Higgs inflation by flat potential and a radiative seesaw mechanism

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in collaboration with Shinya KANEMURA

University of Toyama

Phys. Lett. B **723** (2013) 126,

including some recent developments

In this talk,

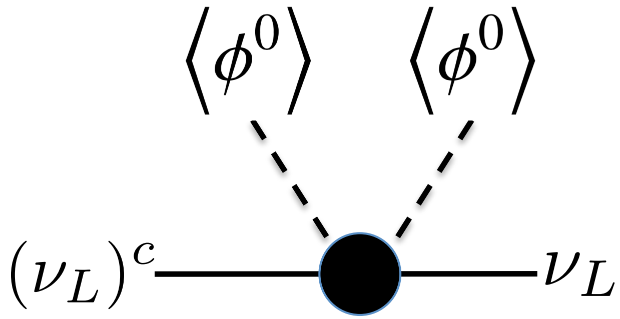
- We discuss Higgs inflation, which explains inflation with minimal number of particles.
- Flat potential scenario is testable at future CMB experiments.
- In the framework of the radiative seesaw model with a multi-Higgs structure, we can solve not only dark matter, neutrino masses but also inflation.
- We mention testability of our model at collider experiments.

1.1.Beyond the SM

- The SM is established by discovering the Higgs boson.
- However, we cannot explain neutrino oscillation, dark matter (DM) and baryon asymmetry of the Universe.

Radiative neutrino mass generation

Z_2 sym.→ stabilizes DM + forbids generating m_ν at the tree level



(N-loop diagram)

$$(m_\nu)_{ij} \simeq \frac{c_{ij}}{(16\pi^2)^N} \frac{v^2}{M}$$

L. M. Krauss, S. Nasri, M. Trodden, PRD **67**, 085002 (2003)
E. Ma, PRD **73**, 077301 (2006)
M. Aoki, S. Kanemura, O. Seto, PRL **102**, 051805 (2009) ...

We consider the simplest model (Ma model).

1.2.Ma model

Φ_2, ν_R: Z_2-odd

$$\mathcal{L}_{\mathrm{Ma}} = \mathcal{L}_{\mathrm{SM}} + |D_\mu \Phi_2|^2 - V_{\mathrm{IDM}}(\Phi_1, \Phi_2) + \mathcal{L}_{\mathrm{Ma\,Yukawa}} + \mathcal{L}_{\mathrm{Majorana}}$$

E.Ma, PRD **73** 077301 (2006)

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

<u>Masses of scalar boson</u>

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

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

- h: CP-even (SM-like) Higgs boson
- H: CP-even scalar boson
- A: CP-odd scalar boson
- $H^\pm$: Charged scalar bosons

Masses of scalar boson are determined by $\lambda_{1\text{-}5}$, μ_2

1.3.Ma model

Φ_2, ν_R: Z_2-odd

$$\mathcal{L}_{\rm Ma} = \mathcal{L}_{\rm SM} + |D_\mu \Phi_2|^2 - V_{\rm IDM}(\Phi_1, \Phi_2) + \mathcal{L}_{\rm Ma\,Yukawa} + \mathcal{L}_{\rm Majorana}$$

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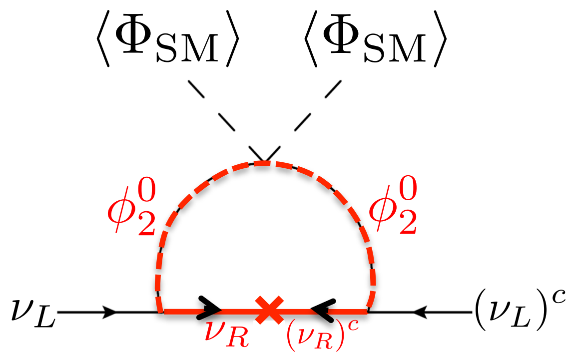
Neutrino masses

$$\mathcal{L}_{\rm Ma\,Yukawa} = h_{ij}\,\overline{(L_L)_i}\,\Phi_2^c\,(\nu_R)_j + h.c.$$

$$\mathcal{L}_{\rm Majorana} = \frac{1}{2} M_i\,\overline{(\nu_R)_i^c}\,(\nu_R)_i + h.c.$$



- 1-loop suppressed masses

$$(m_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2}\sum_k \frac{h_{ik}h_{jk}M_k}{m_0^2 - M_k^2}\left[1 - \frac{M_k^2}{m_0^2 - M_k^2}\ln\frac{m_0^2}{M_k^2}\right]$$

$$m_0^2 = \frac{m_H^2 + m_A^2}{2}$$

Neutrino Yukawa is constrained by the neutrino oscillation data.

1.4.Ma model

Φ_2, ν_R: Z_2-odd

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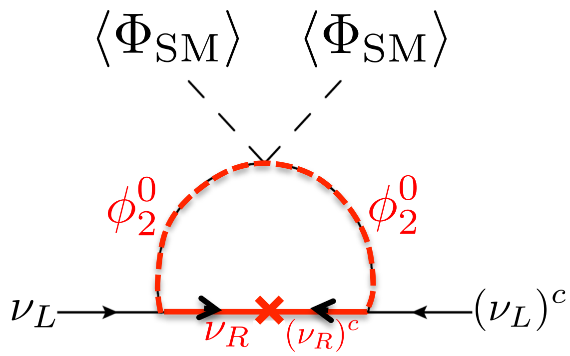
Dark matter

- DM stability is explained by Z_2 symmetry.
- DM candidate is the lightest one of neutral Z_2–odd particles (H^0, A^0, ν_R).



