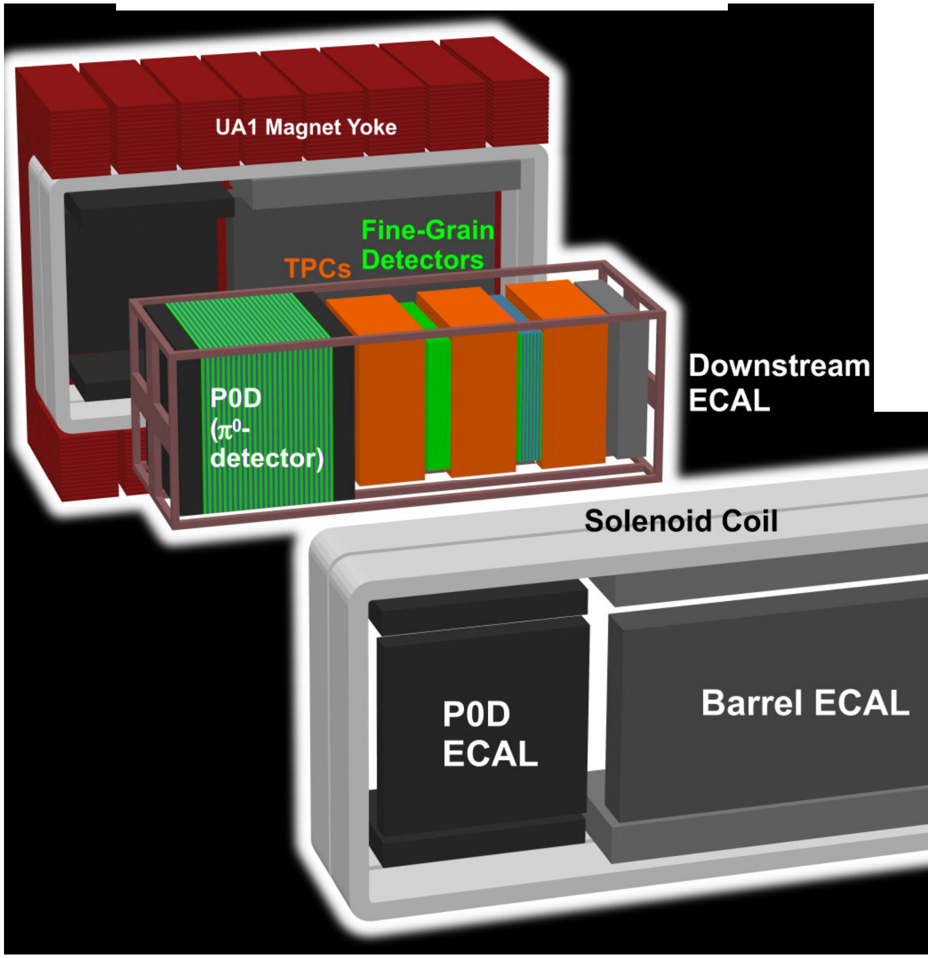


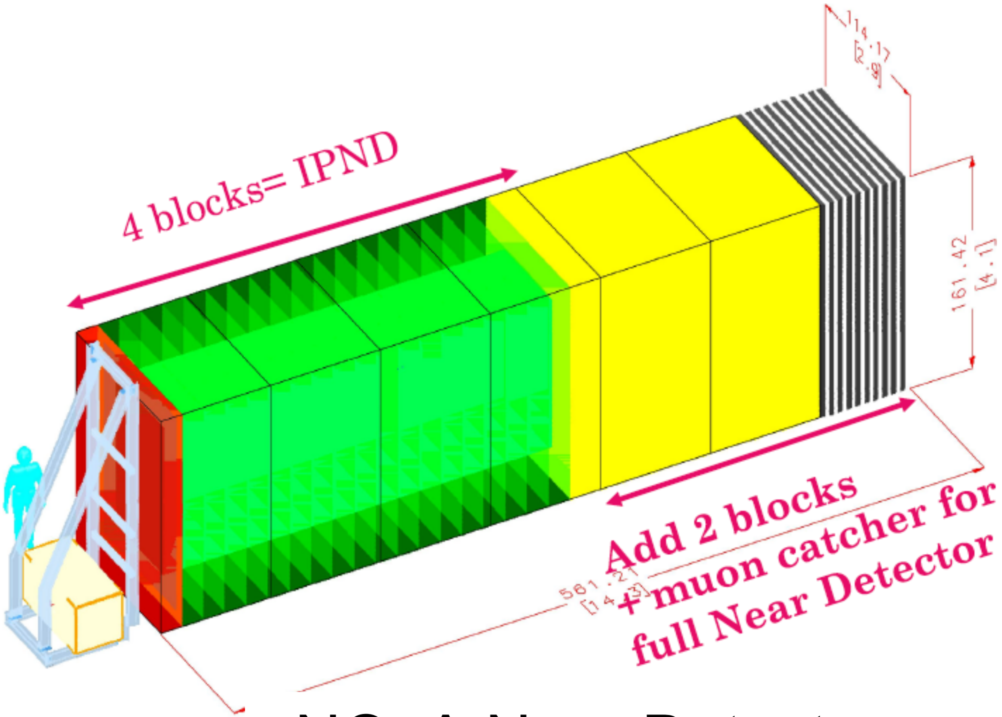
$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\theta)}$$



Use Near Detectors to Measure Beam Flux and Backgrounds

T2K Near Detector

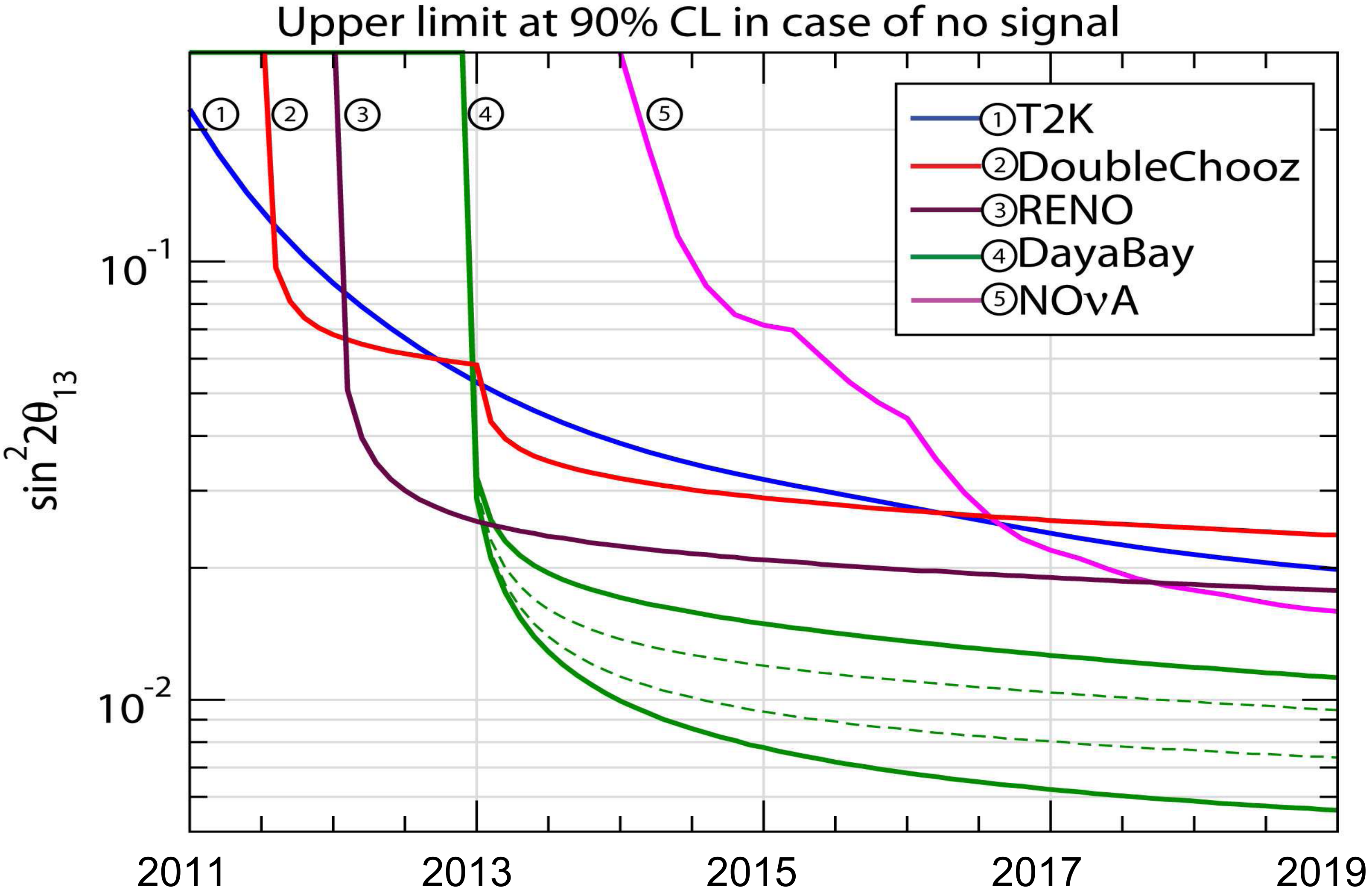




NOνA Near Detector

Sensitivity Estimates for θ_{13} vs Time

Upper limit at 90% CL in case of no signal



Based on M. Mezzetto
arXiv:1003.5800

Moving on to Measuring CP Violation

Measure CP Violation by Comparing

$\nu_\mu \rightarrow \nu_e$ versus $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

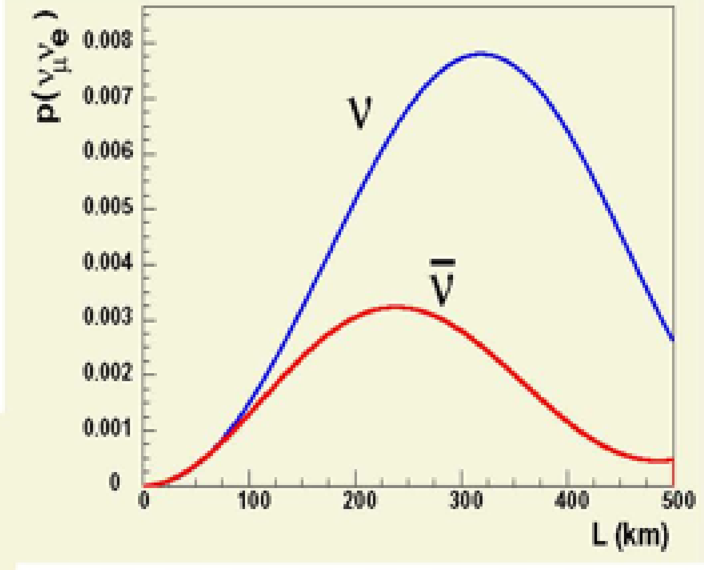
$$p(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13}\text{ driven}$$

$$+\, 8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}cos\delta - s_{12}s_{13}s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \text{CPeven}$$

$$\pm\, 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+\, 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$\pm\, 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

