The Dark Side of θ_{13}, δ_{cp} ,Leptogenesis and Inflation in Type-I Seesaw

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Motivations

- Dark Matter (DM) and massive neutrinos can not be explained in the Standard Model (SM)
- The simplest extension to give a mass to neutrinos is the type-I seesaw mechanism (Minkowiski, Gell-Mann, Ramond, Slansky, Freedman, Niuenhuizen…)
- If θ_{13}=0, the neutrino mixing matrix (U_{PMNS}) can be well approximated by the Tri-Bimaximal Mixing (TBM) pattern Harrison et al (hep-ph/0210197, hep-ph/0302025, hep-ph/0403278…)

Motivations

- In Type-I seesaw, leptogenesis does *not* work if there exists a (residual) flavor symmetry, leading to zero θ_{13} Jenkins et al (0807.4176), Aristizabal Sierra et al (0908.0907), Bertuzzo et al (0908.0161), Hagedorn et al (0908.0240)

$$\epsilon_1 \simeq -\frac{3}{8\pi}\frac{M_1}{\langle H_u^0\rangle^2}\frac{\sum_j m_j^2\,\mathrm{Im}(R_{1j}^2)}{\sum_j m_j |R_{1j}|^2}$$

hep-ph/0202239

- Nonzero θ_{13} and leptogenesis can come from DM radiative corrections in the context of some underlying flavor symmetry, resulting in TBM

- The DM stability can simply come from a Z_2 symmetry

- We keep a spirit of minimality, i.e., fewest free parameters from the DM sector

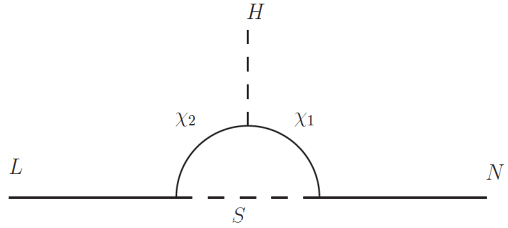
The Model and relevant observables

- A gauge-singlet fermion χ_1, a fermionic $SU(2)_L$ doublet χ_2 and a real gauge-singlet scalar S
- These particles are odd under the Z_2 symmetry
- The values of the observables are taken from PDG (Phys.Rev. D86, 010001 (2012)), T2K (1308.0465) and Planck results (1303.5076).

Field	L	H	N_1	N_2	N_3	χ_1	χ_2	$\tilde{\chi}_2$	S
$SU(2)_L$	2	2	1	1	1	1	2	2	1
$U(1)_Y$	-1/2	1/2	0	0	0	0	1/2	-1/2	0
Z_2	+	+	+	+	+	−	−	−	−

The particle content and corresponding quantum numbers in the model.

$$\mathcal{L} \supset y_{\alpha i} \left(L_\alpha \cdot H\right) N_i - \frac{M_i}{2} N_i N_i + \lambda_\alpha \left(L_\alpha \cdot \chi_2\right) S + \lambda_{H\chi} \left(\chi_2 \cdot \tilde{H}\right) \chi_1 + \lambda_{N_i} \chi_1 N_i S + h.c.$$



	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{23}$	$\sin^2 2\theta_{13}$	Δm^2_{sol} (eV^2)	$\lvert\Delta m^2_{atm}\rvert$ (eV^2)	$\Omega_b h^2$	$\Omega_{DM} h^2$
best-fit	0.857	1	0.095	7.50×10^{-5}	2.32×10^{-3}	0.022	0.120
1σ	0.024	0.301	0.01	2×10^{-6}	1×10^{-4}	3.3×10^{-4}	3.1×10^{-3}