DM is constrained by relic abundance and direct detection.

2.1.What we want to do

- We explain Higgs inflation with the structure of the Ma model.
- We search the effects to TeV scale physics from parameters which satisfy inflation constraints.
- We explore our model by CMB experiments, DM direct search and collider experiments.

2.2.Inflation

- Standard cosmology is very successful to explain the observations.
- Additionally, we need inflation to solve horizon problem and flatness problem.

Guth(1981), Sato(1981)

Higgs inflation

Bezrukov, Shaposhnikov, PLB **659**, 703 (2008)

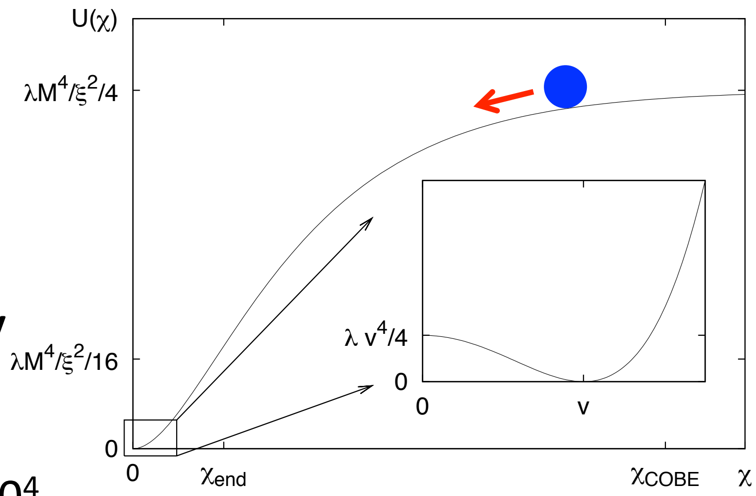
Higgs boson as inflaton

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \mathcal{L}_{\rm SM} - \frac{1}{2}M_P^2 R - \underline{\xi H^\dagger H R}$$

Coupling of the Higgs field to gravity

$$\rightarrow U(\chi) = \frac{\lambda M_P^4}{4\xi^2}\left(1 + \exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2}$$

$\xi \sim 10^4$



The advantage of Higgs inflation is testability via Higgs physics.

2.3.CMB experiments

- The result of Planck (2015) excludes BICEP2 data(2014).

  $r_{0.002}$ <0.10 (95% C.L., Planck TT + lowP + BKP)

  Planck Collaboration, arXiv:1502.02114 [astro-ph.CO]

- Future CMB satellite *"LiteBIRD"* (2020-).

  r>0.01 (10σ discovery), sensitivity: δr<0.001 http://litebird.jp

Prediction of Higgs inflation

-Original scenario Bezrukov, Shaposhnikov, PLB **659**, 703 (2008) predicts r ~0.003.

-In the case of flat potential Hamada, Kawai, Oda, Park, PRL**112**, 241301 (2014),

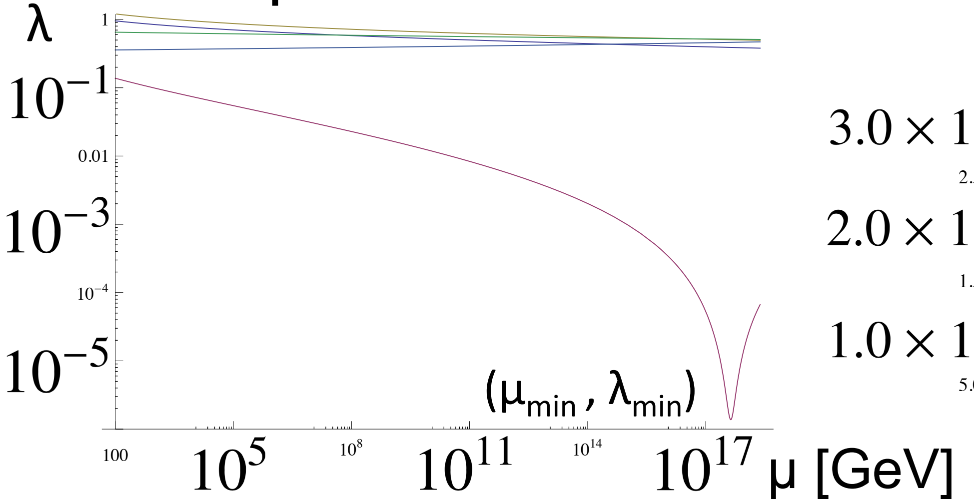
the large r (>0.01) can be obtained by the $\lambda \sim 10^{-6}$(@$\mu \sim 10^{17}$GeV).

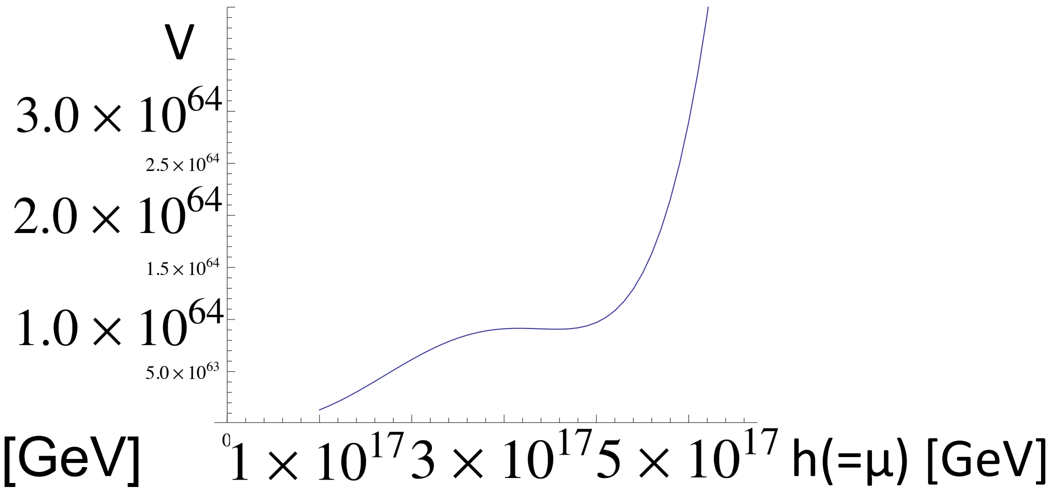
Higgs inflation with the flat potential can be tested at the CMB experiment.