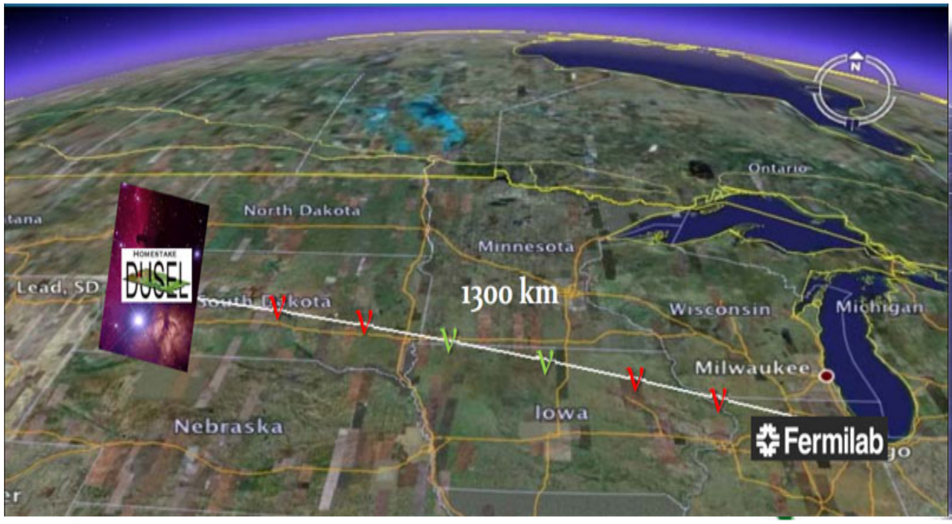


Leptonic CP discovery requires

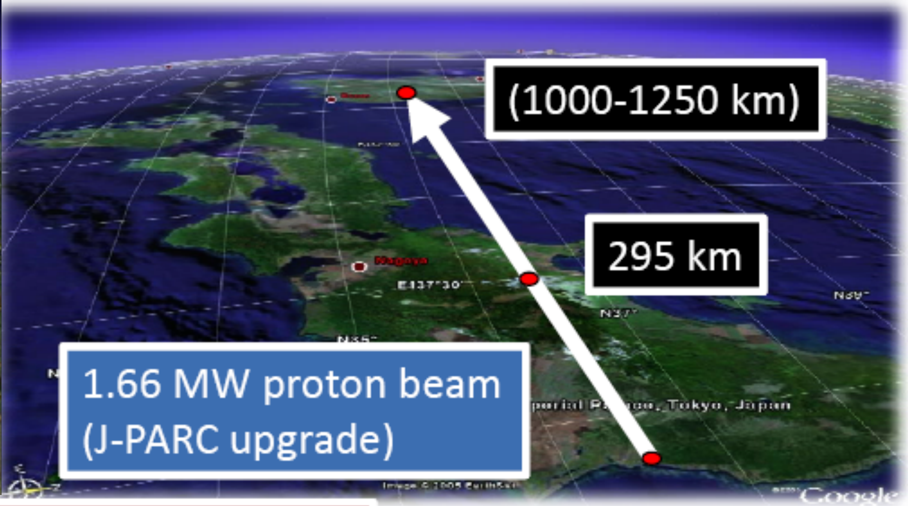
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \neq 0$$

Future Longbaseline Experiments

Homestake Long Baseline Experiment



HyperK Long Baseline Experiment

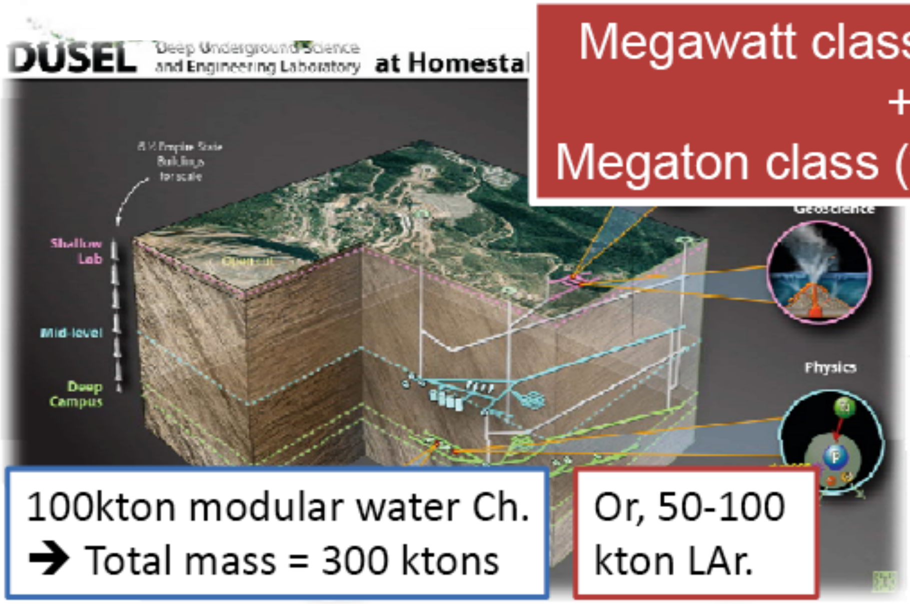


(1000-1250 km)

295 km

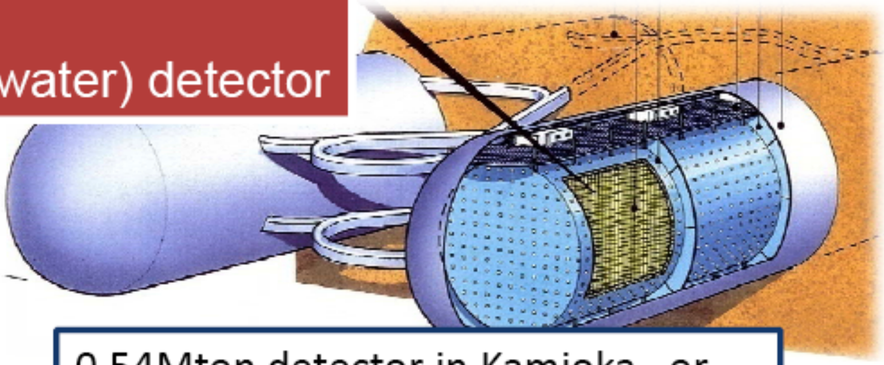
1.66 MW proton beam
(J-PARC upgrade)

Megawatt class super-beam
+
Megaton class (water) detector



100kton modular water Ch.
→ Total mass = 300 ktons

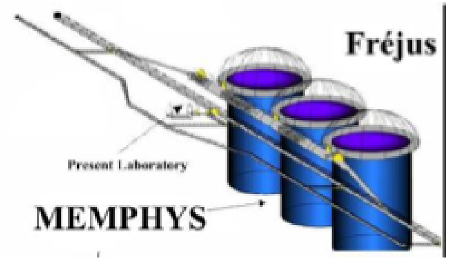
Or, 50-100 kton LAr.



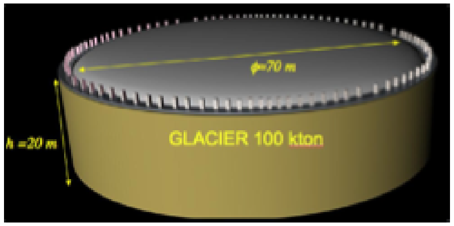
0.54Mton detector in Kamioka, or
0.27 Mton water Cherenkov detector
in Kamioka and Korea.

European Design Study - LAGUNA

(Large Apparatus for Grand Unification and Neutrino Astrophysics)

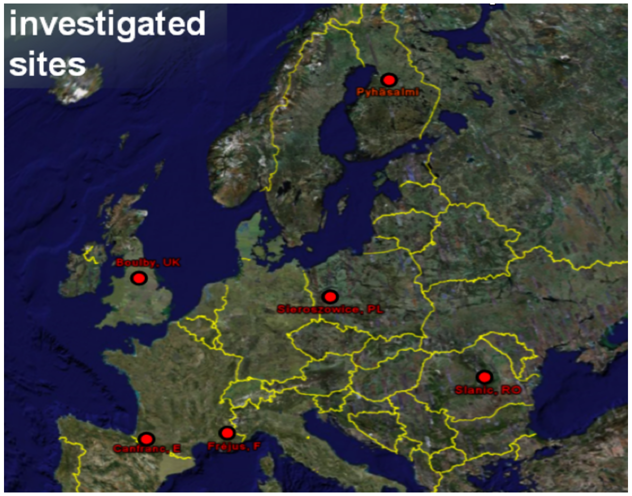


- MEMPHYS - MEgaton Mass PHYSics
  - tanks of 60 m heigth ×65 m ∅
  - ∼440 kt water Cherenkov detector



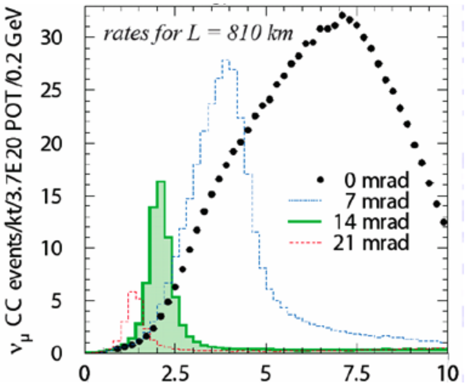
- GLACIER - Giant Liquid Argon Charge Imaging ExpeRiment
  - 20 m heigth ×70 m ∅
  - ∼ 100 kt liquid Ar TPC

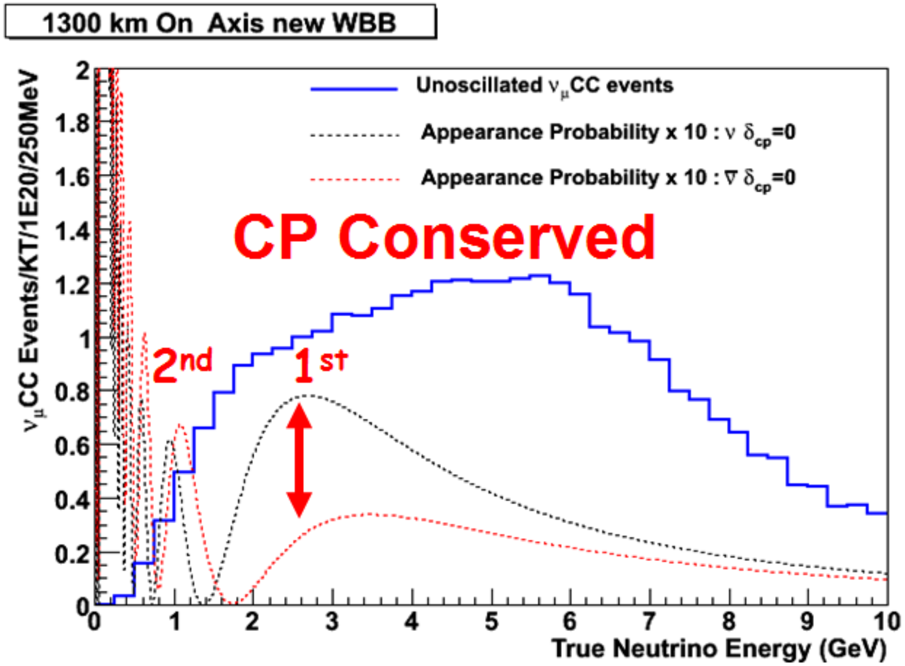
- LENA - Low Energy Neutrino Astronomy
  - 100 m long × 30 m ∅
  - ∼ 50 kt liquid scintillator

