Neutrino Physics Theory

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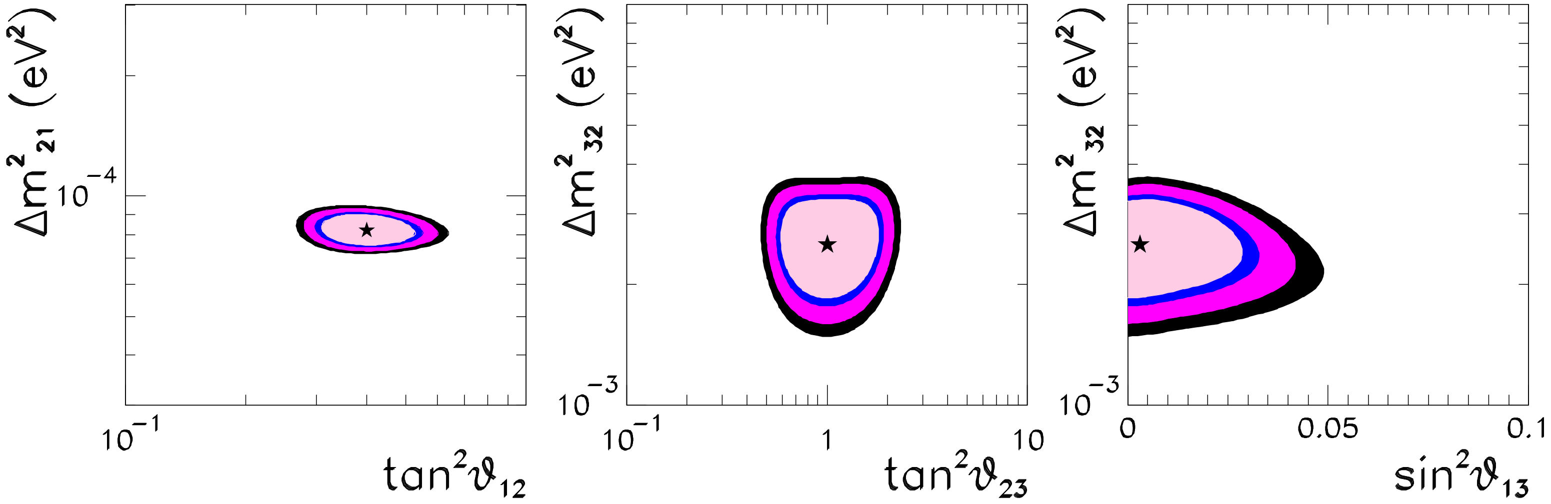
Outline

1. What we learned about neutrinos, what we are sure we still need to find out;
2. The reason this is exciting – The New Standard Model;
3. Understanding neutrino masses – different ideas;
4. Understanding leptonic mixing;
5. Leptogenesis;
6. Concluding remarks;

(M.C. Gonzalez-Garcia, M. Maltoni, hep-ph/0406056, updated)

(M.C. Gonzalez-Garcia, C. Peña-Garay, hep-ph/0306001, updated)



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

$\tan^2\theta_{12} \equiv \frac{|U_{e2}^2|}{|U_{e1}^2|}$; $\tan^2\theta_{23} \equiv \frac{|U_{\mu 3}^2|}{|U_{\tau 3}^2|}$;

