
“CPs and Type-II
Leptogenesis”
CosPA 2016

CP's and Type-II Leptogenesis

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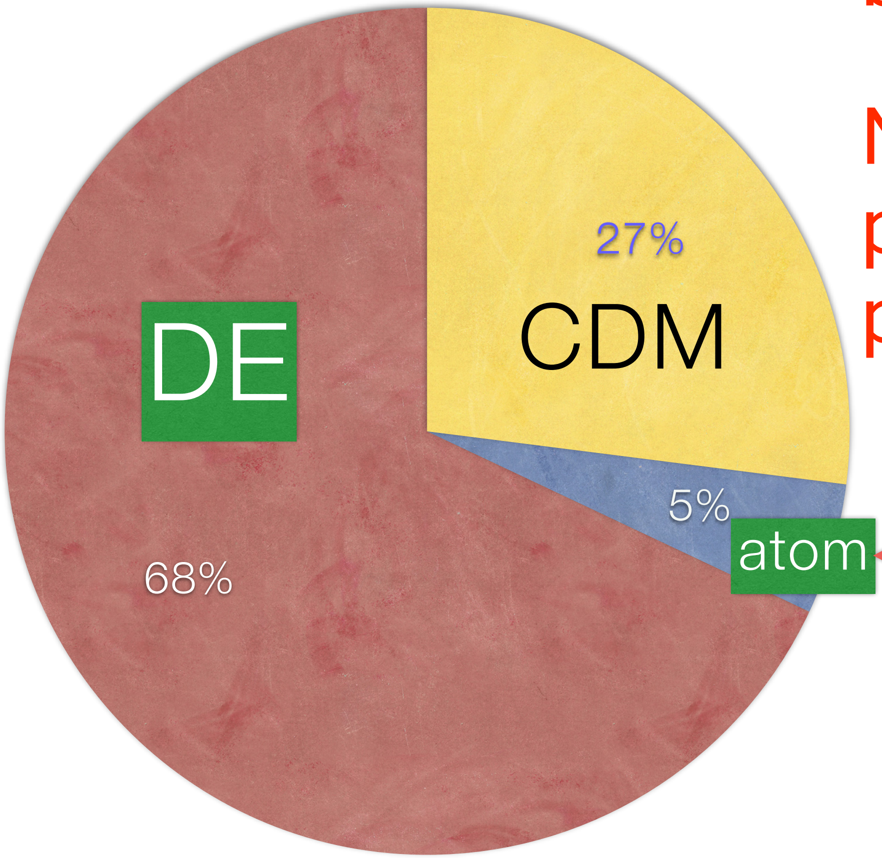


CP violation magnitude by J

New kind leptogenesis possible with PMNS phase

Chiral fields As a GUT follower:
SU(5), SU(7) GUTs

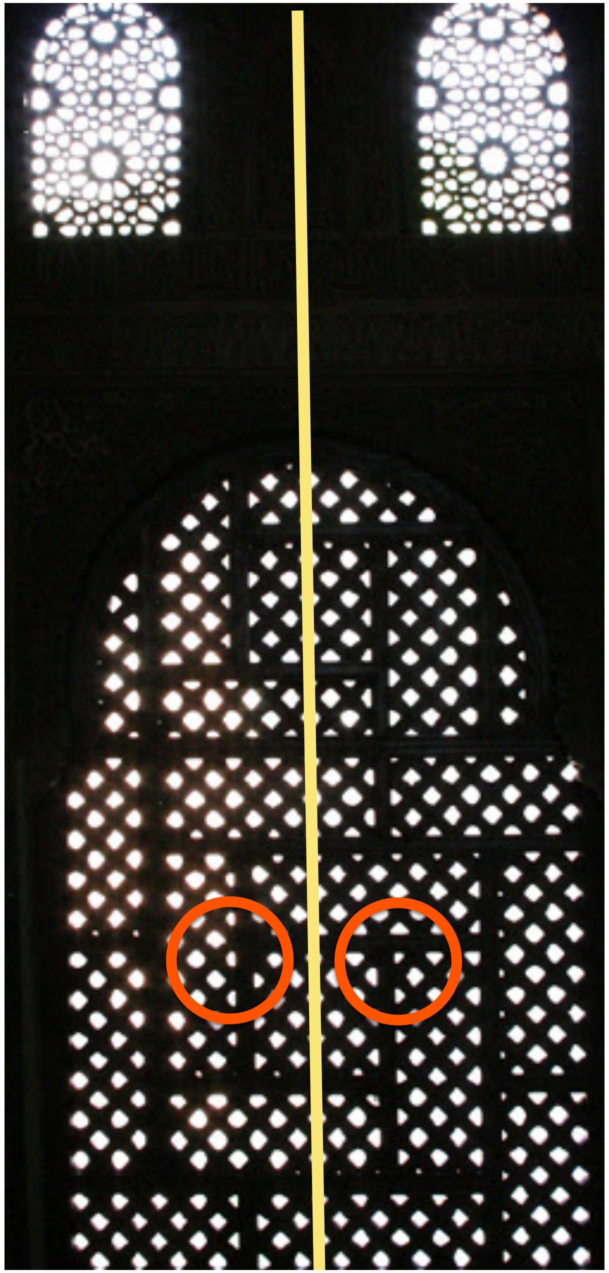
UGUTF:
Kim, PRL 45, 1916 (1980);
arXiv:1503.03104;
JEK, D.Y.Mo, S. Nam,
JKPS 66, 894 (2015) [arXiv:
1402.2978]