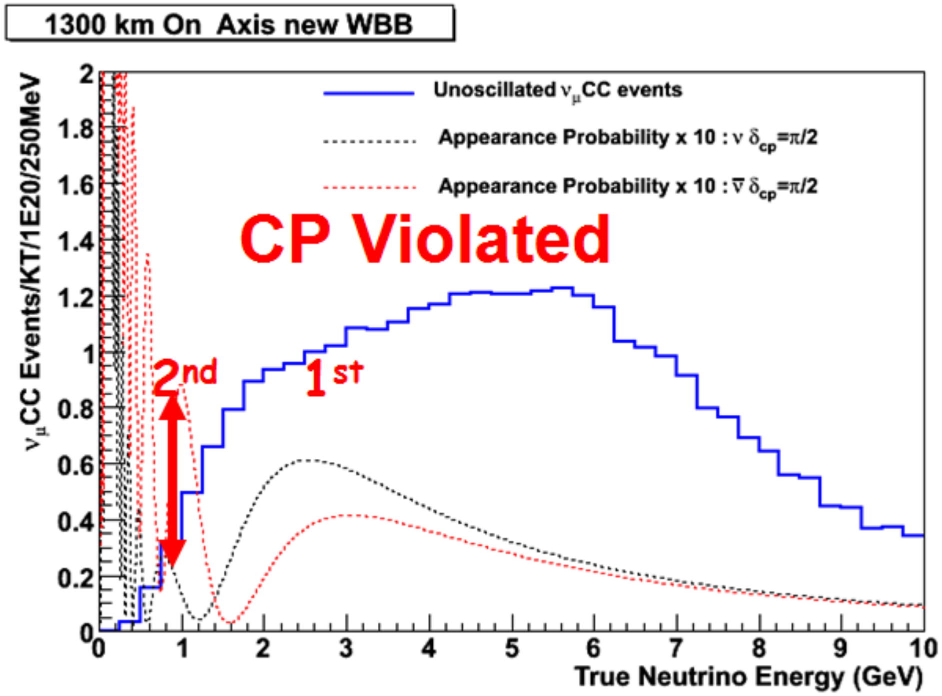


On-axis Beam used for CP Violation

- On-axis beam spans large energy region that allows one to measure the oscillation probability at both the first and second maximum ($\sin^2(1.27\Delta m^2 L/E)$)







1st Maximum : Gives the neutrino mass hierarchy

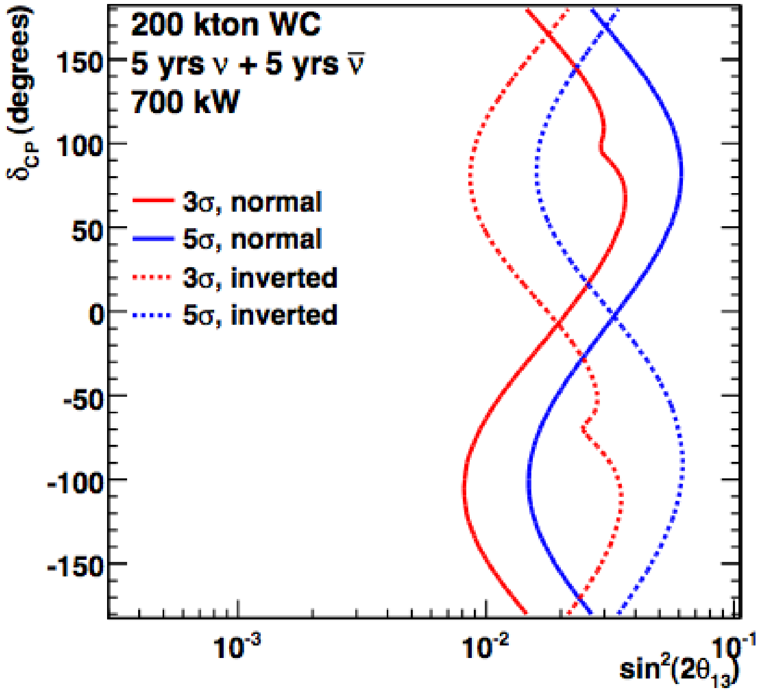
2nd Maximum : Sensitive to CP Violation effects

Sensitivity for Determining Mass Hierarchy and CP

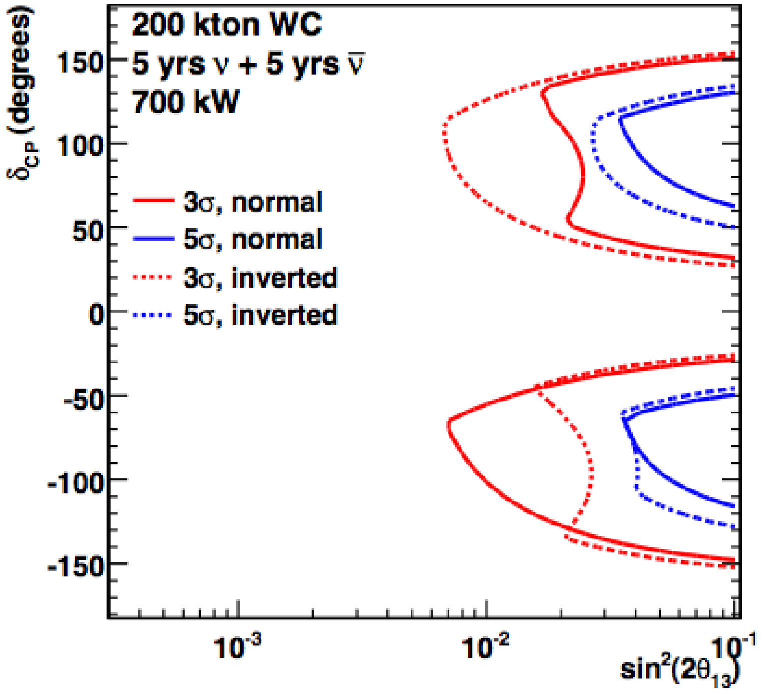
Homestake (DUSEL) Long Baseline Experiment (LBNE)

200 kt WCD detector and 5 yrs of ν + *5 yrs of* $\bar{\nu}$ *running with 700kW:*

Mass Hierarchy

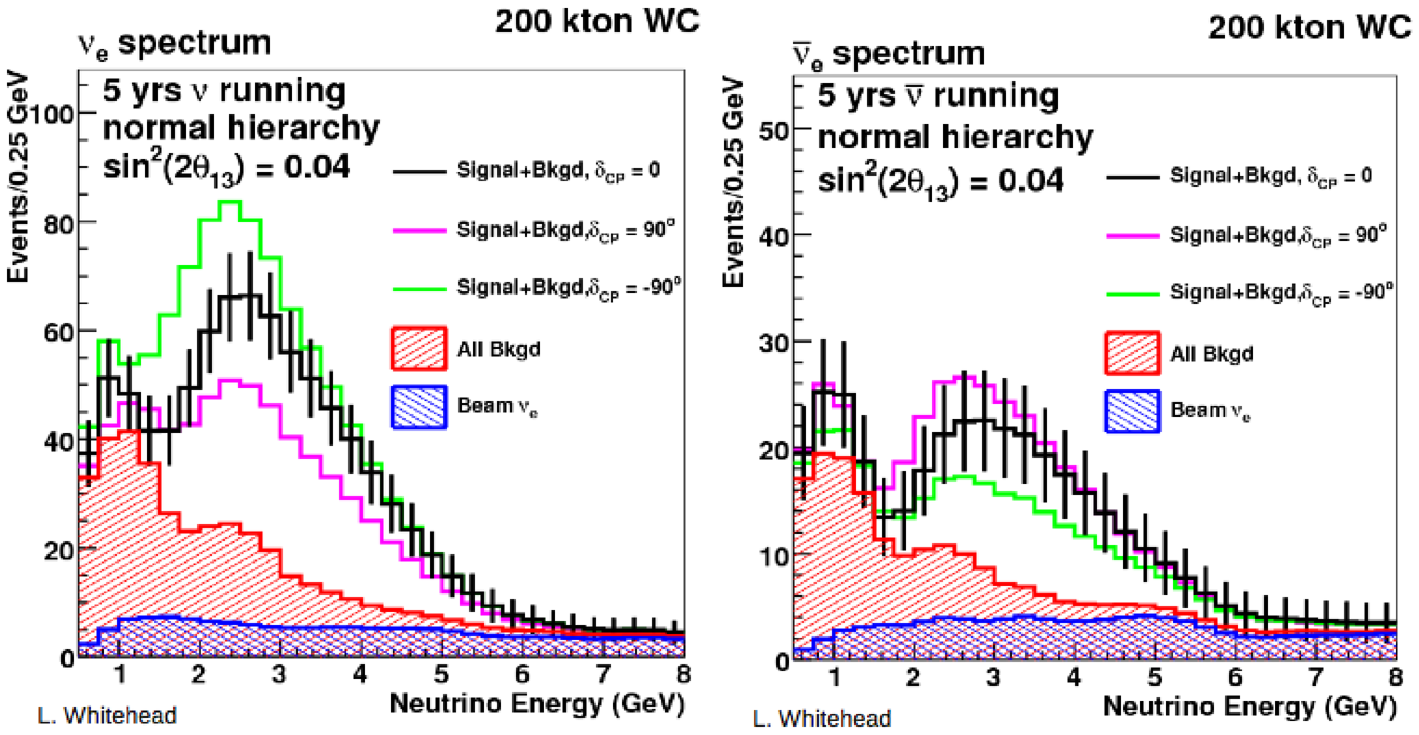


CP Violation



Other Complications for Conventional LBNE Approach

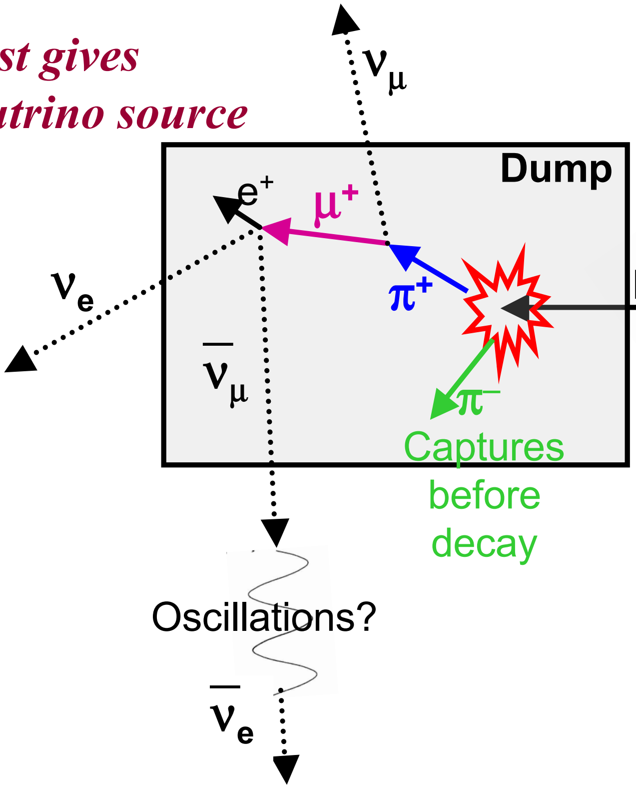
Long Baseline experiments are usually low in antineutrino statistics
→ a combination of style of beam and cross section



