Type II Leptogenesis

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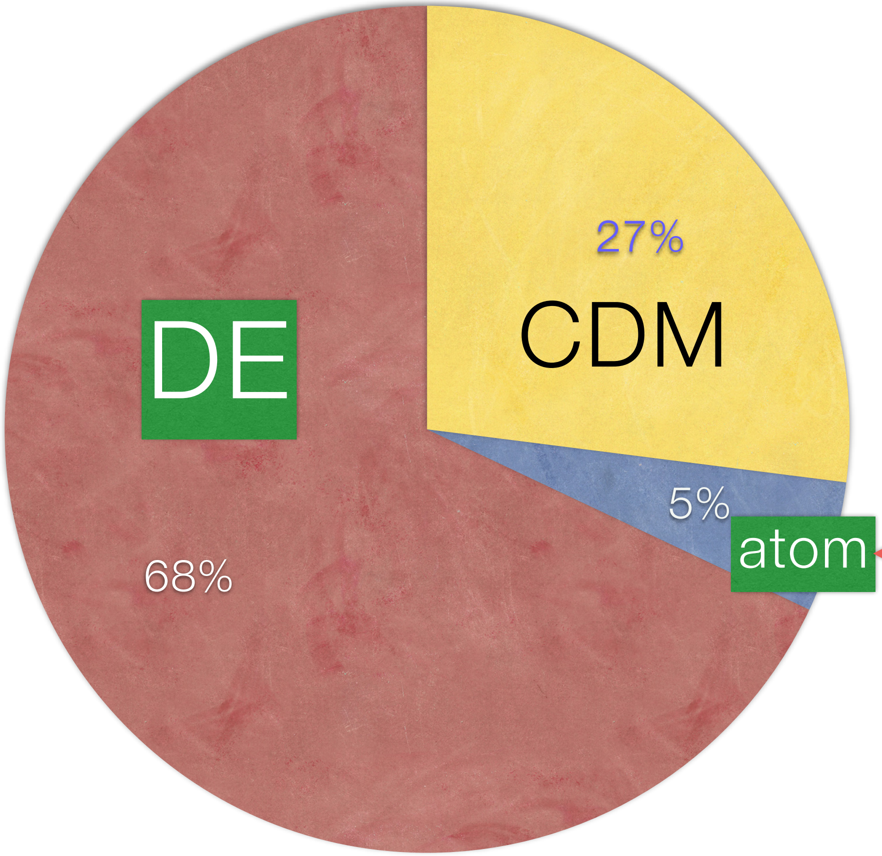
Chicago, 6 Aug 2016



Chiral fields at GUT scale
SU(5), SU(7) GUTs

UGUTF:
Kim, PRL 45, 1916 (1980);
arXiv:1503.03104;
JEK, D.Y.Mo, S. Nam,
JKPS 66, 894 (2015) [arXiv:
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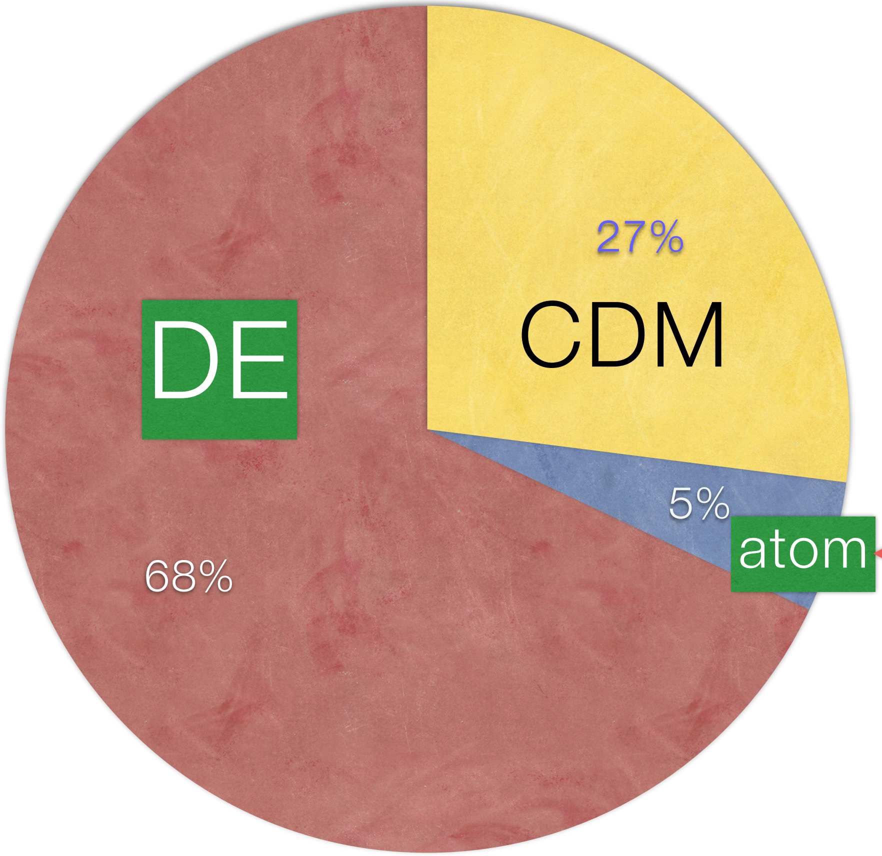
CP violation by J