1. CPs
2. Weak CP violation
3. Short comment on invisible axion
3. Cosmology with CP violation
4. Type-II leptogenesis

1. CPs

Symmetry is beautiful: Gross' framework, beginning with a grand design.

Parity:



Slightly broken!

If there exists a possibility of

$$(\mathbf{CP})\mathcal{L}(\mathbf{CP})^{-1} = \mathcal{L}$$

Then, the CP symmetry is preserved.

The first thing to do is to define fields with CP quantum numbers. Next, find out terms breaking CP.

So, CP violation is an interference phenomenon:

Neutral K mesons are a unique physical system which appears to be created by nature to demonstrate, in the most impressive manner, a number of spectacular phenomena.

....

If the K mesons did not exist, they should have been invented "on purpose" in order to teach students the principles of quantum mechanics.

Lev B. Okun

[talk, A. De Domenico, At Corfu Summer School, 1 Sep. 2016]

and most importantly,

5. Weak CP violation in the SM.

2. Weak CP violation

CKM and PMNS matrices

CP violation magnitude by Jarlskog determinant J

After Cronin et al paper, “Need for a theory of weak CP violation”: KM+…

(1) by light colored scalar,

(2) by right-handed current(s),

(3) by three left-haned families,

(4) by propagators of light color-singlet scalars, and

(5) by an extra U(1) gauge interaction.

By Kobayashi-Maskawa

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

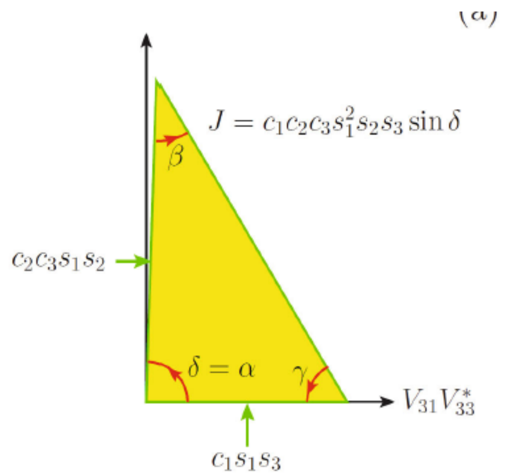
$$\begin{pmatrix} c_1, & s_1 c_3, & s_1 s_3 \\ -c_2 s_1, & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3, & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta} s_1 s_2, & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta}, & c_2 c_3 + c_1 s_2 s_3 e^{i\delta} \end{pmatrix}$$

The individual element of determinant is

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

It strongly hints CP violation in V by the components of Det. V.

The Jarlskog determinant is
$J=|\mathrm{Im}\ V_{11}\ V_{22}\ \ V_{12}{}^{*}V_{21}{}^{*}|$, or $|\mathrm{Im}\ V_{ii}V_{jj}V_{ij}{}^{*}V_{ji}{}^{*}|$
(1/2)Area=Two sides times sin of the angle



Is Im(V_{13} V_{22} V_{31}) the Jarlskog determinant?

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

$$V_{13}^* V_{22}^* V_{31}^* = |V_{22}|^2 V_{11} V_{33} V_{13}^* V_{31}^* - V_{11} V_{23} V_{32} V_{13}^* V_{31}^* V_{22}^* + |V_{31}|^2 V_{12} V_{23} V_{13}^* V_{22}^* - V_{12} V_{21} V_{33} V_{13}^* V_{31}^* V_{22}^* + |V_{13}|^2 V_{21} V_{32} V_{31}^* V_{22}^* - |V_{13} V_{22} V_{31}|^2.$$

unitarity of V

imaginary part of this is J

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

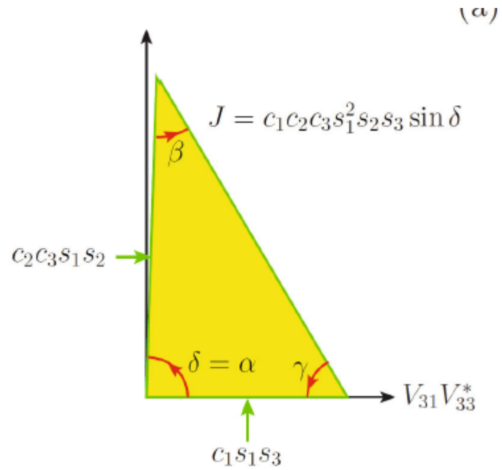
Similar considerations for other elements give the imaginary part as $[(1-|V_{21}|^2) - |V_{31}|^2 + (1-|V_{11}|)^2] J = J$

