Neutrino masses, Inflation and Dark Matter In Grand Unified Theories

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Based on collaborations with

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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 $\supset$ GUTs

GUTs <u>must</u> supplement the SM missing pieces

Origin of tiny neutrino masses

Minkowski, Yanagida, Gell-Mann-Ramond-Slansky, Mohapatra-Senjanovic, ⋯

Seesaw Mechanism is the most elegant way

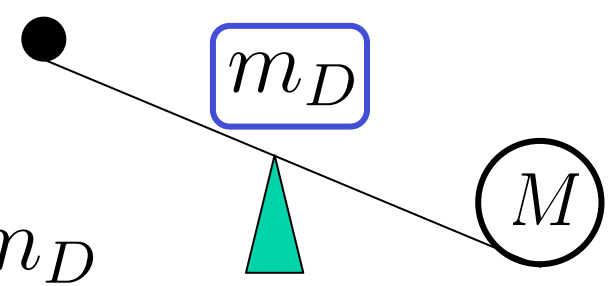
Introducing Right-Handed Neutrinos (type-I seesaw)

$$\mathcal{L} \supset -\sum_{i,j} y_D^{ij} N_i^c \ell_j H - \frac{1}{2}\sum_k M_k N_k^c N_k^c$$

Neutrino Dirac mass after EWSB

Majorana Mass allowed/generated

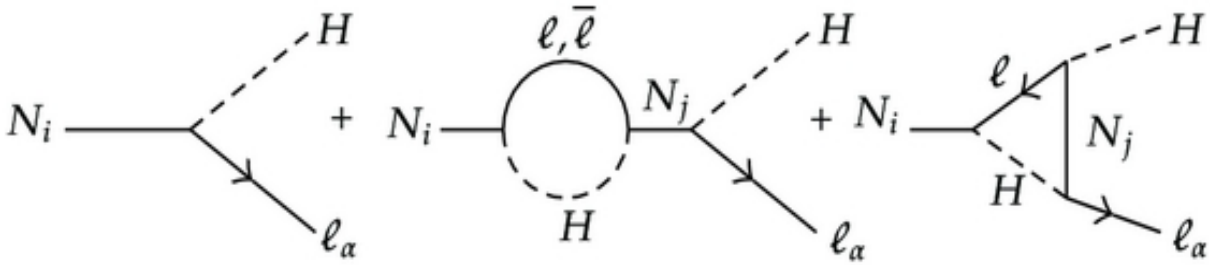
$$m_\nu \simeq m_D^T M^{-1} m_D \ll m_D$$



