CP VIOLATION AND LEPTOGENESIS

NNN15 and UD2

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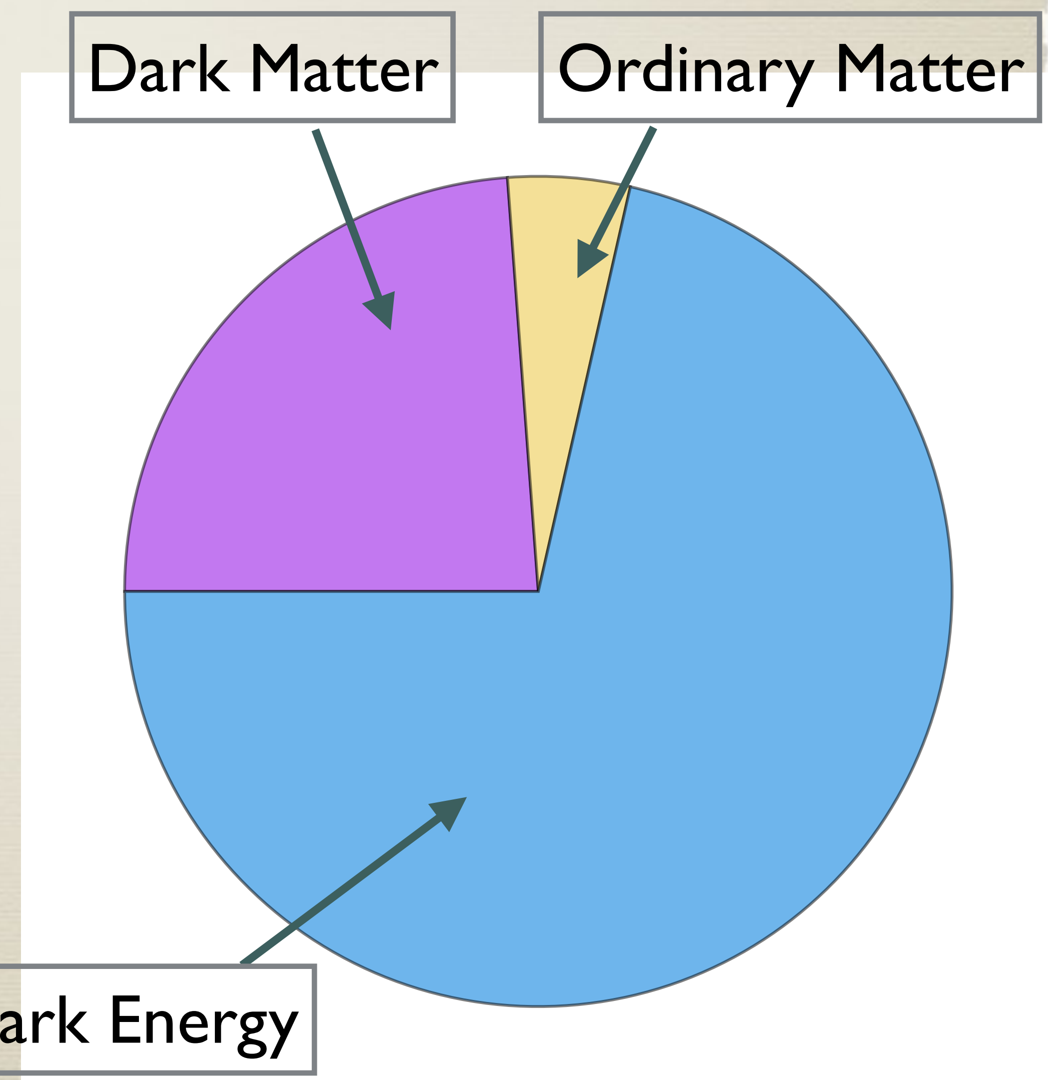
Outline

- What is the baryon asymmetry and why is it important?
- How do we measure it?
- Review Sakharov Conditions
- Leptogenesis
- Connecting leptonic CP Violation to the baryon asymmetry

Content of the Universe

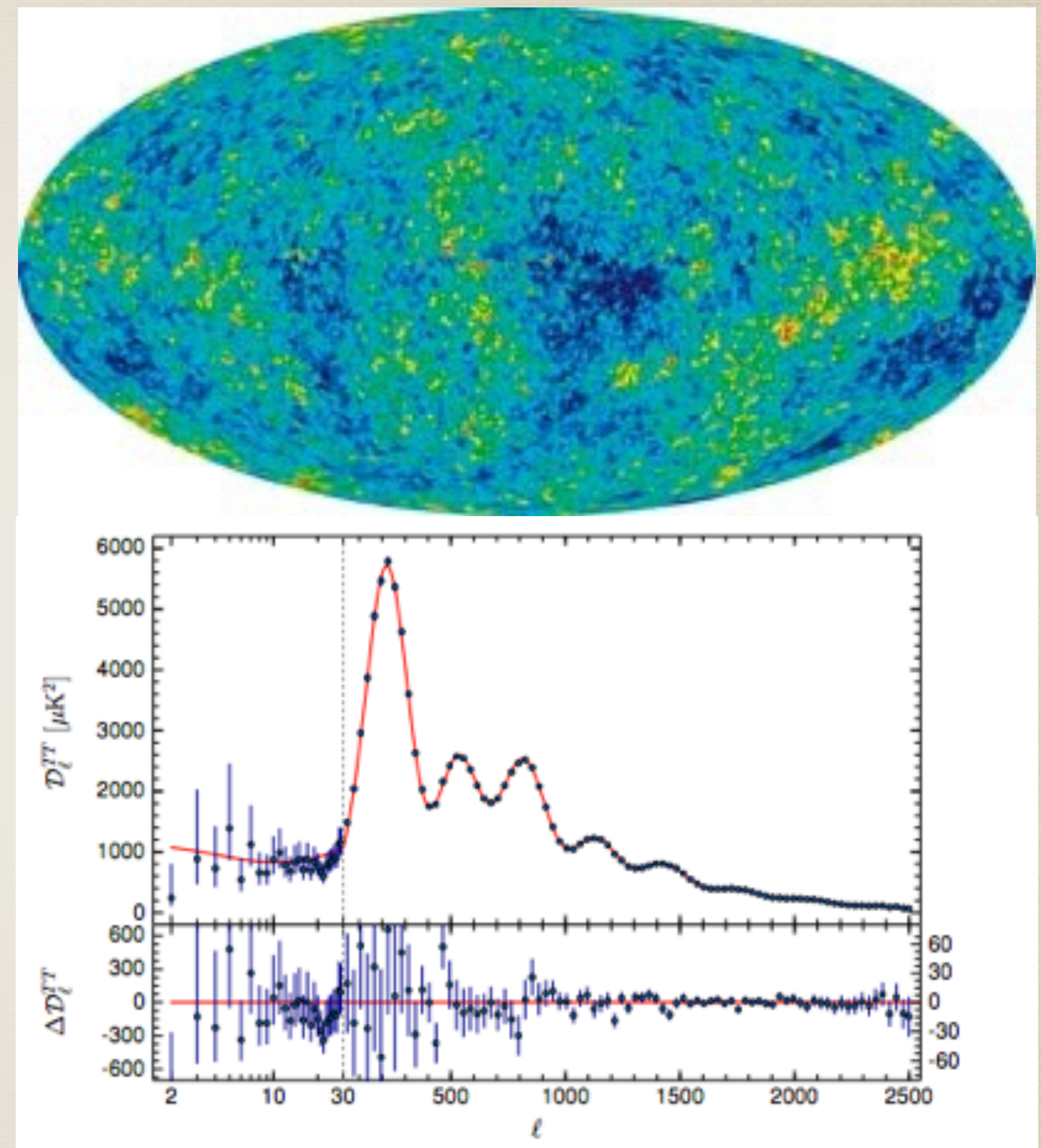
- Stars and Galaxies~0.5%, Neutrinos~0.1-1.5%.
- Mostly proton, neutrons and electron ~4.4%.
- Anti-Matter~0%
- Fortunately for us there exist a matter anti-matter asymmetry
- How was this asymmetry created?
- Initial Condition or dynamical process?