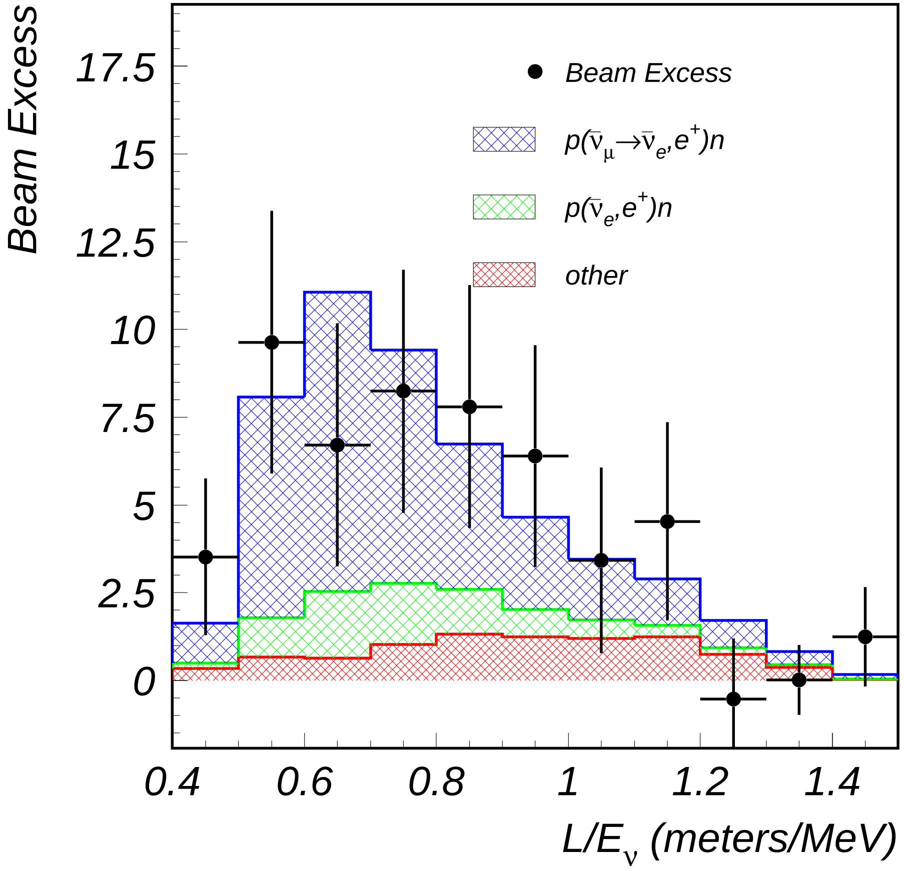
$U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$

$\Delta m^2_{13} > 0$ – Normal Mass Hierarchy

$\Delta m^2_{13} < 0$ – Inverted Mass Hierarchy

(The LSND Anomaly

strong evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$



If oscillations ⇒ $\Delta m^2 \sim 1$ eV^2;

× does not fit into 3 ν picture;

× 2 + 2 scheme "ruled out" (solar, atm);

× 3 + 1 scheme "disfavored" (sbl searches);

× CPTV "ruled out" (KamLAND, atm);

× $\mu \to e\nu_e\bar{\nu}_e$ "disfavored" (KARMEN);

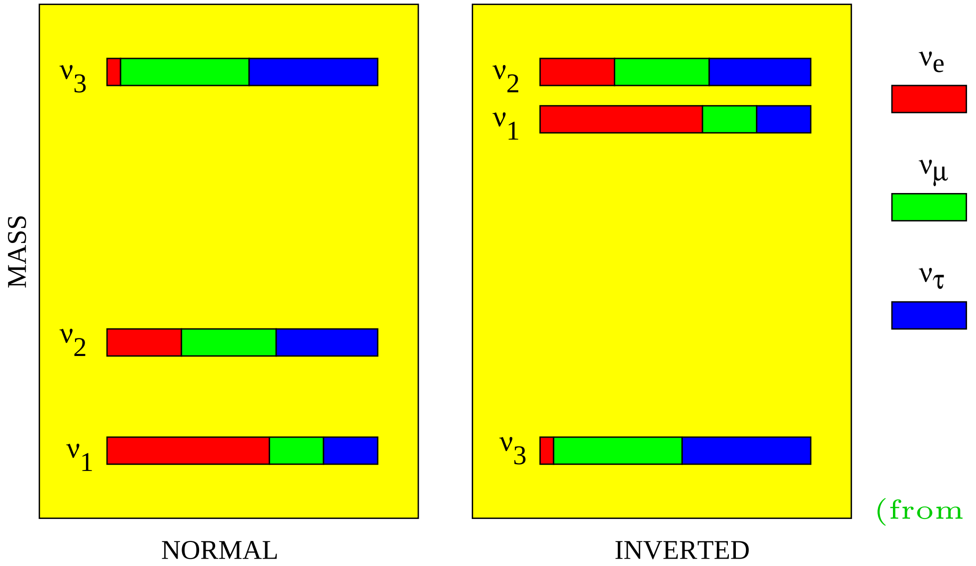
○ 3 + 1 + 1 scheme works (finely tuned?);

○ something completely different;

⇓

[this one gets my vote!])

