Neutrinos: Windows to New Physics

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Neutrinos: Windows to New Physics

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Symmetries of the SM

- The SM is invariant under local transformations of the SU(3)xSU(2)XU(1) group, spontaneously broken to the SU(3)x$U(1)_Q$ subgroup
- The SM has, additionally, 4 global symmetries :

  $U(1)_{B+L}$;$U(1)_{B-L}$; $U(1)_{L_i-L_j}$ [i,j={1,2,3}]

  Last 3 are exact, but $U(1)_{B+L}$ has an EW anomaly, so is not a symmetry at quantum level
- In addition, to solve the strong CP problem, one often invokes the existence of another global symmetry $U(1)_{PQ}$, which has both strong and EW anomalies

- The existence of neutrino masses and mixings, inferred from neutrino oscillation experiments, provides evidence for physics beyond the SM
- Neutrino mixings imply that individual lepton number is not conserved. In effect, because of observed mixing lose 2 SM global symmetries:

  mixing $\leftrightarrow$ $U(1)_{L_i-L_j}$ no longer a symmetry
- Existence of neutrino masses also affects the symmetry structure of SM, indicating the presence of new interactions beyond those of the SM which most likely violate $U(1)_{B-L}$

Disquisitions on Neutrino Masses

- Since neutrinos have zero charge, besides the usual Dirac (particle-antiparticle) mass they can have also a Majorana (particle-particle) mass
- Most general mass term has the structure:

$$L = -\frac{1}{2}\begin{pmatrix}\overline{\nu}_L^c & \overline{\nu}_R\end{pmatrix}\begin{bmatrix} m_T & m_D^T \\ m_D & m_S \end{bmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}$$

where $\nu^c = C\nu^\dagger$. Clear that m_T, m_S are Majorana mass terms, and m_D is a Dirac mass term. These masses break SM symmetries differently

- From a symmetry point of view
  m_T – SU(2) Triplet with $Q_{(B-L)} = -2$
  m_D – SU(2) Doublet with $Q_{(B-L)} = 0$
  m_S – SU(2) Singlet with $Q_{(B-L)} = +2$
  thus their presence is connected to different physics
- What combination of m_T, m_S , and m_D determines the tiny ($m_\nu < 1$ eV) neutrino masses observed is a function of what this underlying physics is
- Discuss each of these mass terms in turn

- Most conservative stance is to admit existence of ν_R, but assume (B-L) remains a symmetry of nature, so $m_\nu \equiv m_D$
- However, must understand what physics gives

$$m_D = \Gamma^\nu \langle\Phi\rangle \ll m_\ell = \Gamma^\ell \langle\Phi\rangle$$

- One possibility is to invoke extra dimensions [Arkani-Hamed Dimopoulos Dvali] Illustrate with d=5 theory compactified to space of radius L

$$S_{Einstein} = M^{*3}/16\pi \int d^4x \int dy \sqrt{-g_5}\, R_5 \quad (d=5)$$

after compactification becomes

$$S_{Einstein} = M^{*3}\, L\, /16\pi \int d^4x \sqrt{-g_4}\, R_4 \quad (d=4)$$

which implies $M_{Planck}{}^2 = M^{*3} L$

- If SM particles live in D3 brane, but ν_R lives in 5d bulk, then neutrino action involving ν_R reads

$$S = M^* \int d^4x dy \sqrt{-g_5}\, \bar{\nu}_R \gamma^\mu i\partial_\mu \nu_R + \int d^4x \sqrt{-g_4}\, \Gamma^\ell \bar{\nu}_R \Phi L_L$$

After compactification

$$M^* \int d^4x dy \sqrt{-g_5}\, \bar{\nu}_R \gamma^\mu i\partial_\mu \nu_R \rightarrow M^* L \int d^4x \sqrt{-g_4}\, \bar{\nu}_R \gamma^\mu i\partial_\mu \nu_R$$