2.4.Flat potential scenario

Hamada, Kawai, Oda, Park, PRL**112**, 241301 (2014)

- Flat potential can be realized with m_t =171.5353GeV.





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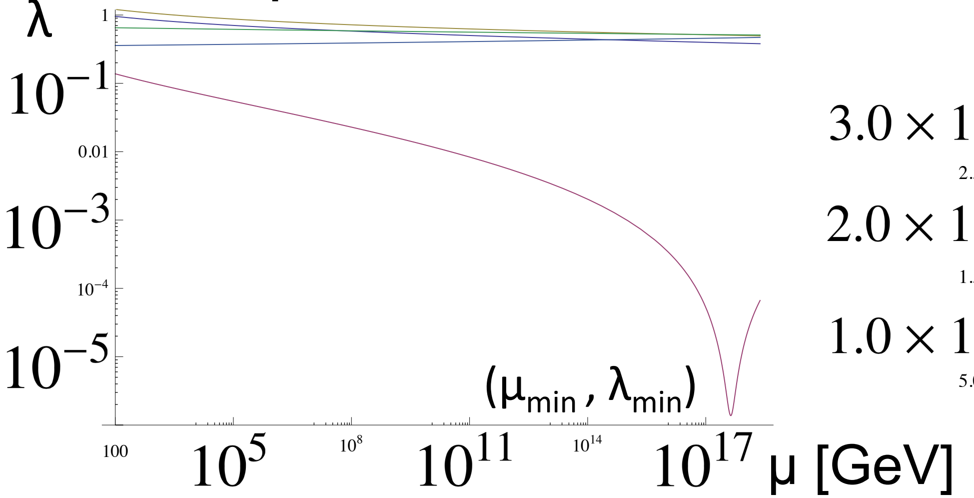
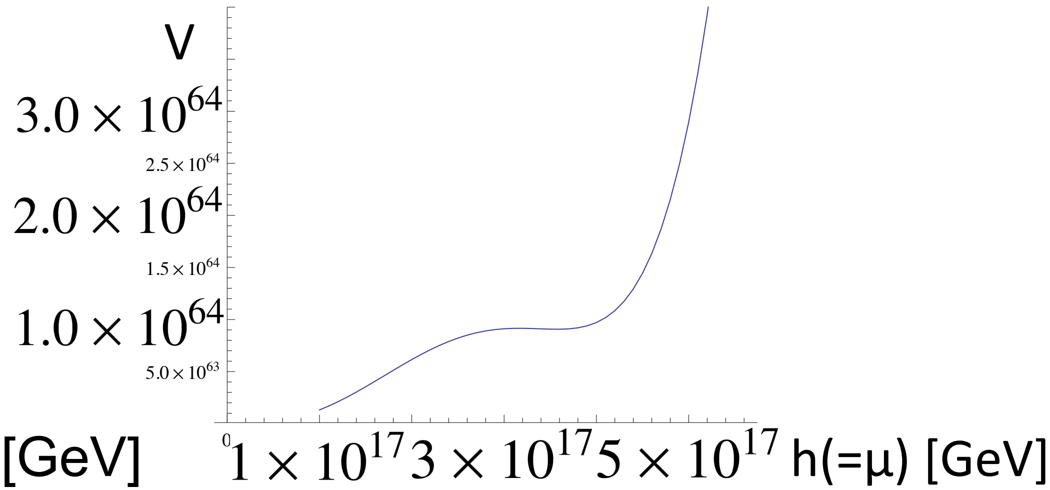




- Higgs inflation is explained by this potential.

→The smallness of ξ in this scenario solves perturbative unitarity .

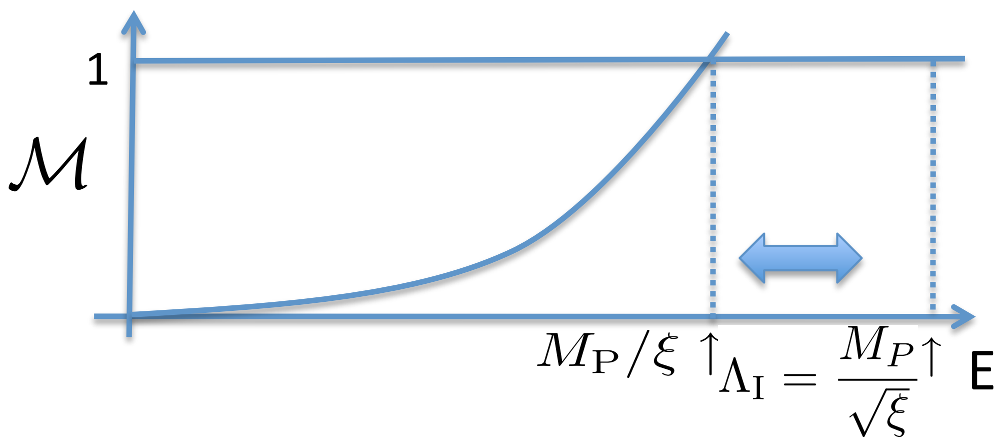
→To satisfy vacuum stability, small top mass is required .