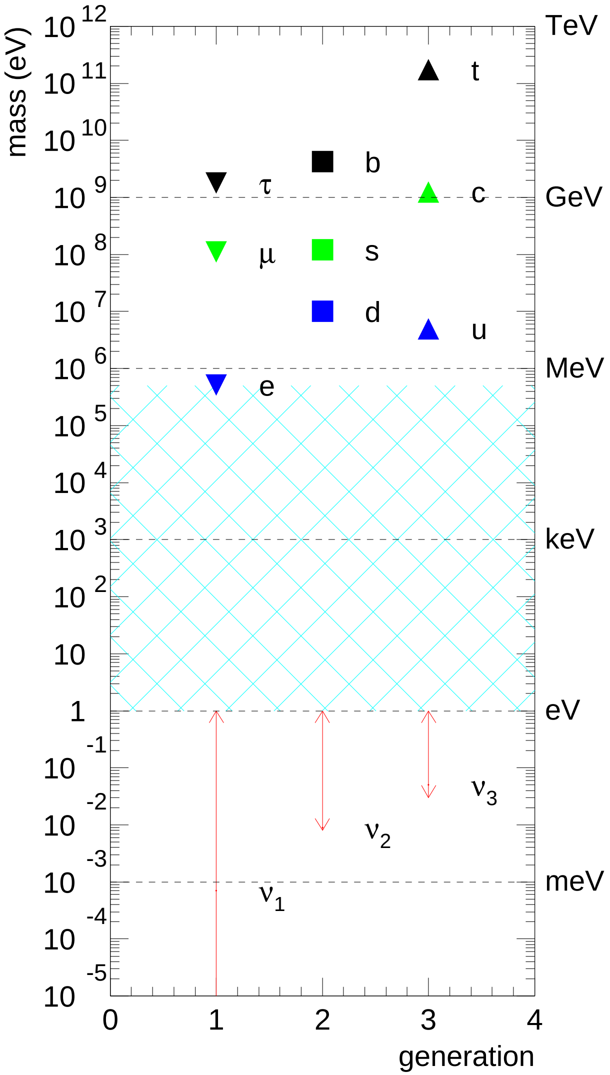
What We Know We Don't Know



(from A. Smirnov, hep-ph/0311259)

- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

What We Are REALLY Excited About:



NEUTRINOS HAVE MASS

albeit a very tiny one...

We don't know why that is, but we have a "gut feeling" it means something important.

Are neutrinos fundamentally different?

Are neutrino masses generated by a distinct dynamical mechanism?

Only Palpable Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Hence, massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different (what this means will become clear later)

$\Bigg($ By the SM I mean a quantum field theory with these characteristics

- Gauge Group ($SU(3)_c \times SU(2)_{\rm L} \times U(1)_{\rm Y}$);
- Particle Content (Q, u, d, L, e, H);
- Most General Renormalizable Lagrangian (uniquely determined);
- Measure All Free Parameters, and You Are Done! $\Bigg)$

What is the New Standard Model? [νSM]

The short answer is – WE DON'T KNOW. Not enough available info!

$$\Updownarrow$$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input, and it looks like it may be coming in the near/intermediate future!

The νSM – Take 1

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\text{SM}} \supset -\lambda_{ij}\frac{L^iHL^jH}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $M \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB } \mathcal{L}_{\nu\text{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = \lambda_{ij}\frac{v^2}{M}.$$

- Neutrino masses are small: $M \gg v \longrightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above M
- What is M? First naive guess is that M is the Planck scale – does not work. Data require $M < 10^{15}$ GeV (anything to do with the GUT scale?)

Example – The Seesaw Mechanism

There are several ways to "UV-complete" this theory. The most elegant one is the see-saw mechanism [Yanagida (1979), Gell-Mann, Ramond, Slansky (1979), Glashow (1979), Mohapatra, Senjanovic (1980)]:

$\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.,}$ $\Rightarrow$ N^α gauge singlet fermions,

$y_{i\alpha}$ dimensionless Yukawa couplings, $M^{\alpha\beta}$ (very large) mass parameters.