Link to the generation of BAU: Leptogenesis

Fukugita-Yanagida, PLB 174 (1986) 45

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



→ Lepton asymmetry of the Universe

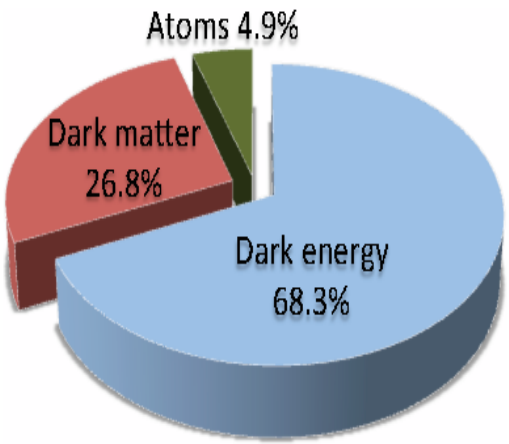
→ BAU from LAU via sphaleron process

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



Precision measurements of CMB anisotropy

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

Thermal relic
or
Non-thermal relic

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

$$H_{inf} < M_{GUT}$$

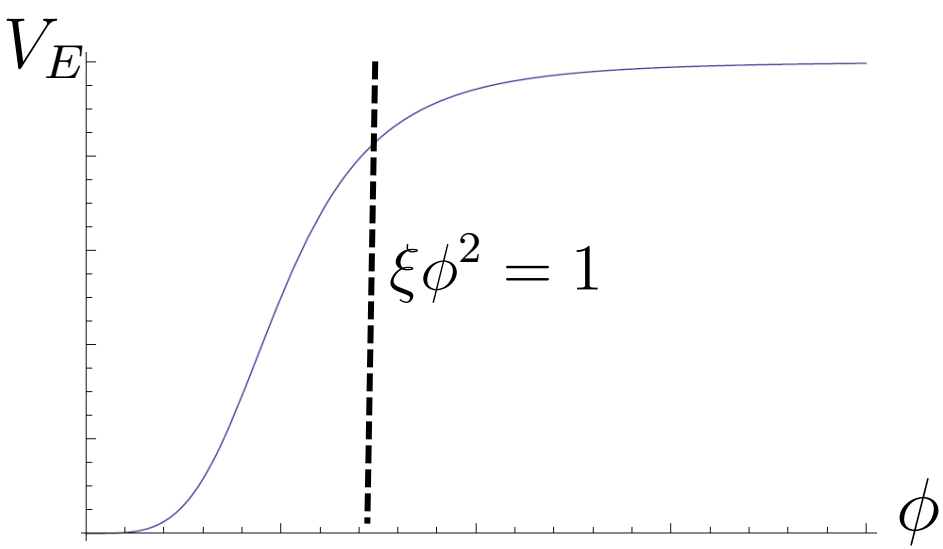
Simple inflation scenario to be incorporated in GUTs

Quartic potential with non-minimal gravitational coupling

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

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

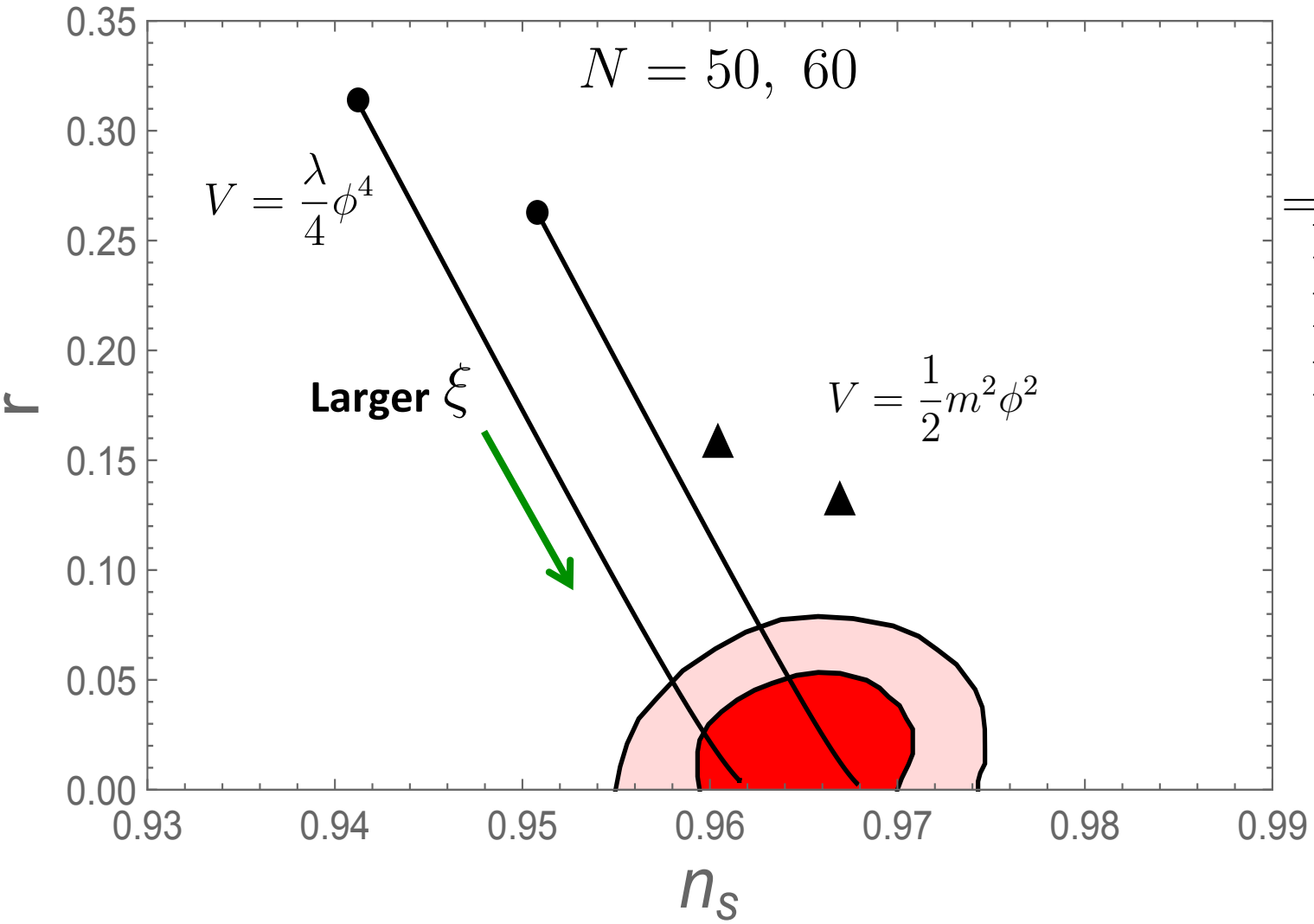
$$S_E = \int d^4x\sqrt{-g_E}\left[-\frac{1}{2}\mathcal{R}_E + \frac{1}{2}(\partial_E\sigma_E)^2 - V_E(\sigma_E(\phi))\right]$$



