Neutrino oscillation experiments

Joachim Kopp, CERN

July 2019

Outline

1. Neutrino sources
2. Neutrino detector technologies
3. Measuring neutrino oscillations

Natural neutrino sources

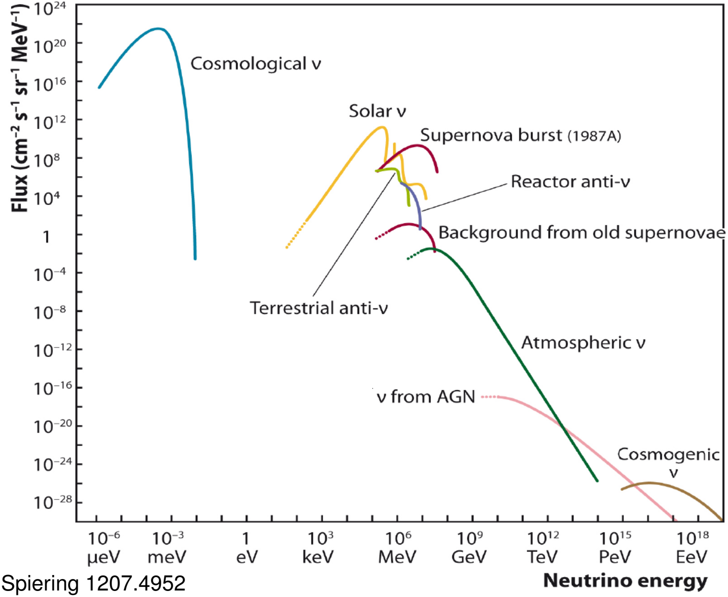
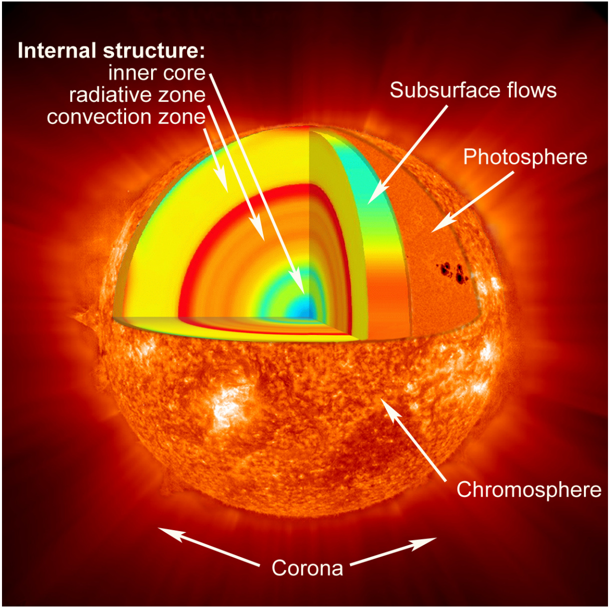
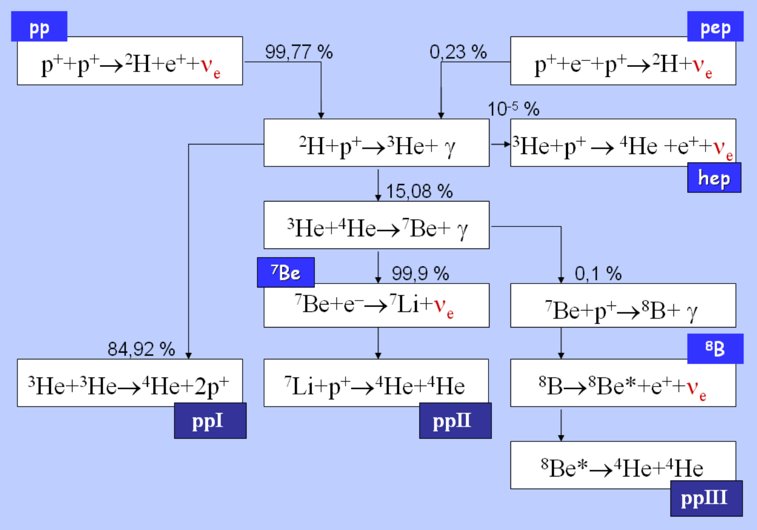


Image: C. Spiering 1207.4952

Solar neutrino production



Solar neutrino production



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

10^{-5} %

${}^2H + p^+ \rightarrow {}^3He + \gamma$

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

${}^7Be$

99,9 %

0,1 %

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p^+ \rightarrow {}^8B + \gamma$

${}^8B$

84,92 %

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

ppIII

Image: Wikimedia Commons

Solar neutrino properties

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

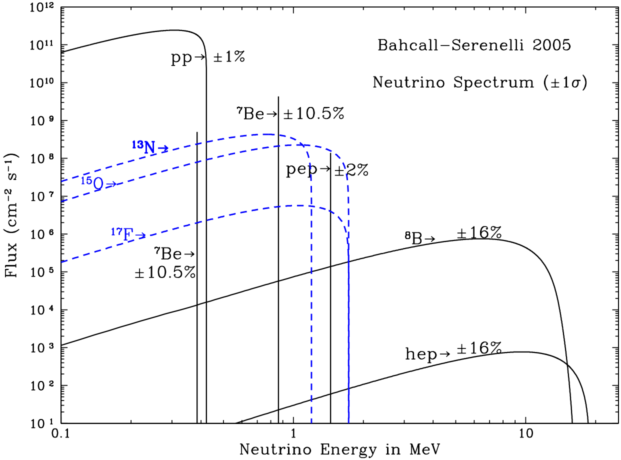
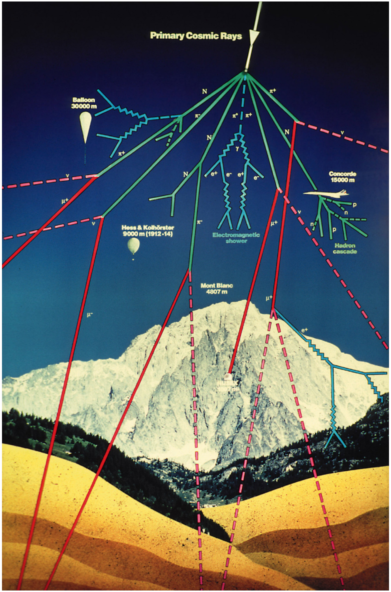
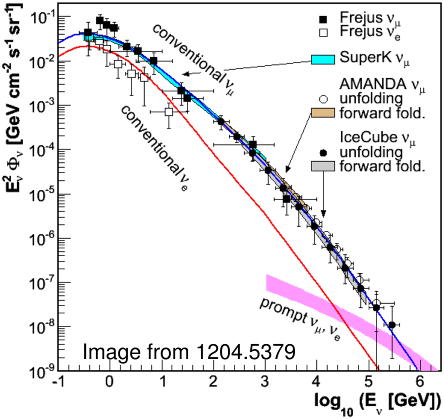


