SMART $U(1)_X$:

Standard **M**odel with **A**xion, **R**ight handed neutrinos, **T**wo Higgs doublets and **U(1)**$_X$ gauge symmetry

N. Okada, D. Raut, and Q. Shafi, arXiv:2002.07110 [hep-ph]
(submitted to EPJC)

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A Need for Theory Beyond the Standard Model

- SM is very successful **but not complete!!**
- 5 Fundamental Questions:

  - *Nature of Dark Matter ?*
  - *Origin of Neutrino Mass ?*
  - *Origin of the Baryon Asymmetry in the Universe ?*
  - *Connection between Cosmological Inflation and particle physics ?*
  - *Resolution of Strong CP Problem?*

Standard Model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
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

➤ 5 reasons for a Theory Beyond the Standard Model

❖ Axion

➢ Strong CP problem:

$$\not{CP} : \mathcal{L}_{\rm QCD} \supset \frac{g_s^2}{32\pi^2}\,\theta_{QCD}\, G^b_{\mu\nu}\tilde{G}^{\mu\nu\, b}$$

G & $\tilde{G}$: Gluons
g_s: Strong Coupling

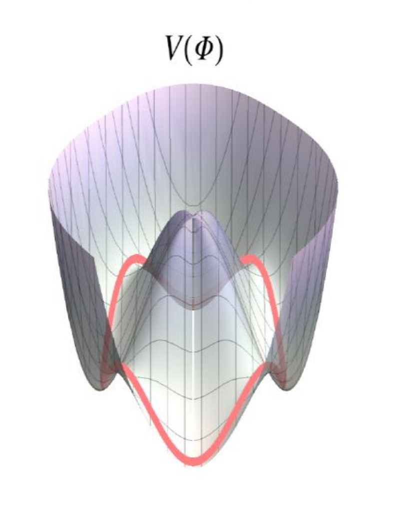
Q. Why is CP violation in strong sector negligibly small?

$\theta_{QCD} < 0.7 \times 10^{-11}$
(Neutron EDM measurement)

❑ Resolution: Peccei-Quinn (PQ) Mechanism and Axion

The axion field a(x) associated with breaking of *anomalous global symmetry* ($U(1)_{PQ}$) *contributes to the CP violation*:

$$\not{CP} : \mathcal{L}_{\rm QCD} \supset \frac{g_s^2}{32\pi^2}\left(\theta + \frac{a(x)}{F_a}\right) G^b_{\mu\nu}\tilde{G}^{\mu\nu\, b}$$



- Non-perturbative QCD interactions generate axion potential with minima located at: $\theta = -\frac{\langle a(x)\rangle}{F_a}$

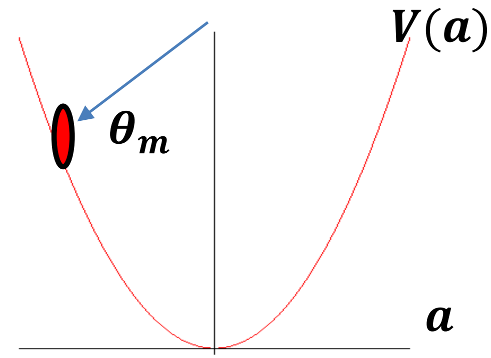
  such that effective θ_{QCD} vanishes at the minima.

R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

➢ The axion can also play the role of the Dark Matter (DM)

Axion Dark Matter (DM)

After rolling down to the potential minima, the axion is most likely displaced from the potential minima. This misalignment from the potential minimum leads to oscillation of axion field and it behaves like a cold DM and dominates the axion relic abundance.



- **If inflation occurs after PQ symmetry breaking, it generates DM isocurvature perturbations:**

$$\mathcal{P}_{\rm iso} = \left(\frac{H_{inf}}{\pi\theta_m F_a}\right)^2 < 8.69\times 10^{-11}$$

(Planck 2018)

$$\Rightarrow \quad \frac{H_{inf}}{F_a} \lesssim 3.0\times 10^{-5}\,\theta_m$$

- **Axion relic abundance:**

$$\Omega_a h^2 \simeq 0.18\,\theta_m^2 \left(\frac{F_a}{10^{12}\ {\rm GeV}}\right)^{1.19}$$