$$V_E(\phi) = \frac{\lambda}{4}\frac{\phi^4}{(1+\xi\phi^2)^2} \to \frac{\lambda}{4\xi^2}$$

Potential becomes very flat in the presence of non-minimal coupling

Non-minimal quartic inflation V.S Planck 2018 result



N=60

ξ	r
10^{-4}	0.24
10^{-3}	0.17
10^{-2}	0.045
0.1	0.0078
1	0.0039
10	0.003

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

SUSY GUTs

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

Seesaw Mechanism?

Inflation?

Non-SUSY GUTs

SM gauge coupling unification?

DM candidate?

Seesaw Mechanism?

Inflation?

SUSY GUTs

Example 1: SUSY SU(5) GUT with RHNs

Introduce Majorana Right-Handed Neutrinos (RHNs)

$$
\begin{aligned}
W &\supset y_D^{ij} N_i^c \psi_{\bar{5}j} H_5 + \frac{1}{2} M_i N_i^c N_i^c \\
&\supset y_D^{ij} N_i^c L_j H_u + \frac{1}{2} M_i N_i^c N_i^c
\end{aligned}
$$

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

Successful Inflation?

Higgs-Lepton inflation

Arai, Kawai & N.O,
PRD 87 (2013) 065009

- 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

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

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!

$$\xi \equiv \frac{\gamma}{4} - \frac{1}{6}$$
$$\lambda \equiv (y_D^\dagger y_D)_{kk}$$

SUSY GUTs

Leontaris, N.O &Shafi, PLB 765 (2017) 256

Example 2: Non-minimal Quartic Inflation in SUSY SO(10)

- Matter 16-plets include RHNs
- Higgs multiplets for SO(10) breaking $\mathbf{16}_H + \overline{\mathbf{16}}_H + \mathbf{45}_H$

$$z \qquad \bar{z} \qquad A$$

$$\mathcal{W} \supset \frac{1}{2} m_A A^2 + \bar{z}(m - yA)z$$

- Suitable Kahler potential

$$\mathcal{K} \supset -3M_P^2 + |\bar{z}|^2 + |z^2| - \frac{3}{2}\gamma\left(\bar{z}z + h.c.\right)$$

- 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

N.O, Okada & Raut, PLB 780 (2018) 422

Example: SU(5)XU(1) GUT with Minimal Seesaw & RHN DM

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
q_L^i	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$1/5$	$+$
$(u_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$-2/3$	$1/5$	$+$
$(d_R^i)^c$	$\mathbf{3}^*$	$\mathbf{1}$	$+1/3$	$-3/5$	$+$
ℓ_L^i	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$-3/5$	$+$
$(e_R^i)^c$	$\mathbf{1}$	$\mathbf{1}$	-1	$1/5$	$+$
$(N_R^j)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$+$
$(N_R)^c$	$\mathbf{1}$	$\mathbf{1}$	0	$+1$	$-$

10-plet

5*-plet

→ DM

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_X$	Z_2
H	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$-2/5$	$+$
Φ	$\mathbf{1}$	$\mathbf{1}$	0	$+2$	$+$