Measuring the Baryon Asymmetry

PLANCK Data

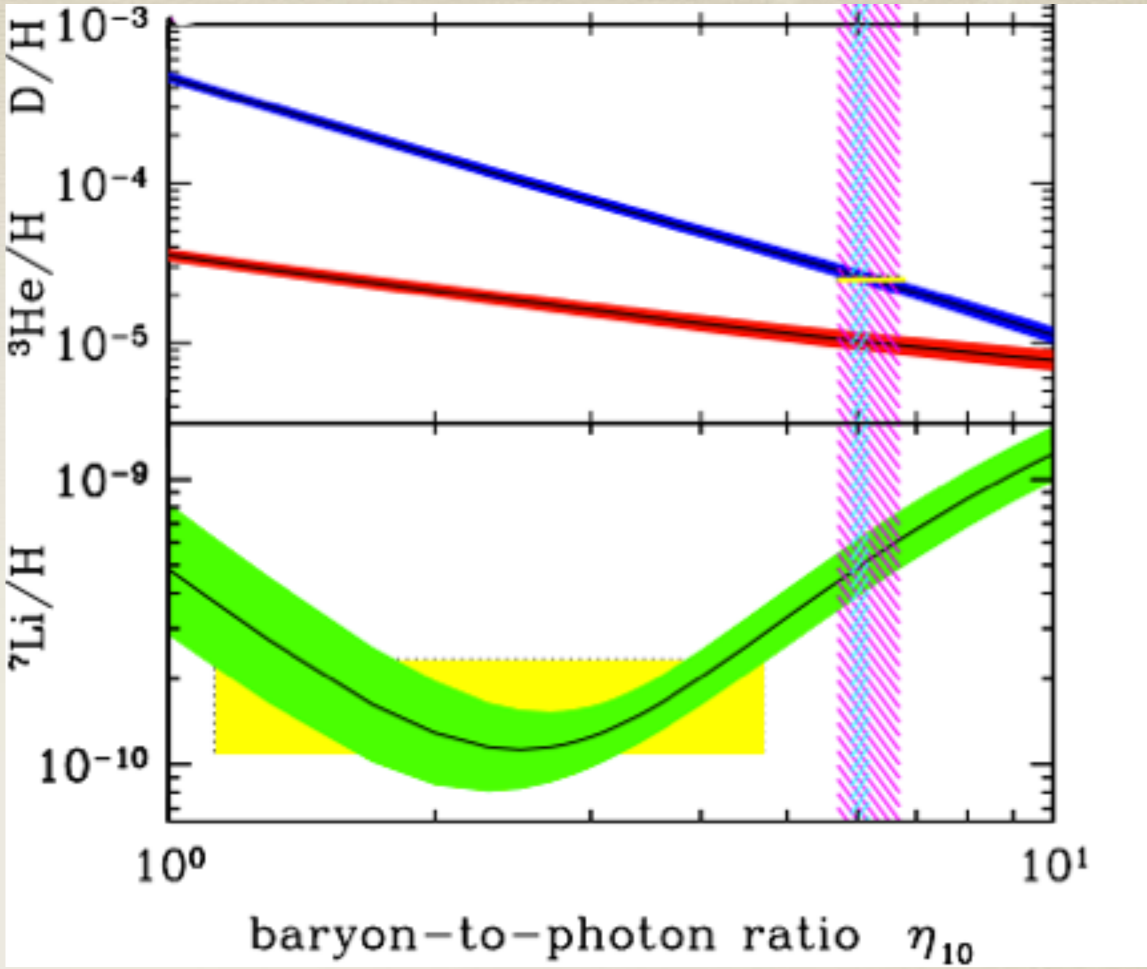
- Acoustic peaks in CMB anisotropy are due to oscillations in photon baryon fluid (T~0.25eV)
- Position and shape of peaks in the power spectrum affected by amount of baryons.



Planck 2015 (1502.01589)

$$\text{baryon/photon} \equiv \eta_{CMB} = (6.08 \pm 0.06) \times 10^{-10}$$

Big Bang Nucleosynthesis



BBN PDG, 2012

- BBN sensitive to era T< 1MeV (age>1 s). p and n fuse to form light elements.
- Light elemental abundance dependent on baryon to photon
- D and H abundance determined using high resolution of spectra from quasars.

$$\text{baryon/photon} \equiv \eta_{BBN} = (6.23 \pm 0.17) \times 10^{-10}$$

Remarkable agreement between η_{CMB} and η_{BBN}

Sakharov Conditions

In order to dynamically generate the baryon asymmetry in the early Universe, Sakharov's Conditions must be satisfied.

Sakharov, 1967

1. Baryon (and/or Lepton) Number Violation.

2. C and CP Violation.

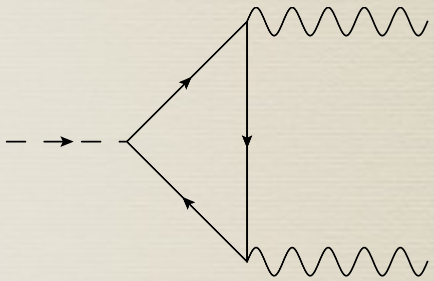
3. Out of equilibrium interactions.

Baryon Number Violation

- If B number is conserved, then baryon asymmetry would reflect highly tuned initial condition.

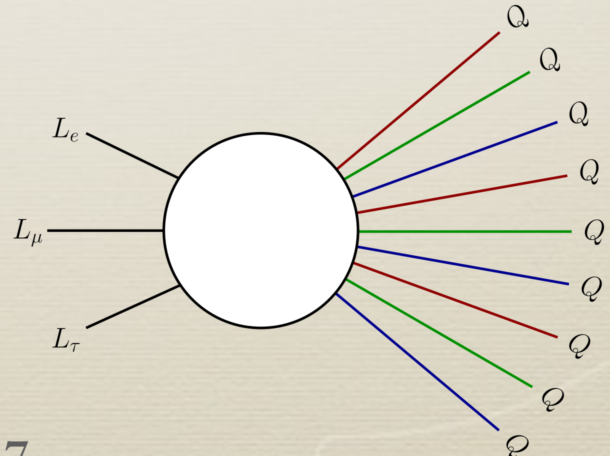
- B, L are accidental symmetries of the SM. Conserved at at tree level but violated at loop-level. t'Hooft, 1976

$$\partial_\nu J^\nu{}_B = \partial_\nu J^\nu{}_L = \frac{N_f}{32\pi^2}\left(g^2 \underbrace{W_{\nu\mu}{}^p \tilde{W}^{p\nu\mu}}_{SU(2)\text{field strengths}} - g'^2 \underbrace{B_{\nu\mu}B^{\nu\mu}}_{U(1)\text{field strength}} \right)$$



B+L violated and B-L conserved

- At high T, transition between different vacua can occur by jumping over barrier: B+L violation via sphaleron.