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

$$J = |c_1 c_2 c_3 s_1^2 s_2 s_3 \sin(\text{delta})|$$

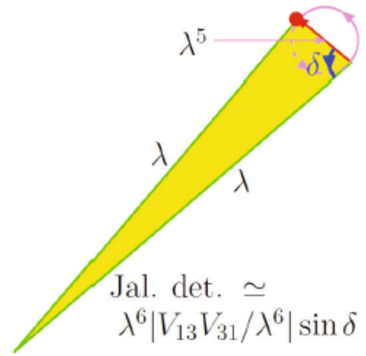
All three families participate.
And also u-type quark masses must be different, and d-type quark masses different.

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.



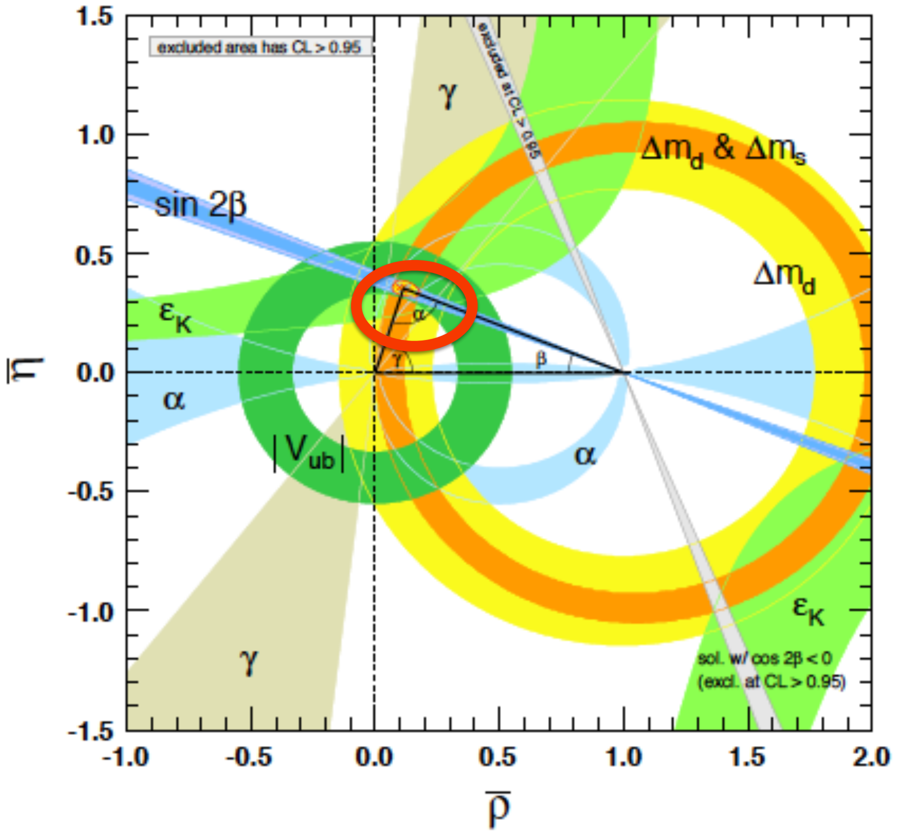


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

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

This is PDG compilation.

α is our δ .