Image: John Bahcall

Atmospheric neutrinos

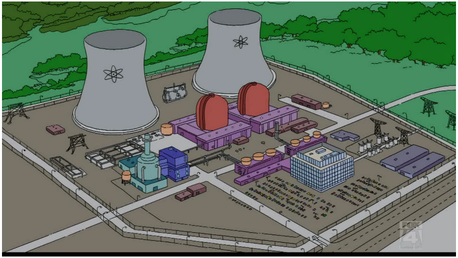


- Energy spectrum:



- Observable at $E \gtrsim$ few $\times$ 100 MeV
  (below: cross sections too low)
- Flavor composition
  $\overset{(-)}{\nu}_e : \overset{(-)}{\nu}_\mu : \overset{(-)}{\nu}_\tau \sim 1 : 2 : 0$

Nuclear reactors



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

$$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$

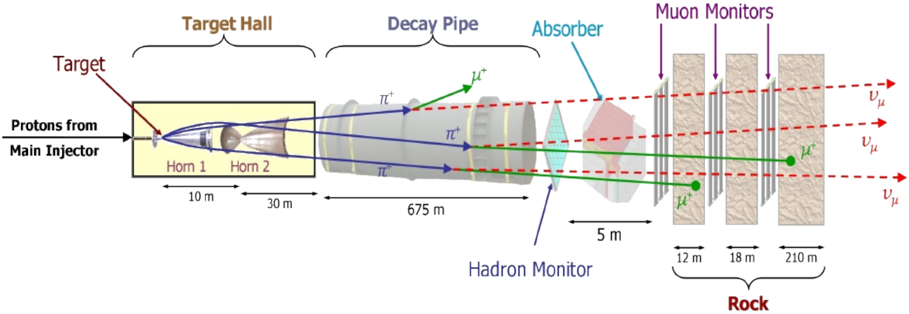
- Typical flux @ 100 m:

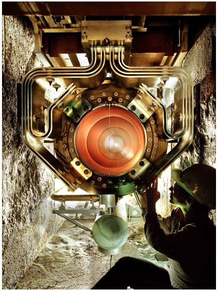
$$10^{15}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1} = 1\ \mathrm{kW\,m}^{-2}$$

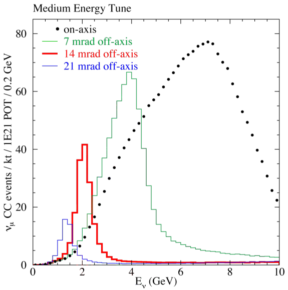
- Neutrino energy: $\lesssim$ 10 MeV
- First-ever detection of neutrinos (Reines & Cowan, 1956)

Fred Reines and Clyde Cowan at the control center of the Hanford experiment (1953)

