Neutrinos

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Recent collaborations with

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- Yuval Grossman *(Technion)*
- Tamar Kashti *(Weizmann)*
- Carlos Peña-Garay *(IAS, Princeton)*
- Esteban Roulet *(Bariloche)*
- Yael Shadmi *(Technion)*
- Alexei Smirnov *(Trieste)*

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Special thanks to

- Concha Gonzalez-Garcia
- Guy Raz

Pauli (1930)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon **a desperate remedy** to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that **my remedy could seem incredible** because one should have seen those neutrons very earlier if they really exist. **But only the one who dare can win** and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: **"Oh, It's well better not to think to this at all, like new taxes".** From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant

W. Pauli

Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. The Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk I

The Standard Model and (a Little) Beyond

1. The SM as a complete theory
2. Neutrino masses in the SM
3. The SM as an effective theory
4. Neutrino masses beyond the SM
5. The seesaw mechanism

What Are Neutrinos?

1. Spin $1/2$ - Fermions
2. $SU(3)_{\mathrm{C}}$ singlets - No strong interactions
3. $U(1)_{\mathrm{EM}}$ singlets - No EM interactions

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4a. $SU(2)$ doublets - Weak interactions (active)

4s. $SU(2)$ singlets - No weak interactions (sterile)

The Standard Model

A Particle Physics Model

1. Symmetry
2. Matter content (spin 1/2 and spin 0 fields)
3. Spontaneous symmetry breaking

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The Standard Model

1. $G_{\rm SM}$ = Local $SU(3)_{\rm C} \times SU(2)_{\rm L} \times U(1)_{\rm Y}$
2. (a) Spin 1/2: $3 \times$
   $\left\{Q(3,2)_{1/6} + U(3,1)_{2/3} + D(3,1)_{-1/3} + L(1,2)_{-1/2} + E(1,1)_{-1}\right\}$

   (b) Spin 0: $\phi(1,2)_{1/2}$
3. $\langle \phi^0 \rangle \neq 0 \implies G_{\rm SM} \to SU(3)_{\rm C} \times U(1)_{\rm EM}$

Fermions of the Standard Model

	Name	Color	EM-charge
$Q(3,2)_{1/6}$	Quark doublets	Yes	$+2/3, -1/3$
$U(3,1)_{2/3}$	Up-quark singlets	Yes	$+2/3$
$D(3,1)_{-1/3}$	Down-quark singlets	Yes	$-1/3$
$L(1,2)_{-1/2}$	Lepton doublets	No	$-1, 0$
$E(1,1)_{-1}$	Charged lepton singlets	No	-1

Interaction basis

Given the Standard Model

1. Symmetry
2. Particle content
3. Renormalizability (no terms of dimension > mass^4)

$$\Longrightarrow \mathcal{L}_L = i\overline{L_i}\gamma_\mu\left(\partial^\mu + \frac{i}{2}gW_b^\mu\tau_b + \frac{i}{2}g'B^\mu\right)L_i - \left(Y_{ij}^\ell\overline{L_i}\phi E_j + \text{h.c.}\right)$$

Mass basis

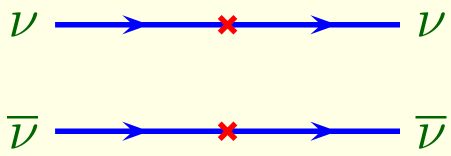
Interaction	→	Mass	
L_i		(ℓ_i^-, ν_i)	3 active ν's: ν_e, ν_μ, ν_τ
W_μ^b, B_μ		$W_\mu^\pm, Z_\mu^0, \gamma_\mu$	$Z_\mu^0 = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu$
ϕ		(ϕ^+, ϕ^0)	ϕ^+ eaten by W^+

$$\Longrightarrow \mathcal{L}_\nu = i\overline{\nu_i}\gamma^\mu\partial_\mu\nu_i - \frac{g}{\sqrt{2}}\left(\overline{\nu_i}\gamma^\mu W_\mu^+ \ell_i^- + \text{h.c.}\right) - \frac{g}{2\cos\theta_W}\overline{\nu_i}\gamma^\mu Z_\mu^0 \nu_i$$

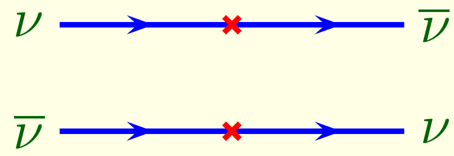
- Charged current interactions ($W^\pm$)
- Neutral current interactions (Z^0)
- No Yukawa interactions (ϕ^0)
- No mass terms

Dirac and Majorana

Dirac



Majorana



$$\mathcal{L}_D = m_D \overline{\nu_R} \nu_L + \text{h.c.}$$

$$\Delta L = 0$$

$$\mathcal{L}_M = \frac{m_L}{2} \overline{(\nu_L)^c} \nu_L + \text{h.c.}$$

$$\Delta L = \pm 2$$

- $\nu^c = C\bar{\nu}^T$, $C =$ charge conjugation matrix
- $\nu, \overline{\nu^c}$ annihilate ν, create $\overline{\nu}$
- $\overline{\nu}, \nu^c$ create ν, annihilate $\overline{\nu}$

$m_\nu = 0$

$$m_\nu \overline{\nu_L^c} \nu_L \; ?$$

Given the Standard Model

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Given the Standard Model

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$$\Downarrow$$

Accidental $B - L$ Symmetry

$$\Downarrow$$

$$\boxed{m_\nu = 0}$$

(to all orders in perturbation theory and beyond!)

Beyond the Standard Model

Reasons Not to Believe the Standard Model

1. The fine-tuning problem
2. The strong CP problem
3. Baryogenesis
4. Gauge coupling unification
5. The flavor puzzle
6. Gravity

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1. Supersymmetry
2. Peccei-Quinn symmetry
3. Heavy sterile neutrinos
4. GUT
5. Horizontal symmetry
6. String theory

Reasons Not to Believe the Standard Model

1. The fine-tuning problem	1. Supersymmetry
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5. The flavor puzzle	5. Horizontal symmetry
6. Gravity	6. String theory

Very likely, there is new physics

$$\Lambda_{\rm EW} \ll \Lambda_{\rm NP} \leq M_{\rm Planck}$$

SM = LEET

Very likely, the Standard Model is a low energy effective theory (LEET) valid only below a scale $\Lambda_{\rm NP} (\gg \Lambda_{\rm EW})$

$\Longrightarrow$ Renormalizability is no longer required

$$\mathcal{L} = \mathcal{L}^{\rm SM} + \frac{1}{\Lambda_{\rm NP}} O_{d=5} + \frac{1}{\Lambda_{\rm NP}^2} O_{d=6} + \cdots$$

- $B - L$ is violated by nonrenormalizable terms

Interaction basis

Given the Standard Model

1. Symmetry
2. Particle content

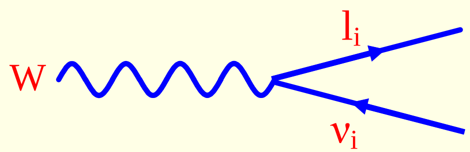
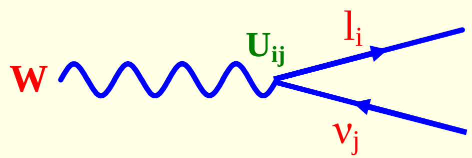
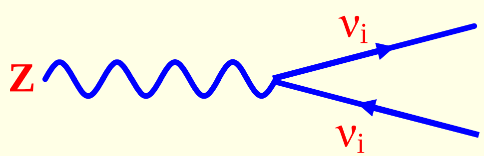
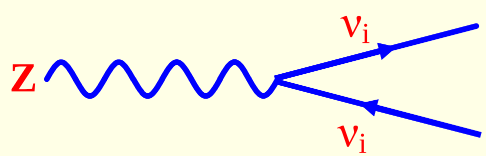
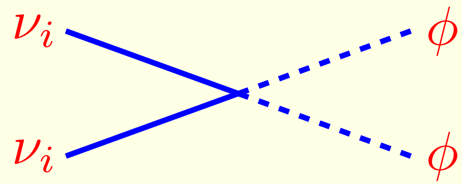
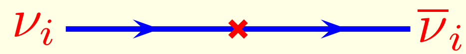
$$\boxed{\mathcal{L}_L = \mathcal{L}_L^{\mathrm{SM}} + \frac{Z^{\nu}_{ij}}{\Lambda_{\mathrm{NP}}}\phi\phi L_i L_j + \mathcal{O}\left(\frac{1}{\Lambda^2_{\mathrm{NP}}}\right)}$$

Mass basis

$$
\begin{aligned}
\mathcal{L}_\nu &= i\overline{\nu_i}\gamma^\mu\partial_\mu\nu_i - \frac{g}{2\cos\theta_W}\overline{\nu_i}\gamma^\mu Z^0_\mu\nu_i \\
&- \frac{g}{\sqrt{2}}\overline{\ell_i}\gamma^\mu U_{ij}W^-_\mu\nu_j + \text{h.c.} \\
&+ m_i\nu_i\nu_i + \text{h.c.} + \cdots
\end{aligned}
$$

- CC interactions involve the mixing matrix U
- Majorana mass terms: $m_i = \frac{Z_i^\nu\langle\phi\rangle^2}{\Lambda_{\text{NP}}}$
- $U + m_i \implies$ 3 masses, 3 mixing angles, 3 phases

Interactions of SM=LEET

Interaction	SM	$+\frac{1}{\Lambda}LL\phi\phi$
CC		
NC		
Yukawa	None	
Masses	None	 (Majorana)

$m_\nu \neq 0$

If the SM is an effective theory, valid only below a scale $\Lambda_{\rm NP} \gg \langle\phi\rangle$

$$\Downarrow$$

- Neutrinos are massive - $\boxed{m_\nu \sim \frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}}}$
- Neutrinos are light - $\frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}} \ll \langle\phi\rangle$

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Examples:

- $\frac{\langle\phi\rangle^2}{\Lambda_{\rm GUT}} \sim 10^{-2}\ eV$
- $\frac{\langle\phi\rangle^2}{M_{\rm Planck}} \sim 10^{-5}\ eV.$

Cosmology:

- $m_\nu \leq \mathcal{O}(eV) \implies \Lambda_{\rm NP} \geq \mathcal{O}(10^{14}\ GeV)$

The See-Saw Mechanism (I)

SM+N

- Add to the SM G_{SM}-singlet fermions, $N(1,1)_0$

$$\Longrightarrow \ \mathcal{L}_N = Y\overline{L}\phi^\dagger N + MNN$$

$$\Longrightarrow \ M_\nu = \begin{pmatrix} 0 & Y\langle\phi\rangle \\ Y\langle\phi\rangle & M \end{pmatrix}$$

- Assume $M \gg \langle\phi\rangle \ \Longrightarrow \ m_N = M, \quad m_\nu = \frac{Y^2\langle\phi\rangle^2}{M}$

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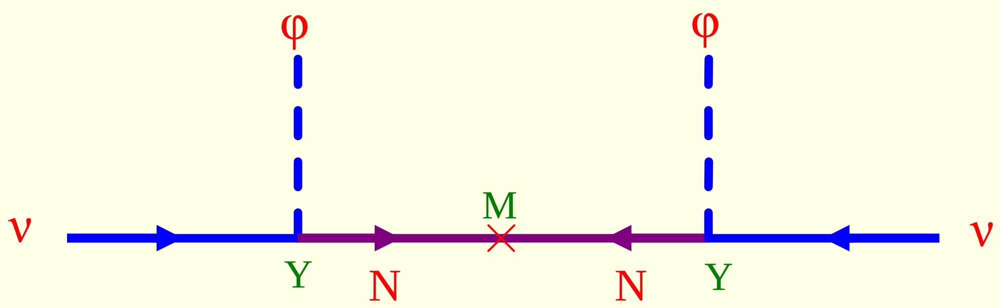
- Assume $M \gg \langle\phi\rangle \ \Longrightarrow \ m_N = M, \quad m_\nu = \frac{Y^2\langle\phi\rangle^2}{M}$

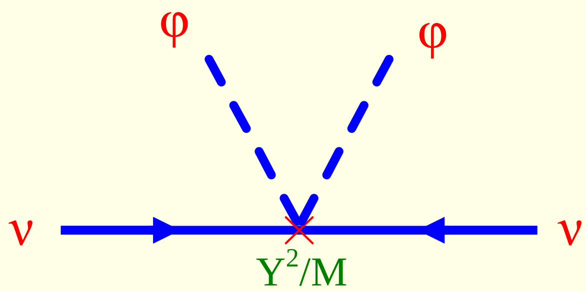
- With 3 L_i and n N_j:
  - $Y = 3 \times n$ matrix, $M = n \times n$ symmetric matrix
  - $M_\nu^{\text{light}} = \langle\phi\rangle^2 \ Y \ M^{-1} \ Y^T$

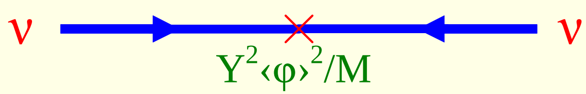
The See-Saw Mechanism

- A diagram in the SM+N:



- At energy scales $E \ll M$:





The See-Saw Mechanism (III)

$$\boxed{m_\nu = \frac{Y^2 \langle \phi \rangle^2}{M}}$$

- The heavier N, the lighter $\nu \Longrightarrow$ "The see-saw mechanism"
- A specific realization of SM=LEET, $\Lambda_{\rm NP} = M/Y^2$
- Arises in many extensions of the SM: SO(10), LRS...

Gell-Mann, Ramond, Slansky (1979)

Yanagida (1979)

Summary

Theoretical Expectations

SM $m_\nu = 0$

NP $10^{-5}\ eV \le m_\nu \le eV's$

$m_\nu \sim \langle\phi\rangle^2/\Lambda_{\rm NP}$

Next

Q: How to search for $m_\nu < eV$?

A: Neutrinos (mainly) from Heaven!