The best-fit value and 1σ standard deviation of relevant observables

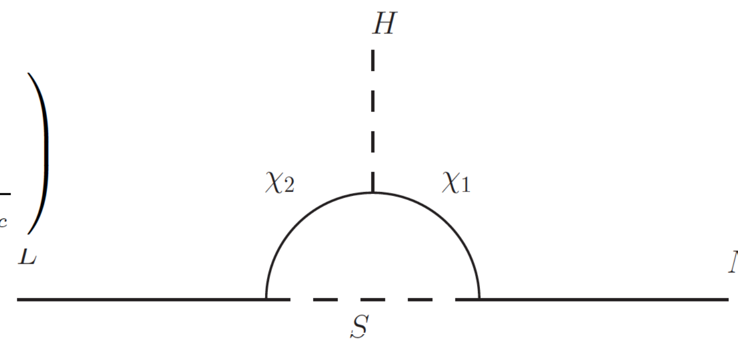
DM radiative corrections

$$m = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix},$$

$$m_D^0 = U_{TBM} P \begin{pmatrix} \sqrt{m_{\nu_1}} & 0 & \\ 0 & \sqrt{m_{\nu_2}} & 0 \\ 0 & 0 & \sqrt{m_{\nu_3}} \end{pmatrix} \begin{pmatrix} \sqrt{m_{N_a}} & 0 & \\ 0 & \sqrt{m_{N_b}} & 0 \\ 0 & 0 & \sqrt{m_{N_c}} \end{pmatrix}$$

$$U_{TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}.$$

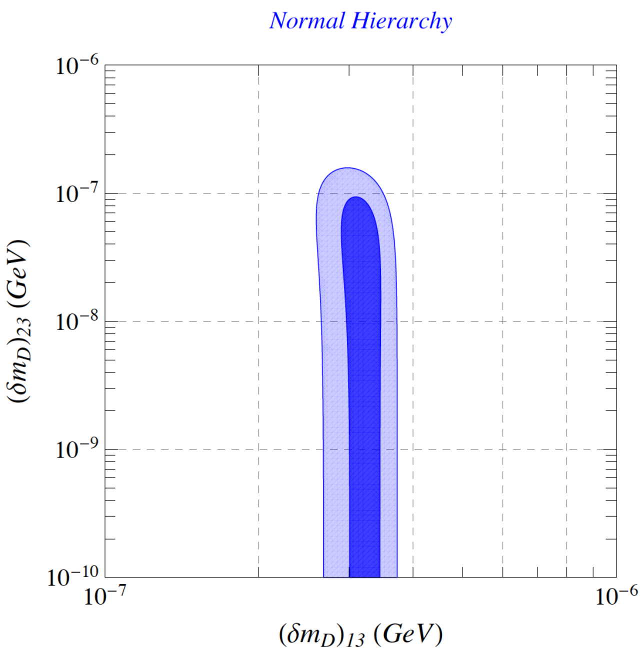
$$\delta m_D = \frac{\langle H^0 \rangle}{\sqrt{2}} \lambda_{H\chi} \begin{pmatrix} \lambda_e \lambda_{N_a} & \lambda_e \lambda_{N_b} & \lambda_e \lambda_{N_c} \\ \lambda_\mu \lambda_{N_a} & \lambda_\mu \lambda_{N_b} & \lambda_\mu \lambda_{N_c} \\ \lambda_\tau \lambda_{N_a} & \lambda_\tau \lambda_{N_b} & \lambda_\tau \lambda_{N_c} \end{pmatrix} f_{loop},$$