&

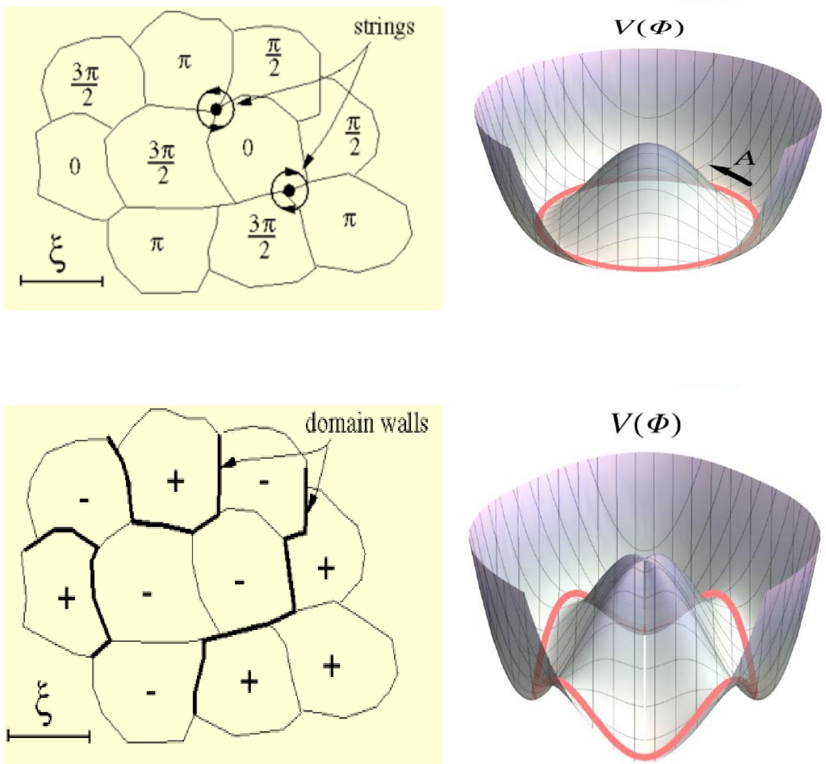
$$\Omega_a h^2 \simeq 0.12$$ ***(Planck 2018)***

$$\Rightarrow \quad F_a \simeq 7.11\times 10^{11}\ {\rm GeV}\ \theta_m^{-1.68}$$

(Isocurvature + relic abundance)

$$H_{inf} < 2.1\times 10^7\ {\rm GeV}\left(\frac{F_a}{7.11\times 10^{11}{\rm GeV}}\right)^{0.405}$$

Resolution of the Axion Domain Wall Problem



Kibble Mechanism

PQ symmetry breaking produce cosmic **strings** efficiently decays at late times by emitting axion and gravitational waves

Axion Domain Wall Problem

If $N_{DW} > 1$, which is typically the case, the string and domain wall form a very stable network which dominate the energy density of the universe.
This is inconsistent with observation

* *For $N_{DW} = 1$ the* axion domain wall network can decay and domain wall problem can be avoided.

➢ **Isocurvature :** $$\frac{H_{inf}}{F_a} \lesssim 3.0 \times 10^{-5}\, \theta_m$$

Inflation takes place after the PQ symmetry breaking, $H_{inf} < F_a = v_{PQ}/N_{DW}$, which exponentially suppress the number density of domain wall and strings associated with PQ symmetry breaking:

Axion Dark Matter and Inflation

- **Axion DM constraints on Hubble during inflation:**

(Natural Choice) $\theta_a \simeq 1$ ➡ $H_{inf} < 2.1 \times 10^7 \text{ GeV}$

- A typical slow roll inflation does not satisfy this constraint:

$$H_{inf} \simeq 10^{13-14}\text{GeV}$$

N. Okada, V. N. Şenoğuz and Q. Shafi, Turk J Phys, 40, (2016), 150-162

❑ Inflection-point Inflation (IPI):

N. Okada and D. Raut, Phys. Rev. D 95, no.3, 035035 (2017)

- **Gauge and Yukawa interactions play crucial role to realize an approximate inflection-point at a horizon exit scale M which can be freely chosen**

- **Gauged U(1) extension of SM with the new U(1) scalar identified as inflaton:**