Theoretical problem of Higgs inflation

C.P.Burgess et al., JHEP **0909**, 103(2009)
C.P.Burgess, H.M.Lee, M.Trott, JHEP **1007**, 007(2010)

- Perturbative unitarity is broken @ $\Lambda_{\rm U} \equiv \frac{M_P}{\xi}$ because the coupling of the Higgs field to gravity contributes to the Higgs-gauge scatterings.

$$\mathcal{M}(W_L\, \chi_h \to W_L\, \chi_h) = \mathcal{M}(W_L\, h \to W_L\, h) + a\,\frac{E^2}{\Lambda_U^2} + b$$



χ_h Is Higgs field of Einstein frame

<Solutions>

①Introducing heavy singlet scalar
G.F.Giudice, H.M.Lee, Phys.Lett.B **694**, 294 (2011)

②The scenario of flat potential
Hamada, Kawai, Oda, Park, PRL**112**, 241301 (2014)

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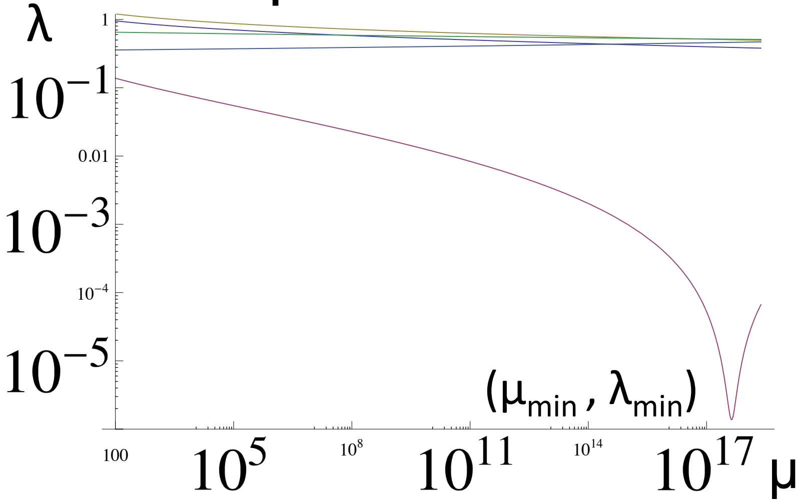
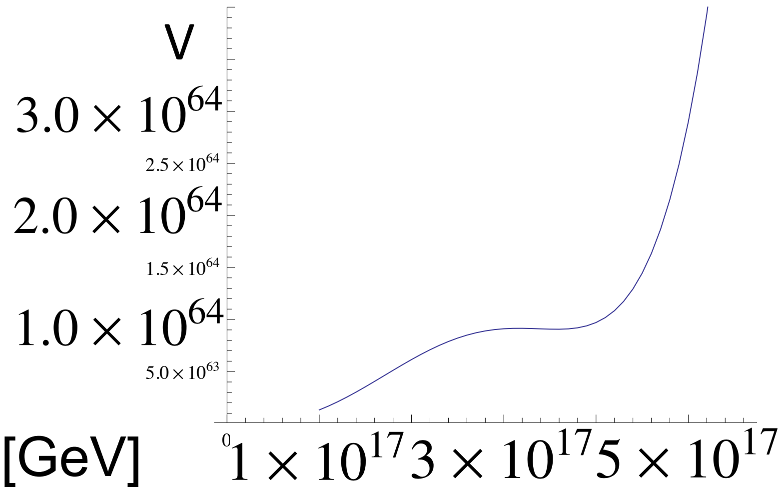




- Higgs inflation is explained by this potential.

