Spontaneous origin of CP phase in the neutrino sector

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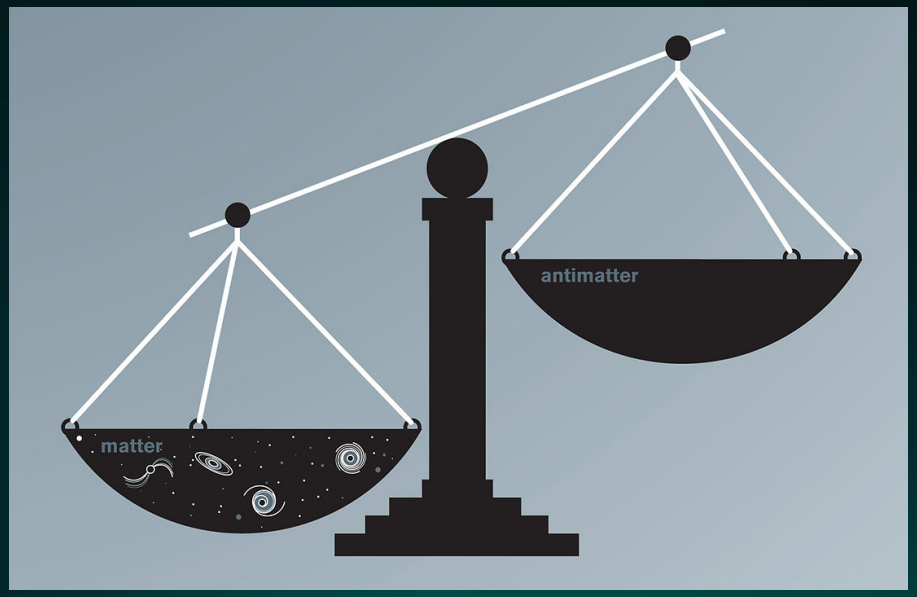
CP violation



- CP violation is necessary to explain Baryogenesis
- CP violation in CKM matrix is not enough
- Origin of CP violation still remains unknown
- Explicit and/or Spontaneous and/or Geometric

Spontaneous CP violation

Originally proposed by T. D. Lee with two scalar doublets.

$$\left.\begin{aligned} \Phi &\to \Phi' = U\Phi \\ \mathcal{L} &\to \mathcal{L}'(\Phi') = \mathcal{L}(\Phi) \end{aligned}\right\} \quad \text{But} \quad \left\{\begin{aligned} &|0\rangle \to \text{CP}\,|0\rangle \neq |0\rangle \\ &\text{CP non-invariant vacuum} \end{aligned}\right.$$

Goal : Build a minimal model that incorporates the spontaneous origin of CP phase in the neutrino sector.

- Minimal in terms of field content and free parameters
- With all real couplings
- A single phase is generated in the EW sector
- Gets propagated in the lepton sector
- Generates a δ_{CP} in the PMNS matrix

Neutrino mass matrix (schematically)

$$M_\nu = A + B + \cdots$$

Complex vev of triplet : $A = \langle\Delta\rangle \in \mathcal{C}$
$B =$ Type I $\in \mathcal{R}$ ✓
$B =$ Type II $\langle\Delta\rangle \in \mathcal{R}$
$B =$ Type III $\in \mathcal{R}$
$B =$ Scotogenic $\in \mathcal{R}$

Complex mass matrix $M_{N_R/\Sigma/f} \in \mathcal{C}$
$A =$ Type I $M_{N_1} \in \mathcal{R}$ and $B =$ Type I $M_{N_2} \in \mathcal{C}$
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321 model

Extend the SM by one triplet Δ, one singlet σ and one N_R

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- σ obtains a complex vev with phase θ_σ

  $\rightarrow$ propagation of θ_σ into a complex triplet vev with phase θ_Δ

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- σ couples with N_R

  $\rightarrow$ give rise to complex mass matrix M_R with phase θ_R

  $\rightarrow$ $\theta_\Delta \neq -\theta_R$ has to be satisfied

Effective phase $(\theta_\Delta + \theta_R)$ in the M_ν generate the CP violating phase in the PMNS matrix.

Scalar potential

$$V(\sigma, H, \Delta) = V_{\rm SM} + V_\sigma + V_{\not\phi} + V_{\sigma H} + V_{\sigma\Delta} + V_{\sigma H\Delta} + V_\Delta + V_{H\Delta} + V_\mu$$