Counting Physical Phases (Quarks)

1. A unitary 3×3 matrix, $V^\dagger V = \mathbf{1} \Longrightarrow 3$ angles $+\ 6$ phases;
2. Mass basis $\equiv M_q^{\rm diag}$ is diagonal and real;
3. Freedom in choosing phases $(P_f = {\rm diag}(e^{i\alpha_1^f}, e^{i\alpha_2^f}, e^{i\alpha_3^f}))$

$$\Downarrow$$

1. $D_L \to P_d D_L,\ D_R \to P_d D_R \quad \Longrightarrow \quad M_d^{\rm diag} \to M_d^{\rm diag}$
   $U_L \to P_u U_L,\ U_R \to P_u U_R \quad \Longrightarrow \quad M_u^{\rm diag} \to M_u^{\rm diag}$;
2. $V \to P_u^* V P_d \Longrightarrow$ remove 5 phases: $6 - 5 = 1$
3. An alternative proof in interaction basis:
   $M_u, M_d :\ U(3)_Q \times U(3)_U \times U(3)_D \to U(1)_B \Longrightarrow 18 - 18 + 1 = 1$

Counting Physical Phases (Leptons)

1. A unitary 3×3 matrix, $U^\dagger U = \mathbf{1} \Longrightarrow 3$ angles $+\ 6$ phases;
2. Mass basis $\equiv M_\ell^{\text{diag}}$ is diagonal and real;
3. Freedom in choosing phases $(P_f = \text{diag}(e^{i\alpha_1^f}, e^{i\alpha_2^f}, e^{i\alpha_3^f}))$

$$\Downarrow$$

1. $E_L \to P_e E_L,\ E_R \to P_e E_R \quad \Longrightarrow \quad M_e^{\text{diag}} \to M_e^{\text{diag}}$;
   $\nu_L \to P_\nu \nu_L \quad \Longrightarrow \quad M_\nu^{\text{diag}} \to P_\nu M_\nu^{\text{diag}} P_\nu \quad \Longrightarrow$ not allowed;
2. $U \to P_e^* U \ \Longrightarrow$ remove 3 phases: $6 - 3 = 3$
3. An alternative proof in interaction basis:
   $M_e, M_\nu : \quad U(3)_L \times U(3)_E \to \text{nothing} \ \Longrightarrow 15 - 12 + 0 = 3$

Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. Flavor Models
5. Leptogenesis

Plan of Talk II

Neutrinos (Mainly) from Heaven

1. Vacuum oscillations
   - Atmospheric neutrinos (AN)
   - Reactor neutrinos (RN)
   - Solar neutrinos (SN)
2. The MSW effect
   - Solar neutrinos (SN)

Vacuum Oscillations

Pontecorvo, 1957

Flavor Transitions (I)

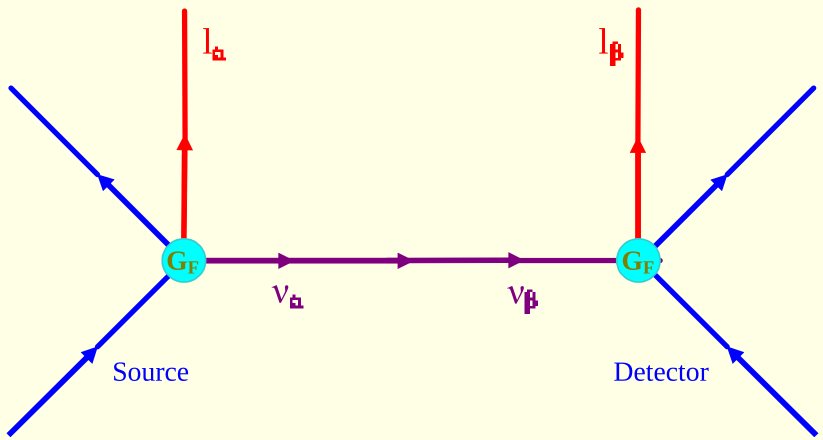
- Flavor basis (production and detection): $\nu_e, \quad \nu_\mu, \quad \nu_\tau$
- Mass basis (free propagation in space-time): $\nu_1, \quad \nu_2, \quad \nu_3$

- In general, flavor eigenstates $\neq$ mass eigenstates
- $U(\nu_1, \nu_2, \nu_3)^T = (\nu_e, \nu_\mu, \nu_\tau)^T$

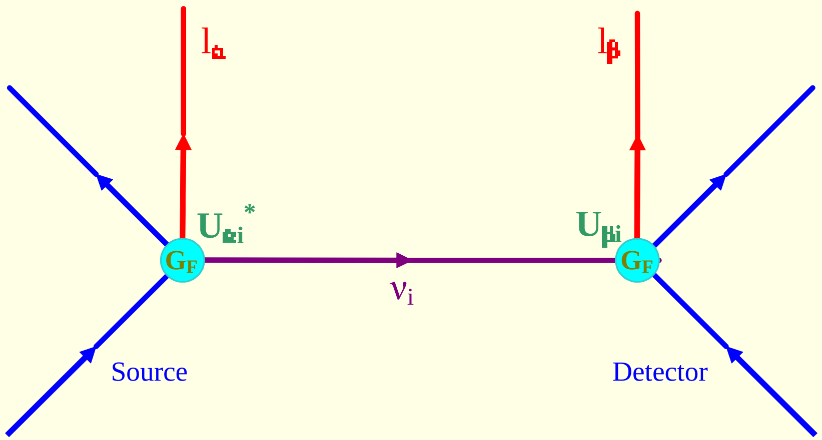
$$\Downarrow$$

- Flavor is not conserved during propagation in space-time
- ν_α is produced but $\nu_{\beta\neq\alpha}$ might be detected $(\alpha, \beta =$ flavors$)$

Flavor Transitions (II)



$= \sum_i$



Flavor Transitions (III)

The probability $P_{\alpha\beta}$ of producing neutrinos of flavor α and detecting neutrinos of flavor β is calculable in terms of

- The neutrino energy E
- The distance between source and detector L
- The mass-squared differences $\Delta m^2_{ij} \equiv m^2_i - m^2_j$
  - ($P_{\alpha\beta}$ is independent of the absolute mass scale)
- U parameters (mixing angles and phase)
  - ($P_{\alpha\beta}$ is independent of the Majorana phases)

Oscillations

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

$|\nu_i(t)\rangle = e^{-iE_i t}|\nu_i(0) \qquad E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2E}$

$$\begin{aligned} P_{\alpha\beta} &= |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 \\ &= \sum_i |\langle\nu_\beta|\nu_i\rangle\langle\nu_i|\nu_\alpha(t)\rangle|^2 \\ &= \delta_{\alpha\beta} - 4\sum_{j>i} \mathcal{R}e(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}) \sin^2\left[(\Delta m^2_{ij}L)/(4E)\right] \\ &\quad + 2\sum_{j>i} \mathcal{I}m(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}) \sin\left[(\Delta m^2_{ij}L)/(2E)\right] \end{aligned}$$

Two Generations

- A single mixing angle: $U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$
- A single mass-squared difference: $\Delta m^2 = m_2^2 - m_1^2$

$$\Downarrow$$

$$P_{\alpha\beta} = \sin^2 2\theta \;\; \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

L/E must be right

- Experimental parameters: $E, \; L$
- Theory parameters: $\Delta m^2, \; \theta$
- $P_{\alpha\beta} = \sin^2 2\theta \; \sin^2 \left[1.27 \; \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L/E}{\mathrm{m/MeV}}\right]$

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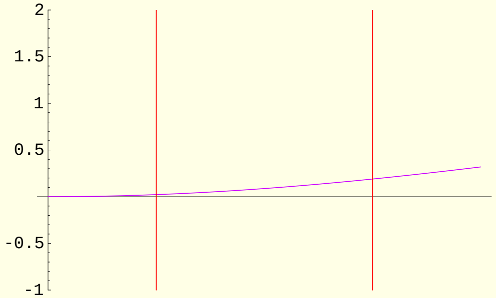
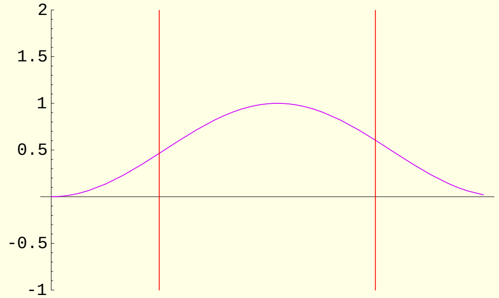


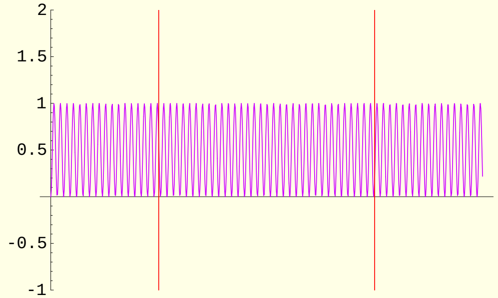
$\Delta m^2 L/E \ll 1$

$P_{\alpha\beta} \to 0$



$\Delta m^2 L/E \sim 1$

$P_{\alpha\beta}$ sensitive to Δm^2



$\Delta m^2 L/E \gg 1$

$P_{\alpha\beta} \to \frac{1}{2}\sin^2 2\theta$

Exploring θ and Δm^2

To allow observation of neutrino oscillation,

- Nature has to be generous: $\sin^2 2\theta \not\ll 1$
- To probe small Δm^2 we need large L/E
- In particular, to probe $\Delta m^2 \sim 10^{-11}\ eV^2$ with $E \sim MeV$ neutrinos, we need the reactor at $L \sim 10^8$ km

Source	E[MeV]	L[km]		Δm^2[eV^2]
SN	1	10^8	$\Longrightarrow$	$10^{-11} - 10^{-9}$
RN	1	10^2	$\Longrightarrow$	$10^{-5} - 10^{-3}$
AN	10^3	10^{1-4}	$\Longrightarrow$	$10^{-4} - 1$

The MSW Effect

Wolfenstein (1978); Mikheev and Smirnov (1985)

Matter Effects

- In vacuum, in mass basis (ν_1, ν_2): $H = p + \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix}$
- In vacuum, in interaction basis (ν_e, ν_a):

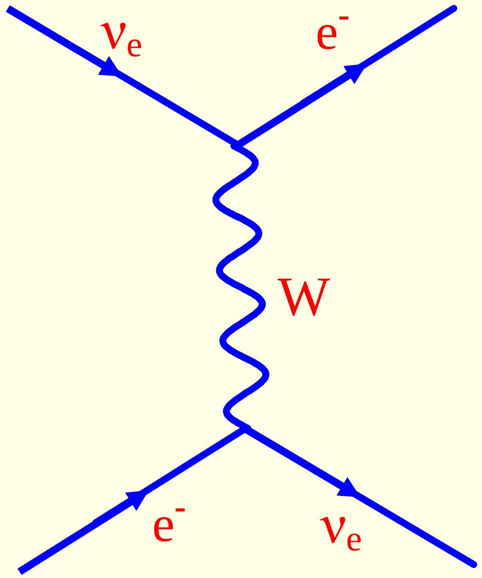
$$H = p + \frac{m_1^2+m_2^2}{4E} + \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

- In matter (e, p, n), in interaction basis (ν_e, ν_a):

$$H = p + V_a + \frac{m_1^2+m_2^2}{4E} + \begin{pmatrix} (V_e - V_a) - \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

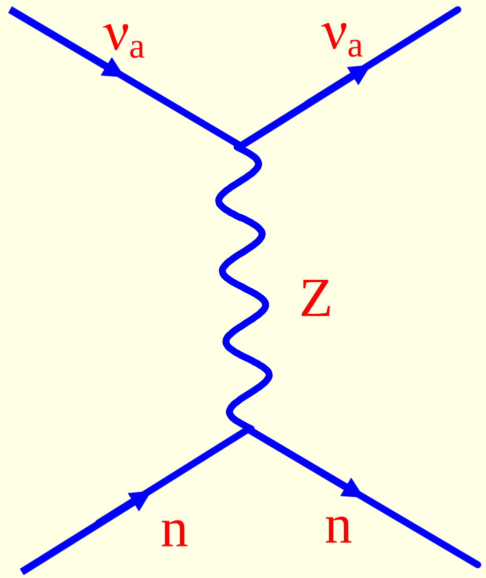
- All active neutrinos have NC interactions, but only ν_e has CC interactions with matter: $V_e - V_a = \sqrt{2} G_F n_e$

CC $\leftrightarrow$ NC



Charged Current Interactions

ν_e only



Neutral Current Interactions

$\nu_a, \quad a = e, \mu, \tau$

$(i)\ \theta_m \neq \theta$

$$H \sim \begin{pmatrix} \sqrt{2}G_F n_e - \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}$$

$$\Downarrow$$

- The mixing angle relating (ν_e, ν_a) to (ν_1^m, ν_2^m) depends on the matter density:

$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - 2\sqrt{2}G_F n_e E}$$

- Example: $\sqrt{2}G_F n_e \gg \frac{\Delta m^2}{2E} \implies \theta_m \to \pi/2$

$\implies \nu_e$ is very close to the heavier mass eigenstate ν_2^m

$(ii)\ \theta_m = \theta_m(t)$

For a neutrino propagating in varying density $n_e(x)$

- The mixing angle changes: $\theta_m = \theta_m(n_e(x))$
- $\tan 2\theta_m(x) = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - 2\sqrt{2} G_F n_e(x) E}$
- As $n_e(x) \ \downarrow$: $\quad \theta_m \ \downarrow$
- In particular,
  - At $n_e \gg n_e^R$: $\quad \theta_m \approx \pi/2$
  - At $n_e^R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F E}$: $\quad \theta_m^R = \pi/4$
  - At $n_e = 0$ (vacuum): $\quad \theta_m = \theta$

$$\Downarrow$$

ν_2^m propagating in $n_e \downarrow$ is mostly ν_e above n_e^R, and mostly ν_a below n_e^R

$(iii)\ \nu_1^m \leftrightarrow \nu_2^m$ transitions

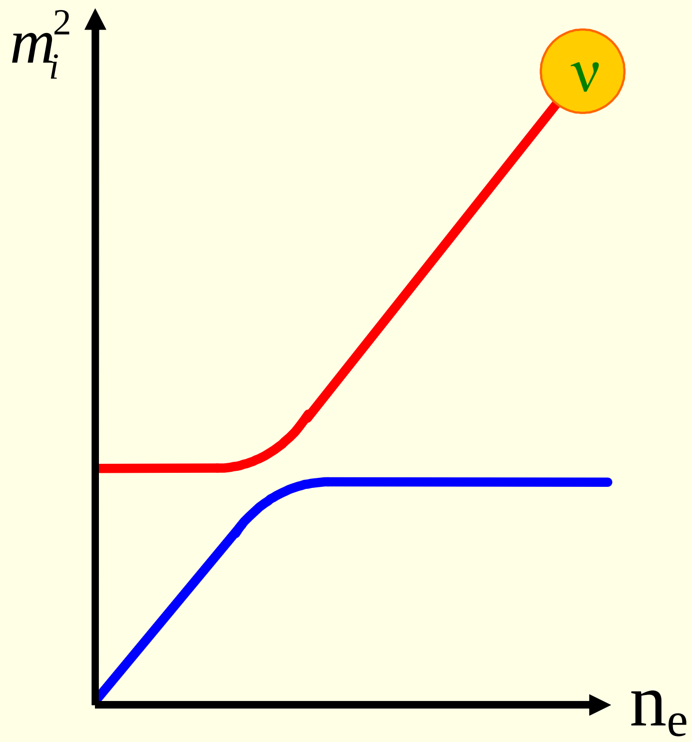
For varying density, $H = H(t)$,

- $e^{-iH(t)t} \neq e^{-i\int H(t')dt'}$
- Instanteneous mass eigenstates $\neq$ eigenstates of time evolution
- The transitions $\nu_{1m} \leftrightarrow \nu_{2m}$ occur

For slowly varying density, $\dot{H}t \ll H$,

- $e^{-i\int H(t')dt'} = e^{-i(Ht+\dot{H}t^2+\cdots)} \approx e^{-iHt}$
- The transitions $\nu_{1m} \leftrightarrow \nu_{2m}$ can be neglected
- The adiabatic condition: $\boxed{\frac{1}{n}\frac{dn}{dx} \ll \frac{\Delta m^2}{E}\frac{\sin^2 2\theta}{\cos 2\theta}}$