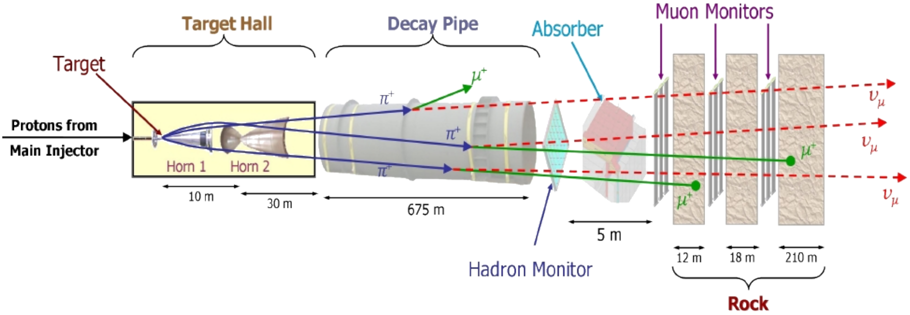
Accelerator neutrinos





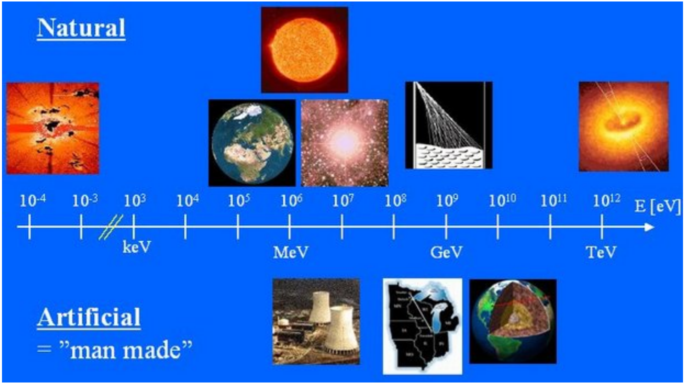


Accelerator neutrinos



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

Neutrino source — Summary



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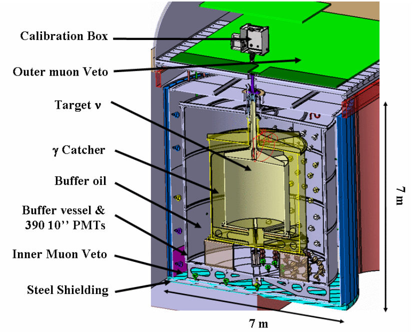
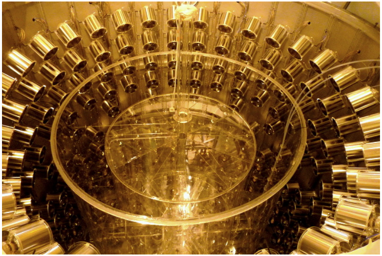
Liquid scintillator detectors





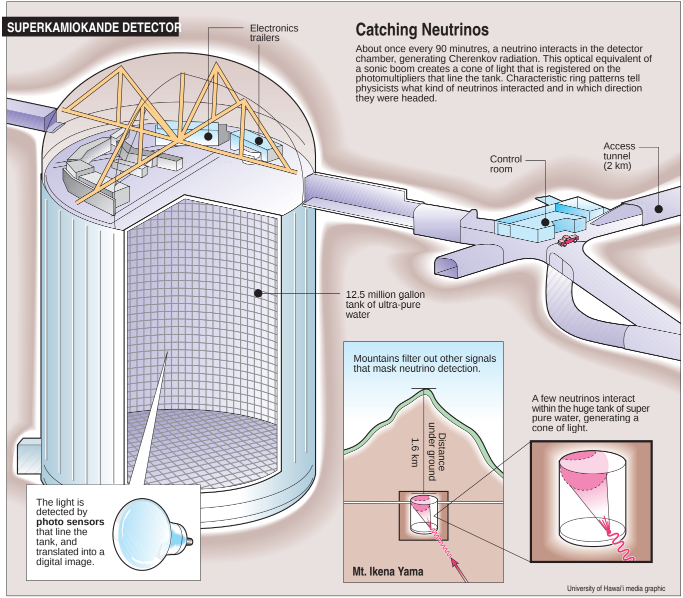
Example: Double Chooz

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

$$\bar{\nu}_e + p \to n + e^+$$

  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



Catching Neutrinos

About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

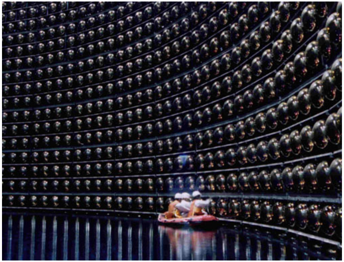
Mountains filter out other signals that mask neutrino detection.

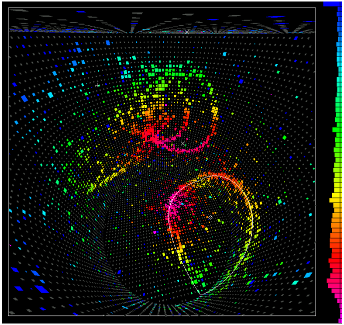
A few neutrinos interact within the huge tank of super pure water, generating a cone of light.

The light is detected by **photo sensors** that line the tank, and translated into a digital image.

University of Hawai'i media graphic

Super-Kamiokande



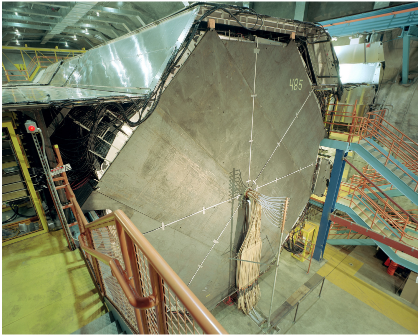


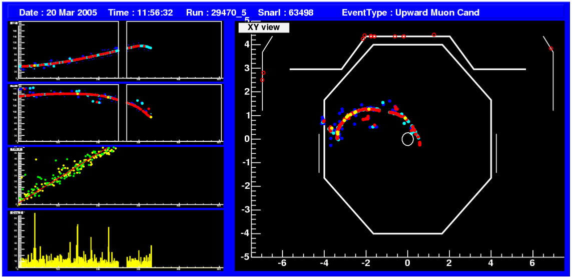
- Detection principle:
  - Observe Čerenkov light from high-*E* secondary particles in

$$\nu + N \to N' + \ell$$

- Sensitive to $E_\nu \gtrsim$ few10 MeV
- Huge targets feasible (Super-K: 22.5 kt)
- Only particles above Čerenkov threshold visible
  - Event reconstruction more challenging

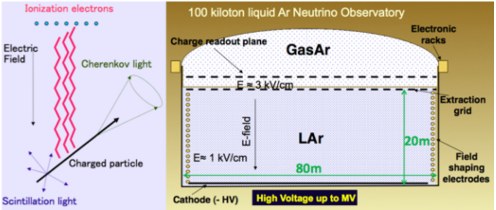
Magnetized iron detectors



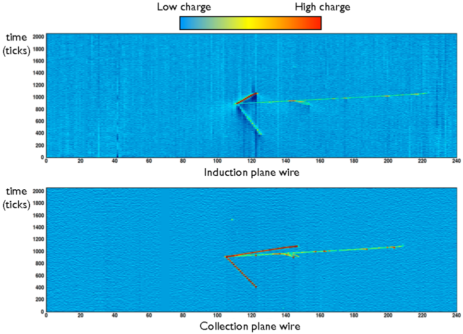


- Interleaved layers of iron (neutrino target) and plastic scintillator (tracking)
- Magnetizeable → distinguish ν and $\bar{\nu}$
- Sensitive to $E_\nu \gtrsim$ GeV
- Limited event reconstruction:
  - Hadrons, electrons: Localized shower
  - Muons: Long track