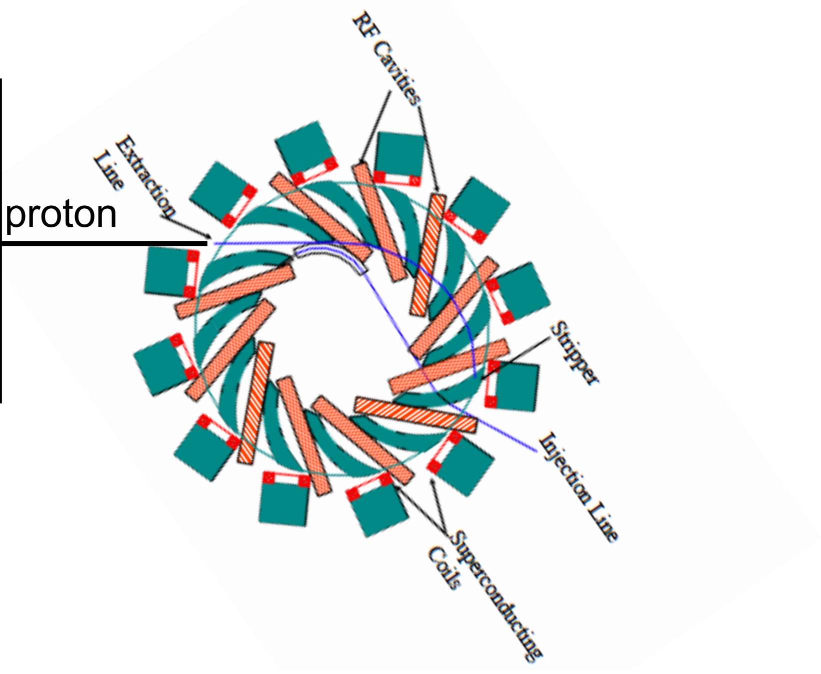
… and the backgrounds are large compared to signal

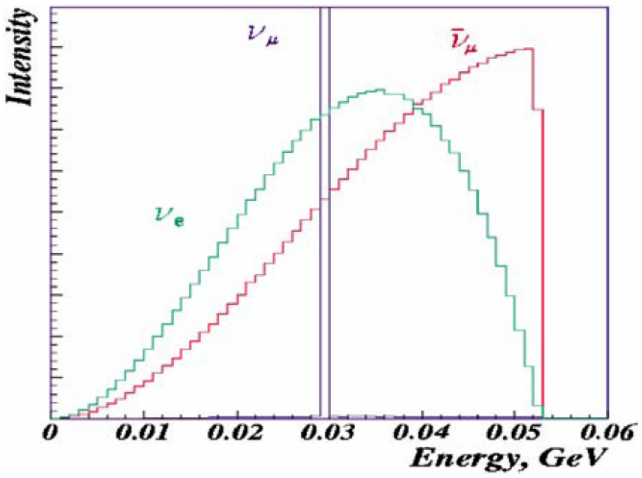
Decay-at-Rest (or Beam Dump) Neutrino Source

Decay-at-Rest gives isotropic neutrino source



Cyclotron (~800 MeV KE proton)

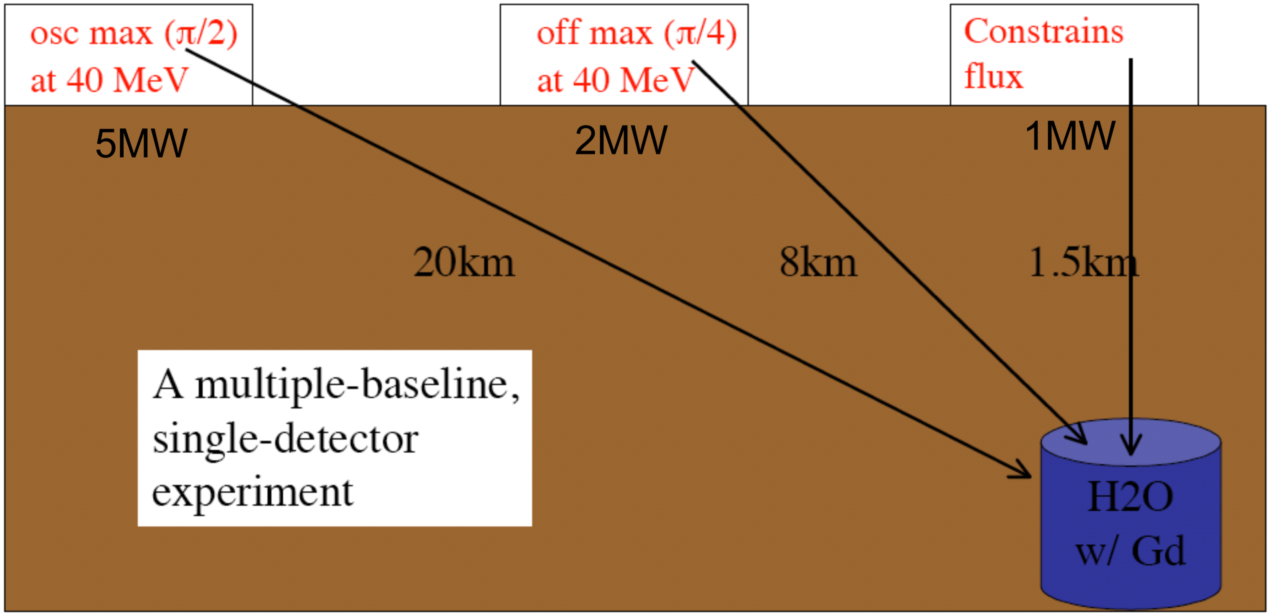




Each π^+ decay gives one ν_μ, one ν_e, and one $\bar{\nu}_\mu$ with known energy spectrum.

Daedalus Experiment

- Multiple beam sources using high-power cyclotrons
  - Very few $\bar{\nu}_e$ produced so can do precise $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ search
  - For study assume each cyclotron 1 MW at ~0.8 GeV
- Detector is assumed to be 300 kton water Cerenkov detector with gadolinium doping
- Osc signal events are $\bar{\nu}_e + p \rightarrow e^+ + n$ (Inverse-beta decay) which can be well identified by a two part delayed coincidence (Like reactor experiments)
- Excellent CP sensitivity alone or combined with LBNE ν-only running



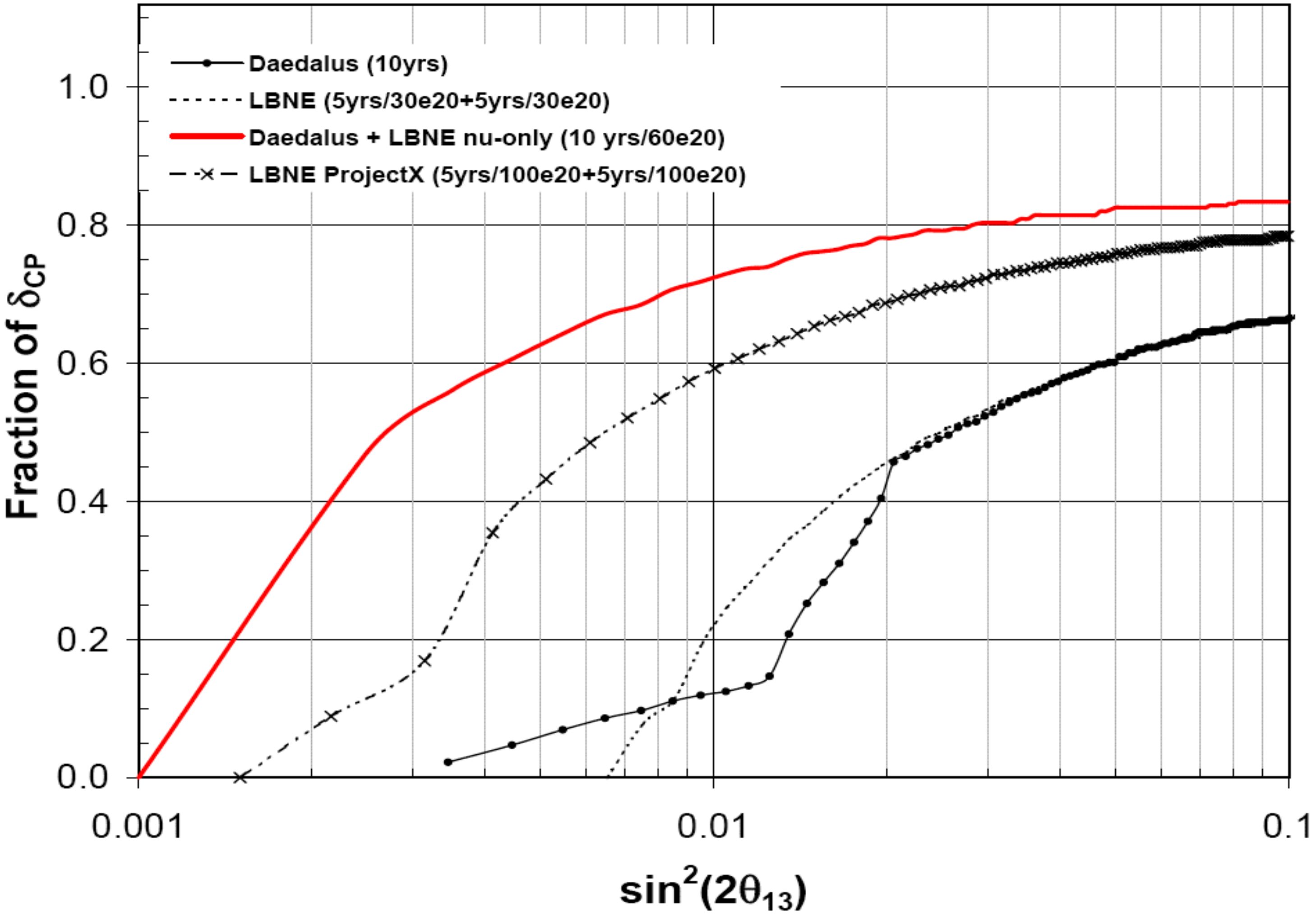
A multiple-baseline, single-detector experiment

Sites have sequential duty factors. Timing used to separate event source.

