Neutrino masses, Inflation and Dark Matter
In Grand Unified Theories

Nobuchika Okada
University of Alabama

Based on collaborations with
Masato Arai, Shinsuke Kawai, George Leontaris,
Satomi Okada, Digesh Raut, Qaisar Shafi

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Problems of the Standard Model

Although the Standard Model (SM) is the best theory so far, New Physics beyond SM is strongly suggested by both experimental & theoretical points of view.

What is missing?

1. Neutrino masses and flavor mixings
2. Dark matter candidate
3. Origin of the baryon asymmetry of the Universe
4. Cosmological Inflation
5. others

New Physics must supplement the missing pieces.
Grand Unified Theory paradigm

- Unification of all the SM gauge interactions
- Quark-lepton Unification
- Electric charge quantization
- Mathematical beauty
- Prediction of proton decay

New Physics ⊂ GUTs

GUTs must supplement the SM missing pieces
Origin of tiny neutrino masses

Seesaw Mechanism is the most elegant way

Introducing Right-Handed Neutrinos (type-I seesaw)

\[ \mathcal{L} \supset - \sum_{i,j} y_{ij}^D N_i^c \ell_j H - \frac{1}{2} \sum_k M_k N_k^c N_k^c \]

Neutrino Dirac mass after EWSB

Majorana Mass allowed/generated

\[ m_\nu \simeq m_D^T M^{-1} m_D \ll m_D \]
Link to the generation of BAU: **Leptogenesis**

CP-asymmetric out-of-equilibrium decay of heavy neutrinos

→ Lepton asymmetry of the Universe

→ BAU from LAU via sphaleron process

**Seesaw Mechanism**

- Tiny neutrino masses
- Baryon Asymmetry of the Universe
Dark Matter Particle

- Existence of DM has been established.
- DM carries 27% of energy budget of the Universe

Properties of DM particle: electrically neutral (quasi) stable non-baryonic

- Thermal relic
- or
- Non-thermal relic

Precision measurements of CMB anisotropy
Cosmological Inflation

Standard paradigm in modern cosmology

Providing solutions to

- Horizon Problem
- Flatness Problem
- Primordial density fluctuation

Inflating away unwanted relics

- Topological defects (monopoles & strings) associated with GUT symmetry breakings must be diluted

Cosmological inflation is necessary for GUTs

\[ H_{inf} < M_{GUT} \]
Simple inflation scenario to be incorporated in GUTs

Quartic potential with non-minimal gravitational coupling

\[ S_{\text{tree}}^E = \int d^4x \sqrt{-g} \left[ - \left( \frac{1 + \xi \phi^2}{2} \right) \mathcal{R} + \frac{1}{2} (\partial \phi)^2 - \frac{\lambda}{4} \phi^4 \right] \]

Einstein frame: \( g_{E\mu\nu} = (1 + \xi \phi^2) g_{\mu\nu} \)

\[ S_E = \int d^4x \sqrt{-g_E} \left[ - \frac{1}{2} \mathcal{R}_E + \frac{1}{2} (\partial_E \sigma_E)^2 - V_E(\sigma_E(\phi)) \right] \]

\[ V_E(\phi) = \frac{\lambda}{4} \frac{\phi^4}{(1 + \xi \phi^2)^2} \rightarrow \frac{\lambda}{4\xi^2} \]

Potential becomes very flat in the presence of non-minimal coupling.
Non-minimal quartic inflation V.S Planck 2018 result

\[ V = \frac{\lambda}{4} \phi^4 \]

\[ V = \frac{1}{2} m^2 \phi^2 \]

\[ N = 50, 60 \]

\[ \xi \quad r \]
\[ 10^{-4} \quad 0.24 \]
\[ 10^{-3} \quad 0.17 \]
\[ 10^{-2} \quad 0.045 \]
\[ 0.1 \quad 0.0078 \]
\[ 1 \quad 0.0039 \]
\[ 10 \quad 0.003 \]

Larger \( \xi \)
GUT models supplemented with Seesaw Mechanism, DM candidate & Inflation

Two categories

SUSY GUTs

✓ SM gauge coupling unification

✓ DM candidate (neutralino/gravitino)

Seesaw Mechanism?

