3-flavor mixing

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

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

3angles θ_{12} θ_{13} and θ_{23}
and complex phase δ

$$P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta | e^{-iH_0 L} | \nu_\alpha \rangle \right|^2 = \sum_{i,j} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\delta m^2_{ij} L/2E}$$

3 masses -> only 2 mass differences
If one mass difference >> other,
then algebra gets simpler.

$\Delta m_{32} \sim \Delta m_{atm}$

$\Delta m_{21} \sim \Delta m_{solar}$

- SuperK is probably measuring:

$$\begin{aligned} P(\nu_\mu \to \nu_\tau) \simeq & \; 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2(\tfrac{\delta m^2_{atm} L}{4E}) \\ = & \; \sin^2(2\theta_{23}) \cos^4(\theta_{13}) \sin^2\left(\frac{\delta m^2_{atm} L}{4E}\right) \end{aligned}$$

- $\mathrm{Sin}^2 2\theta_{23} \sim 1$!

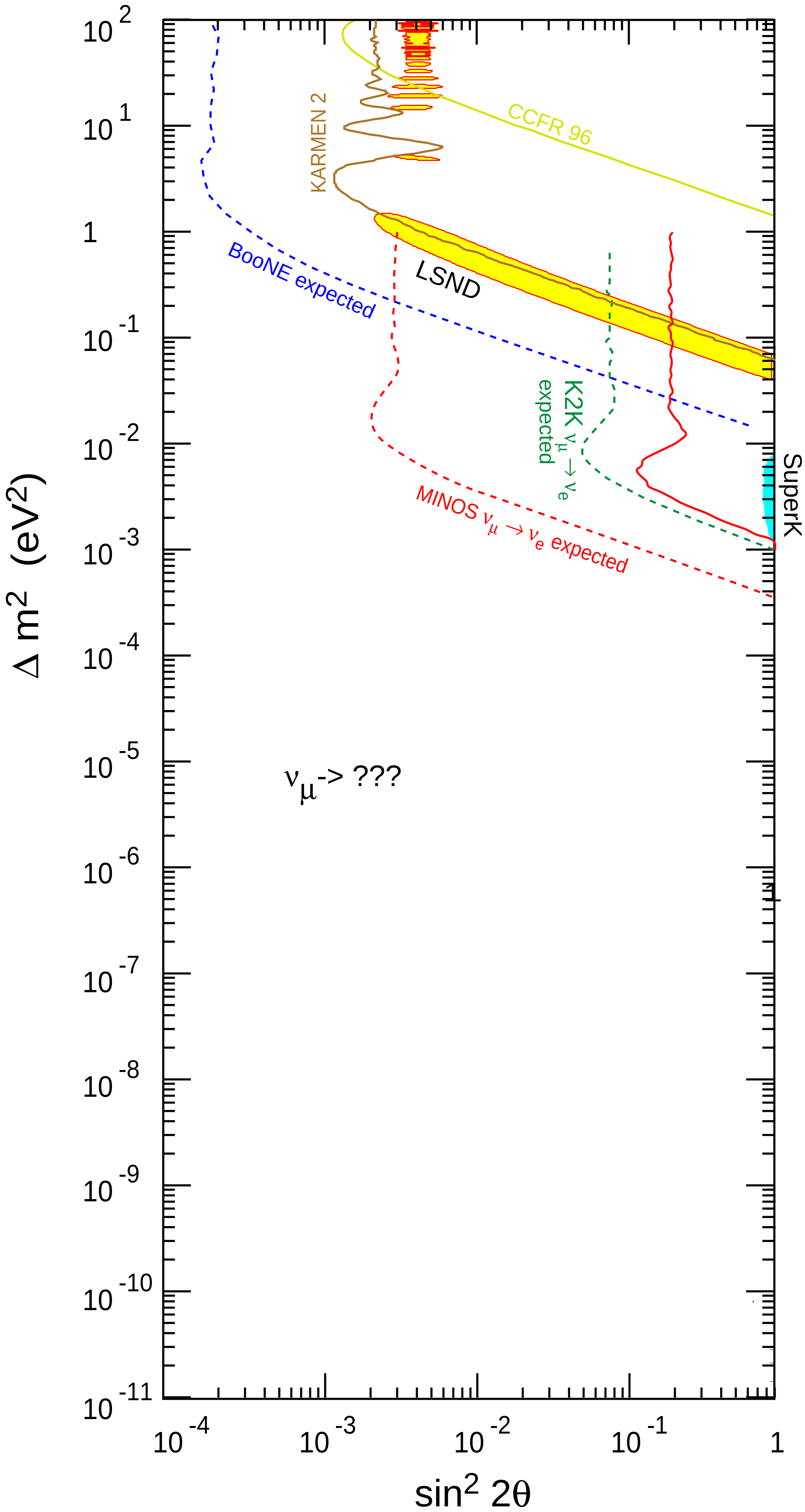
- CHOOZ reactor measures:

$$\begin{aligned} P(\nu_e \to \nu_e) \simeq & \; 1 - 4|U_{e3}|^2(1 - |U_{e3}|^2) \sin^2\left(\frac{\delta m^2_{atm} L}{4E}\right) \\ = & \; 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\delta m^2_{atm} L}{4E}\right), \end{aligned}$$

- $\mathrm{Sin}^2 2\theta_{13} < 0.1$

Not so fast!

- LSND see a signal in ν_μ->ν_e
- Karmen don't
- Boone 2002 will check
- 3 mass differences!
  - 1 or more experiments are wrong
  - There are more than 3 neutrino types



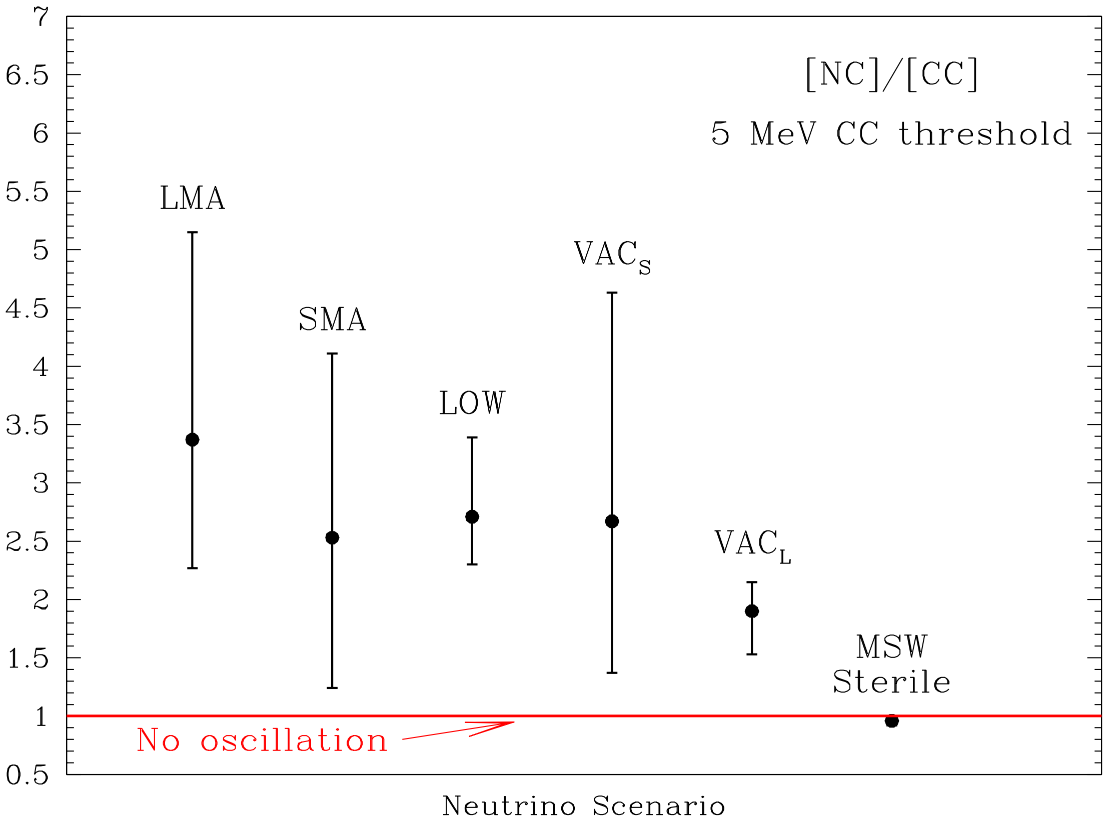
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Δm^2 (eV^2)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\theta$
KARMEN 2
CCFR 96
LSND
BooNE expected
K2K $\nu_\mu \rightarrow \nu_e$ expected
MINOS $\nu_\mu \rightarrow \nu_e$ expected
SuperK
ν_μ-> ???

