New model beyond the minimal standard model

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Reference

N. Haba, K. Kaneta, and R. Takahashi, arXiv:1309.3254 [hep-ph]

Contents

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- no DM candidate	- non-vanishing active ν masses
- BAU	- gauge hierarchy problem
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$$\mathcal{L}_{\rm NMSM} = \mathcal{L}_{\rm MSM} + \mathcal{L}_S(\rm DM) + \mathcal{L}_\Lambda(\rm DE) \\ + \mathcal{L}_N(\nu \ \rm mass, BAU) + \mathcal{L}_\varphi(\rm inflation)$$

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$\Rightarrow$ 130 GeV $\lesssim m_h \lesssim$ 180 GeV $(m_t(M_Z) = 174$ GeV$)$

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	SM	SUSY	NMSM
DM	–	○	○
$m_\nu \neq 0$	–	–	○
BAU	–	–	○
Hierarchy prob.	–	○	–
Vacuum stability	–	○	○
DE	–	–	○
Inflation	–	–	○
GCU	–	○	–

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	SM	SUSY	NMSM	NNMSM-II
DM	−	○	○	○
$m_\nu \neq 0$	−	−	○	○
BAU	−	−	○	○
Hierarchy prob.	−	○	−	×
Vacuum stability	−	○	○	○ w/ $m_h = 126$ GeV
DE	−	−	○	○
Inflation	−	−	○	○
GCU	−	○	−	○

- **We suggest a type-II next to new minimal SM (NNMSM-II) by extending the NMSM to achieve the GCU (a talk about (type-I) next to new minimal SM (NNMSM) will be given by Naoyuki Haba tomorrow).**

2. Model (NNMSM-II)

Particle contents ($i = 1, 2$):

	λ_3	λ_2	S	N_i	φ
$SU(3)_C$	$\mathbf{8}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
Z_2	$+$	$+$	$-$	$+$	$+$

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Lagrangian:

$$\mathcal{L}_{\mathrm{NNMSM-II}} = \mathcal{L}_{\mathrm{MSM}} + \mathcal{L}_S(\mathrm{DM}) + \mathcal{L}_\Lambda(\mathrm{DE}) + \mathcal{L}_N(\nu \text{ mass}, \mathrm{BAU}) + \mathcal{L}_\varphi(\text{inflation}) + \mathcal{L}'(\lambda_3, \lambda_2)$$

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Masses:

- DM mass m_S: abundance, vacuum stability
- Right-handed neutrino masses M_{Ri}: active neutrino mass, BAU
- Inflaton mass: Cosmological data
- Adjoint fermion masses M_3 and M_2: GCU

3. Gauge coupling unification

Renormalization group equations (RGEs) for gauge couplings:

$$2\pi \frac{d\alpha_j^{-1}}{dt} = b_j, \quad \alpha_j \equiv \frac{g_j^2}{4\pi}, \quad t \equiv \ln\mu,$$

with

$$(b_1^{\rm SM}, b_2^{\rm SM}, b_3^{\rm SM}) = (\frac{41}{10}, -\frac{19}{6}, -7),$$

$$(b_1^{\lambda_3}, b_2^{\lambda_3}, b_3^{\lambda_3}) = (0, 0, 2), \quad (b_1^{\lambda_2}, b_2^{\lambda_2}, b_3^{\lambda_2}) = (0, \frac{4}{3}, 0).$$