Inflation?
GUT models supplemented with Seesaw Mechanism, DM candidate & Inflation

Two categories

<table>
<thead>
<tr>
<th>SUSY GUTs</th>
<th>Non-SUSY GUTs</th>
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SUSY GUTs

Example 1: **SUSY SU(5) GUT with RHNs**

Introduce Majorana Right-Handed Neutrinos (RHNs)

\[
W \supset y_D^{ij} N_i^c \bar{\psi}_j H_5 + \frac{1}{2} M_i N_i^c N_i^c \\
\supset y_D^{ij} N_i^c L_j H_u + \frac{1}{2} M_i N_i^c N_i^c
\]

✓ SM gauge coupling unification
✓ DM candidate (neutralino/gravitino)
✓ Seesaw Mechanism

Successful Inflation?
Higgs-Lepton inflation

- Identify inflaton as Higgs-Slepton D-flat direction

\[ L_k = \frac{1}{2} \begin{pmatrix} \varphi \\ 0 \end{pmatrix}, \quad H_u = \frac{1}{2} \begin{pmatrix} 0 \\ \varphi \end{pmatrix}. \]

- Suitable choice of Kahler potential in superconformal framework in SUGRA

\[ \mathcal{K} \supset -3M_P^2 + |L_k|^2 + |H_u|^2 - \frac{3}{2}\gamma (L_k H_u + h.c.). \]

SUGRA action for the inflaton is found to be

\[
S_J = \int d^4x \sqrt{-g} \left[ -\frac{1}{2} \left( M_P^2 + \xi \varphi^2 \right) \mathcal{R} + \frac{1}{2} (\partial \varphi)^2 - \frac{\lambda}{16} \varphi^4 \right]
\]

Nothing but the non-minimal quartic inflation!

\[ \xi \equiv \frac{\gamma}{4} - \frac{1}{6}, \quad \lambda \equiv (y_D^\dagger y_D)_{kk} \]
Example 2: **Non-minimal Quartic Inflation in SUSY SO(10)**

- Matter 16-plets include RHNs
- Higgs multiplets for SO(10) breaking \(16_H + \bar{16}_H + 45_H\)
  \[
  \mathcal{W} \supset \frac{1}{2} m_A A^2 + \bar{z}(m - yA)z
  \]
- Suitable Kahler potential
  \[
  \mathcal{K} \supset -3M_P^2 + |\bar{z}|^2 + |z|^2 - \frac{3}{2} \gamma (\bar{z}z + h.c.)
  \]
- We identify \(z-z^*\) D-flat direction as the inflaton

- SM gauge coupling unification
- DM candidate (neutralino/gravitino)
- Seesaw Mechanism
- Successful Inflation
Non-SUSY GUTs

Example: \textbf{SU(5)XU(1) GUT with Minimal Seesaw & RHN DM}

<table>
<thead>
<tr>
<th></th>
<th>SU(3)$_C$</th>
<th>SU(2)$_L$</th>
<th>U(1)$_Y$</th>
<th>U(1)$_X$</th>
<th>Z$_2$</th>
</tr>
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<tbody>
<tr>
<td>$q^i_L$</td>
<td>3</td>
<td>2</td>
<td>1/6</td>
<td>1/5</td>
<td>+</td>
</tr>
<tr>
<td>$(u^i_R)^c$</td>
<td>3*</td>
<td>1</td>
<td>-2/3</td>
<td>1/5</td>
<td>+</td>
</tr>
<tr>
<td>$(d^i_R)^c$</td>
<td>3*</td>
<td>1</td>
<td>+1/3</td>
<td>-3/5</td>
<td>+</td>
</tr>
<tr>
<td>$\ell^i_L$</td>
<td>1</td>
<td>2</td>
<td>-1/2</td>
<td>-3/5</td>
<td>+</td>
</tr>
<tr>
<td>$(e^i_R)^c$</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>1/5</td>
<td>+</td>
</tr>
<tr>
<td>$(N^j_R)^c$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>+1</td>
<td>+</td>
</tr>
<tr>
<td>$(N_R)^c$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>+1</td>
<td>-</td>
</tr>
</tbody>
</table>