Sterile Neutrinos

- Know from Z width only 3 neutrinos couple to Z.
- Any additional neutrinos can mix but not show up in weak interactions

- Possible signals
  - Different MSW effects in the sun as interactions are different
  - MSW effect in atmospheric neutrinos
  - Missing $\nu d \rightarrow \nu d$ events at SNO as sterile neutrinos won't interact

SNO will tell us



- Sterile neutrinos will depress the neutral current (νd -> νd) rate relative to charged currents.

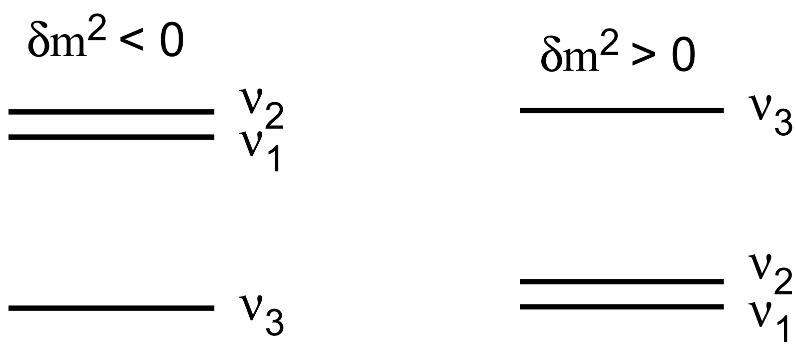
Prospects

- Next 5-10 years
  - Boone will see if there are neutrino oscillations at the $\delta m^2 \sim 0.1\ eV^2$ scale
  - K2K will confirm (or not) SuperK, may measure δm_{23}^2
  - MINOS and CERN-Gran Sasso will start high statistics measurements to $\delta m_{23}^2 \sim 0.002\ eV^2$, may see θ_{13} in ν_e->ν_μ
  - KAMLAND will begin to explore solar neutrino land
  - SNO and Borexino will see (or not see) sterile neutrinos
- We will probably know the major mass difference and mixing angles

