Hot topics in Neutrino Physics (and much more)

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"I have done a terrible thing, I have postulated a particle that cannot be detected" Wolfgang Ernst Pauli, 1930

Fortunately he was **WRONG** and neutrinos can be detected and thus, their **oscillations**!

"Ey! I just met you,
and this is crazy,
but what if... neutrino oscillate?
a nobel maybe?"
Bruno Pontecorvo

Question: Who proposed such idea?

Answer: Bruno **Pontecorvo** in 1957 in analogy to **Kaon** mixing $K^0 \leftrightarrow \bar{K}^0$. It actually was a revolutionary idea! The first **detection** of **neutrino** ν_e was that year!

Chronological ordered events (approximately):

- 1957 Cowan-Reines experiment - **detection of** ν_e
- 1958 Goldhaber ν **helicity exp**: only $\nu_{e,L}$ and $\bar{\nu}_{e,R}$ appear
- 1962 Lederman, Schwartz and Steinberger **discover** ν_μ
- 1962 Maki, Nakagawa, and Sakata **propose** $\nu_\mu \leftrightarrow \nu_e$
- 1967 Pontecorvo predicts a **deficit** in **solar** ν_e
- 1969 Pontecorvo and Gribov calculate the oscillation probability $(\nu_{e,L}, \nu_{\mu,L}) \leftrightarrow (\bar{\nu}_{e,LR}, \bar{\nu}_{\mu,R})$
- 1970-72 **Homesake** exp. indeed measures a **deficit** in ν_e

Solar/Atmospheric neutrinos

TOTALLY PROVED

$\nu_e \to \nu_{\mu,\tau}$ (solar)

Between 1998-2001

- **SuperKamiokande** (evidence)
- **SNO** (confirmation)

$\nu_\mu \to \nu_\tau$ (atmospheric)

Around 1998 SuperK announced the confirmation

- MACRO, **Kamiokande II** (evidence)
- **SuperKamiokande** (confirmation)
- K2K (further measurements)

Accelerator/Reactor neutrino experiments

RECENTLY PROVED

$\nu_\mu \rightarrow \nu_e$ (neutrino appearance)

19th of July, 2013 T2K announced confirmation with 7.5σ C.L

- **MINOS** (evidence)
- **T2K** (confirmation)
- NOνA (further measurements)

$\bar{\nu}_e \rightarrow \bar{\nu}_{\mu,\tau}$ (antineutrino disappearance)

8th of March 2012 Daya Bay announced the confirmation with 5.2σ C.L

- **KamLAND** (evidence)
- **Daya Bay** (confirmation)
- Double Chooz, RENO (further measurements)

The meaning of mixing

Question: What does define a neutrino state?

Answer: Roughly speaking:

- **Weak Eigenstates**: produced at weak vertices - Well defined **Leptonic Flavour** L_α $(\nu_e, \nu_\mu, \nu_\tau)$
- **Mass Eigenstates**: determine the propagation through space - Well defined **mass** m_i (ν_1, ν_2, ν_3)

Weak Eigenstates $\neq$ Weak Eigenstates

NOTE!

We will see that mass eigenstates in vacuum $\neq$ mass eigenstates in matter ¡!

Quantum Mechanical framework: General problem

From flavour ES to mass ES:

U **change of basis** in Hilbert space:

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}|\nu_i(t)\rangle$$

$$|\nu_i(t)\rangle = \sum_i U^\dagger_{i\alpha}|\nu_\alpha(t)\rangle$$

α: flavour ES, i: mass ES

Question: How do $|\nu_i(t)\rangle$ propagate?

Answer: **Mass** eigenstates **propagate** as usual **eigenstates of H**:

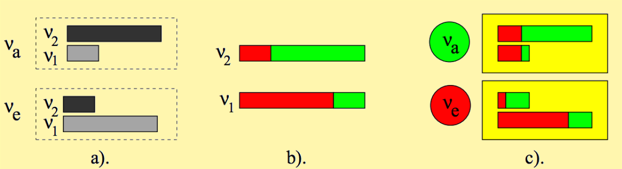
$$|\nu_i(t)\rangle = e^{-iHt}|\nu_i(0)\rangle = e^{\frac{-im_i^2}{2E}L}|\nu_i(0)\rangle$$

Oscillation paradox

Question: Where is the paradox?

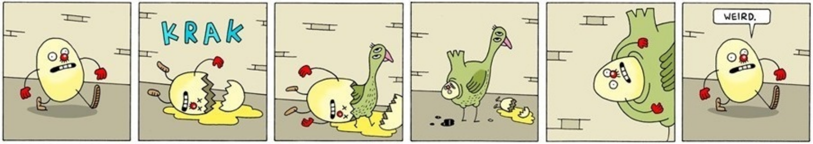
Answer: Follow theses steps to blow your mind:

- **Flavour** ES as a **superposition** of **mass** ES (a)
- **Mass** ES can be written as well as a **composition** of **flavour** ES (b)
- A **pure flavour** ES can be written as a **superposition** of **other flavours** (c)



Question: What is the solution?

Answer: **INTERFERENCE**. The ν_a carried by $\nu_1, 2$ inside ν_e must have **opposite** phase. They **interfere destructively** and give a null net contribution to the total flavour.



Conclusion

ν_e has a **latent** ν_a component not seen due to **particular phase**.
During **propagation** the phase difference changes and the **cancellation disappears**.
This leads to an **appearance** of ν_a component on a **pure** ν_e state.

Overview of vacuum oscillations

Evolution of mass ES:

- **Proportion** of $\nu_{1,2}$ given at the **production point** by θ
- $\nu_{1,2}$ **propagate independently**. Phase diff. given by $m_{1,2}$
- **Mass ES admixtures NEVER change**. No $\nu_1 \leftrightarrow \nu_2$ **transitions**
- **Flavour comp. of mass ES NEVER changes**: given by θ

In summary: image (c) is constant over all the travel

Question: Then, how do ν mix?

Answer: The **relative phase** $\Delta m^2_{ij}/2E$ creates a cons/des **interference** of the **flavour** comp. in $\nu_{i,j}$. Then the initial state is effectively **oscillating** between flavours.

Quantum Mechanical framework: 2 Generations

Question: Why is it important?

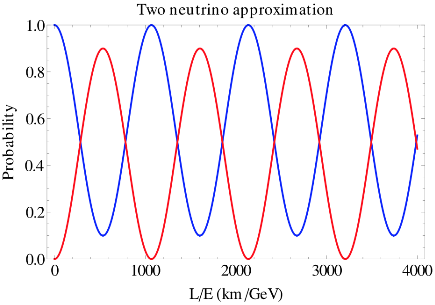
Answer: Although there are 3 families, in many experiments we effectively have important mixing among 2 families

Form of the unitary matrix U

We can describe it as general **rotation matrix** with an unknown **mixing angle** θ:

$$\begin{pmatrix} |\nu_\alpha\rangle \\ |\nu_\beta\rangle \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{U} \cdot \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix}$$

The mixing angle $\theta \neq 0$ for the oscillations to exist.



