

# Neutrino oscillation experiments

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July 2023

# Outline

1 Neutrino sources

2 Neutrino detector technologies

3 Measuring neutrino oscillations

# Natural neutrino sources

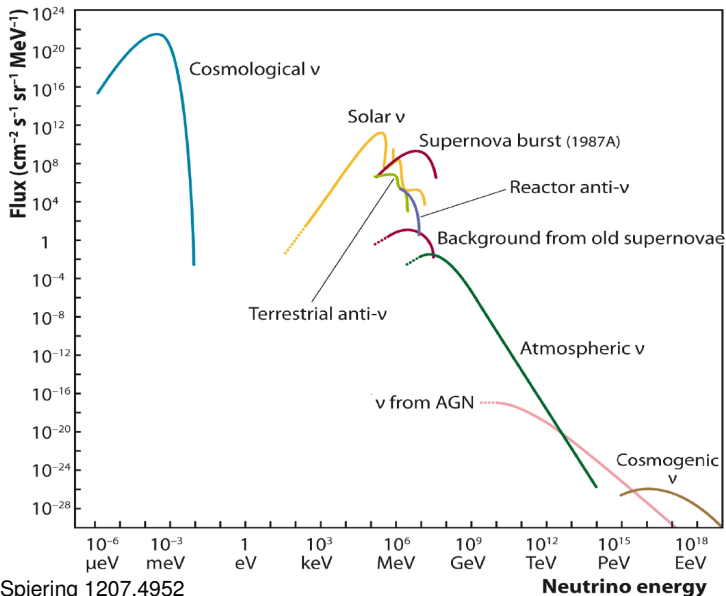
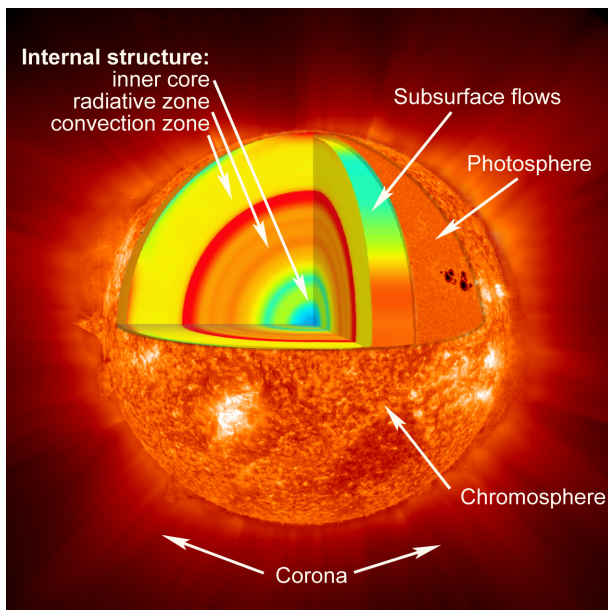


Image: C. Spiering 1207.4952

# Solar neutrino production



# Solar neutrino production

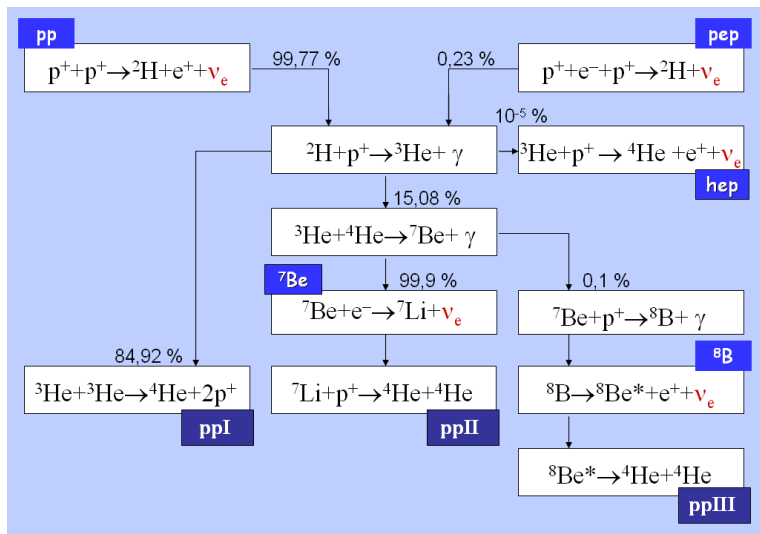


Image: Wikimedia Commons

# Solar neutrino properties

- Pure  $\nu_e$  flux (before oscillations)
- Flux on Earth:  $\sim 10^{11} \text{ cm}^{-2}\text{s}^{-1}$
- Energy  $\lesssim 10 \text{ MeV}$

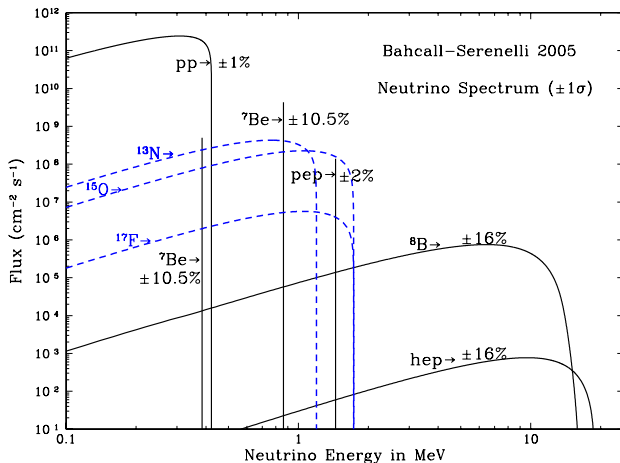
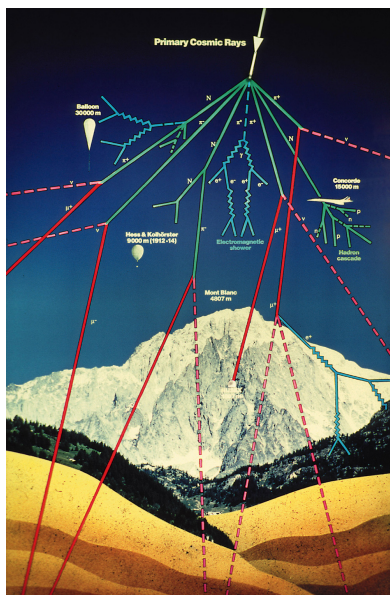
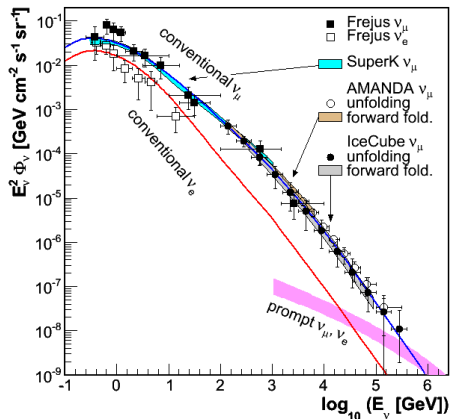


