NEUTRINO PHYSICS II

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10th IDPASC School

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http://www.nu-fit.org

Plan of Lecture II

Neutrino Oscillations in Vacuum

Matter Effects: MSW

The Data and Its Interpretation

Solar Neutrinos

Atmospheric Neutrinos

Accelerator Neutrinos at Long Baselines

Reactor Neutrinos

Fitting all Together: The New Minimal Standard Model

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

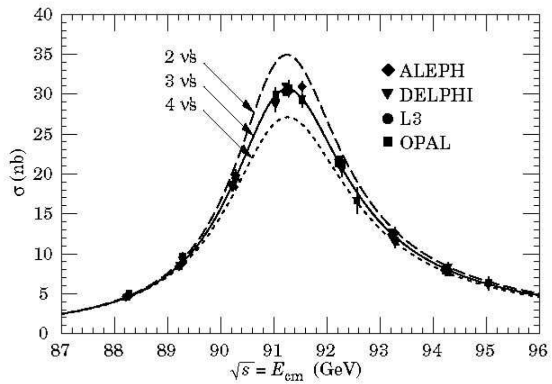
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

Three and only three



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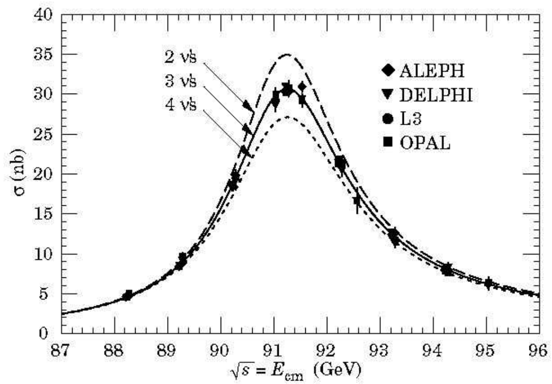

There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$ (hence $L = L_e + L_\mu + L_\tau$)

$\Downarrow$

ν *strictly* massless

- We have observed with high (or good) precision:
  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE)
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
  - $*$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA)
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
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All this implies that L_α are violated

and There is Physics Beyond SM

The New Minimal Standard Model

- Minimal Extension to allow for LFV $\Rightarrow$ give Mass to the Neutrino

  $*$ Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

  $$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose L conservation $\Rightarrow$ Majorana $\nu = \nu^c$

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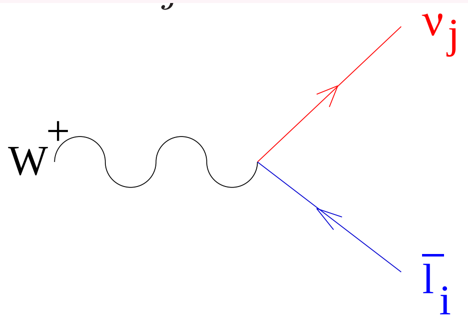
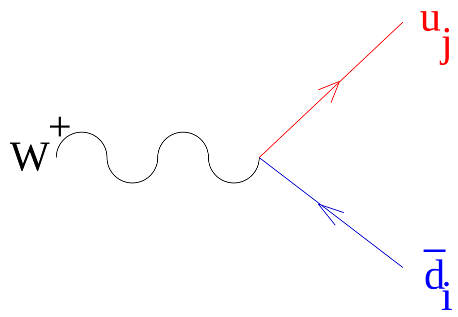
- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\rm LEP}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{\rm CKM}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$





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- In general for $N = 3 + s$ massive neutrinos $U_{\rm LEP}$ is $3 \times N$ matrix

  $U_{\rm LEP} U^\dagger_{\rm LEP} = I_{3\times 3}$ but in general $U^\dagger_{\rm LEP} U_{\rm LEP} \neq I_{N\times N}$

- $U_{\rm LEP}$: $3 + 3s$ angles + $2s + 1$ Dirac phases + $s + 2$ Majorana phases

Effects of ν Mass: Flavour Transitions

- Flavour ($\equiv$ Interaction) basis (production and detection): ν_e, ν_μ and ν_τ
- Mass basis (free propagation in space-time): ν_1, ν_2 and ν_3 ...

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$\Rightarrow$ Flavour is not conserved during propagation

$\Rightarrow$ ν can be detected with different (or same) flavour than produced

- The probability $P_{\alpha\beta}$ of producing neutrino with flavour α and detecting with flavour β has to depend on:
  - Misalignment between interaction and propagation states ($\equiv U$)
  - Difference between propagation eigenvalues
  - Propagation distance

Mass Induced Flavour Oscillations in Vacuum

- If neutrinos have mass, a weak eigenstate $|\nu_\alpha\rangle$ produced in $l_\alpha + N \to \nu_\alpha + N'$ is a linear combination of the mass eigenstates ($|\nu_i\rangle$)

$$|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}{}^{*} \; |\nu_i\rangle$$

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- it can be detected with flavour β with probability

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t)\rangle|^2 = |\sum_{i=1}^{n} U^*_{\alpha i} U_{\beta i} \langle \nu_j | \nu_i(t)\rangle|^2$$

Flavour Oscillations in Vacuum

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- We call E_i the neutrino energy and m_i the neutrino mass

- Under the approximations:

(**1**) $|\nu\rangle$ is a *plane wave* $\Rightarrow |\nu_i(t)\rangle = \mathrm{e}^{-i\,E_i\,t}|\nu_i(0)\rangle$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j\neq i}^{n}\mathrm{Re}[U^\star_{\alpha i}U_{\beta i}U_{\alpha j}U^\star_{\beta j}]\sin^2\left(\frac{\Delta_{ij}}{2}\right) + 2\sum_{j\neq i}\mathrm{Im}[U^\star_{\alpha i}U_{\beta i}U_{\alpha j}U^\star_{\beta j}]\sin\left(\Delta_{ij}\right)$$

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$(\mathbf{2})$ *relativistic* ν

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2E_i}$$

$(\mathbf{3})$ Lowest order in mass $p_i \simeq p_j = p \simeq E$

$$\frac{\Delta_{ij}}{2} = 1.27 \frac{m_i^2 - m_j^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{Km/GeV}}$$

Flavour Oscillations in Vacuum

- The oscillation probability:

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– The last piece $2\sum_{j\neq i}\mathrm{Im}[U^{\star}_{\alpha i}U_{\beta i}U_{\alpha j}U^{\star}_{\beta j}]\sin\left(\Delta_{ij}\right)$ opposite sign for $\overline{\nu}$

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– If $\alpha = \beta \Rightarrow$ $\mathrm{Im}[U^\star_{\alpha i}U_{\alpha i}U_{\alpha j}U^\star_{\alpha j}] = \mathrm{Im}[|U^\star_{\alpha i}|^2|U_{\alpha j}|^2] = 0$

$\Rightarrow$ CP violation observable only for $\beta \neq \alpha$

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- $P_{\alpha\beta}$ depends on Neutrino Parameters
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  - $U_{\alpha j}$ The mixing angles (and Dirac phases)

and on Two *set-up* Parameters:
  - E The neutrino energy
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- No information on mass scale nor Majorana phases

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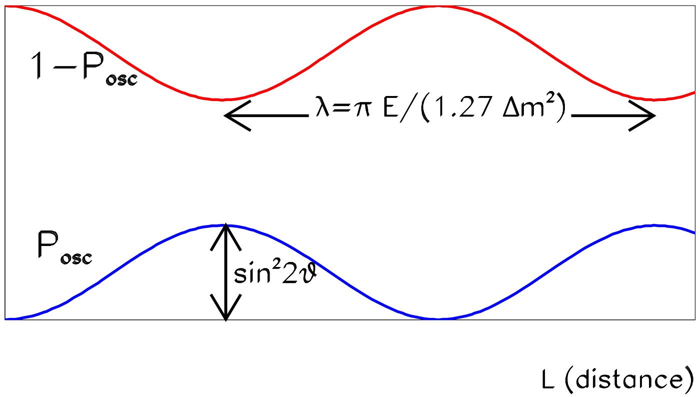

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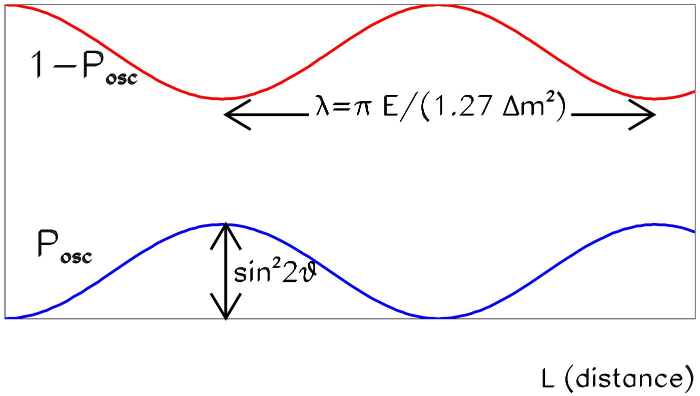

- Changing *at the same time* $\Delta m^2 \to -\Delta m^2$ and $\theta \to -\theta + \frac{\pi}{2}$

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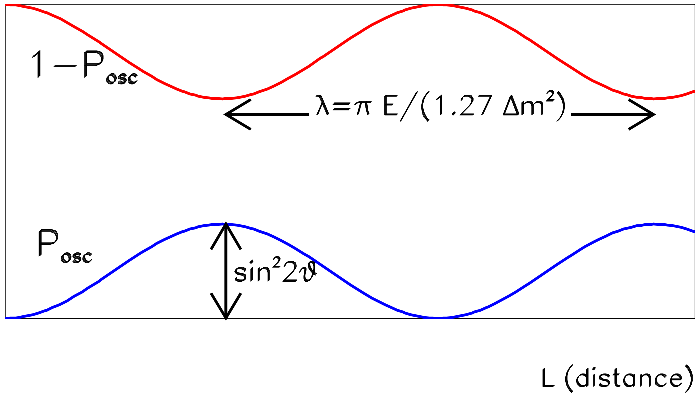

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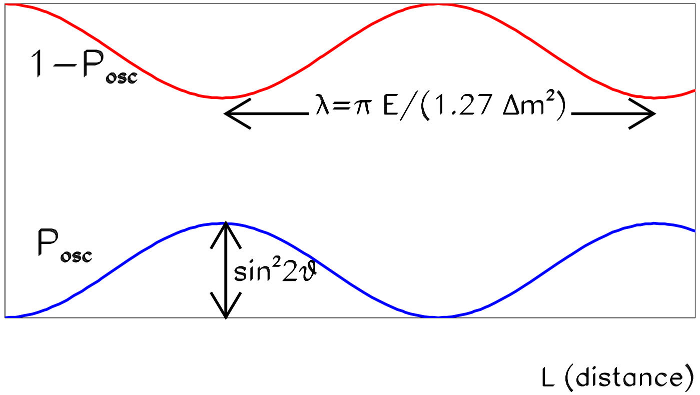

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- U is real $\Rightarrow$ no CP violation

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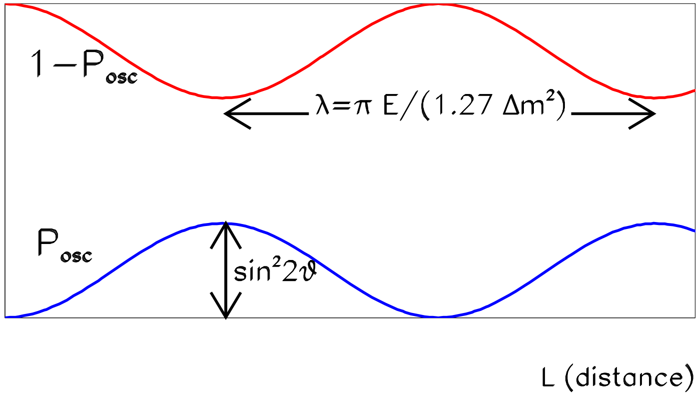

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  $\Rightarrow$ We can chose the convention $\Delta m^2 > 0$ and $0 \leq \theta \leq \frac{\pi}{2}$
- But P_{osc} is symmetric *independently* under $\Delta m^2 \to -\Delta m^2$ or $\theta \to -\theta + \frac{\pi}{2}$

  $\Rightarrow$ We can chose the convention $\Delta m^2 > 0$ and $0 \leq \theta \leq \frac{\pi}{4}$
- U is real $\Rightarrow$ no CP violation

This only happens for 2ν vacuum oscillations

ν Oscillations: Experimental Probes

- Generically there are two types of experiments to search for ν oscillations :

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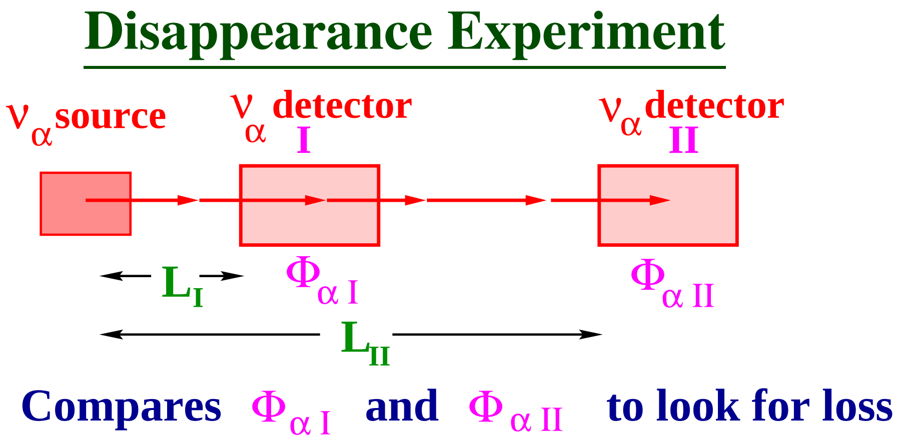

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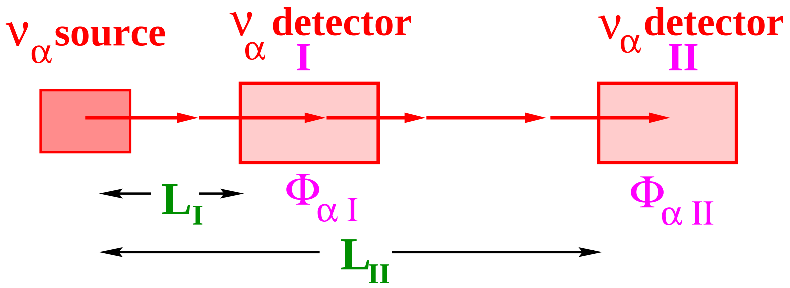
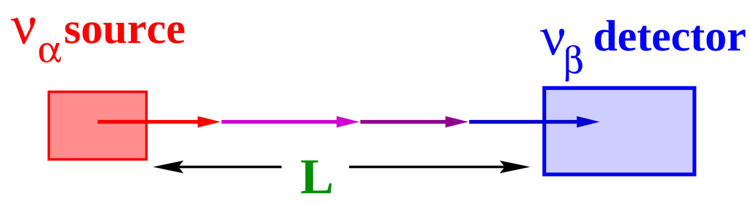
Disappearance Experiment



Compares $\Phi_{\alpha\, I}$ and $\Phi_{\alpha\, II}$ to look for loss

Appearance Experiment



Searches for β diff α

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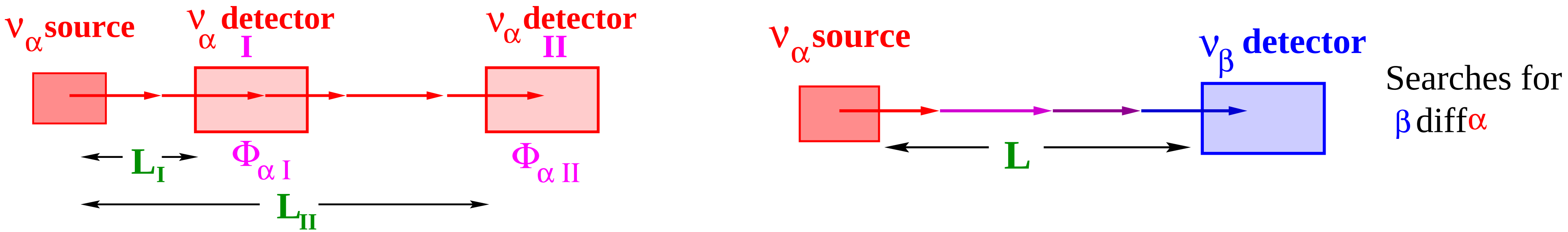
Disappearance Experiment | **Appearance Experiment**



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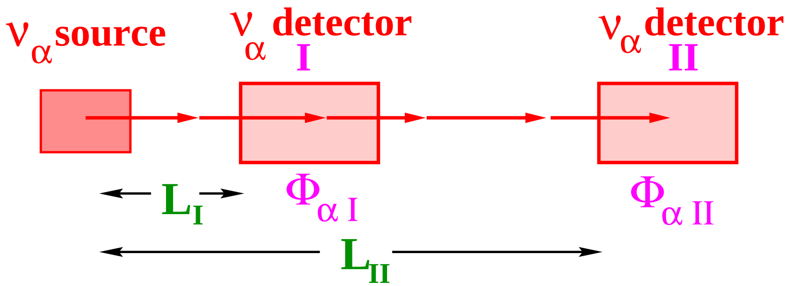

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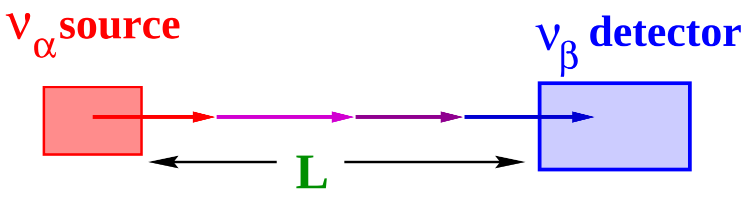
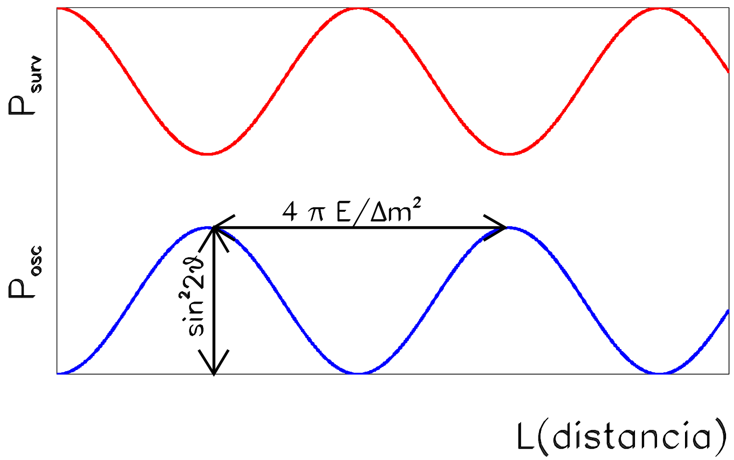


Searches for β diff α

- To detect oscillations we can study the neutrino flavour as function of the Distance to the source



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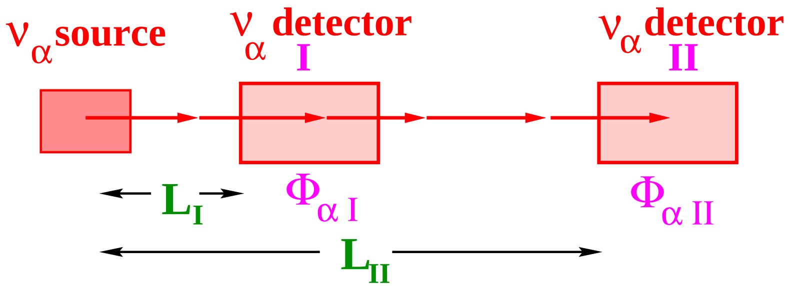

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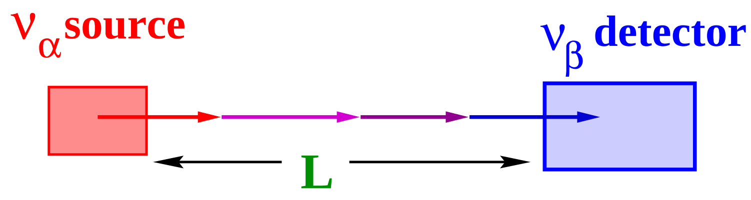