$$\begin{aligned}
V_\sigma &= \underbrace{-m_\sigma^2(\sigma^*\sigma) + \lambda_\sigma(\sigma^*\sigma)^2}_{\sigma \text{ accquires a vev } v_\sigma} \\
V_{\not\phi} &= \underbrace{\boldsymbol{m_\sigma'^2(\sigma^2+\sigma^{*2}) + \lambda_{\sigma 3}(\sigma^3+\sigma^{*3}) + \lambda'_{\sigma 3}(\sigma^*\sigma)(\sigma+\sigma^*) + \lambda_{\sigma 4}(\sigma^4+\sigma^{*4}) + \lambda'_{\sigma 4}(\sigma^*\sigma)(\sigma^2+\sigma^{*2})}}_{\text{generates complex phase } \theta_\sigma \, of \, \sigma \text{ vev}} \\
V_{\sigma H} &= \left[\lambda_{\sigma H}\,(\sigma^*\sigma) + \lambda'_{\sigma H}\,(\sigma^2+\sigma^{*2}) + \lambda'_{\sigma H1}\,(\sigma+\sigma^*)\right](H^\dagger H) \\
V_{\sigma\Delta} &= \left[\lambda_{\sigma\Delta}\,(\sigma^*\sigma) + \lambda'_{\sigma\Delta}\,(\sigma^2+\sigma^{*2}) + \lambda'_{\sigma\Delta 1}\,(\sigma+\sigma^*)\right]\mathrm{Tr}(\Delta^\dagger\Delta) \\
V_{\sigma H\Delta} &= \underbrace{\boldsymbol{(\lambda_{\sigma H\Delta}\sigma + \lambda'_{\sigma H\Delta}\sigma^*)H^{\mathsf{T}} i\sigma_2 \Delta^\dagger H} + \text{ h.c.}}_{\text{propagation of } \theta_\sigma \text{ to } \theta_\Delta} \\
V_\mu &= \underbrace{\boldsymbol{\mu\, H^{\mathsf{T}} i\tau_2 \Delta^\dagger H} + \text{ h.c.}}_{\Delta \text{ acquires a vev } v_\Delta}
\end{aligned}$$

Yukawa sector and ν-mass matrix

$$-\mathcal{L}_Y = \frac{1}{2} Y_\Delta L^\top \mathcal{C} i\tau_2 \Delta L + Y_\nu \overline{L}\tilde{H} N_R + \left(\boldsymbol{y_R \sigma + \widetilde{y_R} \sigma^*}\right) \boldsymbol{\overline{N_R}\, N_R{}^c}$$
$$+ Y_l \overline{L} H e_R + + \frac{1}{2} M_R^0 \overline{N_R}\, N_R^c + \text{h.c.}$$

$$\boxed{M_\nu = Y_\Delta \frac{v_\Delta}{\sqrt{2}} e^{i(\theta_\Delta + \theta_R)} - \frac{v_H^2}{2|M_R|} Y_\nu Y_\nu^\top}$$

Yukawa sector and ν-mass matrix

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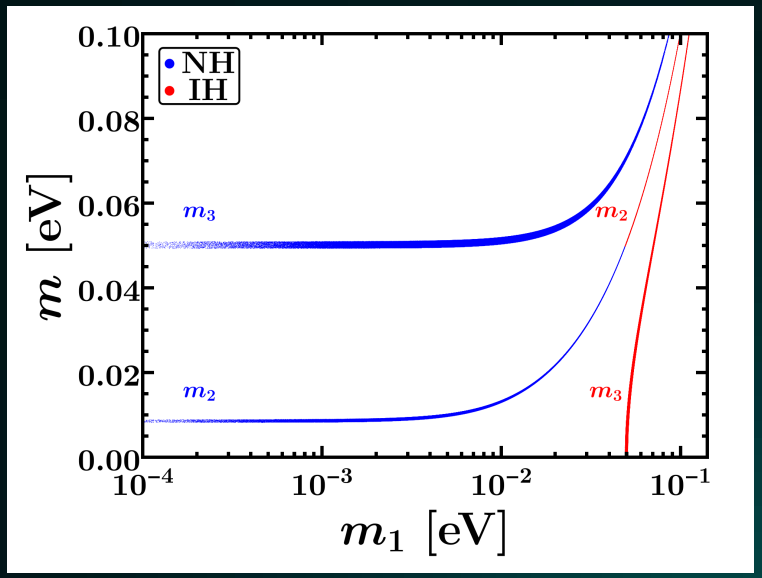
Imposition of discrete symmetries

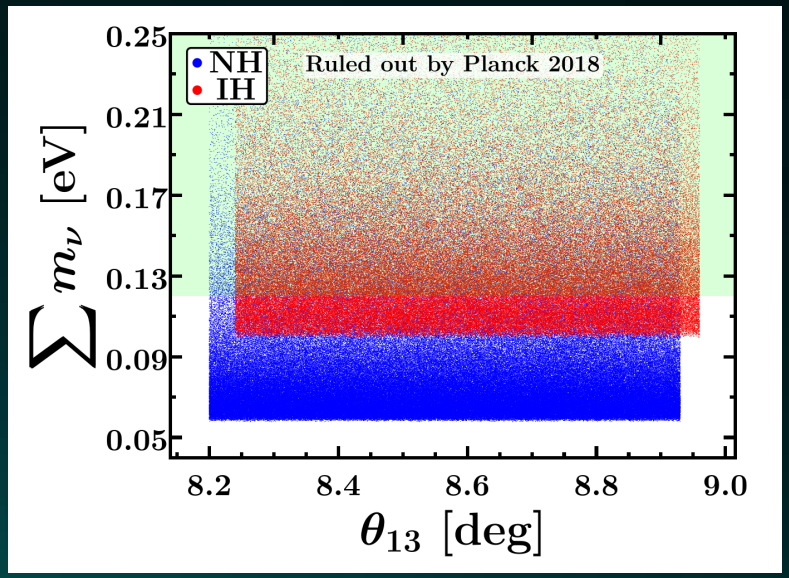
	Charges of the fields			Allowed couplings		
	σ	Δ	N_R, L, e_R	V_ϕ	$V_{\sigma H \Delta}$	Yukawa
✓ $Z_3 : \omega^3 = 1$	ω	ω	ω	$\lambda_{\sigma 3}$	$\lambda_{\sigma H \Delta}$	$Y_\Delta, \widetilde{y_R}, Y_\nu, Y_l$
$Z_8 : \omega^8 = 1$	ω^2	ω^2	ω^3	$\lambda_{\sigma 4}$	$\lambda_{\sigma H \Delta}$	$Y_\Delta, \widetilde{y_R}, Y_\nu, Y_l$