(Described in Conrad and Shaevitz, PRL 104, 141802 (2010))

Exclusion of $\delta_{CP} = 0^0$ or 180^0 at 3σ

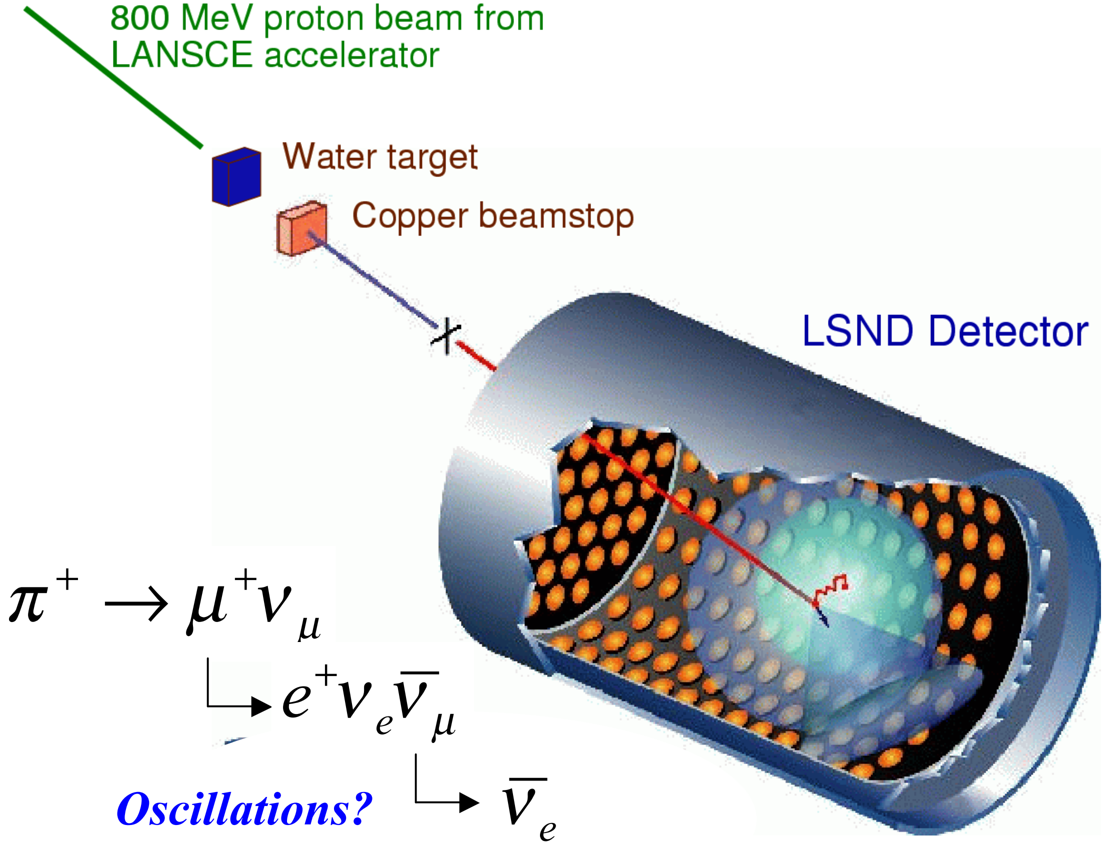
Combined running substantially better than either LBNE or Daedalus alone



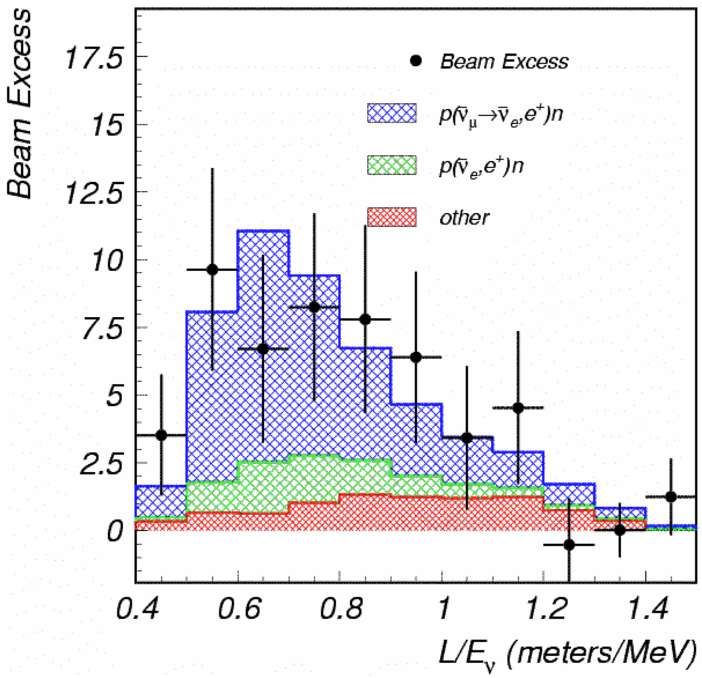
(Recent preprint has similar conclusions:
Agarwalla,Huber,Link,Mohapatra - http://arxiv.org/abs/1005.4055)

Possible Oscillations to Sterile Neutrinos

LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Signal



$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\hookrightarrow \bar{\nu}_e$$



Saw an excess of:
87.9 ± 22.4 ± 6.0 events.

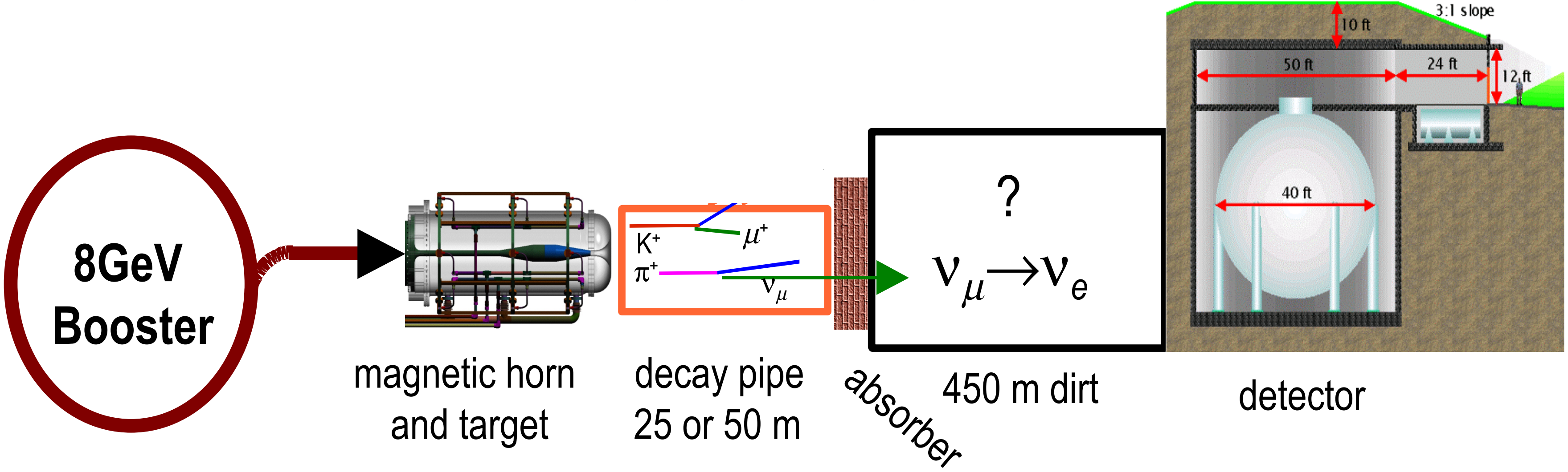
With an oscillation probability of (0.264 ± 0.067 ± 0.045)%.

3.8 σ evidence for oscillation.

LSND in conjunction with the atmospheric and solar oscillation results needs more than 3 ν's

⇒ Models developed with 1 or 2 sterile ν's

The MiniBooNE Experiment at Fermilab



8GeV Booster

magnetic horn and target

decay pipe 25 or 50 m

absorber

?

$\nu_\mu \rightarrow \nu_e$

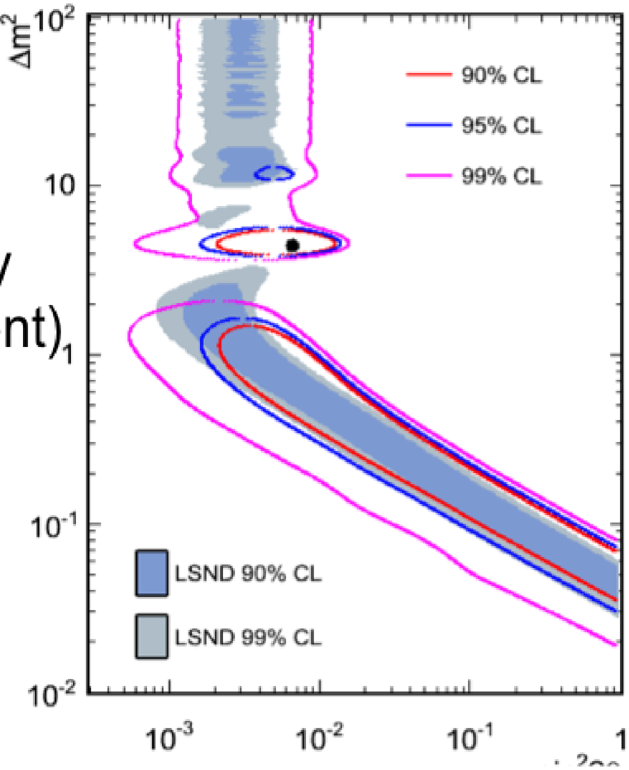
450 m dirt

detector

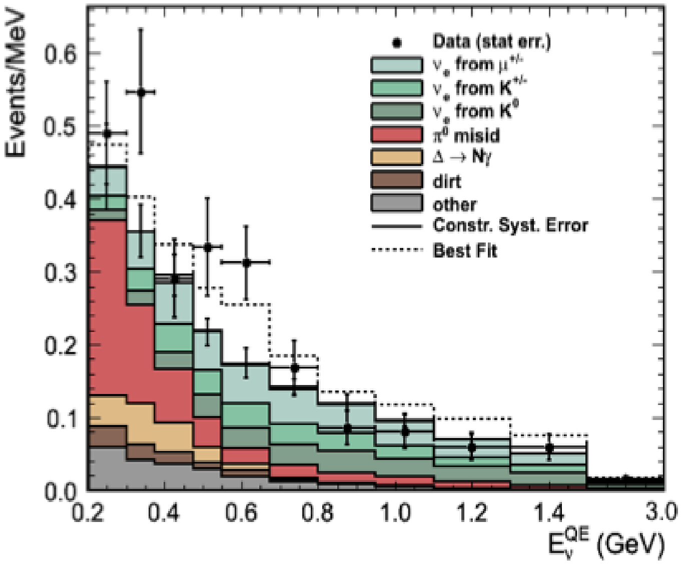
- Goal to confirm or exclude the LSND result - Similar L/E as LSND
  - Different energy, beam and detector systematics
  - Event signatures and backgrounds different from LSND