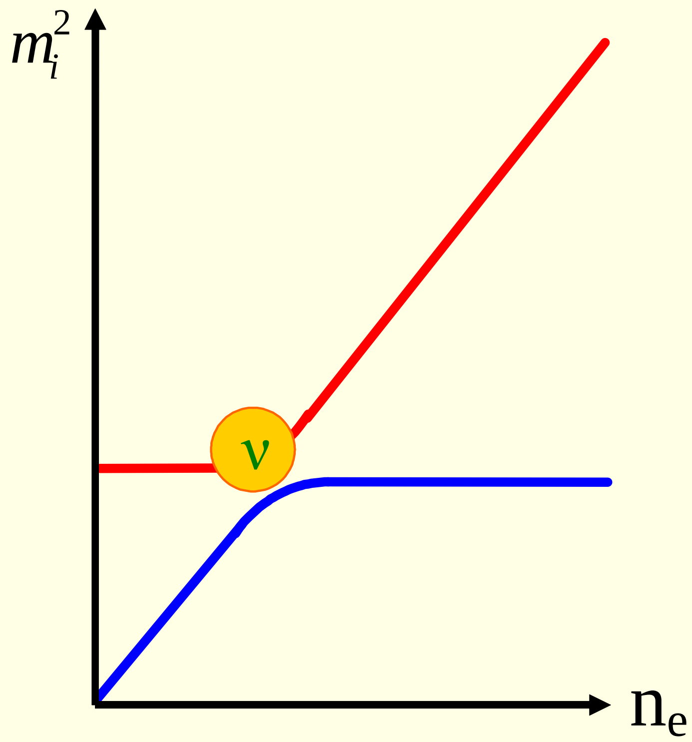
$$E \gg \frac{\Delta m^2}{G_F \; n_e^{\text{prod}}}$$



Production with $n_e^{\text{prod}} \gg n_e^R$

$$\nu = \nu_2^m(\theta_m = \pi/2)$$

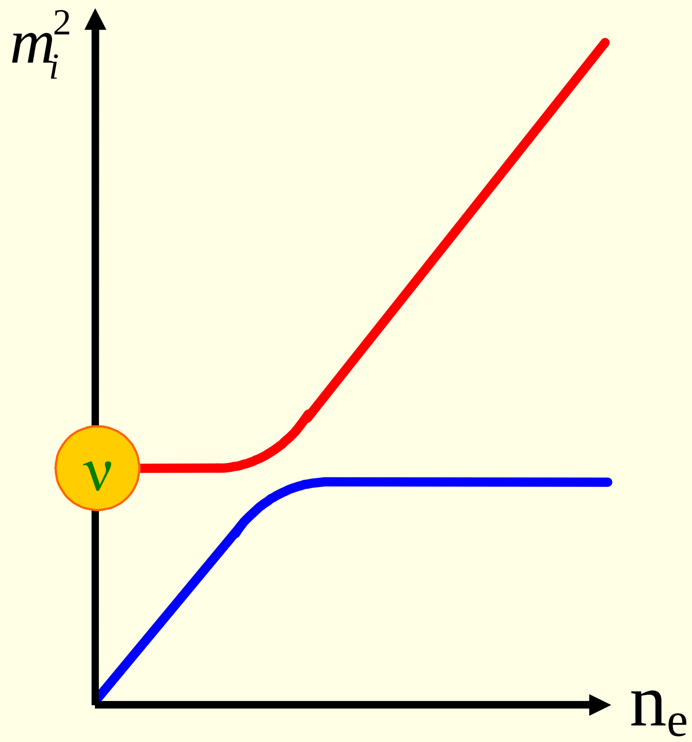
$$E \gg \frac{\Delta m^2}{G_F \;\; n_e^{\text{prod}}}$$



Adiabatic $\left(E \ll \frac{\Delta m^2}{\frac{1}{n}\frac{dn}{dx}} \frac{\sin^2 2\theta}{\cos 2\theta}\right)$ propagation at $n_e \sim n_e^R$

$$\nu = \nu_2^m(\theta_m = \pi/4)$$

$$E \gg \frac{\Delta m^2}{G_F \;\, n_e^{\mathrm{prod}}}$$



Approaching the surface of the Sun

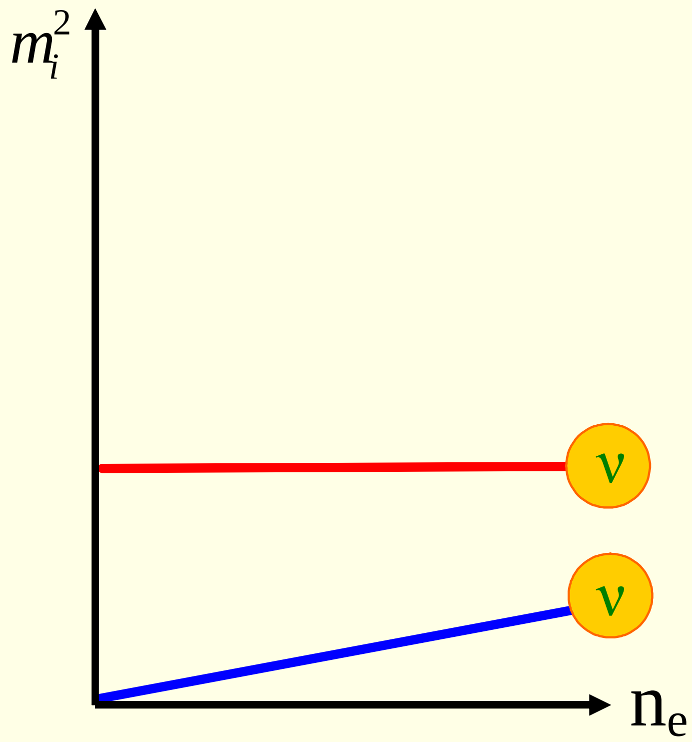
$$\nu = \nu_2^m(\theta_m = \theta) = \nu_2 \implies P_{ee} = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$$

$$\frac{\Delta m^2}{\frac{1}{n}\frac{dn}{dx}}\frac{\sin^2 2\theta}{\cos 2\theta} \gg E \gg \frac{\Delta m^2}{G_F \;\; n_e^{\mathrm{prod}}}$$

$$\boxed{P_{ee} = |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta}$$

1. High sensitivity to θ;
2. The only way to probe small angles
   ($\sin^2\theta \gtrsim 10^{-4}$ for $\Delta m^2 \sim 10^{-4}\ eV^2$)
3. $P_{ee} < \frac{1}{2}$ is possible
   In constrast to averaged vacuum oscillations,
   $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta > \frac{1}{2}$

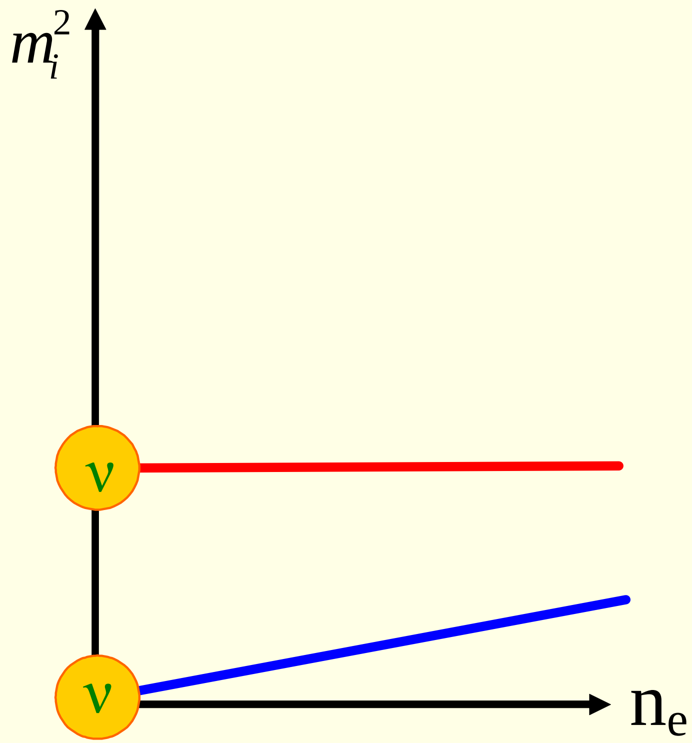
$$E \ll \frac{\Delta m^2 \cos 2\theta}{G_F \; n_e^{\rm prod}}$$



Production with $n_e^{\rm prod} \ll n_e^R$

$$\nu = \sin\theta \; \nu_2^m + \cos\theta \; \nu_1^m$$

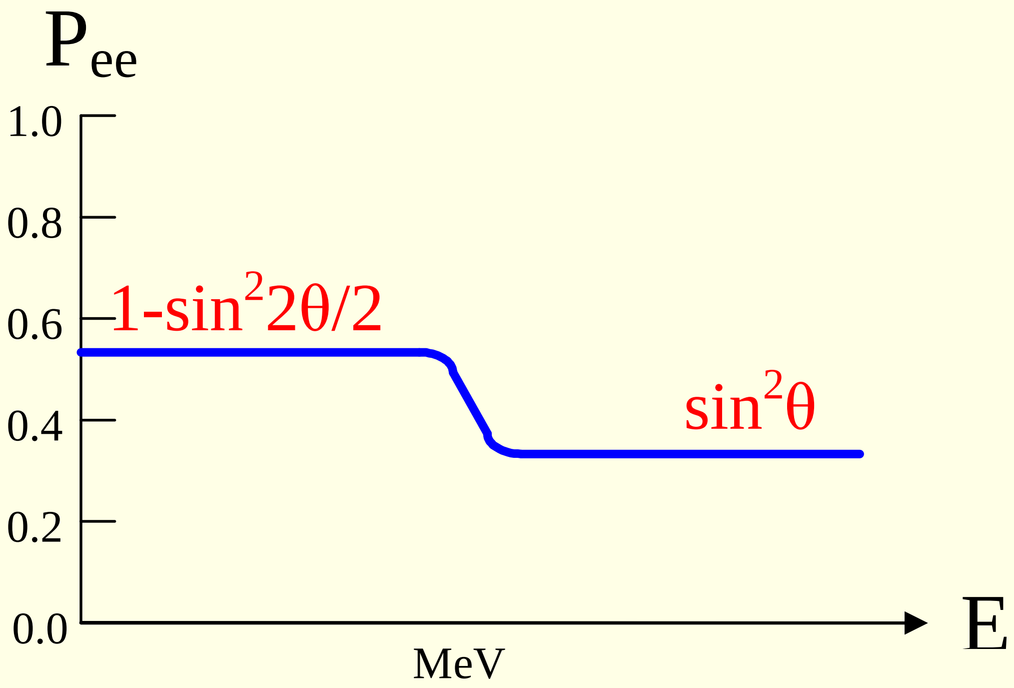
$$E \ll \frac{\Delta m^2 \cos 2\theta}{G_F \;\; n_e^{\rm prod}}$$



Approaching the surface of the Sun

$$\nu = \sin\theta \; \nu_2 + \cos\theta \; \nu_1 = \nu_e \implies P_{ee}(R_\odot) = 1 \implies P_{ee}(\text{Earth}) = 1 - \tfrac{1}{2}\sin^2 2\theta$$

MSW in the Sun, Qualitatively



MSW in the Sun, Quantitatively

- The Sun is a source of MeV ν_e's
  - To have resonance: $n_e^{\text{prod}} > n_e^R = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_F E}$
    $\Longrightarrow$ To probe Δm^2 up to $\sim 10^{-5}\ eV^2$, we need
    $n_e^{\text{prod}} \sim 4 \times 10^{-25}\ \text{cm}^{-3}$
  - To have adiabatic propagation: $\frac{\Delta m^2}{E} \frac{\sin^2 2\theta}{\cos 2\theta} \left| \frac{d \ln n_e}{dx} \right|_{\text{res}}^{-1} \gg 1$
    $\Longrightarrow$ To probe Δm^2 down to $\sim 10^{-9}\ eV^2$, we need
    $r_0 \sim 3 \times 10^9\ \text{cm}\ [n_e(x) \approx 2 n_0 \exp(-x/r_0)]$

Source	$n_0[\text{cm}^{-3}]$	$r_0[\text{cm}]$		$\Delta m^2[\text{eV}^2]$
SN	6×10^{-25}	7×10^9	$\Longrightarrow$	$10^{-9} - 10^{-5}$

Summary: What can we see?

Source	Effect	$\Delta m^2[\mathrm{eV}^2]$
SN	VO	$10^{-11} - 10^{-9}$
SN	MSW	$10^{-9} - 10^{-5}$
KN	VO	$10^{-5} - 10^{-3}$
AN	VO	$10^{-4} - 1$

- If $\theta \not\ll 1$, we should be able to discover neutrino masses in the entire theoretically interesting range: $10^{-11}\ eV^2 < \Delta m^2 < eV^2$
- If $10^{-2} \lesssim \theta \ll 1$ we could still discover it via the adiabatic MSW effect for $\Delta m^2 \sim 10^{-5}\ eV^2$

Next

What do we see?

$\nu_1^m \leftrightarrow \nu_2^m$ transitions

$$\begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

$$\frac{\partial}{\partial t} \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix} = \dot{U}(\theta_m) \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix} + U(\theta_m) \begin{pmatrix} \dot{\nu}_1^m \\ \dot{\nu}_2^m \end{pmatrix}$$

$$i \begin{pmatrix} \dot{\nu}_1^m \\ \dot{\nu}_2^m \end{pmatrix} = \frac{1}{4E} \begin{pmatrix} (m_1^m)^2 - (m_2^m)^2 & -4iE\dot{\theta}_m \\ 4iE\dot{\theta}_m & (m_2^m)^2 - (m_1^m)^2 \end{pmatrix} \begin{pmatrix} \nu_1^m \\ \nu_2^m \end{pmatrix}$$

$$\dot{\theta}_m(t) = \frac{\sqrt{2} G_F E \Delta m^2 \sin 2\theta \;\; \dot{n}_e}{[(m_2^m)^2 - (m_1^m)^2]^2}$$

Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. The Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk III

The Numbers and What They Tell Us

1. Atmospheric Neutrinos (AN)
2. Reactor Neutrinos (RN)
3. Solar Neutrinos (SN)
4. New Physics
5. Grand Unified Theories (GUTs)

The Numbers...

Can I Detect AN?

Can I Detect AN?