Searches for β diff α

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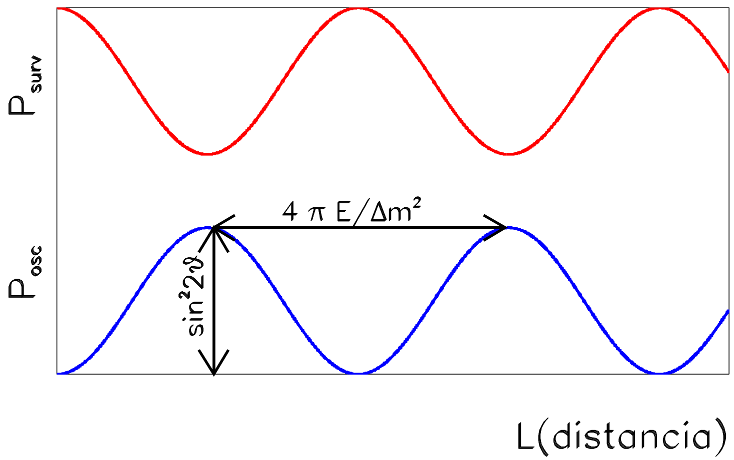
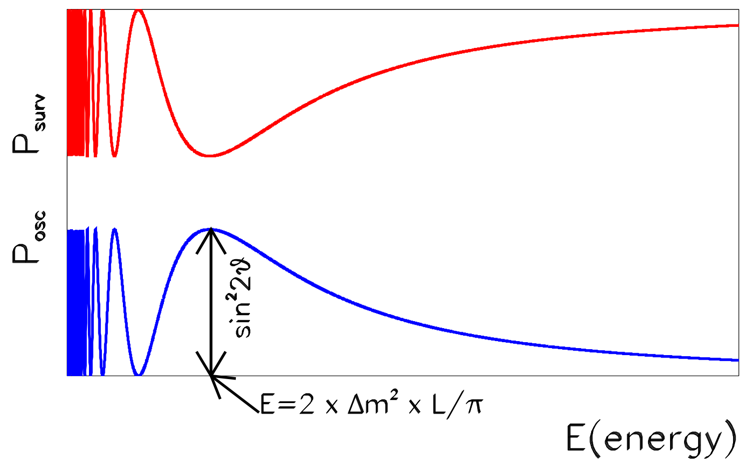


As function of the neutrino Energy



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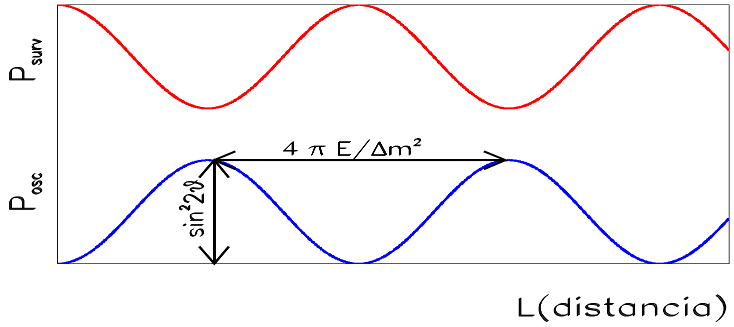

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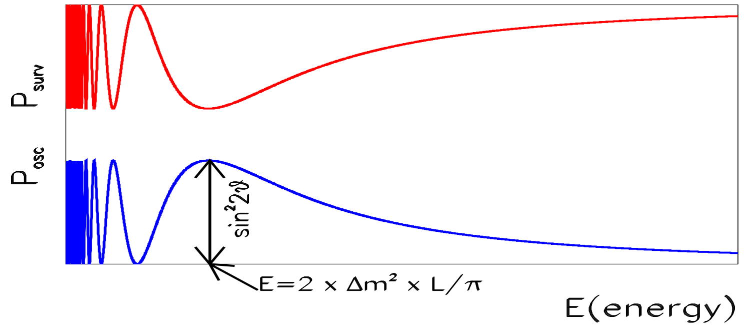

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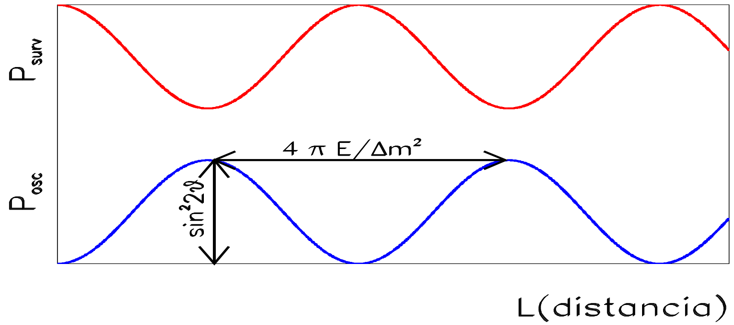

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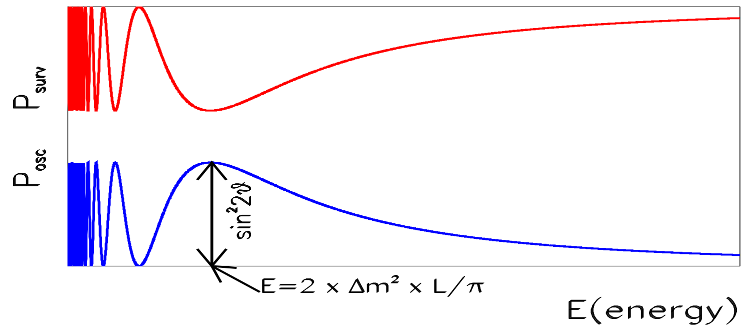
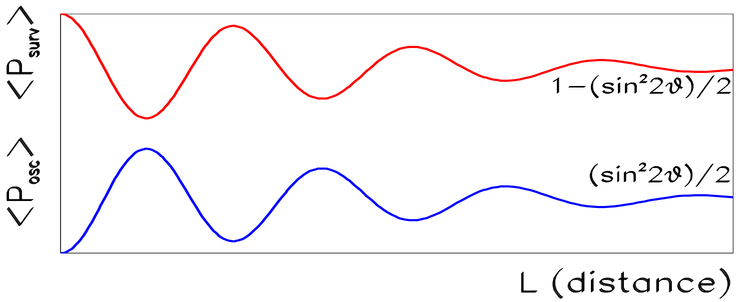
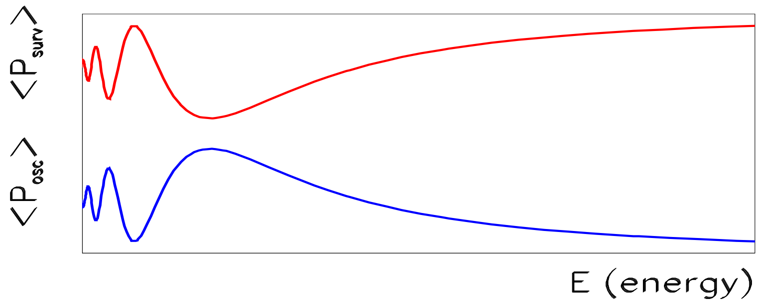


- In real experiments $\Rightarrow$ $\langle P_{\alpha\beta}\rangle = \int dE_\nu \frac{d\Phi}{dE_\nu}\sigma_{CC}(E_\nu) P_{\alpha\beta}(E_\nu)$





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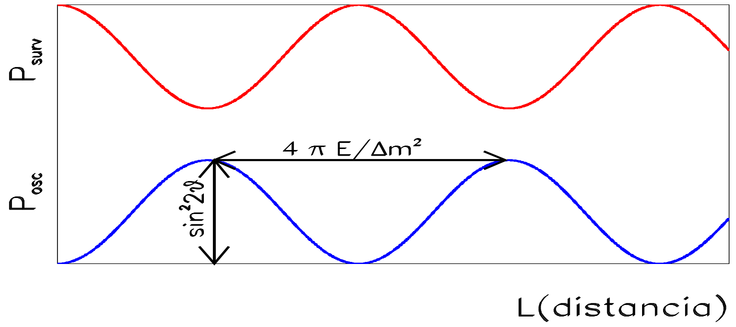

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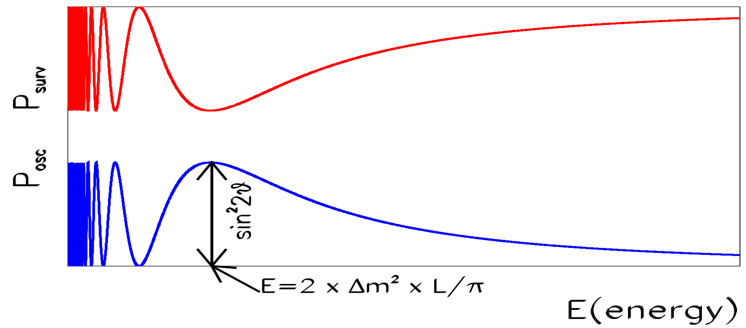

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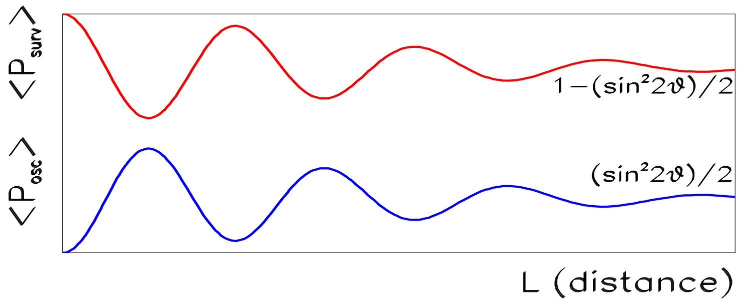
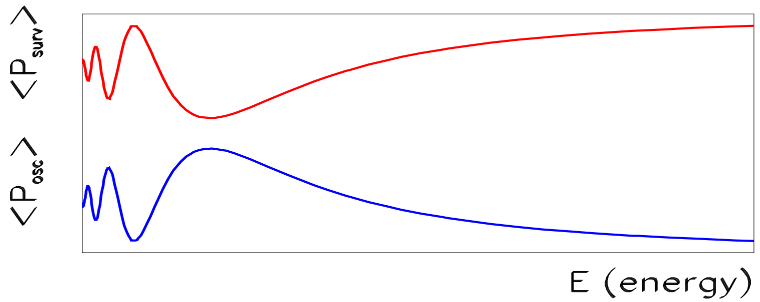




- Maximal sensitivity for $\Delta m^2 \sim E/L$

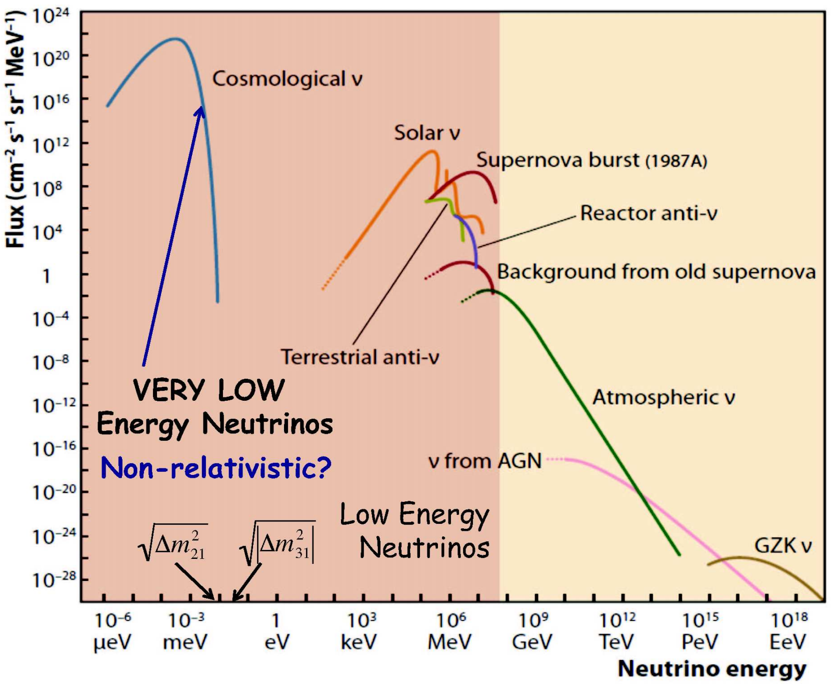
– $\Delta m^2 \ll E/L \;\Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq 0 \to \langle P_{\alpha\neq\beta}\rangle \simeq 0$ & $\langle P_{\alpha\alpha}\rangle \simeq 1$

– $\Delta m^2 \gg E/L \;\Rightarrow \langle \sin^2(\Delta m^2 L/4E)\rangle \simeq \frac{1}{2} \to \langle P_{\alpha\neq\beta}\rangle \simeq \frac{\sin^2(2\theta)}{2} \leq \frac{1}{2}$ & $\langle P_{\alpha\alpha}\rangle \geq \frac{1}{2}$

To allow observation of neutrino oscillations:

– Nature has to be good: $\theta \not\ll 0$

– Need the right set up ($\equiv$right $\langle \frac{L}{E} \rangle$) for Δm^2



Source	E (GeV)	L (Km)	Δm^2 (eV^2)
Solar	10^{-3}	10^7	10^{-10}
Atmos	0.1–10^2	10–10^3	10^{-1}–10^{-4}
Reactor	10^{-3}	SBL: 0.1–1	10^{-2}–10^{-3}
		LBL: 10–10^2	10^{-4}–10^{-5}
Accel	10	SBL: 0.1	$\gtrsim 0.01$
		LBL: 10^2– 10^3	10^{-2}–10^{-3}

Neutrinos in Matter:Effective Potentials

- In SM the characteristic ν-p interaction cross section

$$\sigma \sim \frac{G_F^2 E^2}{\pi} \sim 10^{-43}\text{cm}^2 \quad \text{at } \text{E}_\nu \sim \text{MeV}$$

- So if a beam of $\Phi_\nu \sim 10^{10} \nu' s$ was aimed at the Earth only 1 would be deflected

so it seems that for neutrinos *matter does not matter*

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- But that cross section is for *inelastic* scattering

  Does not contain forward elastic *coherent* scattering

- In *coherent* interactions $\Rightarrow$ ν and medium remain unchanged

  Interference of scattered and unscattered ν waves

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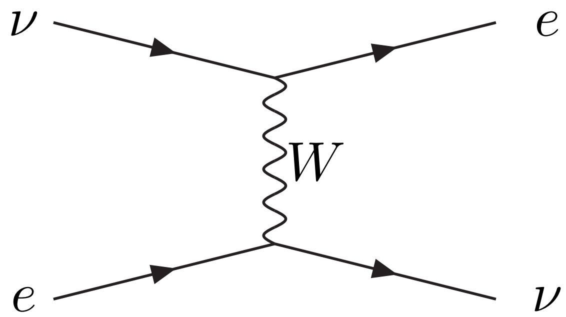

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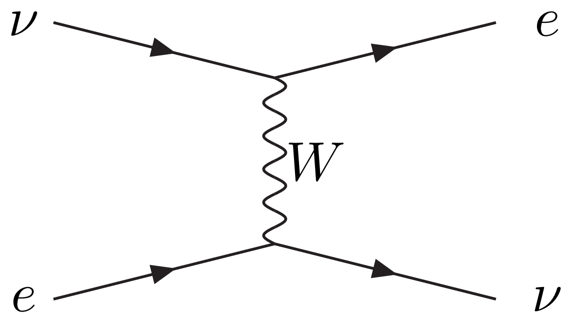

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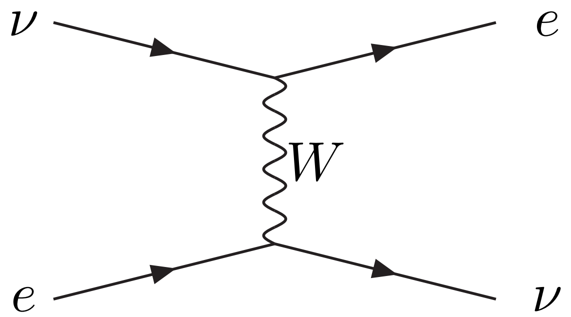

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- Other potentials for ν_e $(\overline{\nu}_e)$ due to different particles in medium

medium	V_C	V_N
e^+ and e^-	$\pm\sqrt{2}G_F(N_e - N_{\bar{e}})$	$\mp\frac{G_F}{\sqrt{2}}(N_e - N_{\bar{e}})(1-4\sin^2\theta_W)$
p and $\bar{p}$	0	$\pm\frac{G_F}{\sqrt{2}}(N_p - N_{\bar{p}})(1-4\sin^2\theta_W)$
n and $\bar{n}$	0	$\mp\frac{G_F}{\sqrt{2}}(N_n - N_{\bar{n}})$
Neutral $(N_e = N_p)$	$\pm\sqrt{2}G_F N_e$	$\mp\frac{G_F}{\sqrt{2}}N_n$

Neutrinos in Matter: Evolution Equation

Evolution Eq. for $|\nu\rangle = \nu_1|\nu_1\rangle + \nu_2|\nu_2\rangle \equiv \nu_e|\nu_\alpha\rangle + \nu_\beta|\nu_X\rangle$ $(X = \mu, \tau, \text{sterile})$

(a) In vacuum in the weak basis

$$-i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix} = E - \frac{m_1^2+m_2^2}{2E} - \begin{pmatrix}-\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix}$$

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(b) In matter (e, p, n) in weak basis

$$-i\frac{\partial}{\partial x}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix} = E - V_X - \frac{m_1^2+m_2^2}{2E} - \begin{pmatrix}V_e - V_X - \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta\\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta\end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_X\end{pmatrix}$$

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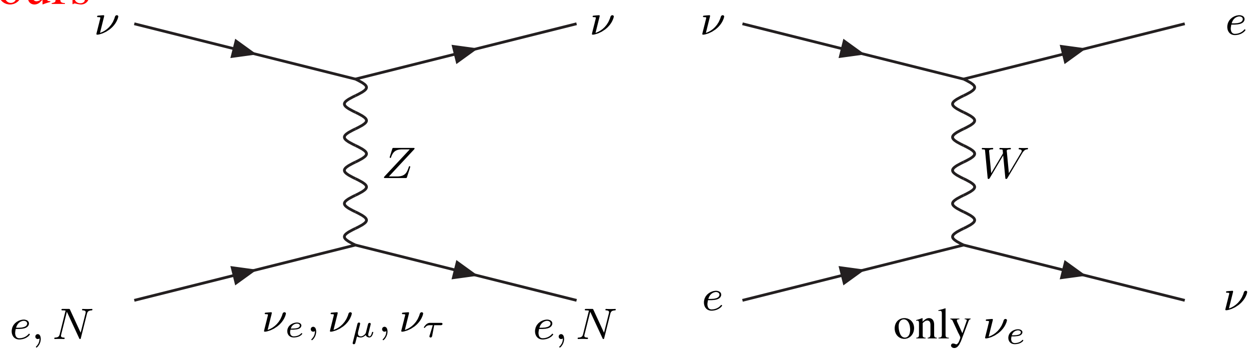
(a)$\neq$ (b) because different flavours have different interactions

For example $X = \mu, \tau$:

$$V_{CC} = V_e - V_X = \sqrt{2}G_F N_e$$

(opposite sign for $\overline{\nu}$)



$\Rightarrow$ Effective masses and mixing are different than in vacuum

– The effective masses: $(A = 2E(V_\alpha - V_\beta))$

$$\mu^2_{1,2}(x) = \frac{m_1^2 + m_2^2}{2} + E(V_\alpha + V_\beta) \pm \frac{1}{2}\sqrt{(\Delta m^2 \cos 2\theta - A)^2 + (\Delta m^2 \sin 2\theta)^2}$$

– The mixing angle in matter

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - A}$$

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$\Rightarrow$ Information on sign Δm^2 and Octact of θ

- For constant potential($\equiv$ constant matter density): θ_m and μ_i are constant along ν path

$\Rightarrow$ the evolution is determined by masses and mixing in matter as

$$P_{osc} = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta\mu^2 L}{2E}\right)$$

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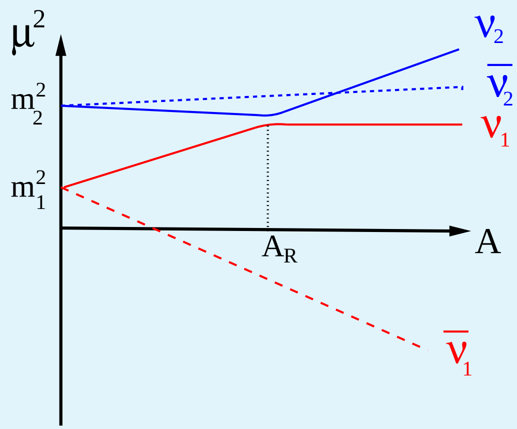
For $A > 0$



At *resonant* potential: $A_R = \Delta m^2 \cos 2\theta$

Minimum $\Delta\mu^2 = \mu_2^2 - \mu_1^2$

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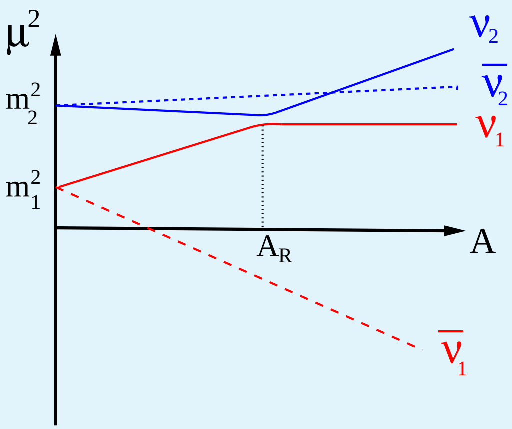