Question: What are the transition probabilities?

Answer: **Depend** on m_{12}^2 and the oscillation angle θ

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2(\Delta_{12} L)$$

$$P_{\alpha\to\alpha} = 1 - \sin^2 2\theta \sin^2(\Delta_{12} L)$$

DO NOT DEPEND ON ABS. VALUE OF m_i

NOTE!

Explicit calculations at the Back-Up slides

Quantum Mechanical framework: 3 Generations

Question: What are the main differences?

Answer: 3 mixtures among 12, 13 and 23 with their respective mixing angles.

PMNS Matrix

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

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

θ_{ij} are the **mix. angles**

δ **CP Violation phase**

α_1, α_2 **Majorana Phase**

$$\cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{bmatrix}$$

Generalised transition probability

Transition probability from pure α to β:

$$P_{\alpha\to\beta} = |\langle\nu_\alpha|\nu_\beta\rangle|^2 = |\sum_i U^\dagger_{\alpha i} U_{\beta i}|^2$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathfrak{Re}\{U^\dagger_{\alpha i} U_{\beta i} U_{\alpha j} U^\dagger_{\beta j}\} \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathfrak{Im}\{U^\dagger_{\alpha i} U_{\beta i} U_{\alpha j} U^\dagger_{\beta j}\} \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

NOTE!

CP violation term: $2\sum_{i>j} \mathfrak{Im}\{U^\dagger_{\alpha i} U_{\beta i} U_{\alpha j} U^\dagger_{\beta j}\} \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$

Fermion Mass in SM

Question: How do they get mass?

Answer: **Fundamental rep.** of fermions

$$\psi = \psi_R + \psi_L$$

$$\mathcal{L}_D = m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

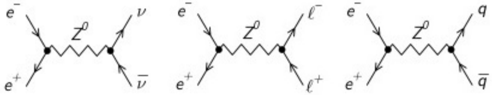
- Mass generated by **helicity** swap!
- RH-LH have different **SU(2), SU(3) rep.** and Y: no flip!

Solution within SM

- RH-LH **Yukawa coupling** with Higgs: mass
- Weak Int is LH: **Neutrinos** must be **massless**
- **RH** neutrinos **excluded**!

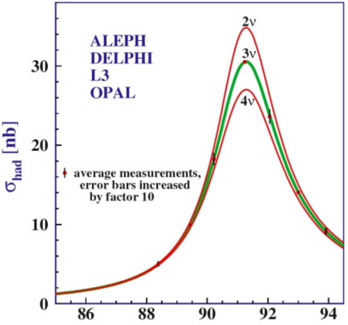
LEP Results about number of neutrino families

Z decays into hadrons and those pair of fermions:



Branching Ratio to hadrons depends on $f\bar{f}$:

Measured **decay width** $\Gamma_h = 2.4952 \pm 0.0023\text{GeV} \leftrightarrow 2.9840 \pm 0.0082$ **families** of neutrinos.
CLOSE ENOUGH !!



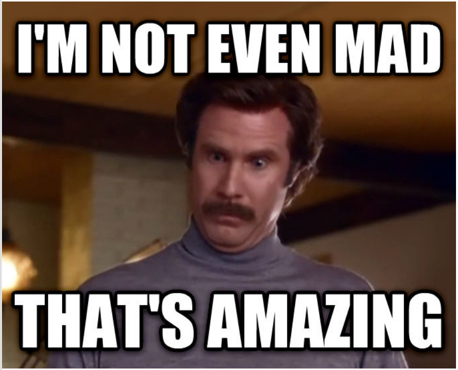
BUT neutrinos DO have mass... And seems very small!

Question: Is this a problem?

Answer: Not at all!

Far to be overwhelmed, theoretical physicist **LOVE** to create new exotic theories to adjust all kind of phenomena:

- Nw renorm. terms in $\mathcal{L}_H$
- SUSY GUT
- Bottom-Up model
- **Seesaw type I**
- Seesaw type II (strikes back)
- Seesaw type III (return of)



A possible solution: Seesaw Mechanism

Force ν_R to exist

We have to add the **Dirac Mass**:

$$\mathcal{L}_D = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$

We **can't** only add this term

Add Majorana Mass term

If neutrino is **Majorana**:

- $\nu_R^c = \nu_L$ (**transform** equivalently under **Lorentz** t.)
- $\bar{\nu} = \nu$ **own antiparticle**
- **Breaks** $U(1)$ **symmetry** (need to be neutral)
- **Violates L.N** conservation $\Delta L = 2$

$$\mathcal{L}_M = m_R \bar{\nu}_R^c \nu_R + m_L \bar{\nu}_L^c \nu_L + h.c$$

Type I SeeSaw Mechanism

General Mass Lagrangian

Combining both Dirac and Majorana mass terms ($m_L = 0$ Gauge Inv.):

$$\mathcal{L}_T = (\nu_L^c \nu_R) \cdot \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \cdot \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}$$

Obviously $\nu_{L,R}$ **are not mass ES**. We have to **diagonalise**.

Results: for $m_D \ll m_R$: explain smallness of m_ν

$$m_1 \approx \frac{m_D^2}{m_R} \leftrightarrow m_2 \approx m_R \longrightarrow \text{lower } m_1, \text{ higher } m_2$$

Assuming $m_D \sim$ MeV (like other fermions), and $m_1 \sim$ eV we obtain that **sterile** neutrinos $m_2 \sim$ TeV

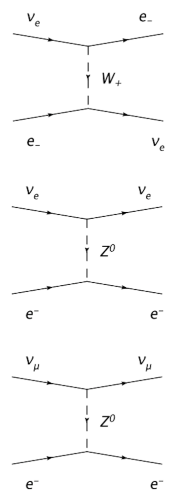
Mikheyev–Smirnov–Wolfenstein effect

Question: What is missing?

Answer: **N.O.** are modified by **MATTER** effects. Propagation through matter $\neq$ propagation through vacuum.

Flavours interact in different ways with matter

- **Stable matter** is composed by e. Not τ, μ.
- ν_e **interacts** with e via **CC** and **NC**
- N_e produce: **CC coh. forward scattering** of ν_e
- $\nu_{\mu,\tau}$ **interact** with e only via **NC**
- Different interactions: **"flavour-dispersion"**



2 generations approach

Oscillations in sun can be studied under this approach

Since **CC** ν_e interactions are **dominant**,ν_τ and ν_μ are usually simplified in **one sole generation**. We add an interacting time ind. potential to the **Hamiltonian**:

$$V = \begin{pmatrix} V_\alpha & 0 \\ 0 & V_\beta \end{pmatrix} = \begin{pmatrix} \delta V/2 & 0 \\ 0 & -\delta V/2 \end{pmatrix} + (V_\beta + V_\alpha)/2$$

Where $V_\alpha - V_\beta = \delta V = \sqrt{2} G_F N_e$. The term $(V_\beta + V_\alpha)/2$ only adds a **global phase**, so we can **exclude** it.

