$SU(5) \times U(1)_X$ Axion Model with Observable Proton Decay

Digesh Raut

draut@udel.edu

University of Delaware

with Nobuchika Okada (U. Alabama) & Qaisar Shafi (U. Delaware)

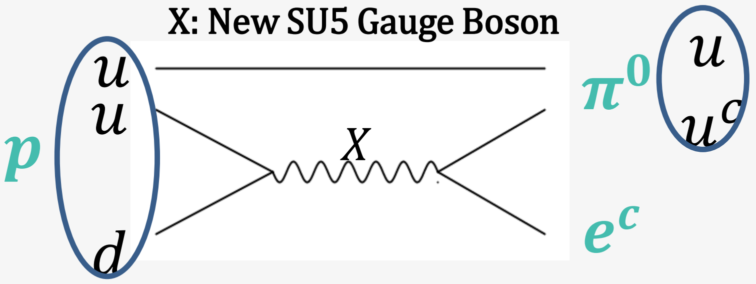
(manuscript in preparation)

❑ Predictions of Grand Unified Theories:

- Unification of all three SM (3-2-1) forces at high energies
- Charge quantization
- Proton decay:

Current Bound Super-K: $\tau_p \gtrsim 1.6 \times 10^{34}$ years

Future Reach Hyper-K: $\tau_p \lesssim 1.3 \times 10^{35}$ years



❑ Model:

$$SU(5) \times U(1)_X \times U(1)_{PQ}$$

Model:

❑ $U(1)_X$ Symmetry:

- Generalization of $\mathbf{U(1)_{B-L}}$: $$Q_X = Q_Y x_H + Q_{B-L}$$ x_H is a free parameter

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

- For $x_H = -\frac{4}{5}$, representation of SM particle unify under $SU(5)$:

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$$

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

- Includes Majorana Neutrinos for anomaly cancellation

❑ $U(1)_{PQ}$ Symmetry:

- Resolution of the Strong CP problem *R.D. Peccei and H.R. Quinn (1977)*

- Provides Axion as a dark matter candidate *S. Weinberg (1978), F. Wilczek (1978)*

Particle Content:

- Three generations of Standard Model Fermions
- Two heavy vector-like fermion pairs
  - SM gauge coupling unification
- Resolution of Strong CP problem (KSVZ type axion)
- Baryon Asymmetry & Inflation
- Break SU(5) and PQ symmetry
- Low Scale Inflation
  - Viability of axion DM scenario

	SU(5)	$U(1)_X$	$U(1)_{PQ}$
$\psi^i_{\bar{5}}$	$\bar{\mathbf{5}}$	$-3/5$	0
ψ^i_{10}	$\mathbf{10}$	$+1/5$	0
$\tilde{\psi}_5$	$\mathbf{5}$	$+3/5$	1
$\tilde{\psi}_{\overline{10}}$	$\overline{\mathbf{10}}$	$-1/5$	1
$(N^c)^j$	$\mathbf{1}$	$+1$	0
Σ	$\mathbf{24}$	0	-1
S	$\mathbf{1}$	0	-1
Φ	$\mathbf{1}$	-2	0
H	$\mathbf{5}$	$-2/5$	0

Axion:

$$V = V(\Sigma, S)$$

$$\langle \Sigma \rangle = \frac{1}{2\sqrt{15}} v_\Sigma \, \mathrm{diag}(-2,-2,-2,3,3)$$
$$\langle S \rangle = \frac{1}{\sqrt{2}} v_S$$

	SU(5)	$U(1)_X$	$U(1)_{PQ}$
Σ	**24**	0	-1
S	1	0	-1

❑ Mass Spectrum:

- 12 massive gauge boson and 37 massive scalars

- **1 Massless Scalar (Axion):**

$$a(x) = \frac{1}{v_{PQ}} \left(v_S \, \chi_S(x) + v_\Sigma \, \chi_\Sigma(x) \right)$$

$$v_{PQ} = \sqrt{v_\Sigma^2 + v_S^2} \qquad f_a = \frac{v_{PQ}}{N_{DM}}$$

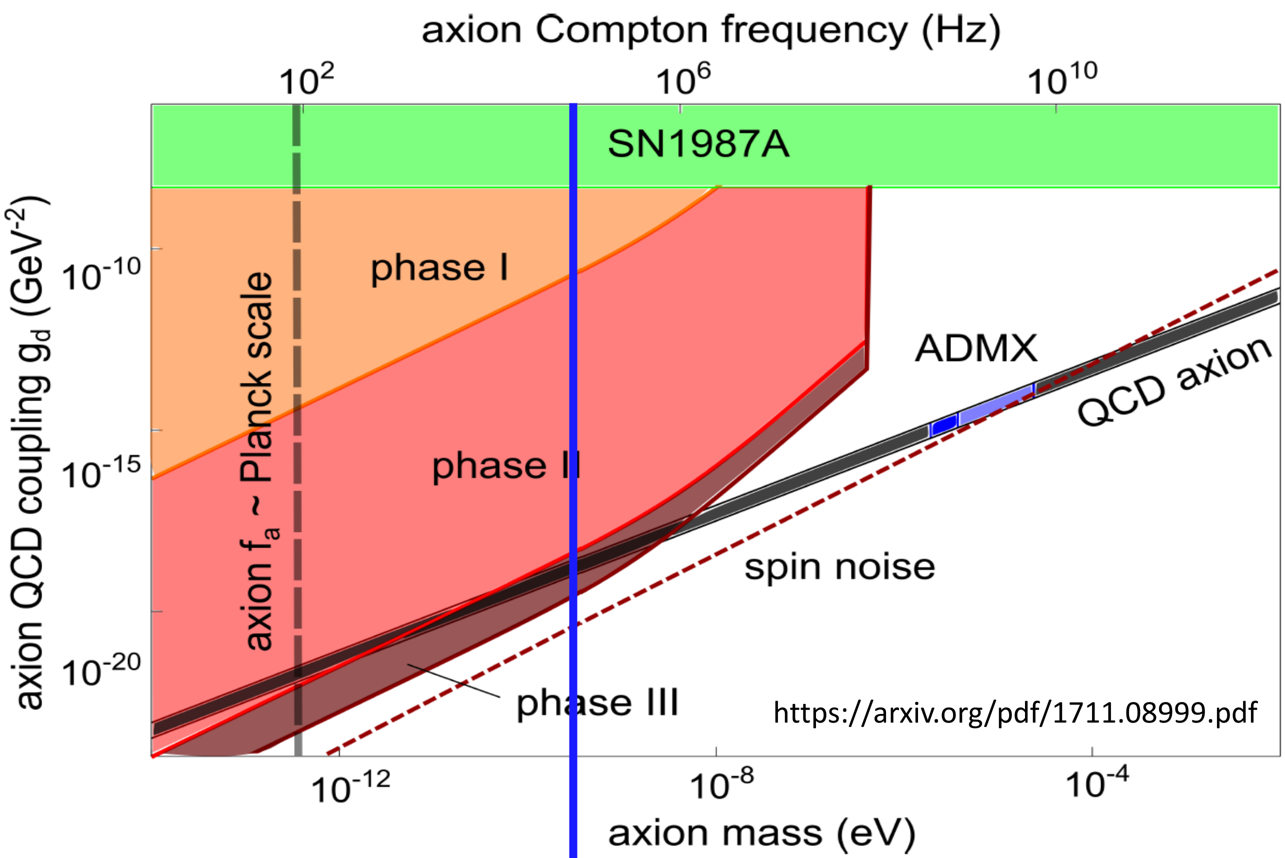
axion decay constant

$$N_{DW} = 3$$

Axion Domain-wall Problem

Axion Search CASPEr:

To avoid rapid proton decay: $f_a \simeq \sqrt{v_\Sigma^2 + v_S^2} \simeq v_\Sigma \gtrsim 10^{16}\mathrm{GeV}$