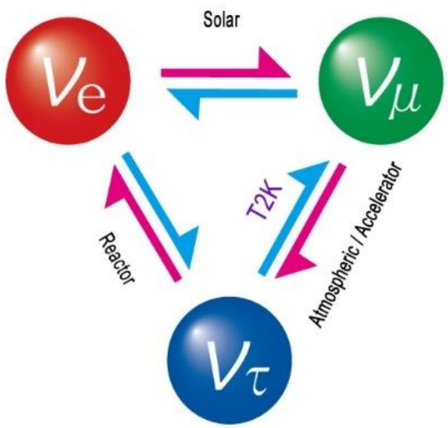
  ✓ Inflationary Predictions are consistent with Planck:

Independent of U(1) particle content

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

➡ $M \leq 0.11 M_P$

❖ Neutrino Mass



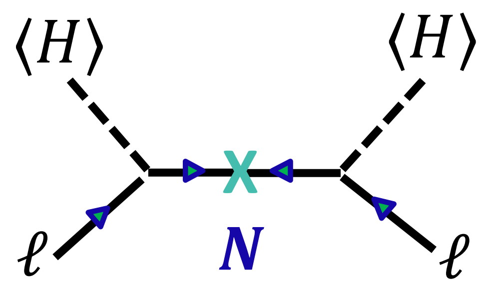
Observation of Neutrino Oscillation and Flavor Mixings (between generations)

➡ $m_\nu \simeq 0.05$ eV

Seesaw Mechanism: Origin of light neutrino masses

- In presence of SM singlet Majorana right handed neutrinos (RHNs): $\boldsymbol{N}$

(type-I Seesaw)



➡ $$m_\nu \simeq m_D \times \frac{m_D}{\boldsymbol{M_N}}$$

- $M_N \simeq 10^{10}$ GeV
- $m_D \simeq 1$ GeV

Implementation in gauged extension of SM:

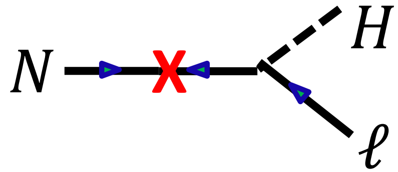
➢ Example, $U(1)_{B-L}$ model,
Here, the RHNs are essential to cancel all the B-L related anomalies.

R. N. Mohapatra and R. E. Marshak Phys. Rev. Lett. 44, 1316

Majorana Neutrinos: Baryogenesis via Leptogenesis

➢ Majorana interactions:

I. Violates CP

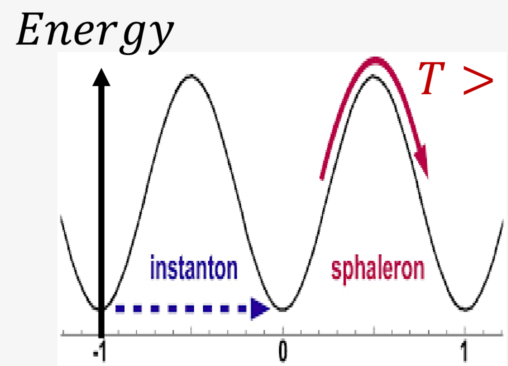
II. Violates Lepton Number: 

$(\Delta L = 1)$

Spharelon Process

- B+L violating transitions, $\Delta(\mathrm{B}+L) \neq 0$, become unsuppressed !!

➡ converts ΔL into ΔB



Non-perturbative QCD vacuum transition

❑ Thermal Leptogenesis with Majorana Neutrinos :

✓ **Sakharov Conditions:** (i) $\Delta B \neq 0$ (ii) CP (iii) Out of (thermal) Equilibrium Decay

- Requirements: *S. Davidson and A. Barra, Phys. Lett. B535 (2002) 25-32*

Lightest Heavy Neutrino mass

$$m_N \gtrsim 10^9 \text{ GeV}$$

Thermalization condition:

$$T_R \gtrsim m_N$$

- **Key Ingredients of our proposed model to address various shortcomings of the SM:**
  - *Axion*
    - *Nature of Dark Matter*
    - *Resolution of Strong CP Problem*
  - *Majorana Neutrinos:*
    - *Origin of Neutrino Mass*
    - *Origin of the Baryon Asymmetry in the Universe*
  - *Inflection-point Inflation*
    - *Viable axion DM scenario*
    - *Connects inflation with low energy particle physics in an essential way*

Standard Model

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

$$\times \mathbf{U(1)_X} \times \mathbf{U(1)_{PQ}}$$

➢ Anomaly free $U(1)_X$ extension of SM :

- Generalization of well known $\mathbf{U(1)_{B-L}}$ model to $\mathbf{U(1)_X}$
- Generalization:

  $\mathbf{U(1)_X}$ charge defined as a linear combination of $\mathbf{U(1)_Y}$ and $\mathbf{U(1)_{B-L}}$, both of which are anomaly free:

$$Q_X = Q_Y x_H + Q_{B-L}$$

S. Oda, N. Okada and D. S. Takahashi, Phys. Rev. D 92, no.1, 015026 (2015)

SMART $U(1)_X$

- ✓ **SM** (Standard Model)
- ✓ **A**xion
  (Strong CP and DM)
- ✓ **R**ight handed **Majorana neutrinos**
  (Neutrino mass and Leptogenesis)
- ✓ **T**wo Higgs doublets
  (Necessary for PQ anomaly)
- ✓ **$U(1)_X$: IPI inflation**
  (Axion Domain Wall & Isocurvature Problem)

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{PQ}$
q^i	**3**	**2**	$1/6$	$(1/6)x_H + (1/3)$	1
$(u^c)^i$	$\mathbf{3}^*$	**1**	$-2/3$	$(-2/3)x_H + (-1/3)$	1
$(d^c)^i$	$\mathbf{3}^*$	**1**	$1/3$	$(+1/3)x_H + (-1/3)$	1
ℓ^i	**1**	**2**	$-1/2$	$(-1/2)x_H + (-1)$	1
$(e^c)^i$	**1**	**1**	1	$(+1)x_H + (+1)$	1
$(N^c)^i$	**1**	**1**	0	$(+1)$	1
H_u	**1**	**2**	$1/2$	$(+1/2)x_H$	-2
H_d	**1**	**2**	$-1/2$	$(-1/2)x_H$	-2
Φ	**1**	**1**	0	(-2)	-2
S	**1**	**1**	0	0	4

SMART $U(1)_X$ and Grand Unification: $x_H = -4/5$

		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	$U(1)_{PQ}$
$(\Psi_{10})^i$	q^i	**3**	**2**	$1/6$	$1/5$	1
	$(u^c)^i$	$\mathbf{3}^*$	**1**	$-2/3$	$1/5$	1
	$(e^c)^i$	**1**	**1**	1	$1/5$	1
$(\Psi_{5^*})^i$	ℓ^i	**1**	**2**	$-1/2$	$-3/5$	1
	$(d^c)^i$	$\mathbf{3}^*$	**1**	$1/3$	$-3/5$	1
	$(N^c)^i$	**1**	**1**	0	1	1
	H_u	**1**	**2**	$1/2$	$-2/5$	-2
	H_d	**1**	**2**	$-1/2$	$+2/5$	-2
	Φ	**1**	**1**	0	-2	-2
	S	**1**	**1**	0	0	4

$x_H = -4/5$

$U(1)_X$ is the origin of charge quantization

N. Okada, S. Okada and D. Raut, Phys. Lett. B 780, 422-426 (2018)

- **Additional two vector-like fermion pairs:**

$$F_5 + F_5^* \supset D + D^c$$ (Similar to SM d^c)

$$F_{10} + F_{10^*} \supset Q + Q^c$$ (Similar to SM q)

- Plays crucial role to achieve unification of SM gauge couplings
- Plays essential role in stabilizing SM Higgs potential
- In SMART $U(1)_X$ with grand unification, vector-like fermions play essential role to stabilize inflaton potential

I. Symmetry Breaking and Axion

➢ Potential and symmetry breaking:

$$V(\Phi,\ S,\ H_u,\ H_d) = V_{\text{High}}(\Phi,\ S) + \Lambda(H_u.H_d)S + V_{\text{Low}}(H_u,\ H_d)$$

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}v_X, \quad \langle S\rangle = \frac{1}{\sqrt{2}}v_{PQ} \qquad \langle H_u\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_u\end{pmatrix}, \quad \langle H_d\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}v_d\\ 0\end{pmatrix}$$

(type-II Higgs doublet model)

- VEV choice: $v_{X,\,PQ} \gg v_{u,d}$

➢ Identification of Axion:

- Only Φ has non-zero $U(1)_X$ charge:

  $\omega(x)$: Absorbed by Z' boson

- S is singlet under $U(1)_X$:

  $a(x)$: Massless NG mode (Axion)