At T> TEW~ 100 GeV

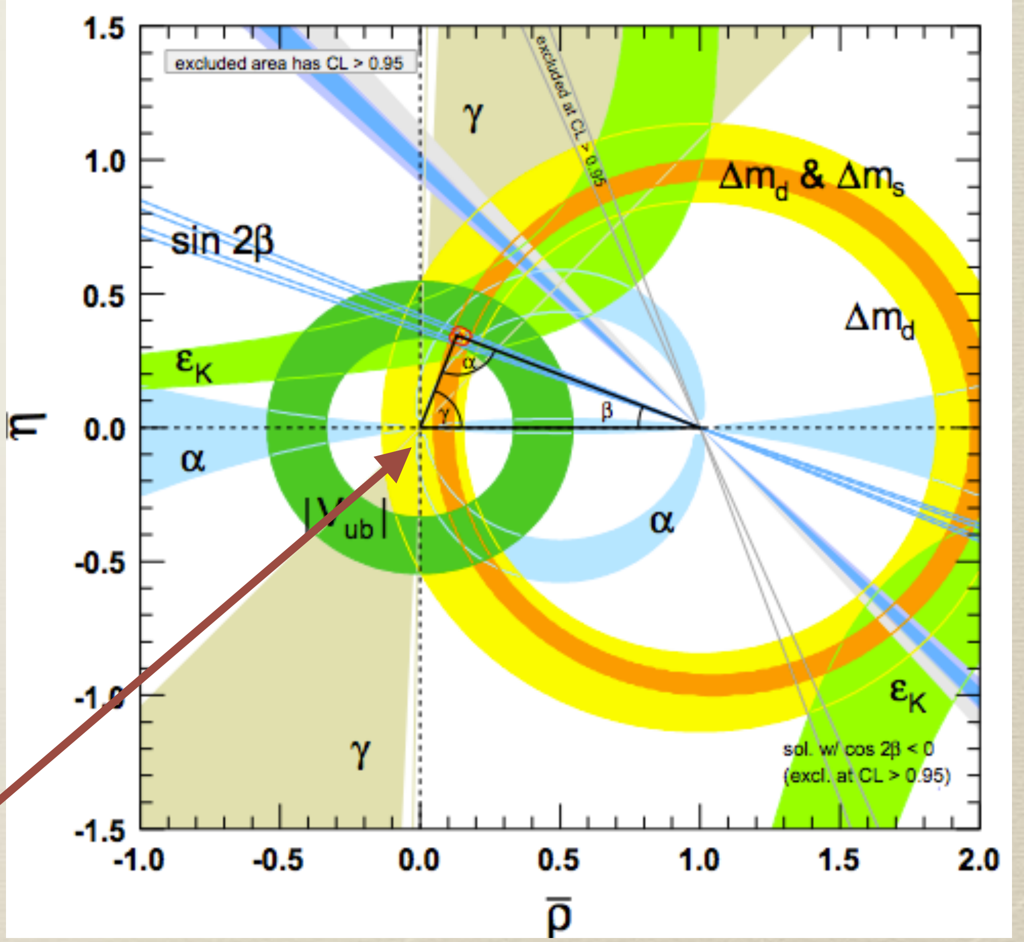
CP-Violation

- CPV necessary otherwise same rate for particle and anti-particle $\longrightarrow$ no excess.

- CP is violated in the quark sector and emerges in kaon and b-systems. There is 1 CPV phase.

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \propto \frac{J \times \Delta m_{tcu}{}^2 \times \Delta m_{dsb}{}^2}{T_{EW}^{12}} \sim 10^{-17}$$

7 orders of magnitude too small.



CKM PDG, 2012

- Need new sources of CPV. Gavela etal Nucl. Phys B430
  In this talk, we focus on leptonic CPV.

area of triangle= Jarlskog invariant/2

Out of Equilibrium

- In equilibrium: $\Gamma_{process} \equiv \Gamma_{inverse}$

- Even if B and CP violating processes occur their effect is cancelled by their inverse processes.

- Thanks to the expansion of the Universe, processes can come out of equilibrium when $\Gamma \sim H$

interaction rate

expansion rate

- In leptogenesis (with type I see-saw) heavy sterile neutrino decays out of equilibrium.

Leptogenesis

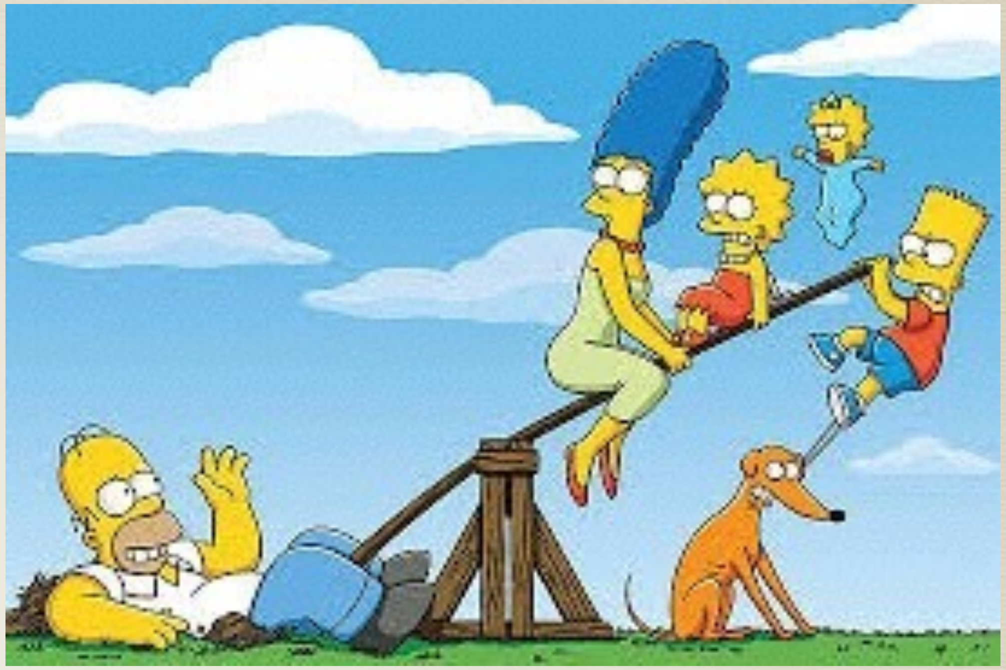
- Leptogenesis can take place in the context of a see-saw model. As the Universe expands, N decays out of equilibrium. N decays generate a lepton asymmetry which is converted to a baryon asymmetry via sphaleron processes.

Fukugita, Yanagida (PLB 174), see others Covi, Roulet, Vissani, Buchmuller, Plumacher

- L - violation
- C and CP-Violation.
- Out of equilibrium: Expansion of Universe.