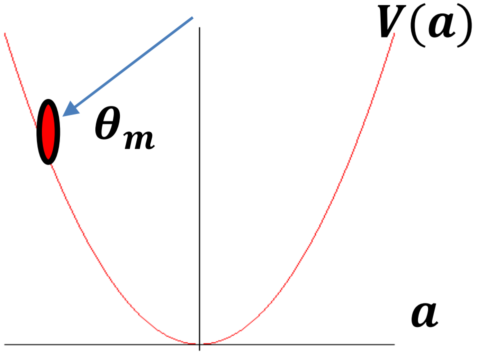


$f_a \gtrsim 10^{16}\mathrm{GeV}$

Axion:

$$\Omega_a h^2 \simeq 0.12 \left(\frac{\theta_a}{3.40\times10^{-3}}\right)^2 \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)^{1.19}$$

$$f_a \simeq \sqrt{v_\Sigma^2 + v_S^2} \simeq v_\Sigma \simeq 10^{16}\mathrm{GeV}$$



- If inflation occurs after PQ symmetry breaking, axion fluctuation predict too large "isocurvature perturbations":

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

(Planck 2018)

- **Relic Abundance + Isocurvature:**

$$\theta \simeq 3.40 \times 10^{-3} \qquad H_{inf} \lesssim 5.73 \times 10^{8}\ \mathrm{GeV}$$

Axion Dark Matter and Inflation:

- 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 (2016)

- **Inflection-point Inflation (IPI):** *N. Okada and D. Raut, Phys. Rev. D 95, no.3, 035035 (2017)*

  - Gauge and Yukawa interactions is crucial to realize an approximate inflection-point at a horizon exit scale M which can be freely chosen.
  - Gauged U(1) extended SM
  - Inflaton field breaks the U(1)

Independent of particle content

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

✓ Inflationary Predictions are consistent with Planck.

	$SU(5)$	$U(1)_X$	$U(1)_{PQ}$
Φ	1	-2	0

$$M \leq 0.20 M_P$$

$$H_{inf} \lesssim 5.73 \times 10^8\ \text{GeV}$$

Gauge Coupling Unification:

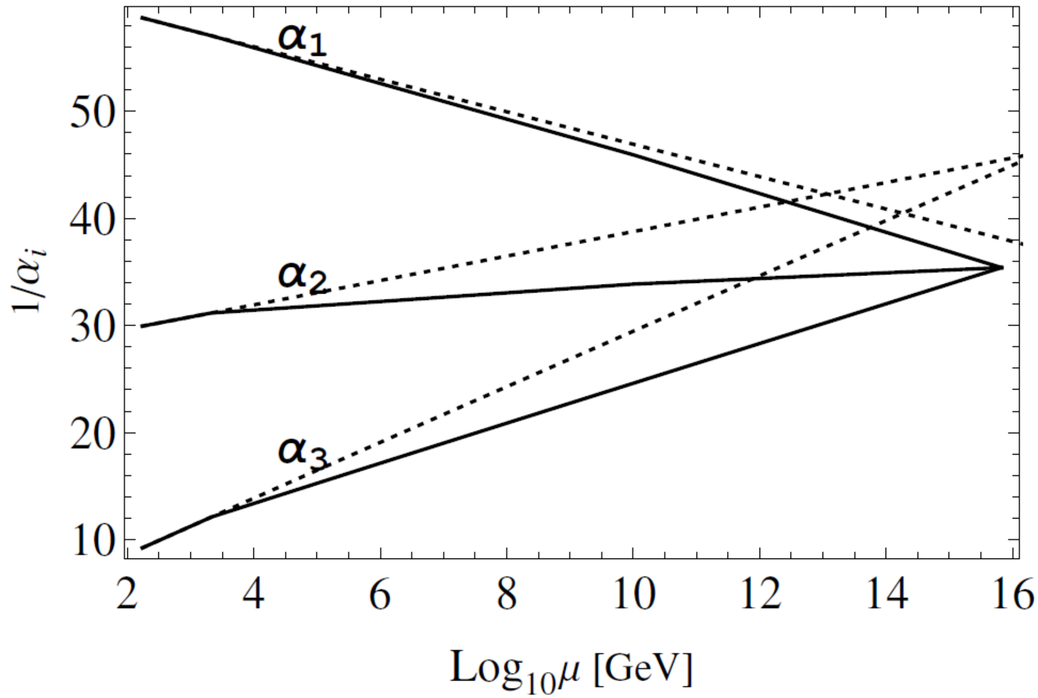
$$\Psi^4_{\bar{5}} = D^c(\mathbf{3}^*, \mathbf{1}, -\mathbf{2}/\mathbf{3}) \oplus L(\mathbf{1}, \mathbf{2}, -\mathbf{1}/\mathbf{2})$$