Must rescale ν_R by factor $1/(M^*L)^{1/2} \equiv M^*/M_{Planck}$

Thus $\Gamma^\nu \equiv [M^*/M_{Planck}]\, \Gamma^\ell$, so get large reduction

- Many issues open:
  - Why is (B-L) conserved if ν_R exists?
  - Are K-K tower of states dangerous?
- Perhaps alternate solution is to have no ν_R

- Realized if one has Triplet mass. Two options:

$$m_T \leftrightarrow \begin{cases} \text{VEV of } \mathbf{T} \\ \qquad\qquad\qquad \text{break SU(2) \& (B-L)} \\ \text{VEV of } \mathbf{T_{eff}} = \Phi\,\tau\,\Phi\,/\,\Lambda \end{cases}$$

- Since $m_T \sim \langle T\rangle$, first possibility requires that $\langle T\rangle \ll \langle\Phi\rangle = v_F \sim 250$ GeV difficult to justify
- Second possibility much more natural. Small neutrino masses result from the large scale Λ entering in $\mathbf{T_{eff}}$, associated with (B-L) breaking

$$m_T \sim \langle \mathbf{T}_{eff}\rangle \sim v_F^2/\Lambda \quad \text{seesaw formula}$$

- See that in this case m_ν offers window to physics well beyond the EW scale $v_F \ll \Lambda$

- Can arrive at similar seesaw formula from singlet breaking [Yanagida, Gell Mann Ramond Slansky] provided $m_S >> m_D$
- Since m_S carries no SM quantum numbers, its scale is unconnected to v_F or Λ_{QCD}. It is, related to the scale of $U(1)_{B-L}$ breaking
- If a hierarchy exists, $m_S >> m_D$, then the neutrino mass matrix

$$M = \begin{pmatrix} 0 & m_D^T \\ m_D & m_S \end{pmatrix}$$

has both large $M_N = m_S$ and small eigenvalues $M_\nu = - m_D^T (m_S)^{-1} m_D$ seesaw

- Principal lessons learned from existence of neutrino masses and mixings are two-fold:

i. There are additional interactions beyond the SM, which break all global symmetries

ii. Small neutrino masses are related to large scale where $U(1)_{B-L}$ breaks down

- Not really possible to tease apart whether M_ν arises from:

 -composite operators $M_\nu \equiv m_T \sim \langle \mathbf{T}_{eff} \rangle \sim v_F^2/\Lambda$

 -large ν_R masses $M_\nu = m_D^T (m_S)^{-1} m_D$

 -combination of both

$$M_\nu = m_T - m_D^T (m_S)^{-1} m_D$$

Recondite Physics

- Looking beyond the SM for hints to the origins of neutrino masses and mixing there are three fruitful avenues to follow:

i. Look for possible new symmetries and symmetry breakings [top-down]

ii. Uncover patterns of observed masses and mixings [bottom-up]

iii. Find connections between physical phenomena [rely on experiments]

- Will illustrate each of these avenues by means of some appealing examples

Extended symmetries

- Interesting insights on neutrinos emerge in Grand Unified Theories (GUTs) where quarks and leptons are in same multiplets:
- In simplest GUT SU(5) ν_R transforms as a singlet under the group

SU(5): 10={Q_L, u^c_R, l^c_R}; 5*={d^c_R, L_L}; 1={ν^c_R}

Thus no constraints exist on the mass term

$$L_{\mathrm{mass}} = -\frac{1}{2} m_{\mathrm{S}} \overline{\nu}_{\mathrm{R}} \nu^{\mathrm{c}}_{\mathrm{R}} + h.c.$$

and there is no connection between SU(5) breaking and (B-L) breaking [$m_S \neq M_{GUT}$]