New kind leptogenesis possible with PMNS phase



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1. CP violation and PMNS matrix

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Sakhrov conditions for B generation:

1. B number violation
2. CP and C violation
3. Out of thermal equilibrium

For 3, we just make sure that the process proceeds in non-equilibrium conditions. If it is a decay, almost surely the condition 3 is satisfied.

The CKM or PMNS matrix is, with the 1st row real,

$$\begin{pmatrix} c_1, & s_1 c_3, & s_1 s_3 \\ -c_2 s_1, & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3, & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta} s_1 s_2, & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta}, & c_2 c_3 + c_1 s_2 s_3 e^{i\delta} \end{pmatrix}$$

The individual element of determinant is

$$\begin{aligned}
V_{11}V_{22}V_{33} &= c_1^2 c_2^2 c_3^2 + c_1^2 s_2^2 s_3^2 + 2c_1 c_2 c_3 s_2 s_3 \cos\delta \\
&\quad - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{11}V_{23}V_{32} &= c_1^2 c_2^2 s_3^2 + c_1^2 s_2^2 c_3^2 - 2c_1 c_2 c_3 s_2 s_3 \cos\delta \\
&\quad + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
V_{12}V_{23}V_{31} &= s_1^2 s_2^2 c_3^2 - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{12}V_{21}V_{33} &= s_1^2 c_2^2 c_3^2 + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
V_{13}V_{21}V_{32} &= s_1^2 c_2^2 s_3^2 - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{13}V_{22}V_{31} &= s_1^2 s_2^2 s_3^2 + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}.
\end{aligned}$$

Is Im(V_{11} V_{22} V_{33}) the Jarlskog determinant?

The Jarlskog determinant is
J=|Im V_{11} V_{22} $V_{12}^{*}V_{21}^{*}$|, or |Im $V_{ii}V_{jj}V_{ij}^{*}V_{ji}^{*}$|

With the usual definition on J:
J=|Im V_{11} V_{33} $V_{13}^{*}V_{31}^{*}$|. Then, on 1=Det V

$$
\begin{aligned}
V_{13}^{*}V_{22}^{*}V_{31}^{*} &= |V_{22}|^2 V_{11}V_{33}V_{13}^{*}V_{31}^{*} - V_{11}V_{23}V_{32}V_{13}^{*}V_{31}^{*}V_{22}^{*} \\
&\quad + |V_{31}|^2 V_{12}V_{23}V_{13}^{*}V_{22}^{*} - V_{12}V_{21}V_{33}V_{13}^{*}V_{31}^{*}V_{22}^{*} \\
&\quad + |V_{13}|^2 V_{21}V_{32}V_{31}^{*}V_{22}^{*} - |V_{13}V_{22}V_{31}|^2.
\end{aligned}
$$