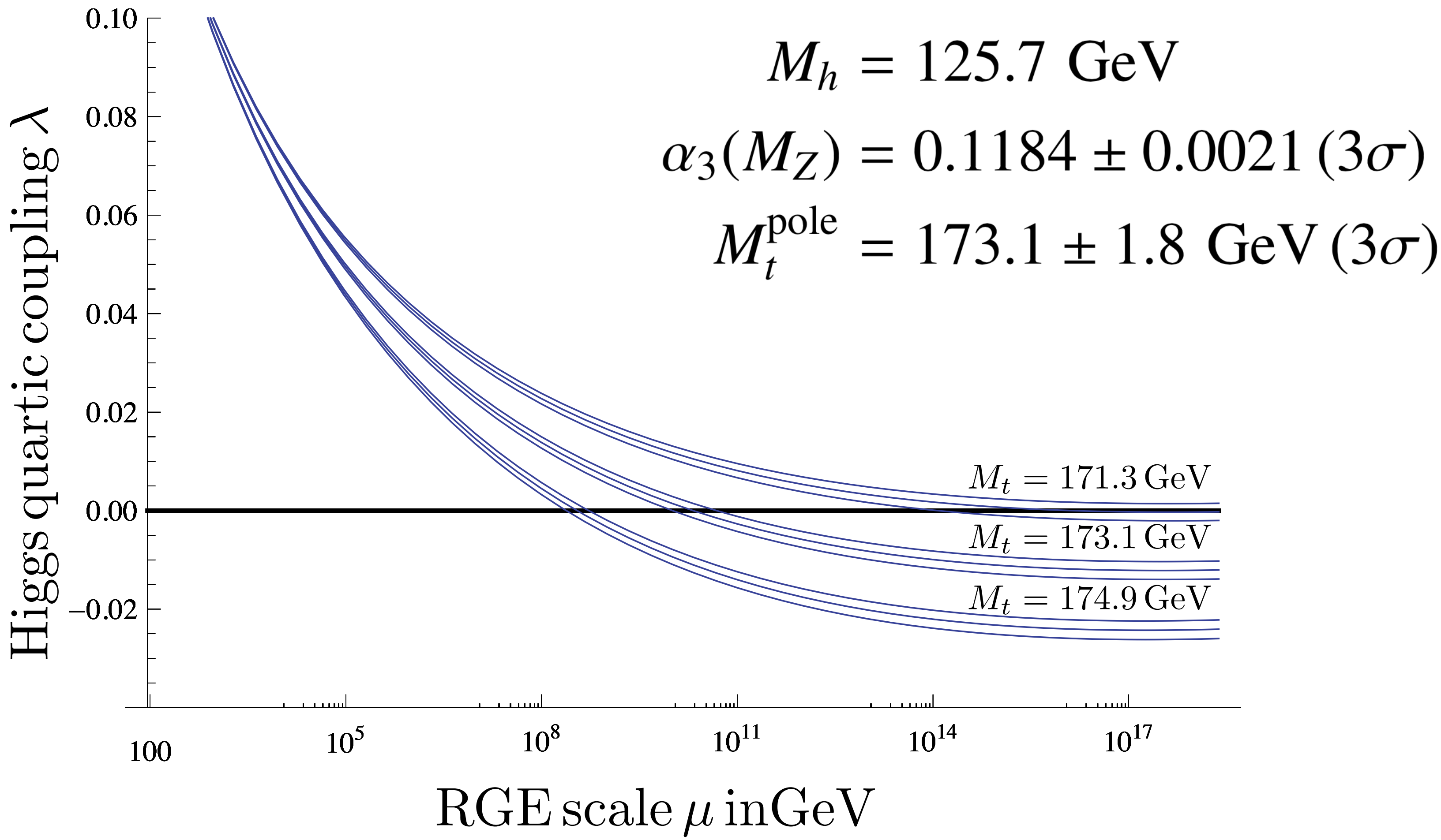
→The smallness of ξ in this scenario solves perturbative unitarity 😃.

→To satisfy vacuum stability, small top mass is required .

ξ~20

Vacuum stability in the SM

G.Degrassi et al., JHEP **1208**, 098 (2012)



Running of the Higgs self coupling is sensitive to the top mass!

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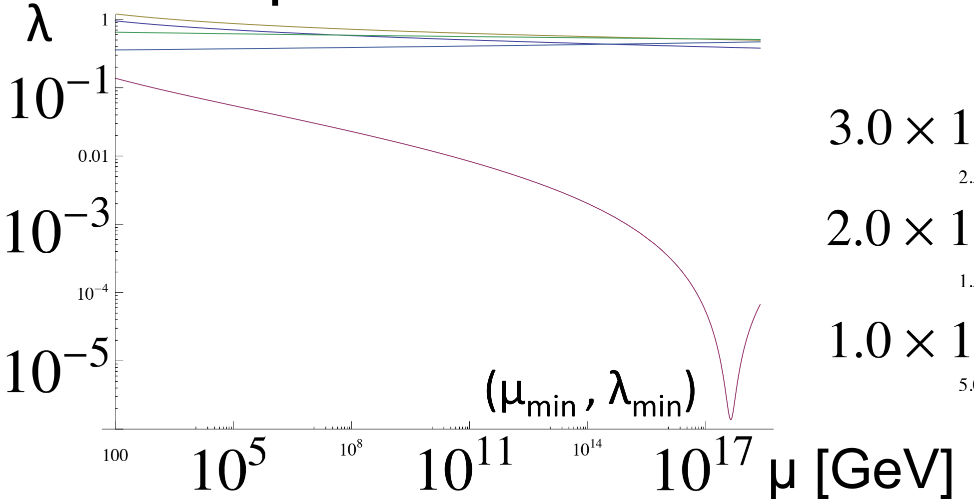

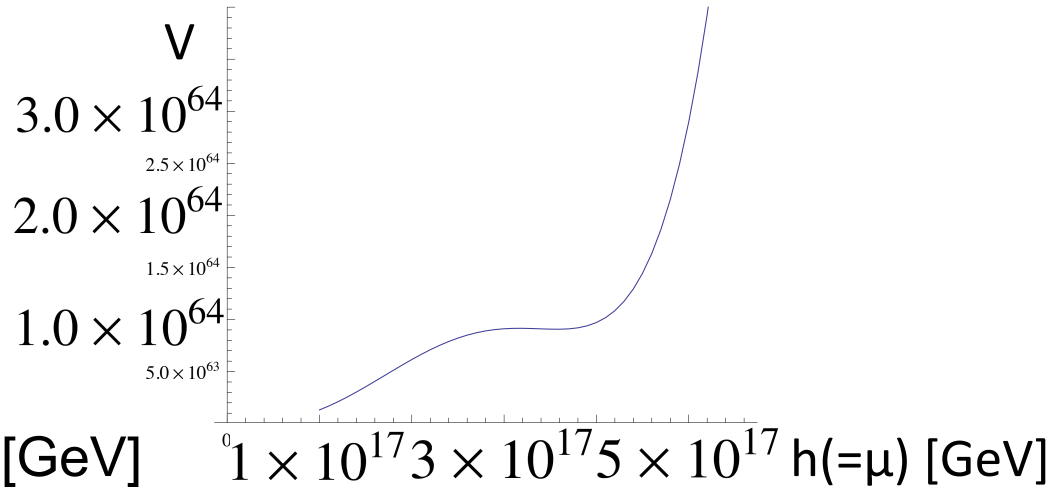

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→The smallness of ξ in this scenario solves perturbative unitarity 😃.