See-Saw Mechanism

- Introduce a RH neutrino (SM singlet) and couple it to the Higgs.



$$\mathcal{L} = -Y_\nu \overline{N} L H - \frac{1}{2}\overline{N^C} M_N N$$

CPV from irremovable phases

Lepton Number is violated

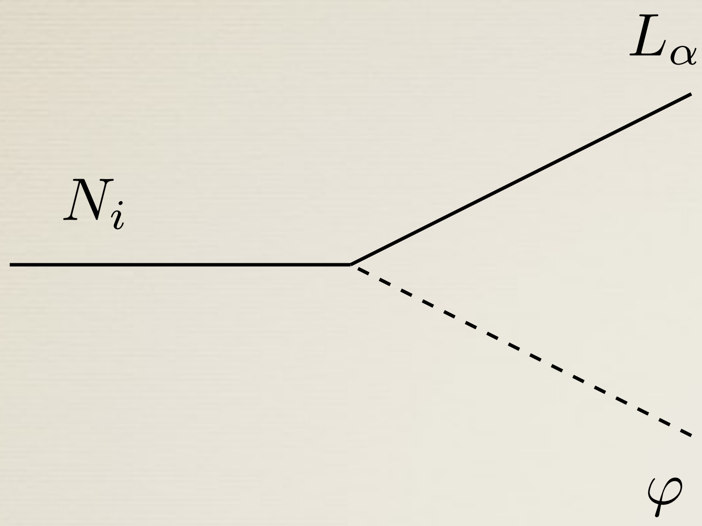
$Y_\nu v$

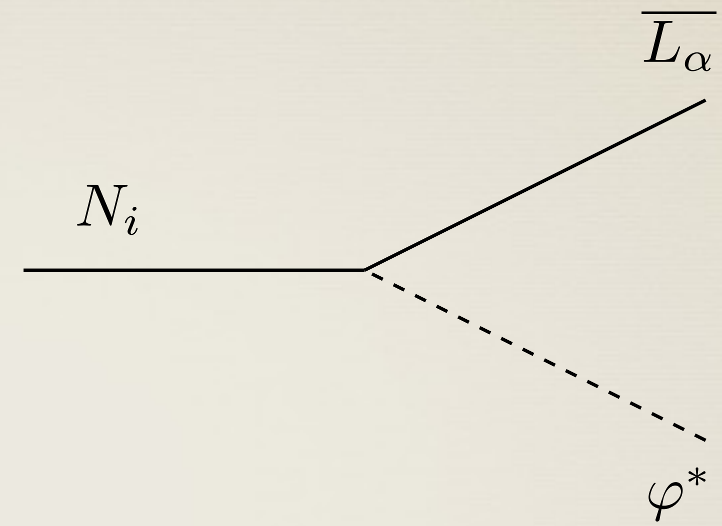
$$\begin{pmatrix} 0 & m_D \\ {m_D}^T & M_N \end{pmatrix} \longrightarrow m_\nu = \frac{{Y_\nu}^2 {v_H}^2}{M_N} \sim \frac{1\mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\mathrm{eV}$$

Minkowski, 1979, Gell-Mann etal 1979, Yanagida, 1979, Mohapatra, Senjanovic 1980

Basic Mechanism

- Heavy, singlet Majorana neutrinos decay out of equilibrium

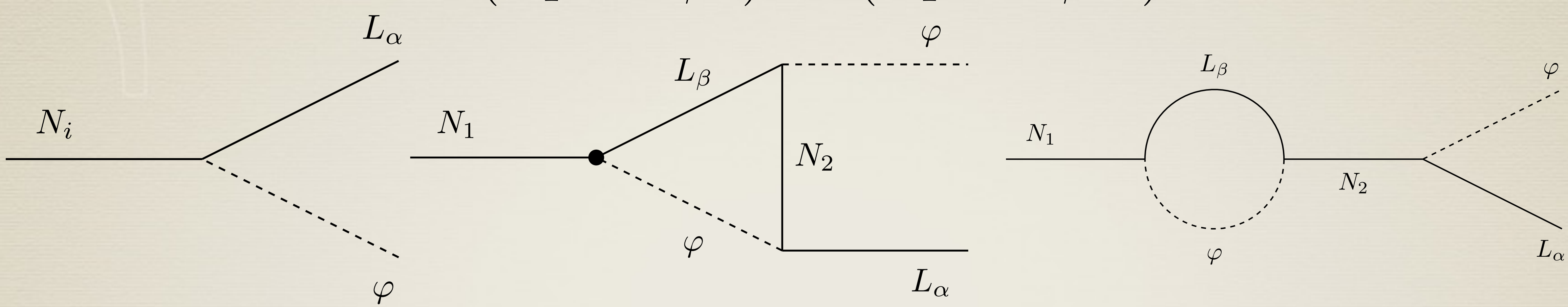




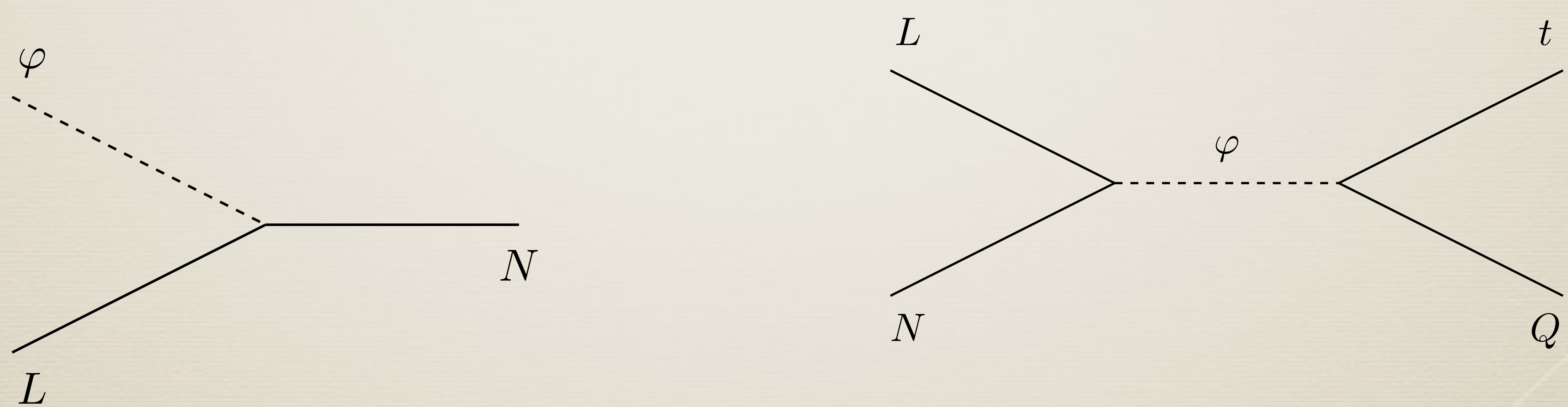
- Occurs at $T \sim M_{N_1}$
- Inverse decay rates faster (slower) than expansion of Universe H, strong (weak) washout.

- Decay asymmetry (ϵ) arises from interference between tree and loop diagrams.

$$\epsilon = \frac{\Gamma(N_1 \longrightarrow \phi L) - \Gamma(N_1 \longrightarrow \phi^\dagger \overline{L})}{\Gamma(N_1 \longrightarrow \phi L) + \Gamma(N_1 \longrightarrow \phi^\dagger \overline{L})}$$



- Washout (k) can occurs due to diagrams such as



$$Y_B = \text{const} \times C_{SP} \times k \times \varepsilon$$

sphaleron conversion factor

washout

decay asymmetry

CPV and Leptogenesis

- Assume Type-1 see-saw with 3 hierarchical N

$RR^T=1$

$$\epsilon_l = \frac{\sum_l [\Gamma(N_1 \longrightarrow HL_l) - \Gamma(N_1 \longrightarrow \overline{HL_l})]}{\sum_l [\Gamma(N_1 \longrightarrow HL_l) + \Gamma(N_1 \longrightarrow \overline{HL_l})]}$$

$$Y = \frac{1}{v_H}\sqrt{M}R\sqrt{m}U^\dagger$$

high energy untestable parameters

low energy parameters

$$\epsilon_l = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{l\beta\rho} m_\beta{}^{\frac{1}{2}} m_\rho{}^{\frac{3}{2}} U_{l\beta}{}^* U_{l\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

1 flavour (T>10¹² GeV)

$$\epsilon_1 = \frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}(\sum_\rho m_\rho{}^2 R_{1\rho}{}^2)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