Image: John Bahcall

# Atmospheric neutrinos



- Energy spectrum:

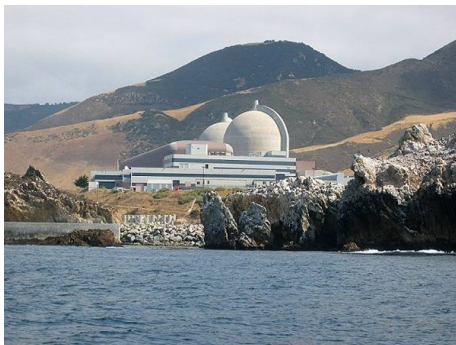
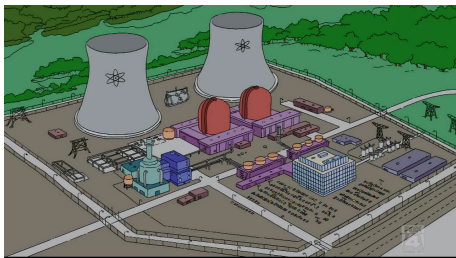


- Observable at  $E \gtrsim 100 \text{ MeV}$  (below: cross sections too low)

- Flavor composition

$$\vec{\nu}_e : \vec{\nu}_\mu : \vec{\nu}_\tau \sim 1 : 2 : 0$$

# Nuclear reactors



- Intense source of  $\bar{\nu}_e$  from



- Typical flux @ 100 m:

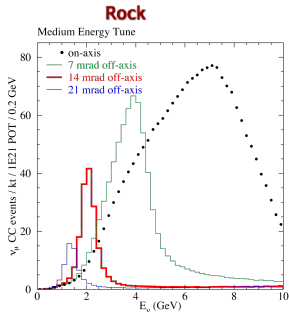
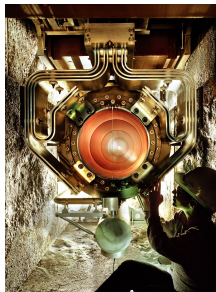
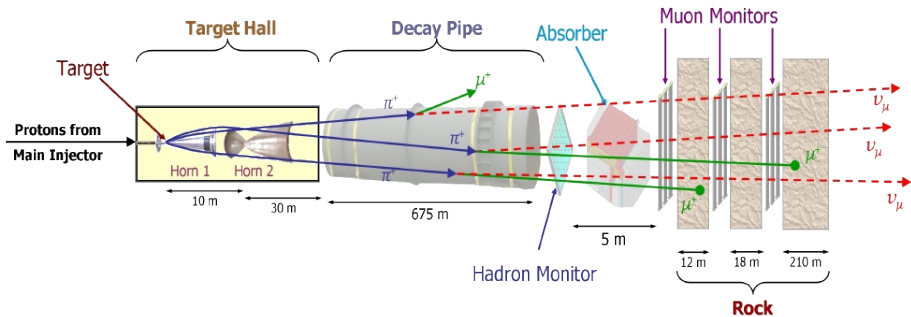
$$10^{15} \text{m}^{-2} \text{s}^{-1} = 1 \text{ kW m}^{-2}$$

- Neutrino energy:  $\lesssim 10 \text{ MeV}$
- First-ever detection of neutrinos (Reines & Cowan, 1956)

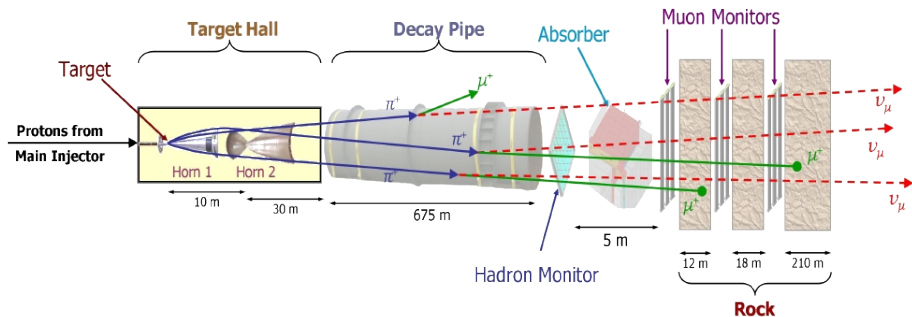




# Accelerator neutrinos

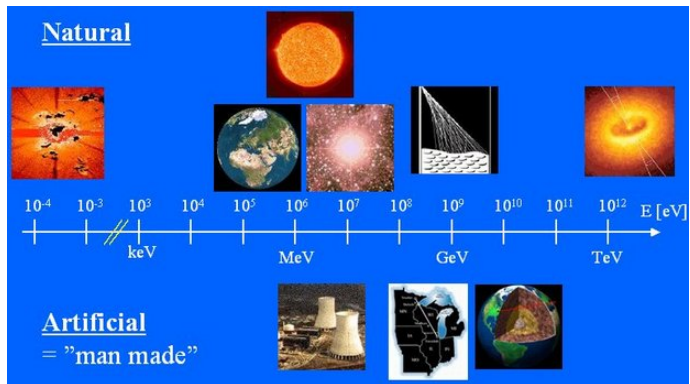


# Accelerator neutrinos



- Energy: few 100 MeV – few 100 GeV
- Flavor composition (depending on horn polarity)
  - ▶  $\nu_\mu$  (with contamination from  $\bar{\nu}_\mu$ ,  $\nu_e$ ,  $\bar{\nu}_e$ )
  - ▶  $\bar{\nu}_\mu$  (with contamination from  $\nu_\mu$ ,  $\nu_e$ ,  $\bar{\nu}_e$ )