The new hamiltonian in the flavour basis is:

$$H'^{eff} = \underbrace{\Delta_{12} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}}_{H'_0} + \begin{pmatrix} \delta V/2 & 0 \\ 0 & -\delta V/2 \end{pmatrix}$$

$$= \Delta_{12}^{eff} \begin{pmatrix} -\cos 2\theta^{eff} & \sin 2\theta^{eff} \\ \sin 2\theta^{eff} & \cos 2\theta^{eff} \end{pmatrix}$$

NOTE!

Although it is not evident in the **flavour basis**, H_0^{eff} is not diagonal in the **vacuum mass basis** $\nu_{1,2}$. This means that the **mass ES in vacuum** are not ES of the Hamiltonian in **matter**.

Results of Diagonalisation

Effective Mass Eigenvalues

$$\frac{m_2^{2eff} - m_1^{2eff}}{2E} \Delta_{12}^{eff} = \sqrt{(\Delta_{12}\cos 2\theta_{12} - \delta V)^2 + \Delta_{12}^2 \sin^2 2\theta_{12}}$$

Effective Oscillation Angle

$$\sin^2 2\theta_{12}^{eff} = \frac{\sin 2\theta_{12}}{\sqrt{(\cos^2 2\theta_{12} - \delta V/\Delta_{12})^2 + \sin^2 2\theta_{12}}}$$

NOTE!

Explicit calculations in the back-up slides

Interesting Conclusions: Evolution of propagating ES

Evolution of the effective mass ES:

- **Flavour** composition of the **effective** mass ES **do not** change
- **Admixtures** of the mass ES in a given neutrino state **do not** change
- That is, $\nu_1^{eff} \not\leftrightarrow \nu_2^{eff}$
- **Oscillation** given by Δ_{12}^{eff} **interference**

Question: Is it exactly the same as vacuum oscillations?

Answer: Very similar dynamics, except for...

- Δ_{12}^{eff} and $\sin^2 2\theta_{12}^{eff}$ are **sensitive** to Δ_{12} sign...
- **Resonance** phenomena

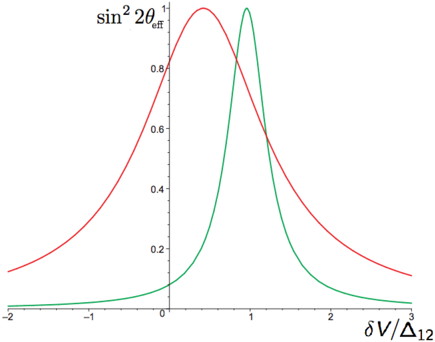
Conclusions: Resonance Enhancement of Oscillations

red: $\sin^2 2\theta_{12} = 0.8$
green: $\sin^2 2\theta_{12} = 0.3$

Transition Probabilities

Just change $\theta \to \theta^{eff}$:

$$P_{e\to\mu} = \sin^2 2\theta_{12}^{eff} \sin^2(\Delta_{12}^{eff} L)$$
$$P_{e\to e} = 1 - \sin^2 2\theta_{12}^{eff} \sin^2(\Delta_{12}^{eff} L)$$



Mixing RESONANCE:

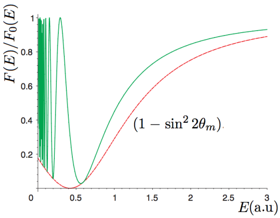
$$\frac{\delta V}{\Delta_{12}} = \cos 2\theta_{12}$$

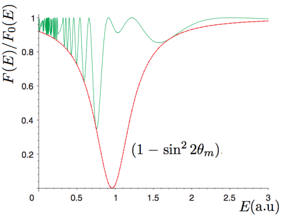
Conclusions: Resonance Enhancement of Oscillations

Question: Why is useful to know where is a resonance?

Answer: We can put the **resonance** in terms of N_e and E:

$$N_e^R = \frac{\Delta m_{12}^2}{\sqrt{2} G_F E} \cos 2\theta \leftrightarrow E^R = \frac{\Delta m_{12}^2}{\sqrt{2} G_F N_e} \cos 2\theta$$





Left: length L, Right: length $10L$

- The **smaller** mixing, the **narrower** the res. layer
- For $E \gg E^R$ oscillation is **suppressed**
- For **high vacuum** mixing, **low matter** mixing

Non-uniform medium: Adiabatic Conversion

Question: What if N_e is not constant?

Answer: Density **changes** on the way of neutrinos and $H = H(t)$:

- $\nu_{1,2}^{eff}$ **are not** longer propagation ES. $\nu_1^{eff} \leftrightarrow \nu_2^{eff}$ may occur
- Mixing angle **changes** throughout the propagation $\theta_{12}^{eff} = \theta_{12}^{eff}(t)$

The time evolution of the system takes the form

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |\nu_{1m}\rangle^{eff} \\ |\nu_{2m}\rangle^{eff} \end{pmatrix} = \begin{pmatrix} \Delta_{1m}^{eff} & i\dot{\theta}_{12m}^{eff} \\ i\dot{\theta}_{12m}^{eff} & \Delta_{2m}^{eff} \end{pmatrix} \cdot \begin{pmatrix} |\nu_{1m}\rangle^{eff} \\ |\nu_{2m}\rangle^{eff} \end{pmatrix}$$

If $|\dot{\theta}_{12m}^{eff}| \propto \dot{N}_e \ll \Delta_{1,2m}$ **adiabaticity** is fulfilled: $\nu_{1m}^{eff} \nleftrightarrow \nu_{2m}^{eff}$

Adiabatic Evolution: The Sun

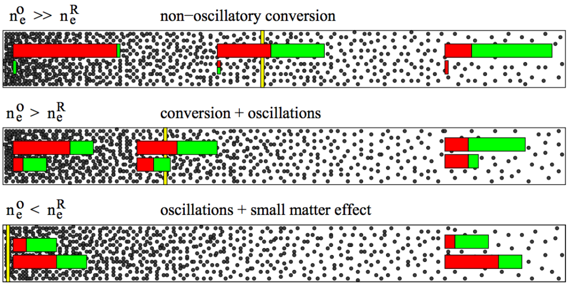
Question: How the states evolve in the adiabatic approx.?

Answer:

- Hamiltonian is approx. **diagonal**
- The **flavour** composition of the ES change according to $\theta_{12m}^{eff}(t)$
- The **admixtures** of the ES in a propagating neutrino state do not change, set at **production point** $\theta_{12m}^{eff}(0)$
- The **phase** difference **increases**: $\Delta_{12m}^{eff}(t)$

NOTE!

IMPORTANT: Actual structure of solar neutrino oscillations!
Sun's density decreases adiabatically



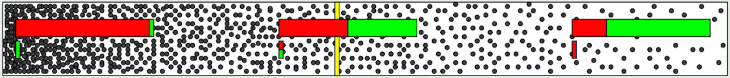
Legend, more or less

- Yellow bar: **resonance** layer
- **Flavour** composition of ES in each phase
- **Admixtures** of ES set at the start

NOTE!