- Matters different in SO(10) where all quarks and leptons, including ν_R ,are in the same representation:

$$SO(10):\ 16=\{Q_L,\ u^c_R,\ d^c_R,\ L_L,\ l^c_R, \nu^c_R\}$$

- Since $U(1)_{B-L} \subset SO(10)$ now $U(1)_{B-L}$ is a local, not global, symmetry
- Mass m_S is related to GUT breaking scale, or to a possible intermediate scale
- This latter case ensues if symmetry breakdown of SO(10) is through the chain:

$$SO(10) \rightarrow SU(3)xSU(2)xSU(2)xU(1)_{B-L} \rightarrow SM$$

$$M_{GUT} \qquad\qquad\qquad\qquad m_S$$

- Possible to contemplate range

  10^{10} GeV $< m_S < 10^{16}$ GeV

- Because $16 \otimes 16 = 10 \oplus 126 \oplus 120$, one can consider Yukawa interactions containing SO(10) Higgs fields in these representations.
- 126_H contains a SM singlet field carrying (B-L) charge, so that naturally $m_S \sim \langle 126_H \rangle$
- Simplest model, leading to quite restrictive mass spectrum, has just 2 Yukawa coupling terms (using either $U(1)_{PQ}$ or SUSY to eliminate 10^*_H couplings) [Babu Mohapatra]
- $L_{Yukawa} = \Gamma^D\, 16 \cdot 16 \cdot 10_H + \Gamma^S\, 16 \cdot 16 \cdot 126^*_H$

  with $m_D = \Gamma^D \langle 10_H \rangle \ll m_S = \Gamma^S \langle 126^*_H \rangle$

- A different class of models, rather than using an elementary 126_H, replace it by a composite Higgs term made up of low- dimension fields:

$$126_H \rightarrow (16_H \cdot 16_H) / M$$

so that $m_S \sim M^2_{GUT} / M$

- Irrespective of whether 126_H (and other Higgs) are composite or not, to obtain a realistic spectrum and mixings for the charged fermions and neutrinos, one imposes some flavor symmetry - typically U(1)X D
- Remnants of these symmetries should be visible in mass matrices

Patterns in the neutrino sector

- Different approach (more bottom-up) is to divine from data the structure of underlying theory
- In 3 neutrino framework [ignore LSND for now]

$$|\Delta m^2_{32}| = \Delta m^2_{atmos} = (2.4 \pm 0.3)\text{x}10^{-3}\ \text{eV}^2$$

$$|\Delta m^2_{21}| = \Delta m^2_{solar} = (7.9 \pm 0.4)\ \text{x}10^{-5}\ \text{eV}^2$$

  are consistent with a hierarchical spectrum $m_3 >> m_2 >> m_1$ (or an inverted hierarchy), as well as other patterns (e.g. $m_3 >> m_2 \approx m_1$)
- As far as mixing goes, two of the angles in the leptonic mixing matrix U_{PMNS} are large $s_{23} \approx 1/\sqrt{2}$; $s_{12} \approx ½$ (actually $s_{12} \approx 0.56$) while the third is bound at 3σ by $s_{13} < 0.22$ and could be small

- Thus, approximately, letting $s_{13}=\varepsilon$, one has

$$U_{PMNS} \approx \begin{bmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & \varepsilon e^{-i\delta} \\ \frac{-1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & \frac{-\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

- Often assumed that pattern seen reflects some (perhaps approximate) family symmetry in the neutrino mass matrix $M_\nu = U^*_{PMNS}\, m_\nu^{diag}\, U^\dagger_{PMNS}$ where

$$m_\nu^{diag} = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 e^{i\alpha_2} & 0 \\ 0 & 0 & m_3 e^{i\alpha_3} \end{bmatrix}$$