# Neutrino source — Summary



# Outline

- 1 Neutrino sources
- 2 Neutrino detector technologies**
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# Liquid scintillator detectors

## Example: Double Chooz

- Scintillating mineral oil
- Doped with gadolinium (large neutron capture cross section) to tag

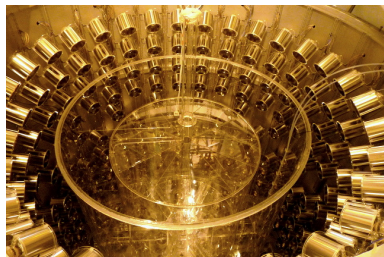
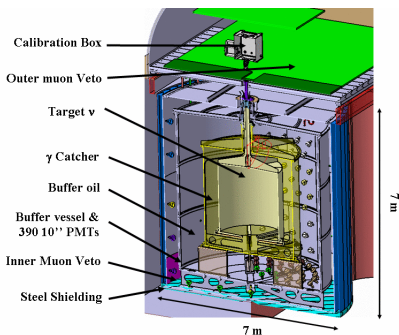


via coincidence of prompt  $e^+$  and delayed  $n$  capture

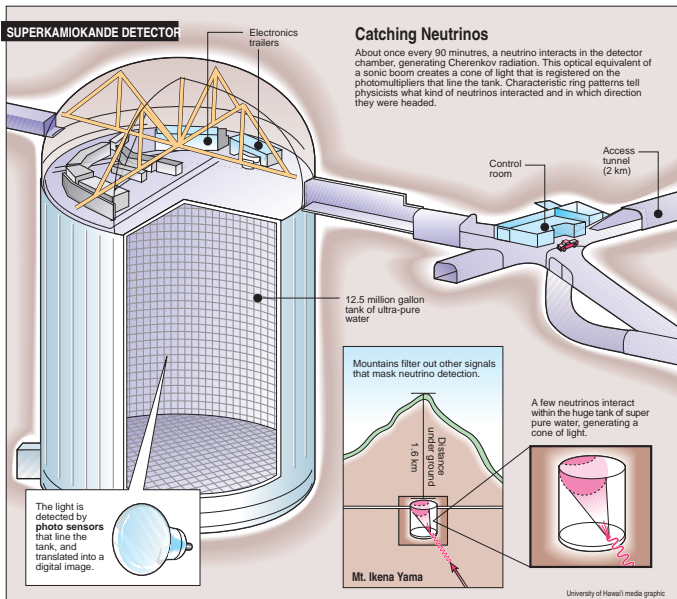
- Challenges:

- ▶ Radiopurity
  - ★ Careful material selection
  - ★ Multiple layers of shielding
- ▶ Suppression of cosmic ray BG
  - ★ Underground
  - ★ Active veto
- ▶ ...

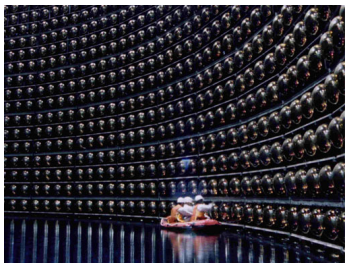
- Sensitive to low- $E$  (MeV) neutrinos



# Water Čerenkov detectors



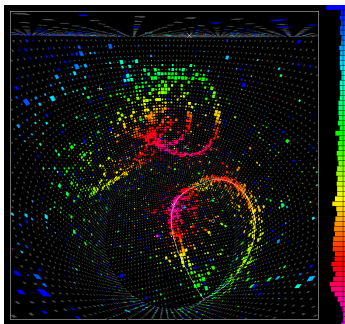
# Super-Kamiokande



- Detection principle:
  - ▶ Observe Čerenkov light from high- $E$  secondary particles in



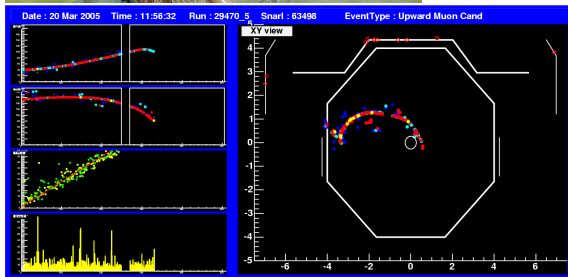
- Sensitive to  $E_\nu \gtrsim \text{few}10 \text{ MeV}$
- Huge targets feasible (Super-K: 22.5 kt)
- Only particles above Čerenkov threshold visible
  - ▶ Event reconstruction more challenging



# Magnetized iron detectors

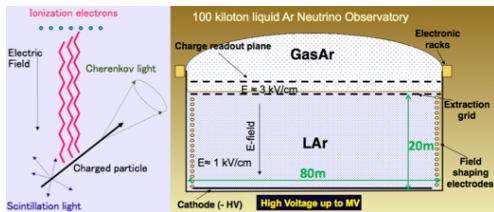


- Interleaved layers of **iron** (neutrino target) and **plastic scintillator** (tracking)
- Magnetizeable  $\rightarrow$  distinguish  $\nu$  and  $\bar{\nu}$
- Sensitive to  $E_\nu \gtrsim \text{GeV}$
- Limited event reconstruction:
  - ▶ Hadrons, electrons: Localized shower
  - ▶ Muons: Long track

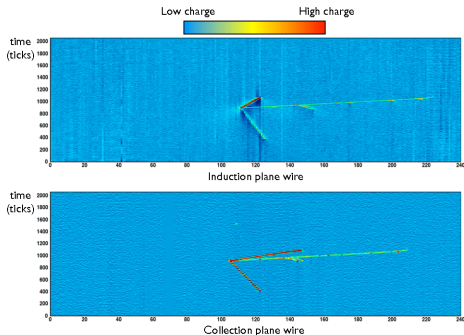




# Liquid Argon Detectors



- Very good event reconstruction capabilities
- Low threshold  $\sim 10 \text{ MeV}$
- Works at the 600 ton level (ICARUS), scalability to bigger sizes not proven