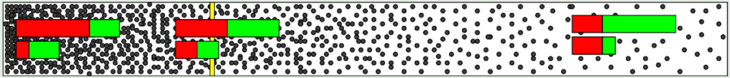
$N_e^R \propto 1/E^R$, so the **high** initial **density** profile it's equivalent to the **low** neutrino **energy** profile, and so on.
Each row represents an energy range!

$N_e^0 \gg N_e^R$ (High energies)



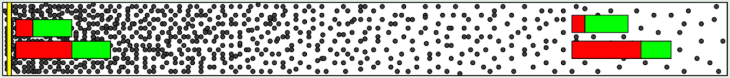
1. Initial **mixing** highly **suppressed**: $E \gg E^R$, $\theta_{12m}^{eff} \to 0$
2. Initial **pure-**ν_e state **mainly** composed by ν_{2m}^{eff}
3. **Admixture** of ES is **not** changing in adiabatic approx. $\to \nu_{2m}^{eff}$ will dominate
4. At **resonance** the **mixing** is **maximal**: **adiabatic conversion** takes place
5. ES **interference** (Oscillations) are strongly **suppressed**

$N_e^0 > N_e^R$



1. Initial **mixing not suppressed**: $\nu_{2m}^{eff} > \nu_{1m}^{eff}$
2. Now **interference** between ES is **considerable**: Oscillations not suppressed
3. **Admixture** of ES is **not** changing in adiabatic approx. $\rightarrow \nu_{2m}^{eff}$ will dominate
4. At **resonance** the **mixing** is **maximal**: **adiabatic conversion** takes place
5. **Interplay** between ad. **conversion** and **oscillations**

$N_e^0 < N_e^R$ (Low energies)

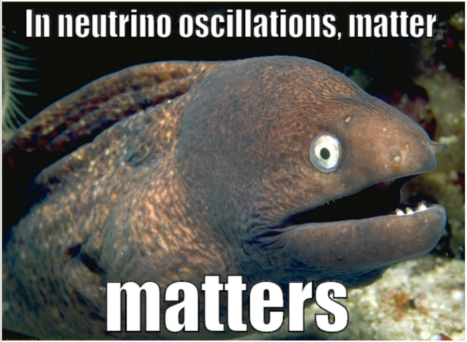


1. Initial **mixing**: $\nu_{2m}^{eff} < \nu_{1m}^{eff}$
2. Now **interference** between ES is **considerable**: Oscillations are the main role
3. **No resonance**: adiabatic conversion **never** takes place
4. **Matter** effect gives only **corrections** to the vacuum oscillation

Conclusions

What have we learned?

- **Sensibility** to mass **hierarchy**
- Oscillation **resonant** enhancement
- **Adiabatic conversion**: important effect
- **Solar** neutrinos may **not oscillate**
- **Interference** can be **suppressed**



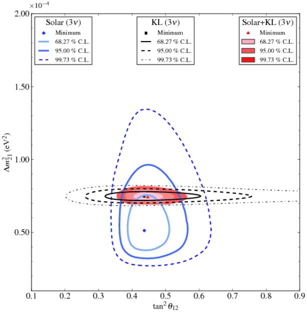
What do we know?

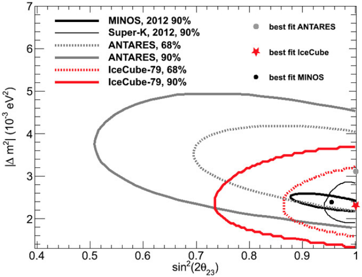
Solar neutrinos

We know θ_{12} with high precision:
$\theta_{12} = 34.06^{+1.16}_{-0.84}$

Atmospheric neutrinos

We know θ_{23} with high precision:
$\theta_{23} = 45 \pm 7.1$





What do we don't know?

Nowadays we have problems here:

- A **precise** value of θ_{13}
- Mass **hierarchy**: $m_3 \gtrless m_1$?
- **CP violation**? Is $\delta \neq 0$?
- Are neutrinos **Majorana** particles?

Question: What can we measure?

Answer:

- θ_{13} is measured with precision by **Reactor** experiments
- Mass **hierarchy** measured with **Accelerator** experiments
- **CP Violation**: very long base-line experiments
- **Majorana** neutrino via **neutrinoless double-beta decay**.

Accelerator Experiments

NOνA (Fermilab)

T2K (Japan)

MINOS (Fermilab)

Reactor Experiments

Daya Bay (China)

Double Chooz (France)

KAMLand (Japan)

Measuring θ_{13}

Question: Which is the best choice?

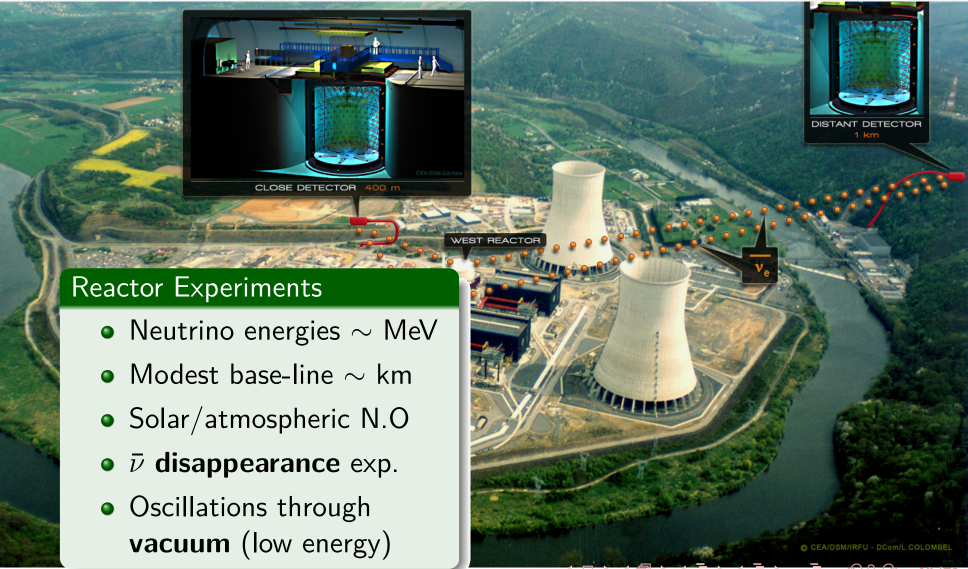
Answer: **Reactor** (**disappearance**) experiments. Survival probability does not depend on other mixing angles:

$$P_{ee} = P_{\bar{e}\bar{e}} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{23}$$

No ν_e beams in **nature**, but a lot of $\bar{\nu}_e$ from **REACTORS**. No hint of δ on this transition.

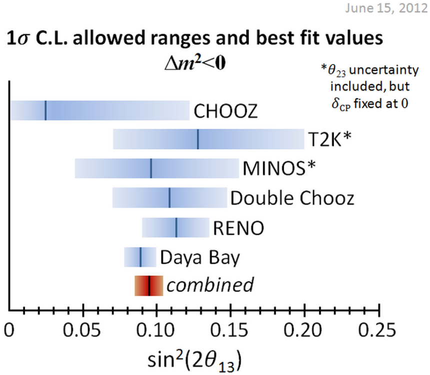
NOTE!