For energies much smaller than M_N, we can integrate out the "right-handed" neutrinos N_α, and obtain the effective Lagrangian

$$\mathcal{L} \supset \left(y^{\mathrm{t}} M_N^{-1} y\right)_{ij} L^i H L^j H + \mathcal{O}\left(\frac{1}{M_N^2}\right) + H.c.$$

Comparing with the previous Lagrangian $\Rightarrow \frac{\lambda}{2M} = \left(y^{\mathrm{t}} M_N^{-1} y\right)$

The νSM – Take 2

One may argue that it is trivial and simpler to just add

$$\mathcal{L}_{\rm Yukawa} = -y_{i\alpha} L^i H N^\alpha + H.c.,$$

and neutrinos get a mass like all other fermions: $m_{i\alpha} = y_{i\alpha} v$

- Data requires $y < 10^{-12}$ (cf. $y_e \sim 10^{-5}$). Why so small?
- Neutrinos are Dirac fermions. $B - L$ exactly conserved
- νSM is a renormalizable theory

This proposal, however, violates the rules of the SM (as I defined them)! The operator $\frac{M}{2}NN$, allowed by all gauge symmetries, is absent. In order to explain this, we are forced to add a symmetry to the νSM. The simplest candidate is a global $U(1)_{B-L}$.

$U(1)_{B-L}$ is upgraded from accidental to fundamental (global) symmetry.

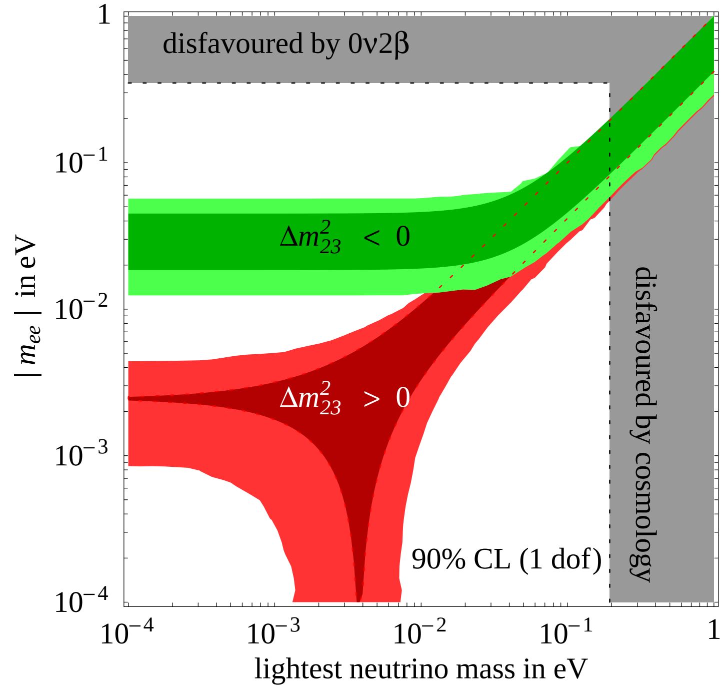
Tie Braker – Violation of Lepton Number (or $B-L$)

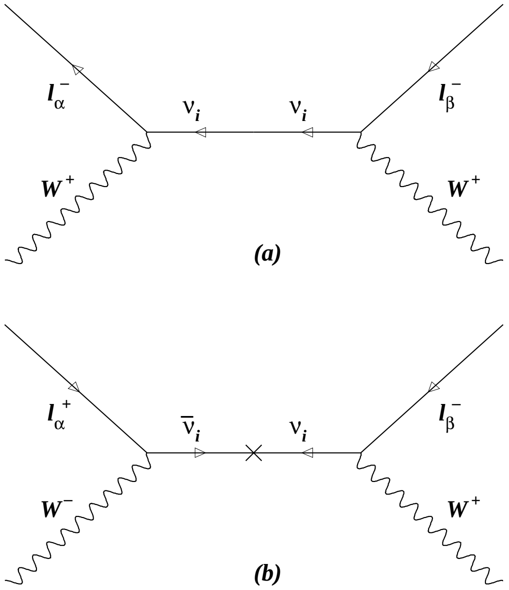
In order to make significant progress, we need to decide which minimal version of the νSM is correct.

The way to do it is to decide whether lepton number is exactly conserved.