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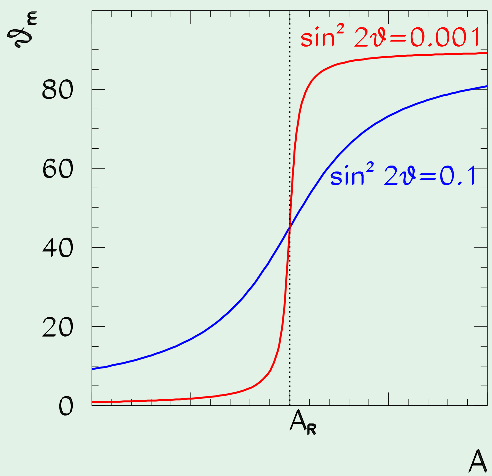

* At $A = 0$ (vacuum) $\Rightarrow \theta_m = \theta$
* At $A = A_R \Rightarrow \theta_m = \frac{\pi}{4}$
* At $A >> A_R \Rightarrow \theta_m \to \frac{\pi}{2} - \theta$

• In terms of the instantaneous mass eigenstates in matter: $$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = U[\theta_m(x)] \begin{pmatrix} \nu_1^m(x) \\ \nu_2^m(x) \end{pmatrix}$$

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we can express the evolution equation in the instantaneous mass basis:

$$i \begin{pmatrix} \dot{\nu}_1^m \\ \dot{\nu}_2^m \end{pmatrix} = \frac{1}{4E} \begin{pmatrix} -\Delta\mu^2(x) & -4\,i\,E\,\dot{\theta}_m(x) \\ 4\,i\,E\,\dot{\theta}_m(x) & \Delta\mu^2(x) \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

Not diagonal ⇒ Instantaneous mass states $\neq$ evolution eigenstates $\equiv$ *Non adiabaticity*

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Not diagonal ⇒ Instantaneous mass states ≠ evolution eigenstates ≡ *Non adiabaticity*

• For $\Delta\mu^2(x) \gg 4\,E\,\dot{\theta}_m(x)$ $\left[\frac{1}{V}\frac{dV}{dx}\Big|_R \ll \frac{\Delta m^2}{2E}\frac{\sin^2 2\theta}{\cos 2\theta}\right]$ ≡ Slowly varying matter potent

⇒ ν_i^m behave approximately as *evolution eigenstates*

⇒ ν_i^m do not mix in the evolution This is the *adiabatic* transition approximation

• In terms of the instantaneous mass eigenstates in matter: $\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = U[\theta_m(x)] \begin{pmatrix} \nu_1^m(x) \\ \nu_2^m(x) \end{pmatrix}$

we can express the evolution equation in the instantaneous mass basis:

$$i \begin{pmatrix} \dot{\nu}_1^m \\ \dot{\nu}_2^m \end{pmatrix} = \frac{1}{4E} \begin{pmatrix} -\Delta\mu^2(x) & -4\,i\,E\,\dot{\theta}_m(x) \\ 4\,i\,E\,\dot{\theta}_m(x) & \Delta\mu^2(x) \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

Not diagonal ⇒ Instantaneous mass states ≠ evolution eigenstates ≡ *Non adiabaticity*

• For $\Delta\mu^2(x) \gg 4\,E\,\dot{\theta}_m(x)$ $\left[\frac{1}{V} \frac{dV}{dx}\Big|_R \ll \frac{\Delta m^2}{2E} \frac{\sin^2 2\theta}{\cos 2\theta} \right]$ ≡ Slowly varying matter potent

⇒ ν_i^m behave approximately as *evolution eigenstates*

⇒ ν_i^m do not mix in the evolution This is the *adiabatic* transition approximation

• Solar neutrinos are ν_e:

– with energies $E_\nu \sim 0.1$–10 MeV

– produced in the core of the Sun where $V_{CC,0} \sim 10^{-14}$–10^{-12} eV

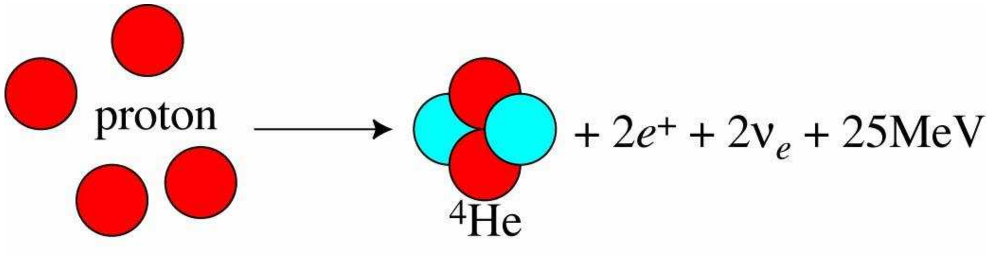
⇒ For $\frac{(\Delta m^2/\text{eV}^2)\sin^2 2\theta}{(E/\text{MeV})\cos 2\theta} \gg 3 \times 10^{-9}$

Averaged oscillation between Sun-Earth & Adiabatic transition in Sun matter

$$P_{ee} = \tfrac{1}{2}\left[1 + \cos 2\theta_{m,0} \cos 2\theta\right] \simeq \tfrac{1}{2}\left[1 - \cos^2 2\theta\right] \simeq \sin^2\theta \le \tfrac{1}{2}$$

Solar Neutrinos

- Sun shines by nuclear fusion of protons into He



And only ν_e are produced

Solar Neutrinos

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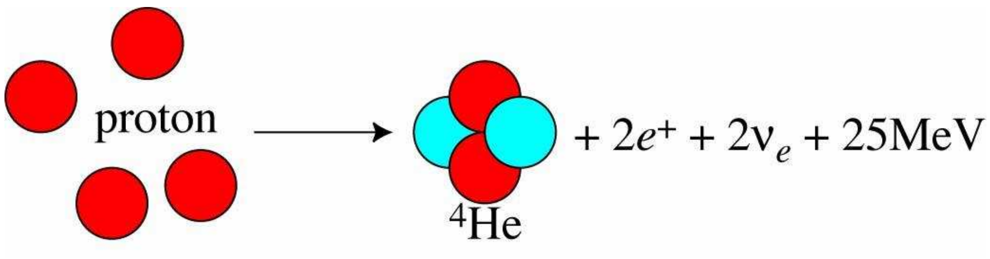
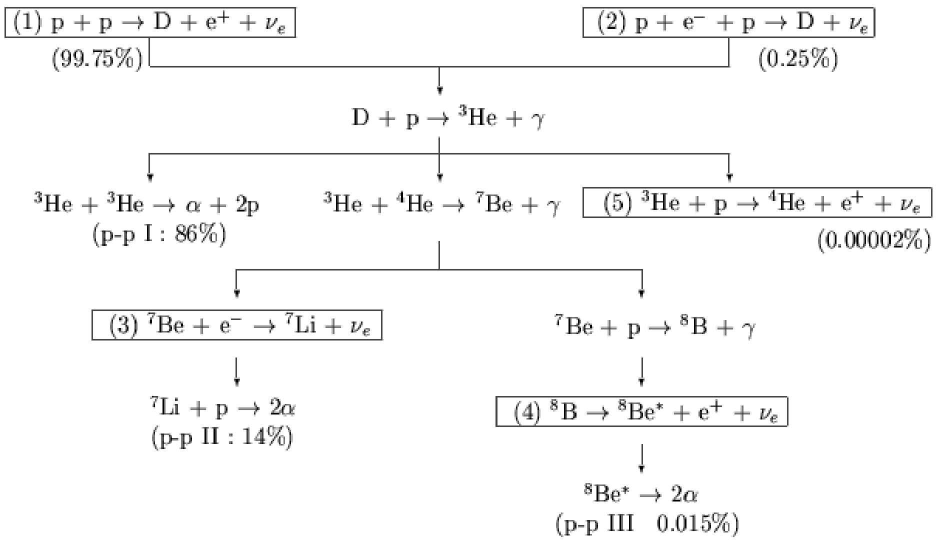


And only ν_e are produced

- Two main chains of nuclear reactions

pp Chain :



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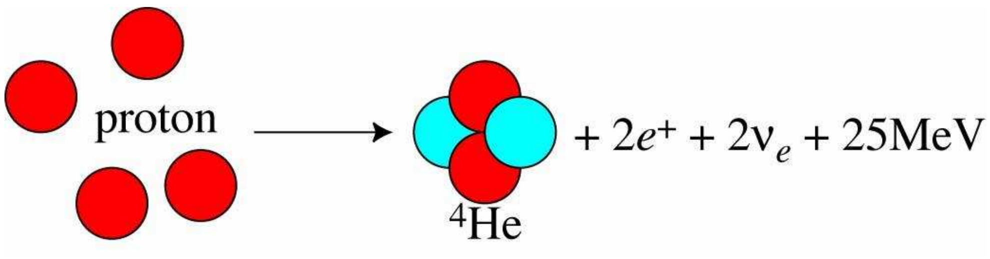

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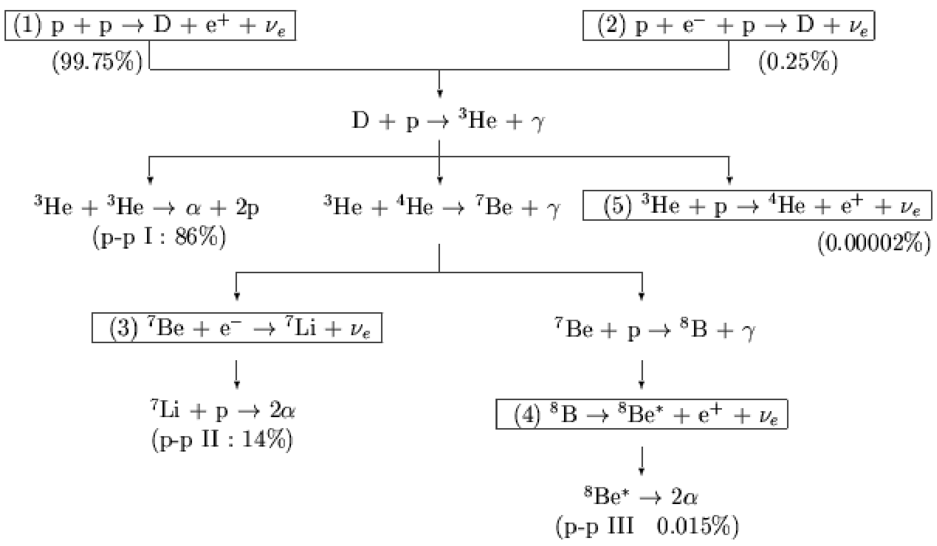
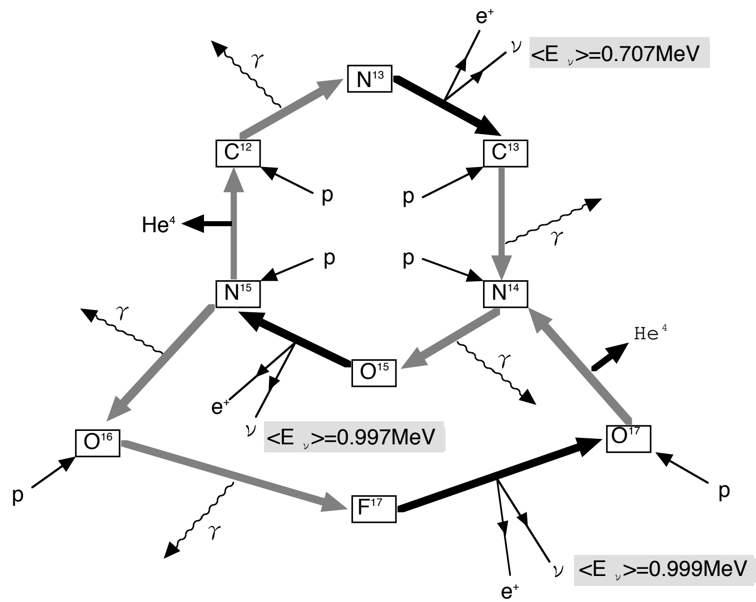
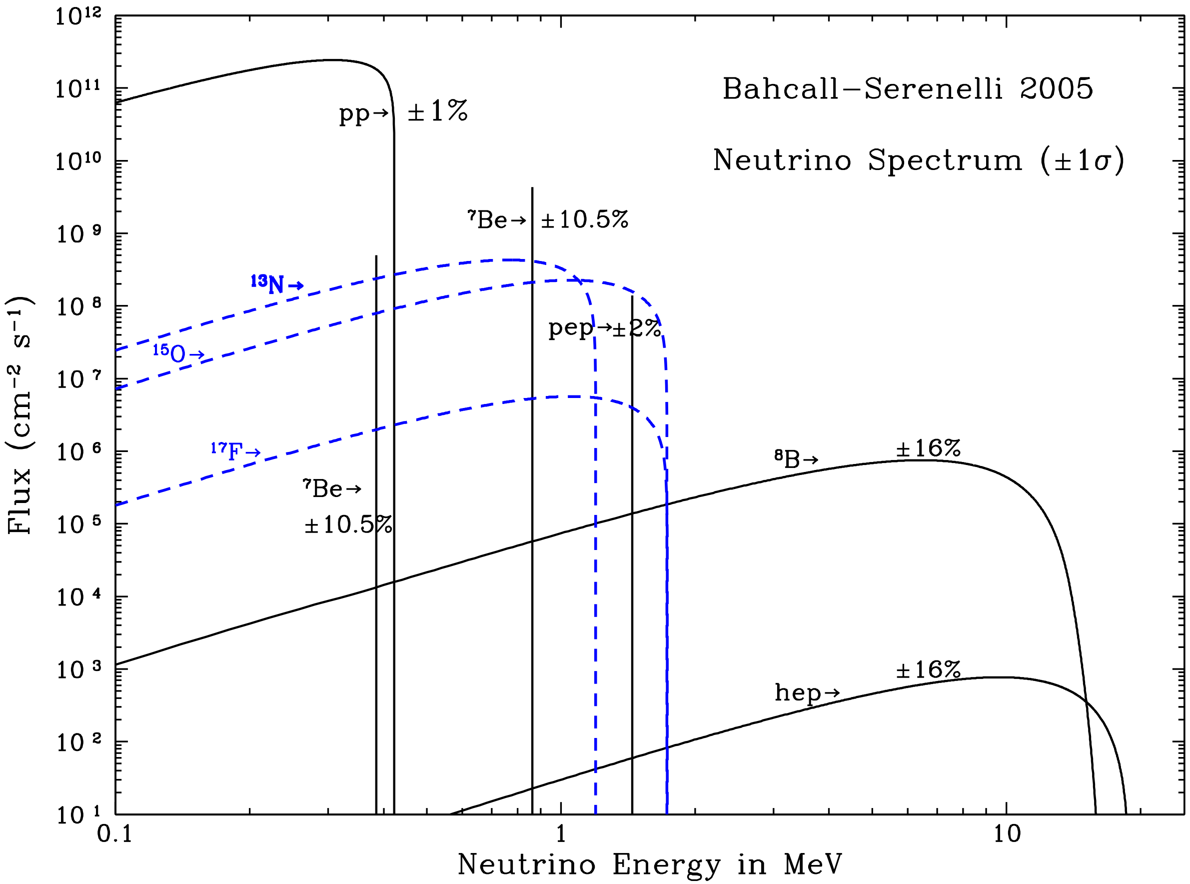


CNO cycle:



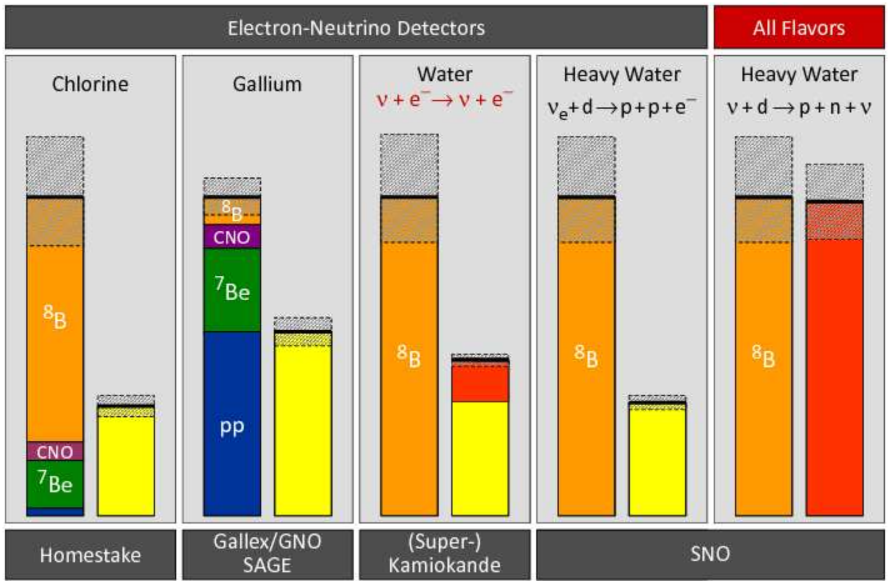
Solar Neutrinos: Fluxes



PP CHAIN	E_ν (MeV)
(pp)	
$p + p \to^2 H + e^+ + \nu_e$	≤ 0.42
(pep)	
$p + e^- + p \to^2 H + \nu_e$	1.552
(^{7}Be)	
$^7Be + e^- \to^7 Li + \nu_e$	$0.862 (90\%)$
	0.384 (10%)
(hep)	
$^2He + p \to^4 He + e^+ + \nu_e$	≤ 18.77
(^{8}B)	
$^8B \to^8 Be^* + e^+ + \nu_e$	≤ 15
CNO CHAIN	E_ν (MeV)
(^{13}N)	
$^{13}N \to^{13} C + e^+ + \nu_e$	≤ 1.199
(^{15}O)	
$^{15}O \to^{15} N + e^+ + \nu_e$	≤ 1.732
(^{17}F)	
$^{17}F \to^{17} O + e^+ + \nu_e$	≤ 1.74

Solar Neutrinos: Results

	Experiment	Detection	Flavour	$E_{\rm th}$ (MeV)
radio-chemical	Homestake	$^{37}\mathrm{Cl}(\nu, e^-)^{37}\mathrm{Ar}$	ν_e	$E_\nu > 0.81$
	Sage + Gallex+GNO	$^{71}\mathrm{Ga}(\nu, e^-)^{71}\mathrm{Ge}$	ν_e	$E_\nu > 0.23$
real time	Kam ⇒ SK	ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$ $\left(\frac{\sigma_{\mu\tau}}{\sigma_e} \simeq \frac{1}{6}\right)$	$E_e > 5$
	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$
		NC $\nu_x d \to \nu_x p\, n$	$\nu_e, \nu_{\mu/\tau}$	$T_\gamma > 5$
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$
	Borexino	$\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$E_\nu = 0.862$



Experiments measuring ν_e observe a deficit

Deficit disappears in NC

⇒ Solar Model Independent Effect

Deficit is energy dependent

Deficit ⇒ $P_{ee} \sim 30\%\ (< 0.5)$ for $E_\nu \gtrsim 0.8$ MeV

⇒ Vaccum oscillations??