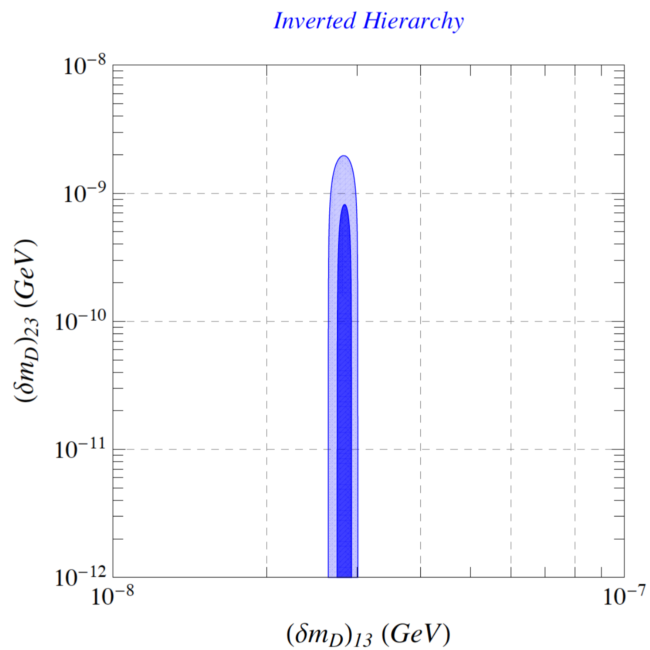


DM corrections to the Dirac neutrino mass, m_D.

$$\mathcal{L} \supset y_{\alpha i} \left(L_\alpha \cdot H \right) N_i - \frac{M_i}{2} N_i N_i + \lambda_\alpha \left(L_\alpha \cdot \chi_2 \right) S + \lambda_{H\chi} \left(\chi_2 \cdot \tilde{H} \right) \chi_1 + \lambda_{N_i} \chi_1 N_i S + h.c.$$

Results on U_{PMNS} angles and mass-squared differences





- $(\delta m_D)_{13}$ alone can amend U_{TBM} to U_{PMNS} with correct Δm^2
- One must need at least two radiative corrections for U_{PMNS} and Δm^2 if $(\delta m_D)_{13}$ is not involved

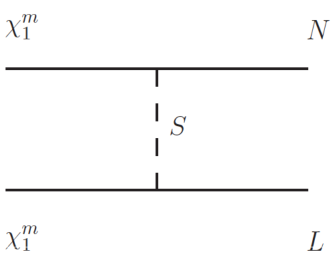
	m_{ν_1} (eV)	m_{ν_2} (eV)	m_{ν_3} (eV)	λ_{N_a}	λ_{N_b}	λ_τ
NH	0	8.66×10^{-3}	4.89×10^{-2}	0	0	0
IH	1.107×10^{-1}	1.11×10^{-1}	0.1	0	0	0
	m_{N_1} (GeV)	m_{N_2} (GeV)	m_{N_3} (GeV)	m_S (GeV)	m_{χ_1} (GeV)	m_{χ_2} (GeV)
NH/IH	1000	2000	3000	700	62	200

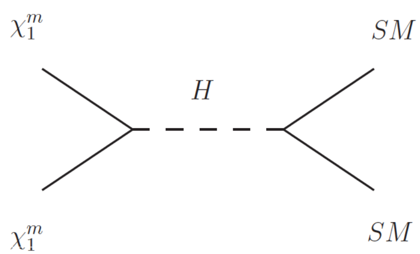
The Benchmark point for the NH and IH cases. $(N_a, N_b, N_c) = (N_1, N_2, N_3)$

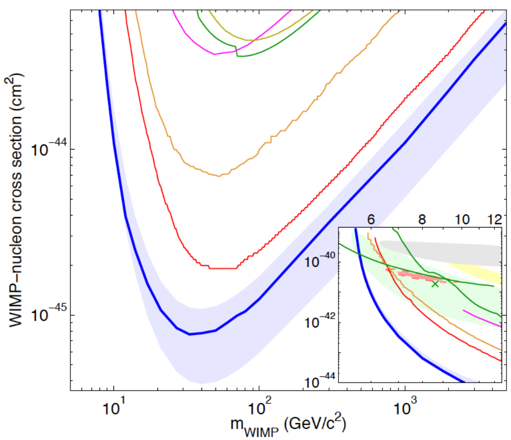
We here keep $m^2_{\nu_2} - m^2_{\nu_1}$ *and* $|m^2_{\nu_3} - m^2_{\nu_2}|$ *to be* Δm^2_{sol} *and* Δm^2_{atm}*, respectively.*