The best bet we have is to look for Neutrinoless Double Beta Decay.

$$\boxed{Z \rightarrow (Z+2)e^- e^-}$$





$\Rightarrow$ Amplitude $\propto \frac{m_\nu}{E}$

Understanding Leptonic Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that leptonic mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix} \qquad \boxed{\text{WHY?}}$$

$[|(V_{MNS})_{e3}| < 0.2]$

They certainly look VERY different, but which one would you label as “strange”?

In the quark sector, the small mixing angles are interpreted, together with the hierarchical quark masses, as evidence for extra structure in the SM, i.e., there is some underlying dynamical principle (symmetry) capable of telling one quark flavor from another.

The same "must to be true" in the leptonic sector. After all, charged lepton masses are also hierarchical (we don't know whether the same is true for the neutrinos yet...) and there is some amount of "theoretical evidence" that quarks and leptons are different low-energy manifestations of a more fundamental unified fermion (GUT).

Hence, there should also be a dynamical principle which naturally explains the form of the MNS matrix. Or should there?. . .

The literature on this subject is very large. The most exciting driving force (my opinion) is the fact that one can make *bona fide* predictions:

⇒ U_{e3}, CP-violation, absolute masses all still unknown!

Unfortunately, theorists have done too good a job, and people have successfully predicted everything…

More data needed to “sort things out.”

Example:

zeroth order guesses that capture dominant features of neutrino mixing (textures).

Note correlations.

Case	Texture	Hierarchy	$\lvert U_{e3}\rvert$	$\lvert\cos 2\theta_{23}\rvert$ (n.s.)	$\lvert\cos 2\theta_{23}\rvert$	Solar Angle
A	$\frac{\sqrt{\Delta m^2_{13}}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	Normal	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)	$\sqrt{\frac{\Delta m^2_{12}}{\Delta m^2_{13}}}$	O(1)
B	$\sqrt{\Delta m^2_{13}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	–	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)
C	$\frac{\sqrt{\Delta m^2_{13}}}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$	Inverted	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	O(1)	$\frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$	$\lvert\cos 2\theta_{12}\rvert \sim \frac{\Delta m^2_{12}}{\lvert\Delta m^2_{13}\rvert}$
Anarchy	$\sqrt{\Delta m^2_{13}}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	Normal[a]	> 0.1	O(1)	–	O(1)

[a] One may argue that the anarchical texture prefers but does not require a normal mass hierarchy.

Its is important to ask what each specific flavor model is teaching us. We have to get more out of them then simply the values of the fermion masses and mixing angles

Do they predict anything else? Do they tell anything about GUTs?, etc

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation ($\mu \to e\gamma$, etc);
- searches for lepton number violation (neutrinoless double beta decay, etc);
- precision measurements of the neutrino oscillation parameters;
- searches for fermion electric/magnetic dipole moments (electron edm, muon $g-2$, etc);
- searches for new physics at the TeV scale – we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is the low-energy SUSY?, etc).

Baryogenesis via Leptogenesis

One of the most basic questions we are allowed to ask (with any real hope of getting an answer) is whether the observed baryon asymmetry of the Universe can be obtained from a baryon–antibaryon symmetric initial condition plus well understood dynamics. [Baryogenesis]

This isn't just for aesthetic reasons. If the early Universe undergoes a period of inflation, baryogenesis is required, as inflation would wipe out any pre-existing baryon asymmetry.

It turns out that massive neutrinos can help solve this puzzle!