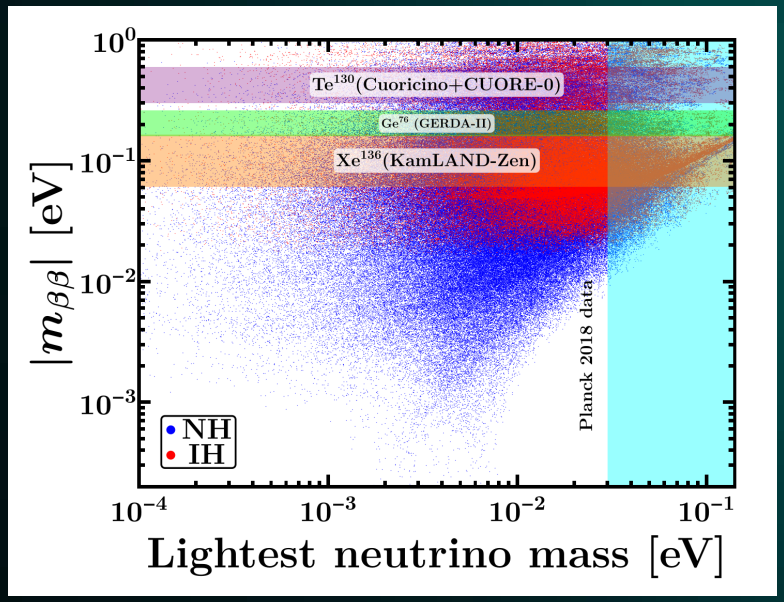
With Z_3 symmetry unbroken : $\theta_\Delta = -\theta_R = \frac{\pi}{6}$

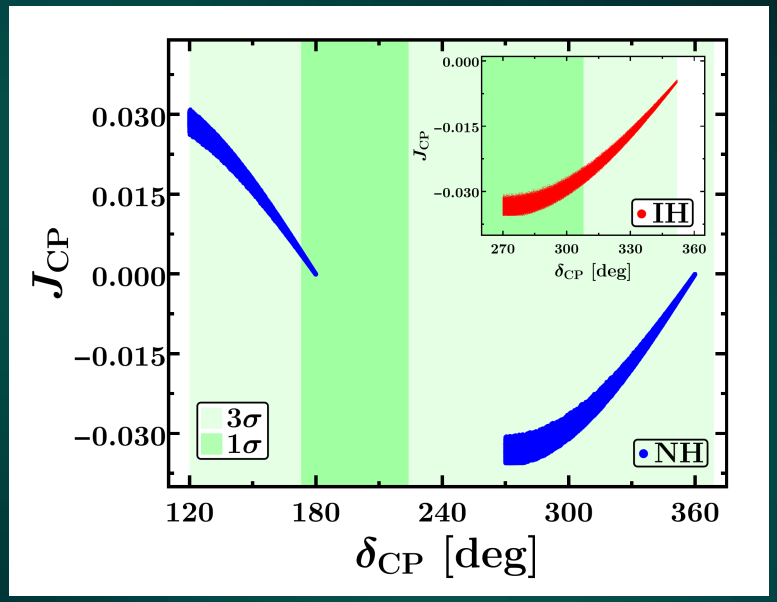
With $V_\mu = \mu H^\top i\tau_2 \Delta^\dagger H +$ h.c. $\leftarrow$ a soft breaking term

Neutrino oscillation data numerical scan and results









Takeaways ...

- A minimal model in terms of field content which can account for a CP violating phase $\delta_{\rm CP}$ in the neutrino sector.
- The origin of $\delta_{\rm CP}$ lies in the spontaneous breaking of CP symmetry in the EW sector and successfully propagated to the neutrino sector.
- Imposition of certain (softly broken) discrete symmetries can result in more minimalistic scenarios.
- Leaves enough room to accommodate DM with next-to-minimal field content and imposing a remnant symmetry after spontaneous breaking.
- Textures of neutrino mass matrix can also be interesting to investigate in this underlying framework.

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Thank You !