$U(1)_X$ extension of DFSZ axion model

Singlet Higgs Sector

	SM	$U(1)_X$	$U(1)_{PQ}$
Φ	1	(-2)	-2
S	1	0	4

$$\Phi(x) = \frac{1}{\sqrt{2}}(\phi(x) + v_X)\, e^{i\omega(x)/v_X}$$

$$S(x) = \frac{1}{\sqrt{2}}(s(x) + v_{PQ})\, e^{ia(x)/v_{PQ}}$$

II. Inflection-point Inflation (IPI)

➢ Effective potential at approximate inflection-point scale $\phi = M$:

$$V(\phi) \simeq V_0 + V_1(\phi - M) + \frac{V_2}{2}(\phi - M)^2 + \frac{V_3}{6}(\phi - M)^3$$

- Derivatives $V_{1,2,3}$ are fixed by inflationary measurements of spectral index (n_s), scalar power spectrum (Δ_s^2) and efolding number (N = 60) *N. Okada and D. Raut, Phys. Rev. D 95, no.3, 035035 (2017)*

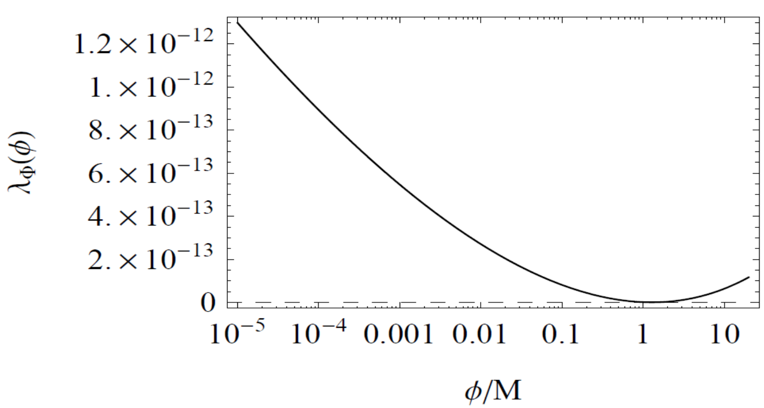
➢ Application to RG improved inflaton potential:

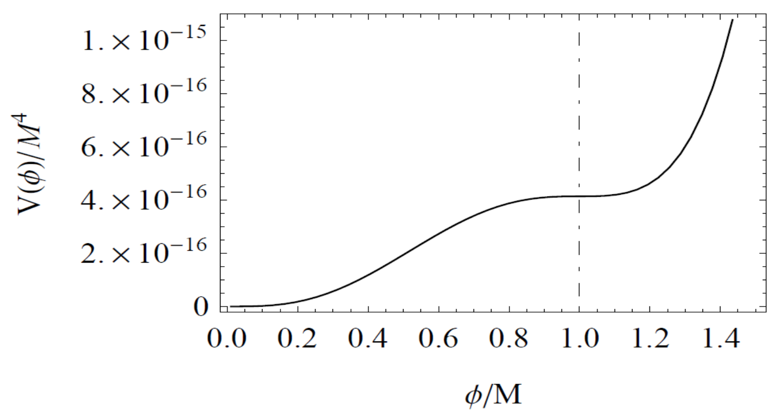
$$V'(M) = V_1 \simeq 0$$
$$V''(M) = V_2 \simeq 0$$

➡

- ○ $g(M), Y_i(M) \gg \lambda(M) \sim 10^{-16}(M/M_P)^2$
- ○ $\beta_\lambda(M) \simeq \# g(M)^4 - \# \Sigma_i Y_i(M)^4 \simeq 0$

- Gauge and Yukawa interaction are crucial
- $\lambda(M)$, g (M), and Y_i (M) are uniquely determined by M





III. Thermal Leptogenesis

➢ Benchmark values:

$\theta_m = 1$ ➡ $M < 0.11\, M_P$	$Y_1(M) < Y_2(M) = Y_2(M)$	$v_X = 1.70 \times 10^{12}\ GeV$
$F_a = 7.11 \times 10^{11}$ GeV $H_{inf} = 2.10 \times 10^{7}$ GeV $M = 0.05 M_P$	$m_{N^{2,3}} \simeq m_{Z'}$ $m_{Z'} = 8.0 \times 10^{-4} v_X$	$m_{N^{2,3}} \simeq 10^{10}$ GeV $m_{N^1} \simeq 10^{9}$ GeV $m_\phi \simeq 10^{5}$ GeV

