Testability of Higgs inflation in a radiative seesaw model

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Motivation and Conclusion

◆The flatness problem and the horizon problem in cosmology can be explained by the slow-roll inflation.

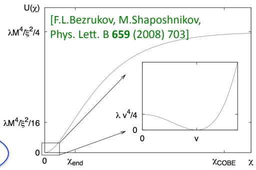
The 126GeV new particle was discovered, it seems to be the Higgs boson.

◆In the Higgs inflation scenario, the Higgs boson plays a role of inflaton.

$$V = V_{SM} + \frac{M_P^2}{2}\mathscr{R} + \xi\Phi_{SM}^2\mathscr{R}$$

Ricci scalar: $\mathscr{R}$, Higgs doublet: $\Phi_{SM} = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix}$

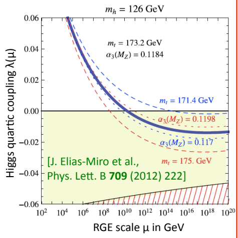
⇒It is basically possible to realize the slow-roll inflation.



$\xi \simeq \mathscr{O}(10^4)$ The coupling is too large!!

◆However, the vacuum is difficult to be stable up to the inflation scale $\frac{M_P}{\sqrt{\xi}}$ in the Standard Model (SM) Higgs potential.

$$V_{SM} = \frac{1}{2}\mu^2\Phi_{SM}^2 + \frac{1}{4}\lambda\Phi_{SM}^4$$



⇒Due to the contribution from the top quark, the critical energy scale is around 10^{10} GeV.

※Unitarity is also violated at $\frac{M_P}{\xi}$. To solve this problem, we should introduce a new particle at the scale of unitarity violation. [G.F.Guidece, H.M.Lee, Phys. Lett. B 694 (2011) 294]

Dark Matter (DM), neutrino masses, etc. may be related to the extended Higgs sector.

◆In our work:

☆The vacuum stability can survive up to the inflation scale by extending the SM to the 2HDM.

☆Introducing right-handed neutrinos, we can explain not only inflation but also DM and neutrino masses simultaneously in the framework of a radiative seesaw scenario.

☆We find the parameter regions where some Higgs doublets become inflatons. This is the new point!

☆Testability of the predicted mass spectrum at the ILC is discussed.

Ⅰ. Extension to the radiative seesaw model

Our work

◆*Extending the SM to the 2HDM and introducing Z_2-odd right-handed neutrinos can resolve vacuum stability, DM and neutrino masses.*

◎Vacuum stability by the 2HDM

$$V = V_{2HDM} + \frac{M_P^2}{2}\mathscr{R} + (\xi_1\Phi_1^2 + \xi_2\Phi_2^2)\mathscr{R}$$

$$V_{2HDM} = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2]$$

$$\Phi_1 = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

There are 5 physical scalar bosons.

$$\beta(\lambda_1) \simeq \frac{1}{16\pi^2}\left[12\lambda_1^2 - 12y_t^4 + \{2\lambda_3^2 + 2(\lambda_3+\lambda_4)^2 + 2\lambda_5^2\}\right]$$

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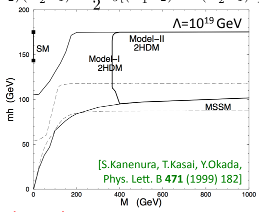


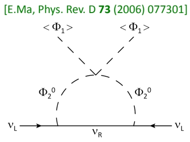
⇒For the effect of extra scalar bosons, vacuum stability is safe up to the inflation scale with m_h =126GeV.