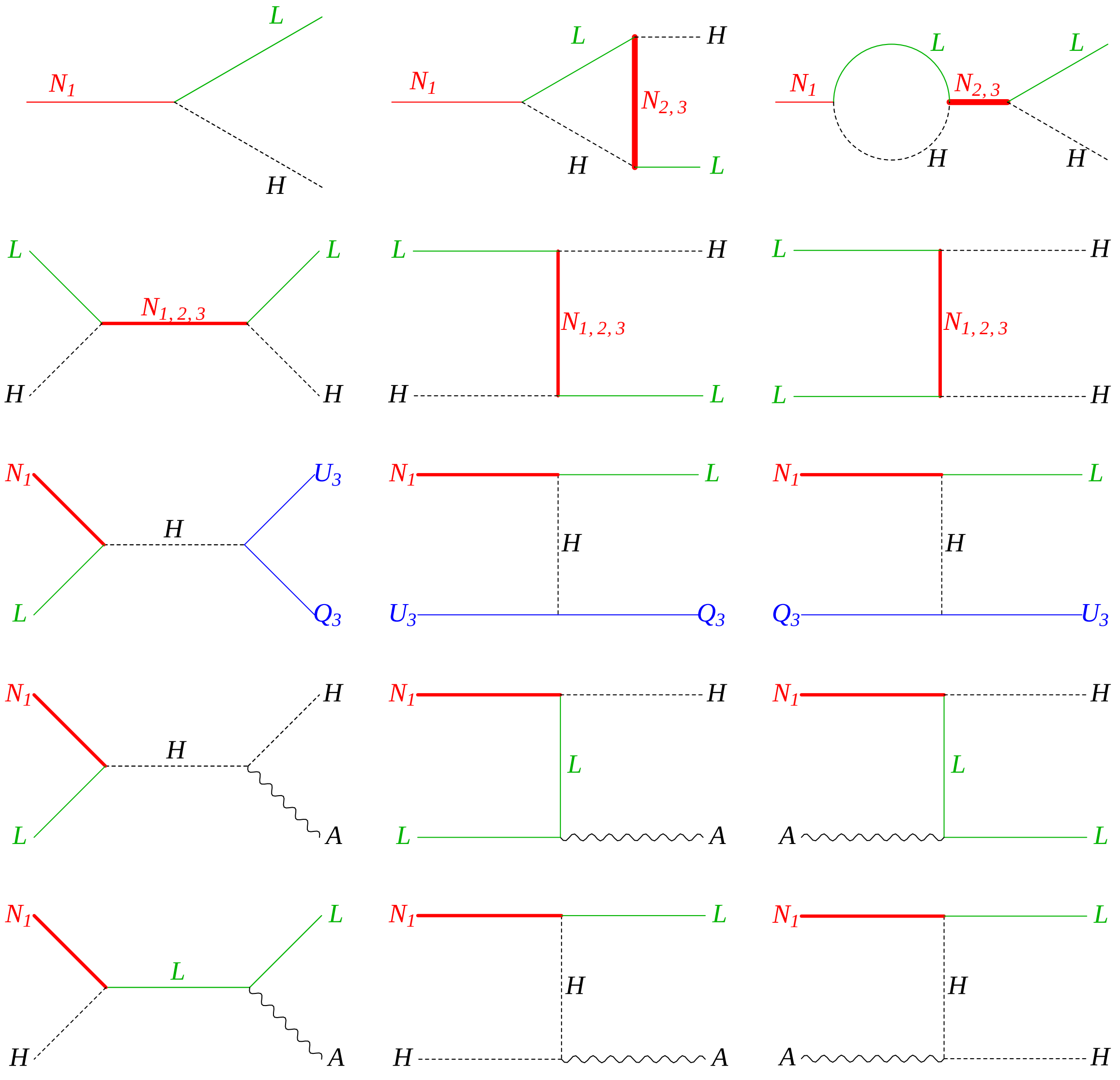
In the old SM, (electroweak) baryogenesis does not work – not enough CP-invariance violation, Higgs boson too light.

Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- Violation of lepton number, which later on is transformed into baryon number by nonperturbative, finite temperature electroweak effects (in one version of the νSM, lepton number is broken at a high energy scale M).
- Violation of C-invariance and CP-invariance (weak interactions, plus new CP-odd phases).
- Deviation from thermal equilibrium (depending on the strength of the relevant interactions).