$$
\begin{aligned}
V_{13}^{*}V_{22}^{*}V_{31}^{*} &= (1-|V_{21}|^2)V_{11}V_{33}V_{13}^{*}V_{31}^{*} \\
&\quad + V_{11}V_{23}V_{13}^{*}V_{21}^{*}|V_{31}|^2 + (1-|V_{11}|^2)V_{12}V_{23}V_{13}^{*}V_{22}^{*} \\
&\quad + |V_{13}|^2(V_{12}V_{21}V_{11}^{*}V_{22}^{*} + V_{21}V_{32}V_{31}^{*}V_{22}^{*}) \\
&\quad - |V_{13}V_{22}V_{31}|^2.
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\begin{aligned}
V_{13}^*V_{22}^*V_{31}^* = {} & |V_{22}|^2 V_{11}V_{33}V_{13}^*V_{31}^* - V_{11}V_{23}V_{32}V_{13}^*V_{31}^*V_{22}^* \\
& + |V_{31}|^2 V_{12}V_{23}V_{13}^*V_{22}^* - V_{12}V_{21}V_{33}V_{13}^*V_{31}^*V_{22}^* \\
& + |V_{13}|^2 V_{21}V_{32}V_{31}^*V_{22}^* - |V_{13}V_{22}V_{31}|^2.
\end{aligned}
$$

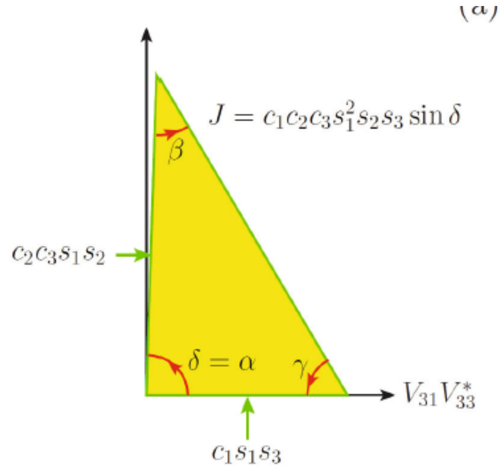
unitarity of V

imaginary part of this is J

$$
\begin{aligned}
V_{13}^*V_{22}^*V_{31}^* = {} & (1-|V_{21}|^2)V_{11}V_{33}V_{13}^*V_{31}^* \\
& + V_{11}V_{23}V_{13}^*V_{21}^*|V_{31}|^2 + (1-|V_{11}|^2)V_{12}V_{23}V_{13}^*V_{22}^* \\
& + |V_{13}|^2(V_{12}V_{21}V_{11}^*V_{22}^* + V_{21}V_{32}V_{31}^*V_{22}^*) \\
& - |V_{13}V_{22}V_{31}|^2.
\end{aligned}
$$

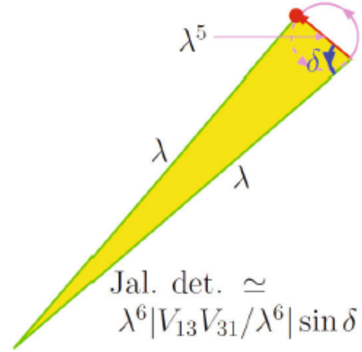
Similar considerations for other elements give the imaginary part as [(1-$|V_{21}|^2$) -$|V_{31}|^2$ +(1-$|V_{11}|$)^2]J=J

There are 6 Jarlskog triangles. One of them corresponds to B-meson decay to K. PDG gives alpha or our delta almost 90 degrees.



We can consider another J: B decaying to pi meson. This has two long sides.

So, delta=90 degrees is a maximal CP violation! in KS parametrization. In other parametrizations too.