DM relic abundance and direct detection

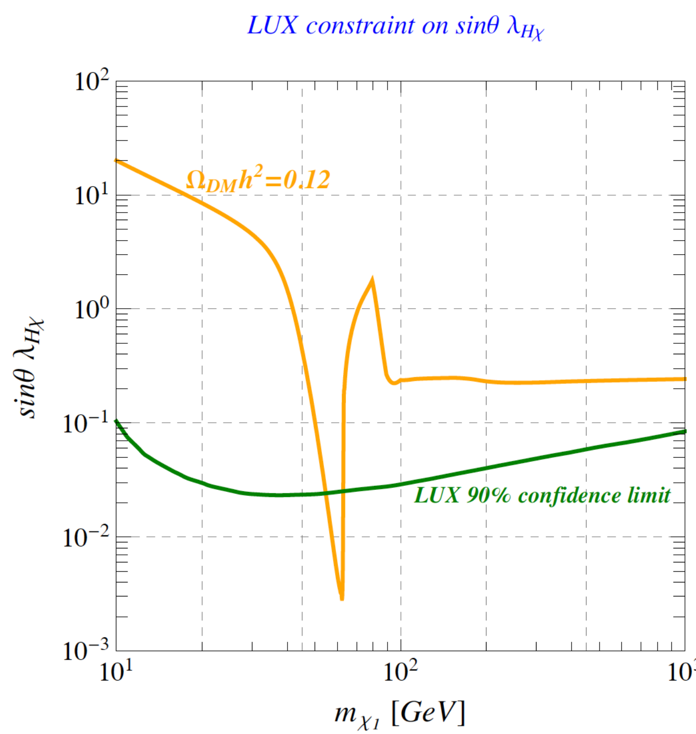
$$\mathcal{L} \supset \quad \lambda_{H\chi}\left(\chi_2 \cdot \tilde{H}\right)\chi_1 + \lambda_{H\tilde{\chi}}\left(\tilde{\chi}_2 \cdot H\right)\chi_1 + \lambda_\alpha\left(L_\alpha \cdot \chi_2\right)S$$
$$+\lambda_{N_i}\,\chi_1 N_i S - \frac{1}{2}m_S^2 - \frac{1}{2}m_{\chi_1}\chi_1\chi_1 - m_{\chi_2}\tilde{\chi}_2\chi_2 + h.c.,$$







LUX SI results arXiv:1310.8214



LUX bounds on the product of $\sin\theta$ *and* λ_H*, where* θ *is the* $\chi_1-\chi_2$ *mixing angle*

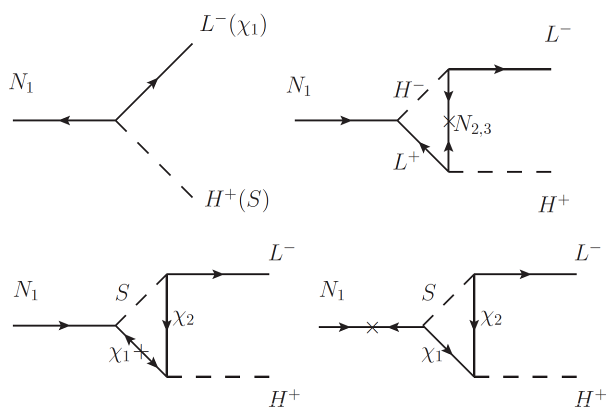
Leptogenesis (TeV N) with new contributions

Two conditions required to generated a lepton asymmetry from N_1 decays:

- Tree-level and loop-level interference with complex coupling constant(s) (λ_{N_1})
- Particles in the loop must be on-shell

In fact, $(\delta m_D)_{13}$ alone can not realize leptogenesis because:

1. In terms of the interference between the tree-level and the DM loops, the lepton asymmetry is zero since $(m_D)_{13} = 0$ due to the TBM mixing pattern
2. In terms of original interference (upper panels), $N_1 > 10^9$ GeV is required (hep-ph/0202239)



Leptogenesis (TeV N) with new contributions

With the spirit of minimality, one can include N_2 (λ_{N_2}) in the game:

- $(\delta m_D)_{13}$ comes from λ_{N_2} for nonzero θ_{13}, $(\delta m_D)_{12}$ comes from λ_{N_1} for leptogenesis
- It, however, suffers from new washout processes, $\chi_1 + S \to L^\pm + H^\mp$

To generate sufficient lepton asymmetry, we employ the resonant enhancement $m_{N_2} - m_{N_1} \sim \Gamma_{N_2}$ (N_2 decay width) (hep-ph/9707235)

We include the following observables in χ^2 fits

	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{23}$	$\sin^2 2\theta_{13}$	Δm^2_{sol} (eV^2)	$\lvert\Delta m^2_{atm}\rvert$ (eV^2)	$\Omega_b h^2$	$\Omega_{DM} h^2$
best-fit	0.857	1	0.095	7.50×10^{-5}	2.32×10^{-3}	0.022	0.120
1σ	0.024	0.301	0.01	2×10^{-6}	1×10^{-4}	3.3×10^{-4}	3.1×10^{-3}

Table 2: *The best-fit value and 1σ standard deviation of relevant observables included in this paper. The values are taken from Refs. [52–54].*

Leptogenesis (TeV N) with new contributions

- We fix $|\lambda_{N_1}|$ to be the best-fit value and vary the phase
- The phase of λ_{N_1} gives rise to δ_{CP} if the flavor symmetry does not provide a phase