E.g. – thermal, seesaw leptogenesis,

$$\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.}$$



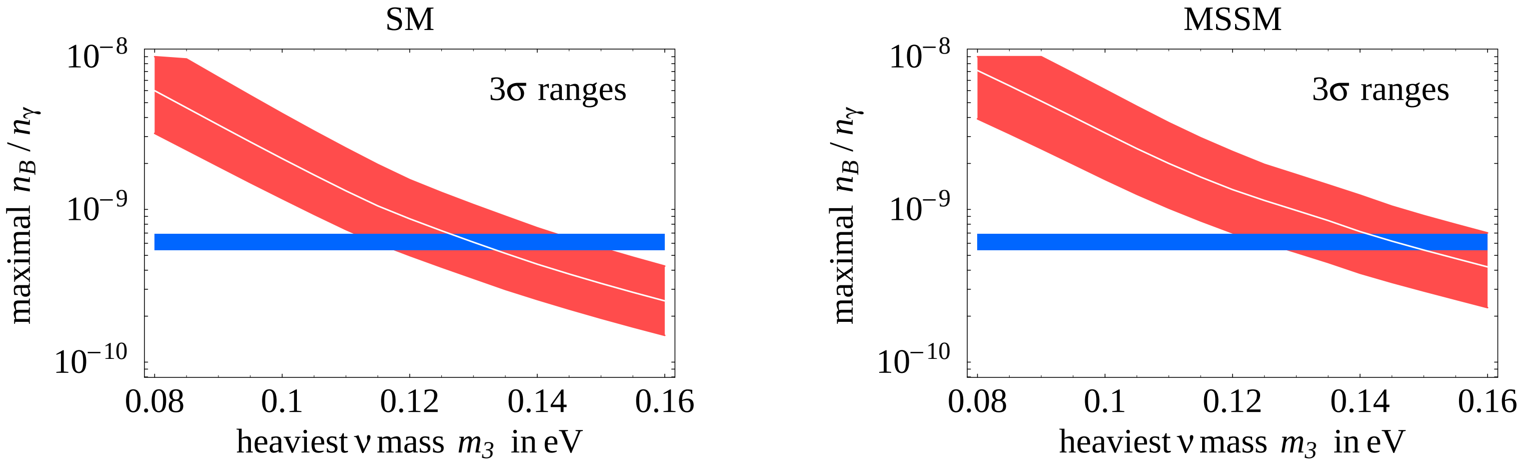
[Fukugita, Yanagida]

- L-violating processes
- $y \Rightarrow$ CP-violation
- deviation from thermal eq. constrains combinations of M_N and y.
- need to yield correct m_ν

not trivial!

[G. Giudice *et al*, hep-ph/0310123]

E.g. – thermal, seesaw leptogenesis, $\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.}$



[G. Giudice *et al*, hep-ph/0310123]

It did not have to work – but it does

MSSM picture does not quite work – gravitino problem

(there are ways around it, of course...)

Relationship to Low Energy Observables?

In general . . . no. This is very easy to understand. The baryon asymmetry depends on the (high energy) physics responsible for lepton-number violation. Neutrino masses are a (small) consequence of this physics, albeit the only observable one at the low-energy experiments we can perform nowadays.

see-saw: y, M_N have more physical parameters than $m_\nu = y^{\rm t} M_N^{-1} y$.

There could be a relationship, but it requires that we know more about the high energy Lagrangian (model depent). The day will come when we have enough evidence to refute leptogenesis (or strongly suspect that it is correct) - but more information of the kind I mentioned earlier is really necessary (charged-lepton flavor violation, collider data on EWSB, lepton-number violation, etc).

$\Big($ There are other “kinds” of leptogenesis, of which I’ll say nothing

- Nonthermal leptogenesis
- Type-II see-saw leptogenesis
- Dirac leptogenesis — Lindner *et al*; Murayama and Pierce
- Soft leptogenesis — Grossman *et al*; Giudice *et al.*
- . . .