◎Introducing Z_2-odd right-handed neutrino

$$\mathscr{L}_{Yukawa} = Y_\ell \overline{L_L}\Phi_1\ell_R + Y_\nu\overline{L_L}\Phi_2^c\nu_R + h.c.$$

	Q_L	u_R	d_R	L_L	ℓ_R	Φ_1	Φ_2	ν_R
SU(3)$_C$	3	3	3	1	1	1	1	1
SU(2)$_I$	2	1	1	2	1	2	2	1
U(1)$_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	$\frac{1}{2}$	$\frac{1}{2}$	0
Z_2	1	1	1	1	1	1	−1	−1

[E.Ma, Phys. Rev. D 73 (2006) 077301]

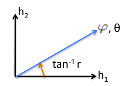


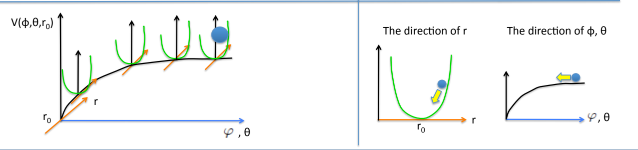
$$(m_\nu)_{ij} = \sum_k \frac{(Y_\nu)_i^k (Y_\nu)_j^k M_R^k}{16\pi^2}\left[\frac{m_H^2}{m_H^2 - M_R^2}\ln\frac{m_H^2}{(M_R^k)^2} - \frac{m_A^2}{m_A^2 - M_R^2}\ln\frac{m_A^2}{(M_R^k)^2}\right]$$

⇒Explain DM by introducing unbroken Z_2 symmetry and neutrino masses in the radiative seesaw model.

◎The behavior of the Higgs fields as inflatons

$$\begin{cases} \Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_1 \end{pmatrix} \\ \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ h_2 e^{i\theta} \end{pmatrix} \end{cases} \Rightarrow \begin{cases} r = \frac{h_2}{h_1} \\ \varphi = \sqrt{\frac{3}{2}}\log(1 + \xi_1 h_1^2 + \xi_2 h_2^2) \end{cases}$$





Ⅱ. Constraint on the parameters

◆*There are 9 parameters, and we can impose 9 constraints.*

◎Constraint from the inflation scale: $\mu_{inf} = 10^{17}$GeV

・WMAP

$$\xi_2\sqrt{\frac{2\{\lambda_1 + a^2\lambda_2 - 2a(\lambda_3+\lambda_4)\}}{\lambda_1\lambda_2 - (\lambda_3+\lambda_4)^2}} \simeq 5\times 10^4$$

$$\frac{\lambda_5}{\xi_2}\frac{a\lambda_2 - (\lambda_3+\lambda_4)}{\lambda_1 + a^2\lambda_2 - 2a(\lambda_3+\lambda_4)} \lesssim 4\times 10^{-12} \quad a \equiv \frac{\xi_1}{\xi_2}$$

・Condition of the stable potential

[for some inflatons]

$$\begin{cases} \lambda_1\xi_2 - (\lambda_3+\lambda_4)\xi_1 > 0 \\ \lambda_2\xi_1 - (\lambda_3+\lambda_4)\xi_2 > 0 \\ \lambda_1\lambda_2 - (\lambda_3+\lambda_4)^2 > 0 \end{cases}$$

[for only one inflaton]

$$\begin{cases} \lambda_1\xi_2 - (\lambda_3+\lambda_4)\xi_1 \lessgtr 0 \\ \lambda_2\xi_1 - (\lambda_3+\lambda_4)\xi_2 \gtrless 0 \end{cases}$$

[J.-O.Gong, H.M.Lee, S.K.Kang, JHEP 1204 (2012) 128]

We find parameter regions in this case.