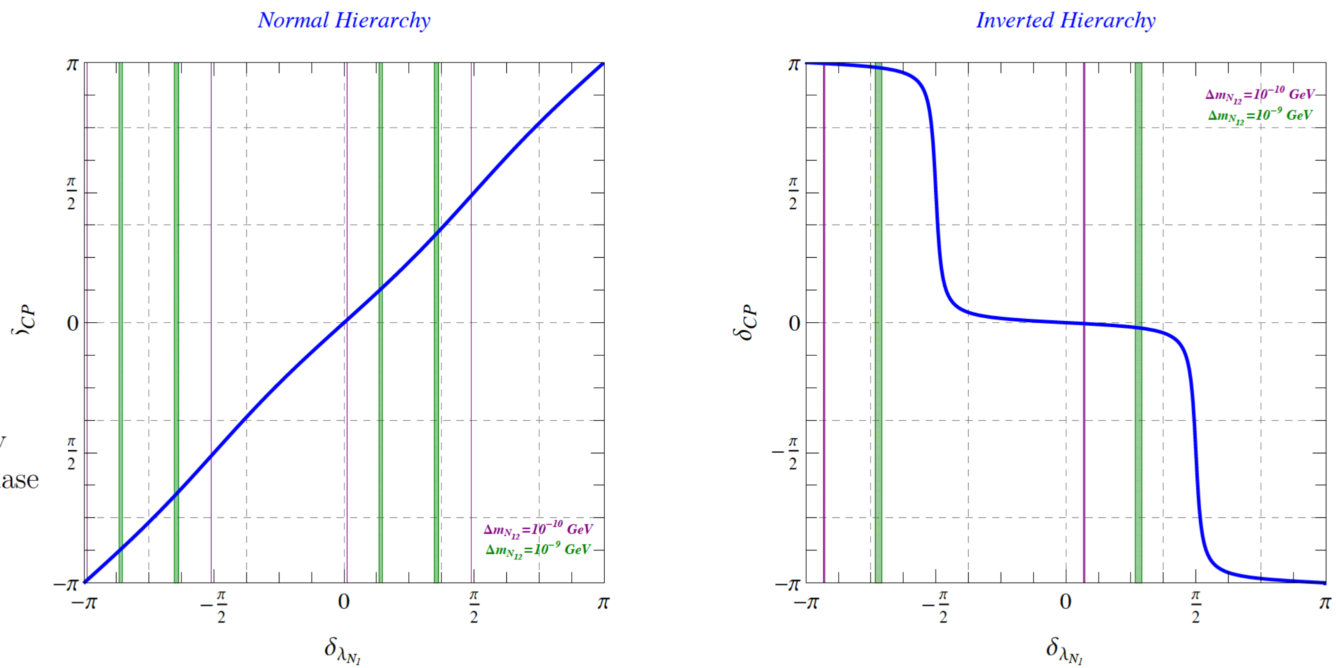


Figure 7: *In the case of TeV N_1, confidence region in green (purple) on the phase of λ_{N_1}, $\delta\lambda_{N_1}$, for $m_{N_2} - m_{N_1} \equiv \Delta m_{N_{12}} = 10^{-9}$ (10^{-10}) GeV. The blue line represents the correlation between $\delta\lambda_{N_1}$ and δ_{CP} in U_{PMNS}.*

	m_{ν_1} (eV)	m_{ν_2} (eV)	m_{ν_3} (eV)	λ_{N_a}	λ_{N_b}	λ_τ
NH	0	8.66×10^{-3}	4.89×10^{-2}	0	0	0
IH	1.107×10^{-1}	1.11×10^{-1}	0.1	0	0	0
	m_{N_1} (GeV)	m_{N_2} (GeV)	m_{N_3} (GeV)	m_S (GeV)	m_{χ_1} (GeV)	m_{χ_2} (GeV)
NH/IH	1000	$1000 + \Delta m_{N_{12}}$	2000	700	62	200

S as Inflaton in chaotic inflation

In the limit of slow-roll inflation, the density and tensor perturbations are related to the inflation potential $V(\phi)$ as:

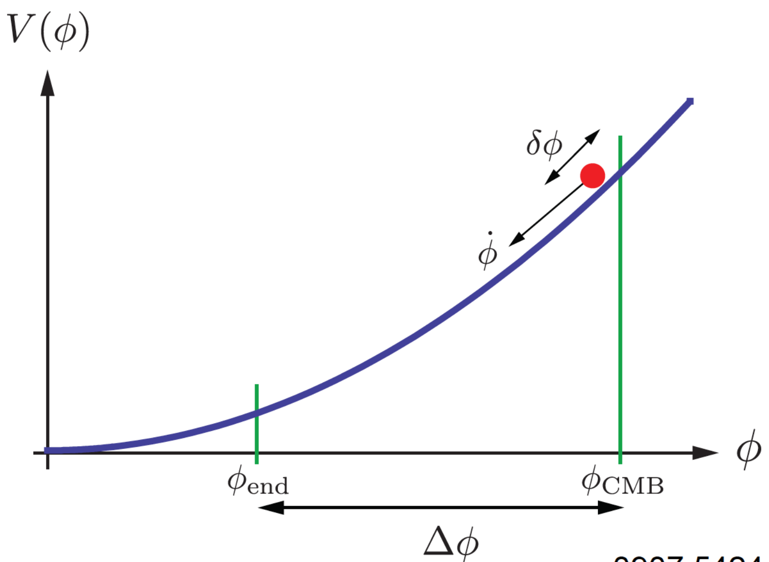
$$\Delta_s^2 \approx \frac{1}{24\pi^2}\frac{V(\phi)}{M_{\rm pl}^4}\frac{1}{\epsilon_V},$$

$$\Delta_t^2 \approx \frac{2}{3\pi^2}\frac{V(\phi)}{M_{\rm pl}^4},$$

$$\epsilon_V = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2\bigg|_{\phi=\phi_{\rm cmb}} = 2\left(\frac{M_{\rm pl}}{\phi_{\rm cmb}}\right)^2,$$

$$V = m_\phi^2\phi^2$$

$$\epsilon_V = \frac{1}{2N_{\rm cmb}} \qquad \phi_{\rm cmb} = 2\sqrt{N_{\rm cmb}}M_{\rm pl},$$