Q. How many AN interact with a human?

$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu p} \times N_p^{\text{human}} \times T^{\text{human}}$$

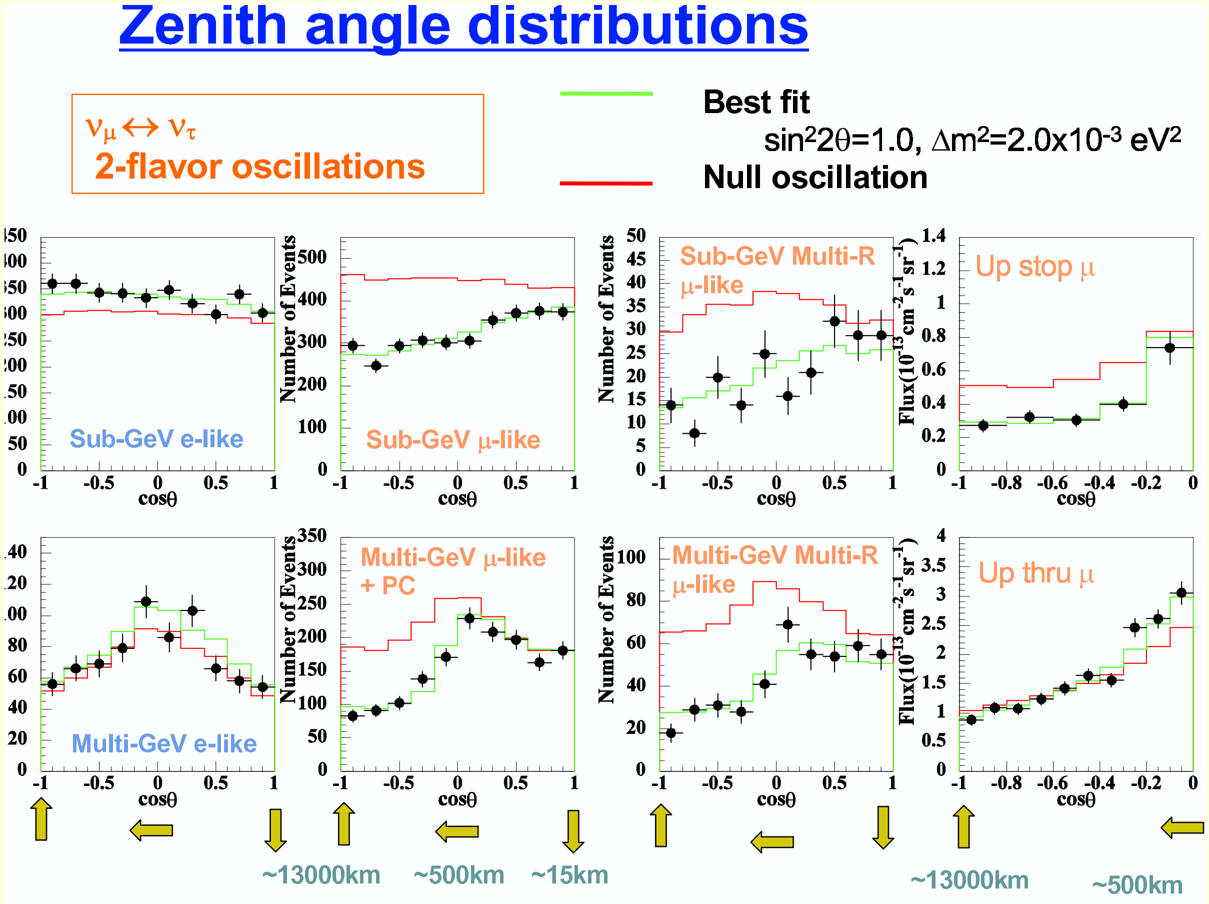
- $\Phi_\nu = \frac{1\ \nu}{\text{cm}^2 \times \text{sec}}$
- $\sigma_{\nu p} \sim 10^{-38}\ \text{cm}^2$
- $N_p^{\text{human}} = \frac{M^{\text{human}}}{\text{gram}} \times N_{\text{A}} \sim 6 \times 10^{28}$
- $T^{\text{human}} \sim 3 \times 10^9$ sec

1-2 interactions per lifetime

Exposure(human) $\sim$ 10 Ton-Year

$\Longrightarrow$ Need Huge (Kton-Year) Detectors

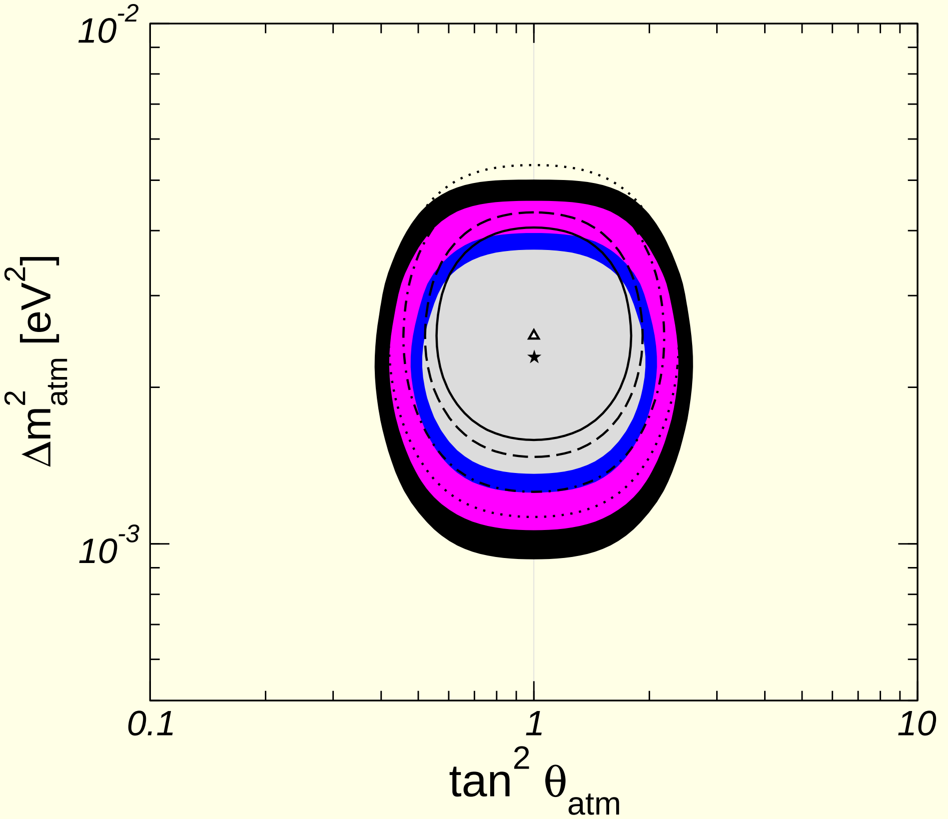
AN - results



Zenith angle distribution of SK

Saji, NOON2004

AN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of the full data sample of AN for oscillation channel $\nu_\mu \to \nu_\tau$

Gonzalez-Garcia, NOON2004

K2K - results and interpretation

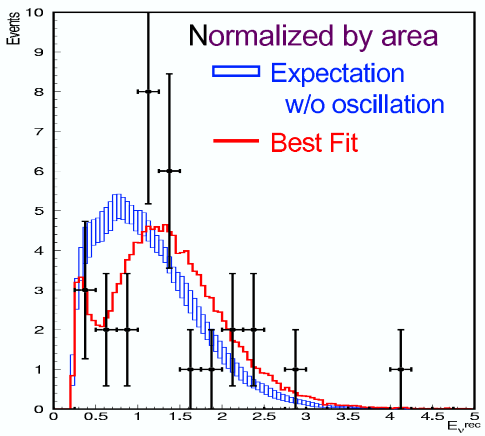
Results of the Oscillation Analysis (K2K-I)

Use both Number of events + Spectrum shape
(June '99 – July '01) (Nov. '99 – July '01)

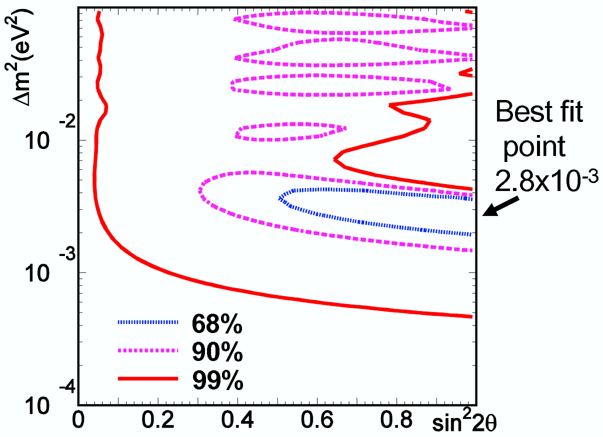
56_{obs} $80.1^{+6.2}_{-5.4}\ _{exp}$

- Null oscillation probability: less than 1%.
- $\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3}$ eV^2 @$\sin^2 2\theta = 1$ (90%CL)

reconstructed Eν



Allowed region



Accelerator ν_μ's with $E \sim 1.3\ GeV$ and $L \sim 250$ km

Ishii, NOON2004

RN - results

Reactor $\overline{\nu}_e$'s with $E \sim$ few MeV:

- CHOOZ

  $L \sim 1$ km

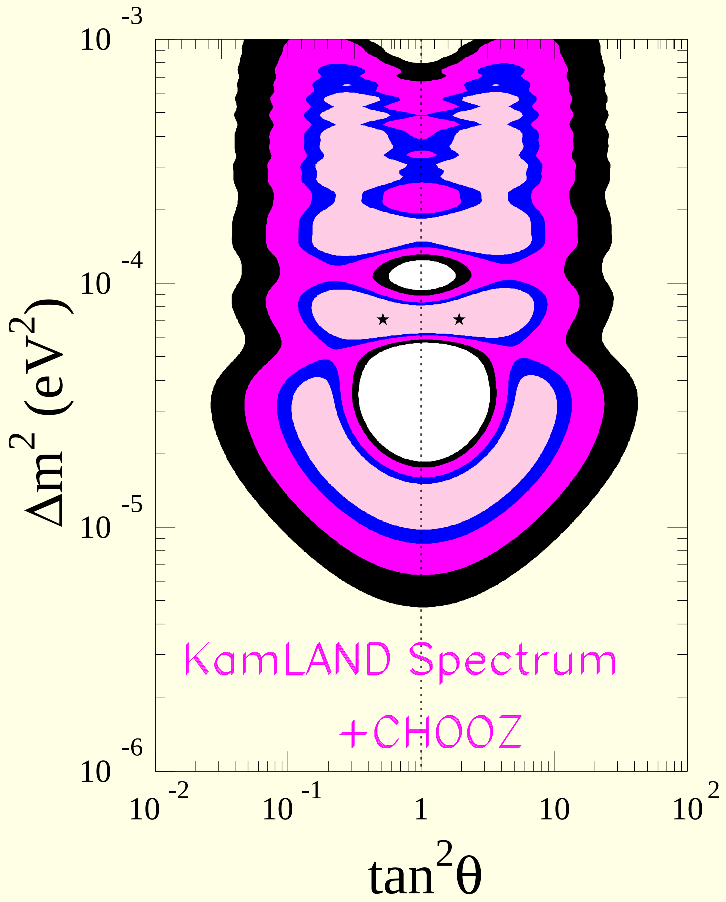
  $$\frac{N_{\text{obs}}}{N_{\text{no-osc}}} = 1.01 \pm 0.028 \pm 0.027$$

- KamLAND

  $L \sim 180$ km

  $$\frac{N_{\text{obs}}}{N_{\text{no-osc}}} = 0.611 \pm 0.085 \pm 0.041$$

RN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of KamLAND and CHOOZ data

Gonzalez-Garcia, NOON2004

SN - The total flux

1	Chlorine	0.30 ± 0.03
1	Sage + Gallex/GNO	0.53 ± 0.03
44	Super-Kamiokande	0.403 ± 0.013
	SNO I CC	0.30 ± 0.02
34	SNO I NC	0.88 ± 0.11
	SNO I ES	0.41 ± 0.04
1	SNO II CC	0.28 ± 0.02
1	SNO II NC	0.89 ± 0.08
1	SNO II ES	0.38 ± 0.05

The beginning: Bahcall, Davis (1964)

SN - SNO (Phase I)

$$\nu_e + \mathrm{d} \to \mathrm{p} + \mathrm{p} + \mathrm{e}^- \qquad \phi_{\mathrm{CC}} = 1.76^{+0.06+0.09}_{-0.05-0.09}$$

$$\nu_a + \mathrm{d} \to \mathrm{p} + \mathrm{n} + \nu_a \qquad \phi_{\mathrm{NC}} = 5.09^{+0.44+0.46}_{-0.43-0.43}$$

$$\nu_a + \mathrm{e}^- \to \nu_a + \mathrm{e}^- \qquad \phi_{\mathrm{ES}} = 2.39^{+0.24+0.12}_{-0.23-0.12}$$

SN - SNO (Phase I)

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$$\nu_a + \mathrm{d} \to \mathrm{p} + \mathrm{n} + \nu_a \qquad \phi_{\mathrm{NC}} = 5.09^{+0.44+0.46}_{-0.43-0.43}$$

$$\nu_a + \mathrm{e}^- \to \nu_a + \mathrm{e}^- \qquad \phi_{\mathrm{ES}} = 2.39^{+0.24+0.12}_{-0.23-0.12}$$

- 5.3σ signal for solar $\nu_e \to \nu_{\mu,\tau}$ transformation

$$\boxed{\phi_{\mu,\tau} = (3.41^{+0.66}_{-0.64}) \times 10^6 \ \mathrm{cm}^{-2}\mathrm{s}^{-1}}$$

- Confirmation of the standard solar model

$$\boxed{\frac{\phi_{\mathrm{NC}}}{\phi_{\mathrm{SSM}}} = 1.01 \pm 0.12}$$

- Consistency check

$$\phi_{\mathrm{NC}} = [\phi_{\mathrm{ES}} - (1-r)\phi_{\mathrm{CC}}]/r, \quad (r \equiv \sigma_{\mu,\tau}/\sigma_e)$$

SNO: SSM Test and Consistency Check

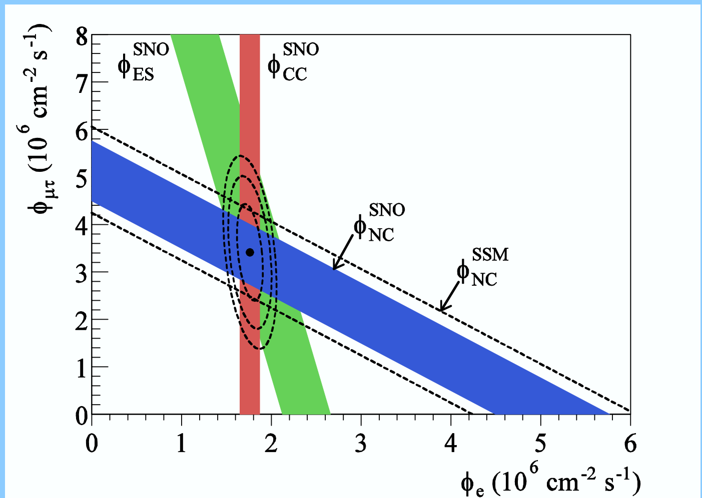
Flux Results – Pure D_2O Phase

$$\Phi_e = 1.76^{+0.05}_{-0.05}(stat.)^{+0.09}_{-0.09}(syst.) \times 10^6 \, cm^{-2} s^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(stat.)^{+0.48}_{-0.45}(syst.) \times 10^6 \, cm^{-2} s^{-1}$$

$5.3\,\sigma$ effect

Neutrinos Massive



Constrained Fit for flavour change test

$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

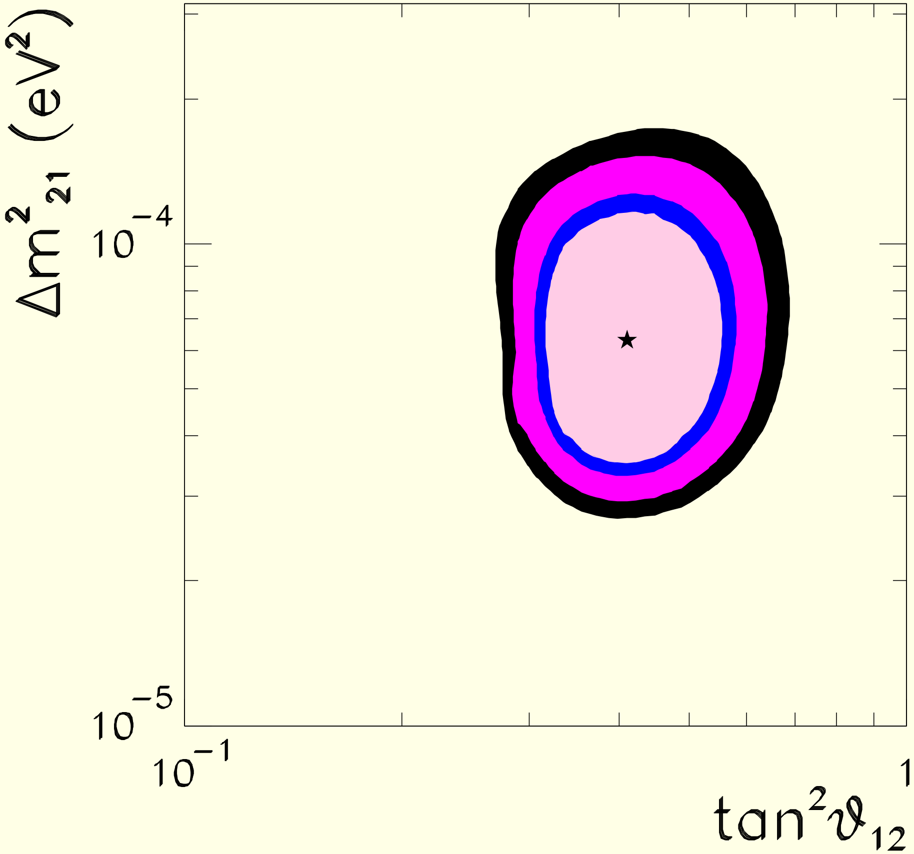
$$\Phi_{SNO} = 5.09^{+(0.44 \oplus 0.46)}_{-(0.43 \oplus 0.43)}$$

