Inflation, Proton Decay, and Higgs Portal Dark Matter in $SO(10) \times U(1)_\psi$

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Standard Model (SM)

- **Standard Model is not the final answer**

- **Phenomenological shortcomings:**
  - **Dark Matter ?**
  - **Neutrino Mass ?**
  - **Baryon Asymmetry ?**
  - **Cosmological Inflation ?**

- **Technical issues:**
  - **Stability of the Electroweak Vacuum?**
  - **Mathematical Elegance of SM gauge group?**

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
q_L^i	3	2	1/6
u_R^i	3	1	2/3
d_R^i	3	1	$-1/3$
ℓ_L^i	1	2	$-1/2$
e_R^i	1	1	-1
H	1	2	$-1/2$

Grand Unified Theory (GUT)

- **A Quest for a Simpler/Elegant Theory**

SM Gauge Group
$SU(3)_c \times SU(2)_L \times U(1)_Y$

→ G_{GUT}

Example
G = SO(10)

- **GUT symmetry unifies SM gauge coupling:**

$$g_i^2/4\pi = \alpha_{i=3,2,1} \rightarrow \alpha_{GUT}$$

- **SO(10):** $\mathbf{16}^i = \boldsymbol{Q}^i \oplus \boldsymbol{L}^i \oplus \boldsymbol{N}_R^i$ (i = 1,2,3)
  - N_R^i : Right-handed neutrinos (RHNs)
  - Seesaw mechanism: Origin of light masses of the SM neutrinos.
  - Leptogenesis: Generates baryon asymmetry of the universe

- **Predicts proton decay:** $\mathbf{16}^i \supset \boldsymbol{Q}^i \oplus \boldsymbol{L}^i$ (SM Quarks ⟺ Leptons)

- **New Particles:** Possible Candidates for Dark Matter, Inflaton,….

Non-SUSY SO(10) and Monopole Problem

- **Requires two-step Symmetry Breaking (SB)**
  - **Example:**

$$SO(10) \xrightarrow{\langle 210_H \rangle = M_{GUT}} SU(4)_c \times SU(2)_L \times SU(2)_R \quad \textbf{(Pati-Salam (PS) Group)}$$
$$\xrightarrow{\langle \overline{126}_H \rangle = M_I} SU(3)_c \times SU(2)_L \times U(1)_Y$$
$$\xrightarrow{\langle 10_H \rangle} SU(3)_c \times U(1)_{EM}.$$

- **Intermediate scale PS SB:** $\langle \overline{126_H} \rangle = M_I \simeq 10^{11}$ GeV   G. Altarelli and D. Meloni, [arXiv:1305.1001 [hep-ph]]
  - Natural scale to implement see-saw mechanism
- $\overline{126}_H, 10_H$: sufficient to reproduce SM fermion masses/mixing   B. Bajc, A. Melfo, et. al [arXiv:hep-ph/0510139]

- **Both (GUT and PS) SB produce monopoles: (mass ≈ SB scale)**
  - Monopole energy density can easily exceed the critical density of Universe
  - This will overclose the universe !!   L. Patrizii and M. Spurio, [arXiv:1510.07125[hep-ex]]
- **If $H_{inf} < M_{\rm I}$, inflation can solve the monopole problem**
  - Inflation dramatically reduces number density of monopoles
- **A typical single field Higgs inflation does not work**

$$H_{inf} \simeq 10^{13-14}\text{GeV} > M_{\rm I}$$

intermediate mass monopoles survive inflation !!