Solar Neutrinos: Results

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	SNO	CC $\nu_e d \to p p e^-$	ν_e	$T_e > 5$
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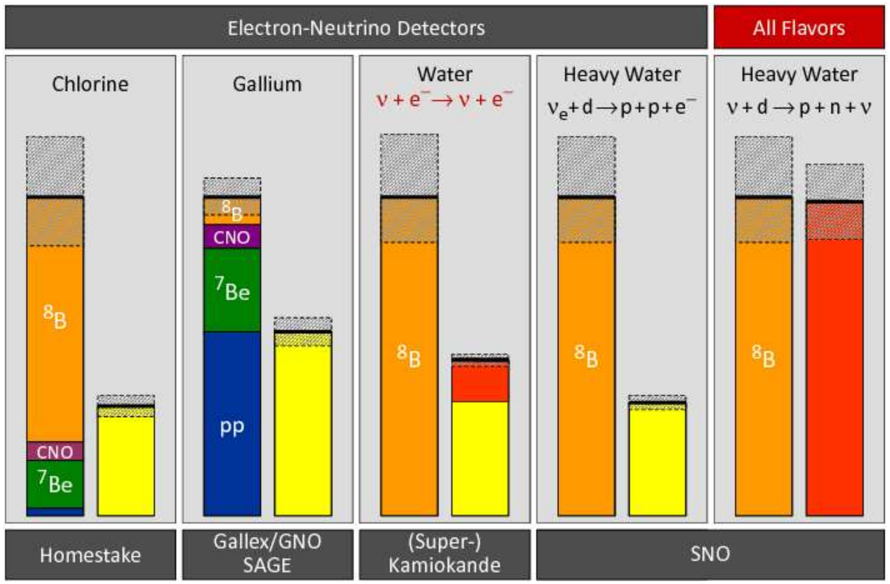
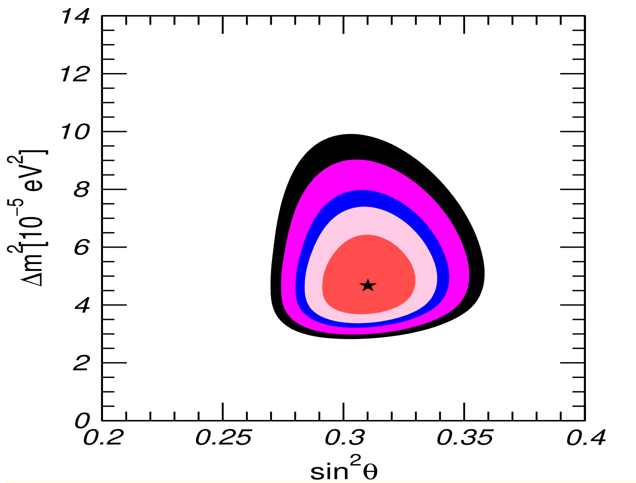
		ES $\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$T_e > 5$
	Borexino	$\nu_x e^- \to \nu_x e^-$	$\nu_e, \nu_{\mu/\tau}$	$E_\nu = 0.862$



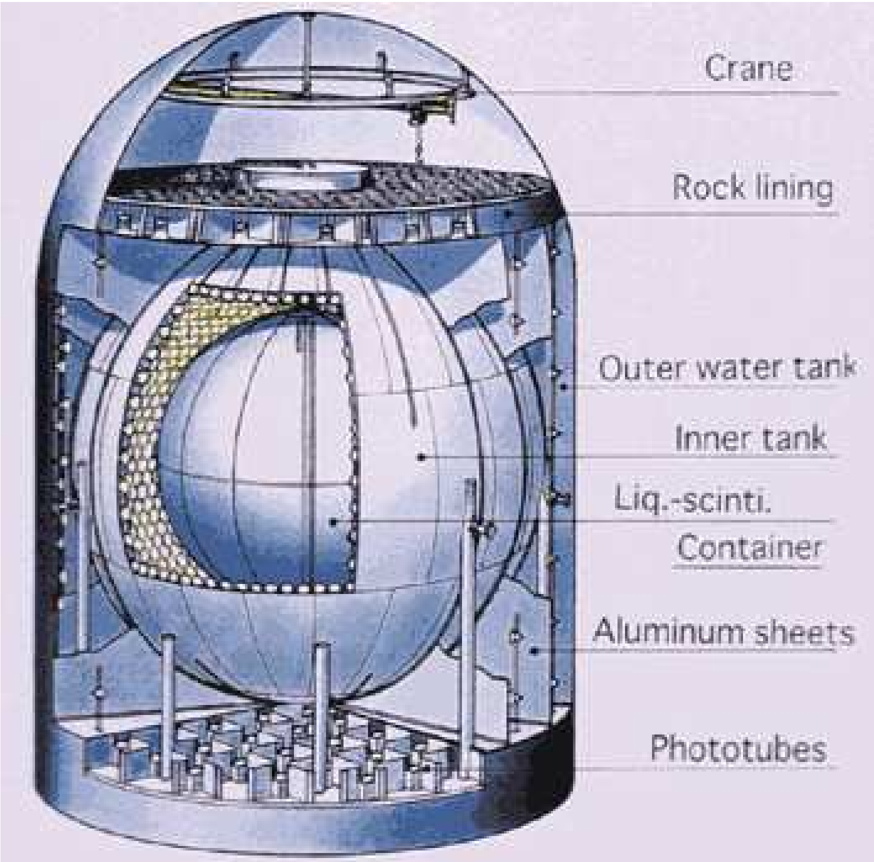
Best explained by $\nu_e \to \nu_{\mu,\tau}$

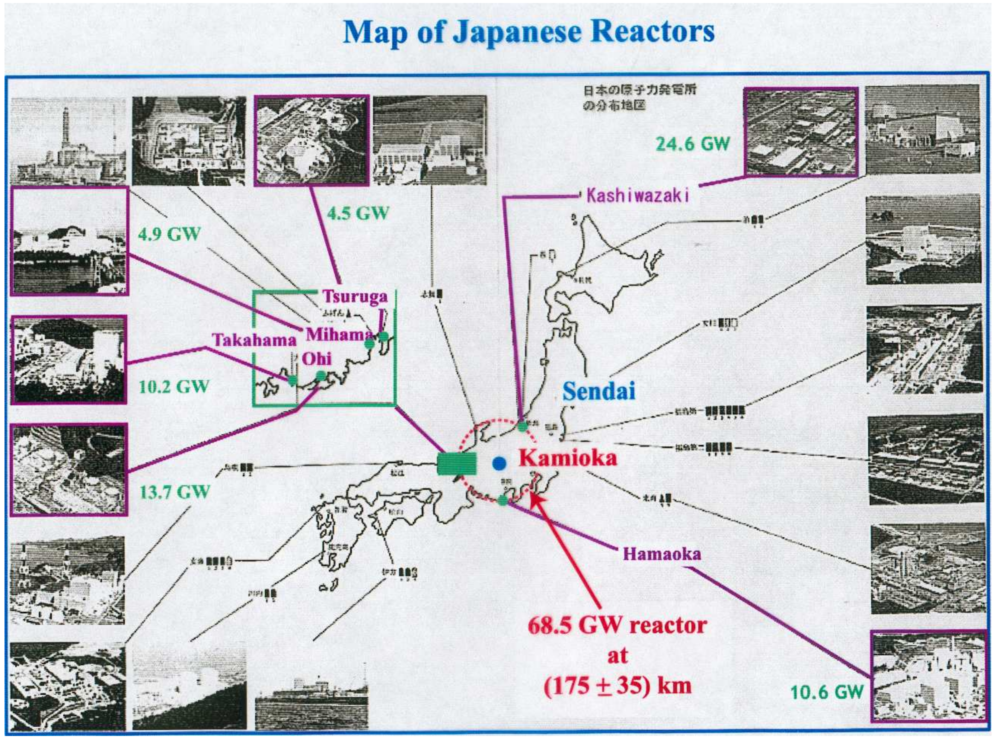


$\Delta m^2 \sim 5 \times 10^{-5}$ eV^2, $\theta \sim \frac{\pi}{6}$

Terrestrial test of LMA: KamLAND

KamLAND: Detector of $\bar{\nu}_e$ produced in nuclear reactors in Japan at an average distance of 180 Km





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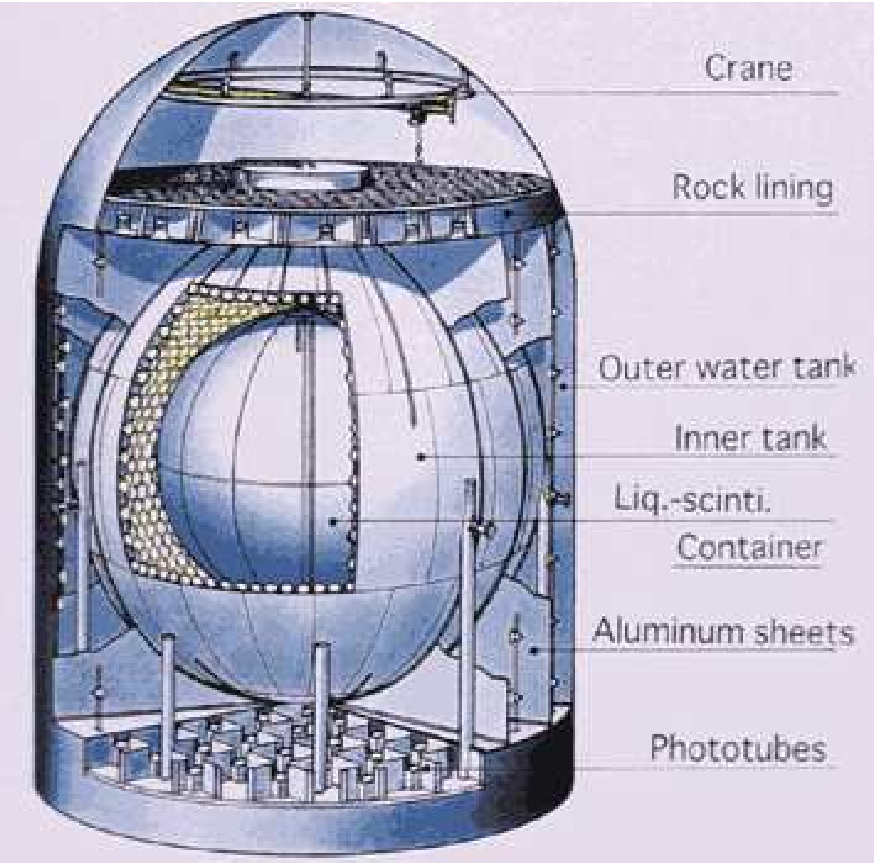
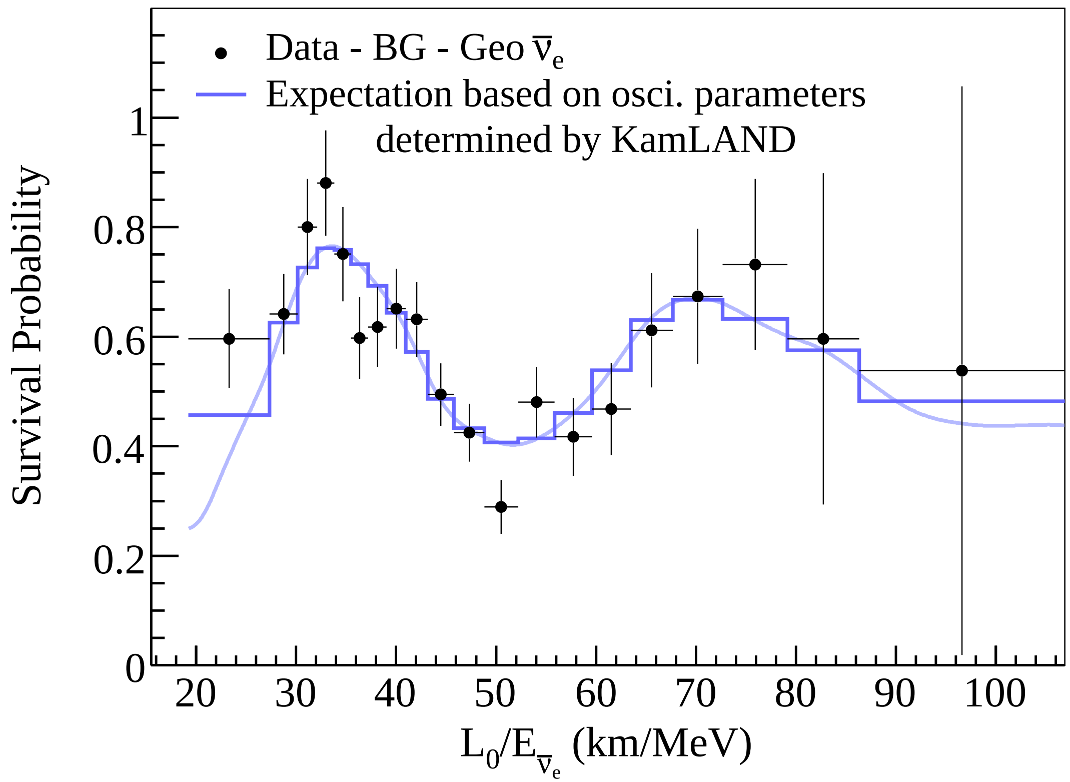


Results of KamLAND compared with P_{ee} for

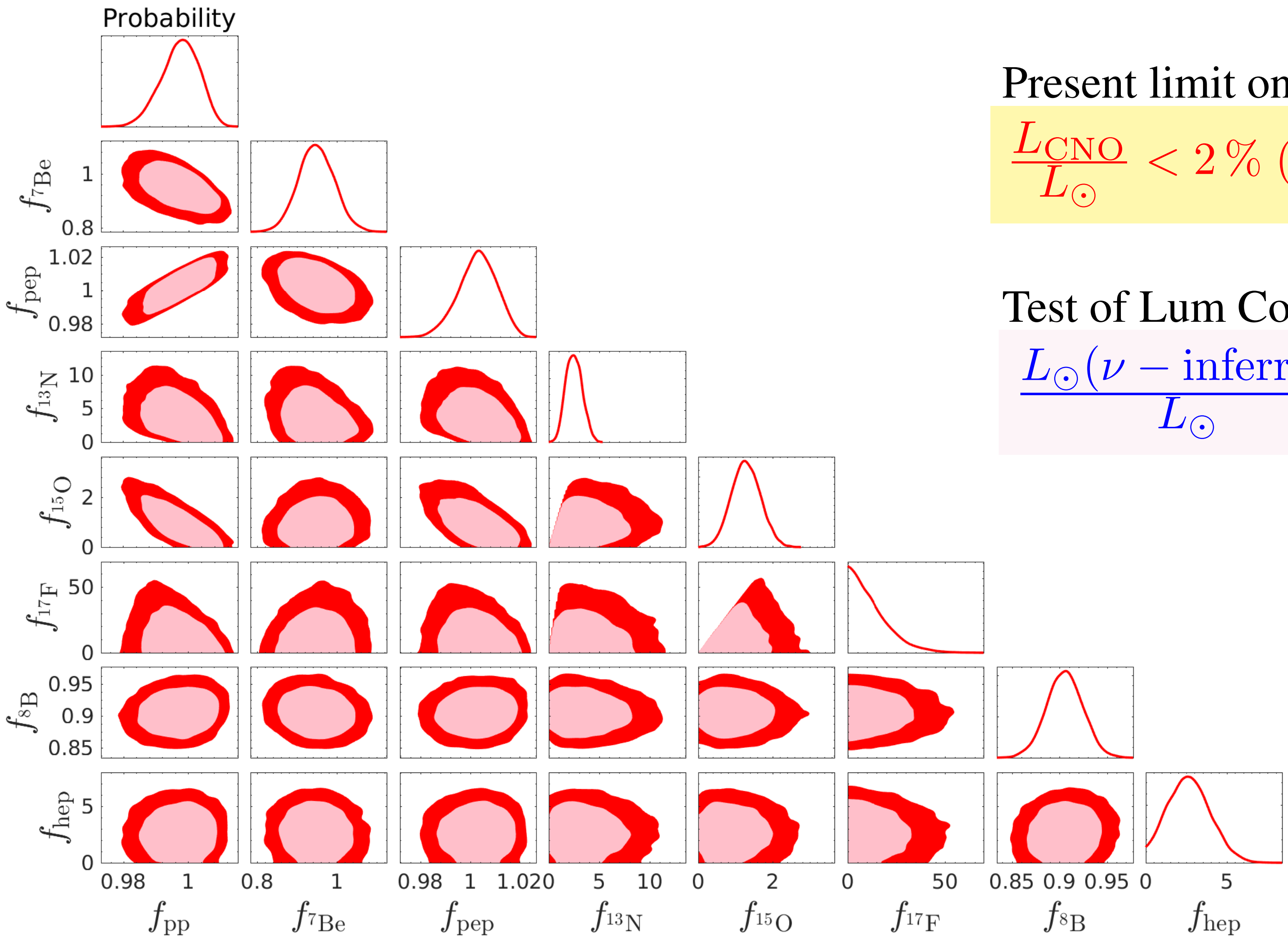
$\theta = 35^\circ$ y $\Delta m^2 = 7.5 \times 10^{-5}$ $(\mathrm{eV/c^2})^2$



Byproduct: Testing How the Sun Shines with $\nu' s$

Fitting together Δm^2, θ and normalization of ν-producing reactions: $f_i = \frac{\Phi_i}{\Phi_i^{SSM}}$

$\Rightarrow$ Constraint on solar energy produced by nuclear



Present limit on CNO:

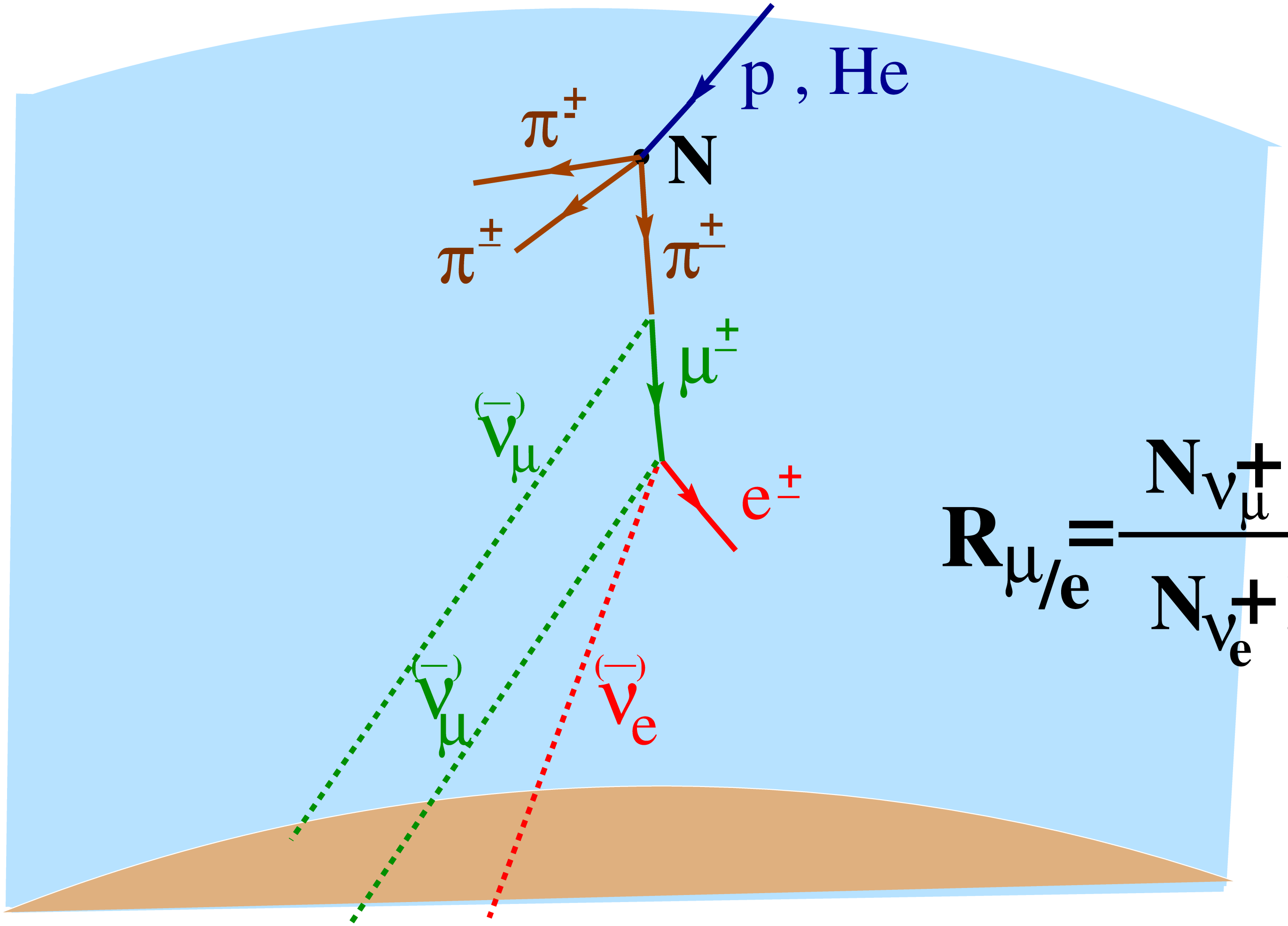
$$\frac{L_{\mathrm{CNO}}}{L_\odot} < 2\,\%\ (3\sigma)$$

Test of Lum Constraint:

$$\frac{L_\odot(\nu - \mathrm{inferred})}{L_\odot} = 1.04 \pm 0.07$$

Atmospheric Neutrinos

Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He . . .) with the atmosphere