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# The challenge

Six parameters to measure:

$$\theta_{23}, \Delta m_{31}^2,$$

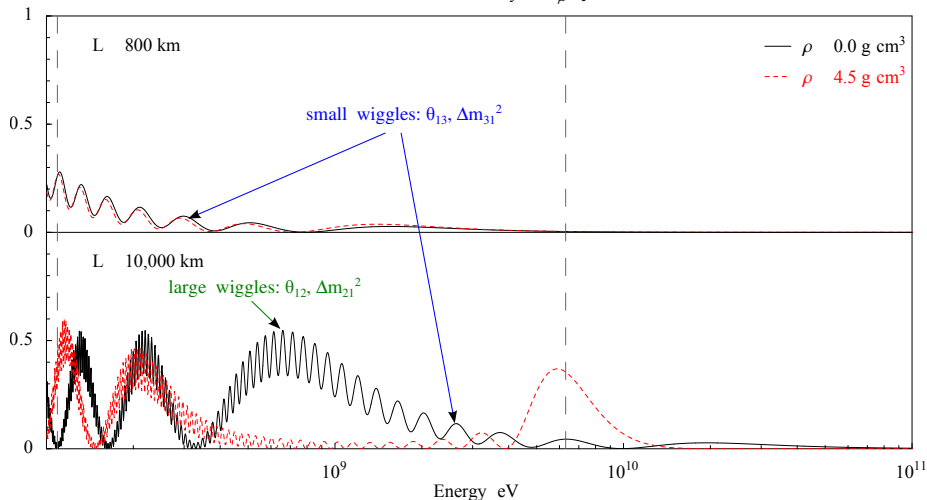
$$\theta_{12}, \Delta m_{21}^2,$$

$$\theta_{13},$$

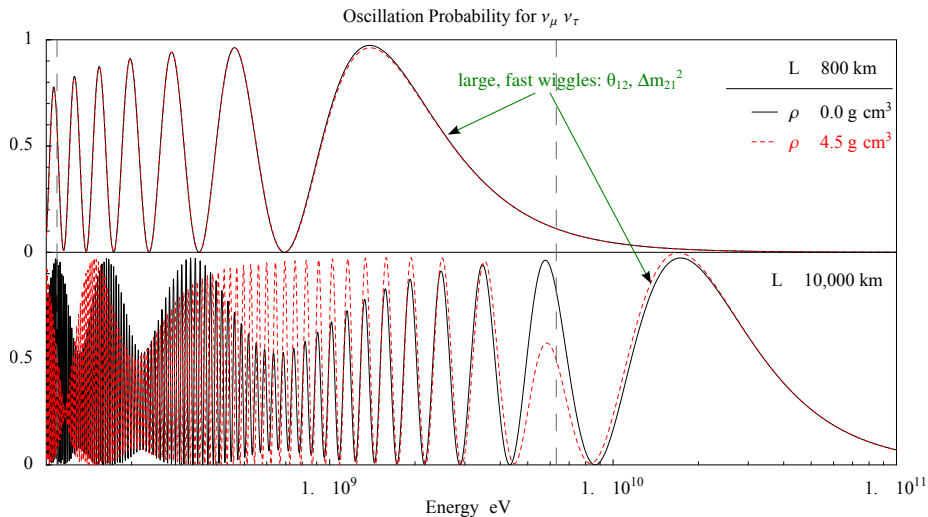
$$\delta_{CP}$$

# Oscillation probability $P_{\mu \rightarrow e}$

Oscillation Probability for  $\nu_\mu \nu_e$



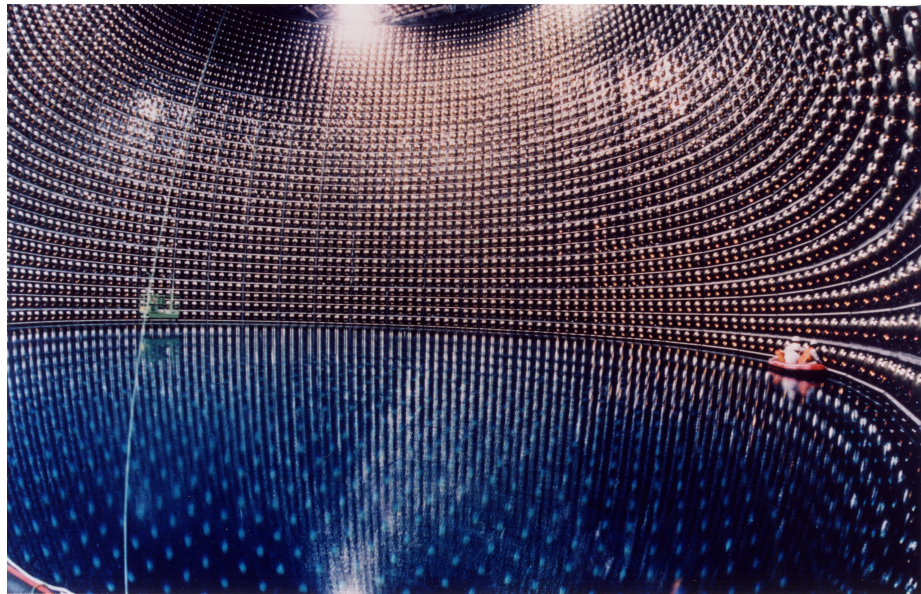
# Oscillation probability $P_{\mu \rightarrow \tau}$



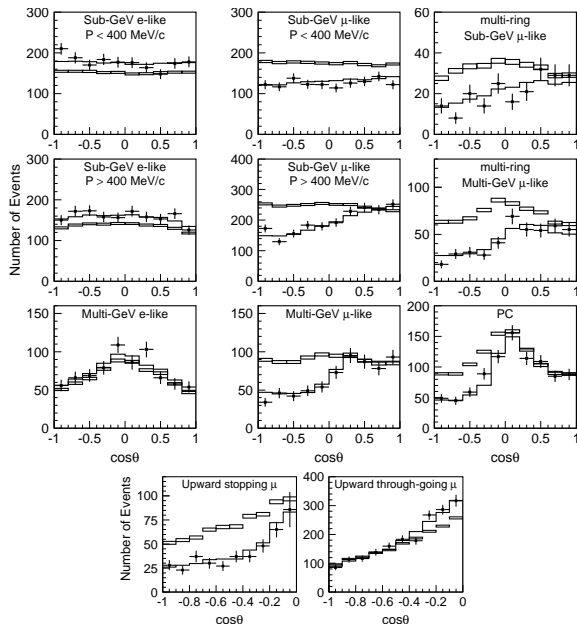
# Strategy

- $\theta_{23}, \Delta m_{31}^2$ 
  - ▶  $\bar{\nu}_\mu$  disappearance (into  $\bar{\nu}_\tau$ )  
at  $L/E \sim 500$  km/GeV
- $\theta_{12}, \Delta m_{21}^2$ 
  - ▶  $\bar{\nu}_e$  disappearance (into  $\bar{\nu}_\mu$   
and  $\bar{\nu}_\tau$ ) at  $L/E \sim 15\,000$  km/GeV
- $\theta_{13}$ 
  - ▶  $\bar{\nu}_e$  disappearance (into  $\bar{\nu}_\mu$   
and  $\bar{\nu}_\tau$ ) at  $L/E \sim 500$  km/GeV