N. Okada, V. N. Şenoğuz and Q. Shafi [arXiv:1403.6403 [hep-ph]]

Inflection-point Inflation (IPI) in U(1) Higgs Model

N. Okada and D. Raut, [arXiv:1610.09362 [hep-ph]]

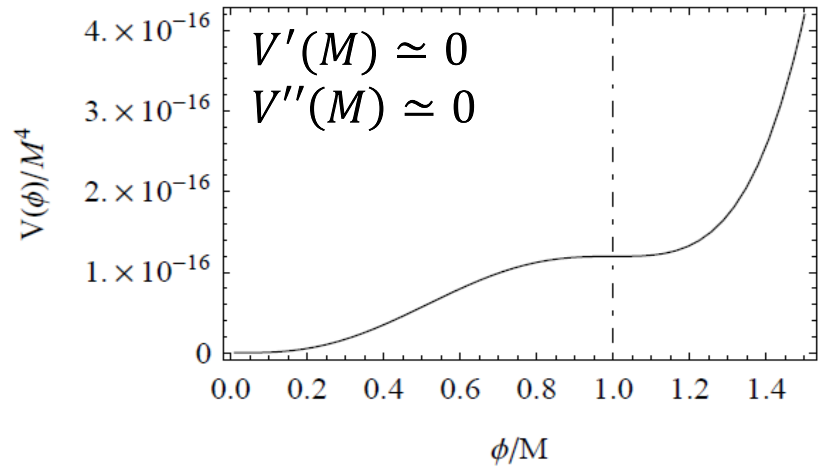
➢ Inflection-point inflation (IPI) works

- Unique realization of a low-scale single field inflation:(M< Planck Mass)

➢ Ingredients to realize IPI with a RG improved $\lambda\phi^4$ potential

- Inflaton: U(1) Higgs Inflation
- Conditions:

○ $\lambda(M) \simeq 0$
○ $\beta_\lambda(M) \simeq \#\, g(M)^4 - \#\, Y(M)^4 \simeq 0$



➢ Predictions of IPI

✓ Inflationary Predictions :n_s set to match Planck Observation; $r \ll 1$
✓ Unique Inflationary Prediction :$\alpha \simeq -2.742 \times 10^{-3}$
✓ Low Energy Parameter are fixed :$\lambda(M)$, $g(M)$, $Y(M)$ fixed by IPI conditions

✓ $$H_{inf} < 1.5 \times 10^{10}\ \mathrm{GeV}\left(\frac{M}{M_P}\right)^3$$

$SO(10) \times U(1)_\psi$ GUT

		$SO(10)$	$U(1)_\psi$	$\mathbf{Z}_2$	
$E_6 \supset$ Fermions ✓ Anomaly free	$16_{SM}^{(i)}$	**16**	$+1$	$-$	✓ SM fermions
	$10_E^{(i)}$	**10**	-2	$+$	✓ DM candidate
	$1_E^{(i)}$	**1**	$+4$	$+$	
Scalars	10_H	**10**	-2	$-$	✓ Symmetry breaking and (Fermion Masses)
	45_H	**45**	$+4$	$-$	
	126_H	**126**	$+2$	$-$	
	210_H	**210**	0	$-$	
	Φ_A	**1**	$+4$	$-$	✓ IPI inflation
	Φ_B	**1**	-8	$-$	

$$SO(10)\times U(1)_\psi \xrightarrow{\langle 210_H\rangle = M_{GUT}} SU(4)_c \times SU(2)_L \times SU(2)_R \times U(1)_\psi$$

$$\xrightarrow{\langle \overline{126}_H\rangle, \langle 45_H\rangle, \langle \Phi_{A,B}\rangle = M_I} SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\xrightarrow{\langle 10_H\rangle} SU(3)_c \times U(1)_{EM}$$

$\mathbf{SO(10) \times U(1)_\psi}$ Mass Spectrum

- **$U(1)_\psi$ sector:** Fixed by IPI conditions

✓ Inflaton mass (Φ_B)

$$m_\varphi = \sqrt{2\lambda(M_I)}M_I \simeq 8.7 \times 10^{-8} \times M_I \left|\ln\left[\frac{M}{M_I}\right]\right| \left(\frac{M_I}{M_P}\right),$$

$$m_{Z'} \simeq 10g(M_I)M_I \simeq 2.3 \times 10^{-2} \times M_I \left(\frac{M}{M_P}\right)^{1/3},$$

$$m_{10}^{(3)} \simeq \tfrac{1}{2}Y(M_I)M_I \simeq \frac{1}{3}m_{Z'}.$$

- Masses not fixed: Remaining 10-plet, $m_{10}^{(1,2)}$; Singlets fermions, $\mathrm{m}_{\mathbf{1}}^{(\mathrm{i})}$; Φ_A.