$$\Psi^4_{10} \supset Q(\mathbf{3}, \mathbf{2}, \mathbf{1}/\mathbf{6})$$

$M_Q = 2200$ GeV

$M_L = 10^{10}$ GeV

$$\tau_p \simeq \frac{1}{\alpha^2_{GUT}} \frac{M^4_{GUT}}{m^5_p} \simeq 5.8 \times 10^{34} \text{years}$$



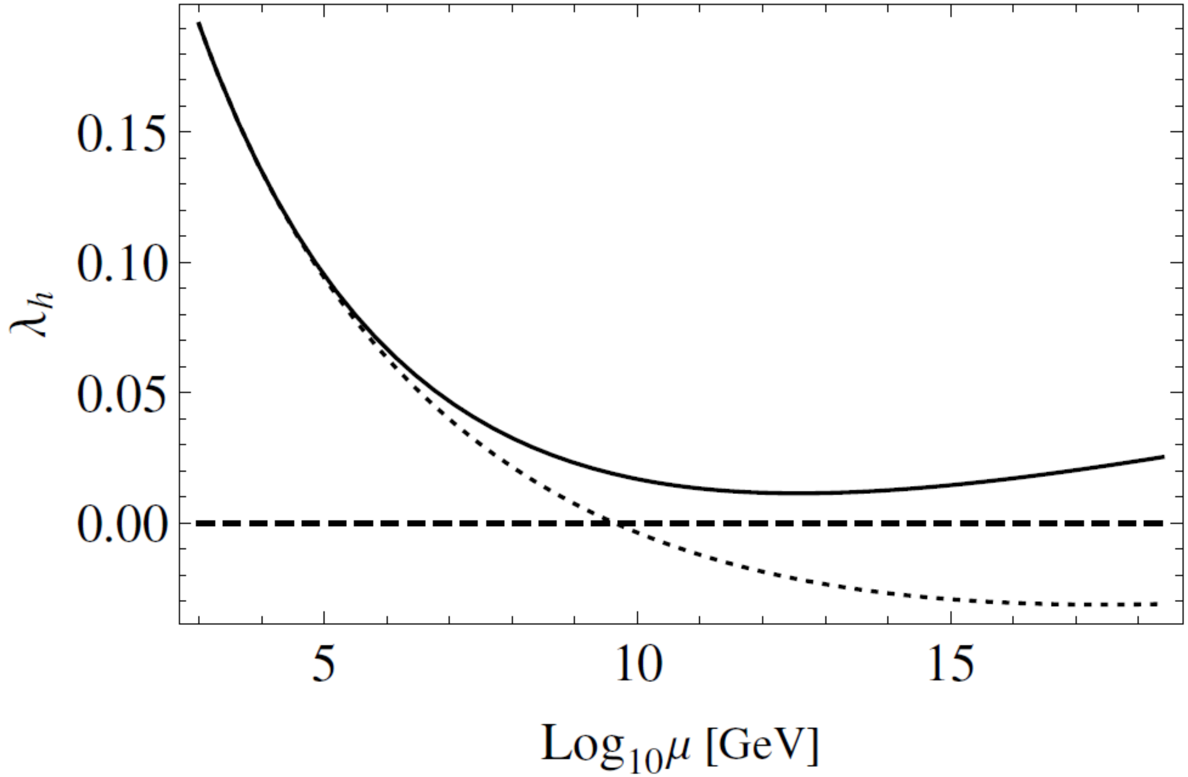
- Current experimental bound: Super-K: $\tau_p > 1.6 \times 10^{34}$ years
- Future experimental reach : Hyper-K: $\tau_p < 1.3 \times 10^{35}$ years