Liquid Argon Detectors



- Very good event reconstruction capabilities
- Low threshold ∼ 10 MeV
- Works at the 600 ton level (ICARUS), scalability to bigger sizes not proven



Outline

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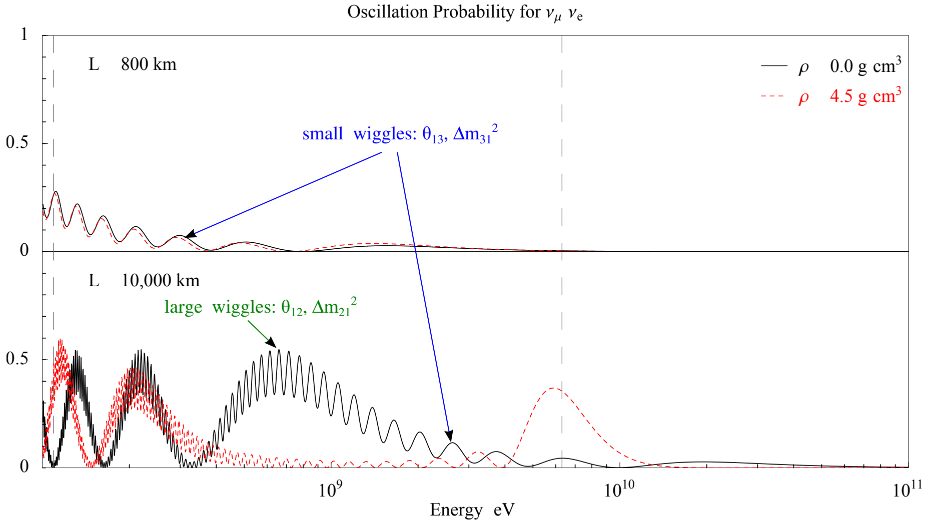
The challenge

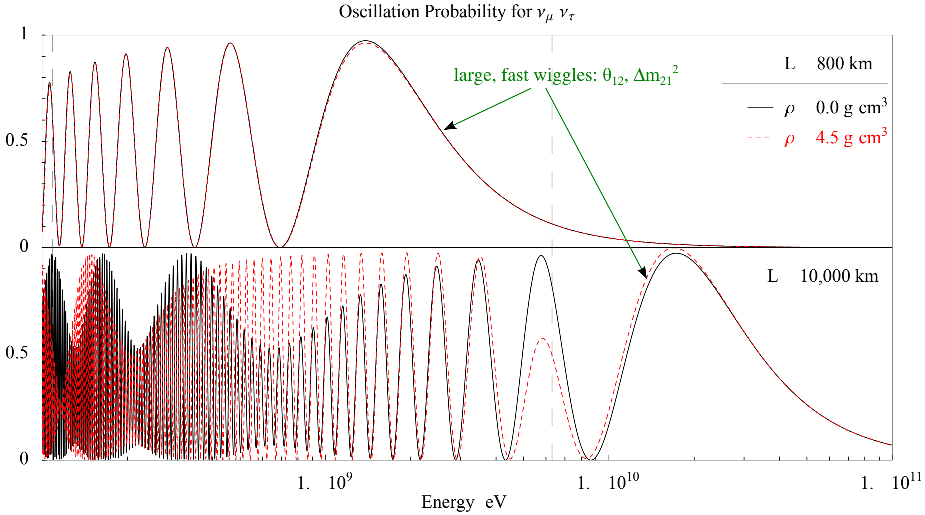
Six parameters to measure:

$$\theta_{23},\ \Delta m^2_{31},$$
$$\theta_{12},\ \Delta m^2_{21},$$
$$\theta_{13},$$
$$\delta_{CP}$$

Oscillation probability $P_{\mu\to e}$



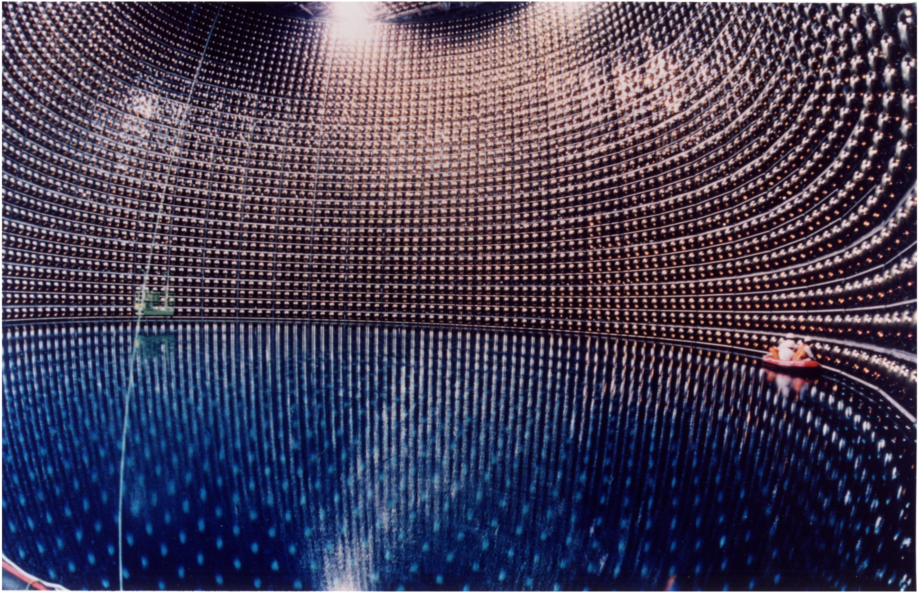
Oscillation probability $P_{\mu\to\tau}$