Without Constraint

$$\Phi_{SNO} = 6.42^{+(1.57 \oplus 0.55)}_{-(1.57 \oplus 0.58)}$$

Graham, NOON2004

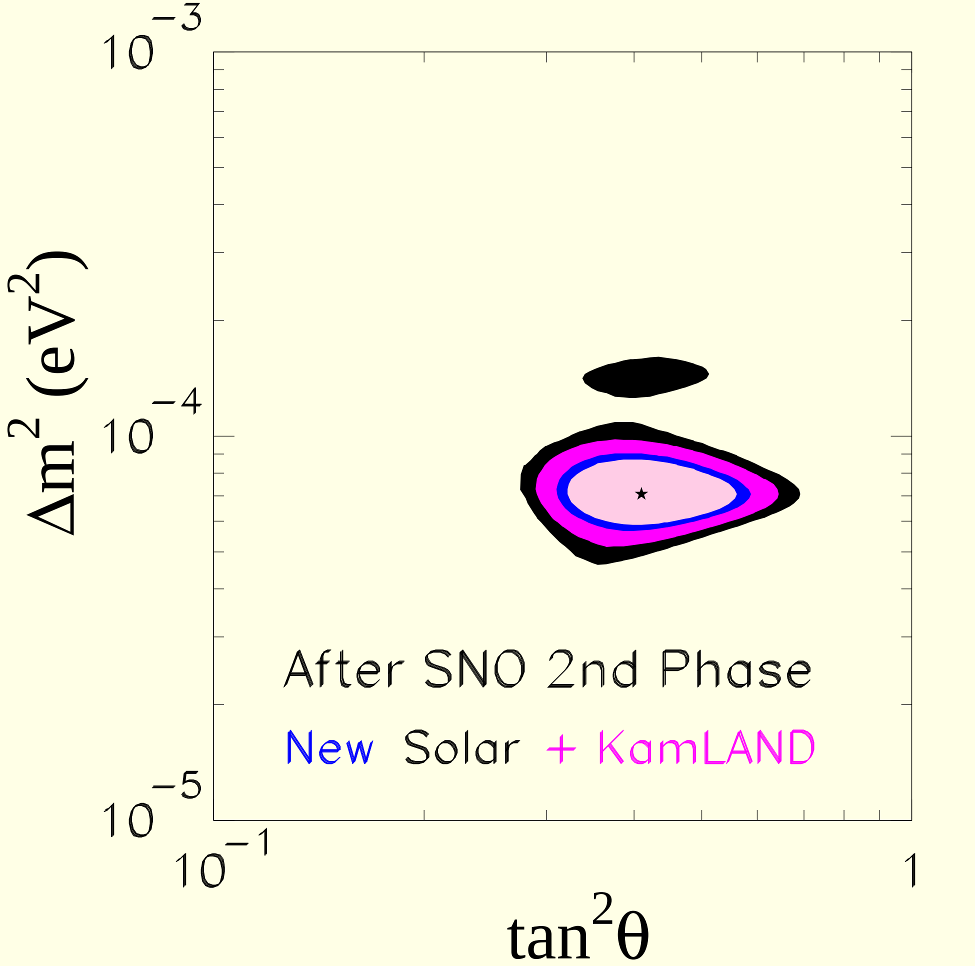
SN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL) from the analysis of solar neutrino data

Gonzalez-Garcia, NOON2004

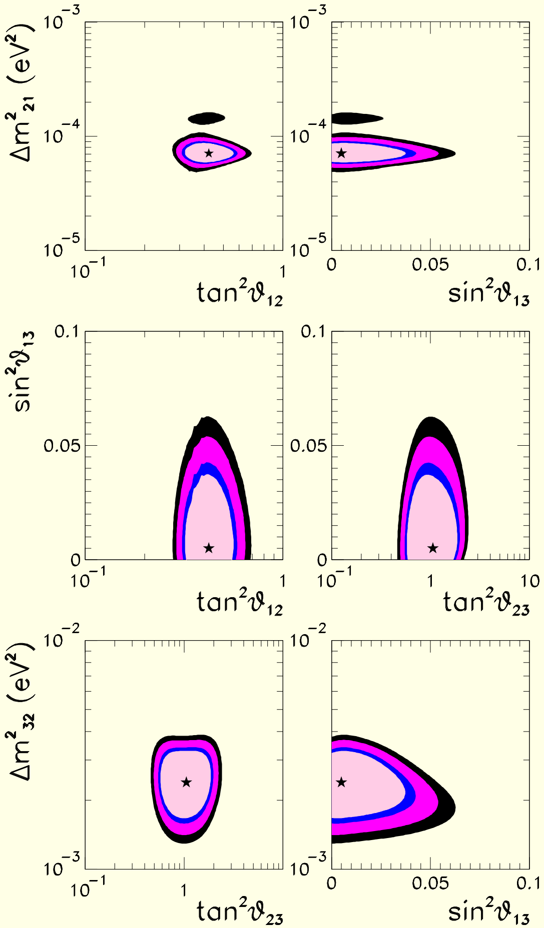
SN + RN - theoretical interpretation



Allowed regions (at 90, 95, 99%, 3σ CL)

Gonzalez-Garcia, NOON2004

A three generation analysis



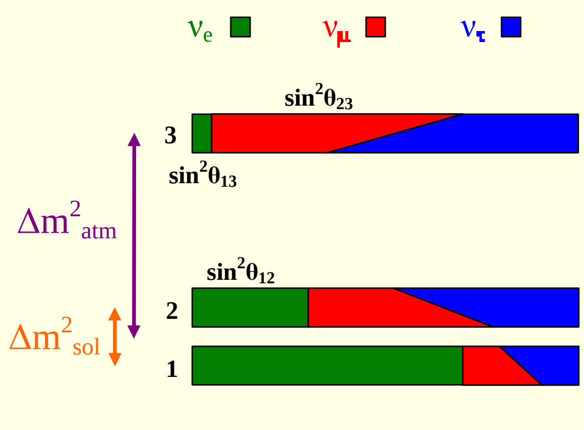
Allowed regions (at 90, 95, 99%, 3σ CL)

Gonzalez-Garcia + Pena-Garay, PRD68:093003, 2003 [hep-ph/0306001]

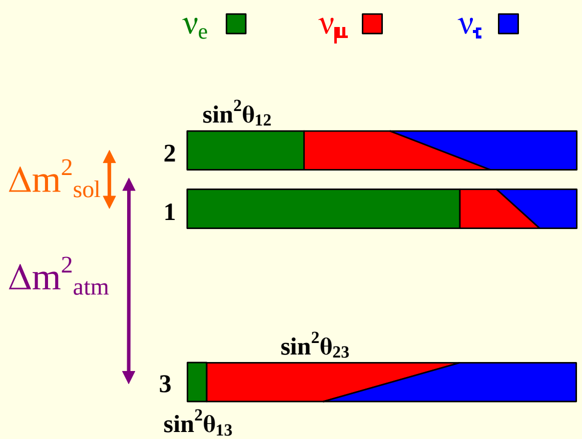
Allowed Ranges for Neutrino Parameters

	Best fit	3σ range
Δm^2_{32} $[eV^2]$	2.4×10^{-3}	$(1.4 - 3.4) \times 10^{-3}$
Δm^2_{21} $[eV^2]$	7.1×10^{-5}	$(5.2 - 9.8) \times 10^{-5}$
$\tan^2\theta_{23}$	1.0	$0.49 - 2.2$
$\tan^2\theta_{12}$	0.42	$0.29 - 0.64$
$\sin^2\theta_{13}$	0.006	≤ 0.054

Mixing and Hierarchy



Normal Hierarchy



Inverted Hierarchy

$$\sin^2\theta_{12} = 0.3, \quad \sin^2\theta_{13} = 0.05, \quad 0.33 < \sin^2\theta_{23} < 0.67$$

What we do not know

- The spectrum:
  Hierarchical or Degenerate?
- The hierarchy:
  Normal or Inverted?
- $|U_{e3}|$:
  Small or Tiny?

...and What They Tell Us

New Physics

The Standard Model is NOT
the complete picture of Nature

New Physics

The Standard Model is NOT the complete picture of Nature

Most likely, the SM is only a low energy effective theory and lepton number is broken at some high energy scale

A specific realization: The See-Saw Mechanism

Heavy SM-singlet fermions, $M \gg \Lambda_{\mathrm{EW}}$

$$\mathcal{L} = Y \phi^\dagger \overline{\nu_L} \nu_R + M \nu_R \nu_R \implies M_\nu = \begin{pmatrix} 0 & Y\langle\phi\rangle \\ Y\langle\phi\rangle & M \end{pmatrix}$$

$$\implies m_\nu = \frac{Y^2 \langle\phi\rangle^2}{M}$$

The Scale of New Physics

- SM = low energy effective theory
- $\mathcal{L}_{\rm NR} \sim \frac{1}{\Lambda_{\rm NP}} \phi\phi L L$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \sim \frac{\langle\phi\rangle^2}{m_\nu}}$$

- AN: $m_\nu \gtrsim 0.04\ eV$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \lesssim 10^{15}\ GeV}$$

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$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \sim \frac{\langle \phi \rangle^2}{m_\nu}}$$

- AN: $m_\nu \gtrsim 0.04\ eV$

$\Longrightarrow$

$$\boxed{\Lambda_{\rm NP} \lesssim 10^{15}\ GeV}$$

1. There is new physics at a scale well below the Planck scale
2. The upper bound is intriguingly close to the GUT scale

GUT

Why Believe in GUT?

1. Coupling unification
2. Multiplet unification
3. Flavor unification

GUT

Why Believe in GUT?

1. Coupling unification
2. Multiplet unification
3. Flavor unification

Why Be Cautious About GUT?

1. Proton decay
2. Doublet-Triplet splitting
3. Flavor splitting
4. Supersymmetry

AN: Three New Facts in Favor of GUT

1. $m_\nu \neq 0$

In SO(10): 1. Singlet fermions exist 2. M_ν related to M_u

$\Longrightarrow \quad m_\nu \neq 0$

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$\Longrightarrow \quad m_\nu \neq 0$

2. $m_\nu \sim 0.05\ eV$

In SO(10): 1. $M_\nu^{\text{Dirac}} = M_u$ 2. $\Lambda_{SO(10)} \sim 10^{16}\ GeV$

$\Longrightarrow \quad m_{\nu_3} \sim \frac{m_t^2}{\Lambda_{SO(10)}} \sim 10^{-3}\ eV$

AN: Three New Facts in Favor of GUT

1. $m_\nu \neq 0$

In SO(10): 1. Singlet fermions exist 2. M_ν related to M_u

$\Longrightarrow \quad m_\nu \neq 0$

2. $m_\nu \sim 0.05\ eV$

In SO(10): 1. $M_\nu^{\text{Dirac}} = M_u$ 2. $\Lambda_{SO(10)} \sim 10^{16}\ GeV$

$\Longrightarrow \quad m_{\nu_3} \sim \frac{m_t^2}{\Lambda_{SO(10)}} \sim 10^{-3}\ eV$

3. $|V_{\mu 3}| \sim 1$

In SU(5): 1. $M_\ell = M_d^T$ (2. $|V_{cb}| \sim 0.04,\ m_s/m_b \sim 0.03$)

$\Longrightarrow \quad |V_{\mu 3} V_{cb}| \sim m_s/m_b \quad \Longrightarrow \quad |V_{\mu 3}| \sim 1$

Summary

- The numbers:

$$\begin{aligned}\Delta m^2_{32} &\sim 2.4\times10^{-3}\ eV^2, \quad \Delta m^2_{21}\sim 7.1\times10^{-5}\ eV^2,\\ \tan^2\theta_{23} &\sim 1.0, \quad \tan^2\theta_{12}\sim 0.42, \quad \sin^2\theta_{13}\leq 0.054.\end{aligned}$$

- The main lessons for theory:
  - There is New Physics
  - Most likely, the SM is only a low energy effective theory
  - $\Lambda_{\rm NP}\sim 10^{15}\ GeV\ (\ll m_{\rm Pl})$
  - The results ($m_\nu\neq 0$, $m_3\sim 10^{-2}\ eV$, $|V_{\mu3}|\sim 1$) fit GUT expectations nicely

Supersymmetry (with R-Parity)

MSSM

- $B - L =$ accidental symmetry $\Longrightarrow\ m_\nu = 0$

MSSM=LEET

- $\frac{1}{\Lambda_{\rm NP}} LL\phi\phi$ allowed (R_p conserving) $\Longrightarrow\ m_\nu \neq 0$ but small
- The supersymmetric partner of see-saw neutrino masses: Sneutrino-antisneutrino mixing $\Longrightarrow$ sneutrino oscillations

Grossman + Haber (1997)

MSSM+N

- Interesting new mechanisms (a-la Giudice-Masiero mechanism for suppressing μ) for $m_N \sim m_{3/2}$ but very light m_ν

Arkani-Hamed et al (2000); Borzumati et al (2000)

Supersymmetry without R-Parity

A Generic Problem

Naively, one mass at Λ_{EW} and two suppressed only by a loop factor.

- Must have a mechanism to ensure approximate lepton symmetry.

An Interesting Point

Many different sources for neutrino masses, allowing hierarchy simultaneously with large mixing.

1. μ and B misaligned: $\frac{m_2}{m_3} \sim \frac{g^2}{64\pi^2}$.
2. μ and B aligned at a high scale: RGE-induced misalignment gives appropriate hierarchy.
3. Only trilinear couplings (λ and λ') significant: $\frac{m_2}{m_3} \sim \frac{m_\tau^2}{3m_b^2}$.

Extra Dimensions

Large Extra Dimensions

If there is no $\Lambda_{NP} \gg$ TeV, the see-saw mechanism cannot be implemented
$\Longrightarrow$ There better be no singlet fermions confined to the brane.