PDG determines

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

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

Ufit determines

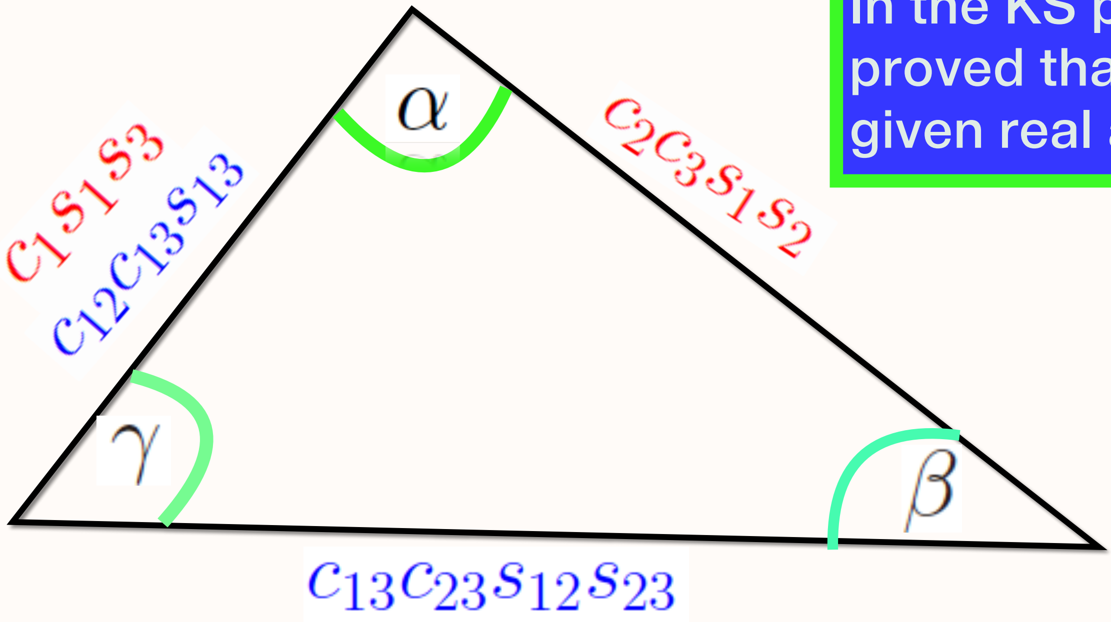
alpha= (88.6+-3.3)^o

CKMfit determines

alpha= $(90.6^{+3.9}_{-1.1})^o$

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

KS parametrization: $J = |c_1 c_2 c_3 s_1^2 s_2 s_3 \sin\alpha|$



In the KS parametrization, we proved that it is maximal with given real angles.

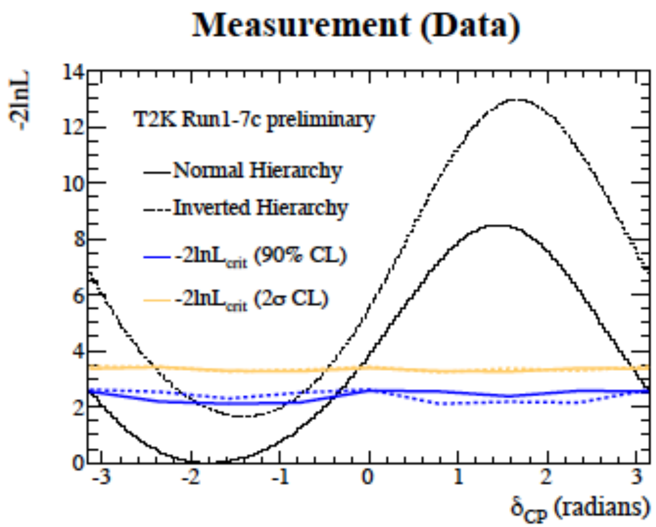
CKM parametrization: $J = |c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\gamma|$

Any parametrization gives the same area.

Maximal CP violation in lepton sector?

T2K experiment [S.V. Cao at PASCOS 2016; K. Iwamoto at ICHEP2016], slightly favors $\delta_{\rm PMNS}$ near -90 degrees.

Determination of $\delta_{\rm PMNS}$ may choose $\delta_{\rm CKM}$ in certain models.



$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

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

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

3. Strong CP problem

Summarized by
Weinberg operator:
[13.08.1979, Received]

L=2 L=-2

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

gives ν mass

Kim-Nilles SUSY operator:
[24.11.1983, Received]

Q=2 Q=-2

$$\frac{1}{M} S_1 S_2 H_u H_d$$

gives TeV scale μ term

Realized in seesaw:
Minkowski [13.04.1977, Published],
Yanagida [13-14 Feb 79, Conf. talk]
......

$$\ell_L H_u N_R$$

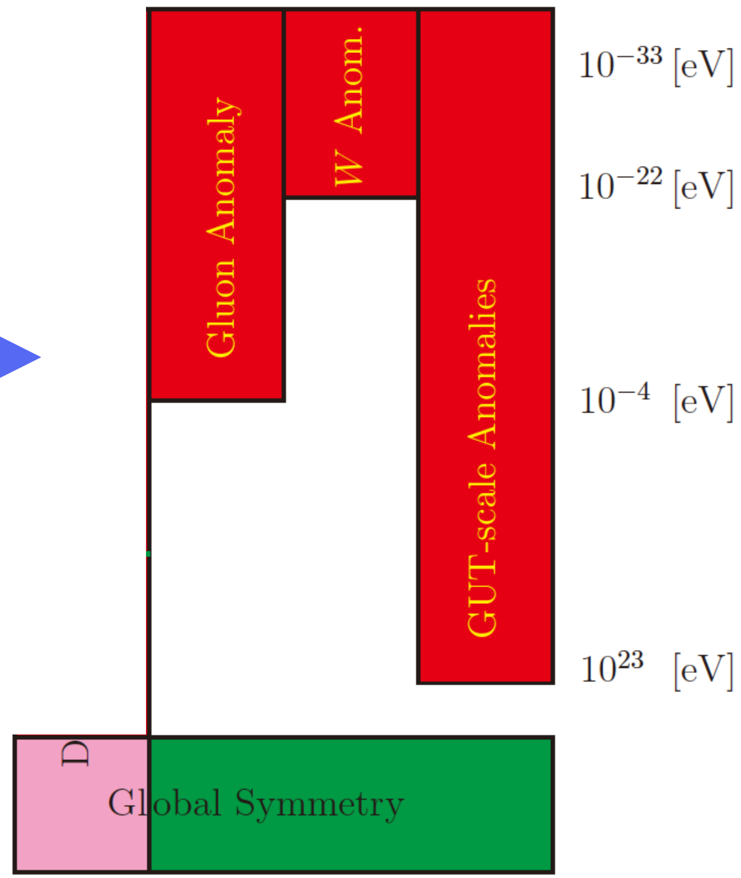
Realized in string comp.:
Many papers,⋯.