- Because uncertainty in masses m_i is large and Majorana phases α_i unknown, it is difficult to reconstruct the matrix M_ν. Better to focus on mixing angles
- In this respect, an interesting starting point is provided by matrices M_ν which produce $s_{13}=0$ and give maximal mixing $s_{23} = 1/\sqrt{2}$. It is easy to see that matrices M_ν that are 2-3 symmetric [C.S. Lam]

$$M_\nu = \begin{bmatrix} X & A & A \\ A & B & C \\ A & C & B \end{bmatrix}$$

precisely accomplish this

- This permutation symmetry can be part of a larger discrete or continuous symmetry [many models exist: A_4, S_3, Z_4, D_4]
- Since this symmetry is approximate in nature ($m_\mu \neq m_\tau$), the way that the symmetry is broken determines the correlation among these angles:

$$s^2_{23} - ½ = F(s_{13}) \qquad F(0)=0$$

with $F(s_{13})$ a model dependent function

- Another approach [Smirnov] uses the observation that:

$$\theta_{12}+\theta_{12}^{had} \approx \theta_{23}+\theta_{23}^{had} \approx \pi/4$$

to build models that display this quark-lepton complementarity (QLC). Is above coincidence?

- Models are a bit forced. Illustrate with an example [Minakata Smirnov]. Recall that:

$$U_{PMNS} = U_l^\dagger U_\nu \quad ; U_{CKM} = U_u^\dagger U_d$$

Imagine that mixing in the doublet Higgs sector comes only from the "down" side (thus $U_u = 1$) and GUT forces:

$$U_l = U_d = U_{CKM}$$

Then get interesting QLC relation if seesaw forces

$$U_\nu = U_{bm} = \frac{1}{2}\begin{bmatrix} \sqrt{2} & \sqrt{2} & 0 \\ -1 & 1 & \sqrt{2} \\ 1 & -1 & \sqrt{2} \end{bmatrix}$$

then $U_{PMNS} = U^\dagger_{CKM} U_{bm}$

Connecting Physical Phenomena

- Third approach for exploring the neutrino window is by looking for physical inter-relations. Best example is provided by Leptogenesis
- The ratio of baryon to photon density in the Universe now $\eta = n_B / n_\gamma$ is a measure of the primordial matter-antimatter asymmetry in the Universe

$$\eta = [(n_{Matter} - n_{Antimatter})_{Primordial}] / n_\gamma$$

and is well determined by WMAP and BBN:

$$\eta = (6.097 \pm 0.206) \times 10^{-10}$$

- The heavy ν_R needed for the seesaw provide a nice mechanism for generating $\eta \neq 0$. In this Leptogenesis scenario [Fukugita Yanagida] a primordial lepton-antilepton asymmetry is generated from out of equilibrium decays of heavy Majorana neutrinos [$N \rightarrow lH$; $N \rightarrow l^{\dagger}H^{\dagger}$]

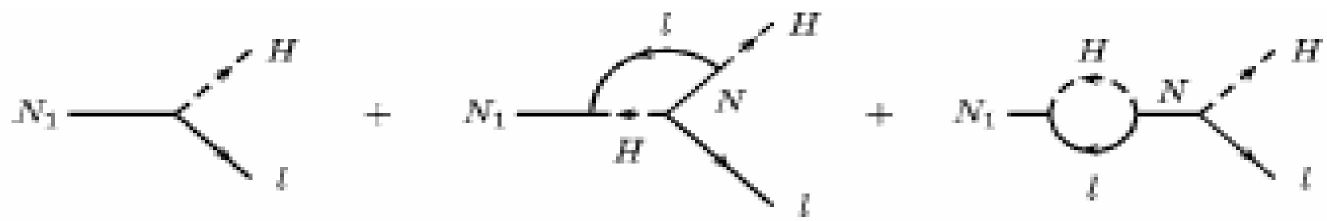


Figure 1 Tree level and one-loop diagrams contributing to heavy neutrino decays whose interference leads to Leptogenesis.

- Because the (B+L) current is anomalous, sphaleron processes [Kuzmin Rubakov Shaposhnikov] transmute this lepton number asymmetry into a baryon number asymmetry.