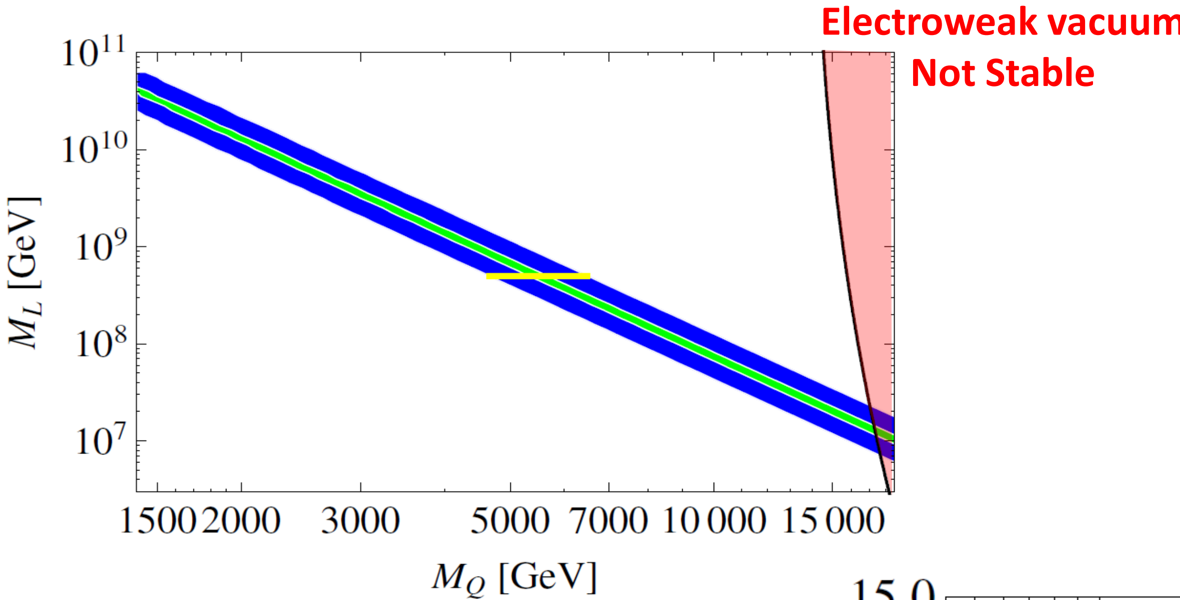
Electroweak Vacuum Stability:

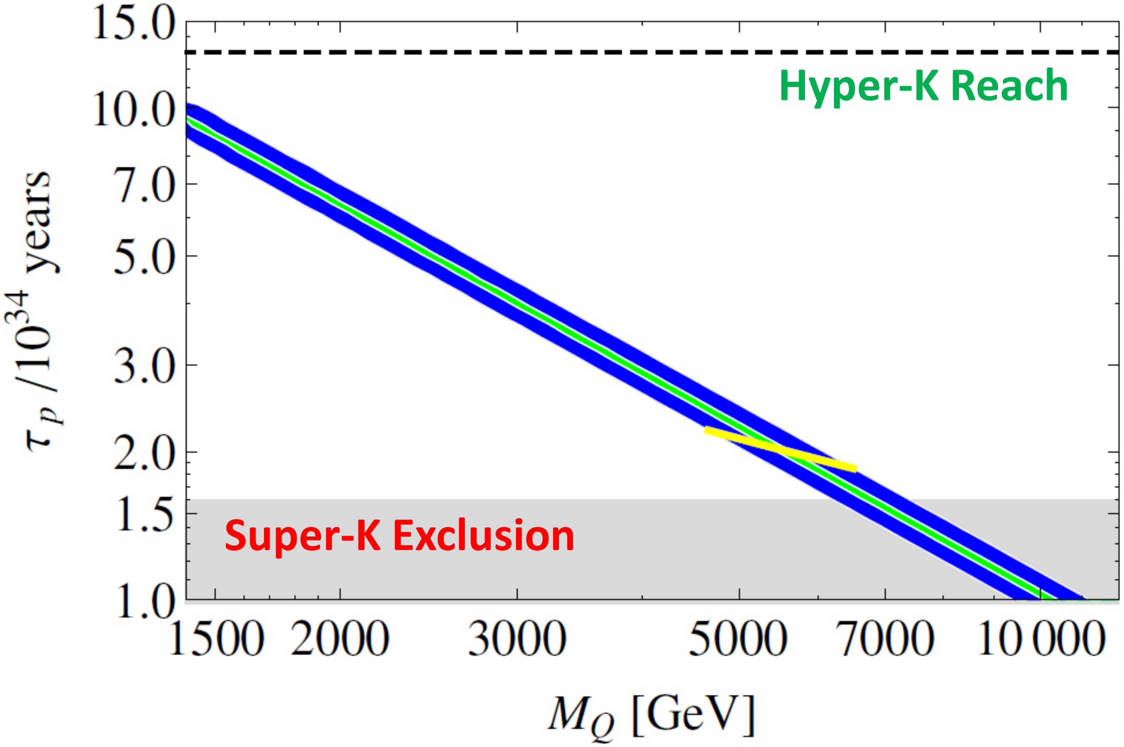
$$\Psi^4_{\bar{5}} = D^c(\mathbf{3}^*, \mathbf{1}, -\mathbf{2}/\mathbf{3}) \oplus L(\mathbf{1}, \mathbf{2}, -\mathbf{1}/\mathbf{2})$$
$$\Psi^4_{10} \supset Q(\mathbf{3}, \mathbf{2}, \mathbf{1}/\mathbf{6})$$