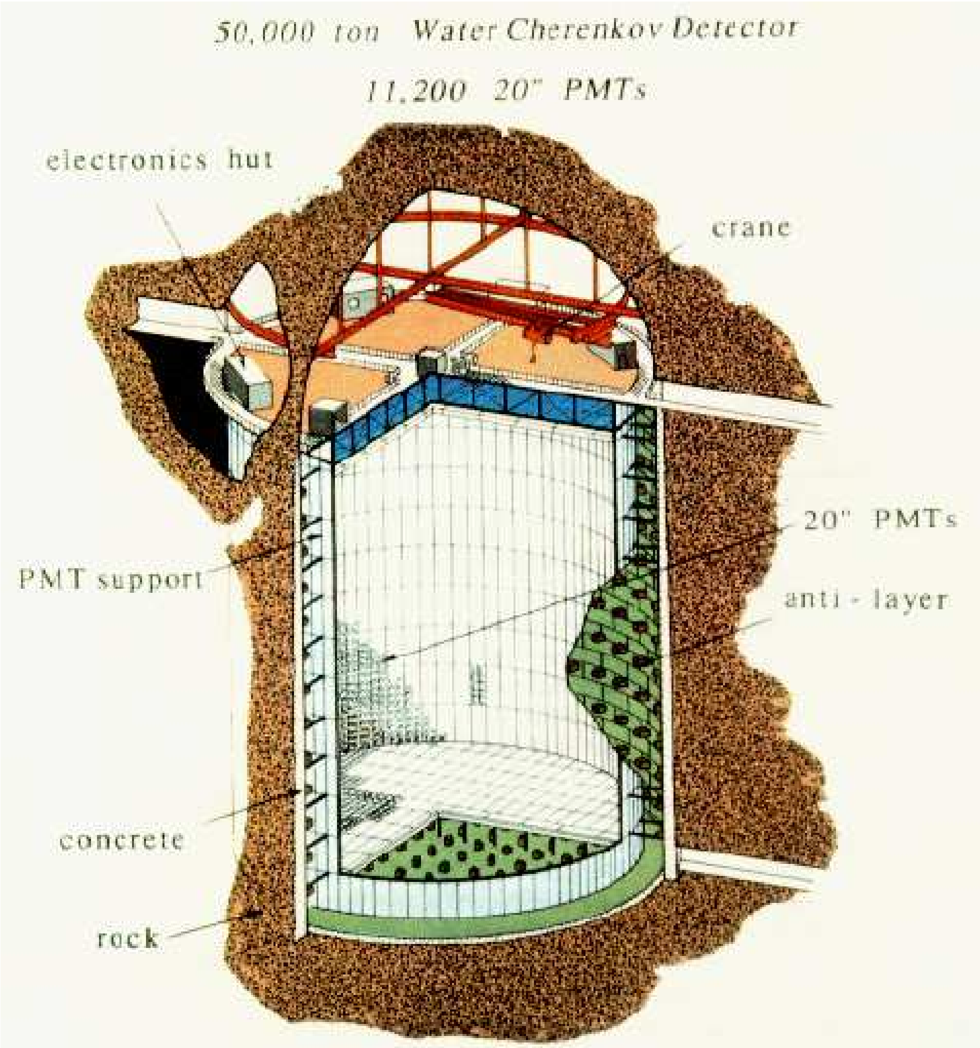


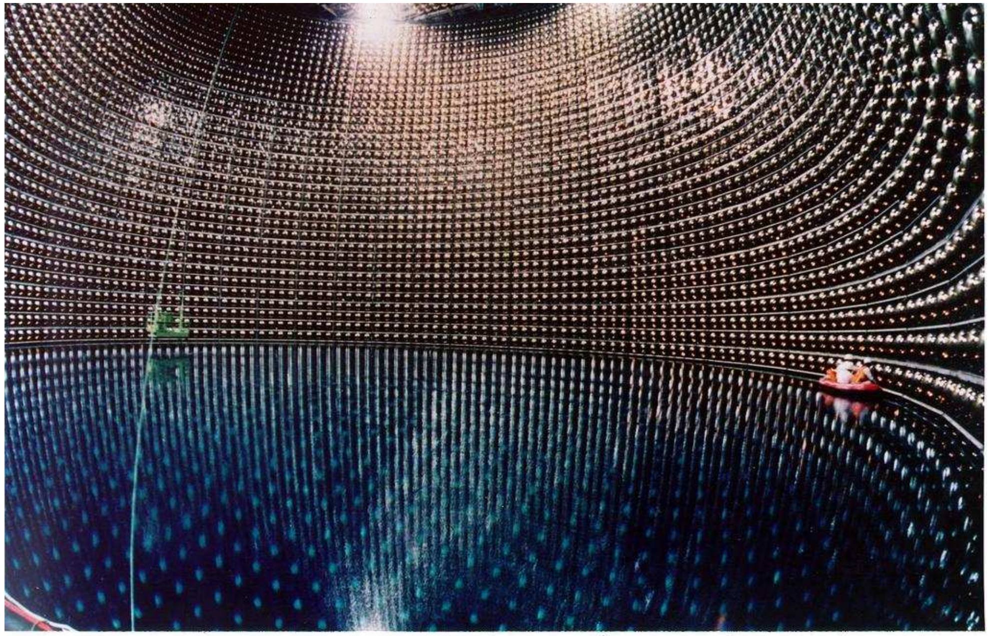
$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

Detection of Atmpospheric Neutrinos: SuperKamiokande

Located in the Kamiokande mine in the center of Japan at $\sim$ 1Km deep

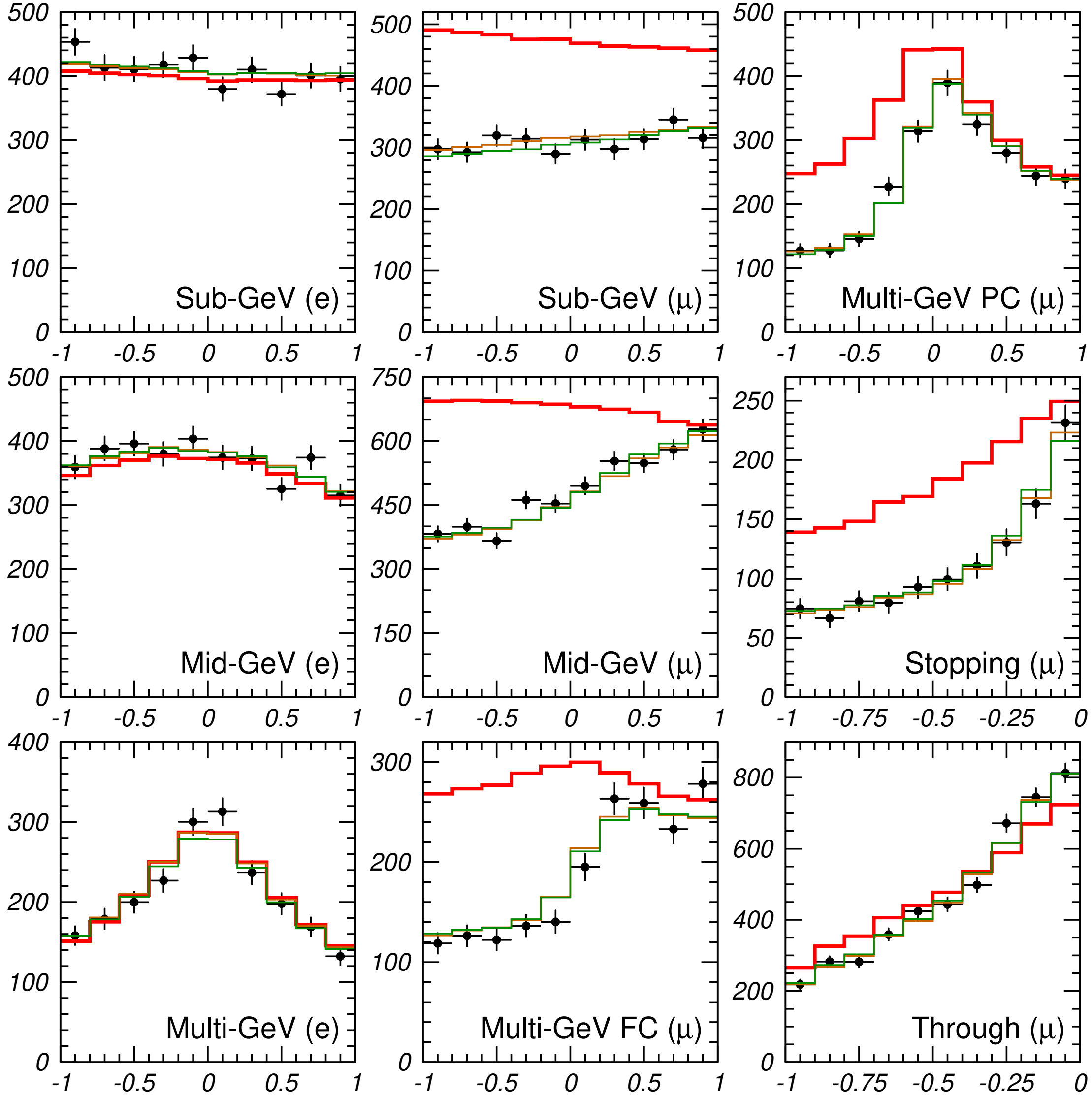
50 Kton of water surounded by $\sim$ 12000 photomultipliers

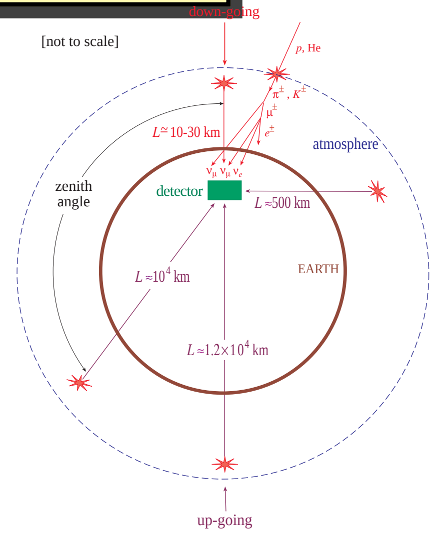


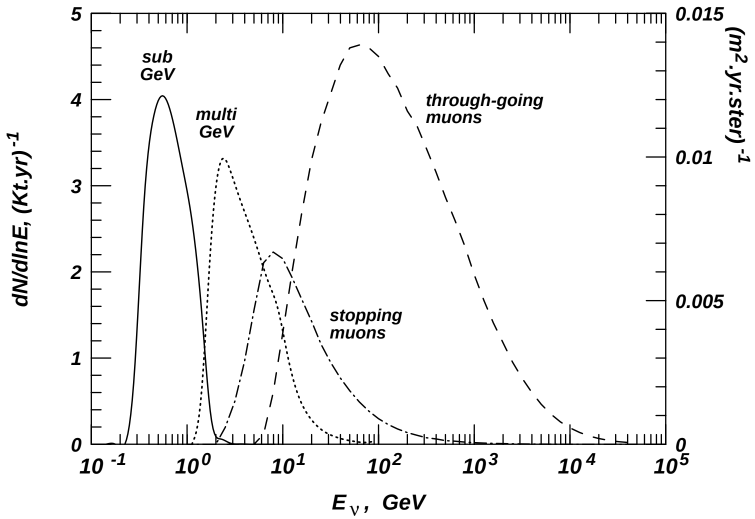


Atmospheric Neutrinos:Results

- SKI+II+III+IV data:



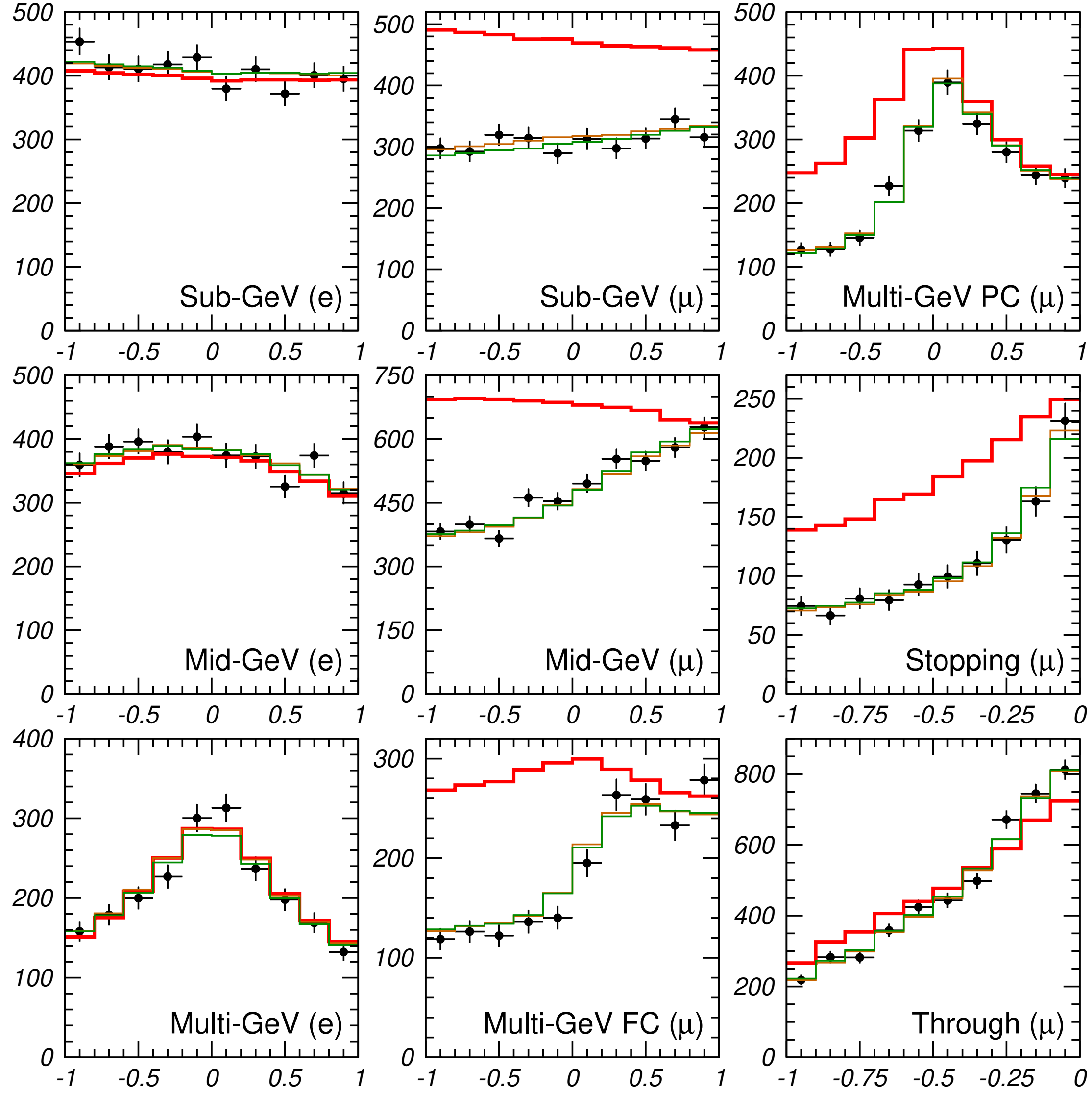


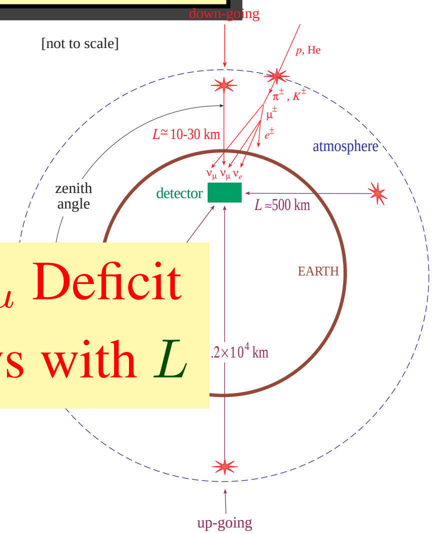


Atmospheric Neutrinos:Results

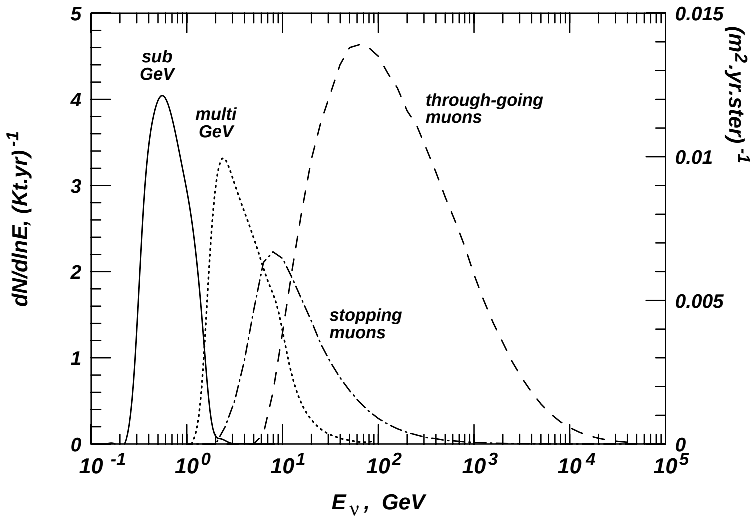
- SKI+II+III+IV data:

ν_e in agreement with SM





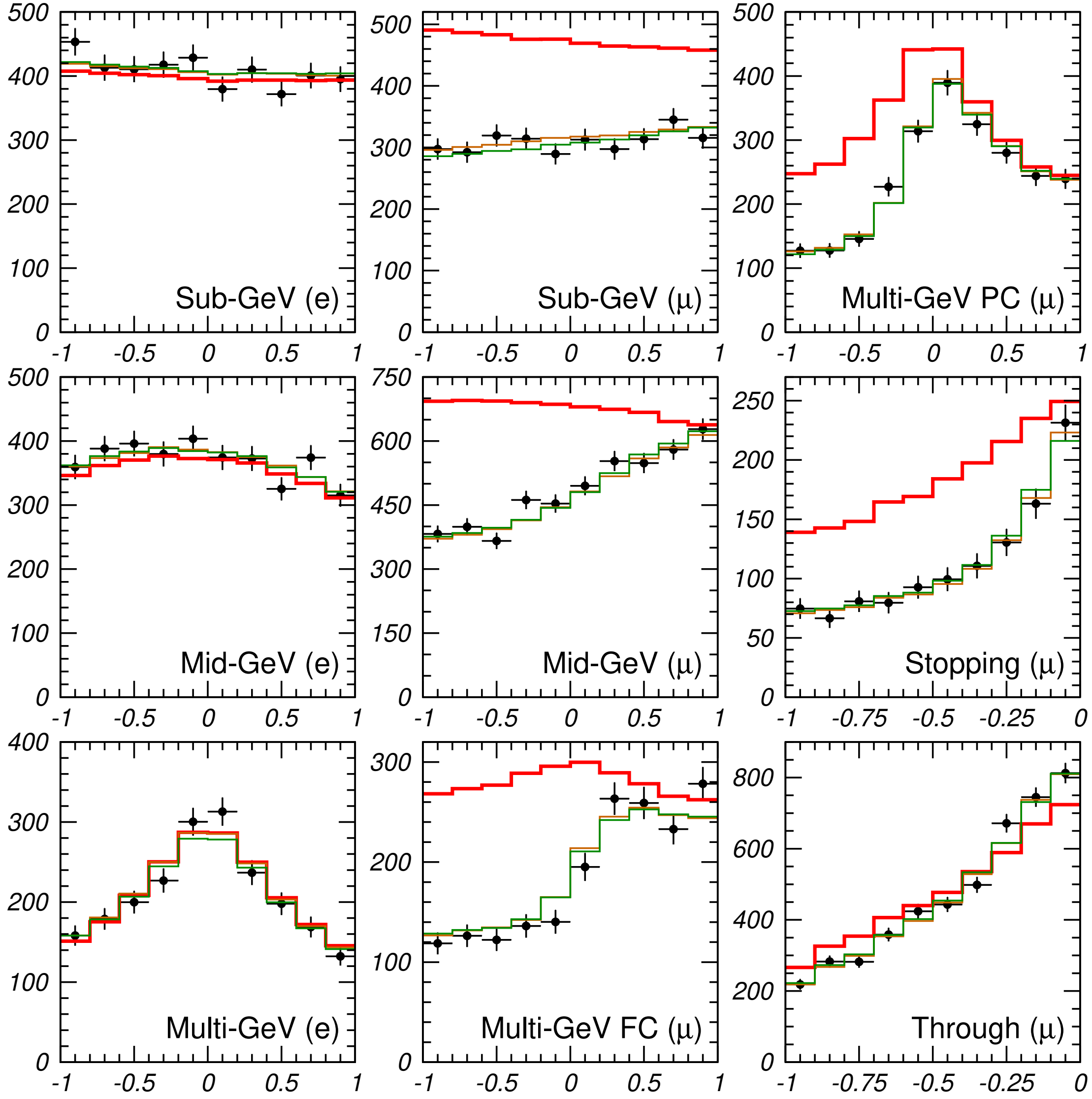
$\rightarrow \nu_\mu$ Deficit grows with L