When we take

$$M_3 \simeq 7.44 \times 10^9 \ \text{GeV and} \ M_2 = 300 \ \text{GeV},$$

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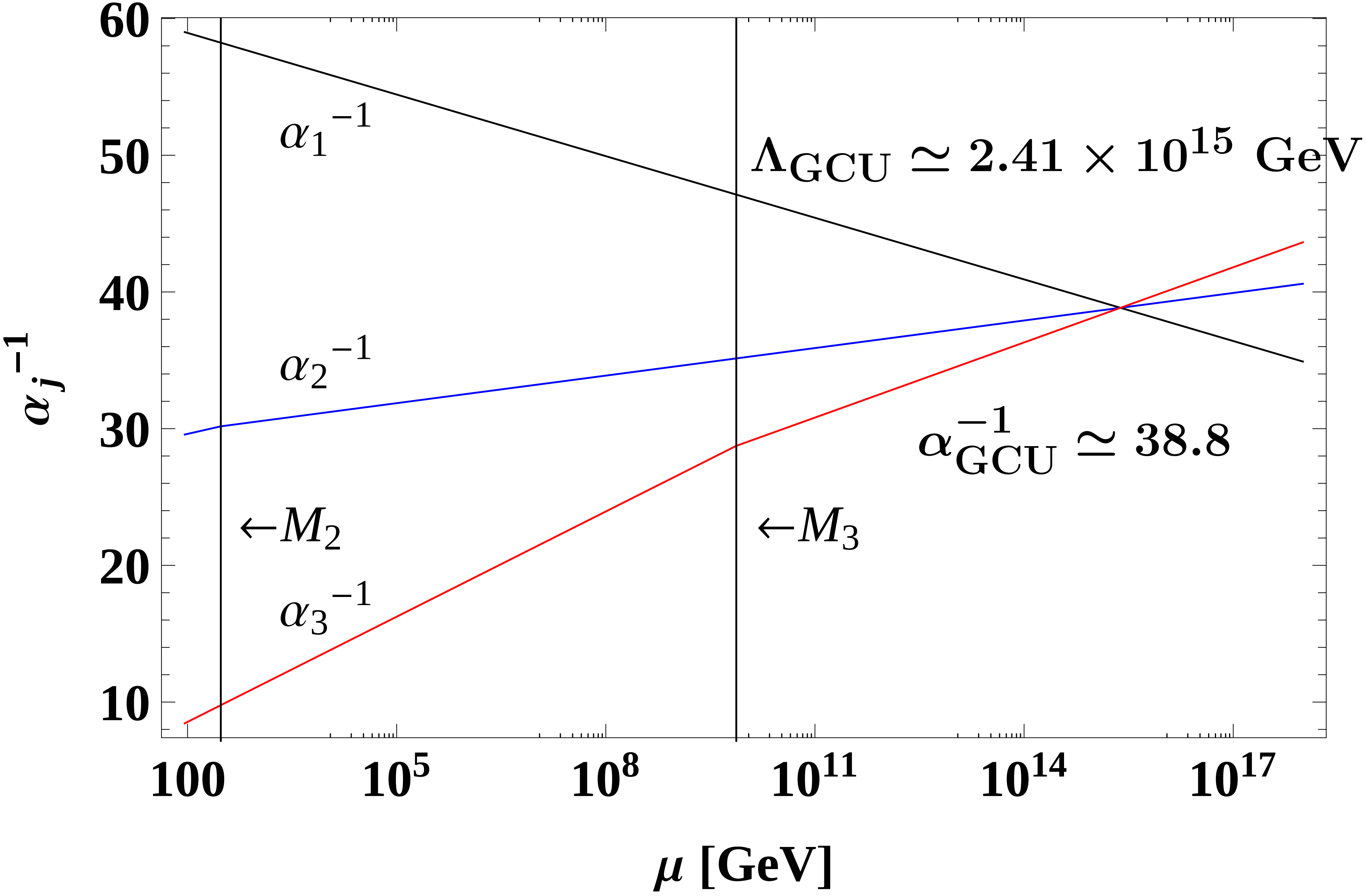


4. Stability, triviality, and dark matter

Scalar sector of the model (singlet S is DM):

$$\mathcal{L}_{\rm MSM} \supset -\frac{\lambda}{2}\left(|H|^2 - \frac{v^2}{2}\right)^2,$$

$$\mathcal{L}_S \supset -\bar{m}_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{\lambda_S}{4!}S^4,$$

RGEs for the scalar quartic couplings:

$$(4\pi)^2\frac{d\lambda}{dt} = 12\lambda^2 + 12\lambda y_t^2 - 12y_t^4 - 3\lambda(g'^2 + 3g^2) + \frac{3}{4}\left[2g^4 + (g'^2 + g^2)^2\right] + k^2,$$