-1/2 +1

$$S_1 H_u X_{\mathrm{doublet}},\ S_2 H_d X'_{\mathrm{doublet}},\ \bar{Q}_L Q_R S_1, \cdots$$

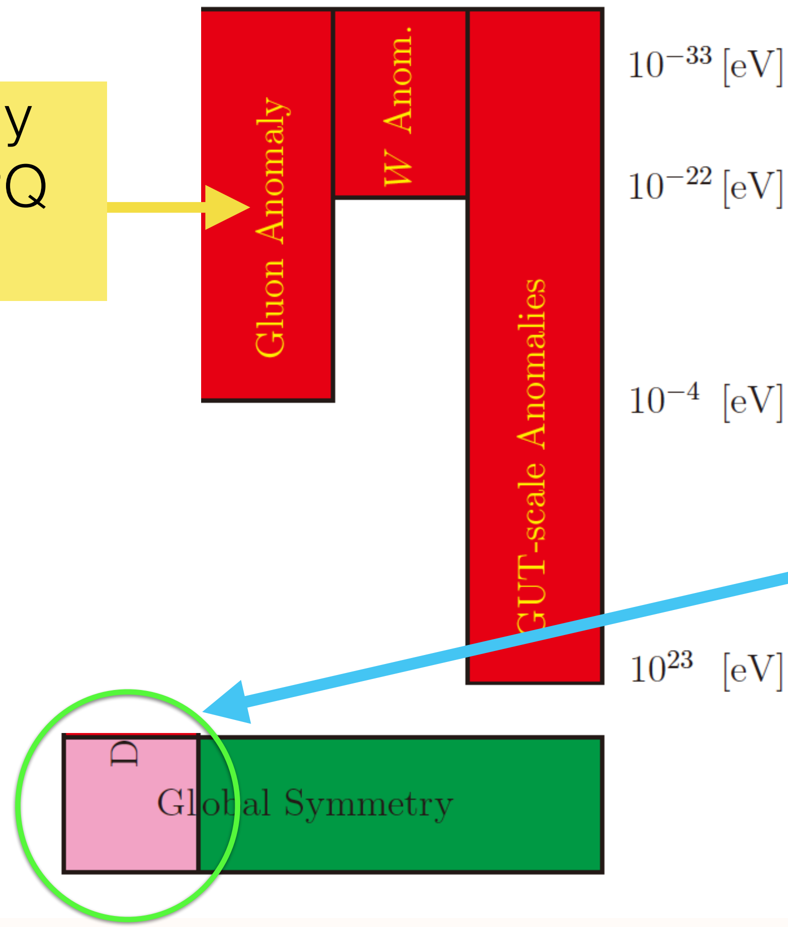
-1 -1

If this is absent,
it is called
axion. And
theta=0 is the
minimum.



Still some term in
V is present with
discrete
symmetry, then
theta=0 is not
guaranteed to be
the minimum.

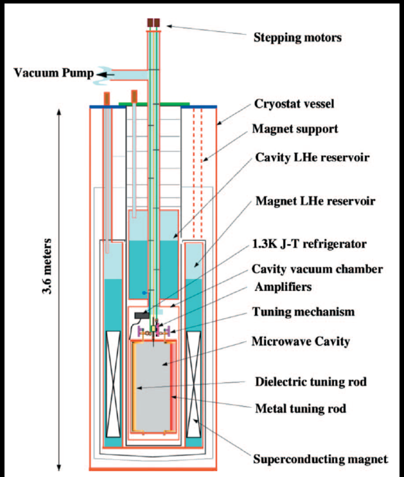
This anomaly breaks the PQ symmetry.

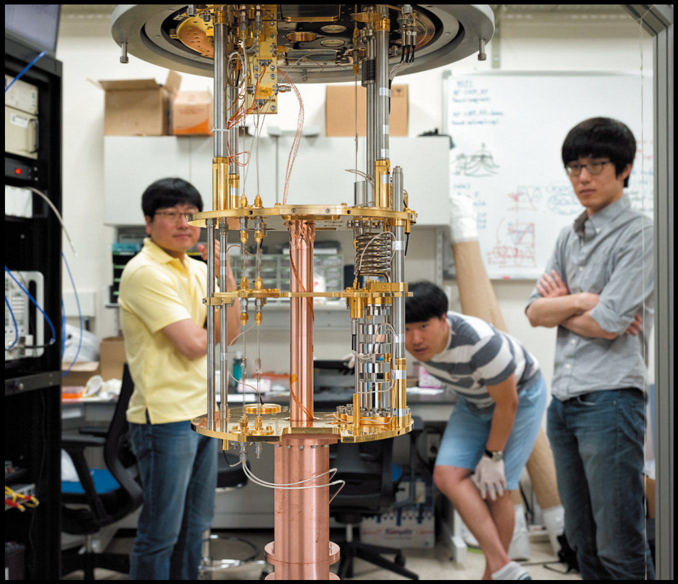


VEV of S_1 gives the f_a scale.

$$\frac{1}{M} S_1 S_2 H_u H_d$$

In SUSY, this KN term is the PQ symmetry defining one.