- Since $\eta \approx 0.35\ \eta_L$ an asymmetry $\eta_L \sim 1.7\text{x}10^{-9}$ will produce the desired baryon asymmetry. Now,

$$\eta_L \approx 7\ \varepsilon\ \kappa /\ g^*$$

where ε is a measure of the CP-asymmetry in the decay of the lightest heavy neutrino N_1, κ takes into account of possible washout of the asymmetry, and $g^* \sim 100$ counts the effective degrees of freedom at $T \sim M_1$

- ε is related to the neutrino spectrum:

$$\varepsilon = -[3/16\pi^2]\ M_1/v_F^2\ \mathrm{Im}\ (\Gamma^*\ M_\nu \Gamma^\dagger)_{11}\ /\ (\Gamma\Gamma^\dagger)_{11}$$

- For $T \sim M_1 \sim 10^{10}$ GeV, one needs very light neutrino masses ($m_\nu <$ eV) to obtain the typical parameters needed for the CP asymmetry ($\varepsilon \sim 10^{-6}$) and the washout ($\kappa \sim 10^{-2}$) to get $\eta_L \sim 1.7 \times 10^{-9}$

Result for κ is independent of initial abundances 10^{-3}eV $< m_\nu <$ eV

Buchmuller Di Bari Plumacher

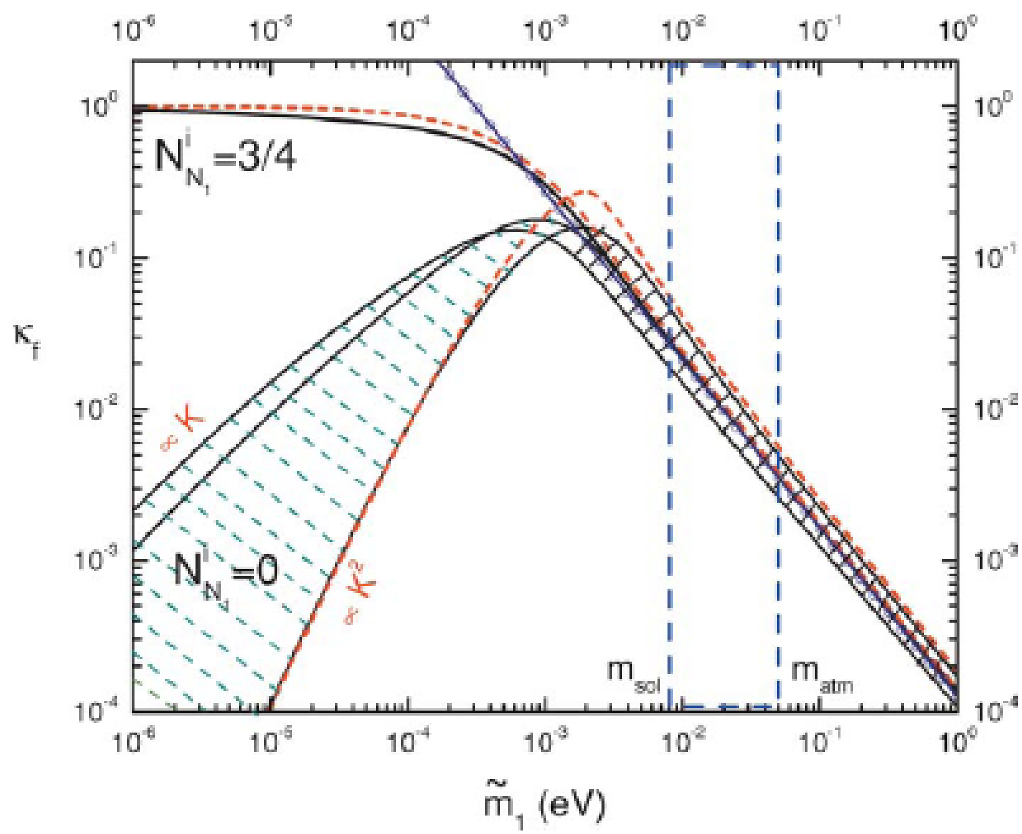


Figure 3 Final efficiency factor when the washout term ΔW is neglected. From (69).