- **$SO(10)$ sector:**

Scalar Mass Sector

	M_I
$\overline{126}_H$	$(\mathbf{10},\mathbf{1},\mathbf{3}),\ (\mathbf{15},\mathbf{2},\mathbf{2})$
45_H	$(\mathbf{15},\mathbf{1},\mathbf{1})$
10_H	$(\mathbf{1},\mathbf{2},\mathbf{2}),\ (\mathbf{6},\mathbf{1},\mathbf{1})$

Only one light Higgs (SM) below scale M_I

Fermion Sector

$\langle(\mathbf{10},\mathbf{1},\mathbf{3})\rangle$: RHN Mass $\sim M_I$

$\langle(\mathbf{15},\mathbf{2},\mathbf{2})\rangle, \langle(\mathbf{1},\mathbf{2},\mathbf{2})\rangle$: SM Fermion Mass

Proton Decay and Mass Splitting

➢ Proton Decay:

- Most severe : $p \to e^+ + \pi^0$
- Current experimental bound: Super-K: $\tau_p > 1.6 \times 10^{34}$ years [arXiv:1610.03597]
- Future experimental reach : Hyper-K: $\tau_p < 1.6 \times 10^{35}$ years

GUT gauge boson mediated

$$\tau_p \simeq \frac{1}{\alpha_{GUT}^2} \frac{M_{GUT}^4}{m_p^5}$$

$$\Rightarrow \boxed{\frac{M_{GUT}}{\sqrt{\alpha_{GUT}}} > 2.5 \times 10^{16} \text{ GeV}}$$

Colored Higgs $(\mathbf{6},\mathbf{1},\mathbf{1}) \subset 10_H$ mediated

$$\tau_p \simeq \frac{1}{Y_u^2 Y_d^2} \frac{m_{HC}^4}{m_p^5}$$

$$\Rightarrow \boxed{m_{HC} > 4.5 \times 10^{11} \text{ GeV}}$$

➢ 10-plet triplet-doublet mass splitting:

S. Dimopoulos and F. Wilczek, [hep-ph/9306242]

$$\mathcal{L} \supset \sum_i \frac{1}{2} Y_A^{(i)} \Phi_A 10_E^{(i)} 10_E^{(i)} + \sum_{i \neq j} \frac{1}{2} Y_{45} 45_H 10_E^{(i)} 10_E^{(j)}$$

$$\boxed{\langle 45_H \rangle = M_I \times diag(1,1,1,0,0) \times i\sigma_2}$$

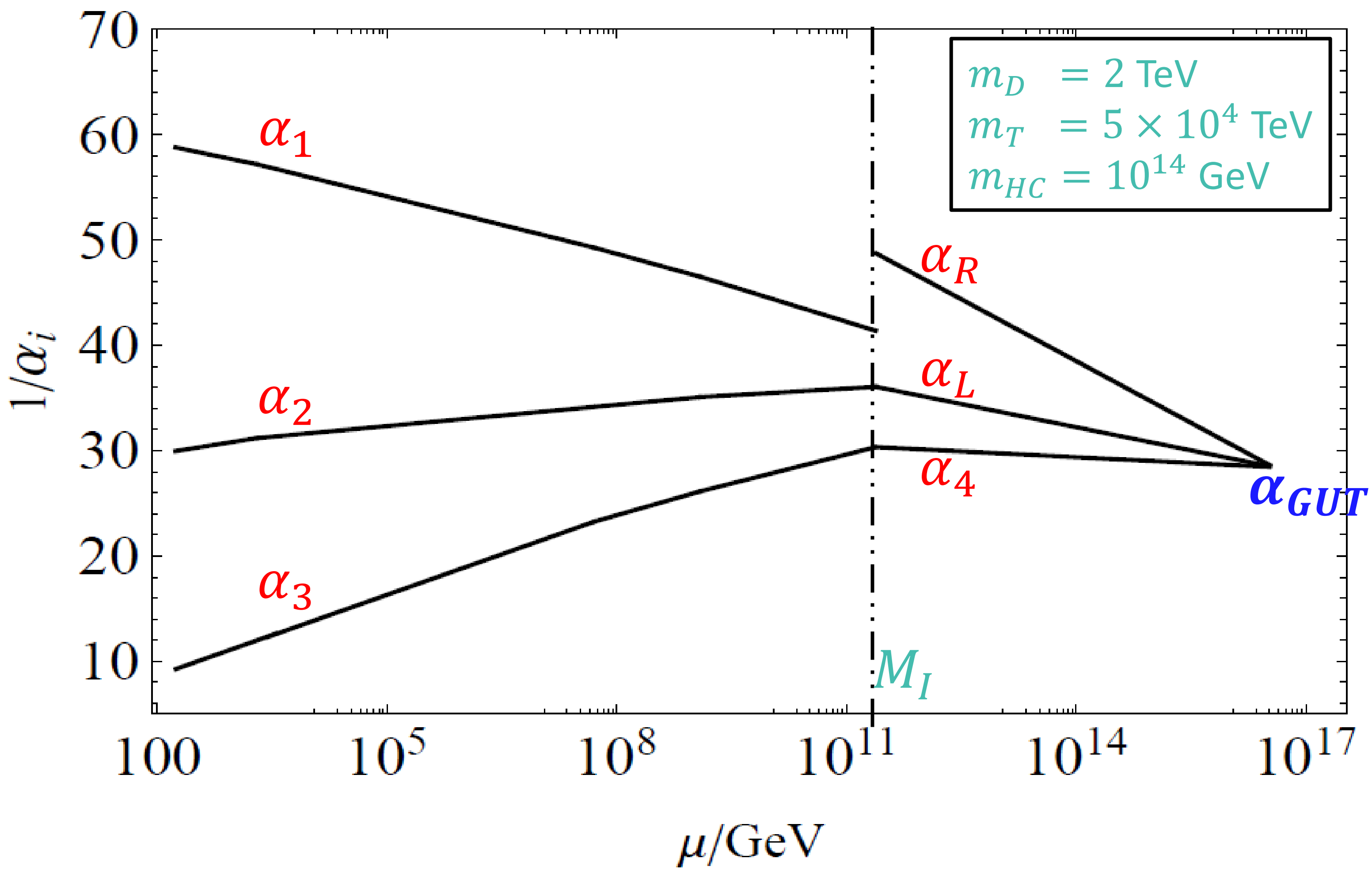
$$10_E = D \oplus \bar{D} \oplus T \oplus \bar{T}$$