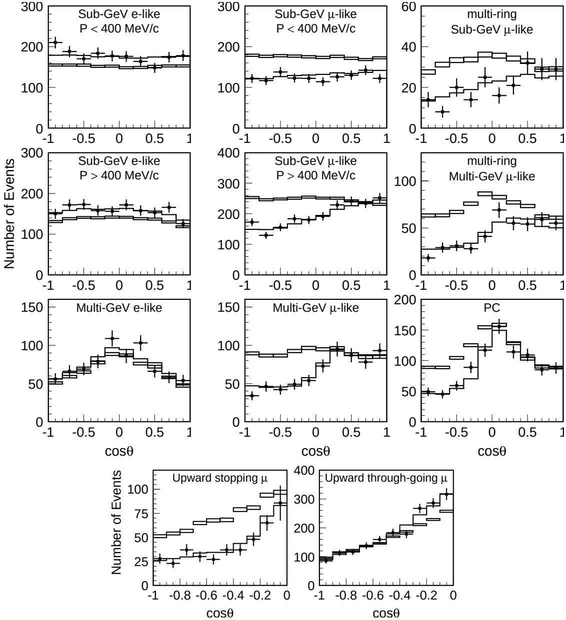
Strategy

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

The beginnings: Super-Kamiokande



The beginnings: Super-Kamiokande (1998)



- Look for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

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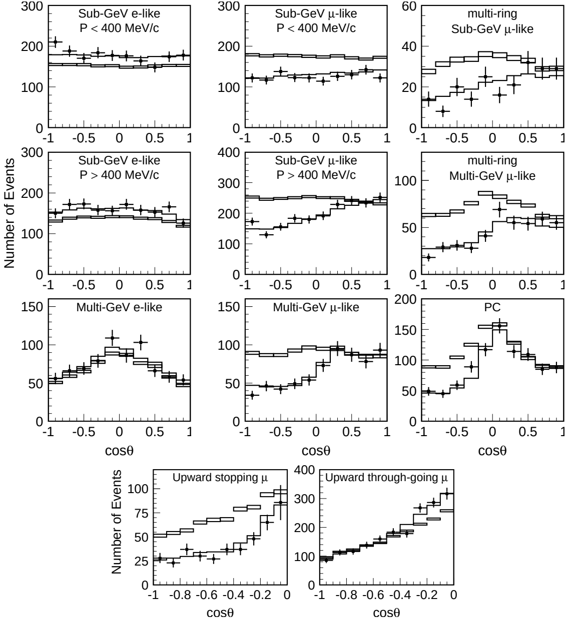

- Look for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$
- Flavor-ID from shape of Čerenkov ring

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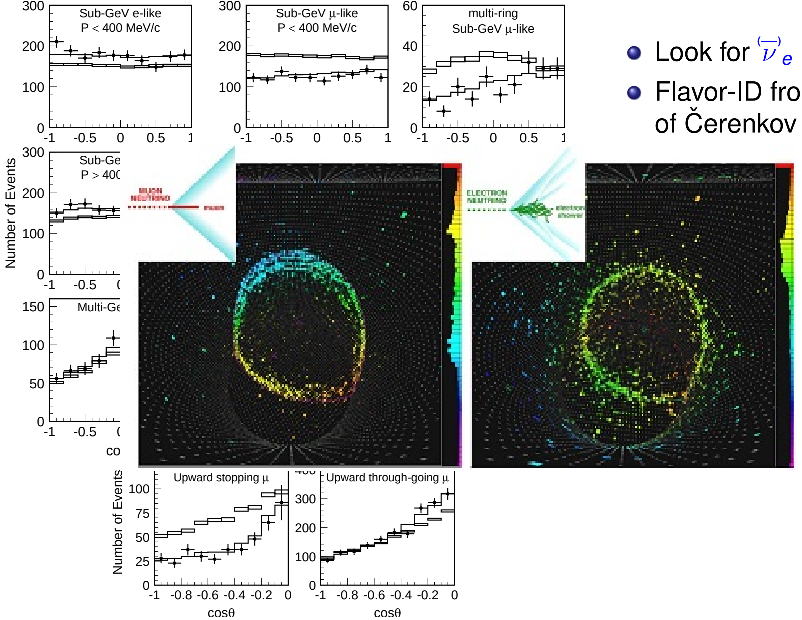

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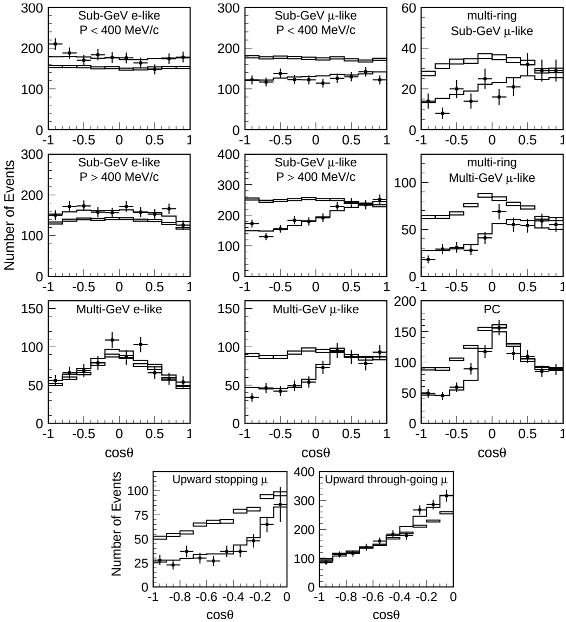
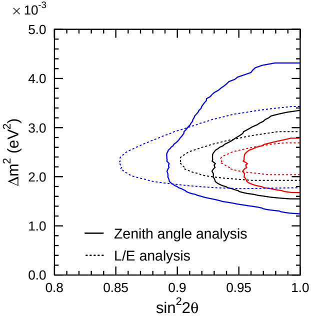


- Look for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$
- Flavor-ID from shape of Čerenkov ring
- Observation
  Lack of upward going $\overset{(-)}{\nu}_\mu$

Super-K two-flavor fit: θ_{23} and $|\Delta m^2_{31}|$



Why does a two-flavor fit work?