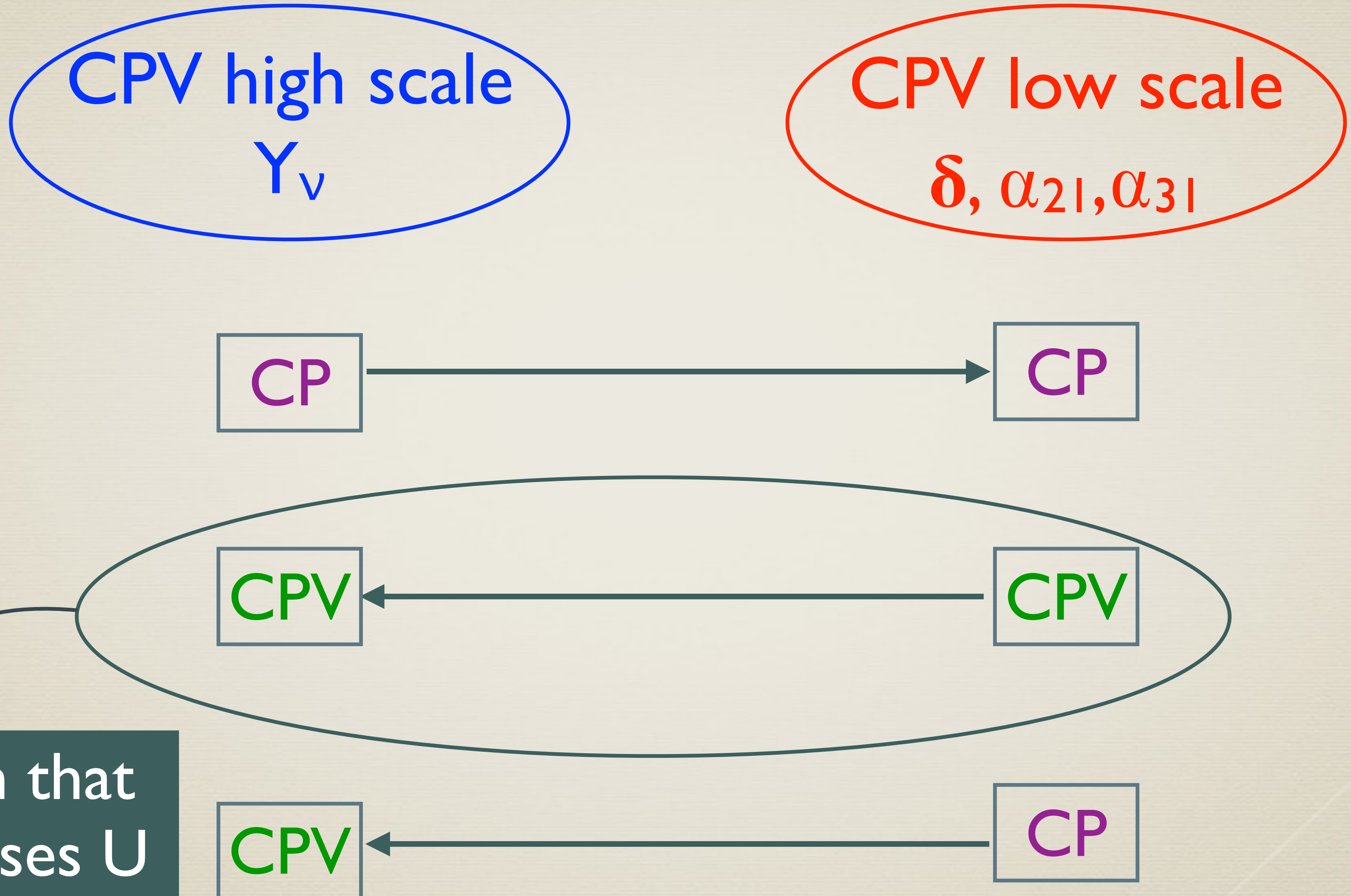
Independent of U_{PMNS}

2 flavour (10^{10}<T<10^{12} GeV)

ϵ_τ ϵ_2

$U_{l\beta}{}^* U_{l\rho} R_{1\beta} R_{1\rho}$

Flavour effects allow a link between low energy leptonic observables and leptogenesis.



Establish that CPV phases U could be responsible for leptogenesis

Pascoli, Petcov, Riotto, PRD and NPB 2007.

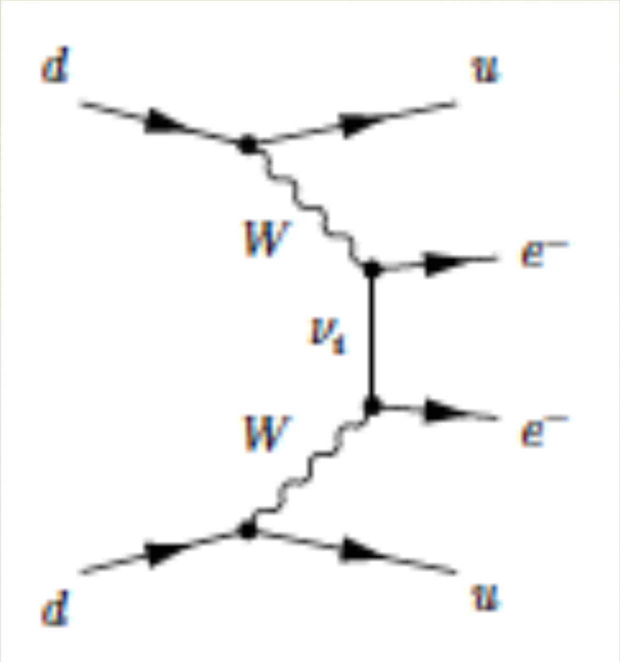
Can we test the ingredients that could establish a link between leptonic observables (low scale) and the baryon asymmetry (high scale)?

Yes we can!
Are neutrinos Majorana?
Is there CPV in the lepton sector?

Lepton Number Violation

- Implementation of see-saw mechanism, the light neutrinos generated are Majorana
- $\beta 0\nu\nu$ can determine the nature of the neutrino via rare decay:

$$(A, Z) \longrightarrow (A, Z+2) + 2e^{-} (\Delta L = 2)$$



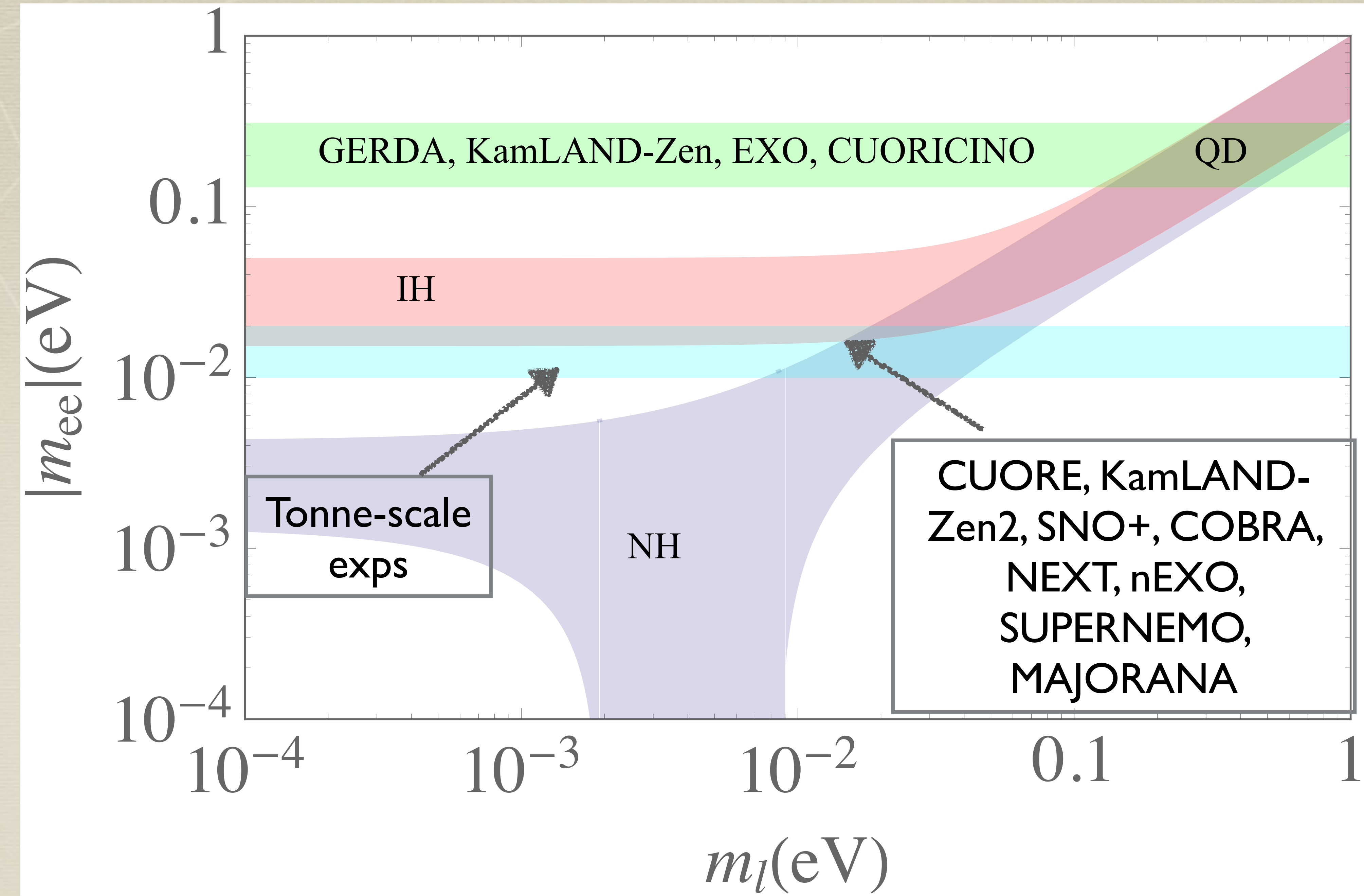
- The half life of rare decay is proportional to effective Majorana mass:

$$|m_{ee}| = |m_1 \cos^2\theta_{12} \cos^2\theta_{13} + m_2 \sin^2\theta_{12} \cos^2\theta_{13} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i(\alpha_{31} - 2\delta)}|$$

partly known

known

unknown

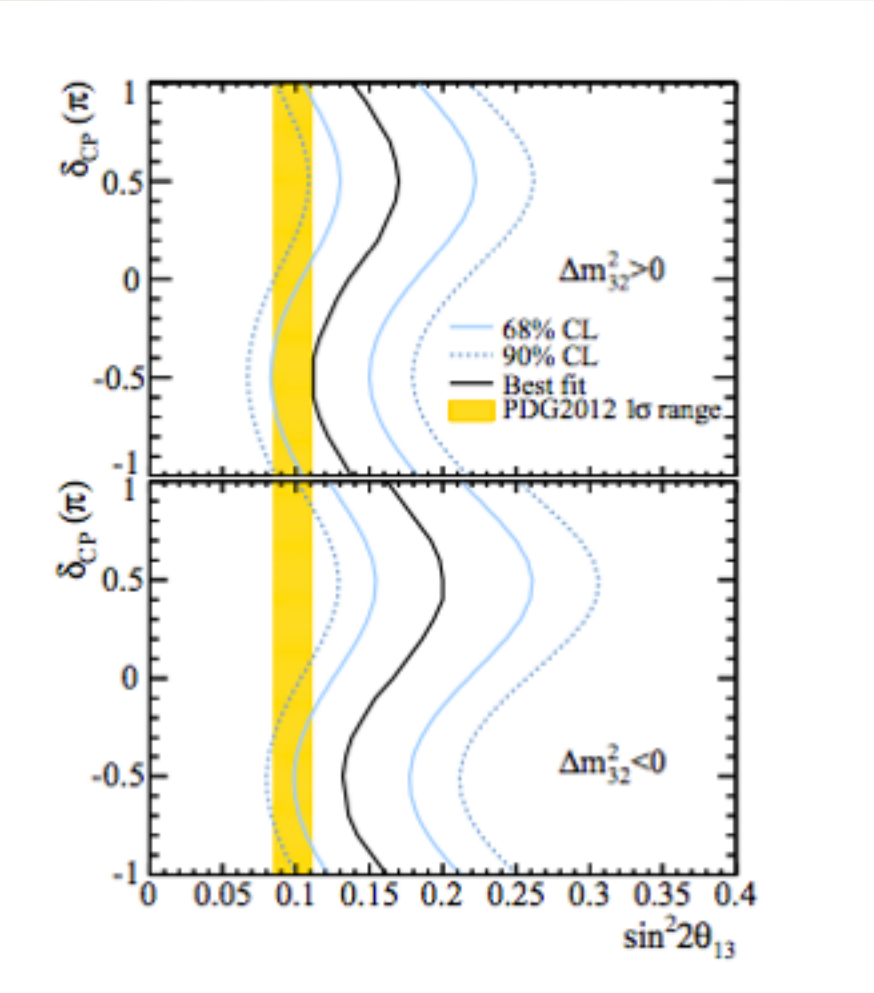


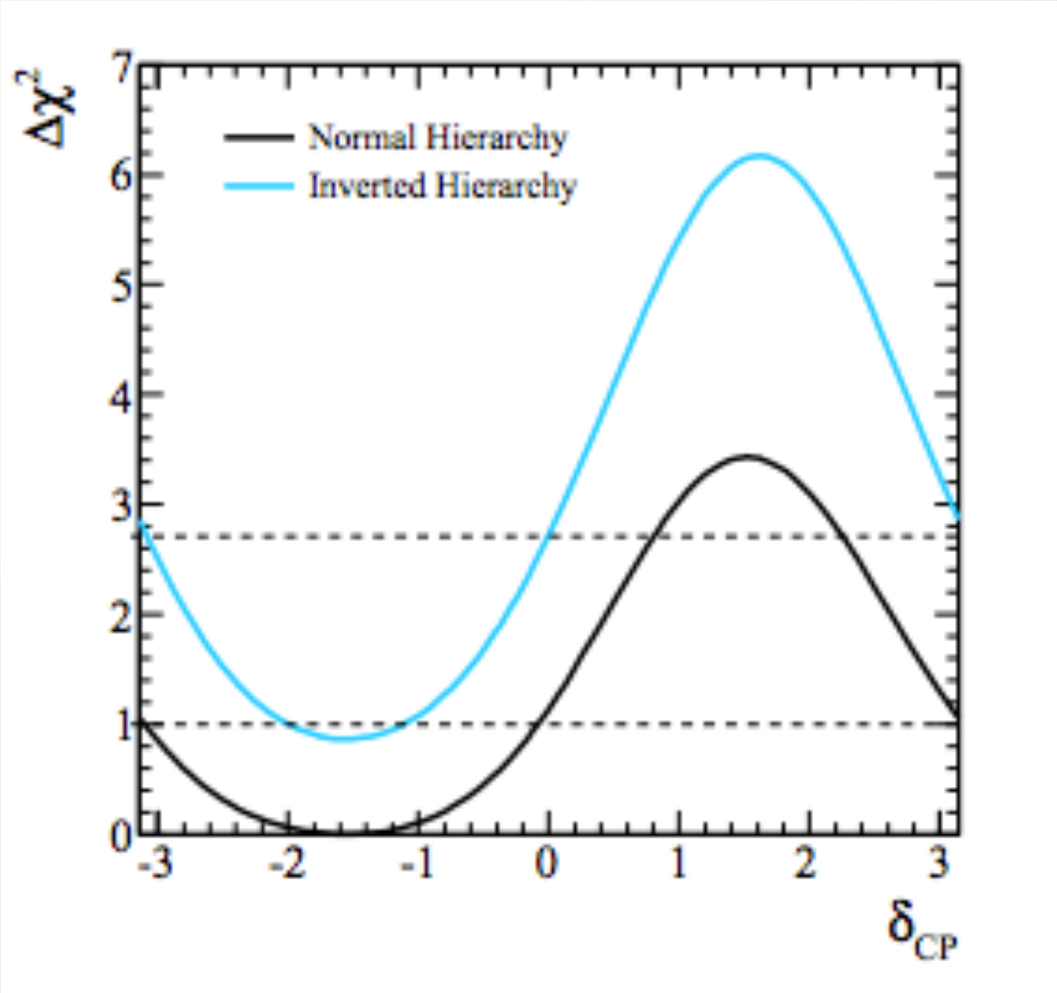
- Wide range of future experiments: positive signal would mean L-violation.