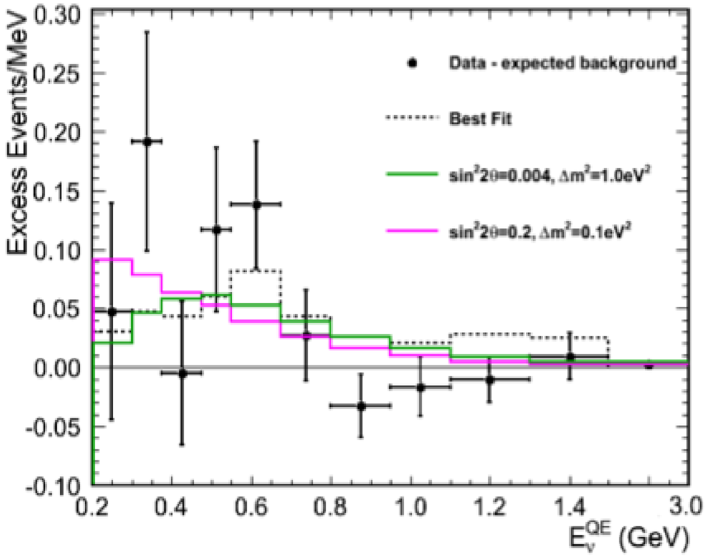
- Since August 2002 have collected data:
  - 6.5×10^{20} POT ν
  - 5.7×10^{20} POT $\bar{\nu}$

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result



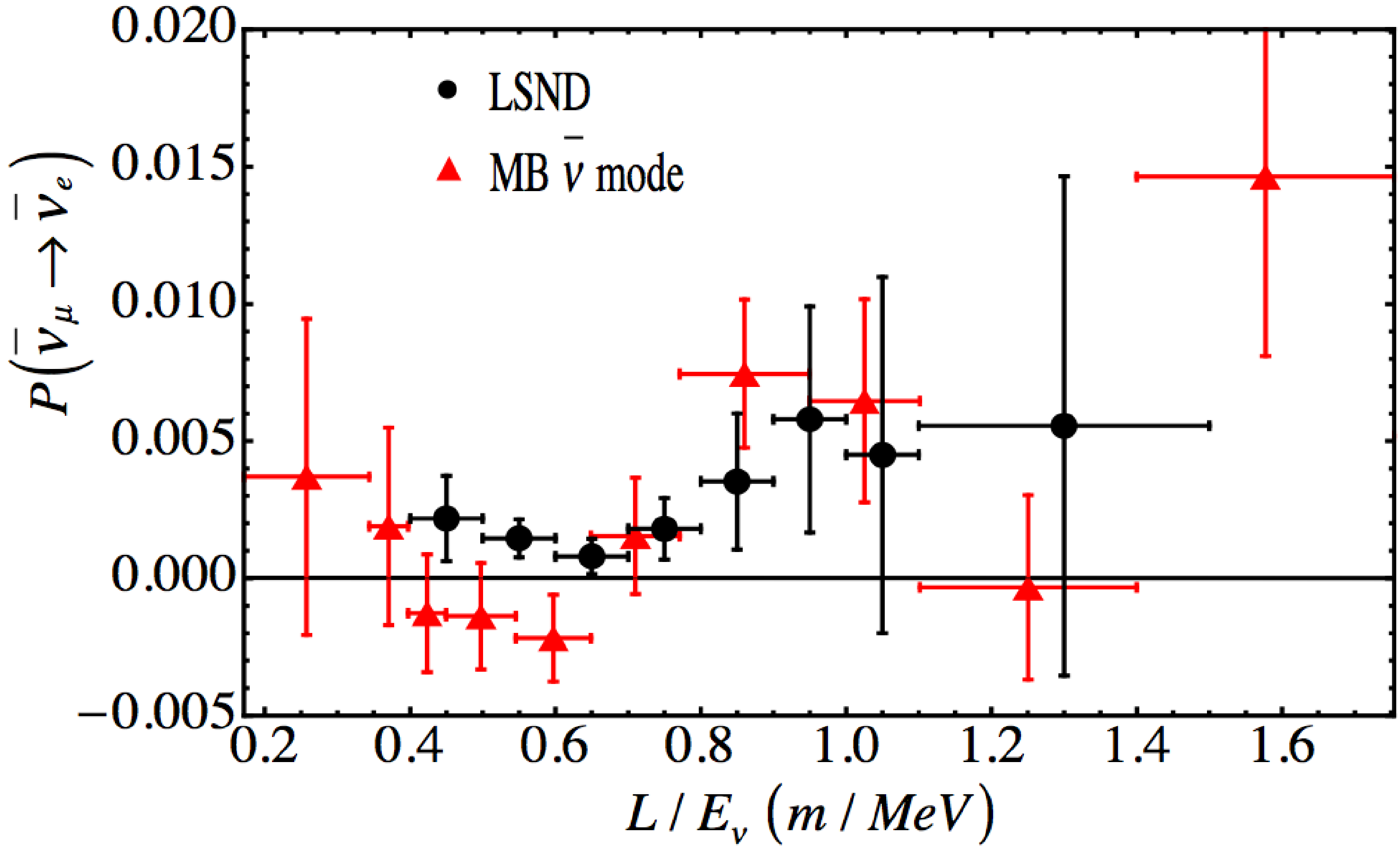
- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta$, Δm^2) = (0.0066, 4.42 eV^2) χ^2/NDF = 11.6/7; Prob.=10.9%





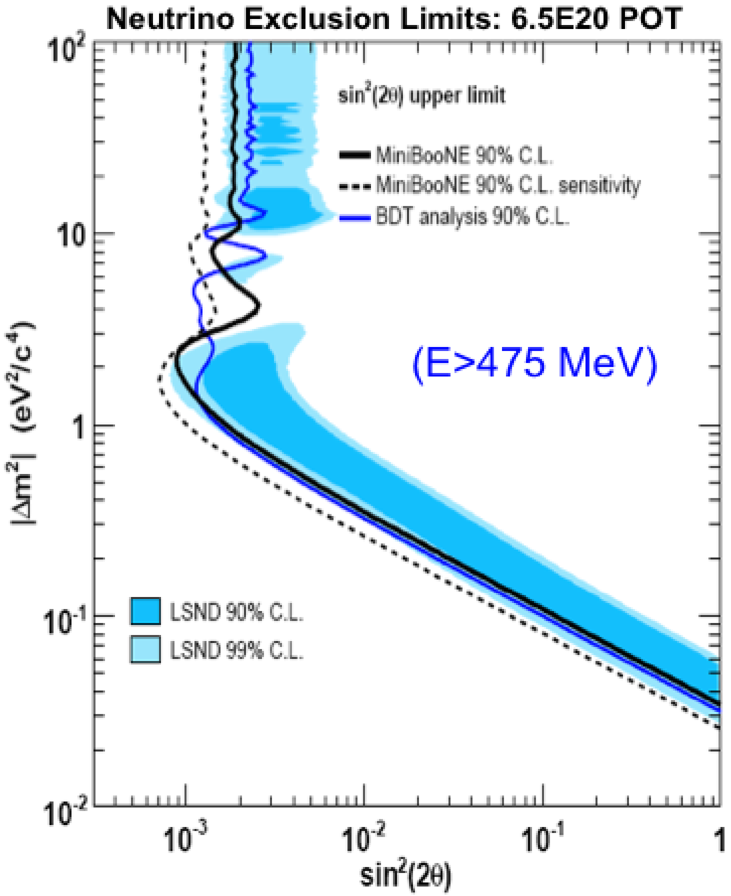
MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Result Consistent with LSND

$$P\left(\bar{\nu}_\mu \rightarrow \bar{\nu}_e\right) = \left(\sin^2 2\theta\right)\sin^2\left(1.27\Delta m^2 L / E\right)$$

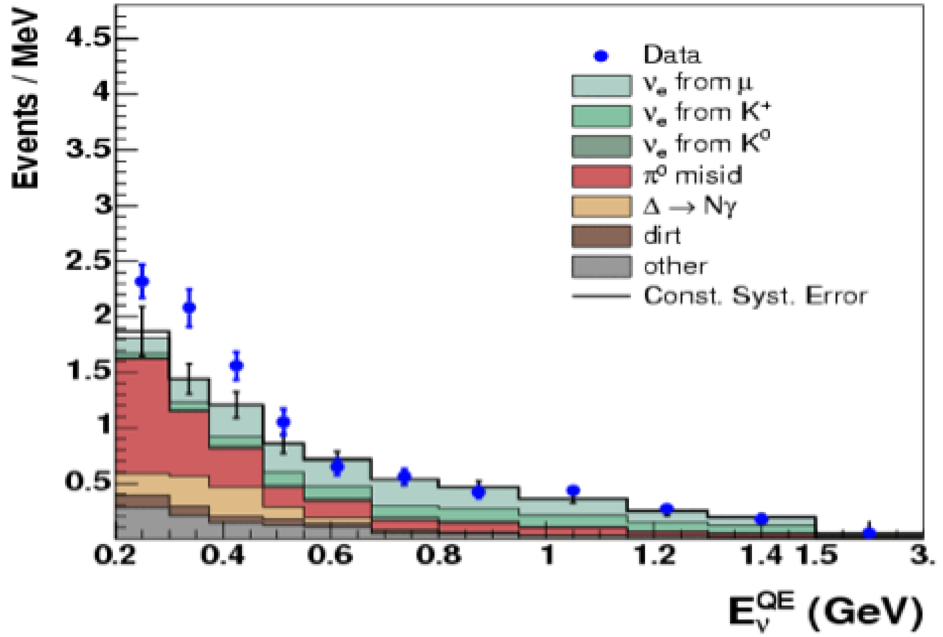


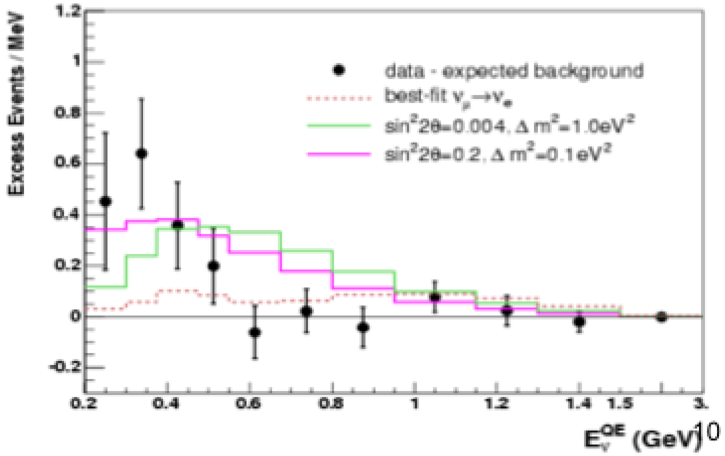
Neutrino mode MB results (2009)

- **6.5E20 POT** collected in neutrino mode
- E > 475 MeV data in good agreement with background prediction
  - ➔ energy region has reduced backgrounds and maintains high sensitivity to LSND oscillations.
  - ➔ A two neutrino fit inconsistent with LSND at the 90% CL assuming CP conservation.
- E < 475 MeV, statistically large (6σ) excess
  - ➔ Reduced to 3σ after systematics, shape inconsistent with two neutrino oscillation interpretation of LSND. Excess of 129 +/- 43 (stat+sys) events is consistent with magnitude of LSND oscillations.