(i) Coupling to bulk fermions: Arkani-Hamed et al (2002), Dienes et al (1999)

$$m_\nu^{\rm Dir} = \frac{Y\langle\phi\rangle}{\sqrt{V_n M_*^n}} = Y\langle\phi\rangle\frac{M_*}{M_{\rm Pl}}$$

(ii) Lepton number breaking on a distant brane: Arkani-Hamed et al (2002)

$$m_\nu^{\rm Maj} \sim \frac{\langle\phi\rangle^2}{M_*}e^{-mr}$$

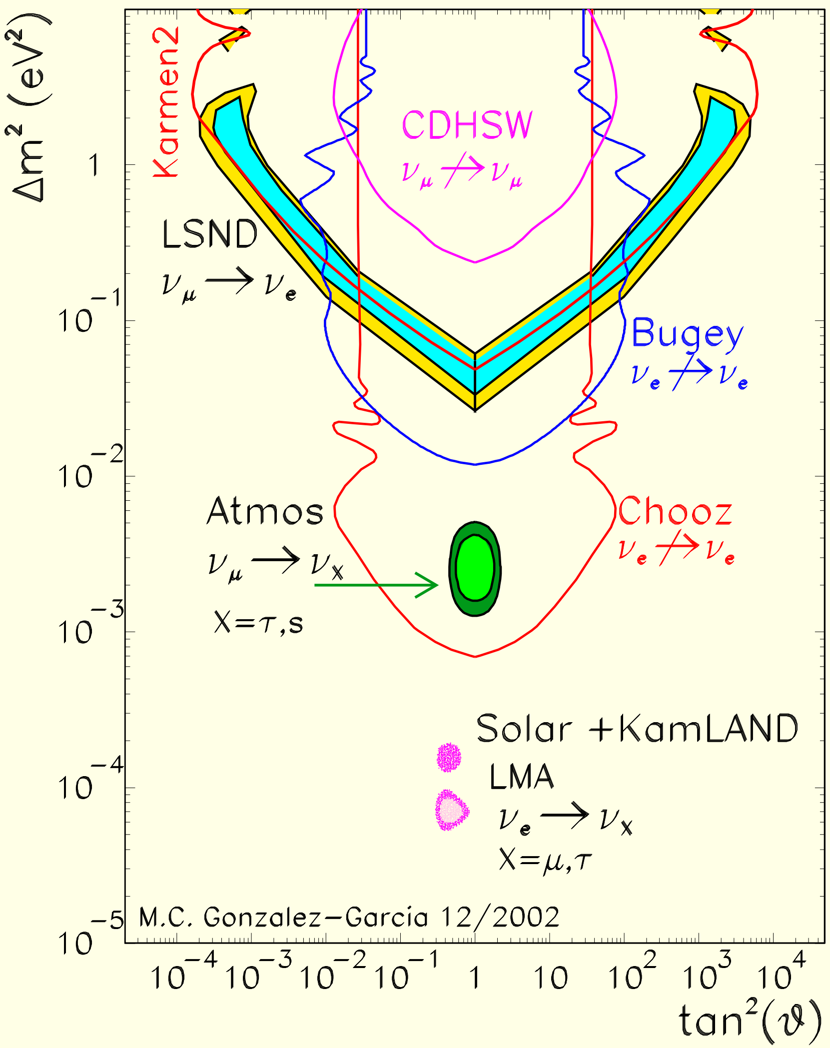
The Randall-Sundrum Scenario

(iii) Warp factor suppression: Grossman + Neubert (2000)

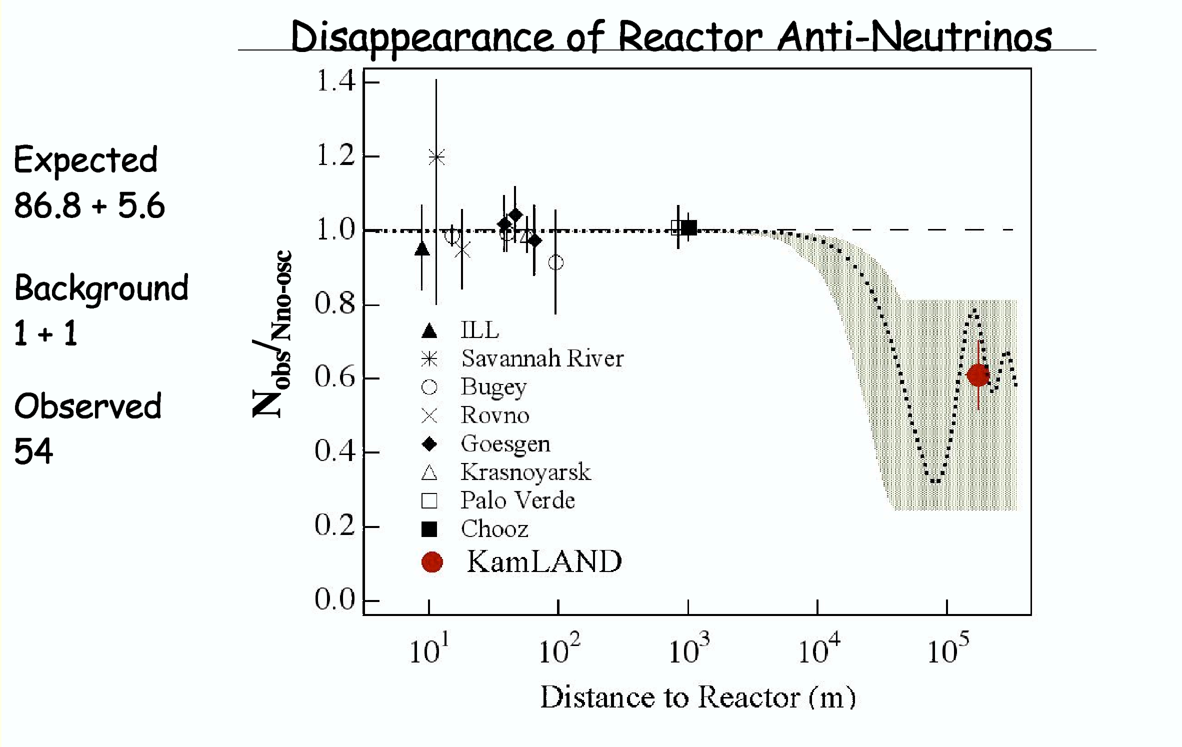
If the zero-mode of a bulk, singlet neutrino (of mass m) is located on the hidden brane,

$$m_\nu \sim \langle\phi\rangle\left(\frac{\langle\phi\rangle}{M_{\rm Pl}}\right)^{m/k-1/2}$$

Summary of Experimental Searches



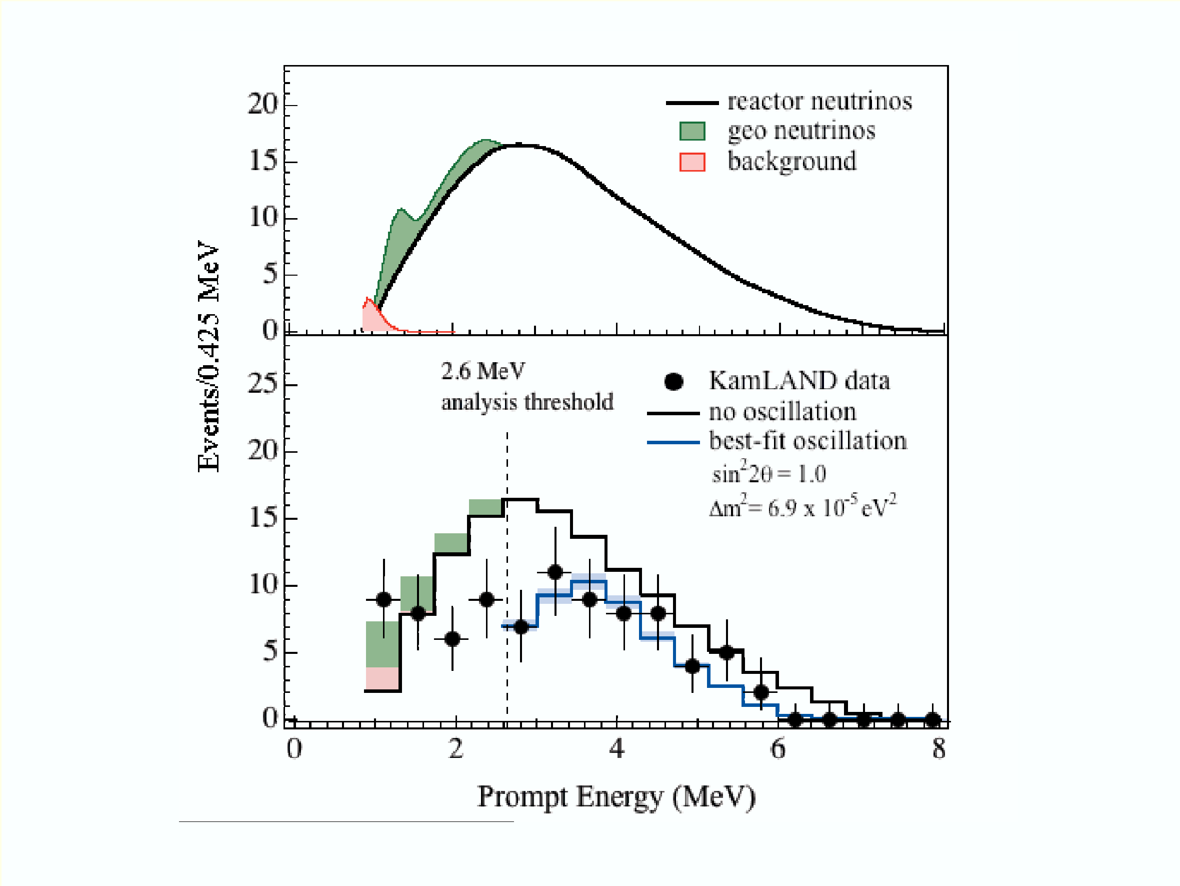
RN - results



N_{obs}/N_{no-osc} = 0.611 ± 0.085 (stat) ± 0.041 (syst)

Reactor $\overline{\nu}_e$'s with $E \sim \ MeV$ and $L \sim 1$ km (CHOOZ)
or $\sim$ 200 km (KamLAND)

KamLAND - results



Plan of Talks

1. The Standard Model and (a Little) Beyond
2. Neutrinos (Mainly) from Heaven
3. The Numbers and What They Tell Us
4. The Flavor Puzzle(s)
5. Leptogenesis

Plan of Talk IV

The Flavor Puzzle(s)

1. The SM flavor puzzle
2. Approximate Horizontal Symmetries
3. Neutrino flavor puzzles
    - Large mixing and strong hierarchy
    - Anarchy

Quark Hierarchy

The SM Flavor Puzzle

The SM flavor parameters are small and hierarchical

U	$Y_t \sim 1$	$Y_c \sim 10^{-2}$	$Y_u \sim 10^{-5}$
D	$Y_b \sim 10^{-2}$	$Y_s \sim 10^{-3}$	$Y_d \sim 10^{-4}$
E	$Y_\tau \sim 10^{-2}$	$Y_\mu \sim 10^{-3}$	$Y_e \sim 10^{-6}$
CKM	$\|V_{us}\| \sim 0.2$	$\|V_{cb}\| \sim 0.04$	$\|V_{ub}\| \sim 0.004$
CPV	$\delta_{\rm KM} \sim 1$		

Approximate Horizontal Symmetries

- Horizontal symmetries = different generations carry different charges (unlike $G_{\rm SM}$)

- Approximate symmetry = broken explicitly by a small parameter of well defined charge (similar to the isospin symmetry of strong interactions) $\Longrightarrow$ 'Selection rules'

- Approximate horizontal symmetries can naturally explain the hierarchy in the quark and charged lepton Yukawa couplings

- The measured neutrino parameters test such flavor models and may shed new light on the flavor puzzles

Neutrino Flavor Parameters

- With three active neutrinos that have Majorana-type masses, there are nine new flavor parameters: three neutrino masses, three lepton mixing angles and three phases in the mixing matrix.
- Four have been measured.
- Are flavor models consistent with

$$|U_{\mu 3}U_{\tau 3}| \sim 0.47 - 0.50$$
$$|U_{e1}U_{e2}| \sim 0.42 - 0.49$$
$$|U_{e3}| \leq 0.23$$
$$\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 0.02 - 0.04$$

- (Inconsistencies might be in the eye of the beholder.)

Neutrino Hierarchy

Abelian or non-Abelian? (I)

- SU(3) with $Q(3), \bar{U}(\bar{3})$: $\Longrightarrow\ m_u = m_c = m_t$
- SU(3) otherwise: $\Longrightarrow\ m_t \ll \langle\phi\rangle$
- SU(2) with $Q(2+1), \bar{U}(2+1)$: $\Longrightarrow\ m_u = m_c$
- The data: $m_u \ll m_c \ll m_t \sim \langle\phi\rangle$

$\Longrightarrow$ **The simplest non-Abelian models are excluded**

Horizontal U(1) Symmetry

- $U(1)$ broken by $\lambda(-1)$ with $|\lambda| \sim 0.2$

Froggatt + Nielsen (1979)

- $Q(3,2,0),\ \bar{U}(5,2,0),\ \bar{D}(3,2,2)$

$$\Longrightarrow M_u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda^8 & \lambda^5 & \lambda^3 \\ \lambda^7 & \lambda^4 & \lambda^2 \\ \lambda^5 & \lambda^2 & 1 \end{pmatrix}, \quad M_d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda^6 & \lambda^5 & \lambda^5 \\ \lambda^5 & \lambda^4 & \lambda^4 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

- Reproduces the data nicely
- The simplest models successfully predict for quarks:

$$\sin\theta_{13} \sim \sin\theta_{12} \sin\theta_{23}, \quad m_i/m_j \lesssim \sin\theta_{ij}, \quad V \sim \mathbf{1}$$

Leurer, Nir, Seiberg (1994)

- The simplest models predict for neutrinos:

$$\sin\theta_{13} \sim \sin\theta_{12} \sin\theta_{23}, \quad m_i/m_j \sim \sin^2\theta_{ij}$$

Abelian or non-Abelian? (II)

- The simplest models of Abelian horizontal symmetries predict:

$m_{\nu_i}/m_{\nu_j} \sim \sin^2\theta_{ij}, \quad \sin\theta_{13} \sim \sin\theta_{12}\sin\theta_{23}$

- The data:

$\sin\theta_{23} \sim 1, \quad \sin\theta_{12} \sim 1, \quad \sin\theta_{13} < 0.2, \quad m_2/m_3 \sim 0.2$

$\Longrightarrow$ The simplest Abelian models are excluded

- It is particularly difficult to explain $\sin\theta_{23} \sim 1$ with $m_2/m_3 \ll 1$

(large mixing $\leftrightarrow$ strong hierarchy)

Abelian or non-Abelian? (III)

The data: $\sin\theta_{23} \sim 1, \quad \sin\theta_{12} \sim 1, \quad \sin\theta_{13} < 0.2, \quad m_2/m_3 \sim 0.2$

Some options:

- $L(1,0,0)$ with an $\mathcal{O}(\lambda)$ accidental cancellation:
  $m_2/m_3 \sim 1(\to \lambda)$, $\sin\theta_{12} \sim \lambda(\to 1)$
- $L(0,0,0)$ with an $\mathcal{O}(\lambda)$ accidental cancellation:
  $m_2/m_3 \sim 1(\to \lambda)$, $\sin\theta_{13} \sim 1(\to \lambda)$
- Very specific Abelian models
- A combination of Abelian (charged fermion) and non-Abelian [neutrino (and sfermion)] symmetries

The Data

In the 2-3 generation sector, there is large mixing, but the corresponding masses are hierarchical

- $|U_{\mu 3} U_{\tau 3}| = \mathcal{O}(1)$.
- $\Delta m^2_{21} / \Delta m^2_{32} \ll 1$ suggests $m_2/m_3 \ll 1$.