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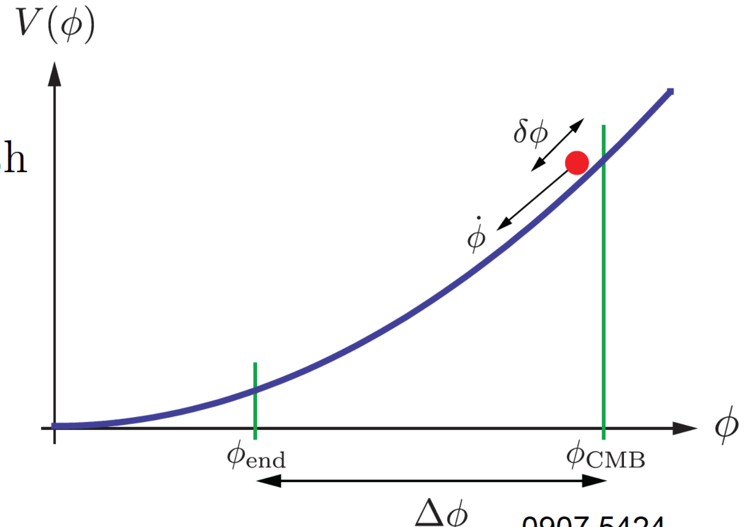
S as Inflaton in chaotic inflation

$$V = m_\phi^2 \phi^2$$

$$r = \frac{\Delta_t^2}{\Delta_s^2} \approx 16\epsilon_V = \frac{8}{N_{\rm cmb}} \sim 0.16$$

with $N_{\rm cmb} \sim 50$

which is consistent with the BICEP2 results with $r = 0.20^{+0.07}_{-0.05}$ or $r = 0.16^{+0.06}_{-0.05}$ after subtracting various dust models (arXiv:1403.3985)



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scalar spectral index

$$n_s = 1 - \frac{2}{N_{\rm cmb}} \sim 0.96,$$

which is also consistent with the *Planck* results (arXiv:1303.5082)

S as Inflaton in chaotic inflation

From the *Planck* results (arXiv:1303.5082),
the scalar perturbation amplitude for $V = m_\phi^2 \phi^2$ is

$$|\Delta_s^2| = 2.2 \times 10^{-9}, \quad \Delta_s^2 \approx \frac{1}{24\pi^2} \frac{V(\phi)}{M_{\rm pl}^4} \frac{1}{\epsilon_V},$$