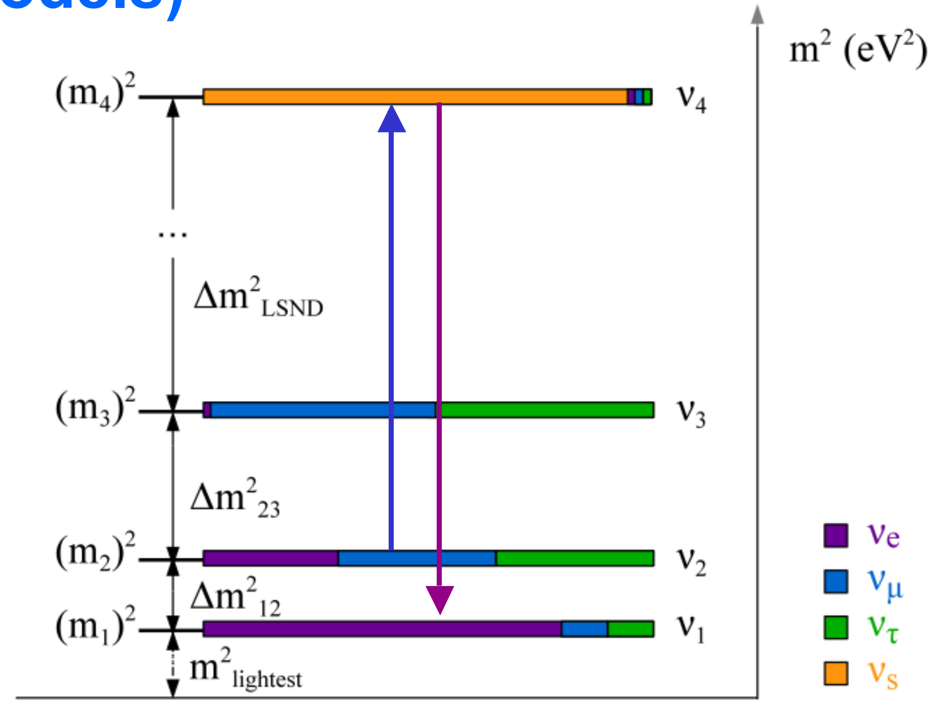
Published PRL 102,101802 (2009)





Phenomenology of Oscillations with Sterile Neutrinos (3+1 Models)

- In sterile neutrino (3+1) models, high Δm^2 ν_e appearance comes from oscillation through ν_s
  - $\nu_\mu \rightarrow \nu_e = (\nu_\mu \rightarrow \nu_s) + (\nu_s \rightarrow \nu_e)$
- This then requires that there be ν_μ and ν_e disappearance oscillations
  - In the past, constraints on disappearance have restricted any (3+1) models
- Information on appearance and disappearance confusing
  - Differences needed between ν versus $\bar{\nu}$ disappearance needed
  - But CPT invariance demands neutrino and antineutrino disappearance to be the same.



Mixing Angles: $U_{e4}, U_{\mu 4}, U_{S4}$

$$U_{e4}^2 + U_{\mu 4}^2 + U_{S4}^2 = 1.0$$

$$\nu_\mu : \left(1 - P_{\nu_\mu \to \nu_S}\right) = \left(1 - \sin^2 2\theta_{\mu S} \sin^2\left(1.27 \Delta m^2 L / E\right)\right)$$

$$\sin^2 2\theta_{\mu S} = 4U_{\mu 4}^2 U_{S4}^2$$

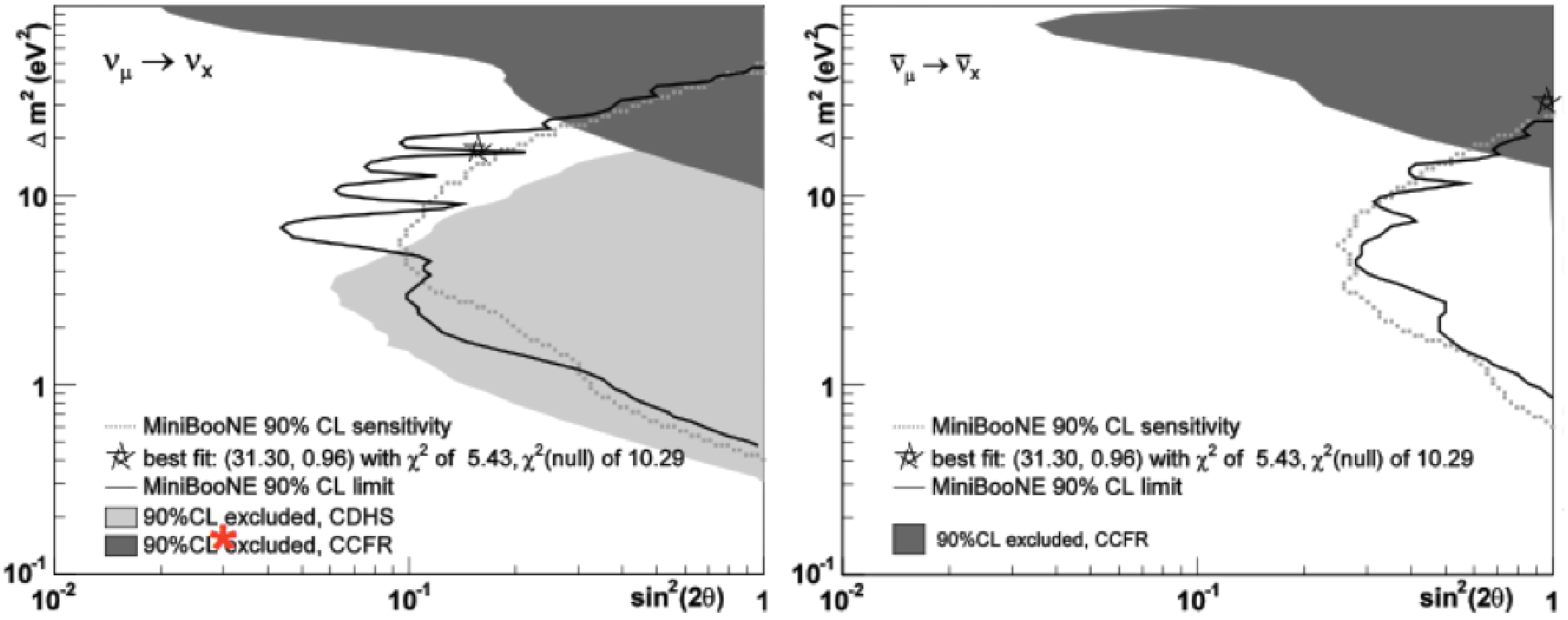
$$\nu_e : \left(1 - P_{\nu_e \to \nu_S}\right) = \left(1 - \sin^2 2\theta_{eS} \sin^2\left(1.27 \Delta m^2 L / E\right)\right)$$

$$\sin^2 2\theta_{eS} = 4U_{e4}^2 U_{S4}^2$$

MiniBooNE, CDHS, CCFR ν_μ and $\overline{\nu}_\mu$ Disappearance Limits

- Stringent limits on ν_μ disappearance from previous experiments
- Less stringent limits for $\overline{\nu}_\mu$ Disappearance
- CPT conservation implies ν_μ and $\overline{\nu}_\mu$ disappearance are the same

⇒ **Restricts application of 3+1 since ν_μ constrains $\overline{\nu}_\mu$ disappearance.**

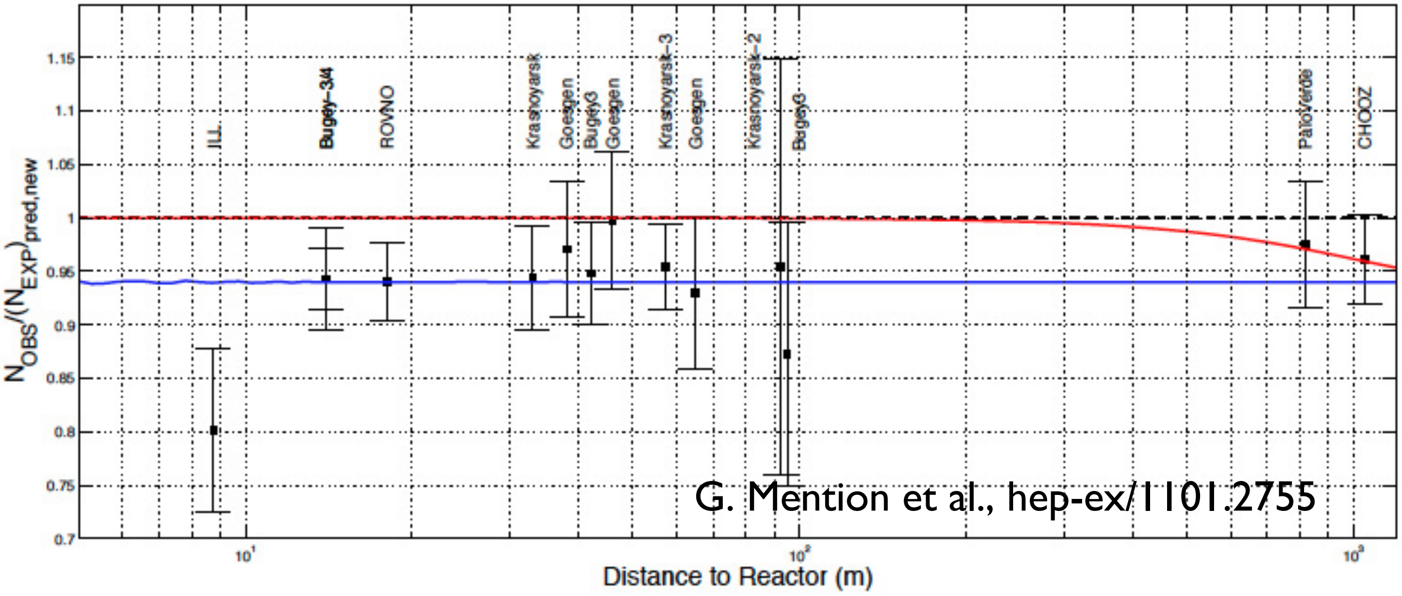


Reactor Antineutrino Anomaly - $\bar{\nu}_e$ Disappearance

Re-analysis of predicted reactor fluxes based on a new approach for the conversion of the measured electron spectra to anti-neutrino spectra.