- The model anomaly free in the presence of 3 RHNs

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

  → U(1)x gauge boson (Z') mass
  RHNs Majorana masses

- Introduction of Z_2 symmetry

3 right-handed neutrinos → 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

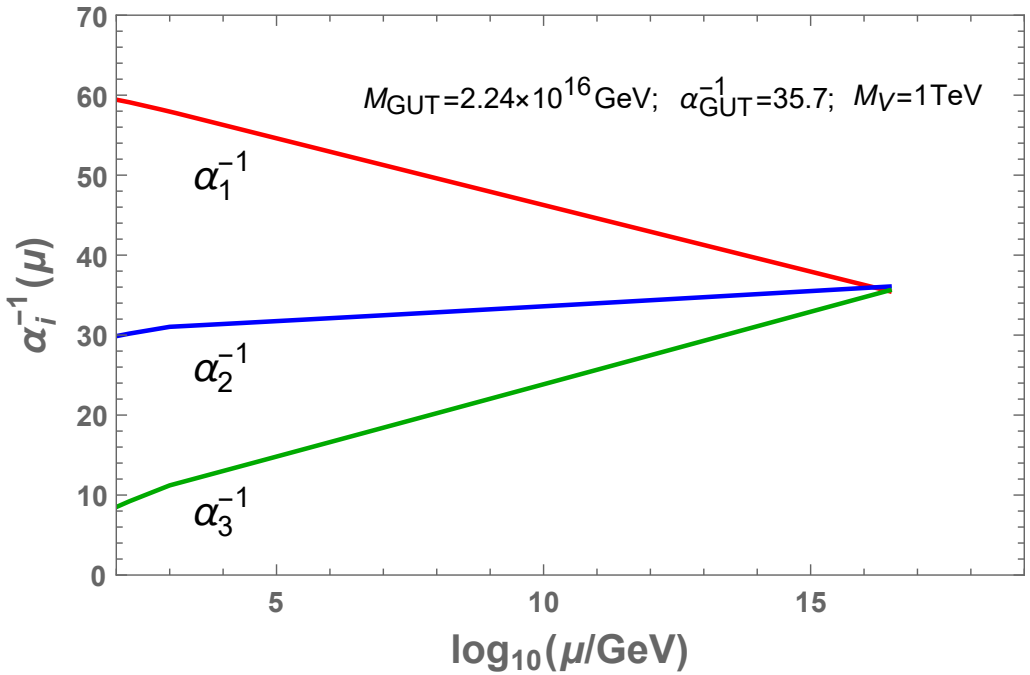
Phenomenological viability of SU(5) x U(1)*x* Model

- 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.

Amaldi et al., PLB 281 (1992) 374;
Chkareuli et al., PLB 340 (1994) 63;
Choudfury et al., PRD 65 (2002) 053002;
Gogoladze et al., PLB 690 (2010) 495



In the presence of vector-like quarks:

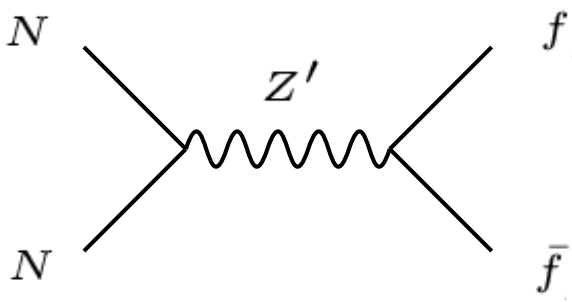
D_L+D_R: (**3, 1,** 1/3)
Q_L+Q_R: (**3, 2**, -1/6)

with mass of O(TeV)