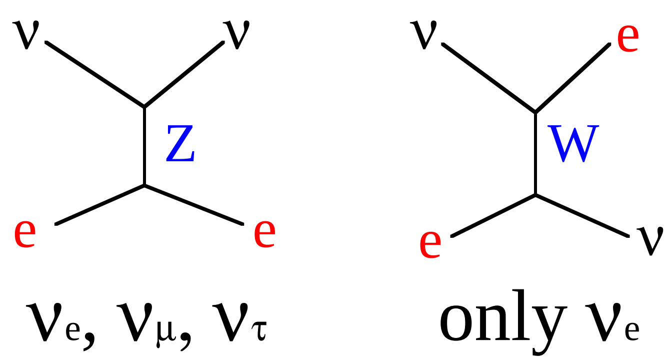
More to do

- There are 3 mixing angles and a CP violating phase

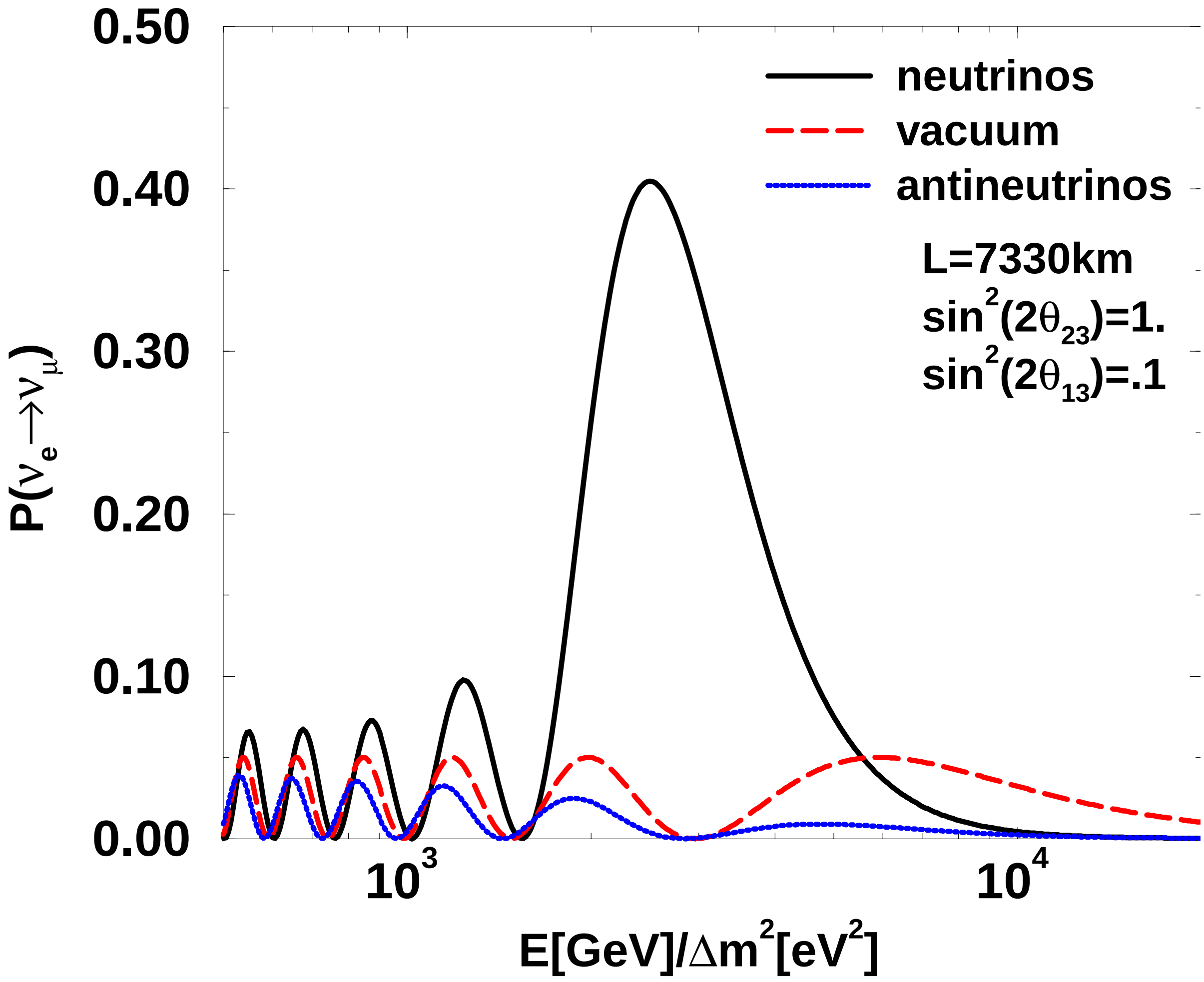
MSW effects can tell us if



If we get real lucky, we may see CP violation



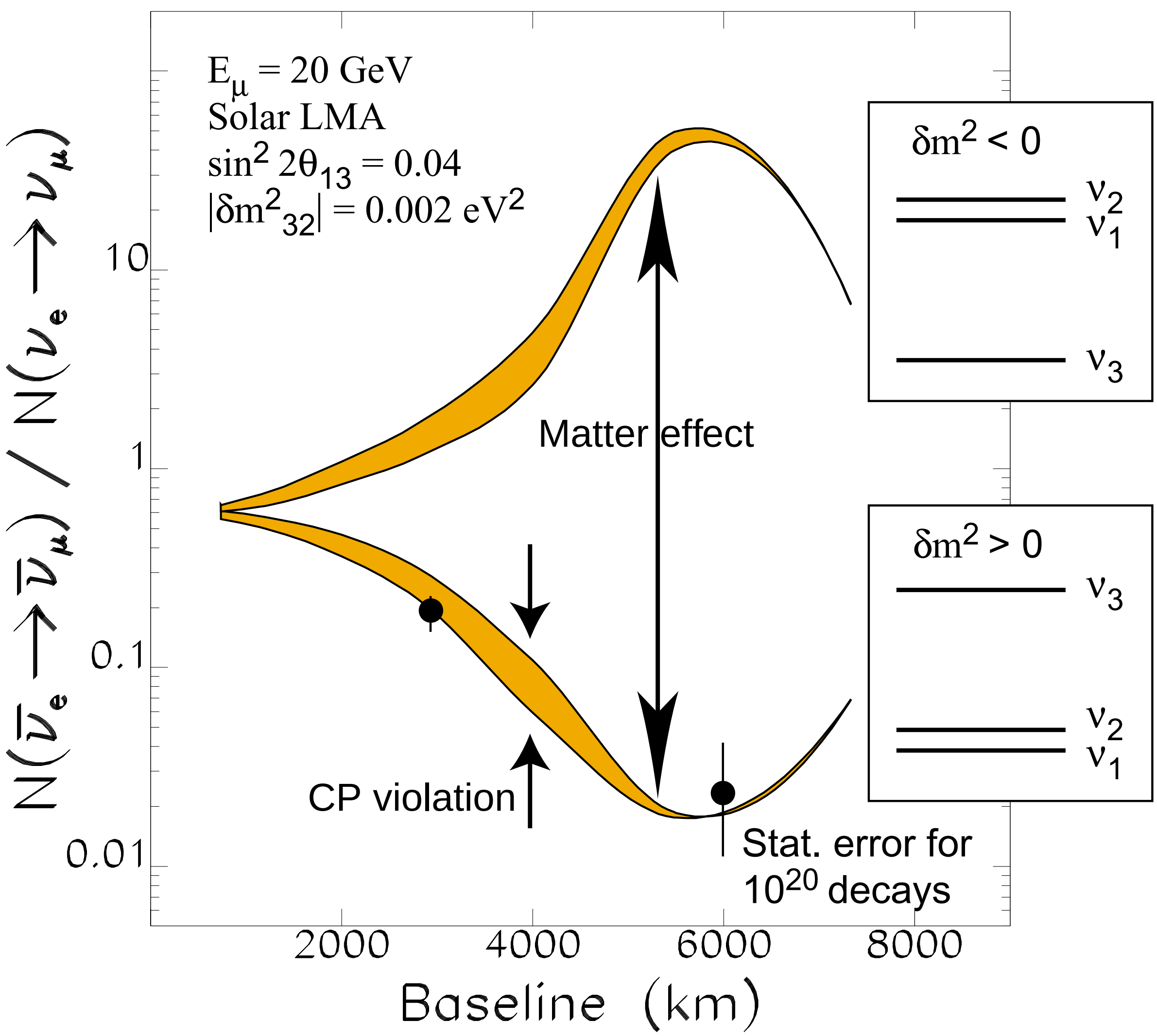
- Interactions with matter can cause enhancements for ν or anti-ν but not both



To see CP violation, all 3 flavors must be involved. Only see it if Dm_{solar} is not too small and the Jarlskog factor J is large.

$$J = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}(\sin\delta)$$

Wrong-Sign Muon Measurements



Bigger ν beams

- Need baselines from 2000-10,000 km to see matter and CP effects

- Super MINOS?
  - Conventional beam with higher energy, more flux

- Neutrino Factory
  - Muon storage ring

  $\mu \rightarrow e\ \nu_\mu$ anti-ν_e

Bigger ν detectors

- NNN workshops
  - Next one at FNAL Aug 7-8
- Consider a neutrino detector 10 times bigger than Super K
  - 1000 neutrinos from a supernova
  - Proton decay
  - Neutrino astrophysics
  - Solar neutrinos
  - Target for long baseline accelerators

Conclusions

- 5 years ago neutrino oscillations were a possibility
  - More solar neutrino data at different energies
  - Better solar models
  - Super K atmospheric neutrinos
  - Confirmation from MACRO, SoudanII …
- They are now an industry
  - K2K
  - MINOS
  - CGS
  - KamLand
  - SuperDuperK
  - Neutrino factories?