# The beginnings: Super-Kamiokande



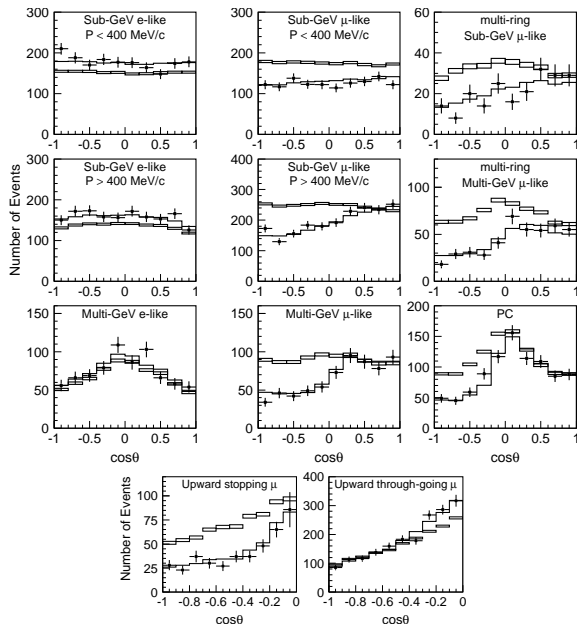
# The beginnings: Super-Kamiokande (1998)



- Look for  $\bar{\nu}_e$  and  $\bar{\nu}_\mu$

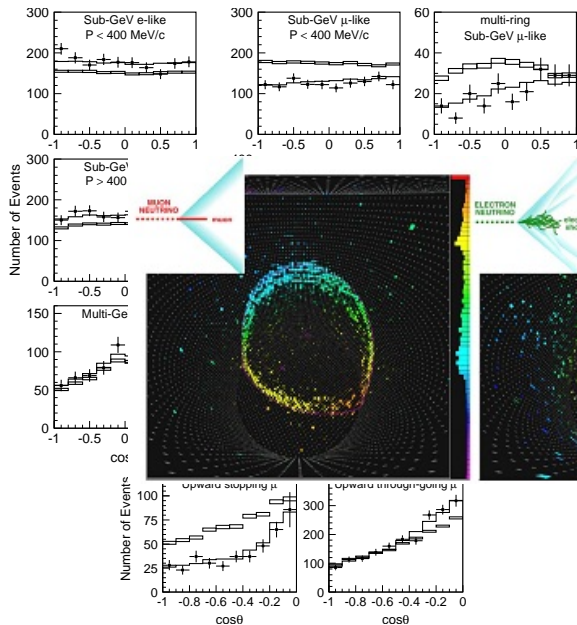


# The beginnings: Super-Kamiokande (1998)



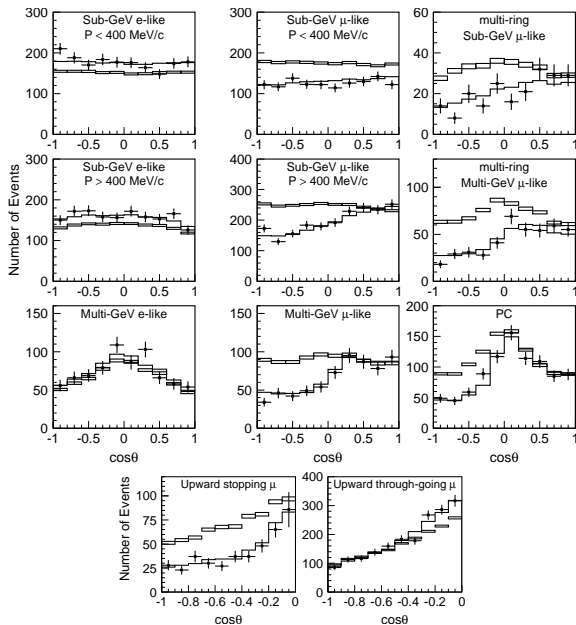
- Look for  $\bar{\nu}_e$  and  $\bar{\nu}_\mu$
- Flavor-ID from shape of Čerenkov ring

# The beginnings: Super-Kamiokande (1998)



- Look for  $\bar{\nu}_e$  and  $\bar{\nu}_\mu$
- Flavor-ID from shape of Čerenkov ring

# The beginnings: Super-Kamiokande (1998)



- Look for  $(\bar{\nu})_e$  and  $(\bar{\nu})_\mu$
- Flavor-ID from shape of Čerenkov ring
- Observation  
Lack of upward going  $(\bar{\nu})_\mu$

# Super-K two-flavor fit: $\theta_{23}$ and $|\Delta m_{31}^2|$

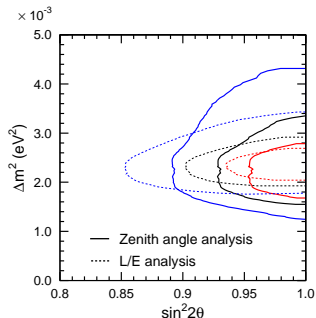
Why does a two-flavor fit work?

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & s_{13} e^{-i\delta} \\ -s_{13} e^{i\delta} & 0 & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} & 1 \end{pmatrix}$$

We know today:

- $\sin \theta_{13} \ll 1$ 
  - ▶ Neglect  $\theta_{13}$
- $|\Delta m_{21}^2| \ll |\Delta m_{31}^2|$ 
  - ▶ If osc. phase  $|\Delta m_{21}^2|L/2E \ll 1$  (relevant at very high  $E$ ),  $\Delta m_{21}^2$  disappears from the expression for  $P_{\alpha \rightarrow \beta}$ .
  - ▶ We can then remove  $\theta_{12}$  by redefining

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \rightarrow \begin{pmatrix} \nu'_1 \\ \nu'_2 \\ \nu'_3 \end{pmatrix} \equiv \begin{pmatrix} c_{12} & -s_{12} \\ s_{12} & c_{12} & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



# Super-K two-flavor fit: $\theta_{23}$ and $|\Delta m_{31}^2|$

Why does a two-flavor fit work?