$\Big)$

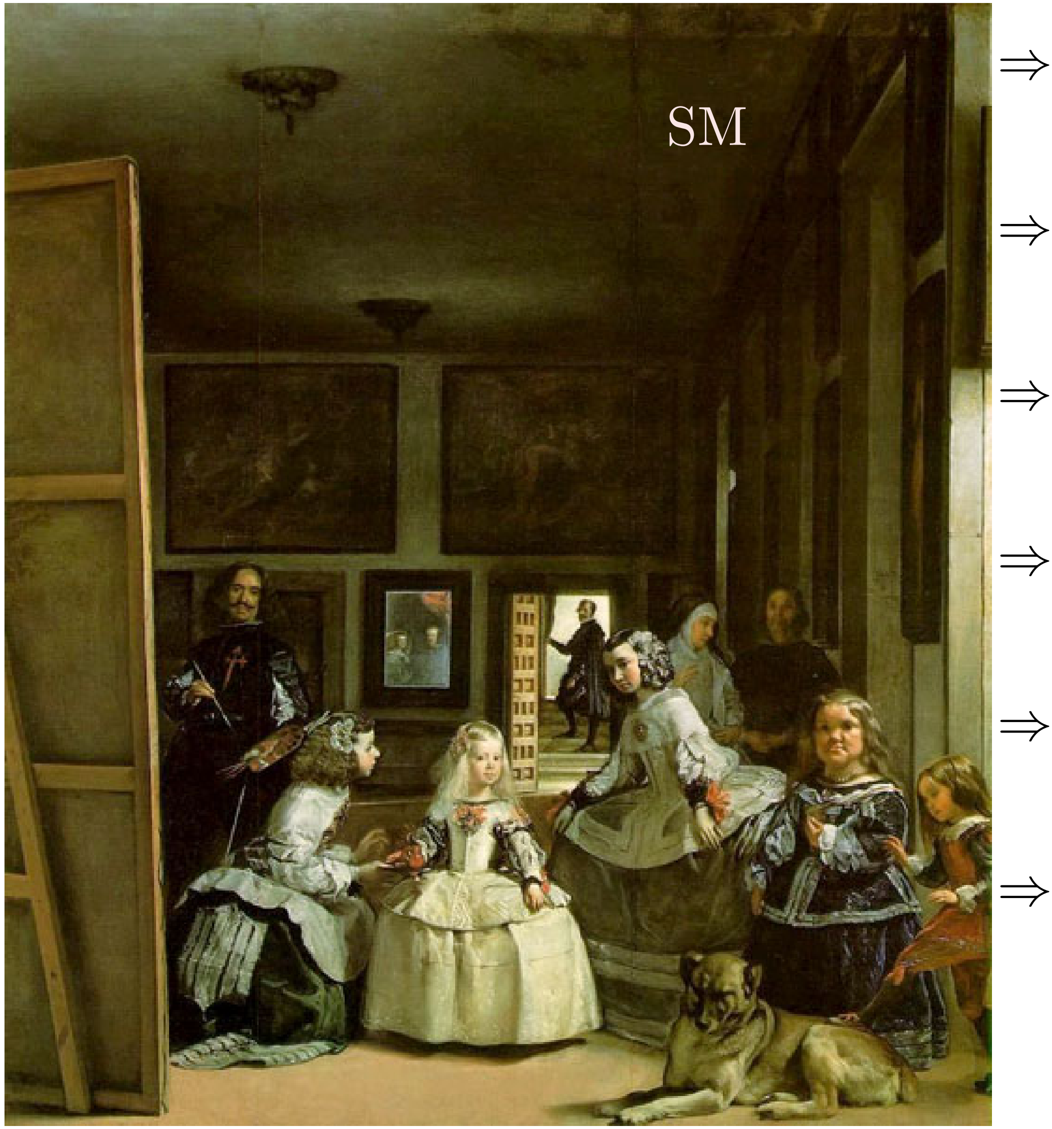
CONCLUSIONS

The venerable Standard Model has finally sprung a leak – neutrinos are not massless!

1. we have a very successful parametrization of the neutrino sector, and we have identified what we know we don't know.
2. neutrino masses are very small – we don't know why, but we think it means something important.
3. lepton mixing is very different from quark mixing – we don't know why, but we think it means something important.
4. we need a minimal νSM Lagrangian. In order to decide which one is "correct" (required in order to attack 2. and 3. above) we must uncover the faith of baryon number minus lepton number ($0\nu\beta\beta$ is the best [only?] bet).

5. We need more experimental input – and more seems to be on the way (this is a truly data driven field right now). We only started to figure out what is going on.
6. The fact that neutrinos have mass may be intimately connected to the fact that there are more baryons than antibaryons in the Universe. How do we test whether this is correct?
7. There is plenty of room for surprises, as neutrinos are very narrow but deep probes of all sorts of physical phenomena. Remember that neutrino oscillations are "quantum interference devices" – potentially very sensitive to whatever else may be out there (e.g., $M_{\rm seesaw} \simeq 10^{14}$ GeV).
8. Finally, we need to resolve the LSND anomaly. If MiniBooNE agrees with the LSND result, life will be much more interesting!

In Summary: There is a νSM, and we are still trying to figure out what it is in it . . .



(with apologies to D. Velásquez)

(with apologies to P. Picasso)