→To satisfy vacuum stability, small top mass is required 😣.

ξ~20

m_t~171GeV

3.1.In our analysis,

- We consider multi−Higgs model to relax the constraint of vacuum stability.
- The Ma model has this structure.
- We calculate β functions to determine the mass spectrum.

3.2.Higgs inflation with Ma model

S.Kanemura, T.M., T.Nabeshima, Phys. Lett. B **723**, 126 (2013)

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \mathcal{L}_{Ma} - \left(\frac{1}{2}M_{pl}^2 + \xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2\right)R$$

Φ_2, ν_R: Z_2-odd

$$\mathcal{L}_{Ma} = \mathcal{L}_{SM} + |D_\mu\Phi_2|^2 - V_{IDM}(\Phi_1,\Phi_2) + \mathcal{L}_{Ma\,\text{Yukawa}} + \mathcal{L}_{Majorana}$$

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Higgs inflation with IDM

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

$$U(\chi,\theta) = \frac{\lambda_{eff}(\mu)}{4\xi_{eff}^2}\left(1 - \exp\left(-\frac{2\chi}{\sqrt{6}}\right)\right)^2 [1 + \delta\cos(2\theta)]$$

Scalar fields as inflatons

- $(h^0, H^0) \to \chi$: mixed CP-even scalar
- $A^0 \to \theta$: CP-odd scalar

$$\lambda_{eff}(\mu) \equiv \frac{\lambda_1(\mu)\lambda_2(\mu) - \lambda_L(\mu)^2}{2}\frac{\lambda_1(\mu)\xi_2^2 + \lambda_2(\mu)\xi_1^2 - 2\lambda_L(\mu)\xi_1\xi_2}{(\lambda_2(\mu)\xi_1 - \lambda_L(\mu)\xi_2)^2},$$

$$\xi_{eff}(\mu) \equiv \frac{\lambda_1(\mu)\xi_2^2 + \lambda_2(\mu)\xi_1^2 - 2\lambda_L(\mu)\xi_1\xi_2}{\lambda_2(\mu)\xi_1 - \lambda_L(\mu)\xi_2}, \quad \lambda_L(\mu) = \lambda_3(\mu) + \lambda_4(\mu)$$

We consider flat potential scenario in the Ma model.

3.3.Constraints on the parameters

$$\frac{\mathcal{L}_J}{\sqrt{-g_J}} = \mathcal{L}_{Ma} - \left(\frac{1}{2}M_{pl}^2 + \xi_1|\Phi_1|^2 + \xi_2|\Phi_2|^2\right)R$$

λ_{1-5} , ξ_{1-2} , μ_{1-2}

$$\mathcal{L}_{Ma} = \mathcal{L}_{SM} + |D_\mu\Phi_2|^2 - V_{IDM}(\Phi_1, \Phi_2) + \mathcal{L}_{Ma\,Yukawa} + \mathcal{L}_{Majorana}$$

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- Flat potential scenario: $\lambda_{eff}(\mu_{min})$ ~10^{-6}
  Hamada, Kawai, Oda, Park, PRL**112**, 241301 (2014)
- CMB observation: $\xi_{eff} = 5 \times 10^4 \sqrt{\lambda_{eff}}$
- Stable minimum condition for inflation, Vacuum stability
  J.-O.Gong, H.M.Lee, S.K.Kang, JHEP **1204**, 128(2012)
- The cases of DM scenario of Ma model

① m_A (~$m_h/2$) ~65GeV(Ωh^2), λ_{hAA} $(=\lambda_3+\lambda_4-\lambda_5)$ <0.02(DD)
LUX Collaboration, PRL **112**, 091303 (2014)

② m_A (~m_H) >800GeV(Ωh^2)
A.Goudelis, B.Herrmann, O.Stål, JHEP **1309**, 106 (2013)

③ $m_{\nu R1}$=10-700GeV(LFV), λ_5~10^{-11}-4×10^{-10}(m_ν, Ωh^2)
A.Vicente, C.E.Yaguna, JHEP **1502**, 144 (2015)

4.1.Results

- Light scalar DM ...This case does not satisfy flat potential scenario.

- However, the scenario of original paper (large ξ, small r) is possible.

S.Kanemura, T.M, T.Nabeshima, Phys. Lett. B **723** 126 (2013)

→Perturbative unitarity is achieved by introducing heavy singlet scalar.

T.M., arXiv:1405.5700 [hep-ph]

- Heavy scalar DM ...This case may be difficult to test at DM direct searches.

→In this talk, we don't consider this case.

- Right handed neutrino DM

- Mass spectrum is determined by the calculation of β function.

→Benchmark: $(\lambda_2, \lambda_3, \lambda_4) = (0.1897, 0.4244, -0.4990)$ satisfies conditions.

$$\mu_2 = 120\text{GeV} \to (m_{H^\pm}, m_H, m_A) = (165, 110, 110)\text{GeV}$$

$$\mu_2 = 200\text{GeV} \to (m_{H^\pm}, m_H, m_A) = (230, 194, 194)\text{GeV}$$

$$\mu_2 = 500\text{GeV} \to (m_{H^\pm}, m_H, m_A) = (513, 498, 498)\text{GeV}$$

$$\vdots$$

[μ_2 is a free parameter.]