The Puzzle

$$M_\nu^{2-3} = \frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}} \begin{pmatrix} A & B \\ B & C \end{pmatrix}$$

- $\tan 2\theta_{23} = \frac{2B}{C-A}$
  Large mixing $\Longrightarrow$ $|B| \sim |C-A|$
- $\frac{m_2 m_3}{(m_2+m_3)^2} = \frac{AC-B^2}{(A+C)^2}$
  Strong hierarchy $\Longrightarrow$ $|AC-B^2| \ll |A+C|^2$
- Large mixing + strong hierarchy: $\Longrightarrow$ $AC - B^2 \ll AC, B^2$

Fine Tuning?

Solutions

1. Accidental hierarchy
2. Several sources for neutrino masses
   (a) A single right-handed neutrino dominance
   (b) Supersymmetric models without R-parity
3. Large mixing from the charged lepton sector
4. Large mixing from the see-saw mechanism
5. (A three generation mechanism ($L_e - L_\mu - L_\tau$ symmetry))

$L_e - L_\mu - L_\tau$ (I)

- An example of an approximate horizontal Abelian symmetry:

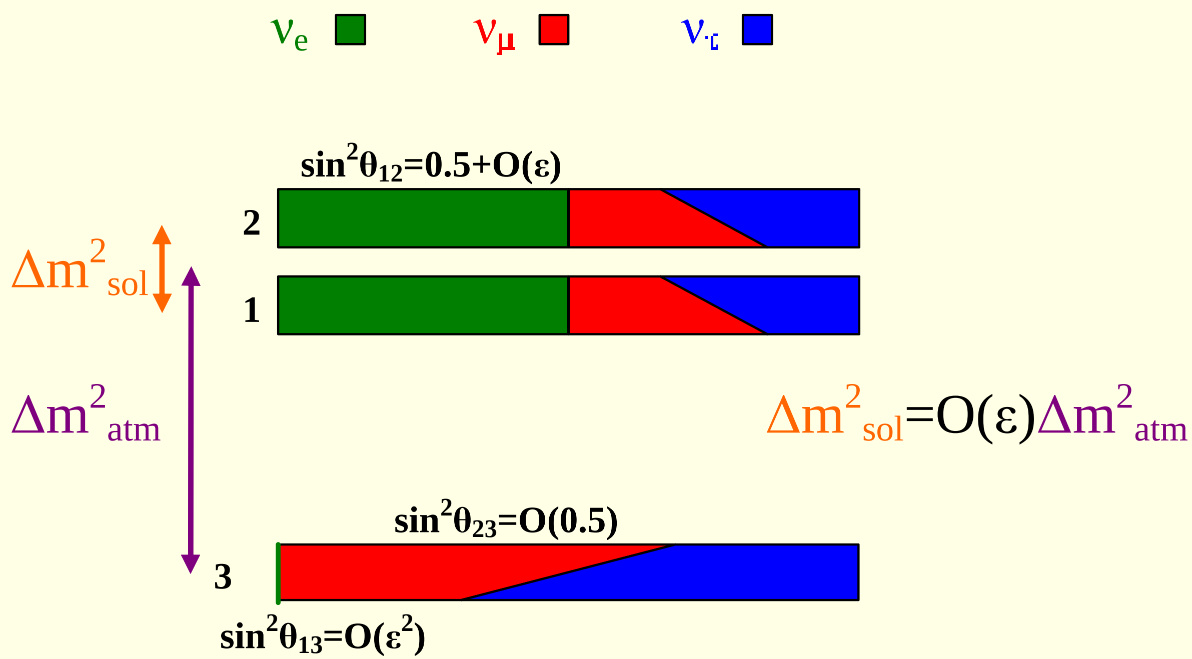
- $U(1)_{e-\mu-\tau}$ broken by $\epsilon_+(+2)$ and $\epsilon_-(-2)$, with $|\epsilon_\pm| \ll 1$.

- $M_\nu \sim \frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}} \begin{pmatrix} \epsilon_- & 1 & 1 \\ 1 & \epsilon_+ & \epsilon_+ \\ 1 & \epsilon_+ & \epsilon_+ \end{pmatrix}, \quad M_\ell \sim \langle\phi\rangle \begin{pmatrix} \lambda_e & \lambda_\mu\epsilon_- & \lambda_\tau\epsilon_- \\ \lambda_e\epsilon_+ & \lambda_\mu & \lambda_\tau \\ \lambda_e\epsilon_+ & \lambda_\mu & \lambda_\tau \end{pmatrix}$

- $\lambda_{e,\mu,\tau}$ affect neither mixing angles nor neutrino masses

- Can estimate all ν-parameters in terms of $m \sim \frac{\langle\phi\rangle^2}{\Lambda_{\rm NP}}$, ϵ_+, ϵ_-.

$L_e - L_\mu - L_\tau$ (II)



$$m_{1,2} = m[1 \pm \mathcal{O}(\epsilon_\pm)], \quad m_3 = m\mathcal{O}(\epsilon_+)$$

$$|U_{\mu 3}U_{\tau 3}| = \mathcal{O}(1), \quad |U_{e1}U_{e2}| = 1/2 - \mathcal{O}(\epsilon_\pm^2), \quad |U_{e3}| = \mathcal{O}(\epsilon_\pm)$$

$L_e - L_\mu - L_\tau$ (III)

$$m_{1,2} = m[1 \pm \mathcal{O}(\epsilon_\pm)], \quad m_3 = m\mathcal{O}(\epsilon_+)$$
$$|U_{\mu 3}| = \mathcal{O}(1), \quad |U_{e3}| = \mathcal{O}(\epsilon_\pm), \quad |U_{e1}U_{e2}| = 1/2 - \mathcal{O}(\epsilon_\pm^2)$$

- Large mixing ($|U_{\mu 3}| \sim 1$) with strong hierarchy ($\frac{\Delta m^2_{21}}{\Delta m^2_{23}} \sim \epsilon_\pm$)
- One small + two large angles: $\sin\theta_{13} \ll \sin\theta_{12}\sin\theta_{23}$
- Pseudo-Dirac SN ($\theta_{12} \approx \pi/4,\ \Delta m^2_{21} \ll m^2_{2,1}$)
- Inverted hierarchy ($m_{1,2} \gg m_3$)
- Relations between $\Delta m^2_{\mathrm{SN}}/\Delta m^2_{\mathrm{AN}}$, $|U_{e1}U_{e2}| - \frac{1}{2}$, $|U_{e3}|$.
- Solar mixing near-maximal:
  $|U_{e1}U_{e2}| = \frac{1}{2} - \mathcal{O}\left[\left(\frac{\Delta m^2_{\mathrm{SN}}}{\Delta m^2_{\mathrm{AN}}}\right)^2\right] = 0.500(2)$
  $\Longrightarrow$ EXCLUDED

Neutrino Anarchy

The Data

None of the measured neutrino flavor parameters is $\ll 1$

- $|U_{\mu 3}U_{\tau 3}| = \mathcal{O}(1)$
- $\frac{m_2}{m_3} \geq \sqrt{\frac{\Delta m^2_{21}}{\Delta m^2_{32}}} = \mathcal{O}(0.15)$
- $|U_{e1}U_{\mu 1}| = \mathcal{O}(1)$
- $|U_{e3}| \leq 0.23$

Future tests:

- $|U_{e3}| \ll 1$?
- $m_3 \gg \sqrt{\Delta m^2_{\rm AN}}$?
- $|U_{\mu 3}U_{\tau 3}| - 1/2 \ll 1$?

The Idea

The charged fermion flavor parameters have a special structure, that is, they are small and hierarchical

$$\Updownarrow$$

Could it be that the neutrino flavor parameters have no special structure, that is, they are anarchical?

Hall, Murayama, Weiner (2000)

Lessons for Theory

A simple (but, perhaps, disappointing) explanation:

- All doublet-lepton fields L_i carry the same horizontal charge

$\Longrightarrow$ The Yukawa couplings and the singlet-neutrino masses are hierarchical, but $m_\nu^{\rm light} \sim \langle\phi\rangle^2 Y M^{-1} Y^T$ is not.

An intriguing possibility:

- The special, Majorana nature of ν's makes them flavor blind

Goswami, Indumathi, Shadmi, Nir (in progress)

An explicit example:

- Horizontal symmetries broken at the same scale as L

$\Longrightarrow$ Y, M (and, consequently, $m_\nu^{\rm light}$) are all anarchical.

Summary

- Neutrino flavor parameters have features that are very different from the charged fermion parameters.
- Some of the features are surprising:
  - Large mixing $\leftrightarrow$ strong hierarchy in the $2-3$ sector;
  - Near-maximal $2-3$ mixing;
  - Two large (s_{12}, s_{23}) and one small (s_{13}) mixing angles.
- Most of the simplest and most predictive flavor models - excluded.
- Quite likely, the neutrino flavor structure involves the heavy, singlet neutrinos in a significant way (the LEET is not enough)
- Neutrino mass anarchy?
  Interplay between flavor and Majorana/Dirac?

Prospects

There is still a lot to be learnt:

1. $|U_{e3}| \ll 1$?
   Small or tiny?
2. $|U_{\mu 3} U_{\tau 3}| \neq \frac{1}{2}$?
   Large or maximal?
3. $m_i =$?
   Hierarchical or degenerate?
4. $\Delta m^2_{32} > 0$?
   Normal or inverted?
5. $m_{ee} =$?
   Majorana or Dirac?

The NP Flavor Puzzle

- Generically, no GIM mechanism to explain the smallness of FCNC
- In SUSY, many new sources of flavor violation and of CPV

$$K-\bar{K}\ \text{mixing}: \Longrightarrow\ \frac{1\ TeV}{\tilde{m}}\frac{\tilde{m}^2_{d_2}-\tilde{m}^2_{d_1}}{\tilde{m}^2}K^d_{12}\leq 10^{-3}.$$

$\Longrightarrow$ The flavor (and phase) structure of SUSY is highly non-generic

  - Universality: degeneracy between sfermion generations
  - Alignment: smallness of supersymmetric mixing angles
  - Heaviness: first two squark generations heavier than TeV
  - (Approximate CP: CPV phases are small)

- Universality $\leftrightarrow$ non-Abelian
- Alignment $\leftrightarrow$ Abelian

L_2, L_3, single N

$$M_\nu = \begin{pmatrix} 0 & 0 & Y_2\langle\phi\rangle \\ 0 & 0 & Y_3\langle\phi\rangle \\ Y_2\langle\phi\rangle & Y_3\langle\phi\rangle & M \end{pmatrix}$$

$\Longrightarrow$ One heavy $[\mathcal{O}(M)]$ and two light $[\mathcal{O}(\langle\phi\rangle^2/M)]$ neutrinos:

$$m_N = M, \quad m_\nu^{\text{light}} = \frac{\langle\phi\rangle^2}{M} \begin{pmatrix} Y_2^2 & Y_2 Y_3 \\ Y_2 Y_3 & Y_3^2 \end{pmatrix}$$

$\Longrightarrow$ Strong hierarchy and (for $Y_2/Y_3 = \mathcal{O}(1)$) large angle:

$$\tan 2\theta_{23} = \frac{2Y_2Y_3}{Y_3^2 - Y_2^2} = \mathcal{O}(1), \quad m_2 = 0, \quad m_3 = \frac{(Y_2^2+Y_3^2)\langle\phi\rangle^2}{M}$$

- $\Delta m^2_{32} \neq 0$ and $\Delta m^2_{21} \neq 0 \Longrightarrow$ at least two N's required

$\Longrightarrow$ 'Single right-handed neutrino dominance'

Plan of Talks

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5. Leptogenesis

Plan of Talk V

Leptogenesis

1. Baryogenesis
2. Leptogenesis
3. Soft leptogenesis

Baryogenesis

Sakharov, 1967

Sakharov Conditions

Nucleosynthesis, CMBR $\Longrightarrow$ $\boxed{Y_B \equiv \frac{n_b - n_{\overline{b}}}{s} = \frac{n_b}{s} \sim 10^{-10}}$

The baryon asymmetry can be dynamically generated ('baryogenesis') provided that

1. Baryon number is violated;
2. C and CP are violated;
3. Departure from thermal equilibrium.

SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by δ_{KM};
3. Departure from thermal equilibrium at the EWPT.

SM Baryogenesis

Sakharov conditions are met within the SM:

1. $B - L$ is conserved, but $B + L$ is violated;
2. CP is violated by δ_{KM};
3. Departure from thermal equilibrium at the EWPT.

The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT;
2. KM CP violation is too suppressed.

KM $\leftrightarrow$ Baryogenesis

The SM violates CP if and only if

1. No degeneracy in either quark sector;
2. All mixing angles $\neq 0, \pi/2$;
3. The KM phase $\neq 0, \pi$.

KM $\leftrightarrow$ Baryogenesis

The SM violates CP if and only if

1. No degeneracy in either quark sector;
2. All mixing angles $\neq 0, \pi/2$;
3. The KM phase $\neq 0, \pi$.

The baryon asymmetry is proportional to:

$$\begin{aligned}
\epsilon_{\mathrm{CPV}} &= \frac{1}{m_W^{12}}(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2) \\
&\times (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \\
&\times \sin\theta_{12}\cos\theta_{12}\sin\theta_{23}\cos\theta_{23}\sin\theta_{13}\cos\theta_{13}\sin\delta_{\mathrm{KM}} \\
&\sim 10^{-18}
\end{aligned}$$

SM and Baryogenesis

The SM $B+L$ violating (but $B-L$ conserving) processes are very fast in the Early Universe ($10^{12}\ GeV \gtrsim T \gtrsim 10^{2}\ GeV$)

$$\Downarrow$$

1. If NP processes generate $B+L \neq 0$ but $B-L=0$, the SM processes will washout a baryon asymmetry $\Longrightarrow B=0$
2. If NP processes generate $B-L \neq 0$ (even with $B=0$, that is, only $L \neq 0$), the SM processes will maintain/generate a baryon asymmetry $\Longrightarrow B \neq 0$

Alternative Scenarios

MSSM baryogenesis is (hardly) viable:

- New scalars $\Longrightarrow$ first order PT is possible;
- At least two new phases $\Longrightarrow$ diagonal CP violation;
- Pushed to a corner of parameter space:
  $m_h < 115$ GeV, $m_{\tilde{t}_1} < m_t$, $\tan\beta < 6$, $m_\chi < 250$ GeV.

GUT baryogenesis not quite dead:

- Minimal SU(5) is dead (again) because $B - L = 0$;
- Inflation will erase B;
- $T_{RH} \ll M_{\mathrm{GUT}}$ is a problem, but preheating might help.