- $\beta 0\nu\nu$ can probe neutrino mass ordering, absolute mass scale and CPV phases (in principle).

CPV in the lepton sector

- Is CPV in δ sufficient to produce the baryon asymmetry?
- T2K and reactor data have shown a slight preference for maximal CPV.





PRL 112, 061802 (2014)

PRD 91.7 (2015) 072010

Consider type-I see saw with 3 hierarchical N

High energy		
M_N	3	0
Y_ν	9	6

→ 3 phases missing →

Low energy		
m_i	3	0
U	3	3

$$\epsilon_l = -\frac{3M_1}{16\pi v^2}\frac{\sum_{l\beta\rho} m_\beta^{\frac{1}{2}} m_\rho^{\frac{3}{2}} U_{l\beta}{}^* U_{l\rho} R_{1\beta} R_{1\rho}}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

R → leptogenesis

α_{21}, α_{31} → leptogenesis

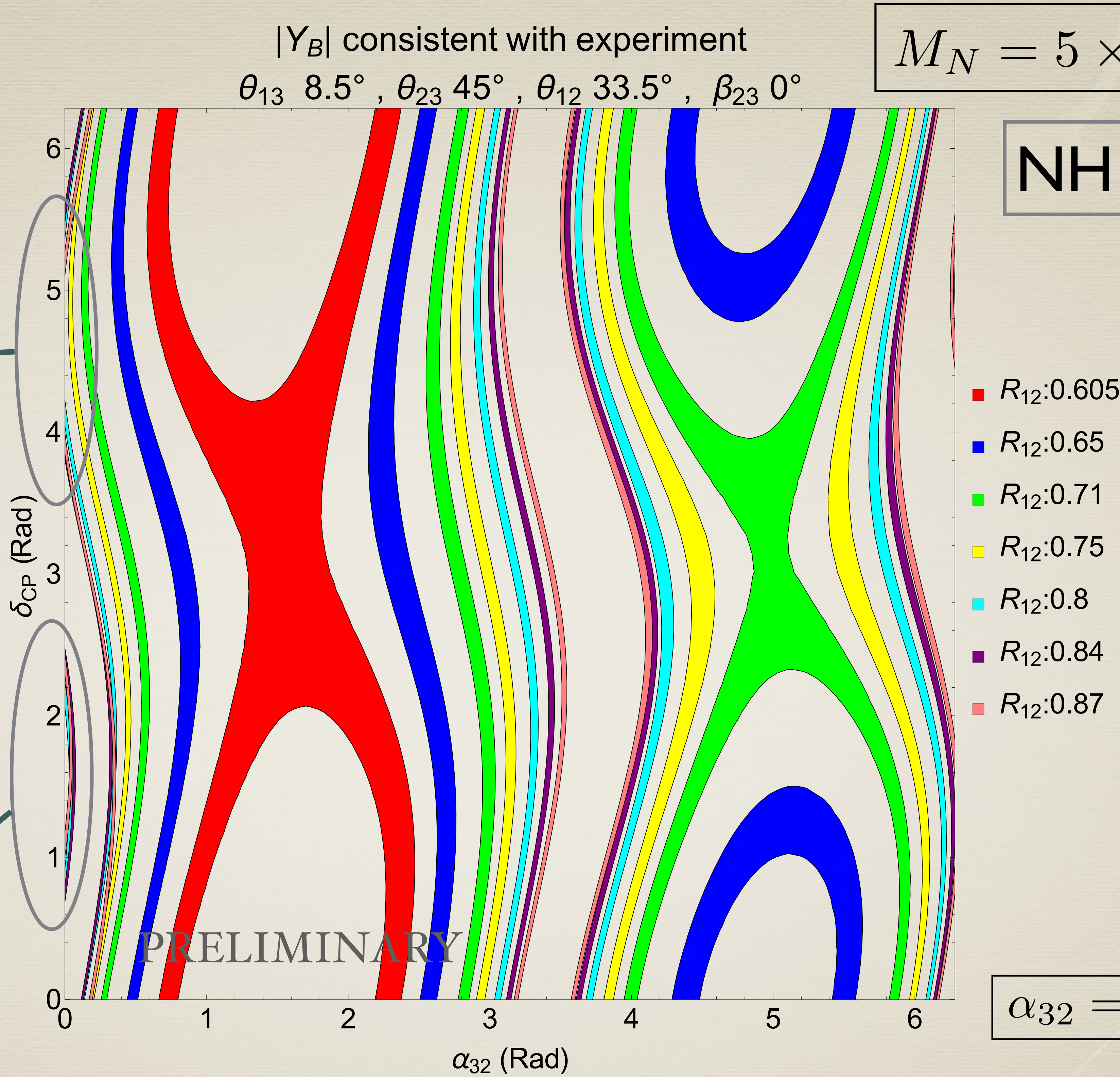
δ → leptogenesis

Isolate contribution of low energy phases → R is real or purely imaginary

In collaboration with Mark Ross-Lonergan, Silvia Pascoli and Serguey Petcov

$M_N = 5 \times 10^{11}\,\mathrm{GeV}$

NH spectra