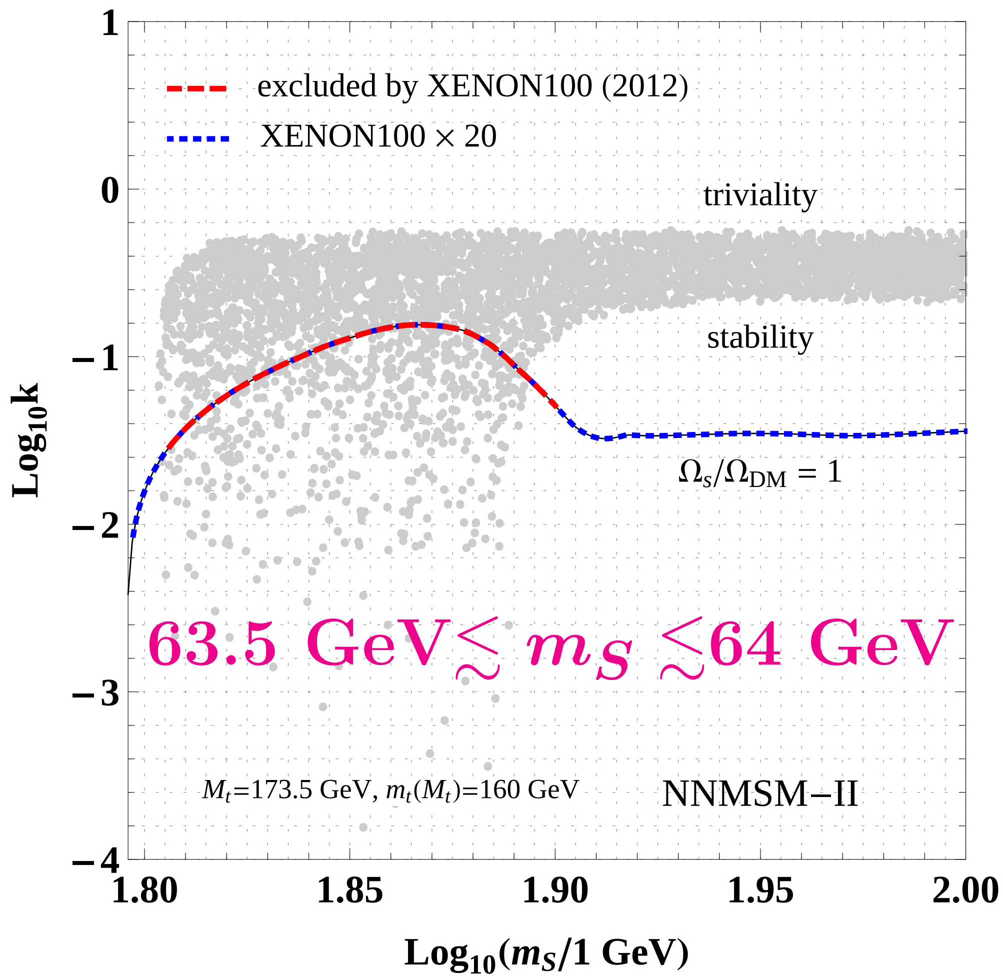
$$(4\pi)^2\frac{dk}{dt} = k\left[4k + 6\lambda + \lambda_S + 6y_t^2 - \frac{3}{2}(g'^2 + 3g^2)\right],$$

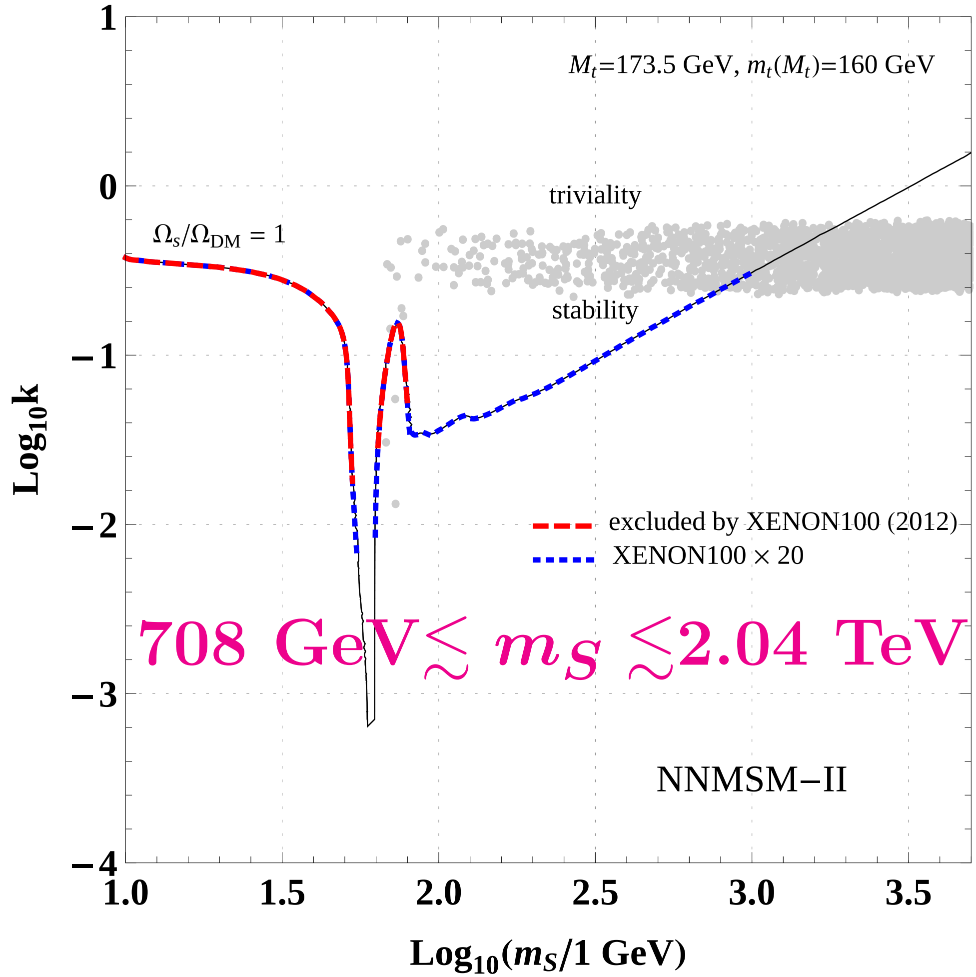
$$(4\pi)^2\frac{d\lambda_S}{dt} = 3\lambda_S^2 + 12k^2.$$

- The contribution from k is positive in the β-function of λ.