DM & LHC Phenomenology

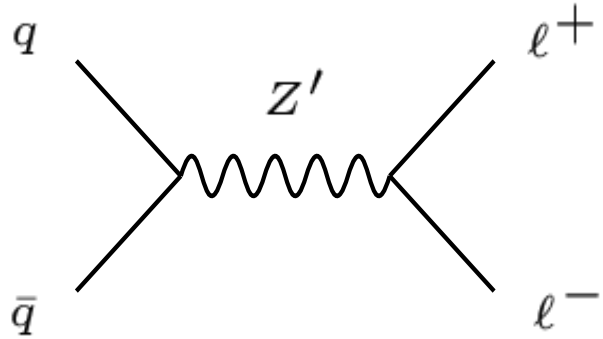
(1) Z'-portal RHN DM

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

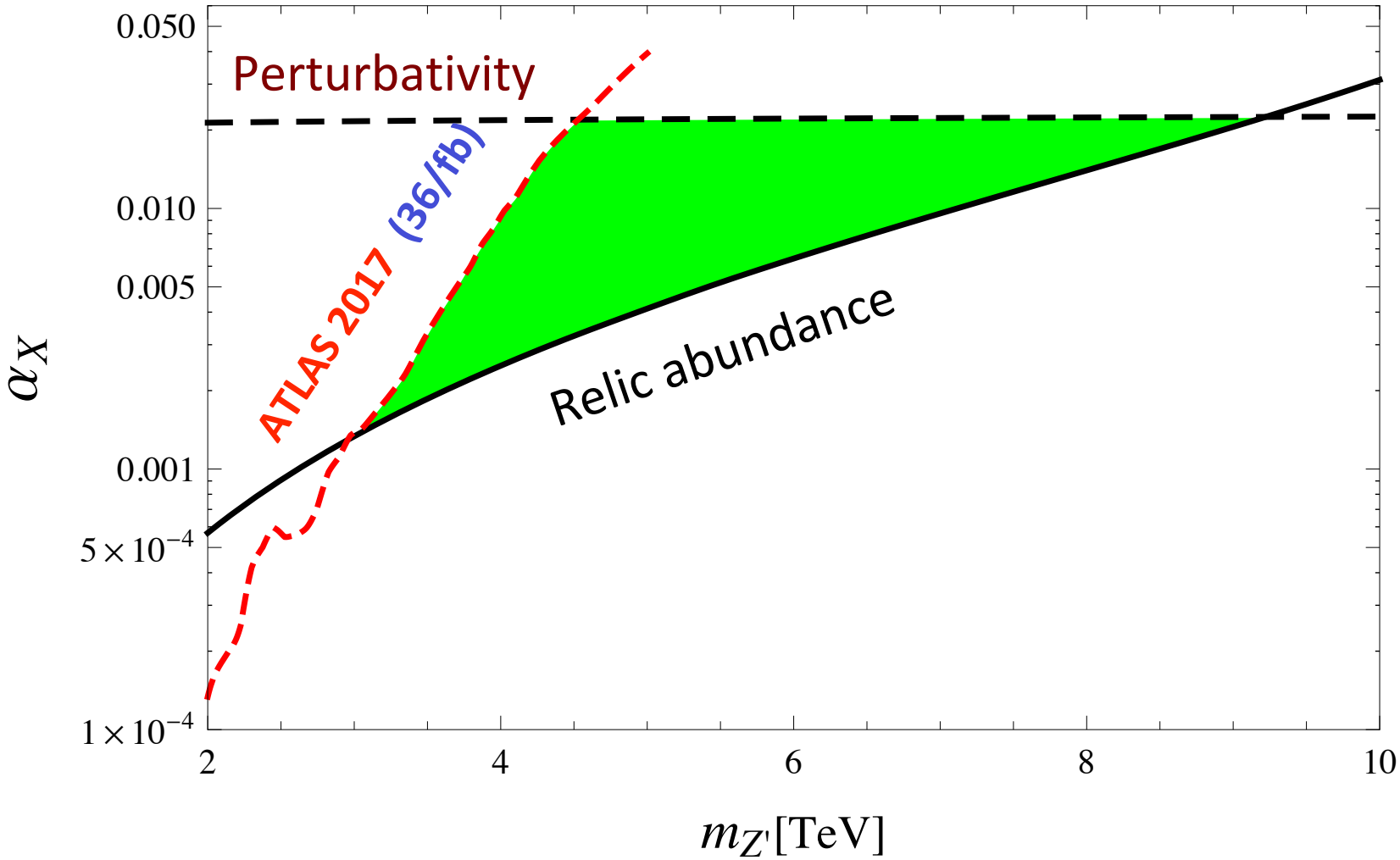


(2) Z' boson search at the LHC Run-2

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



➢ Cosmological & LHC Run-2 constraints



$$3.0 \leq m_{Z'}[\mathrm{TeV}] \leq 9.2$$

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: SO(10)xU(1) equipped with Seesaw Mechanism, Higgs-portal DM & inflection-point Inflation
By N.O, Raut & Shafi, in preparation