➢ Lightest Neutrino (N^1) Interactions: Z' and Inflaton

$$(N^c)^1 (N^c)^1 \to Z' \to \overline{f_{SM}} f_{SM}$$

$$N_R{}^1 N_R^1 \leftrightarrow \phi\phi$$

- To prevent washing out of lepton asymmetry generated through thermal leptogenesis, these processes should decouple before plasma temperature drops to $T \simeq m_{N^1}$.

$$\left. \frac{\sigma(T) \times n_{eq}(T)}{H(T)} \right|_{T = m_{N^1}} < 1 \quad ➡ \quad v_X > 7.92 \times 10^{10}\ \text{GeV}$$

(Consistent to our VEV choice)

IV. Reheating

$$10^9 \lesssim T_R/[\mathrm{GeV}] < v_{PQ,X}$$

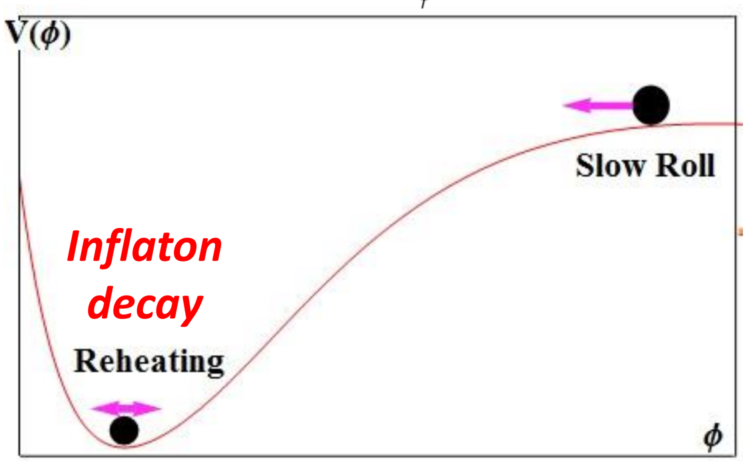
Thermalization of N_1

To avoid restoration of PQ and $U(1)_X$ symmetry

$$v_X > 7.92 \times 10^{10}\ \mathrm{GeV}$$

Preserve baryon asymmetry from thermal leptogenesis

$$m_\phi \simeq 10^5\ \mathrm{GeV}$$



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

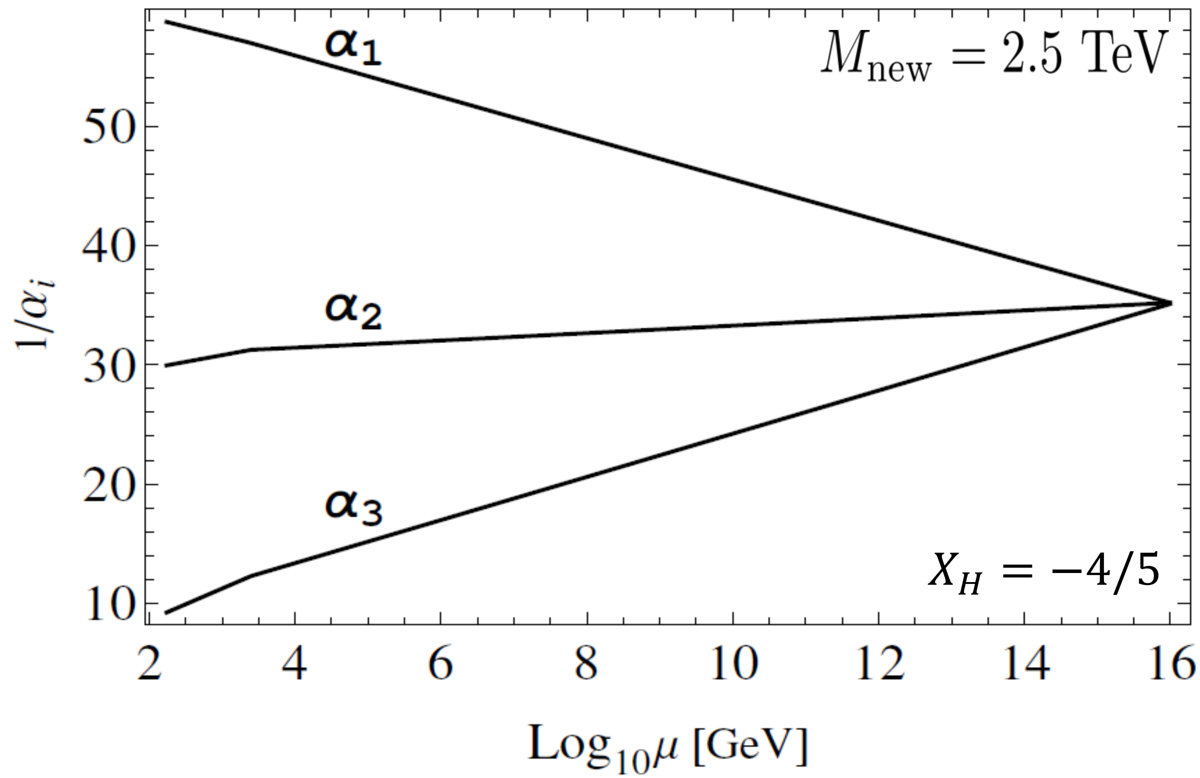
$$V \supset \sqrt{2} = \lambda' v_X \left(\Phi H^\dagger_{u/d} H_{u/d}\right)$$