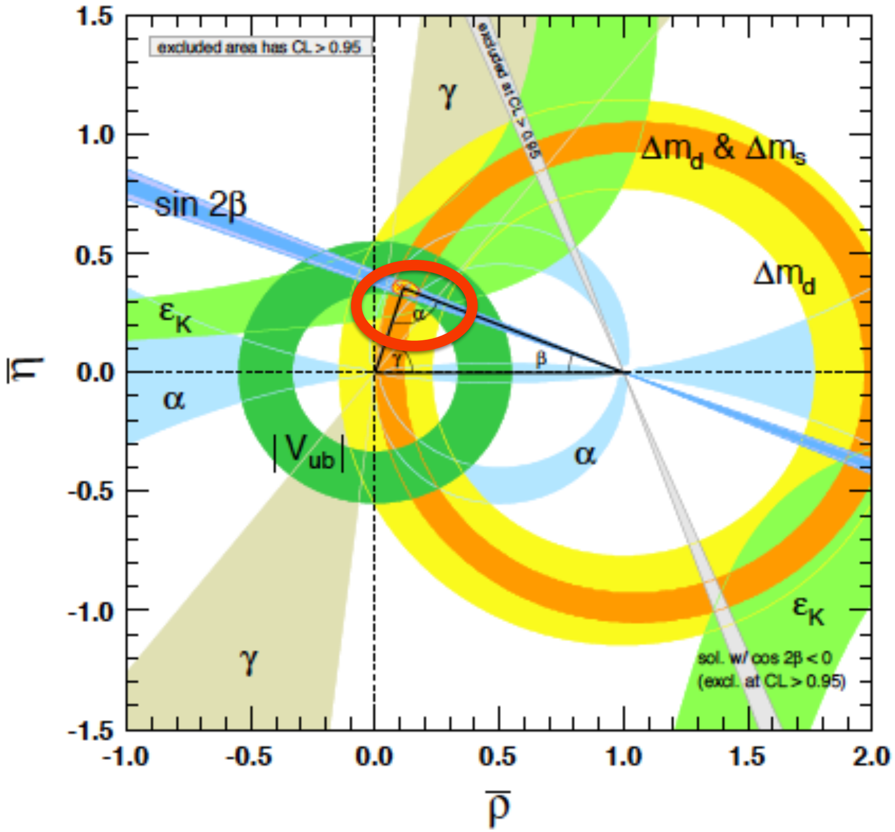


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

and the Jarlskog invariant is $J = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$.

This is PDG compilation. α or ϕ_2 is our δ .

PDG determines

Combining the $B \to \pi\pi$, $\rho\pi$, and $\rho\rho$ decay modes [105], α is constrained as

$$\alpha = (85.4^{+3.9}_{-3.8})^\circ.$$

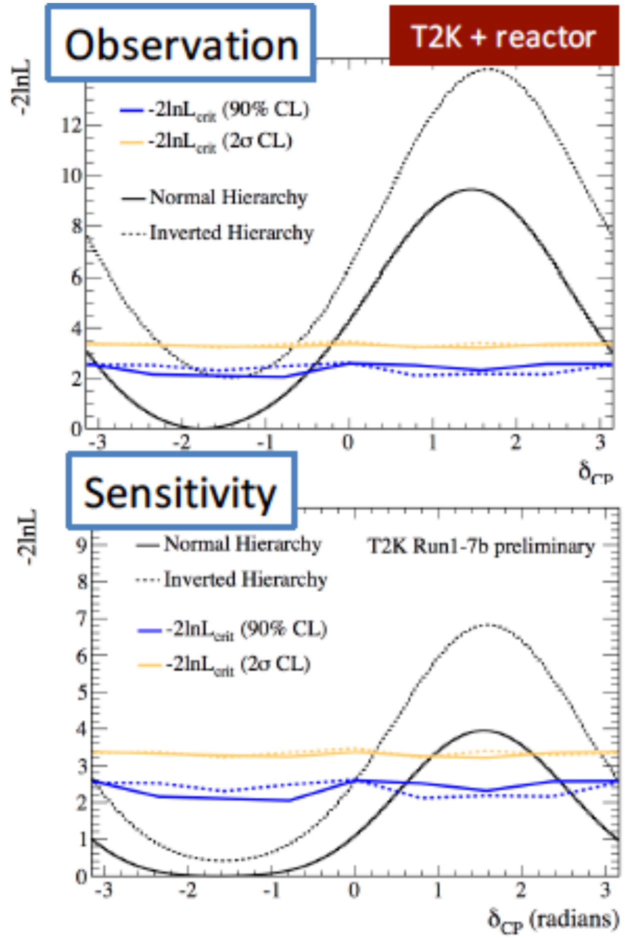
This implies that the weak CP violation in the quark sector is almost maximal with some forms of CKM matrix.