- Since ε cannot be to small for Leptogenesis to work, this provides a lower bound on M_1 [Davidson Ibarra]. For $\tilde{m}_1 > 10^{-3}\,\mathrm{eV}$ one finds

  $M_1 > 2x\ 10^9$ GeV   BDP

- Furthermore, Leptogenesis also provides an upper bound on the light neutrinos masses, since washout rate $W \sim \Sigma_i\ m^2_i$. One finds

  $m_i < 0.1$ eV   BDP

- Inference from Leptogenesis of heavy neutrinos with masses in the 10^{10} GeV range associated with a sub eV light neutrino spectrum is very encouraging!

- Leptogenesis is a triumph for neutrinos and, if η is generated this way, we owe our existence to the CP phases in the neutrino sector!
- However, the fact that Leptogenesis occurred at temperatures $T \sim M_1 > 2x\ 10^9$ GeV has significant import for SUSY theories
- If the reheating temperature after inflation T_R is too high in SUGRA one overproduces gravitinos, with catastrophic consequences since gravitino decay products destroy the light elements produced in BBN. To avoid trouble:

$T_R < 10^7$ GeV   Kawasaki et al

- But Leptogenesis argues $T_R > M_1 > 2x\ 10^9$ GeV

- There are solutions to gravitino problem, but these in general alter the "normal" SUSY expectations coming from SUGRA:

  $m_{3/2}$ >100 TeV — Gherghetta et al

  $\tilde{g}$ is LSP $\tilde{\tau}$ is NLSP — Fujii et al

- LFV provides another example of tension between SUSY and Leptogenesis. Prediction for $\mu \rightarrow e\gamma$ are model dependent but sensitive to mass of heavy neutrinos [BR~ $(M_3 \ln M_X/M_3)^2$] and to satisfy present bounds $M_3 < 10^{13}$ GeV
- Seeking compatibility between SUSY and Leptogenesis leads to testable experimental predictions and insights into neutrino physics

Wild Speculations

LSND musings

- There well may be more surprises in the neutrino sector. A prime example is provided by the LSND result
- LSND result for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations

  $\Delta m^2 \sim 1\ eV^2$; $s^2 \sim 10^{-3}$

  cannot be reconciled in a 3 ν framework.
- We await Mini BooNe results, but if phenomena is true it requires different physics
  -sterile neutrinos

  -CPT violation

- Easy to find candidates for sterile neutrinos in string/GUT theories

  E_6 27 $\supset$ 9 SU(3) singlets $\supset$ 2 SU(2)xU(1) singlets
- What is challenging is to get m_{st}~ eV. Normal trick is to use discrete symmetry to set $m_{st}=0$ and get a small mass from breaking of symmetry (e.g 2-3 symmetry Mohapatra et al)
- Models are quite complex and phenomenology of 3+1 models shaky (3+2 better)
- CPT violation is a much bolder suggestion [Barenboim et al] since allows differences between $\overline{\nu}_\mu - \overline{\nu}_e$ and $\nu_\mu - \nu_e$ oscillations

- Unfortunately, phenomenology does not work better here!

All data ↔ CPT OK

LSND ↔ CPT viol.

- Barenboim and Mavromatos claim, however, that matters are improved by including quantum decoherence effects