$M_Q = 2200$ GeV
$M_L = 10^{10}$ GeV

- **Stability of Electroweak Vacuum:**




Electroweak vacuum
Not Stable
M_L [GeV]
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
1500 2000 3000 5000 7000 10 000 15 000
M_Q [GeV]


Hyper-K Reach
Super-K Exclusion
$\tau_p/10^{34}$ years
15.0
10.0
7.0
5.0
3.0
2.0
1.5
1.0
1500 2000 3000 5000 7000 10 000
M_Q [GeV]

Thermal Leptogenesis

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

S. Davidson and A. Barra (2002)

Lightest Neutrino (N^1) Interactions:

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

N. Okada, D. Raut, and Q. Shafi, Eur. Phys. J. C 80 22 (2020)

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

P. S. B. Dev, R. N. Mohapatra and Y. Zhang (2018)

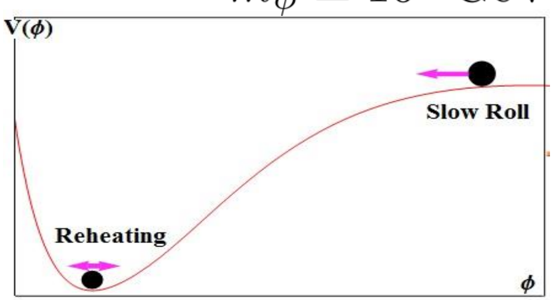
- These processes should decouple before plasma temperature drops to $T \simeq m_{N^1}$ to prevent washing out of lepton asymmetry generated through thermal leptogenesis:

$$\left.\frac{\sigma(T)\times n_{eq}(T)}{H(T)}\right|_{T=m_{N^1}} < 1 \quad \Rightarrow \quad v_X > 5.95 \times 10^{10} \text{ GeV}$$

(Consistent to our VEV choice)

Reheating:

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



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

$$V \supset= 2\lambda' v_X \left(\Phi H^\dagger H\right)$$

$$T_R \simeq 10^{10} \text{ GeV} \left(\frac{\lambda'}{9.86\times 10^{-9}}\right)$$

Summary

Key features of the $\mathrm{SU}(5) \times \mathrm{U}(1)_{\mathrm{X}} \times \mathrm{U}(1)_{\mathrm{PQ}}$ model proposal :

- GUT and PQ symmetry breaking are intimately related to each other
- Predict observable proton decay
- Axion can be searched at CASPEr experiment
- Low scale Inflation implemented to make the axion scenario phenomenologically viable
- Leptogenesis can generate baryon asymmetry

draut@udel.edu **Questions/Comments ?**