Appearance experiments (accelerator) are capable of measuring θ_{13}, but with **less precision**: probabilities depend on **other mixing angles**.



Reactor Experiments

- Neutrino energies $\sim$ MeV
- Modest base-line $\sim$ km
- Solar/atmospheric N.O
- $\bar{\nu}$ **disappearance** exp.
- Oscillations through **vacuum** (low energy)



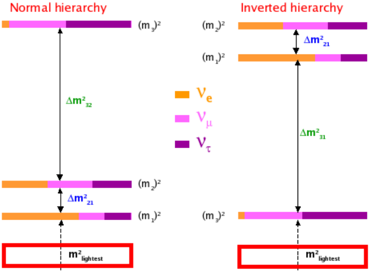
θ_{13} is not completely known!

Recent results of **T2K** and **Daya Bay** set $\theta_{13} \neq 0$, but small. **RENO** published in the last november new results: $\sin^2 2\theta_{13} = 0.100 \pm 0.025$ *arXiv:1312.4111*
KEEP TUNED

NOTE!

Details about specific Reactor experiment (Daya Bay) in Back-Up slides

Different mass hierarchies



Question: Why hierarchy is a problem?

Answer: To get a **complete picture** of the nature of neutrino we need to know which neutrino is the **heaviest** and which the **lightest**!

Question: Why do we know the order Δ_{12}?

Answer: MSW in Sun oscillations! :

$$P_{ee} = \sin^2 2\theta_{12} + \cos^2 2\theta_{12} \cos^2 2\theta^{eff}_{12m0}$$

And $\cos^2 2\theta^{eff}_{12m0}$ **distinguish** the **sign** of Δ_{12}

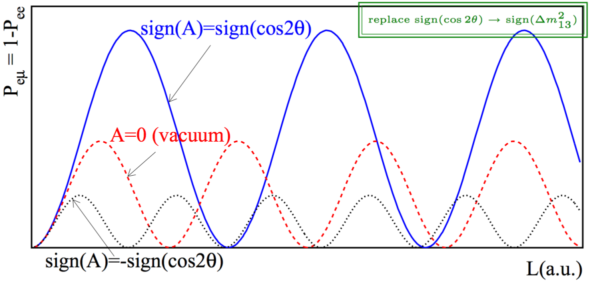
Question: And why not Δ_{23}?

Answer: Again, using MSW effect:

$$P_{\mu e} = \sin^2 2\theta_{23} \sin^2 2\theta^{eff}_{13} \sin^2(\Delta^{eff} L) + O(\Delta_{12})$$

Atmosphere matter effects are **not enough**! We need to 'provoke" those oscillations...

Measurement of Δ_{13}



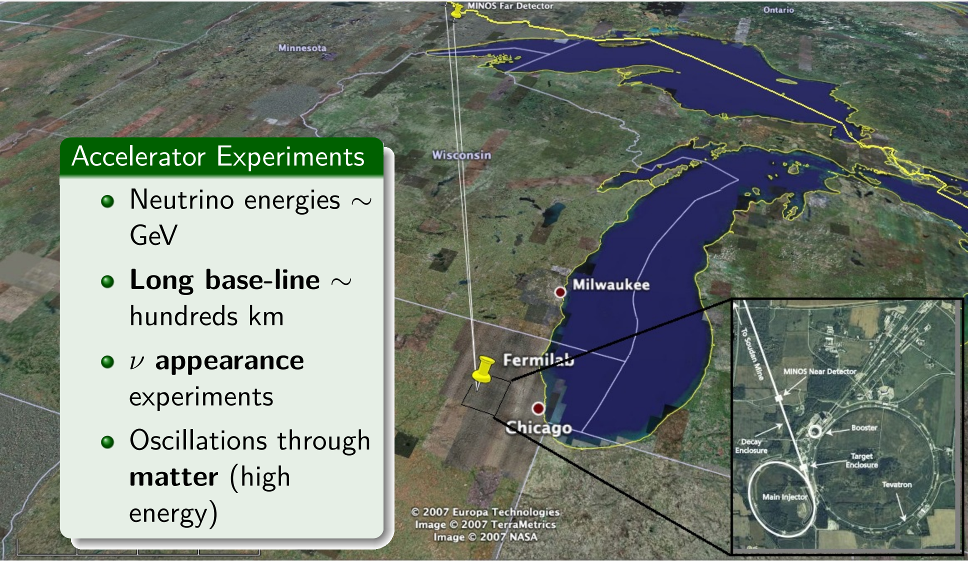
Question: Which is the best choice?

Answer: Accelerator (appearance) Experiments:

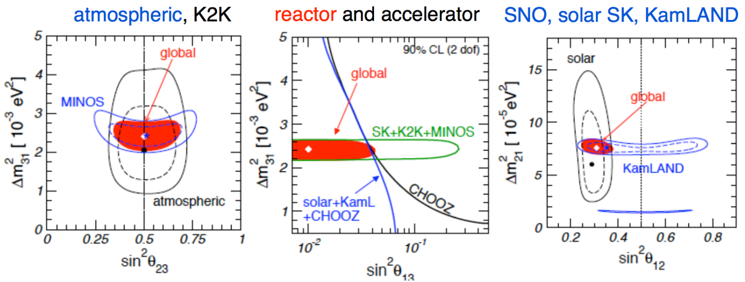
- Oscillation through **matter**
- $\Delta^{eff}_{13} L$ large enough: long baseline (done)
- Good **measuring** of $\sin^2 2\theta_{13}$

Accelerator Experiments

- Neutrino energies $\sim$ GeV
- **Long base-line** $\sim$ hundreds km
- ν **appearance** experiments
- Oscillations through **matter** (high energy)



Complete picture



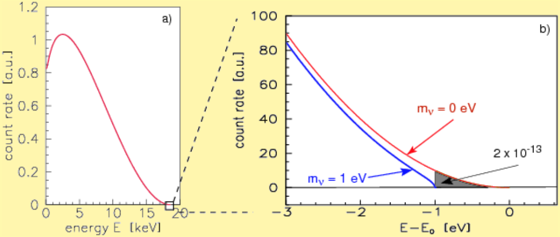
Mixing Angles: arXiv:0808.2016

- $\tan^2 2\theta_{12} = 0.457^{+0.04}_{-0.029}$
- $\sin^2 2\theta_{13} = 0.100 \pm 0.025$
- $\sin^2 2\theta_{23} = 45 \pm 7.1$
- $\Delta m^2_{12} = 7.59^{+0.20}_{-0.21} \cdot 10^{-5}\text{eV}^2$
- $\Delta m^2_{13} = 2.43^{+0.13}_{-0.13} \cdot 10^{-3}\text{eV}^2$
- $\Delta m^2_{23} \approx \Delta m^2_{13}$

Mainz and Troitsk Experiments I

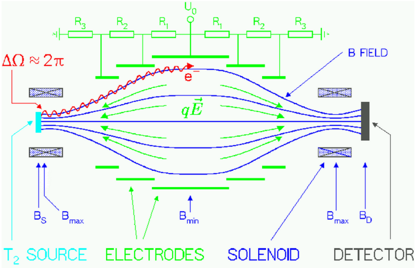
Question: What are they based on?