[KM and KS]

Maximal CP violation in lepton sector?

T2K experiment [S.V. Cao at PASCOS 2016], slightly favors δ_{PMNS} near -90 degrees.

Determination of δ_{PMNS} may choose δ_{CKM} in certain models.



Is $\delta_{\rm PMNS} = \pm\delta_{\rm CKM}$?

JEK + S. Nam, arXiv:1506.08491
JEK + D. Y. Mo + M-S. Seo, arXiv:1506.08984

2. Leptogenesis

Sphaleron processes at electroweak scale changes B and L numbers but no change of (B-L).

If generation of B at GUT scale accompanies L such that creation of (B-L)=0, then we end up most probably B=0 after the effective sphaleron processes. B and L generation processes at high temperature must occur through processes which generate nonzero (B-L).

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SU(5) is not working.

GUT: Use (B-L) breaking interaction in SO(10) for B and L generation processes.

SU(3)xSU(2)xU(1): Just use N at high energy scale.

Type-I leptogenesis:

Neutrino mass
summarized by
Weinberg operator:

L=2

L=-2

$$\frac{1}{M}\ell\ell H_u H_u$$

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Realized in seesaw with renormalizable terms:
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L=+1 L=0 L=-1

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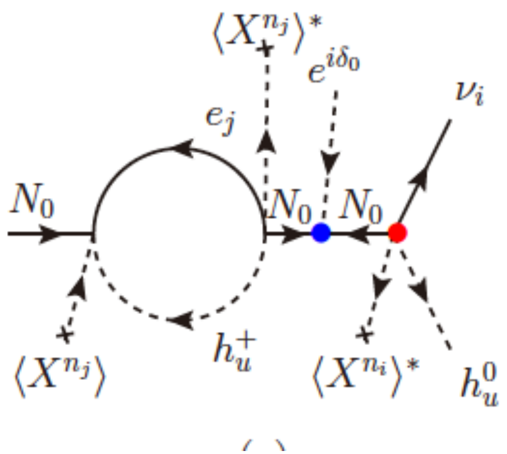
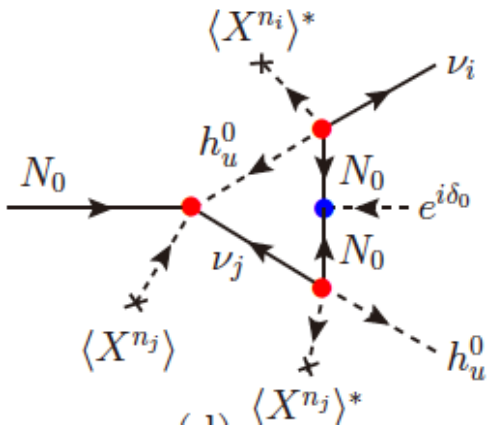
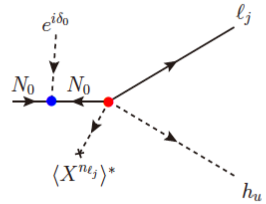
Who cares about renormalizable terms very importantly at low energy?

In cosmology, however, it is important. Not to worry about L number of Higgs doublets, we choose the first one. It is a first guess. It leads to the Type-I leptogenesis.





With only one N, phase can be zero. At least two heavy neutrinos are needed.