ADMX

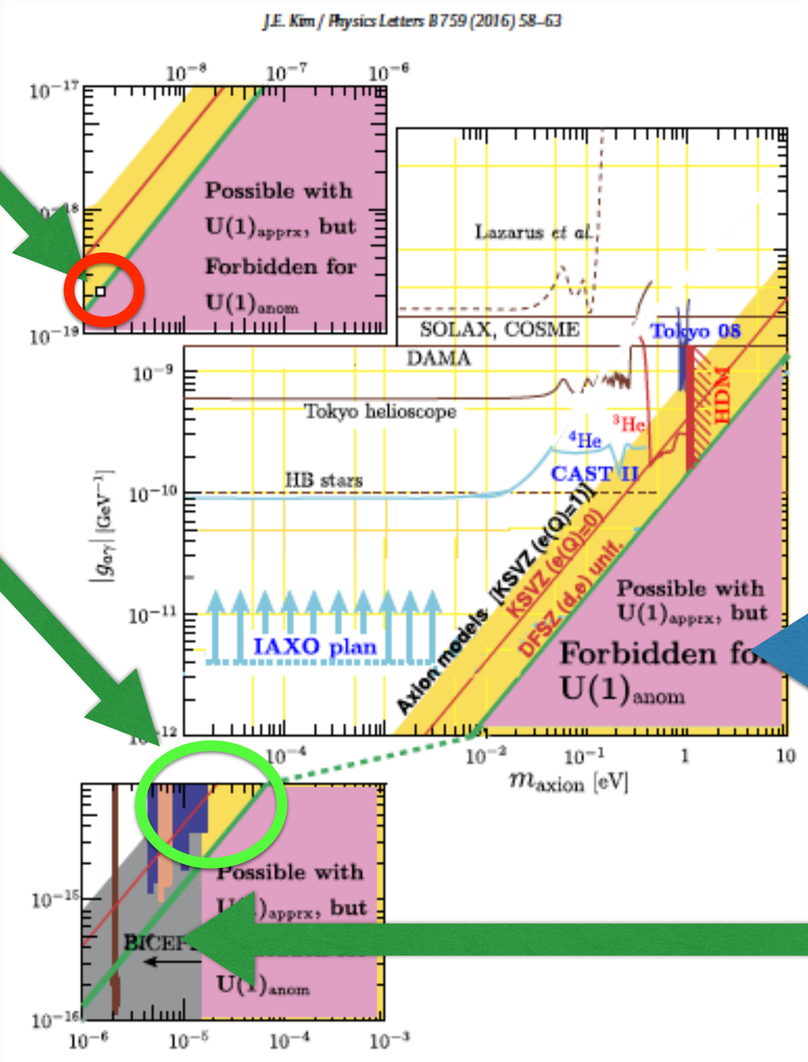
CAPP: ???

Detection suggested : 1983
CAPP started : 2013

Sikivie's cavity detector

MI axion

A small allowed region by $U(1)_{\rm anom}$



$g_{a\gamma}(= 1.57 \times 10^{-10}\, c_{a\gamma\gamma})$ vs. m_a plot

Kim-Semertzidis-Tsujikawa, Front. Phys. 2 (2014) 60

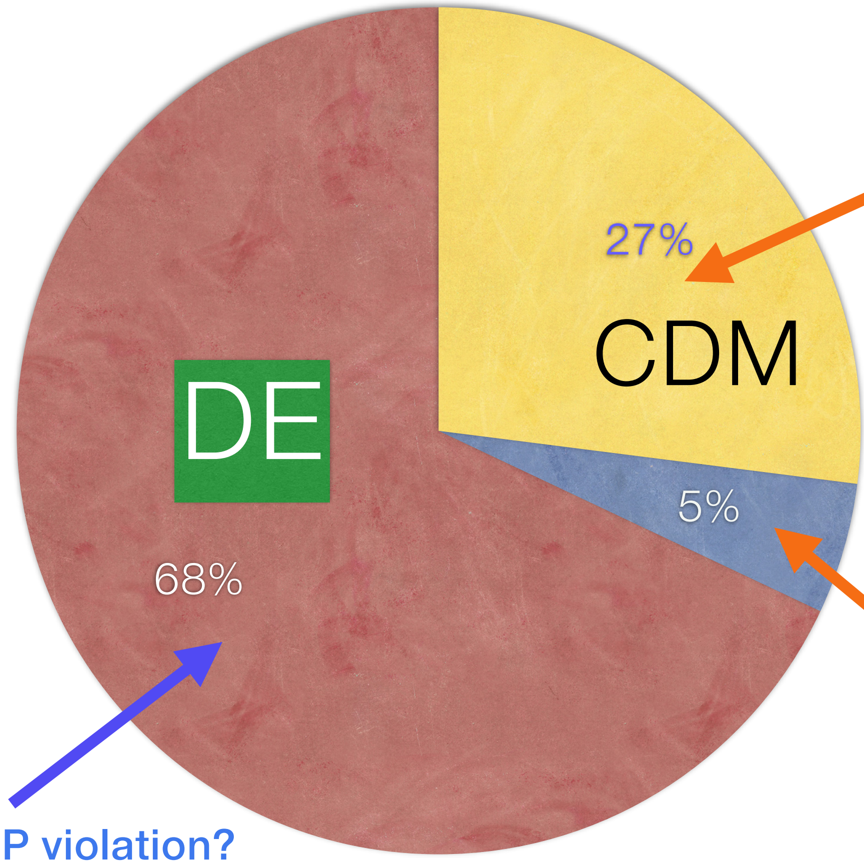
Kim-Nam, 1603.02145[hep-ph]