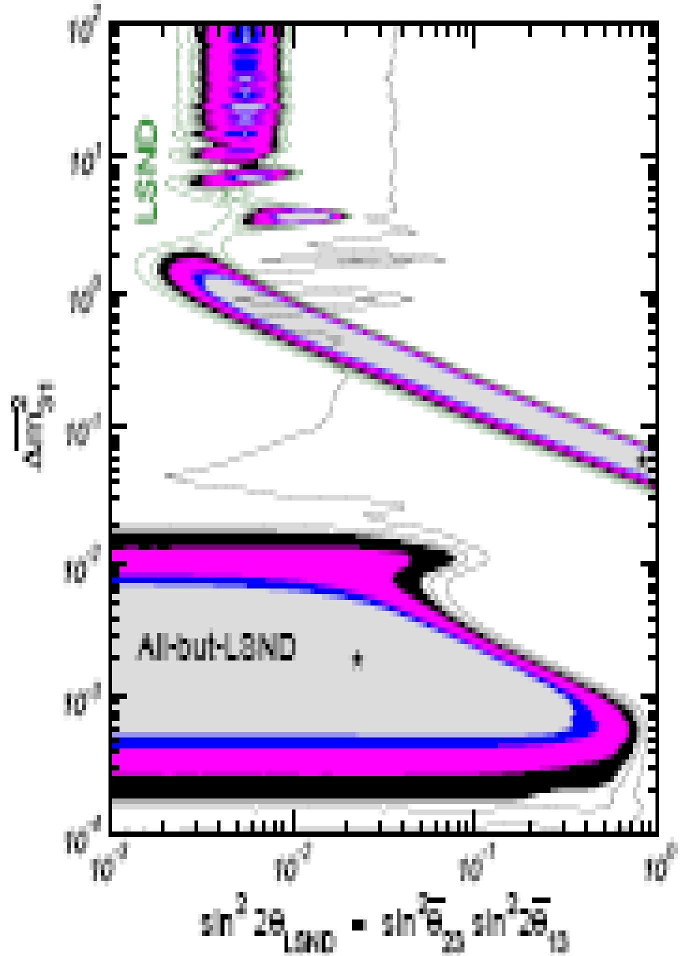


Figure 6: 90%, 95%, 99%, and 3σ CL allowed regions (filled) in the $(\Delta m^2_{LSND}, \sin^2 2\theta_{LSND})$ plane required to explain the LSND signal together with the corresponding allowed regions from our global analysis of all-but-LSND data. The contour lines correspond to $\Delta\chi^2 = 13$ and 16 (3.2σ and 3.6σ, respectively).

Gonzales-Garcia Maltoni Schwetz

Mass varying neutrinos

- Neutrinos with environment-dependent masses have been suggested recently by Fardon Nelson Wiener (FNW) to account for the dark energy the Universe
- Data from WMAP provides accurate values for the cosmological parameters $\Omega = 8\pi G_N \rho / 3 H^2$ and Ω_i with $\Omega = \Sigma_i \Omega_i$:

$\Omega - 1 = -0.010 +0.016-0.009$ *flat Universe*

$\Omega_m = 0.234 \pm 0.035$ *25% matter*

$\Omega_{de} = 0.72 \pm 0.04$ *75% dark energy*

Furthermore, matter is dominantly dark matter and the *dark energy* has negative pressure

- In more detail, in a flat Universe, combining WMAP data with that from the Supernova Legacy Survey gives for the dark energy equation of state:

$$\omega = p_{de} / \rho_{de} = -0.97 + 0.07 - 0.09$$

  consistent with the dark energy being a cosmological constant ($\omega_\Lambda = -1$)
- Even though neutrinos are a subdominant component ($\Omega_\nu < 0.014$) of the Universe's density now, what FNW suggested is that ρ_{de} tracks ρ_ν. More precisely, in the FNW picture neutrinos and dark energy are assumed to be coupled

- In the NR regime examined by FNW

$$\rho_{dark} = m_\nu n_\nu + \rho_{de}(m_\nu)$$

- Because the two components are coupled, neutrino masses are determined dynamically by minimizing the above

$$n_\nu + \partial \rho_{de}(m_\nu) / \partial m_\nu = 0$$

neutrino masses depend on density: $m_\nu = m_\nu(n_\nu)$

- The equation of state for the dark sector follows from the energy conservation equation

$$\partial \rho_{dark} / \partial t = -3H(\rho_{dark} + p_{dark}) = -3H\rho_{dark}(\omega + 1)$$