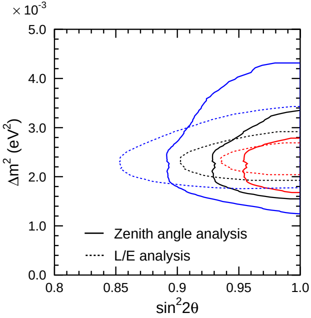
$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & 0 & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

We know today:

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

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \to \begin{pmatrix} \nu_1' \\ \nu_2' \\ \nu_3' \end{pmatrix} \equiv \begin{pmatrix} c_{12} & -s_{12} & \\ s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Super-K two-flavor fit: θ_{23} and $|\Delta m^2_{31}|$



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We know today:

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

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

    and

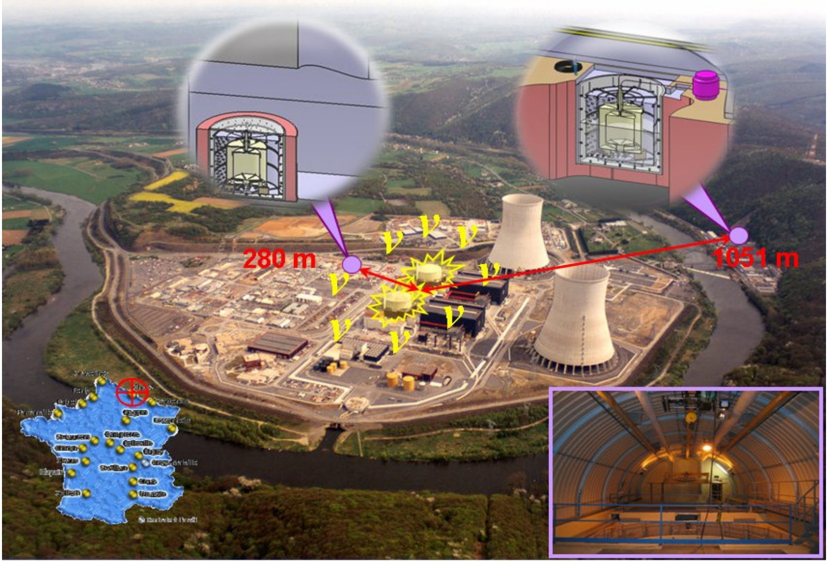
    $$\phi(\nu_\mu) \simeq 2\phi(\nu_e)$$

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

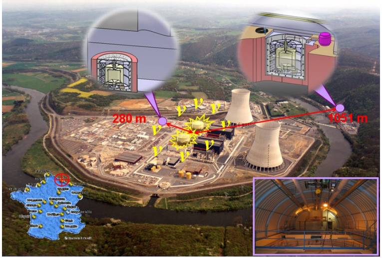
Solar neutrinos: θ_{12} and Δm^2_{21}

see exercises

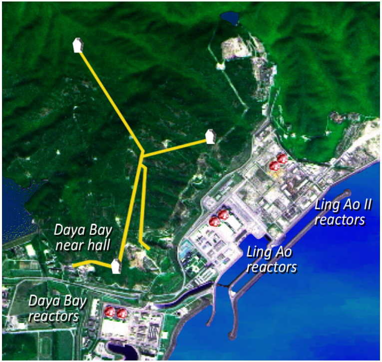
Reactor experiments

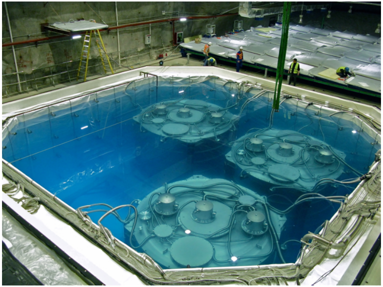


Reactor experiments: θ_{13}

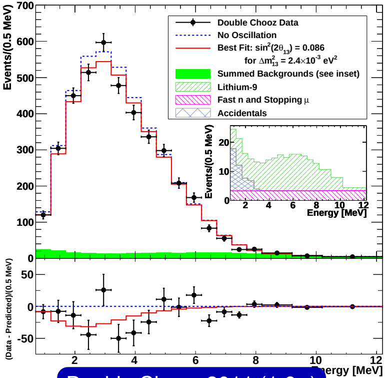


- Use $\bar{\nu}_e$ from nuclear reactor (Peak energy $\sim$ 4 MeV)
- Near detector to measure unoscillated flux and spectrum (reduction of systematic uncertainties)
- Far detector to measure oscillated flux and spectrum

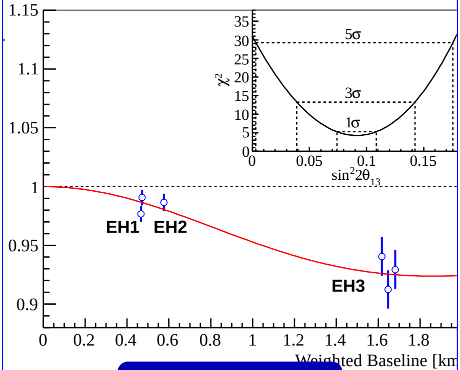




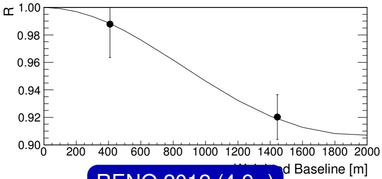
Reactor experiments: θ_{13}



Double Chooz 2011 (1.9σ)



Daya Bay 2012 (5.2σ)