Answer: **Tritium** end-point β **spectrum**:



- ν_e mass as superpos. of mass ES
- Are m_i **hierarchical** or **degenerated**?
- **Degenerated**: they could be at the range $\sim$ **eV**.
- **Hierarchical**: **low** E range - precision $\sim 2eV$ doesn't help!

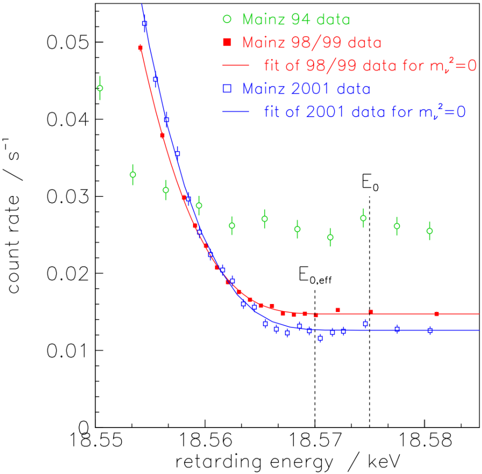
Measuring set up



Question: How do they proceed? MAC-E Filter

- **Tritium** emits β **isotropically**
- Almost 2π S.A is driven and **focused** by MF
- EF **deflects** β: only **high energy** β are recollimated (less BG)
- Integrating high-energy pass filter

Mainz Results 1998 - 2001



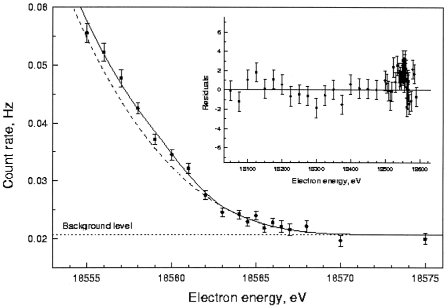
Final results

$m_\nu < 2.2\text{eV}$ **95% C.L**

$m^2_\nu = -1.6 \pm 2.5_{\text{stat}} \pm 2.1_{\text{sys}}\text{eV}^2$

E_0^{eff} is the effective end-point (taking in account the response function of the setup)

Troitsk Results 1998 - 2002



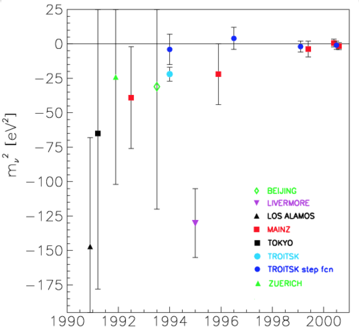
Final results

$$m_\nu^2 = -1.9 \pm 3.4_{\text{stat}} \pm 2.2_{\text{sys}}\text{eV}^2$$

$m_\nu < 2.5\text{eV}$ **95% C.L**

Negative mass neutrinos?

Conclusions



Question: Why do neutrino mass appear to be negative?

Answer: Systematic **"Troistk anomaly"**: DAEMONS (dark currents ...) Until know those are the **most accurate** results for the measuring of the neutrino **absolute mass** scale

Future perspective:

KATRIN experiment: β spec. of ^{3}H

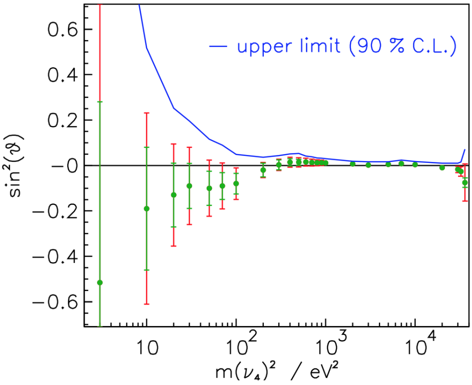
- **Higher resolution** $\sim$ 200meV
- Using **MAC-E-Filter**

Mainz and Troitsk Experiments II

Question: What do they do now?

Answer:

- Using data from last 15 years
- **Repeat** analysis for 4 ν families
- Take into account **corrections** from $|U_{e4}|$
- Try to extract a **suitable** $\sin\theta_{14}$ and m_4

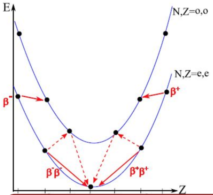


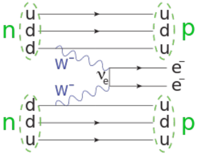
UNTIL NOW, **NO SUCCESS**

$\beta\beta0\nu$ Decay

Question: Why do $\beta\beta2\nu$ occur?

Answer: **Nuclei** with odd Z can **decay** into an atom Z-2 if the one with Z-1 has fewer binding energy *tau* $\sim 10^{20}$y





76 32 Ge GERDA
130 52 Te CUORE
136 54 Xe
next

Question: Can $\beta\beta0\nu$ occur?

Answer: Indeed, if ν are **Majorana** particles. As discussed:

- **No** conservation of **leptonic number**
- Very **low probability** for this to happen *tau* $\sim 10^{25}$y

NEXT Experiment

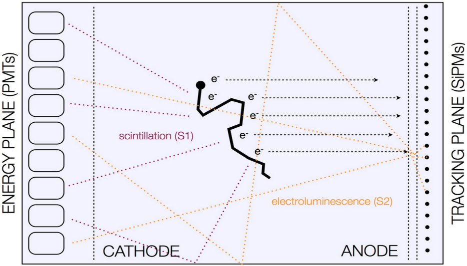
Question: What is about?

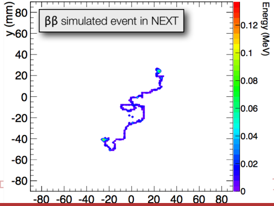
Answer: TPC filled with ultra-pressured ^{136}Xe :

- SiPM plane for **tracking**: E-L
- PM plane to **recoil energy**
- Strong EF driving e^- and **amplifying** the signal

Special features

- Ultra Low BG: inside water tank
- Working on 100Kg prototype - looking for 1ton





Conclusions

We know:

Oscillations in vacuum and matter
The three oscillation angles
Mass differences

We want to know:

Mass hierarchy
Mass scale
Majorana or Dirac particles?
Existence of Sterile neutrinos
CP violation?

Question: Will we ever know?