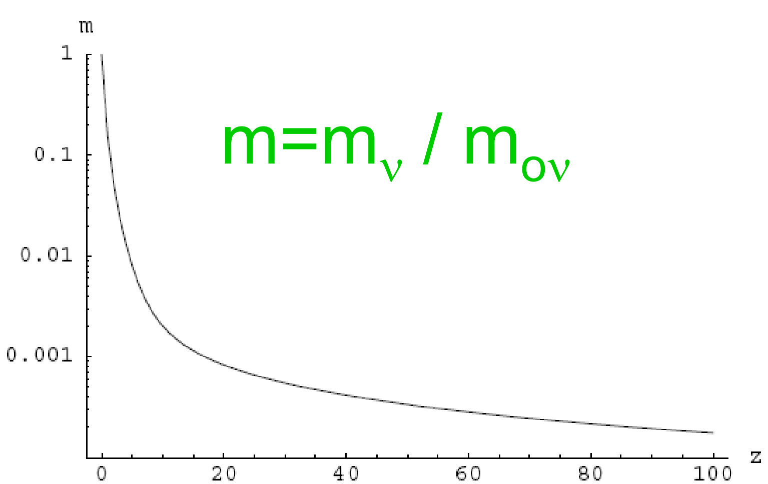
and in NR limit one finds

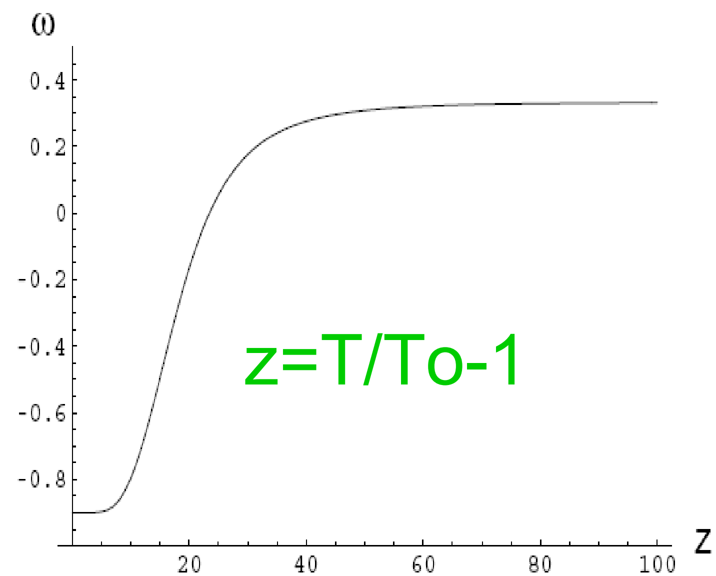
$$\omega + 1 = m_\nu n_\nu / \rho_{dark} = m_\nu n_\nu / [m_\nu n_\nu + \rho_{de}]$$

- If $\omega \approx -1$ the neutrino contribution to ρ_{dark} is a small fraction of ρ_{de}. Furthermore, one can show [Peccei] that model reduces to having a cosmological constant, which runs with m_ν
- Thus $\rho_{de} = -p_{de} \equiv V(m_\nu)$ and $m_\nu = m_\nu(n_\nu)$ is determined by the minimization condition

$$n_\nu + \partial V(m_\nu) / \partial m_\nu = 0$$

- Typical example $V(m_\nu) \sim m_\nu^{-\alpha}$ leads to





- There are many issues one can raise concerning neutrino models of dark energy:
  - What physics fixes $V(m_\nu)$?
  - What dynamical principle demands that $\partial \rho_{dark} / \partial m_\nu = 0$?
  - Many models lead to dynamical instability, since $c_s^2 = \partial p / \partial \rho < 0$
- Nevertheless, idea intriguing since it associates the dark energy sector, through the seesaw mechanism, to the SU(3)xSU(2)xU(1) singlet sector connected with heavy neutrinos
- Because this sector is difficult to probe, easy to imagine that the physics which determines the Universe’s late dynamics lurks there

Concluding Remarks

- Neutrino Physics has opened windows into phenomena beyond the SM, associated in the first instance with (B-L)-breaking
- It is also providing hints of possible flavor symmetries and of unification, although no unequivocal theoretical direction has surfaced
- Deeper puzzles and mysteries may well surface in the future, involving neutrinos and their role in the Universe