- Decay width: $\Gamma_\phi \simeq \dfrac{2\lambda'^2 v_X^2}{\pi\, m_\phi}$

$$T_R \simeq 10^{10}\ \mathrm{GeV} \left(\frac{\lambda'}{1.10\times 10^{-9}}\right)$$

IV. Grand Unification and proton decay

SM + New Particle (fermions + doublet Higgs)



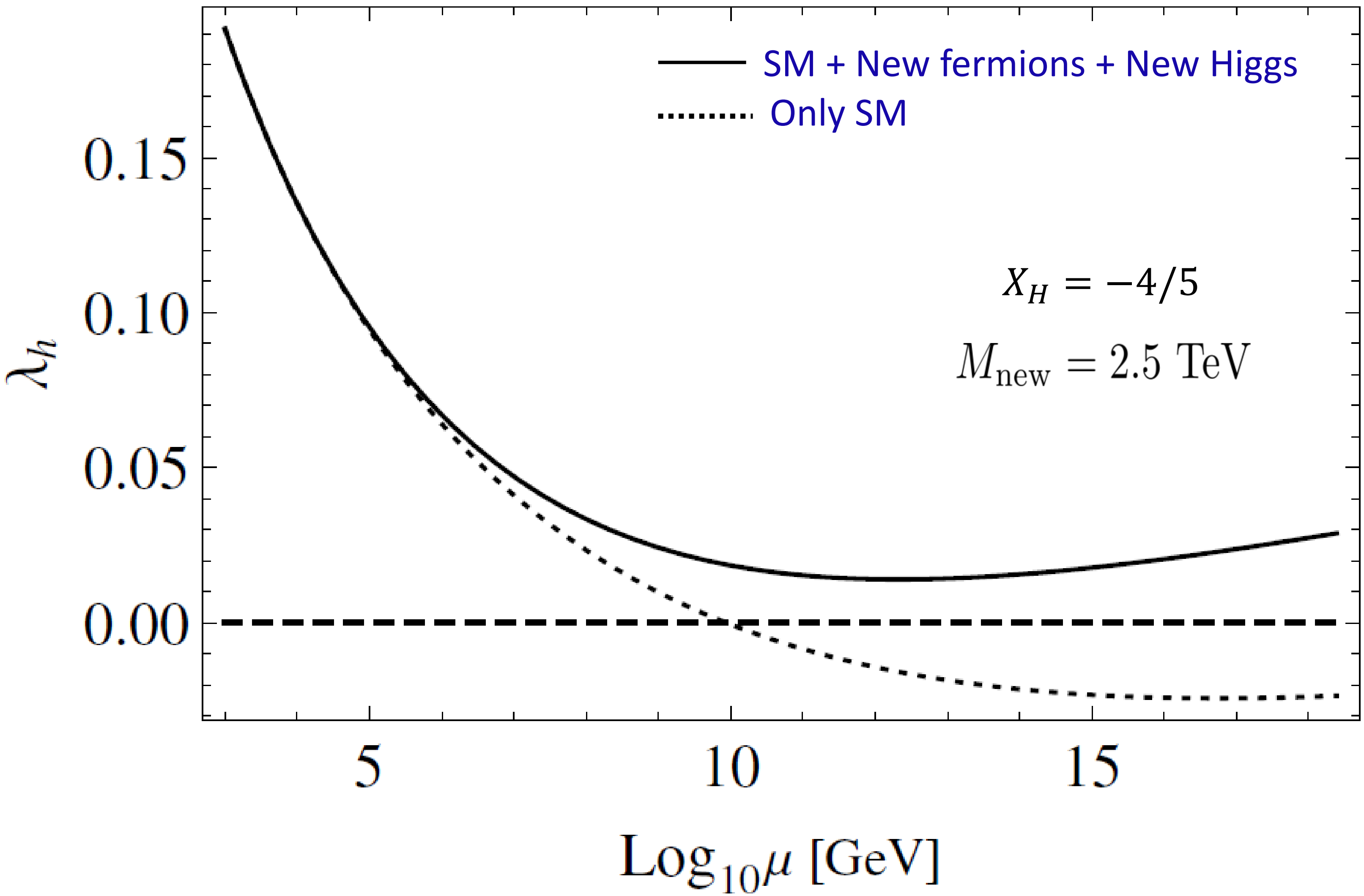
$1/\alpha_{GUT} \simeq 35$

$M_{GUT} \simeq 9.8 \times 10^{15}$ GeV

$$\tau_p \simeq \frac{1}{\alpha_{GUT}^2} \frac{M_{GUT}^4}{m_p^5} \simeq 2.6 \times 10^{35} \text{ years}$$

- Current experimental bound: Super-K: $\tau_p > 10^{34}$ years