$$m_D^{(1,2)} = m_{10}^{(1,2)} \equiv m_D$$

$$m_T^{(1,2)} = |m_D \pm m_{45}| \simeq m_T$$

SO(10) Gauge Coupling Unification

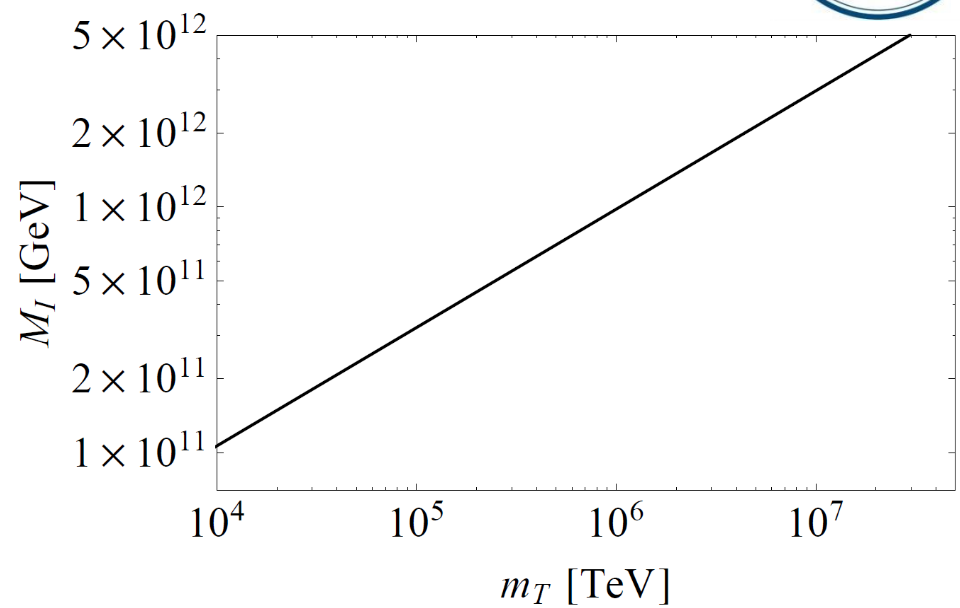
- EW $< \mu < M_I$: SM Gauge Couplings : $\alpha_{1,2,3}$
- $M_I < \mu < M_{GUT}$: PS Gauge Couplings : $\alpha_{4,L,R}$
- $\alpha_4(GUT) = \alpha_L(GUT) = \alpha_4(GUT) \equiv \alpha_{GUT}$