◎Constraint from the electroweak scale: $\mu_{EW} = 10^2$GeV

・The direct search for DM [XENON100, Phys. Rev. Lett 109 (2012) 181301]

$$\sigma(AN\to AN) \simeq \frac{\lambda_{hAA}^2}{4m_h^4}\frac{m_N^2}{\pi(m_A+m_N)^2}f_N^2 \quad \lambda_{hAA} \equiv \lambda_3 + \lambda_4 - \lambda_5$$

[L.L.Honorez, E.Nezri, J.F.Oliver, M.H.G.Tytgat, JCAP 0702 (2007) 028]

$$\lambda_{hAA} \lesssim 0.036 \quad 63\,\text{GeV} \le m_A \le 66\,\text{GeV}$$

・The vacuum expectation value $v = 246$GeV

・The SM-like Higgs boson $\lambda_1 = 0.262 \leftarrow m_h \simeq 126$GeV

◎Fine tuning $a\lambda_2(\mu_{inf}) - [\lambda_3(\mu_{inf}) + \lambda_4(\mu_{inf})] \simeq 10^{-6}$

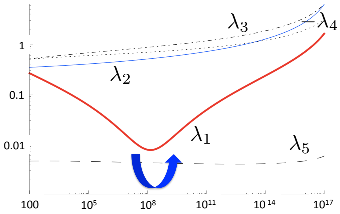
◎Triviality $\lambda_i \lesssim 2\pi (i = 1-5)$

◎Vacuum stability $\lambda_1 > 0\,,\ \lambda_2 > 0\,,\ \lambda_3 + \lambda_4 + \lambda_5 + \sqrt{\lambda_1\lambda_2} > 0$

Ⅲ. Prediction and Testability

◎Mass spectrum of the scalar bosons

・The result of renormalization group equations analysis



	λ_1	λ_2	λ_3	λ_4	λ_5
10^2GeV	0.26	0.34	0.51	-0.50	0.0046
10^{17}GeV	1.6	6.3	6.3	-3.2	0.0058

・The mass formula

$$m_h^2 = \lambda_1 v^2$$
$$m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$
$$m_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3+\lambda_4+\lambda_5)v^2$$
$$m_A^2 = \mu_2^2 + \frac{1}{2}(\lambda_3+\lambda_4-\lambda_5)v^2$$

⇒ $m_h \simeq 126$ GeV, $m_{H^\pm} \simeq 140$ GeV, $m_H \simeq 67.1$ GeV, $m_A \simeq 65.0$ GeV

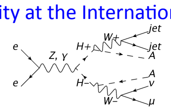
Prediction!

◎In this mass spectrum, it is difficult to test at the LHC.

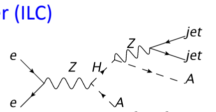
[R. Barbieri, L.J.Hall, V.S.Rychkov, Phys. Rev. D 74 (2006) 015007]

[Q.-H.Cao, E.Ma, G.Rajasekaran, Phys. Rev. D 76 (2007) 095011]

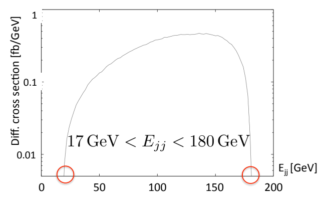
◎Testability at the International Linear Collider (ILC)

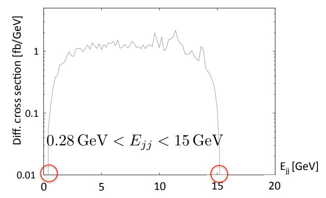


$$\frac{m_{H^\pm}^2 - m_A^2}{4m_{H^\pm}^2}\left(\sqrt{s} - \sqrt{s - 4m_{H^\pm}^2}\right) < E_{jj} < \frac{m_{H^\pm}^2 - m_A^2}{4m_{H^\pm}^2}\left(\sqrt{s} + \sqrt{s - 4m_{H^\pm}^2}\right)$$



$$\frac{m_H^2 - m_A^2}{4m_H^2}\left(\sqrt{s} - \sqrt{s - 4m_H^2}\right) < E_{jj} < \frac{m_H^2 - m_A^2}{4m_H^2}\left(\sqrt{s} + \sqrt{s - 4m_H^2}\right)$$





◆We can measure mass sets of ($H^\pm$, A) and (H, A) independently by the end point analysis.