Answer: Great revelations in the next 20 years!!
Precision measurements of θ: PINGU, ANTARES, ORCA, NOνA, HyperK...
Mass hierarchy: NewGen Accelerator Exp: T2K, NOνA
Mass scale: KATRIN
Majorana or Dirac particles?: $0\nu\beta\beta$ Decay: NEXT, EXO...
Existence of Sterile neutrinos: KATRIN

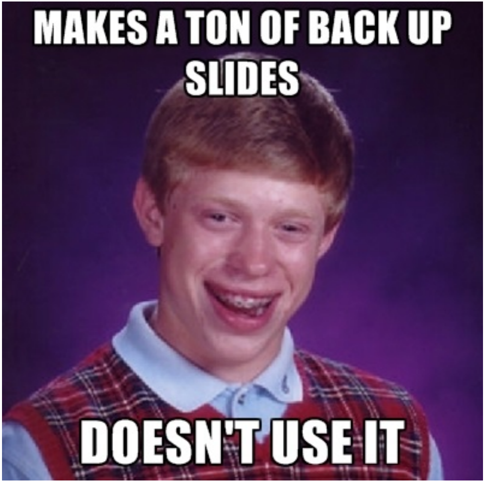
CP Violation - Leptogenesis?

"One small step for a neutrino, a giant leap for universe"

THANKS FOR WATCHING!

"This is not even wrong!" Wolfgang Ernst Pauli

BACK UP SLIDES



Lagrangian Framework

Free Lagrangian - General fermionic particle

Arbitrary representation of ψ (Dirac, Weyl, Majorana...). We force the kinetic terms not to mix: propagating degree of freedom

$$\mathcal{L} = \bar{\psi}_\alpha \partial\!\!\!/ \psi_\alpha + \bar{\psi}_\alpha M_{\alpha\beta} \psi_\beta$$

M is not longer necessarily diagonal $\rightarrow \psi_\alpha$ are not physical states - mass term not well defined in $\mathcal{L}$

Question: Do we know such kind of fermions?

Answer: Indeed.

- Neutrinos: PMNS mixing matrix
- Quarks: CKM mixing matrix
- Charged leptons: ?¿ still no evidence of this phenomena

Unitary transformation U diagonalize $M' = U^\dagger M U = \text{diag}\{m_\alpha\}$

The propagating particles are defined now by $\psi'_j = {U_{j\alpha}}^\dagger \psi_\alpha$

$$\mathcal{L} = \bar{\psi}'_j \partial\!\!\!/ \psi'_j + \bar{\psi}'_j M'_{jj} \psi'_j$$

Neutrinos have to be massive to oscillate!

NOTE!

U is not defined in the 4-dimension Lorentz space but in the fermionic flavour space. Then $U\gamma^\mu U^\dagger = \gamma^\mu$

Question: How do $|\nu_\alpha(t)\rangle$ propagate?

Answer: We need to start from the propagation of $|\nu_i(t)\rangle$

$$i \underbrace{}_{U^\dagger U} \frac{\partial |\nu_i(t)\rangle}{\partial t} = H_0 \underbrace{}_{U^\dagger U} |\nu_i(t)\rangle$$

$$U' \left(i \frac{\partial |\nu_\alpha(t)\rangle}{\partial t} \right) = H_0 U' |\nu_\alpha(t)\rangle$$

$$i \frac{\partial |\nu_\alpha(t)\rangle}{\partial t} = H_0' |\nu_\alpha(t)\rangle$$

With the hamiltonian given by:

$$H_0 = E + \frac{1}{2E} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}$$

The transformed hamiltonian looks like

$$H_0' = E + \frac{m_1^2 m_2^2}{4E} + \frac{\Delta m_{12}^2}{2E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}$$

$E + \frac{m_1^2 m_2^2}{4E}$ only add a global phase in the propagation. Thus we can neglect it.

$$\begin{pmatrix} |\nu_\alpha(t)\rangle \\ |\nu_\beta(t)\rangle \end{pmatrix} = \frac{\Delta m_{12}^2}{2E} \begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} \cdot \begin{pmatrix} |\nu_\alpha(t)\rangle \\ |\nu_\beta(t)\rangle \end{pmatrix}$$

NOTE!

From now on we define $\Delta_{ij} = \frac{\Delta m_{12}^2}{2E}$ through all the presentation.

The solution of the system:

$$\begin{pmatrix} |\nu_\alpha(t)\rangle \\ |\nu_\beta(t)\rangle \end{pmatrix} = e^{i\Delta_{12}[\sigma_1 \sin 2\theta - \sigma_3 \cos 2\theta]L} \cdot \begin{pmatrix} |\nu_\alpha(0)\rangle \\ |\nu_\beta(0)\rangle \end{pmatrix}$$

And using $e^{i\omega(\vec{n}\vec{\sigma})} = I\cos\omega + i(\vec{n}\vec{\sigma})\sin\omega$:

$$|\nu_\alpha(t)\rangle = [\cos(\Delta_{12}L) - i\sin(\Delta_{12}L)\cos 2\theta]|\nu_\alpha(0)\rangle + [i\sin(\Delta_{12}L)\sin 2\theta]|\nu_\beta(0)\rangle$$
$$|\nu_\beta(t)\rangle = [i\sin(\Delta_{12}L)\sin 2\theta]|\nu_\alpha(0)\rangle + [\cos(\Delta_{12}L) + i\sin(\Delta_{12}L)\cos 2\theta]|\nu_\beta(0)\rangle$$

Finding the new eigenbasis

Question: How do we find the matter-mass eigenstates?

Answer: We have to diagonalise $H_0'^{eff}$ and find the eigenstates given by $m_{1,2}^{eff}$. EASY TASK!

Just take a close look...

$$\Delta_{12}\begin{pmatrix} -\cos 2\theta + \frac{\delta V}{\Delta_{12}} & \sin 2\theta \\ \sin 2\theta & \cos 2\theta - \frac{\delta V}{\Delta_{12}} \end{pmatrix} = \Delta_{12}^{eff}\begin{pmatrix} -\cos 2\theta^{eff} & \sin 2\theta^{eff} \\ \sin 2\theta^{eff} & \cos 2\theta^{eff} \end{pmatrix}$$

Question: What is the best guess we can do?

Answer: The most basic guess we can do, for an unknown C:

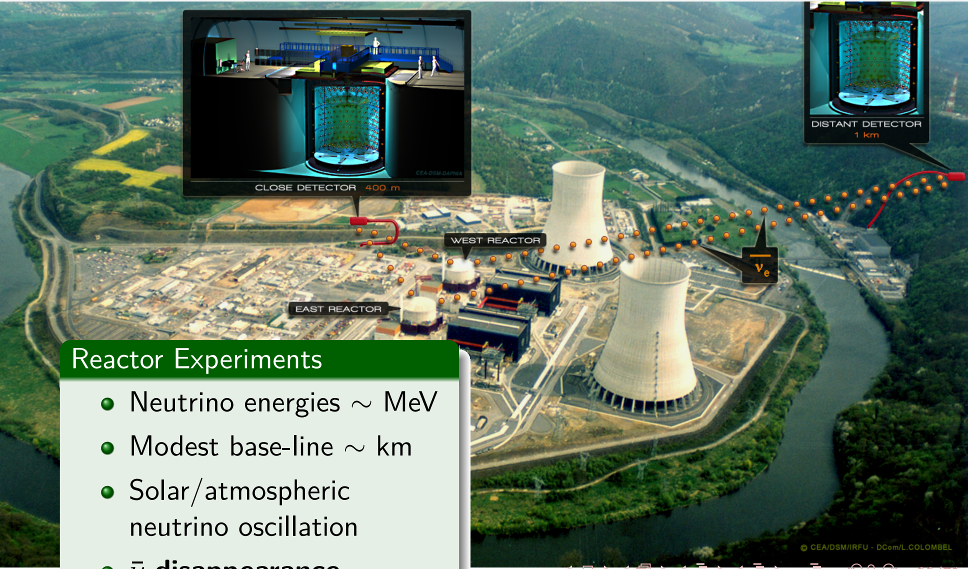
$$\Delta^{eff} = C\Delta_{12} \quad \sin 2\theta^{eff} = \sin 2\theta_{12}/C$$