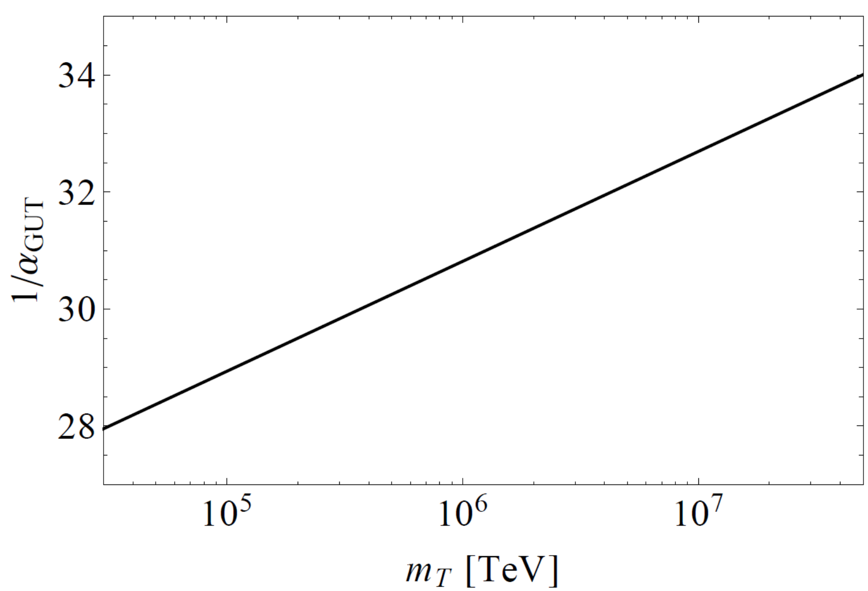


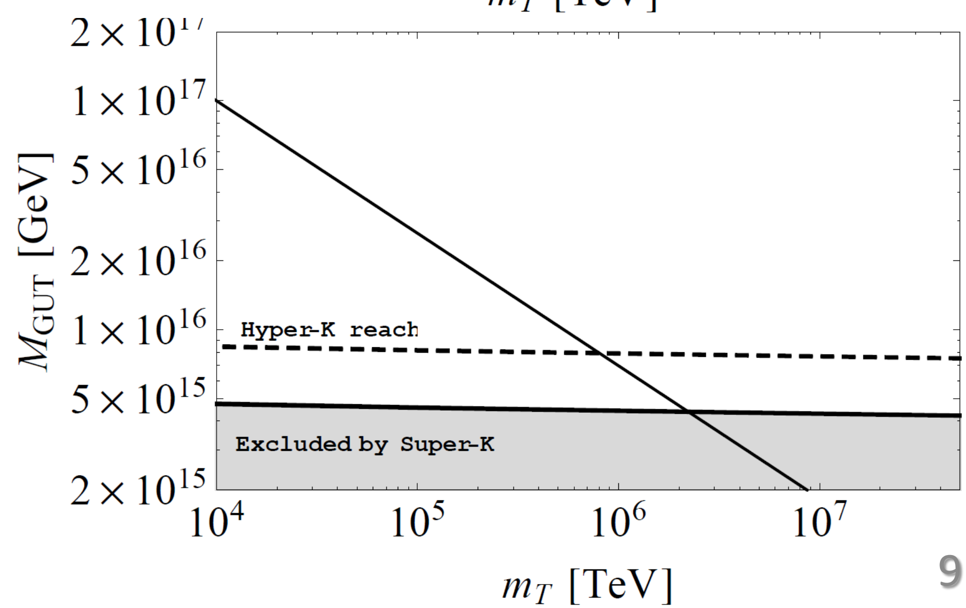
SO(10) Gauge Coupling Unification

If $m_T^{(i)} = m_D^{(i)}$:

- $M_I \simeq 1.7 \times 10^9$ GeV
- $M_{GUT} \simeq 1.4 \times 10^{19}$ GeV
  ($>$ **Planck Mass!**)