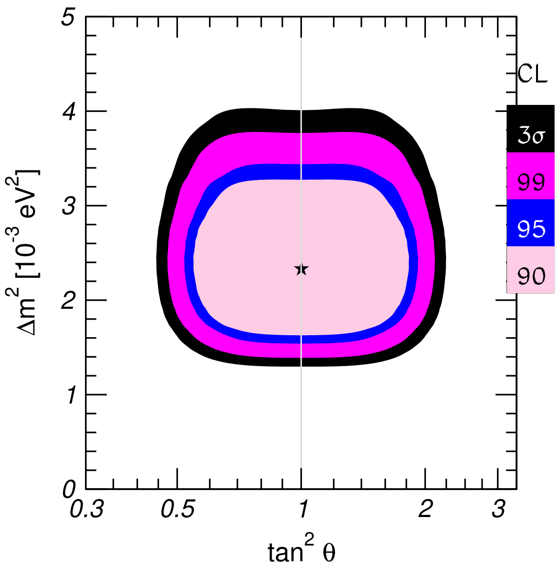
$\rightarrow \nu_\mu$ Deficit decreases with E

Atmospheric Neutrinos: Results

- SKI+II+III+IV data:



Best explained by $\nu_\mu \to \nu_\tau$



$$\Delta m^2 \sim 2.4 \times 10^{-3} \text{ eV}^2$$
$$\tan^2\theta \sim 1 \Rightarrow \theta \sim \frac{\pi}{4}$$

Alternative Oscillation Mechanisms

- Oscillations are due to:
  - Misalignment between CC-int and propagation states: Mixing $\Rightarrow$ Amplitude
  - Difference phases of propagation states $\Rightarrow$ Wavelength. For Δm^2-OSC $\lambda = \frac{4\pi E}{\Delta m^2}$

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- ν masses are not the only mechanism for oscillations

Violation of Equivalence Principle (VEP): Gasperini 88, Halprin,Leung 01

Non universal coupling of neutrinos $\gamma_1 \neq \gamma_2$ *to gravitational potential* ϕ

$$\lambda = \frac{\pi}{E|\phi|\delta\gamma}$$

Violation of Lorentz Invariance (VLI): Coleman, Glashow 97

Non universal asymptotic velocity of neutrinos $c_1 \neq c_2 \Rightarrow E_i = \frac{m_i^2}{2p} + c_i p$

$$\lambda = \frac{2\pi}{E\Delta c}$$

Interactions with space-time torsion: Sabbata, Gasperini 81

Non universal couplings of neutrinos $k_1 \neq k_2$ *to torsion strength* Q

$$\lambda = \frac{2\pi}{Q\Delta k}$$

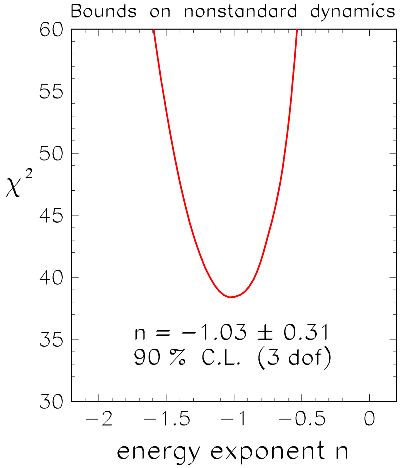
Violation of Lorentz Invariance (VLI) Colladay, Kostelecky 97; Coleman, Glashow 99

due to CPT violating terms: $\bar{\nu}_L^{\alpha} b_{\mu}^{\alpha\beta} \gamma_{\mu} \nu_L^{\beta} \Rightarrow E_i = \frac{m_i^2}{2p} \pm b_i$

$$\lambda = \pm \frac{2\pi}{\Delta b}$$

Alternative Mechanisms vs ATM ν's

- With early SK ATM's
  they could be rule out as dominant



Fogli, Lisi and Marrone hep-ph/0105139

Different L/E dependence:

$P_{\mu\tau} = \alpha \sin^2(\beta L E^n)$

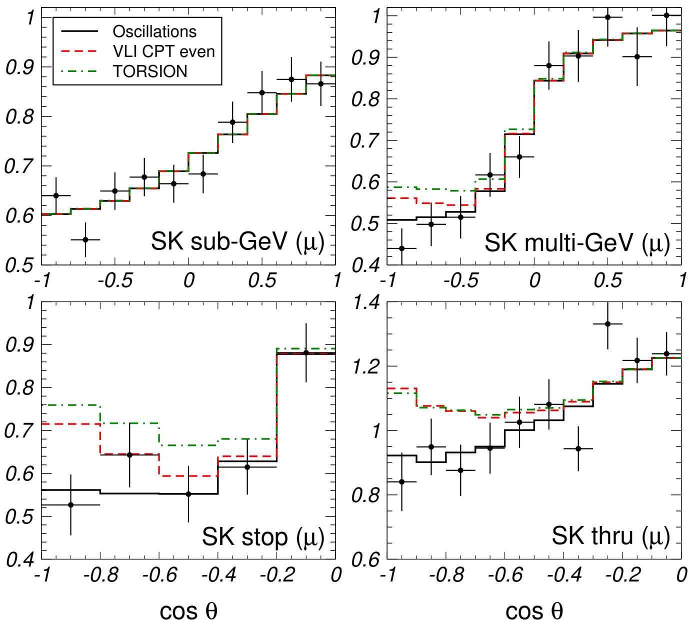
$n = -1$ oscillations

$n = 1$ Viol Equiv. Principle

$n = 1$ Viol Lorentz invariance

Fit : $n = -1.03 \pm 0.31$ 90%CL

- And soon after severly constrained (MCG-G, M. Maltoni PRD 04,07)



At 90% CL:

$$\frac{|\Delta c|}{c} \leq 1.2 \times 10^{-24}$$

$$|\phi\, \Delta\gamma| \leq 5.9 \times 10^{-25}$$

$$|Q\, \Delta k| \leq 4.8 \times 10^{-23} \text{ GeV}$$

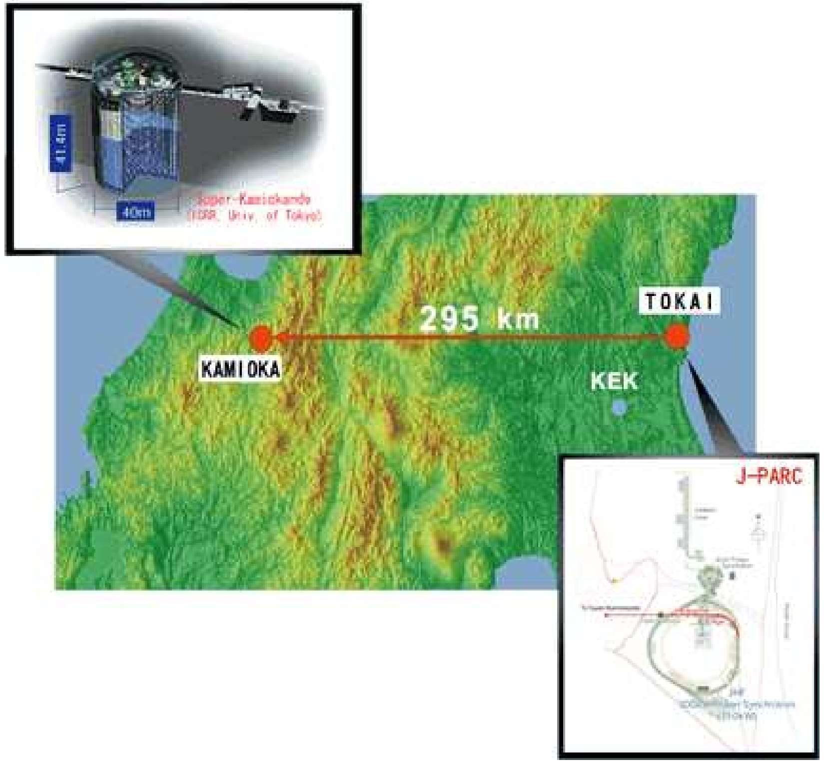
$$|\Delta b| \leq 3.0 \times 10^{-23} \text{ GeV}$$

ν_μ Disappearance in Accelerator ν Fluxes

T2K:

ν_μ produced in Tokai (Japan)

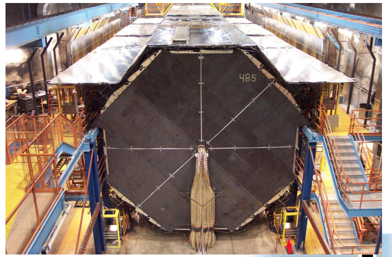
detected in SK at $\sim$ 250 Km



MINOS, NOνA

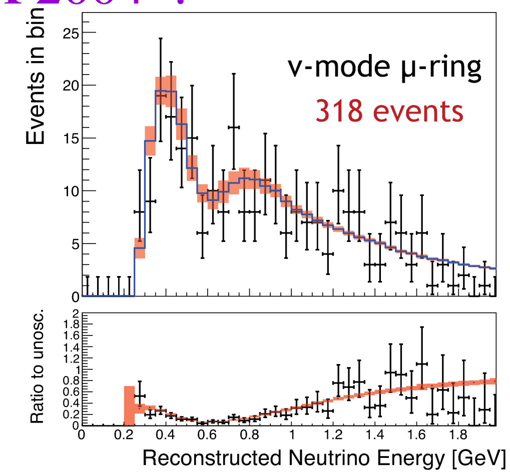
ν_μ produced en Fermilab (Illinois)

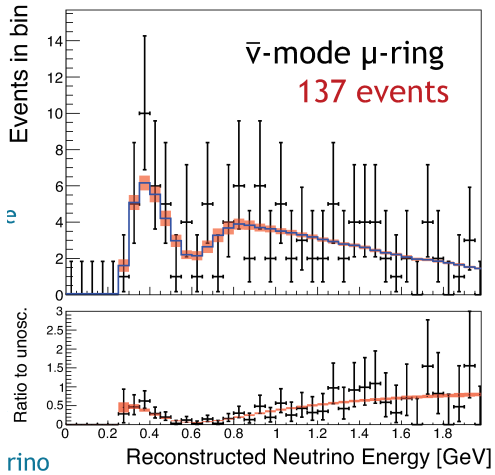
detected in Minnesota at $\sim$ 800 Km



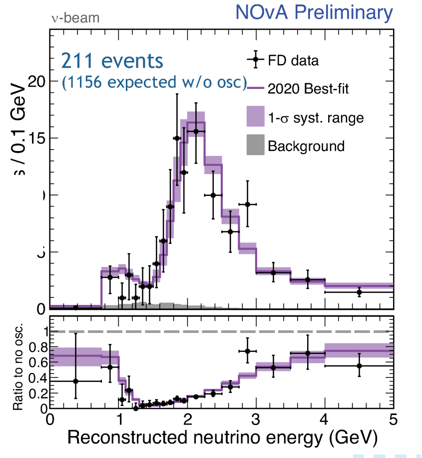
Long Baseline Experiments: ν_μ Disappearance

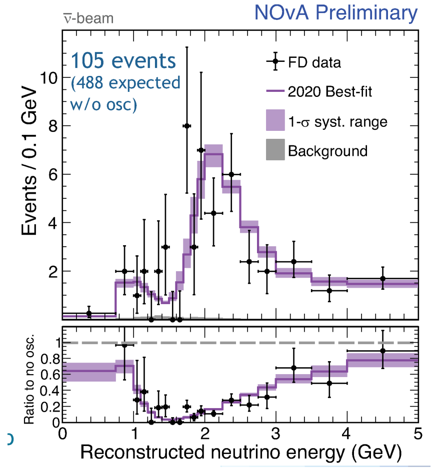
K2K/T2K 2004–:





NOνA: 2015–





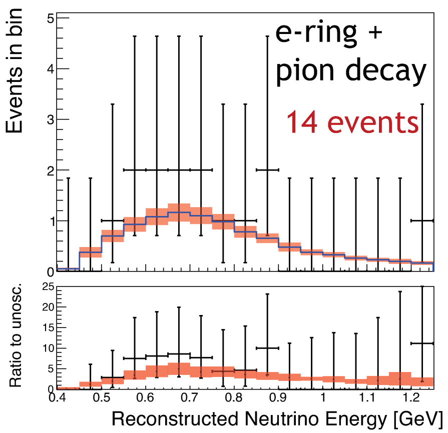
ν_μ oscillations with $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2 and mixing compatible with $\frac{\pi}{4}$

Long Baseline Experiments: ν_e Appearance

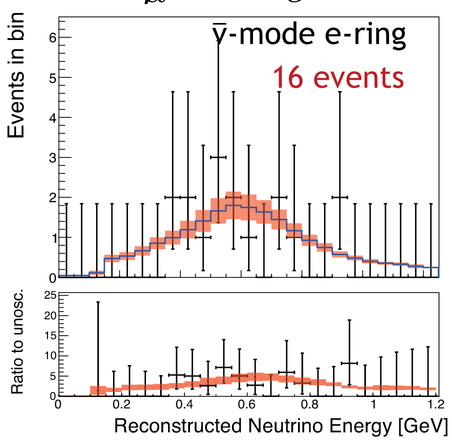
- Observation of $\nu_\mu \to \nu_e$ transitions with $E/L \sim 10^{-3}$ eV^2

T2K

$\nu_\mu \to \nu_e$



$\bar{\nu}_\mu \to \bar{\nu}_e$



NOνA

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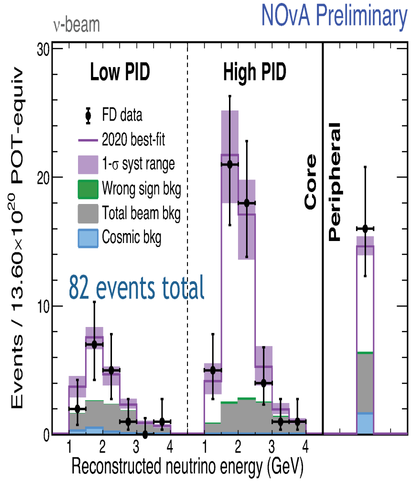
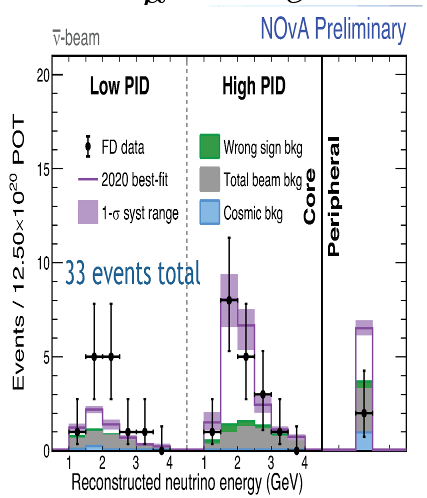


$\bar{\nu}_\mu \to \bar{\nu}_e$



- Test of $P(\nu_\mu \to \nu_e)$ vs $P(\bar{\nu}_\mu \to \bar{\nu}_e) \Rightarrow$ Leptonic CP violation

Medium Baseline Reactor Experiments

- Searches for $\bar{\nu}_e \to \bar{\nu}_e$ disapperance at $L \sim$ Km ($E/L \sim 10^{-3}$ eV^2)
- Relative measurement: near and far detectors

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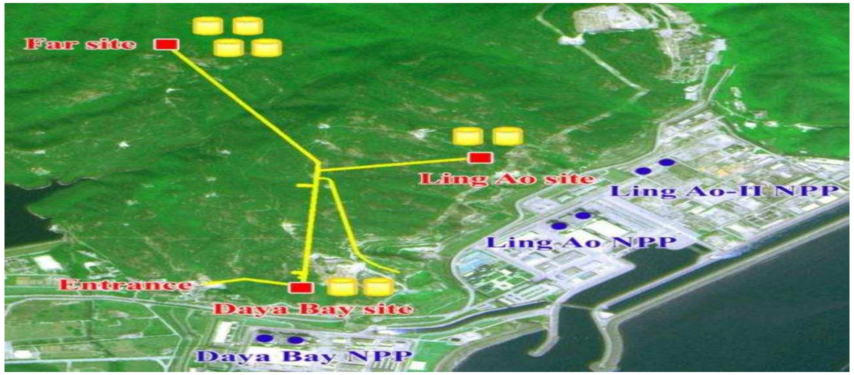
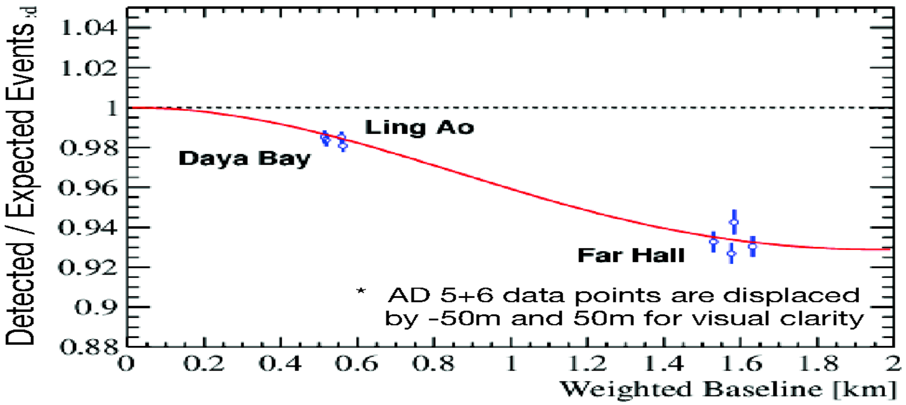
Daya-Bay





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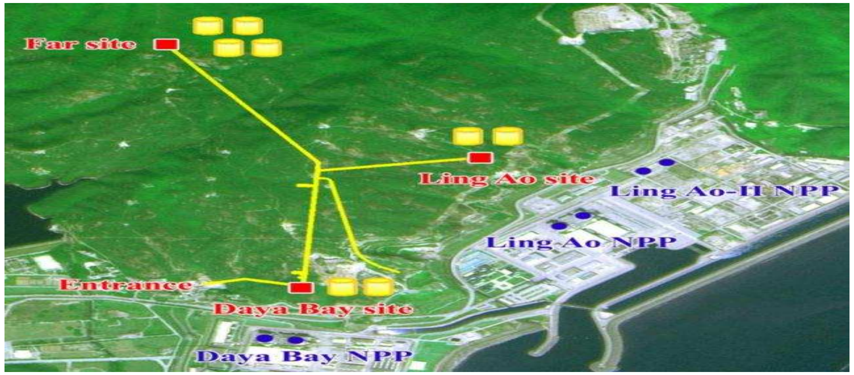
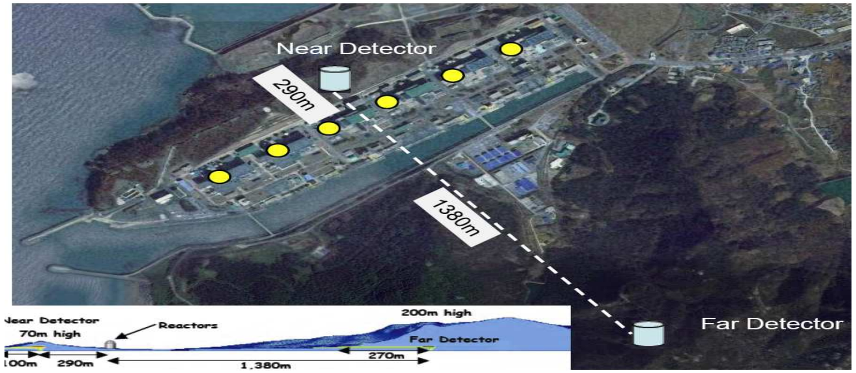
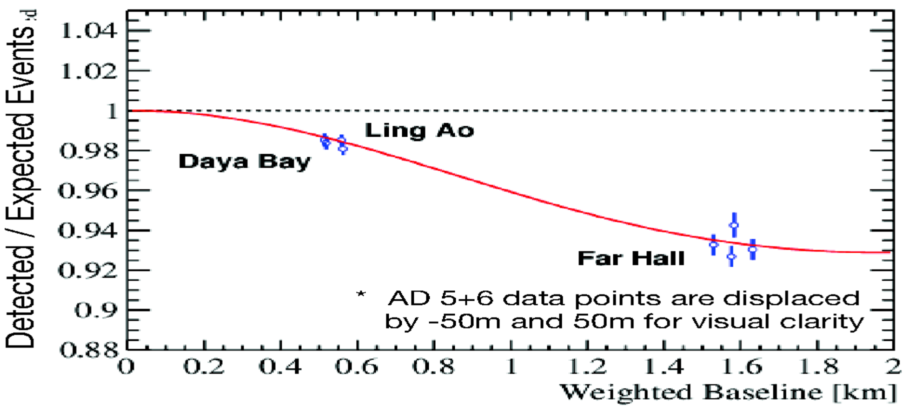
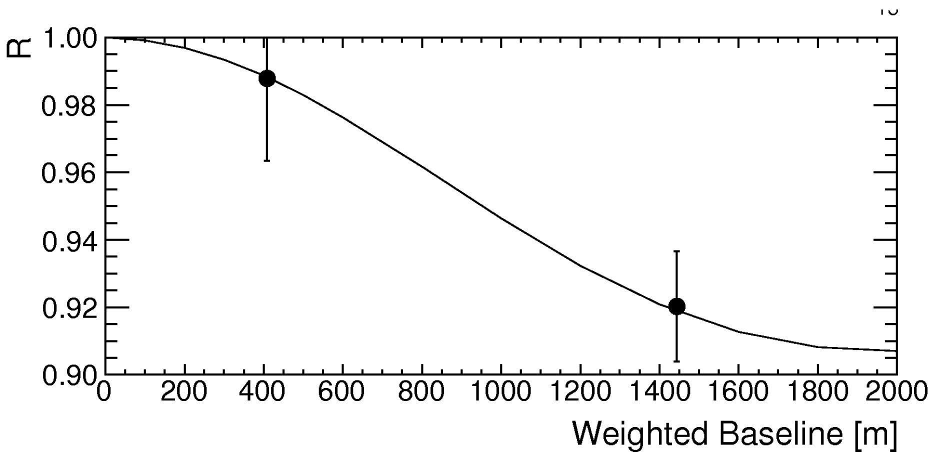