4.2.Phenomenology

IDM@LHC E.Dolle, X.Miao, S.Su, B.Thomas, Phys. Rev. D **81**, 035003 (2010)

- H^+H^- is many background and mass difference of HA is too small.

4.2.Phenomenology

Testing at the LHC is difficult.

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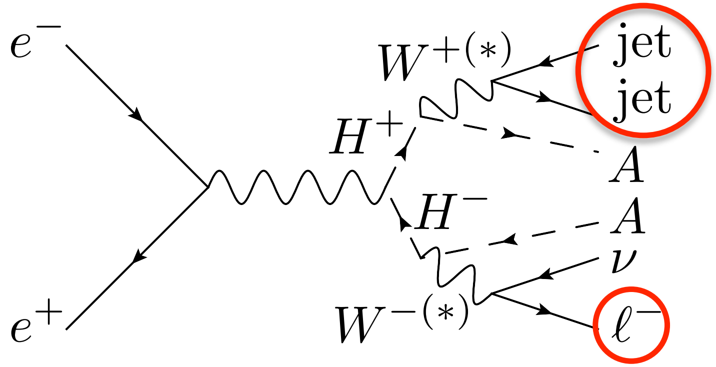
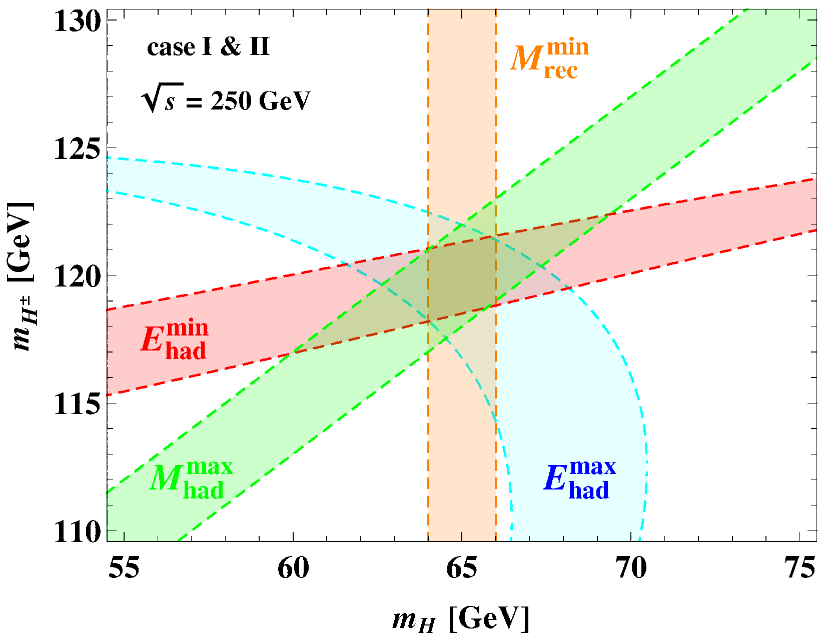
IDM@ILC M.Aoki, S.Kanemura, H.Yokoya, Phys. Lett. B**725**, 302 (2013)

- Mass spectrum is determined by ±2GeV accuracy.
- Upper bound of m_{H+} is √s/2.

$$m_{H^\pm} = 120\text{GeV} \to \sigma_{H^+H^-} = 11\text{fb}@\sqrt{s} = 250\text{GeV}$$
$$m_{H^\pm} = 120\text{GeV} \to \sigma_{H^+H^-} = 79\text{fb}@\sqrt{s} = 500\text{GeV}$$
$$m_{H^\pm} = 160\text{GeV} \to \sigma_{H^+H^-} = 53\text{fb}@\sqrt{s} = 500\text{GeV}$$





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m_{H+} can be measured at the ILC.

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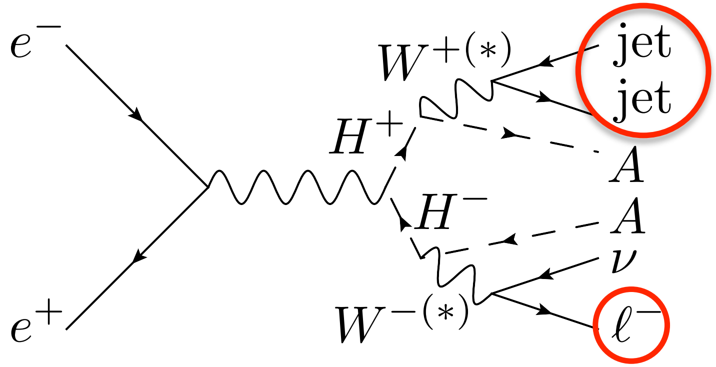

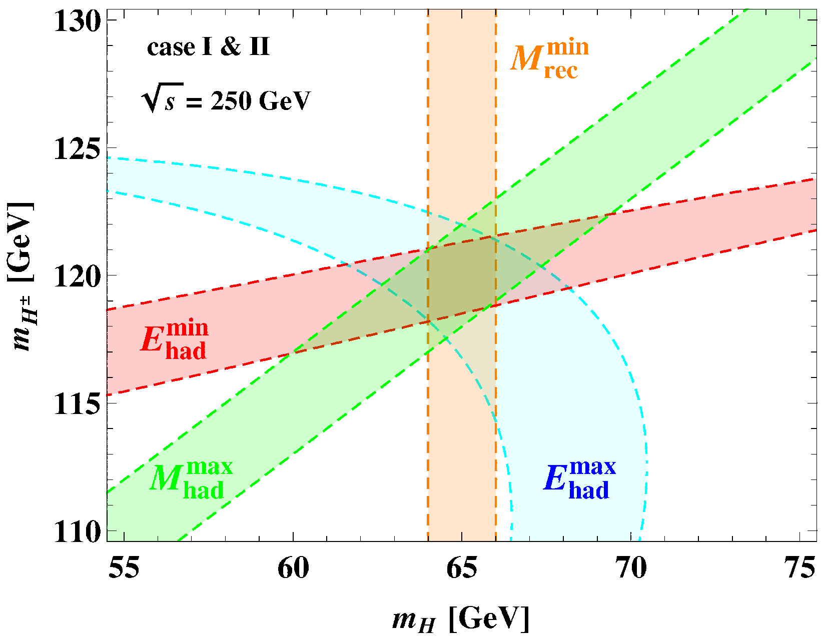

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LFV constraints of ν_{R1} as DM in Ma model