Leptogenesis and Reheating

➢ **Thermal Leptogenesis:** $m_{NR} \gtrsim 10^{9-10}$ GeV

S. Davidson and A.~Barra, [hep-ph/0202239]

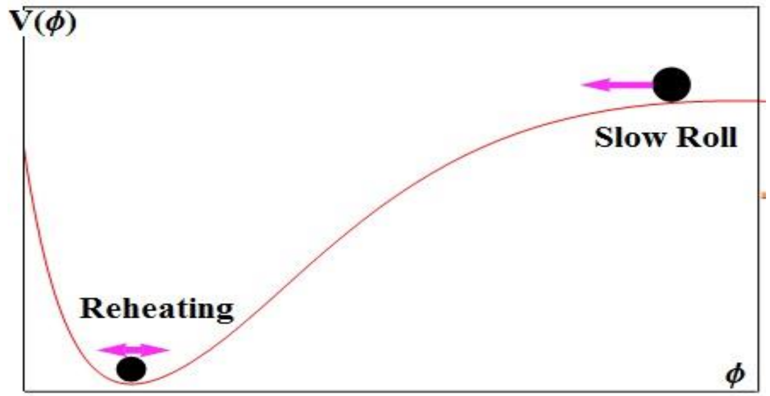
$$10^{9-10}[\mathrm{GeV}] < T_R < M_I$$

$$V \supset \Lambda \Phi_A 10_H^2$$

- $10_H \supset (\mathbf{1}, \mathbf{2}, \mathbf{2}) = H_u \oplus H_d$
- $H_u \supset H \sin\beta$
- $H_d \supset H^\dagger \cos\beta$

$$V \supset \frac{\Lambda \sin 2\beta}{2} \varphi H^\dagger H$$

➡ $\Gamma(\varphi \to H^\dagger H) \simeq \frac{\Lambda^2 \sin^2 2\beta}{4\pi \, m_\varphi}$



$$T_R \simeq \left(\frac{90}{\pi^2 g_*}\right)^{1/4} \sqrt{\Gamma_\varphi M_P}$$

Inflaton decay-products thermalize the universe

➡ $$T_R \simeq 10^{10} \text{ GeV} \left(\frac{\Lambda[\mathrm{GeV}]}{4.2 \times 10^5}\right)$$

Higgs-portal Dark Matter

- **DM Candidates: $\{10_E , 1_E\}$**
- **Colored triplets decay mediated by colored Higgs:**

  $m_{HC} < 3 \times 10^{14}$ GeV ➡ triplet lifetime ≪ 1 second

- **Singlet-Doublet DM:**

$$\mathcal{L} = \frac{1}{2} Y_A \Phi_A 10_E 10_E + \frac{1}{2} Y_B \Phi_B 1_E 1_E + \boxed{Y_H 1_E 10_E 10_H}$$

- $10_H \supset H \sin\beta \oplus H^\dagger \cos\beta$
- $10_E \supset D \oplus \bar{D}$

  - Mixture of $1_E(S)$ and Doublet (neutral) $\subset 10_E$

$$\boxed{\mathcal{L} \supset m_D D\bar{D} + m_S SS + \frac{\sqrt{2} m_0}{v_h}\left(\cos\beta D H^\dagger S + \sin\beta \bar{D} H S\right) + \text{h.c}}$$

$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix} D_0 & \bar{D}_0 & S \end{pmatrix} \begin{pmatrix} 0 & m_D & m_0 \sin\beta \\ m_D & 0 & m_0 \cos\beta \\ m_0 \sin\beta & m_0 \cos\beta & m_S \end{pmatrix} \begin{pmatrix} D_0 \\ \bar{D}_0 \\ S \end{pmatrix}$$

- **$m_D >> m_S, m_0$:**
  - DM is mostly the Singlet Component
  - DM interacts with SM particle through Higgs-portal Interactions