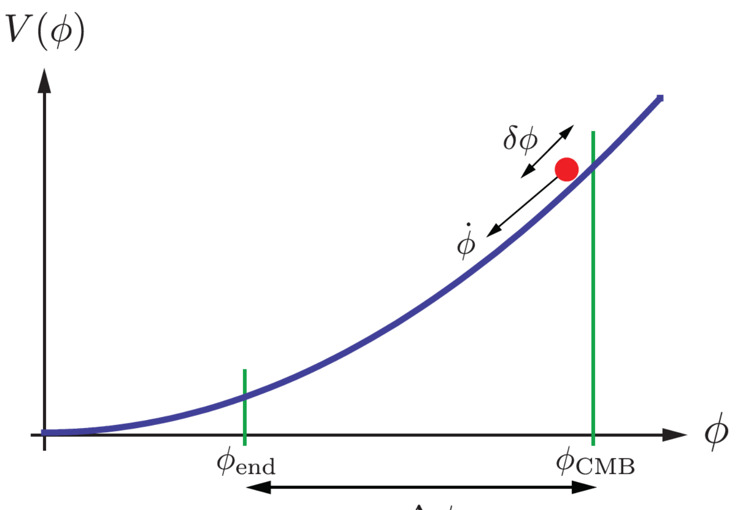
which implies

$$m_\phi \sim 10^{13} \text{ GeV}$$

with $N_{\rm cmb} \sim 50$

In order to get nonzero θ_{13} and leptogenesis,

$$m_{N_i} \gtrsim m_S \sim 10^{13} \text{ GeV}$$



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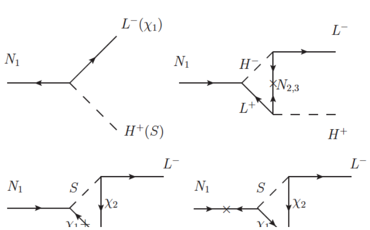
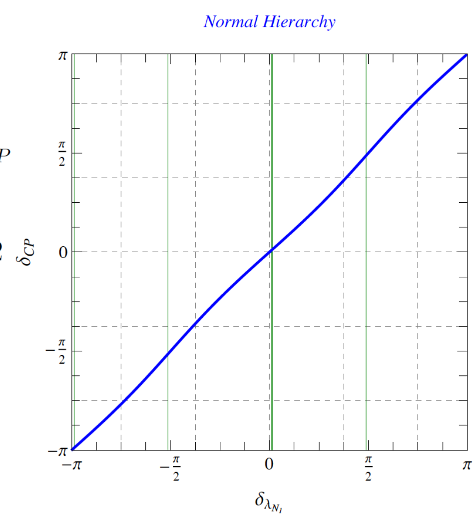
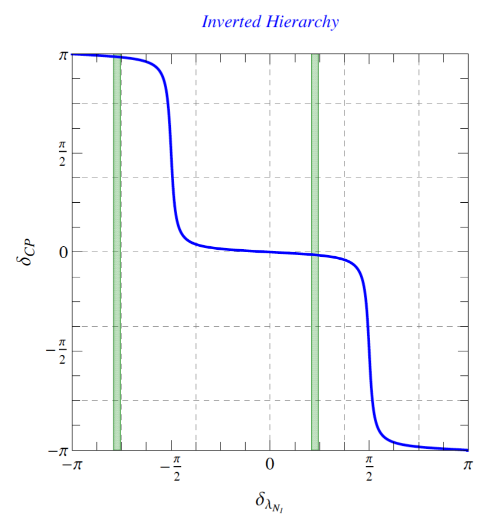
S as Inflaton in chaotic inflation

	m_{ν_1} (eV)	m_{ν_2} (eV)	m_{ν_3} (eV)	λ_{N_a}	λ_{N_b}	λ_μ	λ_τ
NH	0	8.66×10^{-3}	4.89×10^{-2}	0	0	0	0
IH	1.107×10^{-1}	1.11×10^{-1}	0.1	0	0	0	0
	m_{N_1} (GeV)	m_{N_2} (GeV)	m_{N_3} (GeV)	m_S (GeV)	m_{χ_1} (GeV)	m_{χ_2} (GeV)	λ_e
NH/IH	1.65×10^{13}	3×10^{13}	4.5×10^{13}	1.5×10^{13}	62	200	1

- Here, we use only $\delta(m_D)_{13}$, i.e., λ_{N_1} only with $\lambda_e = 1$
- we fix λ_{N_1} to the best-fit value and vary its phase $\delta_{\lambda_{N_1}}$
- Only CP-violating source comes from $\delta(m_D)_{13}$, i.e, δ_{CP} is linked to leptogenesis
- For HN, one of the confidence regions has $\delta_{CP} = -\pi/2$ favored by the T2K experiments (arXiv:1311.4750)







Conclusions

- In the type-I seesaw, θ_{13}=0 and zero lepton asymmetry if there exists a flavor symmetry resulting in the TBM.
- The dark particles, odd under a Z_2 symmetry, break the flavor symmetry to achieve θ_{13}~ 9^0 and leptogenesis.
- Only one radiative correction is needed for degenerate TeV heavy neutrinos and sub-TeV DM to achieve the goals.
- The singlet S can play the role of the inflaton with m_S~10^{13} GeV.

Conclusions

- With $m_{S,}$ m_N ~ 10^{13} GeV, one needs only one radiative correction to achieve the goals.
- There is a direct connection between δ_{cp} and leptogenesis, which is absent from the original leptogenesis in the type-I seesaw.
- For concrete model building, one should be very careful about radiative corrections from particles in question apart from the dark particles.
- These additional corrections might spoil the connection between the DM and SM neutrinos.