$U(1)_{\rm anom}$ forbidden

If H_I is greater than f_a, there is the isocurvature constraint.

4. Type-II Leptogenesis

Covi, Kim, Kyae, Nam:
1601.00411v3



Oscillating CDM axions are oscillate around CP violating phases.

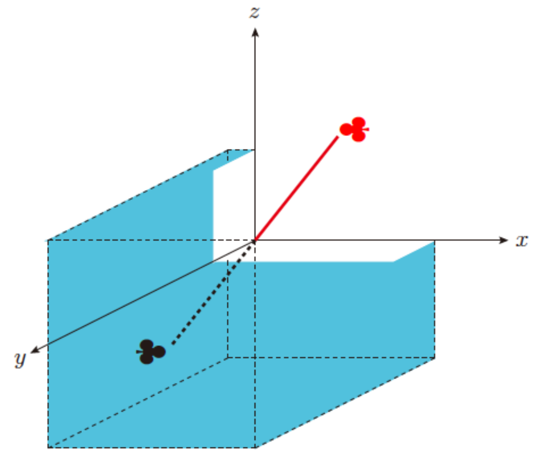
CP violation in weak interactions.

Is DE also related to CP violation?

Quintessential axion: Kim-Nilles, [hep-ph/0210402], [arXiv:1311.0012[hep-ph]]

Sakharov 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.

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).

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

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

gives ν mass

Realized in seesaw with renormalizable terms:

Minkowski, Yanagida······

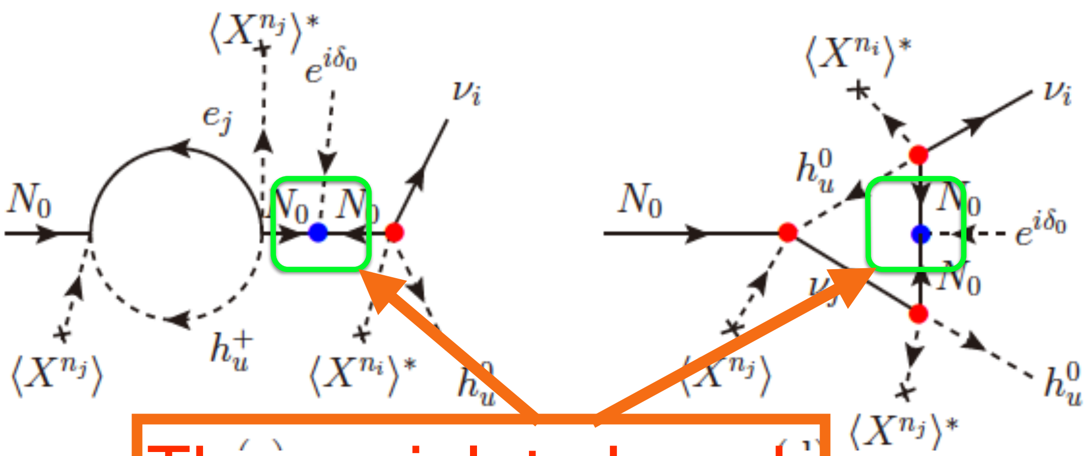
L=+1	L=0	L=-1

$$\ell_L H_u N_R$$

L=+1	L=-1	L=0

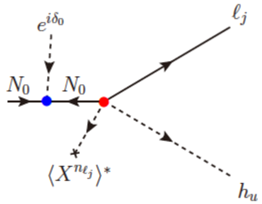
Who cares about renormalizable terms very importantly at low energy?

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.