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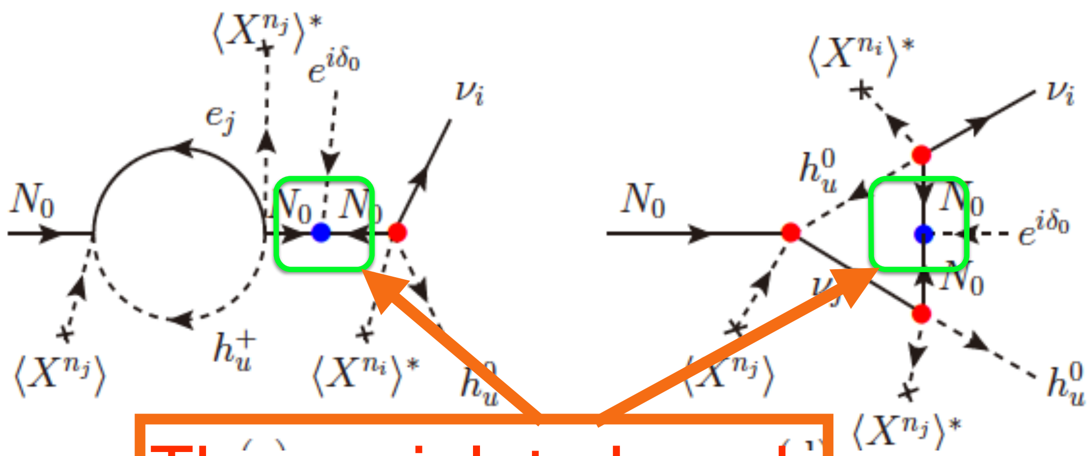

These violate L and CP simultaneously.

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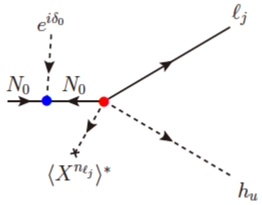
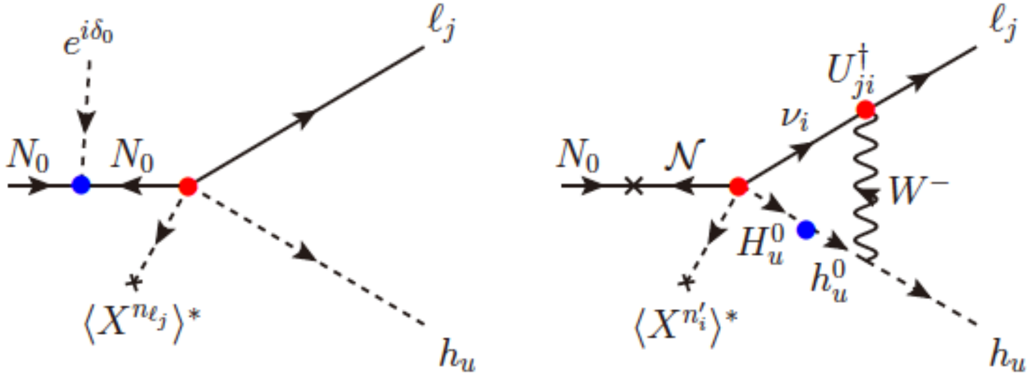
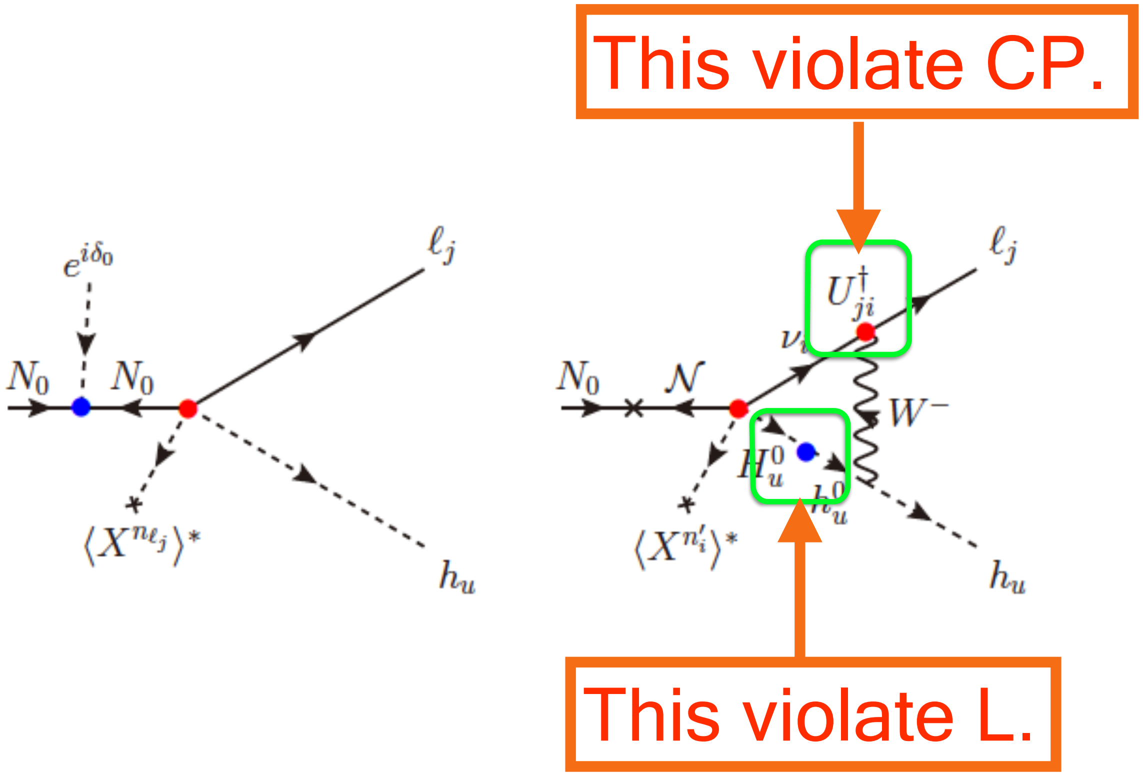