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13} e^{-i\delta} \\ & 1 & \\ -s_{13} e^{i\delta} & & 0 & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \\ & & 1 \end{pmatrix}$$

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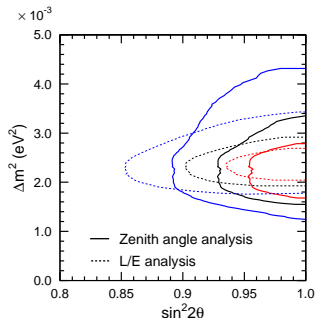
- $\sin \theta_{13} \ll 1$ 
  - ▶ Neglect  $\theta_{13}$
- $|\Delta m_{21}^2| \ll |\Delta m_{31}^2|$ 
  - ▶ At low  $E$ :

$$P_{e \rightarrow \mu} \simeq P_{e \rightarrow \tau} \simeq \frac{1}{2} P_{\mu \rightarrow e}$$

and

$$\phi(\nu_\mu) \simeq 2\phi(\nu_e)$$

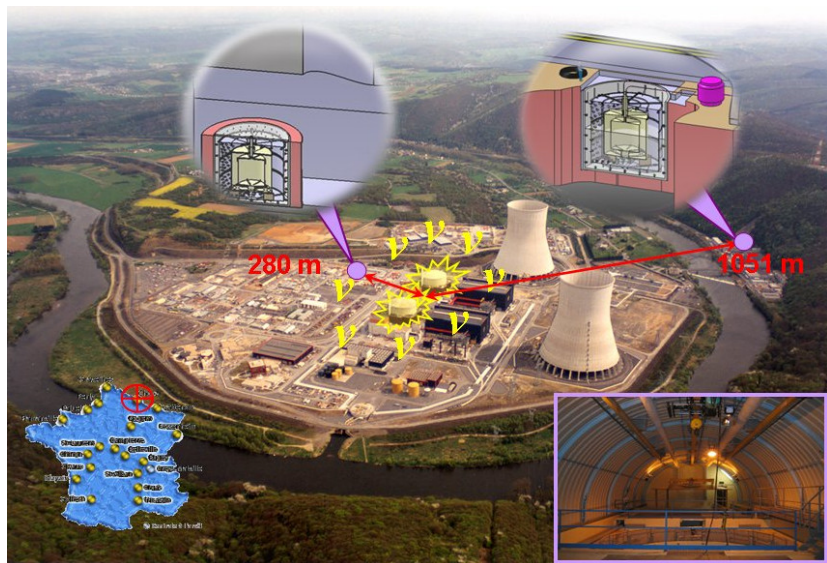
- ▶  $\nu_e \leftrightarrow \nu_\mu, \nu_\tau$  oscillations proportional to  $\sin^2 2\theta_{12}$  cancel out



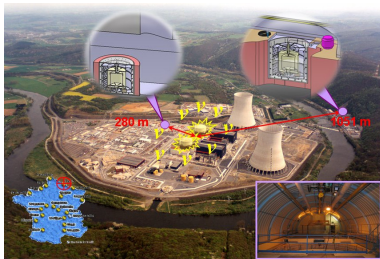
# Solar neutrinos: $\theta_{12}$ and $\Delta m_{21}^2$

see exercises

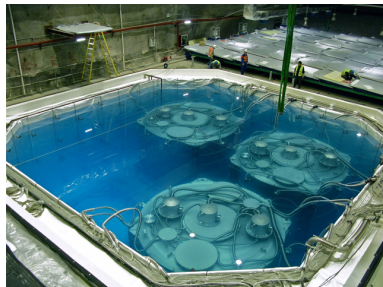
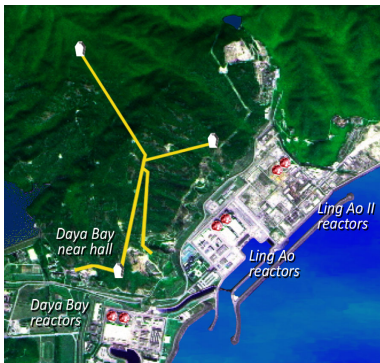
# Reactor experiments



# Reactor experiments: $\theta_{13}$

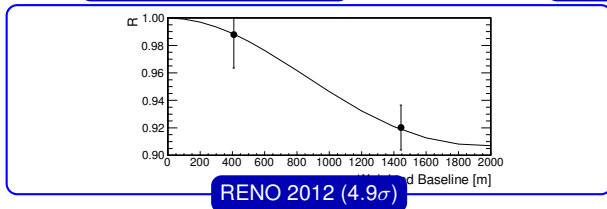
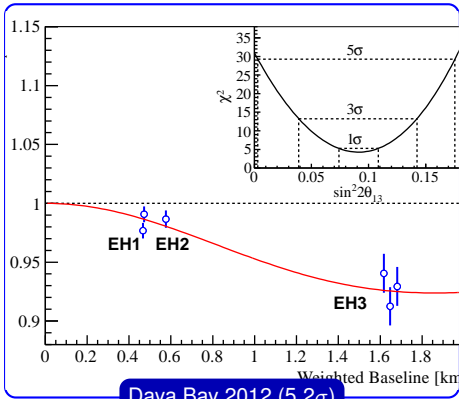
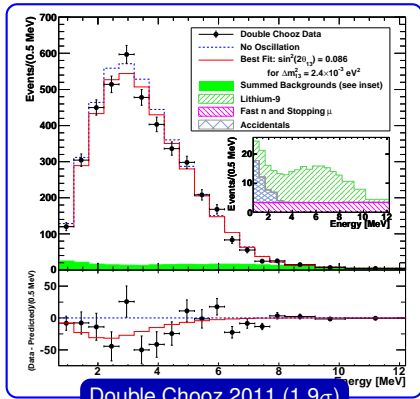


- Use  $\bar{\nu}_e$  from nuclear reactor (Peak energy  $\sim 4$  MeV)
- Near detector to measure unoscillated flux and spectrum (reduction of systematic uncertainties)
- Far detector to measure oscillated flux and spectrum