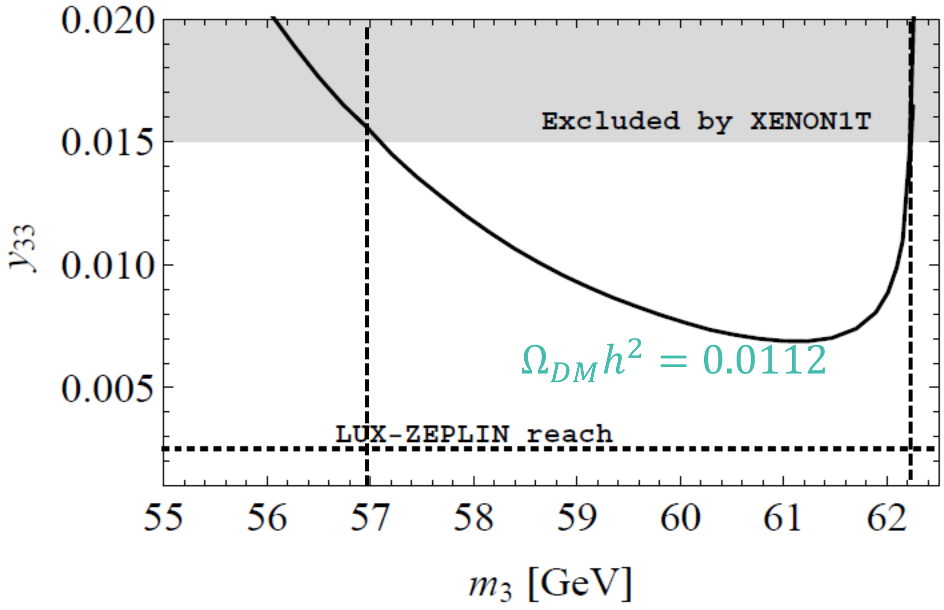
    ➡ **Higgs-portal DM Scenario**

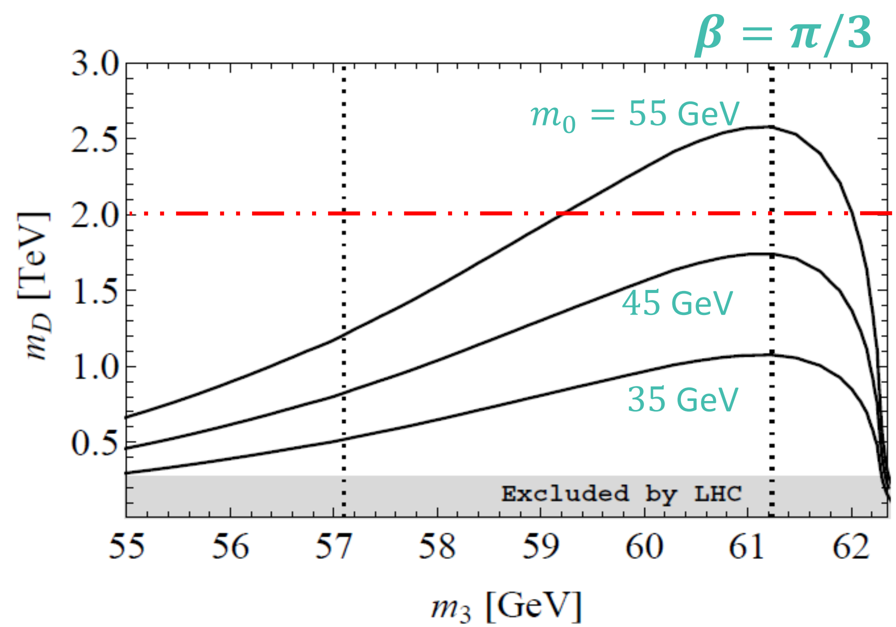
Higgs-portal Dark Matter

➢ Mostly Singlet DM (ψ_3) :

$m_D >> m_S, m_0$:

$$m_3 \simeq m_S - m_0 \left(\frac{m_0}{m_D} \right) \sin 2\beta$$





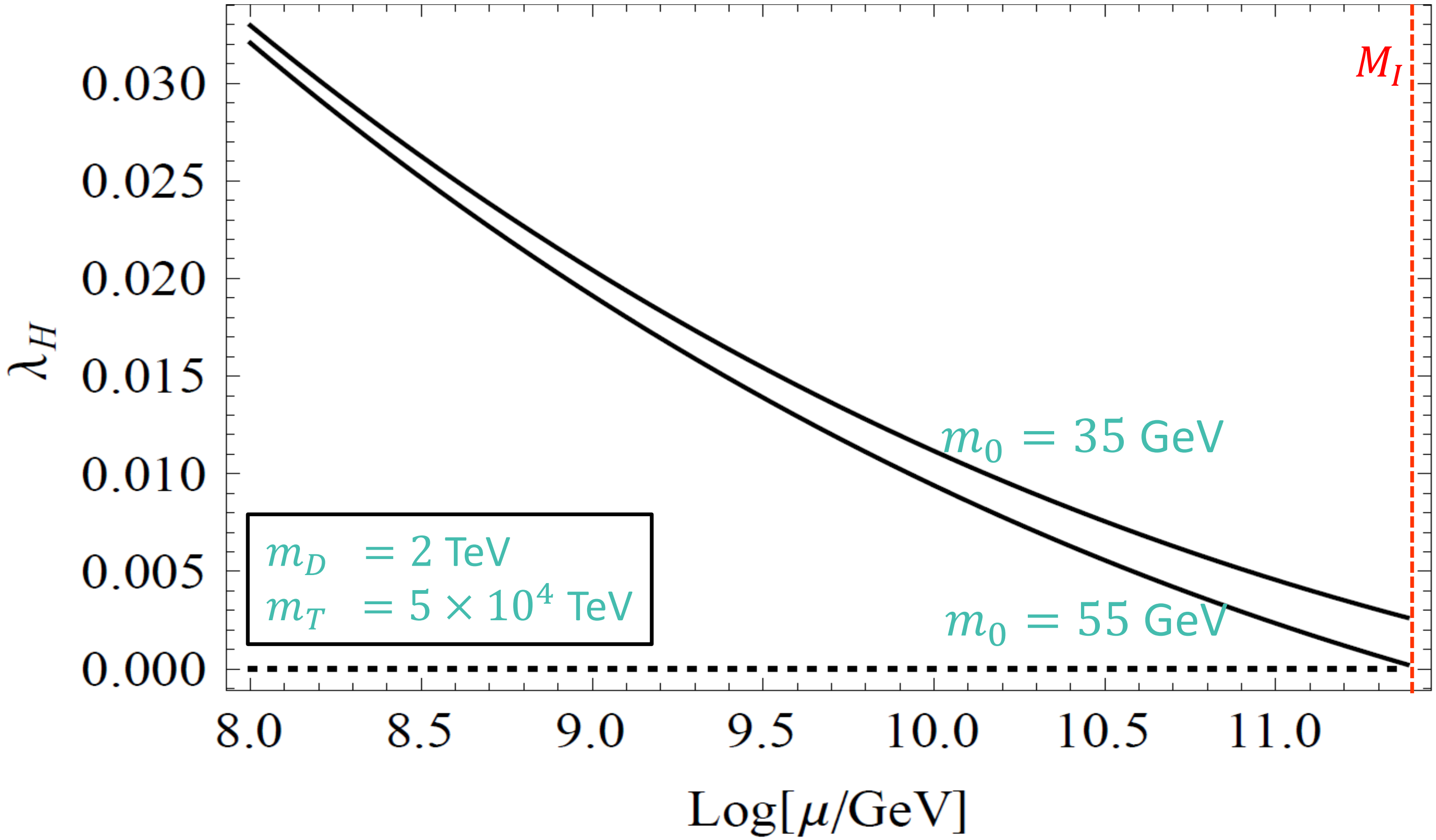
- Higgs-portal DM is excluded except for $m_D \simeq \frac{m_h}{2}$.
- Scenario will be fully explored by future direct DM detection experiment.

Electroweak Vacuum Stability

- **Stability Condition:** $\lambda_H\ (\mu < M_I) > 0$

$$16\pi^2 \frac{d\lambda_H}{d\ln\mu} = \beta_{SM}(m_D, m_T) + \boxed{\theta(\mu - m_D)\left(4\lambda_H {Y_H}^2 - 4{Y_H}^4\right)}$$

- $\mathcal{L} \supset Y_H\left(\cos\beta D H^\dagger S + \sin\beta \bar{D} H S\right)$
- $Y_H = \sqrt{2} m_0 / v_h$



Summary

$$\mathbf{SU(10) \times U(1)_\psi \supset SM}$$

- **Phenomenological shortcomings:**
  - **Monopole Problem (Low Scale Inflation) ?** ✓
  - **Neutrino Mass ?** ✓
  - **Baryon Asymmetry ?** ✓
  - **Dark Matter ?** ✓

- **Technical issues:**
  - **Stability of the Electroweak Vacuum?** ✓

Thank you

Questions?