Find C using:

$$\Delta_{12}(\cos 2\theta - \frac{\delta V}{\Delta_{12}}) = \Delta_{12}^{eff} \cos 2\theta^{eff}$$
$$\sin^2 2\theta^{eff} = 1 - \cos^2 2\theta^{eff} = \sin^2 2\theta/C^2$$

It's straight forward to find that:

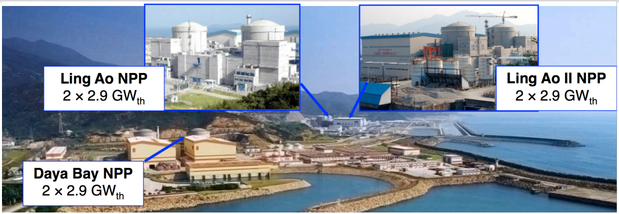
$$C = \frac{1}{\Delta_{12}}\sqrt{(\Delta_{12}\cos 2\theta_{12} - \delta V)^2 + \Delta_{12}^2 \sin^2 2\theta_{12}}$$



Reactor Experiments

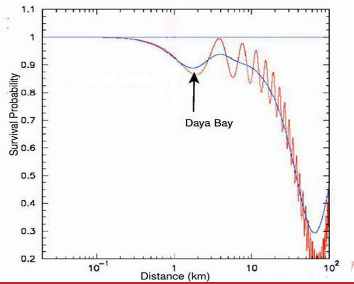
- Neutrino energies ∼ MeV
- Modest base-line ∼ km
- Solar/atmospheric neutrino oscillation
- $\bar{\nu}$ **disappearance**

Daya Bay Experiment



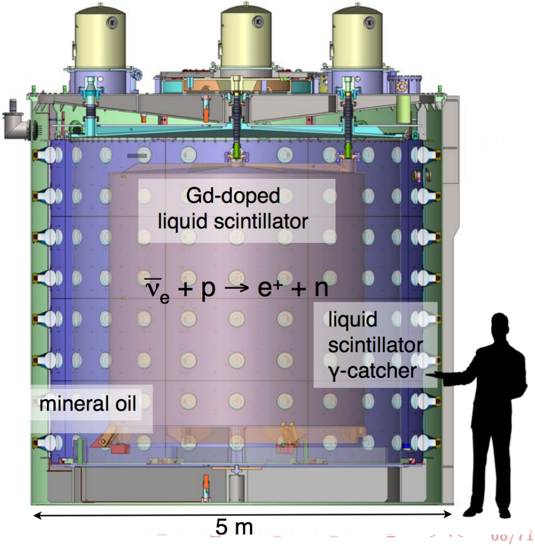
Question: What are the main features?

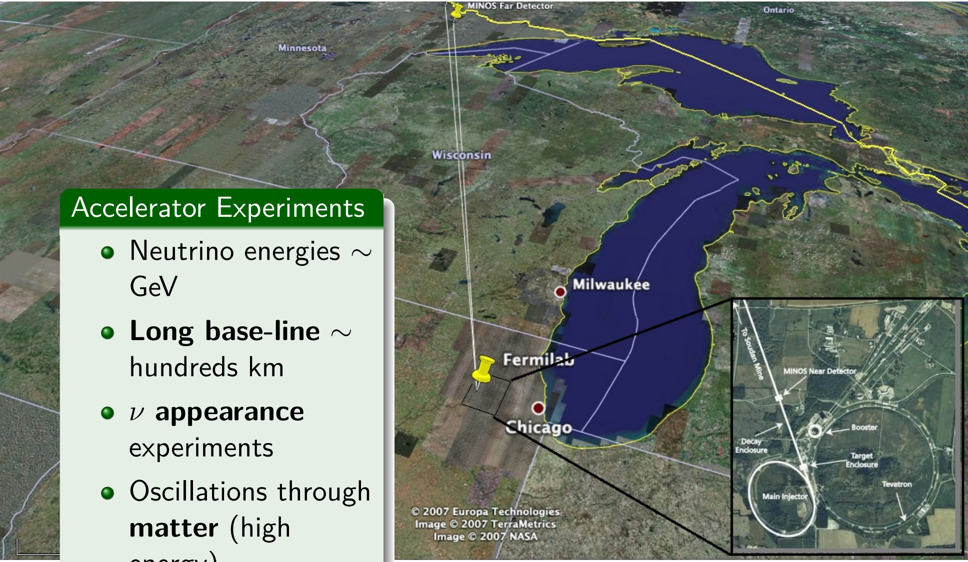
- 6 Reactors produce $\sim 6 \times 1020$ $\bar{\nu}_e/\mathrm{sec}/\mathrm{GW}$
- Far-Near detector 1.5km
- Measure amount of $\bar{\nu}_e$ in both detectors and compare



Measuring

- Mass target: water
- $\bar{\nu}_e$ interacts with p and emits β^+
- β^+ carries almost all E_ν: scintillation detection

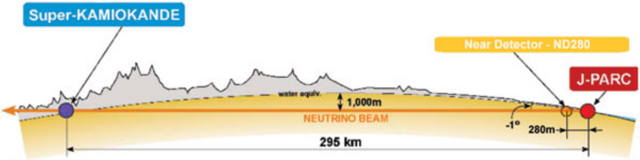




Accelerator Experiments

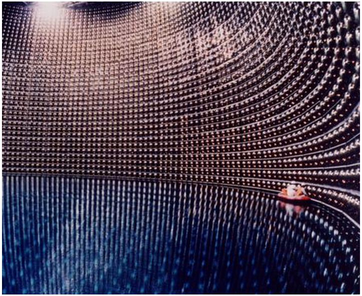
- Neutrino energies ∼ GeV
- **Long base-line** ∼ hundreds km
- ν **appearance** experiments
- Oscillations through **matter** (high energy)

T2K Experiment



Question: What are the main features?

- Pure ν_μ beam 30GeV from J-PARC accelerator
- Near Detector ND280 measures ν_μ composition
- Far Detector (295 km) at Kamiokande measures ν_e composition



They measure

- From ν_e appearance: θ_{13}
- From ν_μ disappearance: θ_{23}
- Oscillations through matter: Δ_{13}, Δ_{23}

Special Feature: Off-axis

In order to increase the energy resolution: detector placed off-axis (≈ 0.04 rad). Loses counts but peaks the energy!