δ alone can produce baryon asymmetry

$\alpha_{32} = \alpha_{31} - \alpha_{21}$

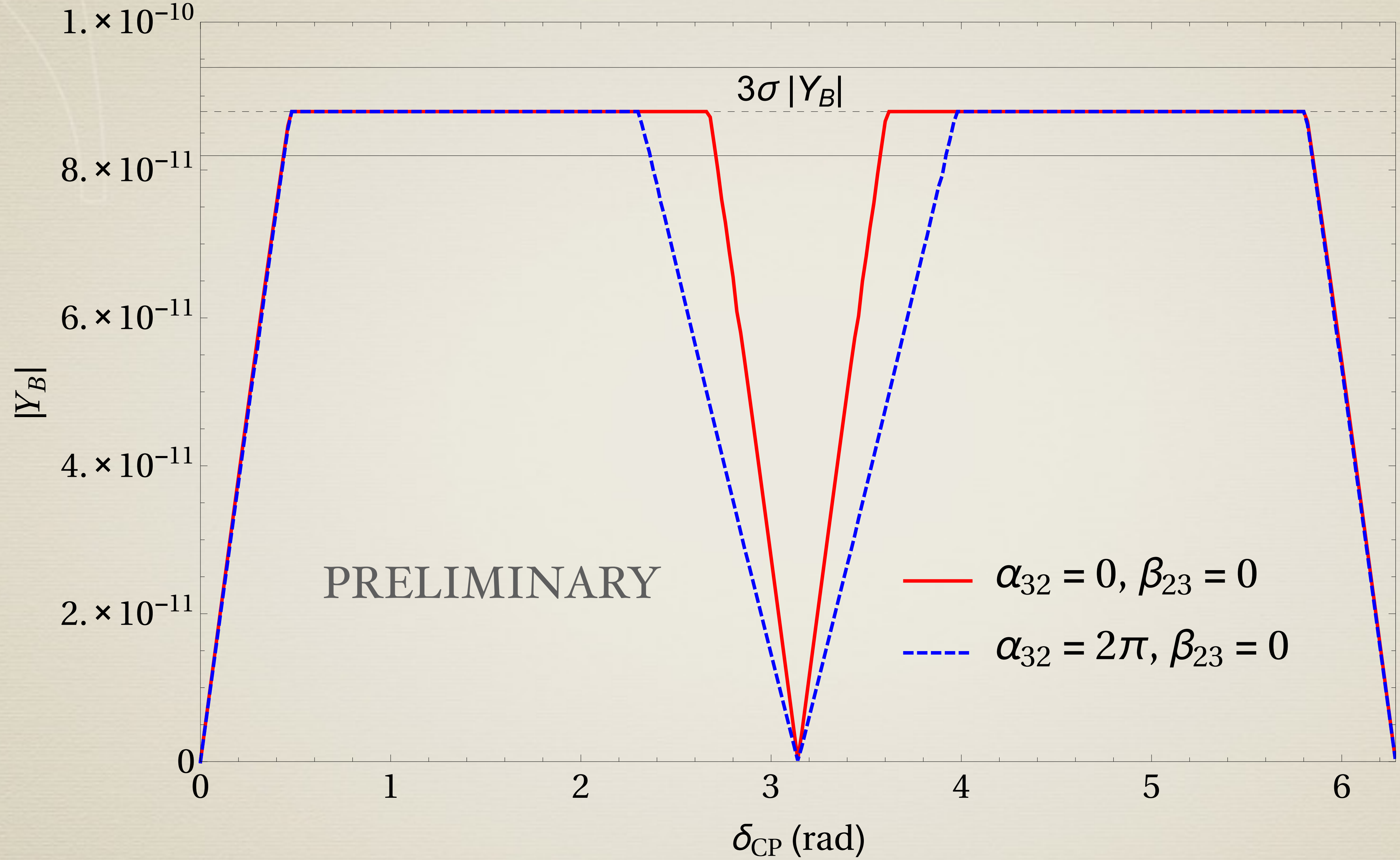
α_{32} is dominant but contribution from δ can produce baryon asymmetry

$\alpha_{32} = \alpha_{31} - \alpha_{21}$

$M_N = 5 \times 10^{11} \mathrm{GeV}$

NH spectra

all other parameters have been marginalised

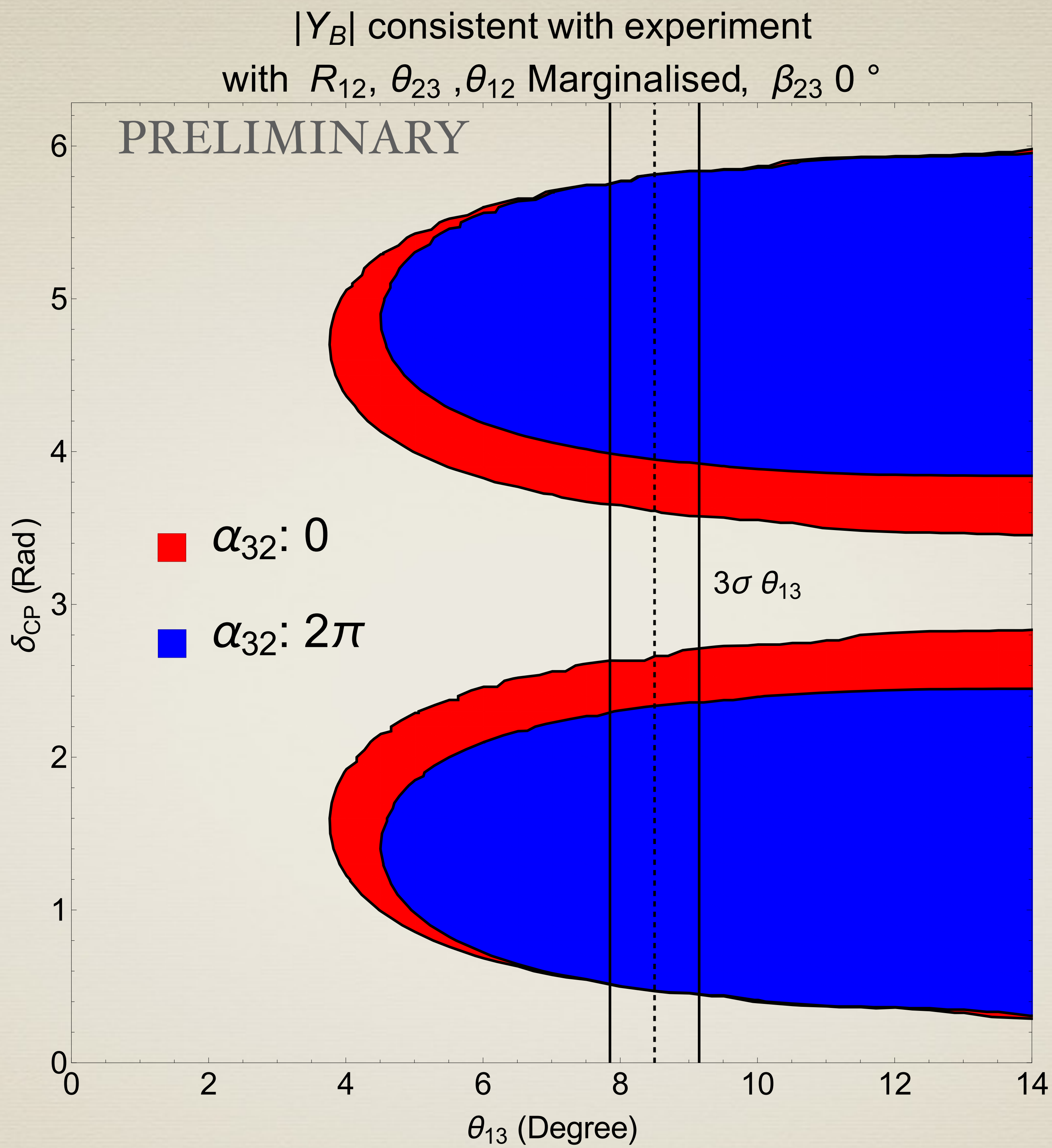


δ can produce baryon asymmetry

$M_N = 5 \times 10^{11}\,\mathrm{GeV}$

$\alpha_{32} = \alpha_{31} - \alpha_{21}$

NH spectra



Need non-zero value of θ_{13} to produce baryon asymmetry

Conclusions

- CP violation and L violation are key ingredients for leptogenesis to occur.

- Interesting hints of maximal CPV from LBL experiments. Future LBL can make precision measurements of δ.

- $\beta 0\nu\nu$ could indicate L-violation and Majorana CPV. Indication of link between lepton sector and leptogenesis.

In the context of see-saw type I and flavour effects, the CPV phase could generate the baryon asymmetry