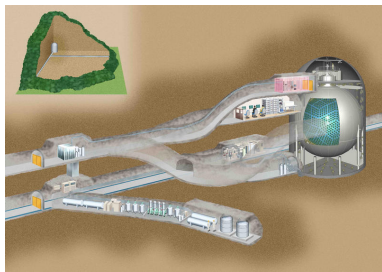
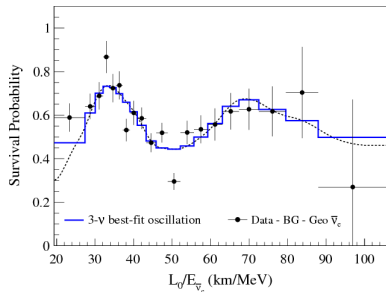
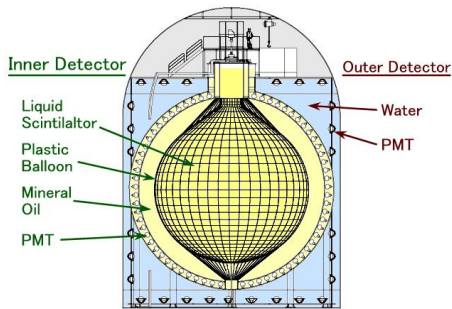




# Reactor experiments: $\theta_{13}$

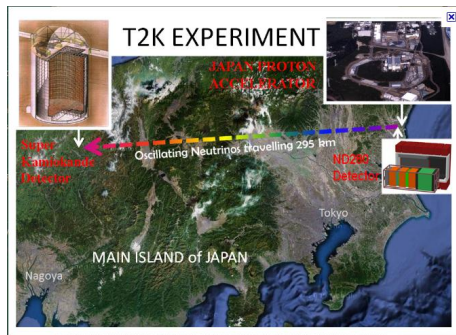
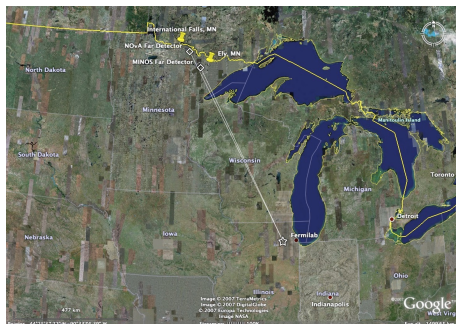


# KamLAND reactor experiment: $\theta_{12}$ and $\Delta m_{21}^2$



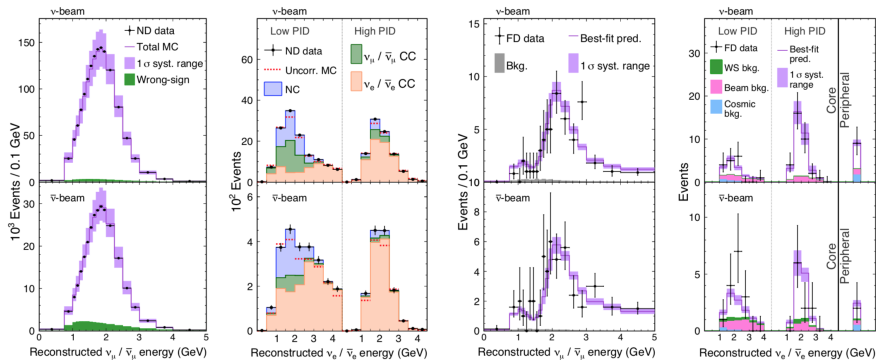
- $\bar{\nu}_e$  from Japanese nuclear reactors
- Average baseline  $\sim 180$  km.

# Accelerator experiments



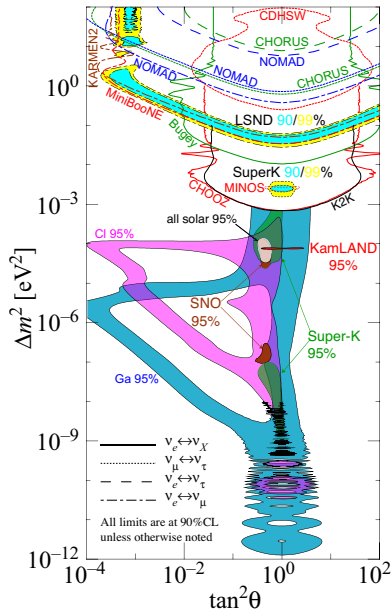
- Measure  $\bar{\nu}_{\mu}$  disappearance and  $\bar{\nu}_{e}$  appearance in a  $\bar{\nu}_{\mu}$  beam

# $\theta_{23}$ , $|\Delta m_{31}^2|$ and $\theta_{13}$ from $\text{NO}\nu\text{A}$

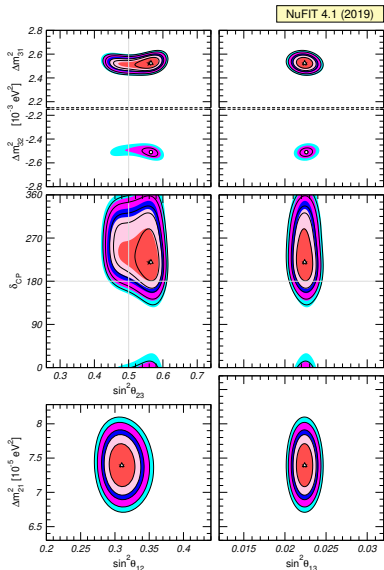


- Clear evidence for  $\nu_e$  appearance
- Confirms  $\theta_{13} \neq 0$

# Global status of neutrino oscillations



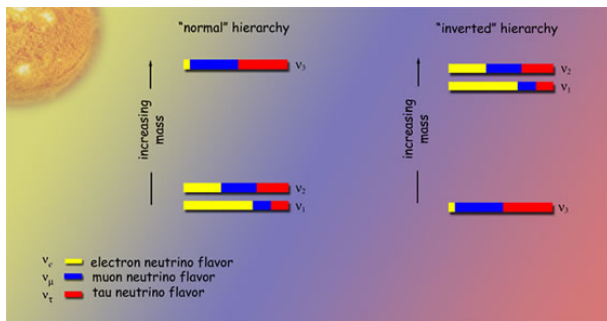
<http://hitoshi.berkeley.edu/neutrino>



<http://www.nu-fit.org>

# Future accelerator experiments: $\text{sgn}(\Delta m_{32}^2)$

Two possible neutrino mass hierarchies:



- Distinguishable most easily by exploiting matter effects:

$$\sin 2\theta_{\text{eff}} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + \left(\cos 2\theta - 2EV/\Delta m^2\right)^2}}$$

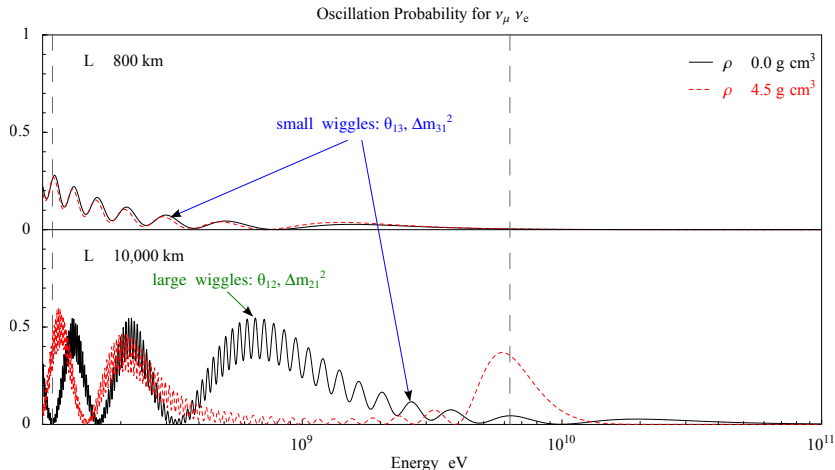
$\Delta m^2 > 0$ : Resonance for  $\nu$ ;  $\Delta m^2 < 0$ : Resonance for  $\bar{\nu}$

- Note:  $\text{sgn}(\Delta m_{21}^2)$  known from matter effects in solar neutrino oscillations

# Future accelerator experiments: $\text{sgn}(\Delta m_{32}^2)$

Idea:

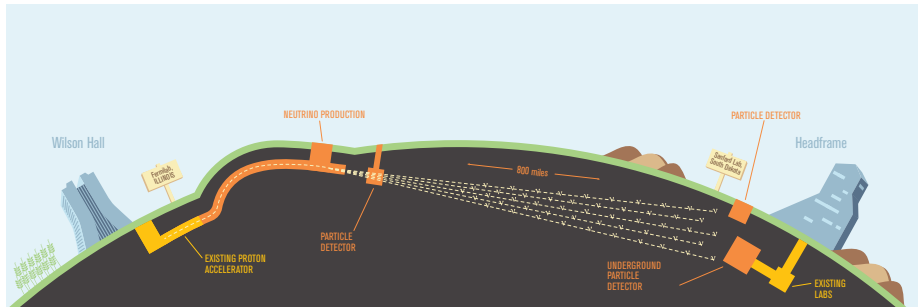
- Accelerator experiment with very long baseline ( $\gtrsim 500$  km)
- Look for resonantly enhanced  $\nu_\mu \rightarrow \nu_e$  oscillations



# Future accelerator experiments: $\text{sgn}(\Delta m_{32}^2)$

Idea:

- Accelerator experiment with very long baseline ( $\gtrsim 500$  km)
- Look for resonantly enhanced  $\nu_\mu \rightarrow \nu_e$  oscillations



DUNE



# CP violation in the neutrino sector

Remember: Leptonic mixing matrix has one complex phase, which flips sign under a  $CP$ -transformation

$$\begin{aligned} P_{\mu \rightarrow e} &\simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1+A)\Delta]}{(1+A)^2} \\ &- \alpha \sin 2\theta_{13} \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin A\Delta}{A} \frac{\sin[(1+A)\Delta]}{1+A} \\ &+ \alpha \sin 2\theta_{13} \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin A\Delta}{A} \frac{\sin[(1+A)\Delta]}{1+A} \\ &+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2} \end{aligned}$$

with

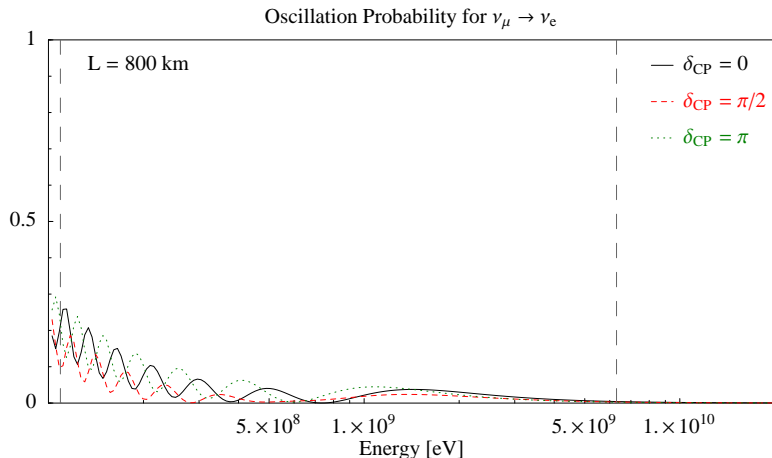
$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2,$$

$$\Delta = \Delta m_{31}^2 L / 4E,$$

$$A = 2\sqrt{2}G_F n_e E / \Delta m_{31}^2$$

# CP violation in the neutrino sector

**Remember:** Leptonic mixing matrix has **one complex phase**, which flips sign under a  $CP$ -transformation



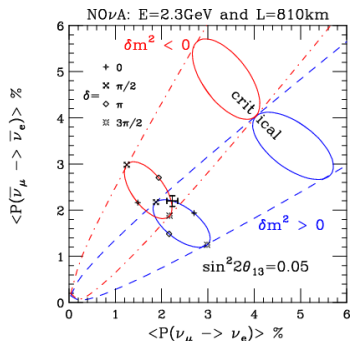
# CP violation in the neutrino sector

**Remember:** Leptonic mixing matrix has **one complex phase**, which flips sign under a  $CP$ -transformation

**Strategy:** Precision measurement of  $\nu_\mu \leftrightarrow \nu_e$  oscillations

**Main challenge:** Disentangling effect of  $\delta_{CP}$  from

- CP violation due to matter effects
- Uncertainties in other oscillation parameters



Stephen Parke 0807.3311