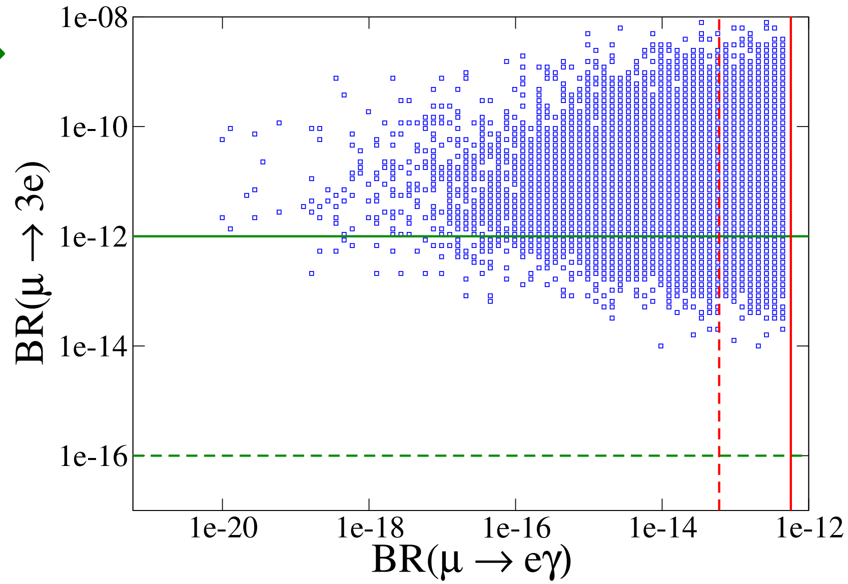
A.Vicente, C.E.Yaguna, JHEP **1502**, 144 (2015)→

- The case of ν_{R1} as DM in Ma model is tested by searching LFV processes.

〈Assumptions〉

-No co-annihilation with scalar bosons

-$m_{\nu R3}$<10TeV



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- Mass spectrum is determined by ±2GeV accuracy.
- Upper bound … /2.

ν_{R1} as DM can be excluded by LFV experiments.

LF… M in Ma model

… C.E.Yaguna, JHEP **1502**, 144 (2015)→

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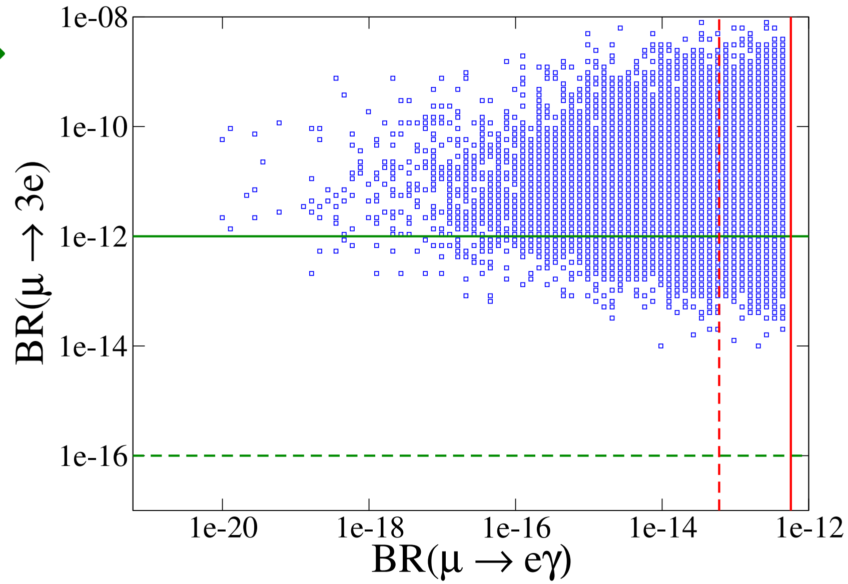

4.3.Testability of our scenario

Testing at the LHC is difficult.

m_{H+} can be measured at the ILC.

ν_{R1} as DM can be excluded by LFV experiments.

Our scenario in the Ma model satisfying the inflation constraints can be tested at collider experiments.

$$(\lambda_2, \lambda_3, \lambda_4) = (0.1897, 0.4244, -0.4990)$$

+

Such a inflation scenario can be tested at CMB experiments.

Conclusions

- We discuss Higgs inflation with Ma model which explains DM and Neutrino masses at the same time.
- For such multi-Higgs models, the constraint from vacuum stability can be relaxed.
- Our model can be testable by future CMB experiments, ILC and LFV experiments.

Future prospect

- Resonant leptogenesis with the heavy scalar DM of Ma model is studied. S.Kashiwase, D.Suematsu, PRD **86**, 053001 (2012)

→It may be possible to realize leptogenesis satisfying the inflation constraints.
(ν_{Ri} do not contribute to the running of $\lambda_i(\mu)$.)

Thank you for your attention!

감사합니다!