Reno





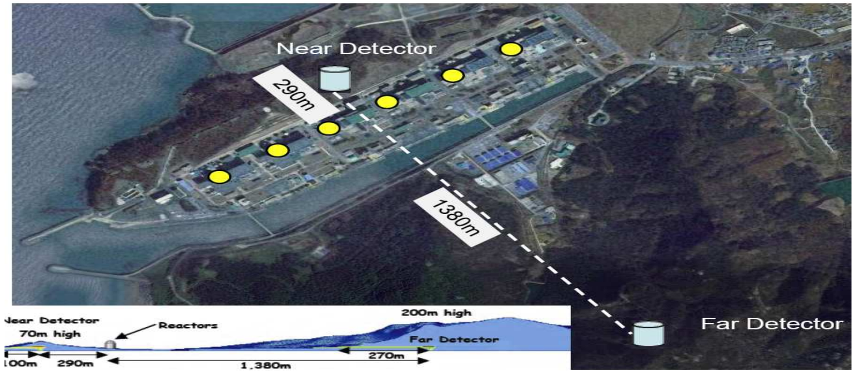


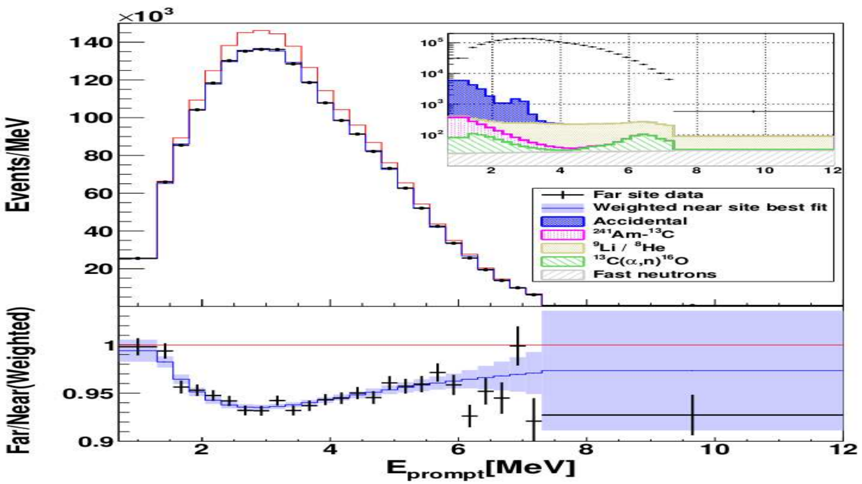
Medium Baseline Reactor Experiments

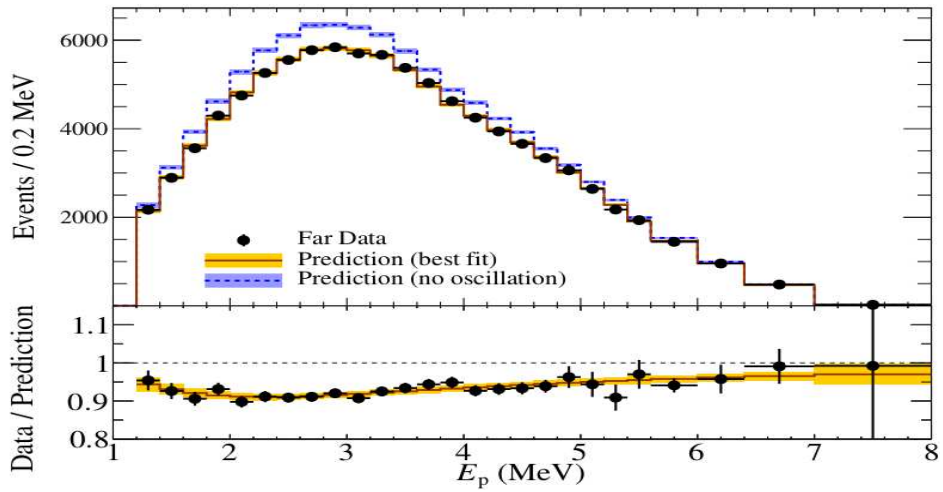
- Searches for $\bar{\nu}_e \to \bar{\nu}_e$ disapperance at $L \sim$ Km ($E/L \sim 10^{-3}$ eV^2)
- Relative measurement: near and far detectors

Daya-Bay

Reno







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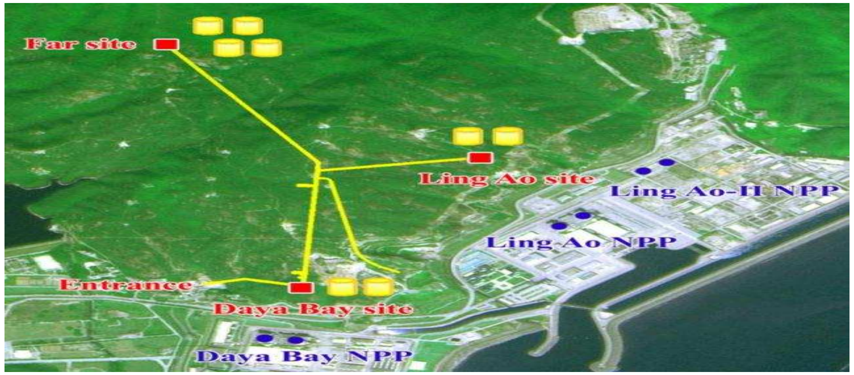

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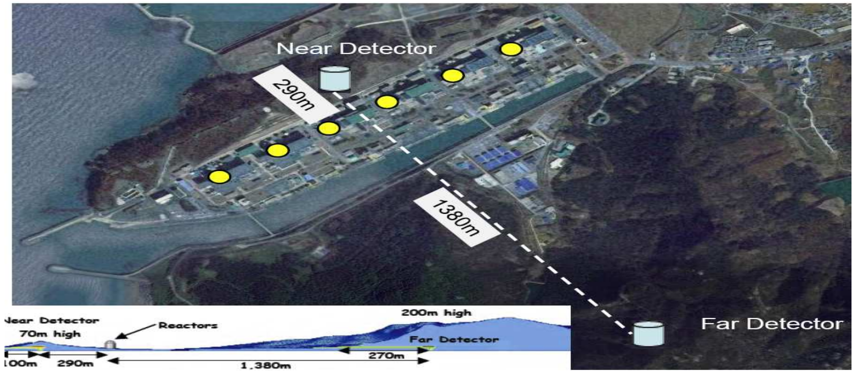
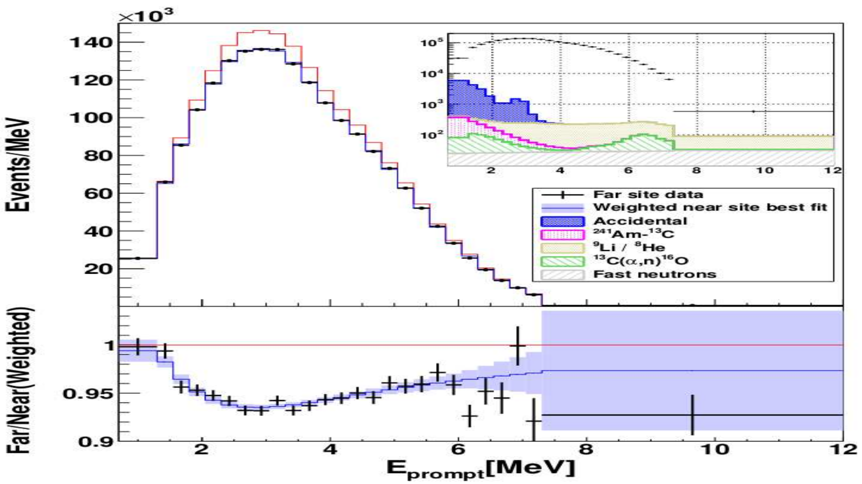
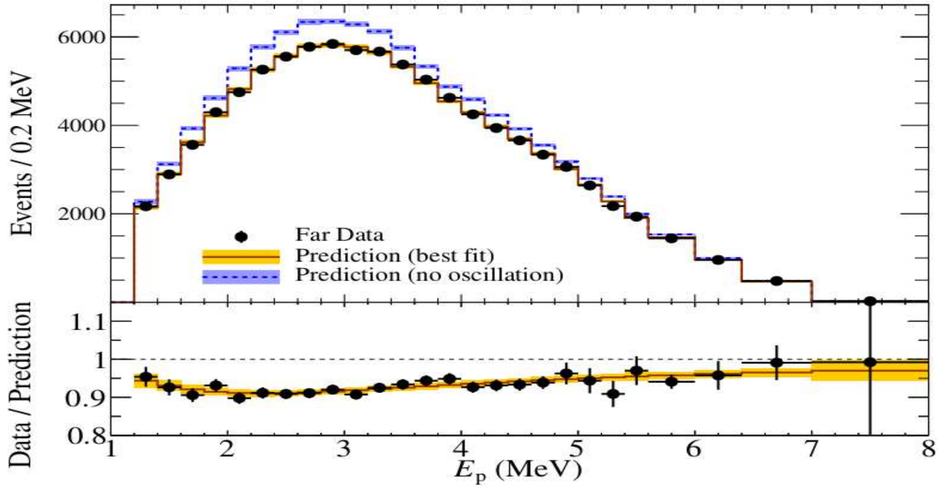






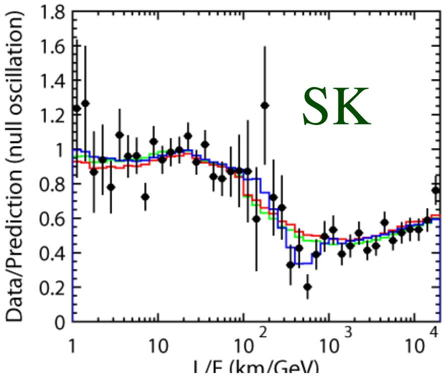
Described with $\Delta m^2 \sim 2.5 \times 10^{-3}$eV^2 (as ν_μ ATM and LBL acc but for ν_e) and $\theta \sim 9^\circ$

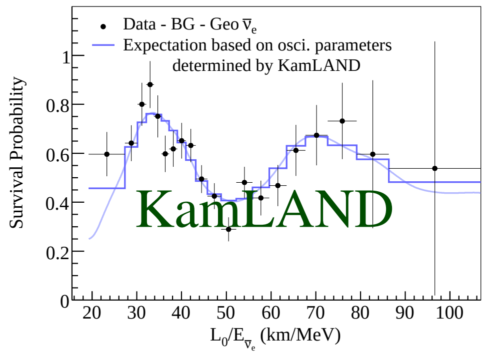
- We have observed with high (or good) precision:

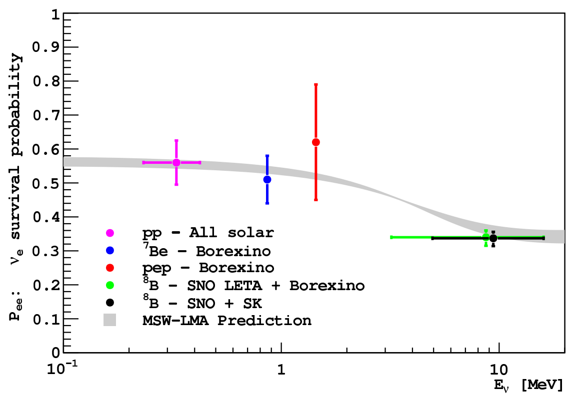
  - $*$ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, ICECUBE) $\frac{\Delta m^2}{\text{eV}^2} \sim 2\,10^{-3}$
  - $*$ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**) $\theta \sim 45^\circ$
  - $*$ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA) $\theta \sim 8^\circ$
  - $*$ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**) $\frac{\Delta m^2}{\text{eV}^2} \sim 10^{-5}, \theta \sim 30^\circ$
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
  - $*$ Reactor $\overline{\nu_e}$ disappear at $L \sim 1$ Km (D-Chooz, **Daya Bay, Reno**) $\frac{\Delta m^2}{\text{eV}^2} \sim 2\,10^{-3}, \theta \sim 8^\circ$

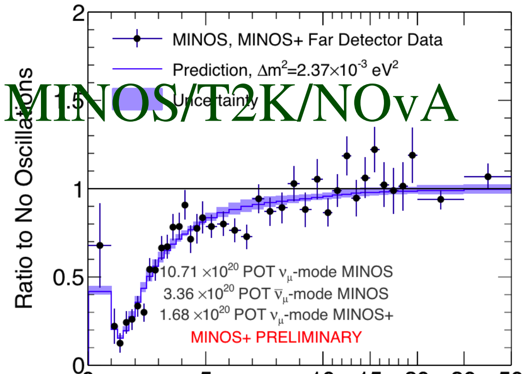
- Confirmed: Vacuum oscillation L/E pattern with 2 frequencies

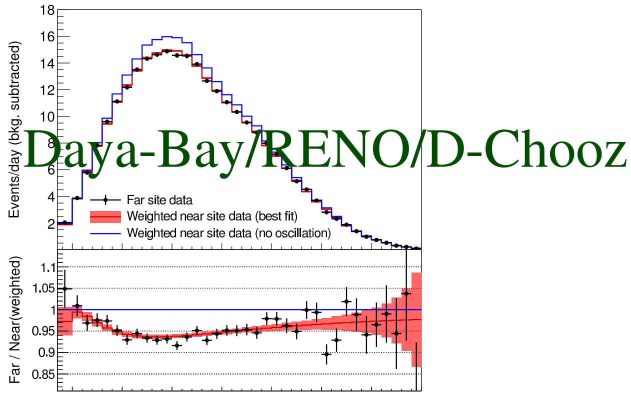
MSW conversion in Sun









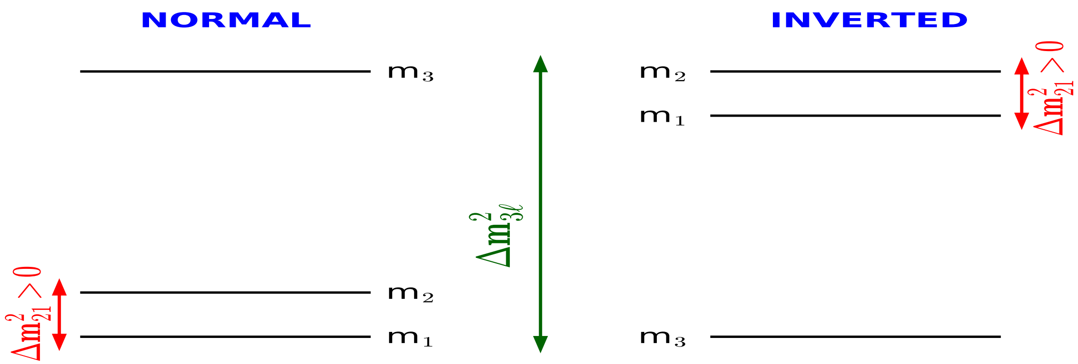


3ν Flavour Parameters

- For **for 3 ν's** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Convention: $0 \leq \theta_{ij} \leq 90^\circ$ $\quad 0 \leq \delta \leq 360^\circ$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

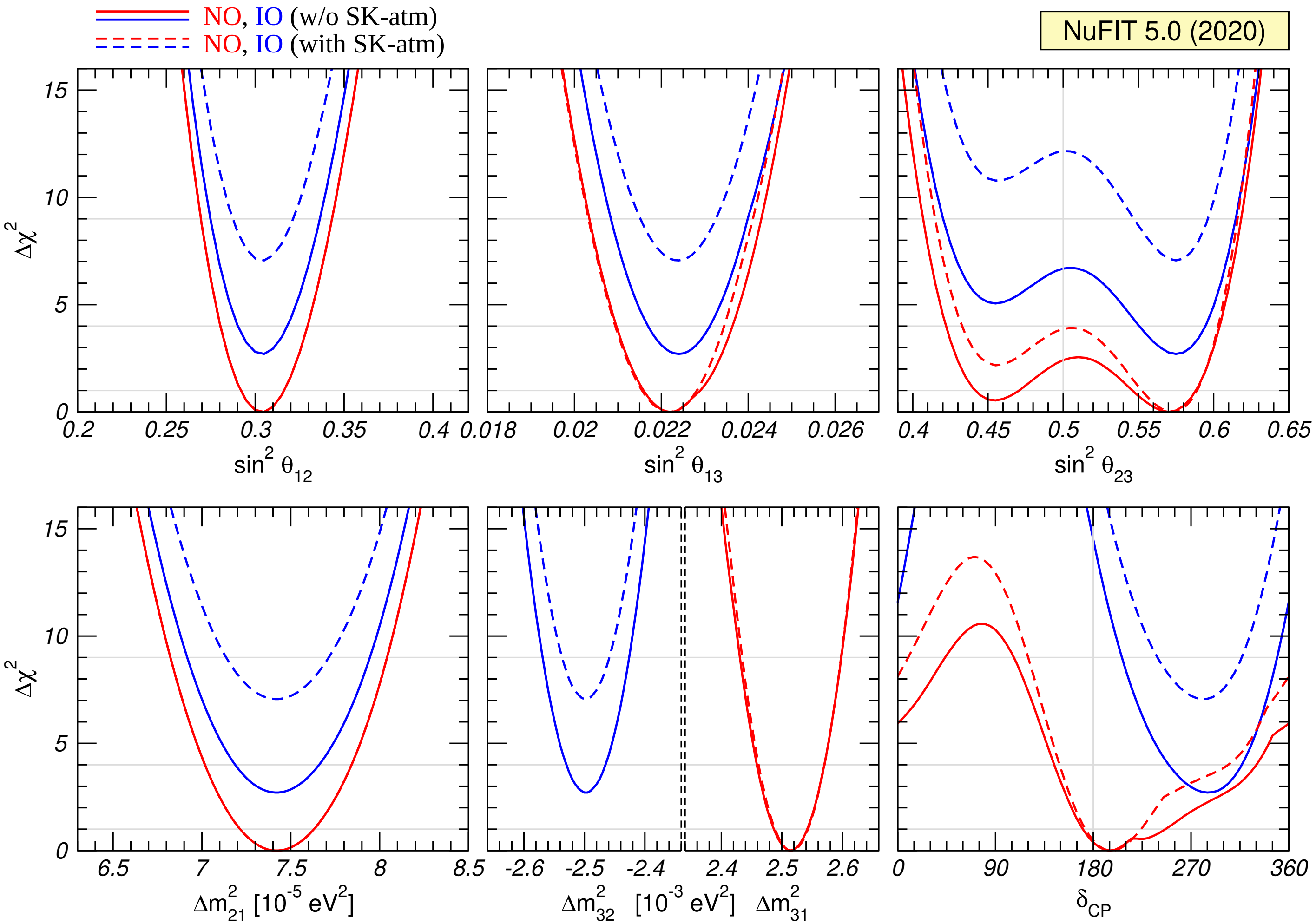
$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

Experiment	Dominant Dependence	Important Dependence
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13} $\Delta m^2_{3\ell}$	
Atmospheric Experiments (SK,IC)		θ_{23}, $\Delta m^2_{3\ell}$, θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$ θ_{23}	
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}, θ_{23}