\[ \text{10-plet} \quad \text{5*-plet} \quad \rightarrow \text{DM} \]

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<tbody>
<tr>
<td>$H$</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
<td>-2/5</td>
<td>+</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>+2</td>
<td>+</td>
</tr>
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The model anomaly free in the presence of 3 RHNs

U(1) symmetry breaking by \( \langle \Phi \rangle = \frac{vX}{\sqrt{2}} \)

\( \rightarrow U(1) \times \) gauge boson (Z’) mass
RHNs Majorana masses

Introduction of \( Z_2 \) symmetry

3 right-handed neutrinos \( \rightarrow 2+1 \)

- 2 RHNs for the **Minimal Seesaw**
  - King, NPB 576 (2000) 85;
  - Frampton, Glashow & Yanagida, PLB 548 (2002) 119

- \( Z_2 \)-odd **1 RHN** for thermal Z’-portal Dark Matter
Phenomenological viability of SU(5) x U(1)x Model

- Successful gauge coupling unification?
- Theoretical consistency & consistency with the current experimental results?
- Successful Inflation?
Gauge coupling unification with extra-quarks

It is known that in the presence of vector-like heavy quarks with mass at the TeV scale, the successful gauge coupling can be achieved.


In the presence of vector-like quarks:

\[ D_L + D_R: \ (3, 1, \ 1/3) \]
\[ Q_L + Q_R: \ (3, 2, \ -1/6) \]

with mass of \( O(\text{TeV}) \)
DM & LHC Phenomenology

(1) $Z'$-portal RHN DM

RHN DM communicates with the SM particles through $Z'$ boson mediated processes

(2) $Z'$ boson search at the LHC Run-2

Search for a narrow resonance with the di-lepton final state at ATLAS and CMS with LHC Run-2
Cosmological & LHC Run-2 constraints

The (green) shaded region is the final result for the allowed parameters, with 36 fb [15], and our result is shown by the (red) dashed line. Combining all three constraints, we have obtained the upper bound on \( \alpha \) as a function of \( m_Z' \) in the range of 3 to 9.2 TeV. In Figure 1, we also show our combined results from the DM relic abundance being the up-type (\( \alpha \)) and down-type (\( m_Z' \)) quarks, respectively. By integrating the diagonal masses in the standard manner, while the U(1) boson resonance at the LHC. We can see these two constraints are complementary to narrow down the allowed parameter region. In Figure 1, we also show our combined results from the DM relic abundance. The diagonal masses in the standard manner, while the U(1) gauge boson bound in the range of 3 to 9.2 TeV.
SU(5)XU(1) GUT with Minimal Seesaw & RHN DM

✓ SM gauge coupling unification

✓ Minimal Seesaw

✓ RHN Z’-portal DM

✓ Inflation: non-minimal quartic inflation by identifying the U(1) Higgs field with inflaton
Summary

- What is missing in the SM must be supplemented by New Physics (GUT models)

- We have considered GUTs with Seesaw Mechanism, Dark Matter Candidate & Successful Inflation

- We have discussed 3 successful models in SUSY and Non-SUSY contexts

Another non-SUSY example: $\text{SO}(10) \times \text{U}(1)$ equipped with Seesaw Mechanism, Higgs-portal DM & inflection-point Inflation

By N.O, Raut & Shafi, in preparation