3. Type-II leptogenesis

Covi, Kim, Kyae, Nam:
1601.00411v3



One N can do it, but different Higgs doublets needed. Anyway, these are the fields at high energy scale.



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H$_u$

H$_d$

N

$\mathcal{N}$

h_u

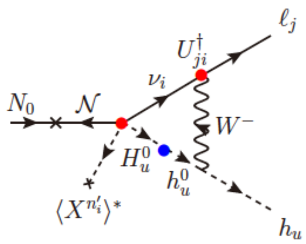
Definition of lepton numbers:

L=+1 L=+1

$$f N_1 h_u \ell_L , \qquad \tilde{f} \mathcal{N}_1 H_u \ell_L$$

$$\Delta m_0 \, N_1 \, \mathcal{N}_1 + \mu_H^2 H_u H_d + \text{H.c.}$$

$$\Delta \mathcal{L} \ni \mu'^2 h_u^* H_u + m_0' \, N_1 N_1 + m_0'' \, \mathcal{N}_1 \mathcal{N}_1 + \text{h.c.}$$



Definition of lepton numbers:

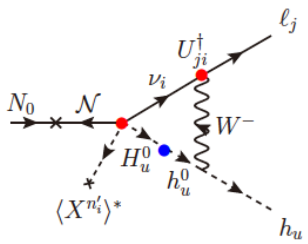
H_u	L=-2
H_d	L=+2
N	L=-1
$\mathcal{N}$	L=+1
h_u	L=0

$$f N_1 \overbrace{h_u \ell_L}^{L=+1}, \qquad \tilde{f} \mathcal{N}_1 \overbrace{H_u \ell_L}^{L=+1}$$

$$\Delta m_0 \, N_1 \mathcal{N}_1 + \mu_H^2 H_u H_d + \text{H.c.}$$

These conserve L.

$$\Delta\mathcal{L} \ni \mu'^2 h_u^* H_u + m_0' \, N_1 N_1 + m_0'' \, \mathcal{N}_1 \mathcal{N}_1 + \text{h.c.}$$



Definition of lepton numbers:

H_u L=-2

H_d L=+2

N L=-1

$\mathcal{N}$ L=+1

h_u L=0

L=+1 L=+1

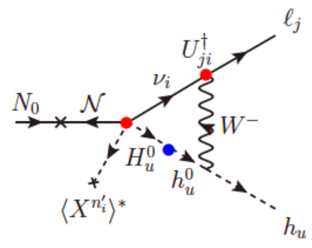
$$f\,N_1\,h_u\ell_L\,, \qquad \tilde{f}\mathcal{N}_1\,H_u\ell_L$$

$$\Delta m_0\,N_1\,\mathcal{N}_1 + \mu_H^2 H_u H_d + \text{H.c.}$$

These conserve L.

$$\Delta\mathcal{L} \ni \mu'^2 h_u^* H_u + m_0'\,N_1 N_1 + m_0''\,\mathcal{N}_1\,\mathcal{N}_1 + \text{h.c.}$$

This violate L .



In models with SU(2)xU(1) breaking at high temperature, this kind of leptogenesis is present.
[Mohapatra-Senjanovic in non-SUSY models; also in SUSY models]

In models with only one CP phase from high energy scale, leptogenesis phase can be related to the PMNS phase. There is only one phase in the theory.
So what else can it be?
Even, phases of heavy neutrinos are expressible in terms of this fundamental phase.
[JEK-Nam, 1506.08491]

Sphaleron processes might enter into equilibrium for

[D'Onofrio+, 1404.3565]

$$\Gamma_{\rm sph}^{\rm broken} = \kappa\alpha_W^4 T^4 \left(\frac{4\pi v}{g_W T}\right)^7 e^{-\frac{E_{\rm sph}}{T}}$$

E_{sph}=1.524 v / g_W. So, until T is lowered to T*=131.7 GeV,

$$\frac{\Gamma_{\rm sph}^{\rm broken}}{T^3 H(T)} = \kappa\alpha_W^4 \left(\frac{4\pi k}{g_W}\right)^7 e^{-1.52k\frac{4\pi}{g_W}} \sqrt{\frac{90}{\pi^2 g_*}}\frac{M_P}{T} \geq 1$$

$$U = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -c_2 s_1 & e^{-i\delta_{\mathrm{PMNS}}} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta_{\mathrm{PMNS}}} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta_{\mathrm{PMNS}}} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta_{\mathrm{PMNS}}} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta_{\mathrm{PMNS}}} \end{pmatrix}_{\mathrm{KS}} \begin{pmatrix} e^{i\delta_a} & 0 & 0 \\ 0 & e^{i\delta_b} & 0 \\ 0 & 0 & e^{i\delta_c} \end{pmatrix}_{\mathrm{Maj}}$$

$$\epsilon_{\mathrm{L}}^{N_0}(W) \approx \frac{\alpha_{\mathrm{em}}}{2\sqrt{2}\sin^2\theta_W} \frac{\Delta m_h^2}{m_0^2} \sum_{i,j} \mathcal{A}_{ij} \sin[(\pm n_P + n' - n_i + n_j)\delta_{\mathrm{X}}]$$

$$\delta_{\mathrm{PMNS}} = n_P \delta_{\mathrm{X}} \text{ and } \delta_a = n_a \delta_{\mathrm{X}};$$

$$\sin[\delta_{\mathrm{PMNS}} + \delta_a - (n_1 - n_3)\delta_{\mathrm{X}}].$$

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one FN phase

$$\delta_{\rm PMNS} = n_P \delta_{\rm X} \;\; \text{and} \;\; \delta_a = n_a \delta_{\rm X};$$

$$\sin[\delta_{\rm PMNS} + \delta_a - (n_1 - n_3)\delta_{\rm X}].$$

family indices

For $\epsilon_L \simeq 6 \times 10^{-6}$

we need [1601.00411]:

$$c_2 c_3 \sin\delta_c + c_1 s_2 s_3 \sin(\delta_c + \delta_{PMNS}) \simeq 2.4 \times 10^{-2}$$

6. Conclusion

1. We introduced a new leptogenesis mechanism in theories with SU(2)xU(1) breaking at high temperature.
2. $\mathrm{delta}_{\mathrm{PMNS}}$ is related to the leptogenesis phase in certain CP violation models.
3. One light intermediate scale Majorana neutrino N_0 can achieve the goal since the CP phase is provided by the PMNS phase.