- Future experimental reach : Hyper-K: $\tau_p < 1.3 \times 10^{35}$ years

V. SM Higgs potential stabilization

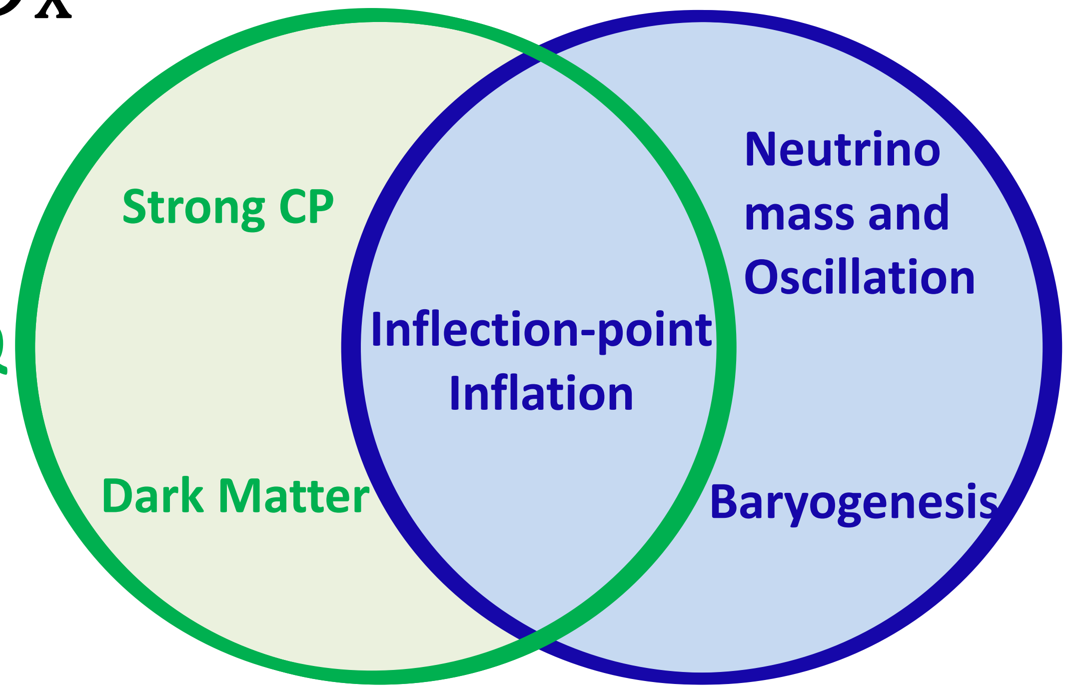


RG running of the SM Higgs quartic coupling

Summary

SMART–U(1)$_X$:

SM x U(1)$_{PQ}$



U(1)$_X$

A single model to address 5 fundamental shortcomings of the SM

- **SMART U(1)$_X$ with grand unification:**
  - **Charge quantization** ✓
  - **Stability of the Electroweak Vacuum?** ✓

Thank you

Questions?

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