- Reactor flux prediction increases by 3%.
- Re-analysis of reactor experiments show a deficit of electron anti-neutrinos compared to this prediction – at the 2.14σ level
- Could be oscillations to sterile with Δm^2~1eV^2 and $\sin^2 2\theta$~0.1

⇒ Relaxes restriction on 3+1 since now have $\bar{\nu}_e$ disappearance



G. Mention et al., hep-ex/1101.2755

Red line: Oscillations assuming 3 neutrino mixing

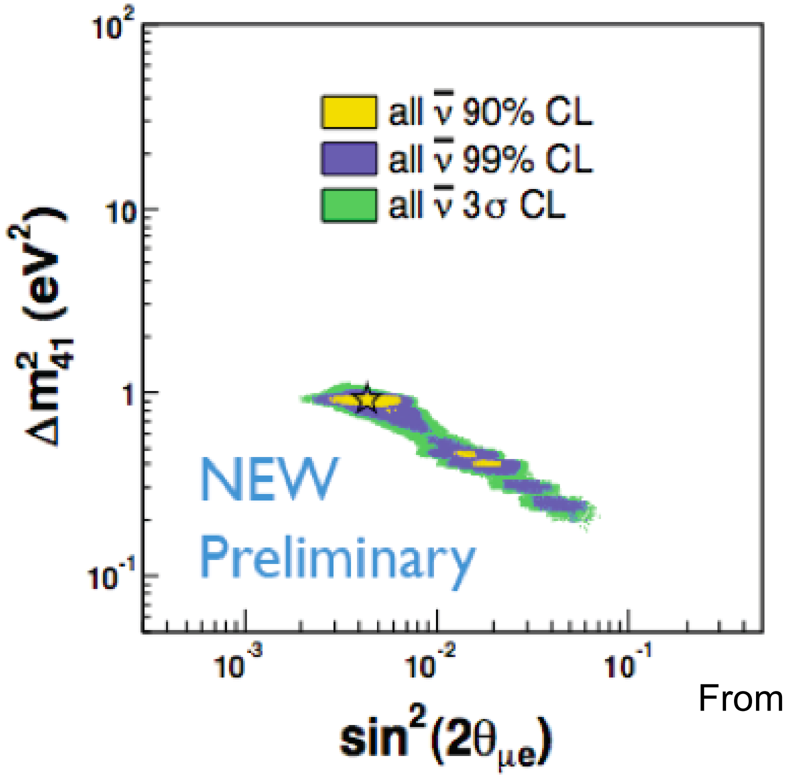
Blue line: Oscillations in a 3 + 1 (sterile neutrino) model

$\bar{\nu}$ – Only Data: 3+1 Fits with Sterile Neutrinos

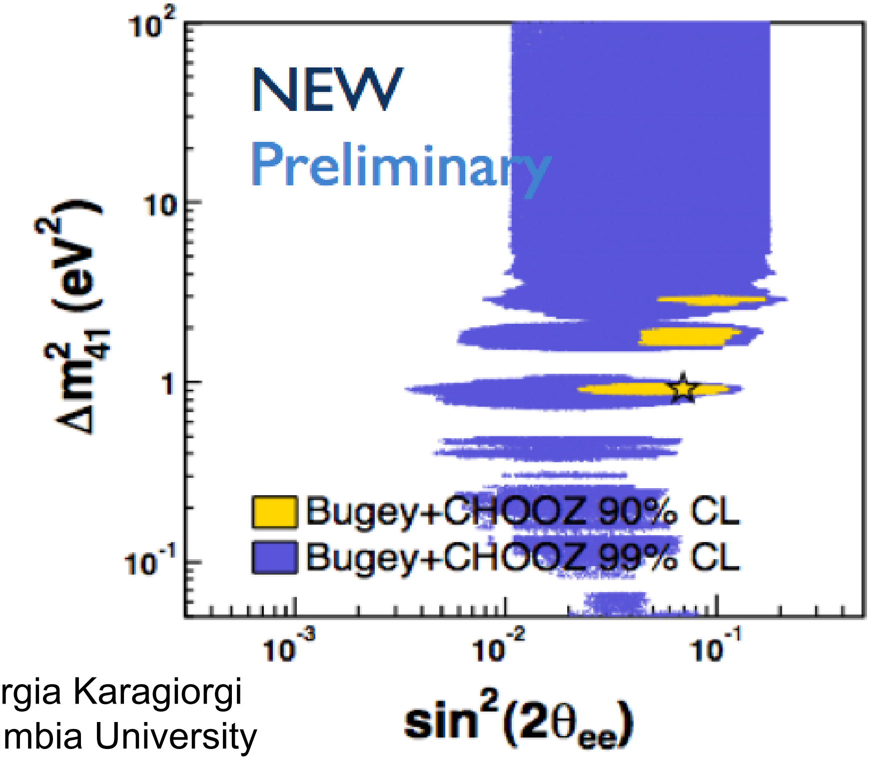
- $\bar{\nu}$ Data from LSND, MiniBooNE, Karmen, Reactor
- Good fits and compatibility for antineutrino - only data.
- MiniBooNE ν_e appearance and CDHS ν_μ disappearance do not fit

⇒ Need CP (and maybe CPT) violation ⇒ 3+2 Model

all $\bar{\nu}$



$\bar{\nu}$ disappearance



From Georgia Karagiorgi
Columbia University

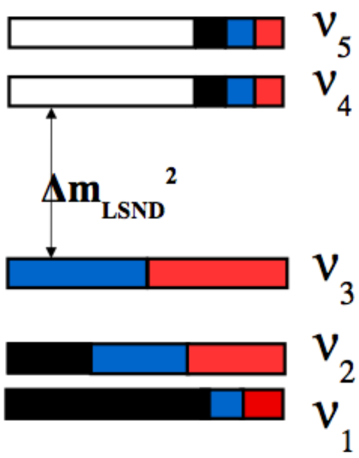
Global 3+2 Fits with Sterile Neutrinos

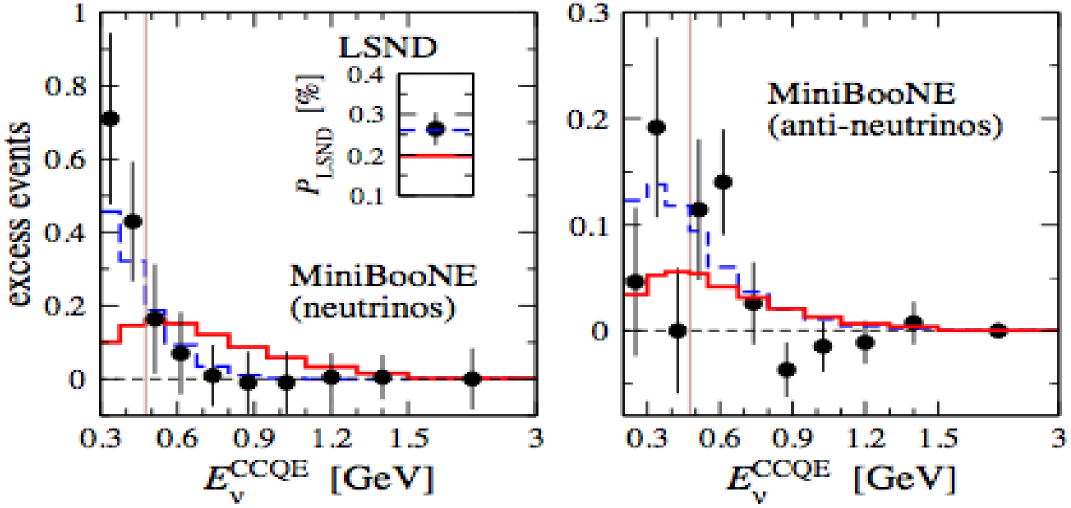
(Kopp,Maltoni,and Schwetz - hep-ph:1103.4570)

- In 3+2 fits, CP violation allowed so $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

	Δm^2_{41}	$\lvert U_{e4}\rvert$	$\lvert U_{\mu4}\rvert$	Δm^2_{51}	$\lvert U_{e5}\rvert$	$\lvert U_{\mu5}\rvert$	δ/π	χ^2/dof
3+2	0.47	0.128	0.165	0.87	0.138	0.148	1.64	110.1/130

- But still hard to fit appearance and disappearance simultaneously





Red: Fit to Disapp + App
Blue: Fit to App Only

- Compatibility between data sets better but still not very good
  - LSND+MB($\bar{\nu}$) vs Rest = 0.13%
  - Appearance vs Disappearance = 0.53%

Next Steps

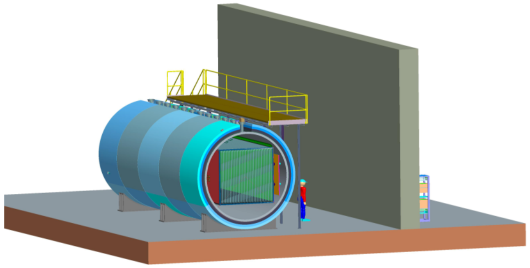
- Search for effects from high Δm^2 sterile neutrinos
  - Address MiniBooNE/LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance signal
- Address MiniBooNE low-energy ν_e excess
  - Could be oscillations or something else
- Very short baseline ν_e and $\bar{\nu}_e$ disappearance
- Two detector ν_μ, $\bar{\nu}_\mu$ disappearance

Future Plans and Prospects

Approved program:

1. Increase by x2-x3 the MiniBooNE $\bar{\nu}$ data over the next 2 years
   ⇒ Reach 3 to 4 σ

2. New MicroBooNE Exp in front of MiniBooNE (2013)
   Liquid Argon TPC detector which can address the low-energy excess:
    - Reduced background levels
    - Can determine if low-energy excess due to single electron or photon events?



Other ideas:

- New two detector experiments for appearance and disappearance
  - At Fermilab using using new detectors in MiniBooNE beamline
  - CERN PS neutrino beam with Icarus style detectors at 130m/850m
- Very short baseline ν_e disappearance
  - Use high rate radioactive sources in Borexino detector
  - Small detector close (<10m) to nuclear reactor
  - Decay-at-rest beam close to a large detector (Nova, LAr_1kton)

Final Comments

- Reactor and longbaseline experiments will be soon providing new information on θ_{13}
  - θ_{13} is a important physics parameter for modeling ν mixing
  - θ_{13} is key for planning future long-baseline experiments to measure CP violation and the mass hierarchy

- Next generation longbaseline experiments have the promise to give information on the mass hierarchy and CP violation if $\sin^2 2\theta_{13} > \sim 0.01$

- There are a number of results and hints that suggest that there may be oscillations to sterile neutrinos at the $\Delta m^2 \sim 1\ \mathrm{eV}^2$ level
  - Further running and new experiments are being planned to address this possibility

⇒ Exciting times for neutrino physics