Status 9/2021: Global 3 ν Flavour Parameters

Global 6-parameter fit http://www.nu-fit.org

Esteban, Maltoni, Schwetz, Zhou, MCG-G ArXiv:2007.14792



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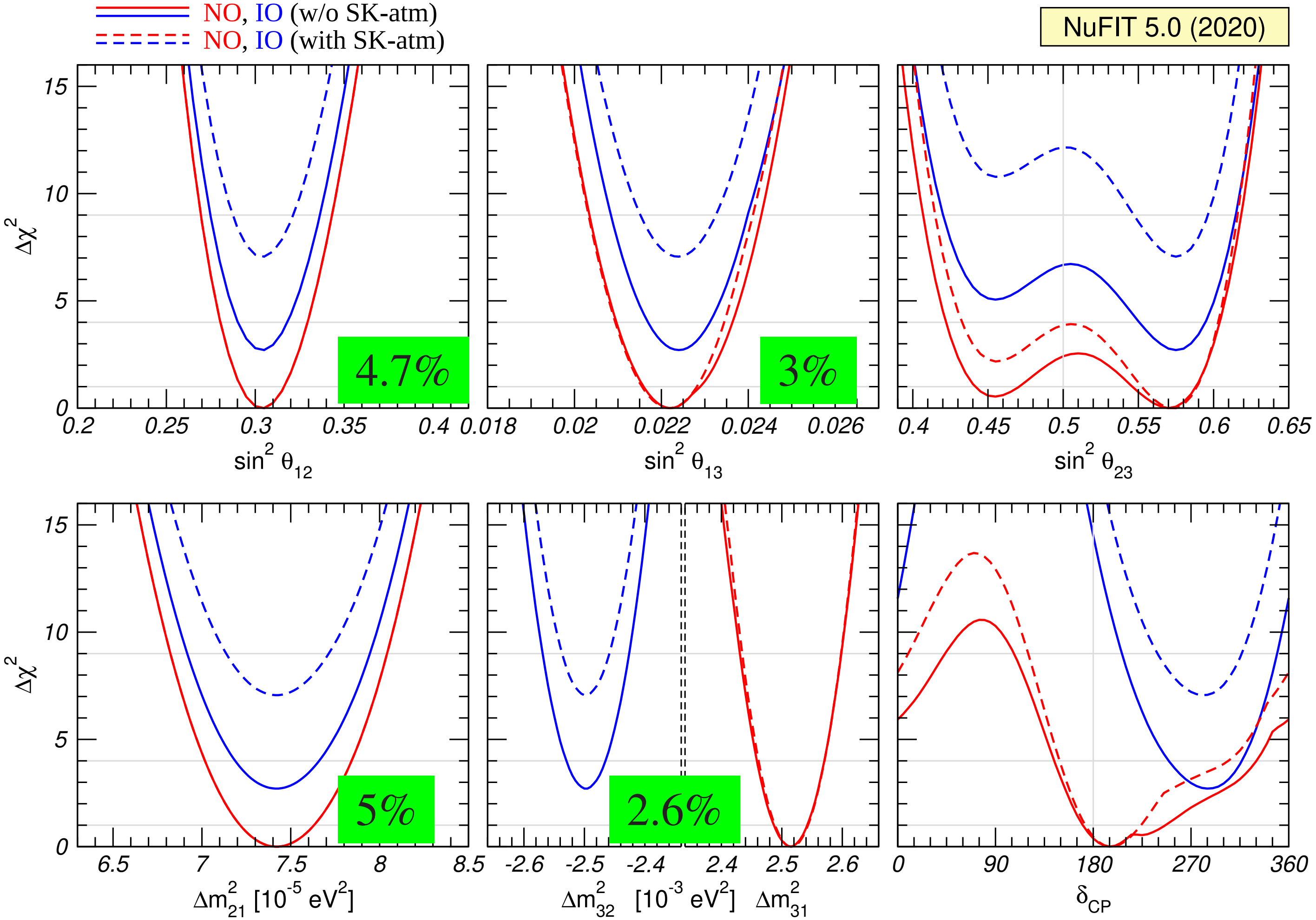
Precision $\frac{x_{3\sigma}^{up} - x_{3\sigma}^{low}}{3x^{av}}$



- Best determined:

  $\theta_{12}, \theta_{13}, \Delta m^2_{21}, |\Delta m^2_{3l}|$

  $[\Delta m^2_{3l} = \Delta m^2_{31} > 0$ (NO)

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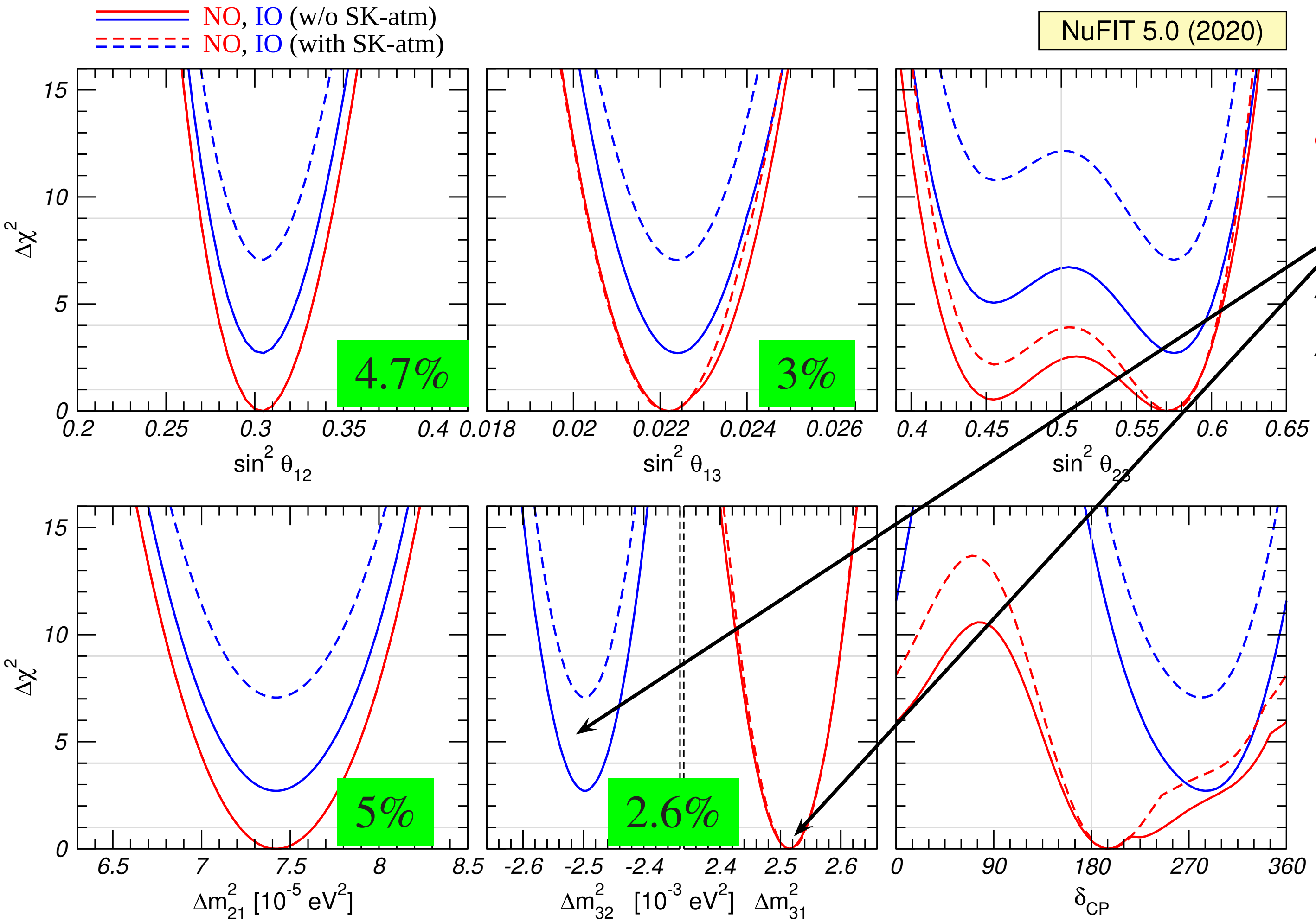

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$*$ Mass Ordering

$$\Delta\chi^2_{\rm NO-IO,w/o\ SK-atm} = 2.7$$
$$\Delta\chi^2_{\rm NO-IO,with\ SK-atm} = 7.1$$

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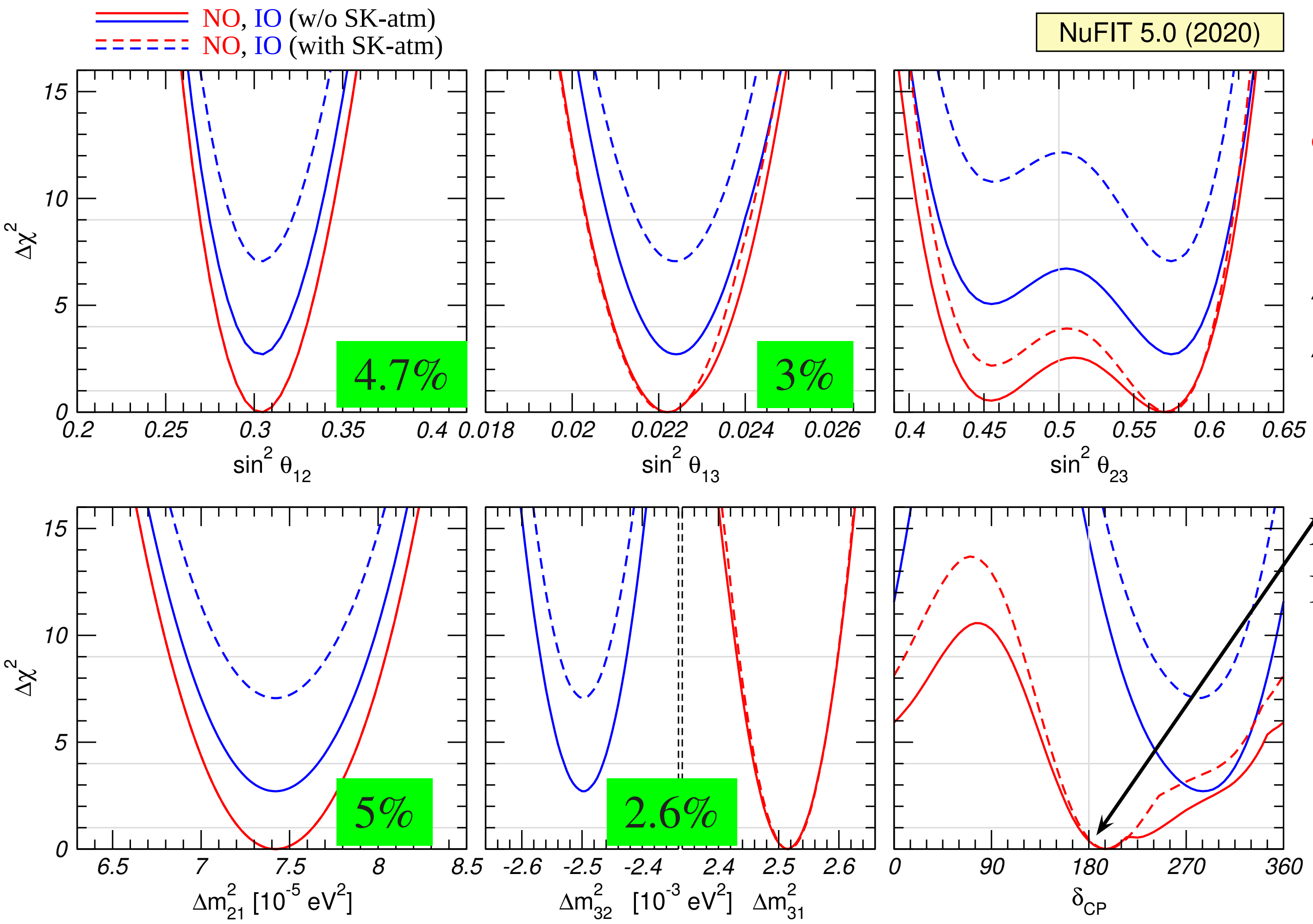

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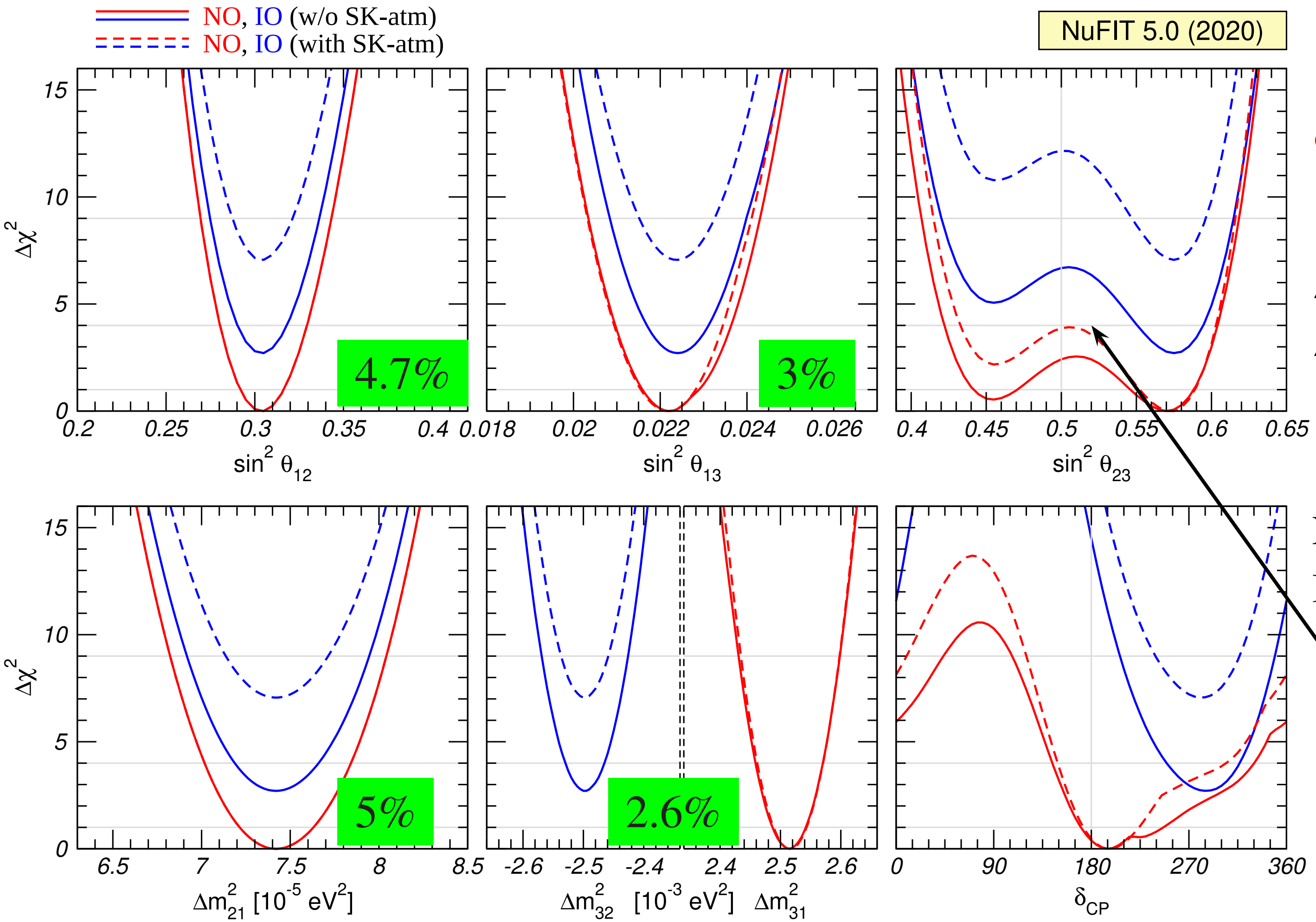

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Flavour Parameters: Mixing Matrix

- We have the three leptonic mixing angles determined (at $\pm 3\sigma/6$)

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.844 & 0.513 \to 0.579 & 0.143 \to 0.156 \\ 0.233 \to 0.507 & 0.461 \to 0.694 & 0.639 \to 0.778 \\ 0.261 \to 0.526 & 0.471 \to 0.701 & 0.611 \to 0.761 \end{pmatrix}$$

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- Also very different flavour mixing of leptons vs quarks

Leptonic CPV in 3ν Mixing: Jarlskog Invariant

- Leptonic $\not{C}$P $\Rightarrow P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar\nu_\alpha \to \bar\nu_\beta}$
- In 3ν always

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar\nu_\alpha \to \bar\nu_\beta} \propto J \quad \text{with} \quad J = \text{Im}(U_{\alpha 1} U^*_{\alpha_2} U_{\beta 2} U^*_{\beta_1}) = J^{\max}_{\text{LEP,CP}} \sin\delta_{\text{CP}}$$

$$J^{\max}_{\text{LEP,CP}} = \frac{1}{8} c_{13} \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 2\theta_{12}$$

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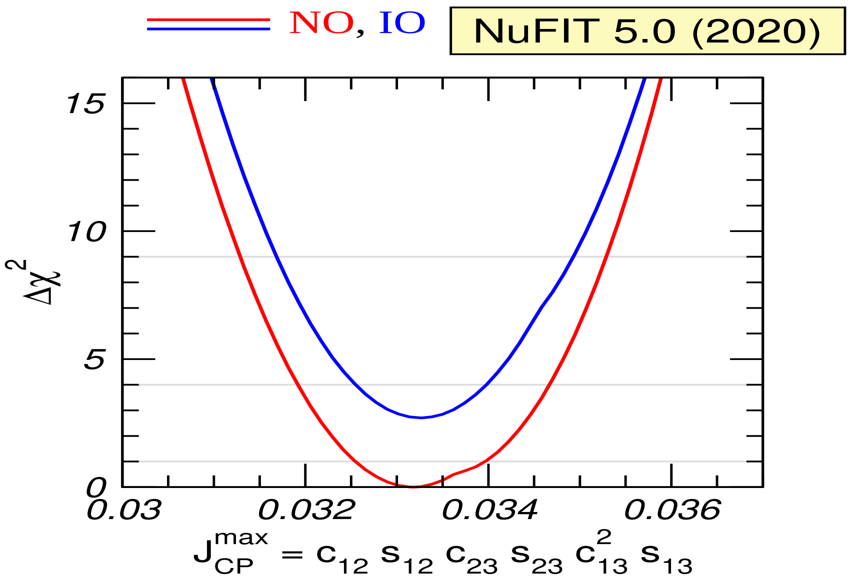
- Maximum Allowed Leptonic CPV:



$J^{\max}_{\text{LEP,CP}} = (3.29 \pm 0.07) \times 10^{-2}$

to compare with

$J_{\text{CKM,CP}} = (3.04 \pm 0.21) \times 10^{-5}$

$\Rightarrow$ Leptonic CPV may be largest CPV in New Minimal SM

if $\sin\delta_{\text{CP}}$ not too small

Near Future for CP and Ordering: Strategies

- $\nu/\bar{\nu}$ comparison with or without Earth matter effects in $\nu_\mu \to \nu_e$ & $\bar{\nu}_\mu \to \bar{\nu}_e$ at LBL:
  DUNE (wide band beam, L=1300 km), HK (narrow band beam, L=300 km)

$$P_{\mu e} \simeq s^2_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\Delta_{31} \pm V}\right)^2 \sin^2\left(\frac{\Delta_{31} \pm V\, L}{2}\right)$$
$$+8\, J^{\rm max}_{\rm CP}\, \frac{\Delta_{12}}{V}\, \frac{\Delta_{31}}{\Delta_{31} \pm V}\, \sin\left(\frac{V L}{2}\right) \sin\left(\frac{\Delta_{31} \pm V L}{2}\right) \cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

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- Reactor experiment at $L \sim 60$ km (vacuum) able to observe the difference between oscillations with Δm^2_{31} and Δm^2_{32}: JUNO, RENO-50

$$P_{\nu_e,\nu_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + s_{12}^2 \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]$$

  – Challenge: Energy resolution

Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Oscillations DO NOT determine the lightest mass

  Only model independent probe of m_ν β decay: $\sum m_i^2 |U_{ei}|^2 \leq (1.1 \text{ eV})^2$ Katrin 2019
- Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay
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ν masses are BSM physics effects to be put together with *all other NP effects*:
from charged LFV, Collider signals, Cosmo-astroparticle... to establish
the Next Standard Model

Confirmed Low Energy Picture and MY List of Q&A

- At least two neutrinos are massive ⇒ There is NP
- Oscillations DO NOT determine the lightest mass

  Only model independent probe of m_ν β decay: $\sum m_i^2 |U_{ei}|^2 \leq (1.1\text{ eV})^2$ Katrin 2019
- Dirac or Majorana?: We do not know, *anxiously* waiting for ν-less $\beta\beta$ decay
- Three mixing angles are non-zero (and relatively large) ⇒ very different from CKM
- Leptonic CP and Ordering: "Hints" but not confirmation

  Definite answer may require new oscillation experiments
- Only three light states? Old anomalies supporting light sterile neutrinos but tensions with new experiments and cosmology
- Other NP at play in oscillations Interesting effects of NP with light mediators
- What about a UV complete model?: It will need a positive signal in colliders
- Neutrinos in Cosmology? • Astrophysics/Astronomy with Neutrinos? ...

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Young people with fresh new ideas needed!!!

AND HERE YOU ARE!!