Leptogenesis

Fukugita and Yanagida, 1986

Neutrino Masses

- Atmospheric + Solar Neutrinos $\Longrightarrow$ $\boxed{m_{\nu_3} \gtrsim 0.05\ eV}$

- The Seesaw Mechanism $\Longrightarrow$ $\boxed{m_\nu \sim \frac{Y^2 \langle \phi \rangle^2}{M_N}}$

$\Longrightarrow M_{N_3}/Y_3^2 \lesssim 10^{15}\ GeV$

- Implications:

1. Lepton number is violated (M_N)
2. New sources of CP violation (Y)
3. If $\Gamma_{N_1} < H(T = M_{N_1})$ $(\Longrightarrow M_{N_1}/Y_1^2 \gtrsim 10^{15}\ GeV)$
   $\Longrightarrow N_1$ decays out of equilibrium

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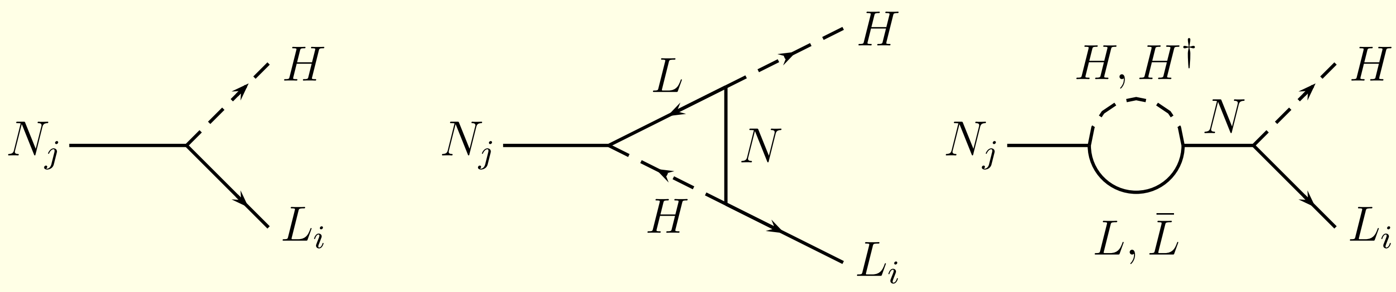
   $\Longrightarrow N_1$ decays out of equilibrium

$$\Downarrow$$

$$\boxed{\text{LEPTOGENESIS}}$$

Leptogenesis at Work



- Lepton number violation at tree level,
- Direct CP violation at one loop,
- Requires 3 generations + 2 N's.

$$\epsilon_L \equiv \frac{\Gamma(N \to LH) - \Gamma(N \to \overline{L}H^\dagger)}{\Gamma(N \to LH) + \Gamma(N \to \overline{L}H^\dagger)} = \frac{1}{8\pi} \sum_k \frac{\mathcal{I}m[(Y^\dagger Y)^2_{k1}]}{(Y^\dagger Y)_{11}} \times f\left(\frac{M_k^2}{M_1^2}\right)$$

$$Y_L = \frac{2T^3}{\pi^2 s}\, d\, \epsilon_L \sim 0.004\, d\, \epsilon_L, \qquad Y_B = -\frac{28}{79} Y_L.$$

See-saw CPV $\leftrightarrow$ Leptogenesis

- $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$
- $m_D = Y\langle\phi\rangle = 3 \times 3$ matrix
- $M = 3 \times 3$ symmetric matrix

$\Longrightarrow$ $\boxed{M_\nu \text{ has 6 physical phases}}$

See-saw CPV $\leftrightarrow$ Leptogenesis

- $M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix}$
- $m_D = Y\langle\phi\rangle = 3 \times 3$ matrix
- $M\ = 3 \times 3$ symmetric matrix

$\Longrightarrow$ $\boxed{M_\nu \text{ has 6 physical phases}}$

1. It is no problem to have $\epsilon_L \sim 10^{-6}$ with reasonable parameters
2. $M_\nu^{\text{light}} = m_D M^{-1} m_D^T$ has 3 physical phases
3. Neutrino oscillation experiments are sensitive to only one of these three phases
4. It could happen that CPV(leptogenesis)$\neq 0$ while CPV(low-energy)=0

Implications

The final Y_B depends on four parameters:

- ϵ_L, the CP asymmetry;
- M_1, the mass of the lightest N;
- $\tilde{m}_1 \equiv \frac{(Y^\dagger Y)_{11} v^2}{M_1}$, the effective neutrino mass;
- $\bar{m}^2 = m_1^2 + m_2^2 + m_3^2$, the sum of light neutrino masses-squared.

Successful baryogenesis requires

- $M_1 \gtrsim 4 \times 10^8$ GeV ($\Longrightarrow T_{RH} \gtrsim 3 \times 10^9$ GeV);
- $m_3 \lesssim 0.12$ eV;
- No model-independent bound on low energy phases.

Supersymmetric Leptogenesis

- MSSM+N: $W = MNN + YH_uLN$
- The seesaw mechanism $\Longrightarrow$ $M \gg m_Z$

$\Longrightarrow$ Supersymmetry is strongly motivated

- But the picture is not very different from SM+N:
  - Direct CP violation;
  - N and $\widetilde{N}$ give similar contributions, $\epsilon_L^{\rm MSSM} \approx 2\epsilon_L^{\rm SM}$;
  - $Y_B = -\frac{32}{92}Y_L$;

Supersymmetric Leptogenesis

- $\epsilon_L \gtrsim 10^{-6} \;\Leftrightarrow\; \tilde{m}/M \sim 10^{-8}$

SUSY breaking effects negligible

- $\mathrm{NS}: \; T_{RH} \lesssim 10^9 \; GeV \;\Leftrightarrow\; \mathrm{LG}: \; T_{RH} \gtrsim 3 \times 10^9 \; GeV$

Gravitino problem?

Soft Leptogenesis

Grossman, Kashti, Nir, Roulet, 2003

D'Ambrosio, Giudice, Raidal, 2003

Soft Supersymmetry Breaking

$$\mathcal{L}^N_{\text{soft}} = B\widetilde{N}\widetilde{N} + AH\widetilde{L}\widetilde{N}$$

- A new source of lepton number violation B
- A new source of CP violation $\phi_N = \arg(AMB^*Y^*)$

Soft Leptogenesis?

Highlights

- Indirect CP violation (conceptually interesting!)
- ϵ_L from only $\widetilde{N}$ decays ('sleptogenesis')
- One generation is enough
- Three SUSY-breaking factors, yet significant effects (surprising!)
- $B < \tilde{m}M$
- No gravitino problem

Implications

ϵ_L depends on four parameters:

- M, the mass of the (lightest) $\widetilde{N}$;
- Y, the Yukawa coupling;
- A, the trilinear scalar coupling (we fix $A \sim \tilde{m}Y$)
- B, the bilinear scalar coupling.

Successful soft leptogenesis requires:

- $M \lesssim 5 \times 10^8$ GeV
- $Y \lesssim 10^{-4}$
- $\frac{B}{M} \sim \frac{MY^2}{16\pi} \lesssim$ GeV

Summary

- If the seesaw mechanism is responsible for the light neutrino masses, leptogenesis is unavoidable.
- Whether leptogenesis accounts for the observed baryon asymmetry is a quantitative question and depends on several unknown parameters.
- Parameters related to the light neutrino sector are required to have values within very reasonable ranges.
- Soft supersymmetry breaking terms may have significant effects on leptogenesis.

Conclusions

Conclusions

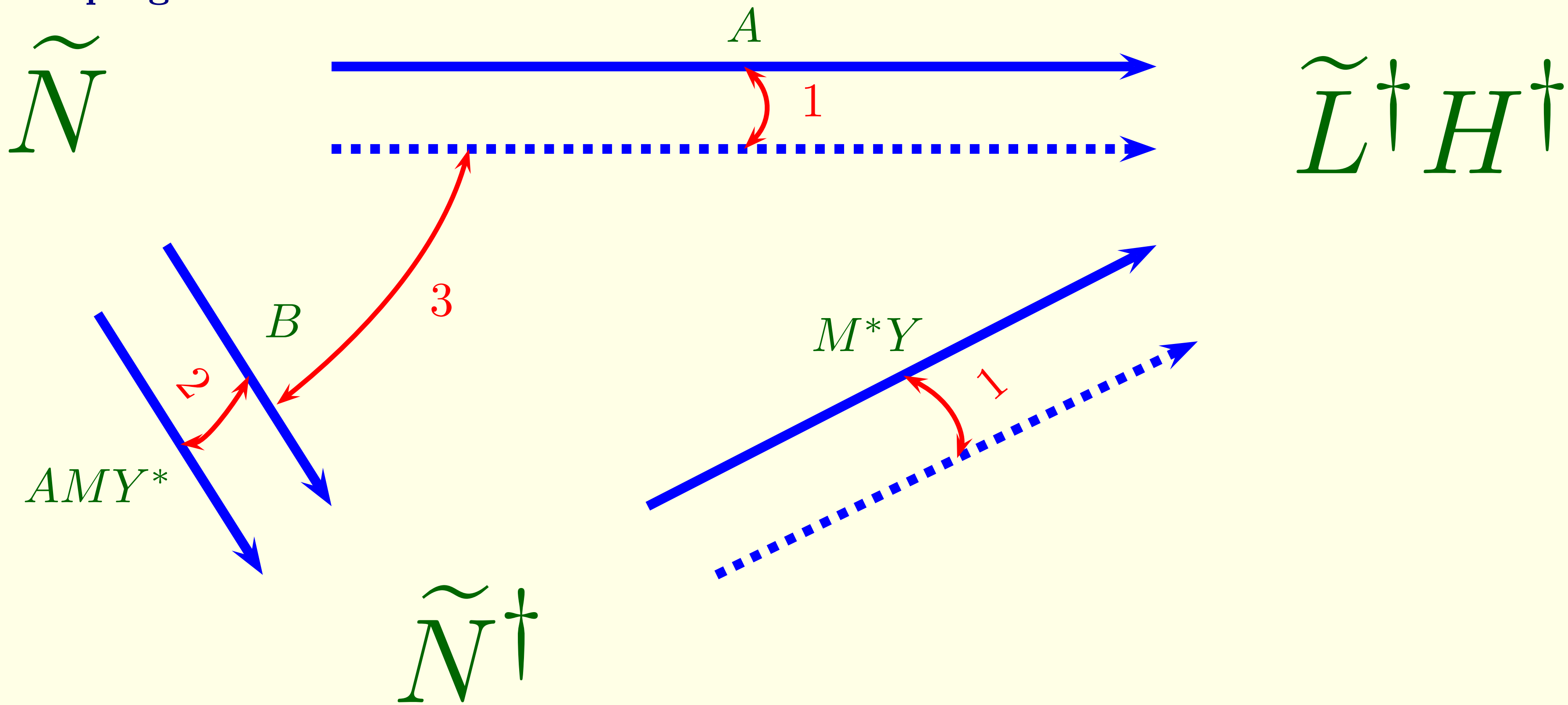
We have learnt a lot from our search for neutrino masses:

1. SM is not a complete picture of Nature
2. NP at a scale $\Lambda_{\rm NP} \leq 10^{15}$ GeV
3. $SO(10) \Longrightarrow m_\nu \sim 10^{-2}$ eV - confirmed
4. $SU(5) \Longrightarrow |V_{\mu 3} V_{cb}| \sim \frac{m_s}{m_b}$ - confirmed
5. Most of the simplest and most predictive flavor models - excluded
6. Interesting implications for
   (a) Supersymmetry without R-parity
   (b) Extra dimensions
7. Leptogenesis may account for the baryon asymmetry

Conclusions

There is still a lot to be learnt:

1. Neutrinoless double beta decay: m_{ee}
   Majorana or Dirac?
2. Cosmology, direct searches, $0\nu 2\beta$: m_i
   Hierarchical or degenerate?
3. LBL, ν-factory, AN: $\mathrm{sign}(\Delta m^2_{32}), |U_{e3}|, |U_{\mu 3} U_{\tau 3}| - 1/2, \delta_{\mathrm{CPV}}$
   Normal or inverted hierarchy?
   Small or tiny 1-3 mixing?
   Large or maximal 2-3 mixing?
   Leptonic CP violation?
4. Lepton flavor violation: $\mu \to e\gamma, \tau \to \mu\mu\mu, \tilde{\nu} \leftrightarrow \tilde{\nu}^\dagger, \ldots$
   Solutions to the flavor puzzles?
5. ...



1. In decay: Leptogenesis, $\epsilon'(K \to \pi\pi)$
2. In mixing: Soft leptogenesis, $\epsilon(K \to \pi\ell\nu)$
3. In interference: Soft leptogenesis, $S_{\psi K}(B \to \psi K_S)$

Soft Leptogenesis at Work

$$M_{12}^* \sim B/M$$

$$\widetilde{N} \;\rightrightarrows\; \widetilde{N}^\dagger \longrightarrow \widetilde{L}^\dagger H^\dagger, L\widetilde{H}$$

$$\Gamma_{12}^* \sim AY^*$$

$$\epsilon_L \;\sim\; \delta_{\tilde{L}\bar{L}} \times \mathcal{I}m\frac{\Gamma_{12}}{M_{12}} \times \frac{(\Delta m/\Gamma)^2}{1+(\Delta m/\Gamma)^2}$$

- CP violation is encoded in $\mathcal{I}m\frac{\Gamma_{12}}{M_{12}} \sim \left|\frac{AMY^*}{2\pi B}\right| \sin\phi_N$
- Lepton number violation is encoded in $\frac{\Delta m}{\Gamma} \sim \frac{8\pi|B|}{|MY|^2}$
- $\delta_{\tilde{L}\bar{L}} = \frac{|A_{\tilde{L}}|^2-|A_{\overline{L}}|^2}{|A_{\tilde{L}}|^2+|A_{\overline{L}}|^2}$ vanishes in the supersymmetric limit

$$\boxed{\epsilon_L \;\sim\; \frac{32\pi AB\sin\phi_N}{M^3Y^3}\;\delta_{\tilde{L}\bar{L}}}$$

Finite Temperature Effects

- In the supersymmetric limit,

$$\Gamma(\widetilde{N}^\dagger \to \widetilde{L}^\dagger H^\dagger) = \Gamma(\widetilde{N}^\dagger \to L\widetilde{H})$$
$$\Gamma(\widetilde{N}^\dagger \to \widetilde{L} H) = \Gamma(\widetilde{N}^\dagger \to \overline{L}\overline{\widetilde{H}}) = 0,$$
$$\Longrightarrow \ \delta_{\tilde{L}\bar{L}} = 0$$

- At $T = 0$ the relevant effect is scalar-fermion mass splitting,

$$\delta_{\tilde{L}\bar{L}} \sim \tilde{m}^2_{\tilde{N}}/M^2$$
$$\Longrightarrow \delta_{\tilde{L}\bar{L}} \text{ is tiny}$$

- At $T \sim M$ Pauli blocking/Bose-Einstein stimulation give

$$\delta_{\tilde{L}\bar{L}} = \frac{(1+n_B)^2-(1-n_F)^2}{(1+n_B)^2+(1-n_F)^2} \text{ where } n_{F,B} = [\exp(M/2T) \pm 1]^{-1}$$
$$\Longrightarrow \boxed{\delta_{\tilde{L}\bar{L}} = \mathcal{O}(1)}$$

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How can [susy-breaking]^3 be relevant?

- $\epsilon_L \sim \delta_{\widetilde{L}\overline{\widetilde{L}}} \; \frac{A}{MY} \; \frac{32\pi B}{M^2 Y^2}$

  - $\delta_{\widetilde{L}\overline{\widetilde{L}}}$ from finite temperature effects, not a suppression factor;
  - Naively, $A \sim \tilde{m}Y$, $B \sim \tilde{m}M$: $\epsilon_L \sim \left(\frac{\tilde{m}}{M}\right)^2 \frac{1}{Y^2}$
    For example, $M \sim 10^9$ GeV, $Y \sim 10^{-3} \implies \epsilon_L \sim 10^{-6}$;
  - However, for $B/M \gtrsim MY^2 \implies \Delta m/\Gamma \gg 1 \implies$ suppression.