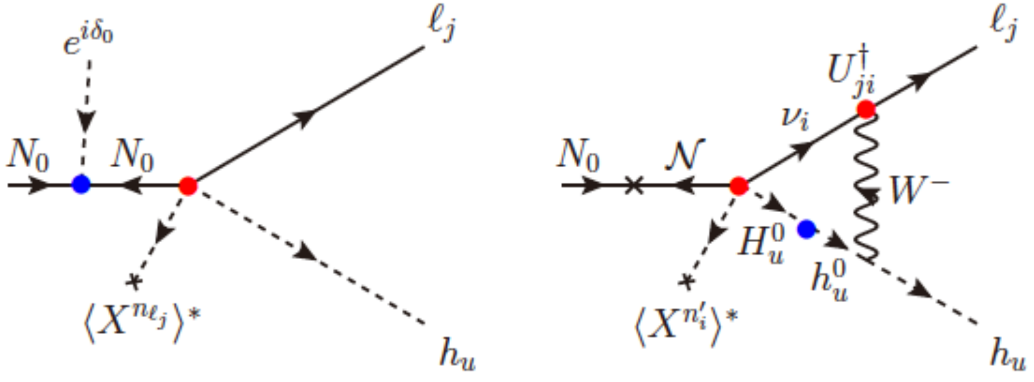


These violate L and CP simultaneously.

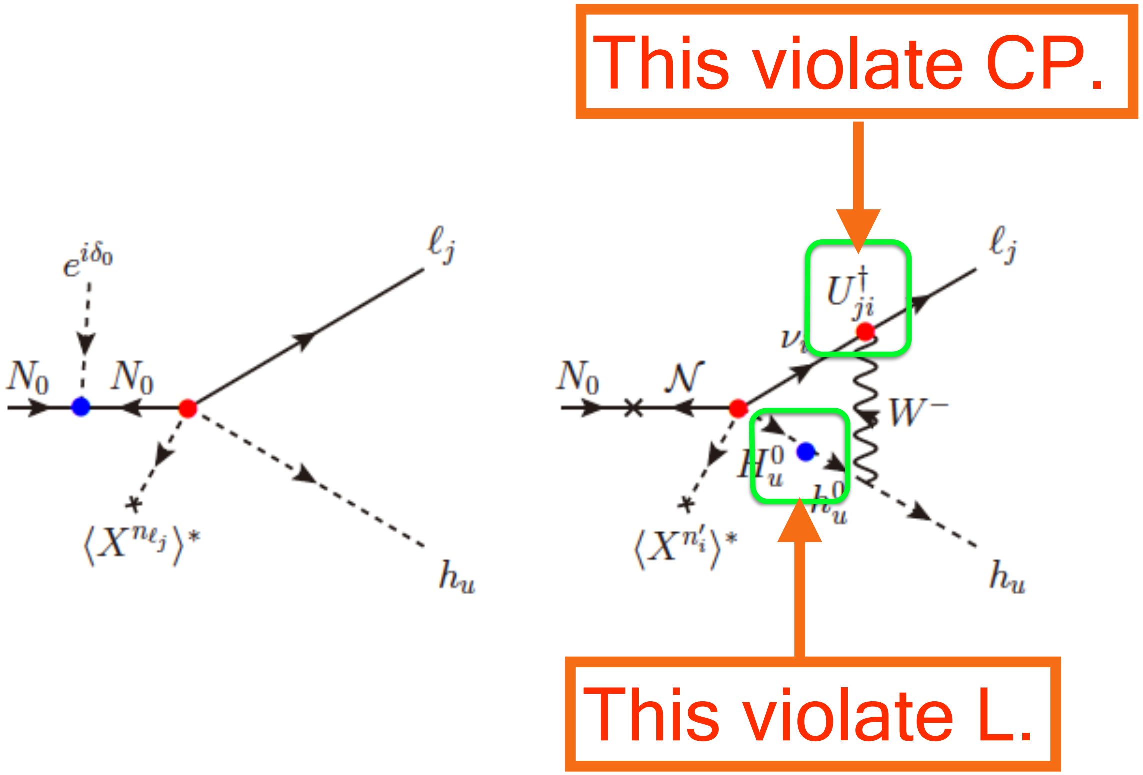
With only one N, phase can be zero. At least two heavy neutrinos are needed.



Type-II leptogenesis:



Different Higgs doublets needed.
Anyway, these are the fields at high energy scale.



One N and one {\cal N} can do it, but different Higgs doublets needed. Anyway, these are the fields at high energy scale.

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

Definition of lepton numbers:

L=+1 L=+1

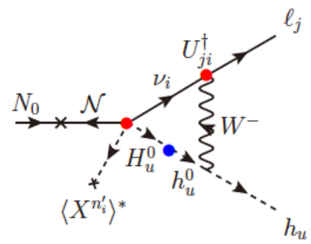
$$f N_1 h_u \ell_L , \qquad \tilde{f} \mathcal{N}_1 H_u \ell_L$$

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

These conserve L.

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

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]

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

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

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]:

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

5. Conclusion

1. CP violation: the source of atoms in the Universe: Baryogenesis. J is given in a simple form. Maybe sources of DM (axion) and quintessential axion also.
2. Need certain CP violation models with SU(2)xU(1) breaking at high temperature.
3. Type-II leptogenesis: $\text{delta}_{\text{PMNS}}$ is related to the leptogenesis phase.