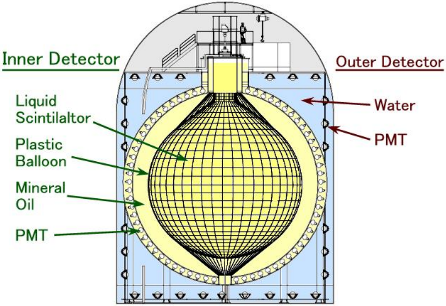
RENO 2012 (4.9σ)

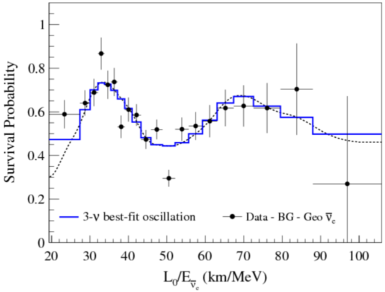
$$\sin^2 2\theta_{13} = 0.0876 \pm 0.0026$$

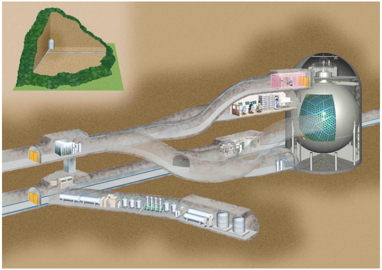
Gonzalez-Garcia et al. 1209.3023

Global best fit 2019 ($\sim 9\sigma$)

KamLAND reactor experiment: θ_{12} and Δm^2_{21}

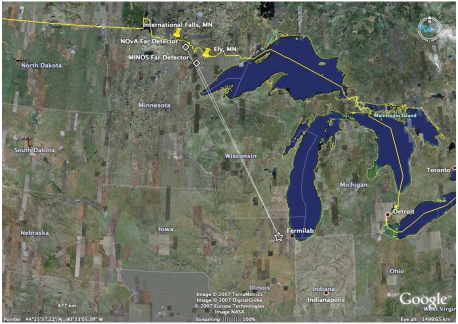


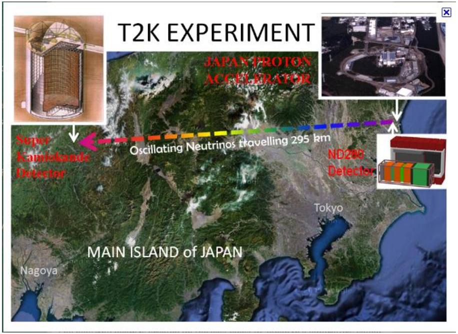




- $\bar{\nu}_e$ from Japanese nuclear reactors
- Average baseline $\sim$ 180 km.

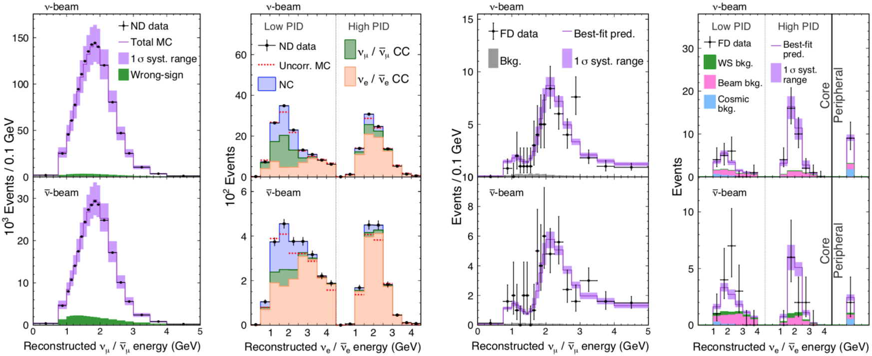
Accelerator experiments





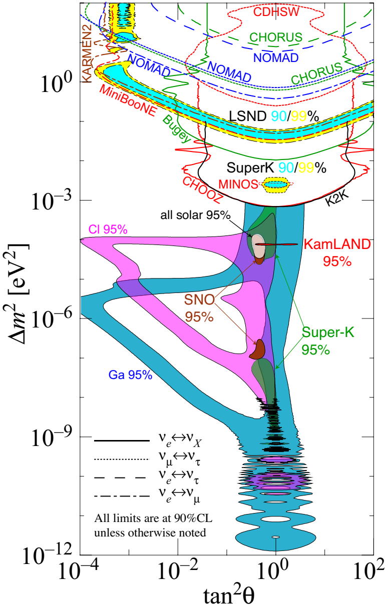
- Measure $\overset{(-)}{\nu}_\mu$ disappearance and $\overset{(-)}{\nu}_e$ appearance in a $\overset{(-)}{\nu}_\mu$ beam

θ_{23}, $|\Delta m^2_{31}|$ and θ_{13} from NOνA

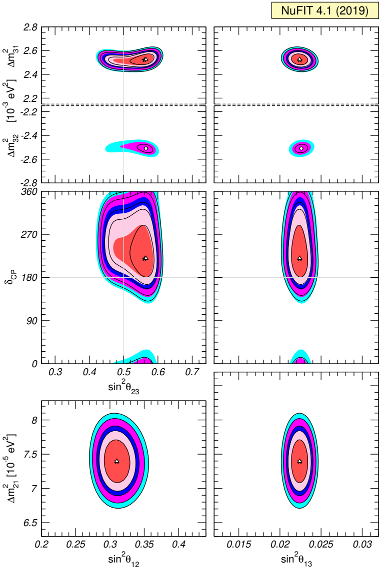


- Clear evidence for ν_e appearance
- Confirms $\theta_{13} \neq 0$

Global status of neutrino oscillations



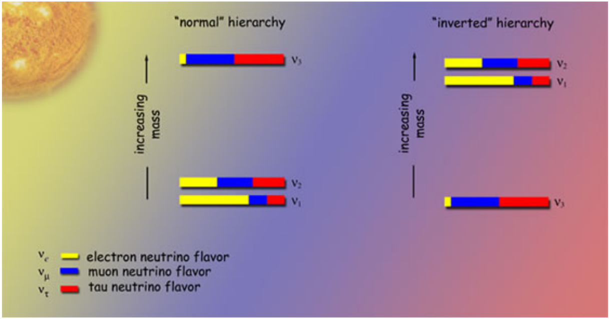
http://hitoshi.berkeley.edu/neutrino



http://www.nu-fit.org

Future accelerator experiments: $\mathrm{sgn}(\Delta m^2_{32})$

Two possible neutrino mass hierarchies:



- Distinsguishable most easily by exploiting matter effects:

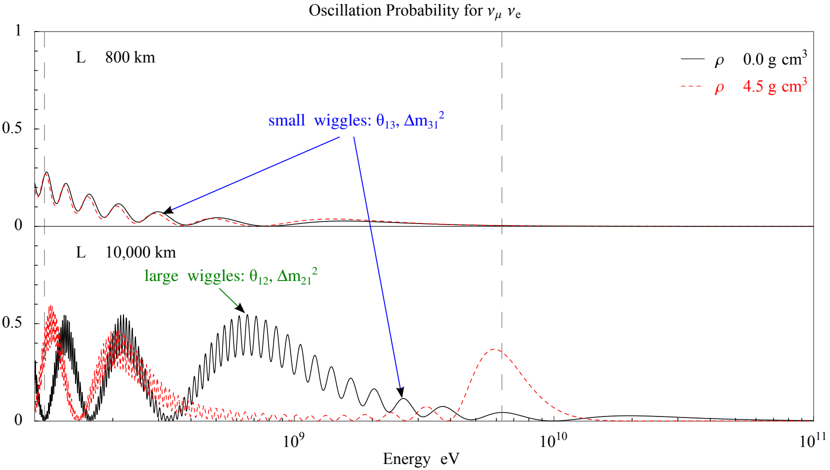
$$\sin 2\theta_{\text{eff}} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + \left(\cos 2\theta - 2EV/\Delta m^2\right)^2}}$$

  $\Delta m^2 > 0$: Resonance for ν; $\Delta m^2 < 0$: Resonance for $\bar{\nu}$
- Note: $\mathrm{sgn}(\Delta m^2_{21})$ known from matter effects in solar neutrino oscillations

Future accelerator experiments: $\mathrm{sgn}(\Delta m^2_{32})$

Idea:

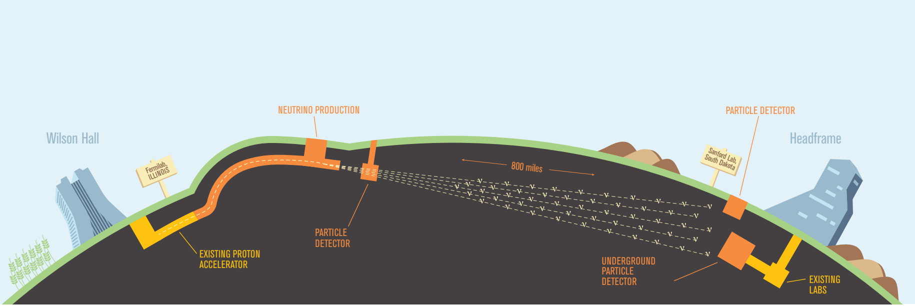
- Accelerator experiment with very long baseline ($\gtrsim 500$ km)
- Look for resonantly enhanced $\nu_\mu \to \nu_e$ oscillations



Future accelerator experiments: sgn(Δm^2_{32})

Idea:

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



DUNE

CP violation in the neutrino sector

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

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

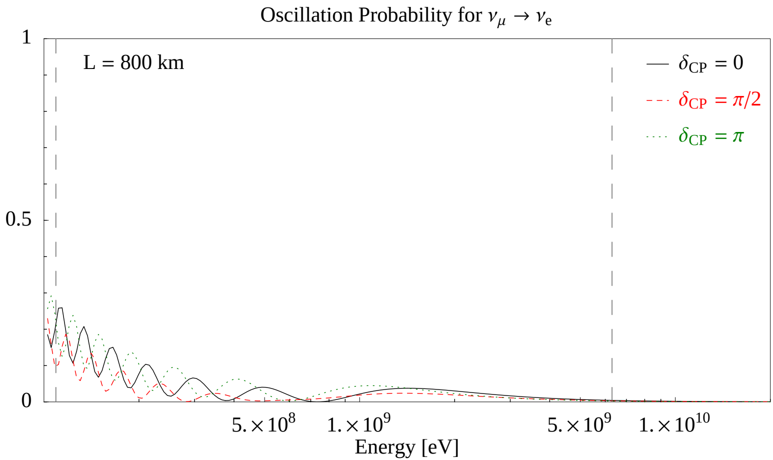
with

$$\begin{aligned}
\alpha &= \Delta m^2_{21} / \Delta m^2_{31}\,, \\
\Delta &= \Delta m^2_{31} L / 4E\,, \\
A &= 2\sqrt{2} G_F n_e E / \Delta m^2_{31}
\end{aligned}$$

Akhmedov et al. hep-ph/0402175

CP violation in the neutrino sector

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



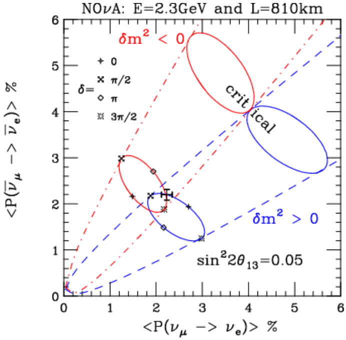
CP violation in the neutrino sector

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 δ_{CP} from

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



Stephen Parke 0807.3311