4. Stability and dark matter

Stability and triviality ($0 \leq (\lambda, k, \lambda_S) \leq 4\pi$ for $M_Z \leq \mu \leq M_{pl}$), correct DM abundance w/ $m_h = 126$ GeV and $M_t = 173.5$ GeV:





- **Vacuum stability, triviality, and the correct abundance of DM are sensitive to k.**

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- **In the NNMSM-II, when we take $m_t(M_t) = 160\ \mathrm{GeV}$ ($M_t = 173.5\ \mathrm{GeV}$) and $m_h = 126\ \mathrm{GeV}$, there are two allowed regions for the vacuum stability, triviality, and the correct abundance of DM.**

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- **A larger (smaller) M_t leads to a smaller (larger) allowed region.**

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- **DE is given by the small cosmological constant, $\mathcal{L}_\Lambda = (2.3 \times 10^{-3}\ \mathrm{eV})^4$.**
- **There are also other setups for the realization of GCU: $M_{3,i}$ and $M_{2,i}$ with $M_{3,i} = M_{2,i}$ or $M_{3,i} \neq M_{2,i}$.**
  $\Rightarrow$ Type-III NNMSM

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- $M_3 \simeq 7.44 \times 10^9$ **GeV and** $M_2 = 300$ **GeV can realize the GCU.**

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- $M_3 \simeq 7.44 \times 10^9$ GeV and $M_2 = 300$ GeV can realize the GCU.
- There are two allowed regions for the vacuum stability, triviality, the correct abundance of DM, $m_h = 126$ GeV, and $M_t = 173.5$ GeV: 63.5 GeV$\lesssim m_S \lesssim$64 GeV and 708 GeV$\lesssim m_S \lesssim$2.04 TeV.

Appendix

Proton decay

$$\begin{aligned}
\Gamma(p \to \pi^0 e^+) &= \alpha_H^2 \frac{m_p}{64\pi f_\pi^2}(1+D+F)^2 \left(\frac{4\pi\alpha_{\mathrm{GCU}}}{\Lambda_{\mathrm{GCU}}} A_R\right)^2 \\
&\quad \times (1 + (1+|V_{ud}|^2)^2), \\
\alpha_H &= -0.0112 \pm 0.0034 \ \mathrm{GeV}^3, \\
D &= 0.80, \\
F &= 0.47, \\
A_R &\simeq 0.93,
\end{aligned}$$

Our model predicts

$$\tau(p \to \pi^0 e^+) = 8.55^{+9.65}_{-3.36} \times 10^{33} \ \text{years.}$$

The experimental bound is

$$\tau(p \to \pi^0 e^+) > 8.2 \times 10^{33} \ \text{years.}$$

Appendix

Inflation

Coleman-Weinberg potential for the inflation:

$$\mathcal{L}_\varphi = -B\varphi^4 \left[\ln\left(\frac{\varphi^2}{\sigma^2}\right) - \frac{1}{2} \right] - \frac{B\sigma^4}{2}.$$

When we take

$$(\phi, \sigma, B) \simeq (6.60 \times 10^{19}\ \mathrm{GeV}, 9.57 \times 10^{19}\ \mathrm{GeV}, 10^{-15}),$$

the model can lead to

$$n_s = 0.96, \quad r = 0.1, \quad dn_s/d\ln k \simeq 8.19 \times 10^{-4},$$
$$(\delta\rho/\rho) \sim \mathcal{O}(10^{-5}).$$

The experimental bounds are

$$n_s = 0.959 \pm 0.007\ (68\%;\ \text{Planck+WP+highL}),$$
$$r < \begin{cases} 0.11\ (95\%;\ \text{no running}) \\ 0.26\ (95\%;\ \text{including running}) \end{cases},$$
$$dn_s/d\ln k = -0.015 \pm 0.017\ (95\%).$$

Appendix

Abundance and stability of new fermions

- **A particle with mass of M is very rarely produced thermally if the reheating temperature after the inflation is lower then $M/(35 \sim 40)$.**
- **Therefore, we require the reheating temperature in the model as**

$$T_{RH} < \frac{M_3}{40} \simeq 1.86 \times 10^8 \text{ GeV}.$$