HIGGS INFLATION AND SCALAR DARK MATTER WITH RIGHT-HANDED NEUTRINOS

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1.MOTIVATION

The problems in the standard cosmology (Big Bang cosmology)

• Flatness problem • Homogeneity and isotropic problem • Monopole problem etc…

Inflation!

Completed the standard model (SM) of the particle physics

Can we explain inflation in the SM?

Exciting report from BICEP2!!

Tensor-to-scalar ratio：r
$$r = 0.2^{+0.07}_{-0.05}$$
P. A. R. Ade *et al.* [BICEP2 Collaboration], arXiv:1403.3985

Contradict Planck experiment? $(r < 0.11)$
P. A. R. Ade et al. [Planck Collaboration], arXiv:1303.5082

Tensor fluctuation was generating during inflation

Restriction of inflation models

> Is it possible to realize tensor-to-scalar ratio from BICEP2 experiment within SM particle contents?

2.HIGGS INFLATION
Bezrukov and Shaposhnikov, PLB 659 (2008) 703

Action in Jordan frame   Introduce non-minimal coupling (interaction with gravity)

$$S_J \supset \int d^4x \sqrt{-g} \left\{ -\frac{M_{\rm pl}^2 + \xi h^2}{2}R + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{\lambda}{4}\left(h^2 - v^2\right)^2 \right\}$$

Press down

Conformal transformation
$$\hat{g}_{\mu\nu} \equiv \Omega^2 g_{\mu\nu} \quad (\Omega^2 \equiv 1 + \xi h^2/M_{\rm pl}^2)$$

Action in Einstein frame

$$S_E \supset \int d^4x \sqrt{-\hat{g}} \left\{ -\frac{M_{\rm pl}^2}{2}\hat{R} + \frac{\partial_\mu \chi \partial^\mu \chi}{2} - \frac{\lambda}{4\Omega(\chi)^4}\left(h(\chi)^2 - v_{\rm EW}^2\right)^2 \right\}$$

Here,
$$\frac{d\chi}{dh} = \sqrt{\frac{\Omega^2 + 6\xi^2 h^2/M_{\rm pl}^2}{\Omega^4}}$$

$$\equiv V(\chi)$$

Result from previous works

The most important conclutions

$$M_t \simeq 171.1 \text{ GeV}$$ Y. Hamada, H. Kawai, K. —y. Oda and S. C. Park, PRL 112 (2014) 24301
$$M_t \simeq 171.6 \text{ GeV}$$ Bezrukov and Shaposhnikov, arXiv:1403.6078

On the other hand…
$$M_t = 173.34 \pm 0.76 \text{ GeV}$$ [ATLAS and CDF and CMS and D0 Collaborations], arXiv:1403.4427
$$M_t = 174.34 \pm 0.64 \text{ GeV}$$ [Tevatron Electroweak Working Group Collaboration], arXiv:1407.2682

Small top Yukawa coupling is needed to keep positive value up to inflation scale.
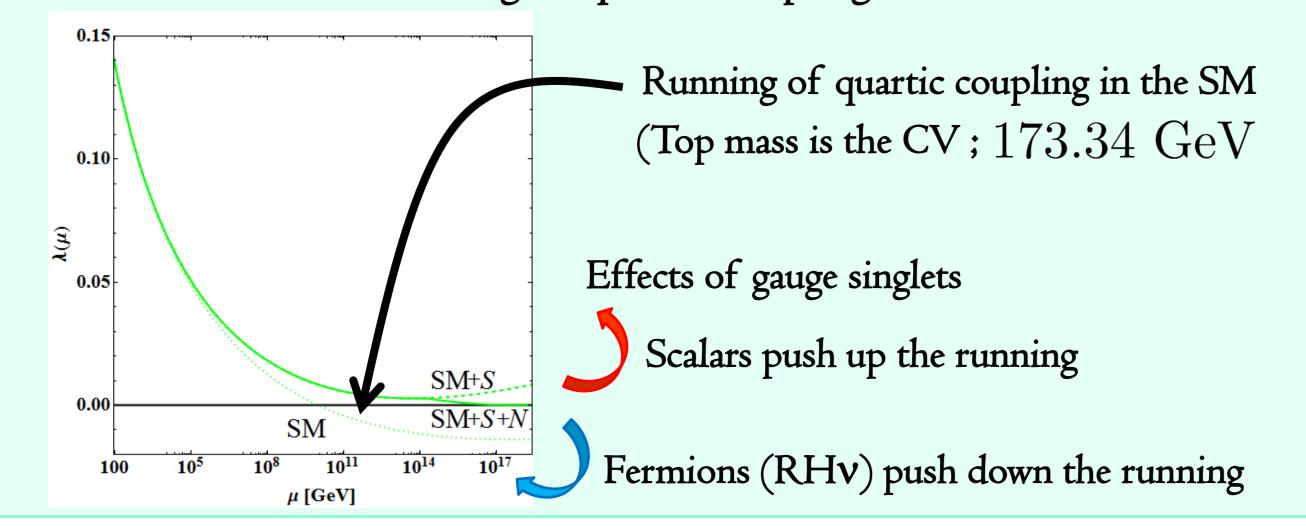
> Can we construct a Higgs inflation model respecting collider experiment results?

3.MODEL

Expansion by gauge singlets : SM+right-handed ν+real scalar field (Z_2 odd)

Lagrangian
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_S + \mathcal{L}_N \quad \text{Each terms…}$$

$$\mathcal{L}_{\rm SM} \supset -\lambda \left(|H|^2 - \frac{v_{\rm EW}^2}{2}\right)^2$$

$$\mathcal{L}_S = -\frac{m_S^2}{2}S^2 - \frac{k}{2}|H|^2 S^2 - \frac{\lambda_S}{4!}S^4 + \text{(kinetic terms)}$$

$$\mathcal{L}_N = -\left(\frac{M_R}{2}\bar{N}^c N + y_N \bar{L}HN + \text{c.c.}\right) + \text{(kinetic terms)}$$

Effect of new fields on the running of quartic coupling

Running of quartic coupling in the SM
(Top mass is the CV ; 173.34 GeV)

Effects of gauge singlets

Scalars push up the running

Fermions (RHν) push down the running

4.ANALYSES

Renormalization group equations (RGEs) @ 2-loop order

RGEs to solve (general expression)

$$(4\pi)^2 \frac{dX}{dt} = \beta_X$$

X correspond to proper couplings
(Please see our paper for the detail of β_X)

| | m_S | M_R | Energy |

$X_1 =$
Gauge couplings of the SM
Top Yukawa coupling

$X_2 = X_1+$
Scalar quartic couplings

$X_3 = X_2+$
Neutrino Yukawa coupling

Constrain on the portal coupling between Higgs boson and new scalar fields

$$\log_{10} k(M_Z) \simeq -3.63 + 1.04 \log_{10}\left(\frac{m_{\rm DM}}{\text{GeV}}\right) \quad \text{where,} \quad m_{\rm DM}^2 = m_S^2 + kv_{\rm EW}^2/2$$

Assumption : Extra scalar explains DM abundance

Constraint on neutrino Yukawa coupling (Seesaw mechanism)
$$y_N = \sqrt{0.1 \text{ eV} \cdot M_R}/v \quad \Rightarrow \quad \text{Atmospheric mass scale should be explained}$$

Cosmological parameters of inflation

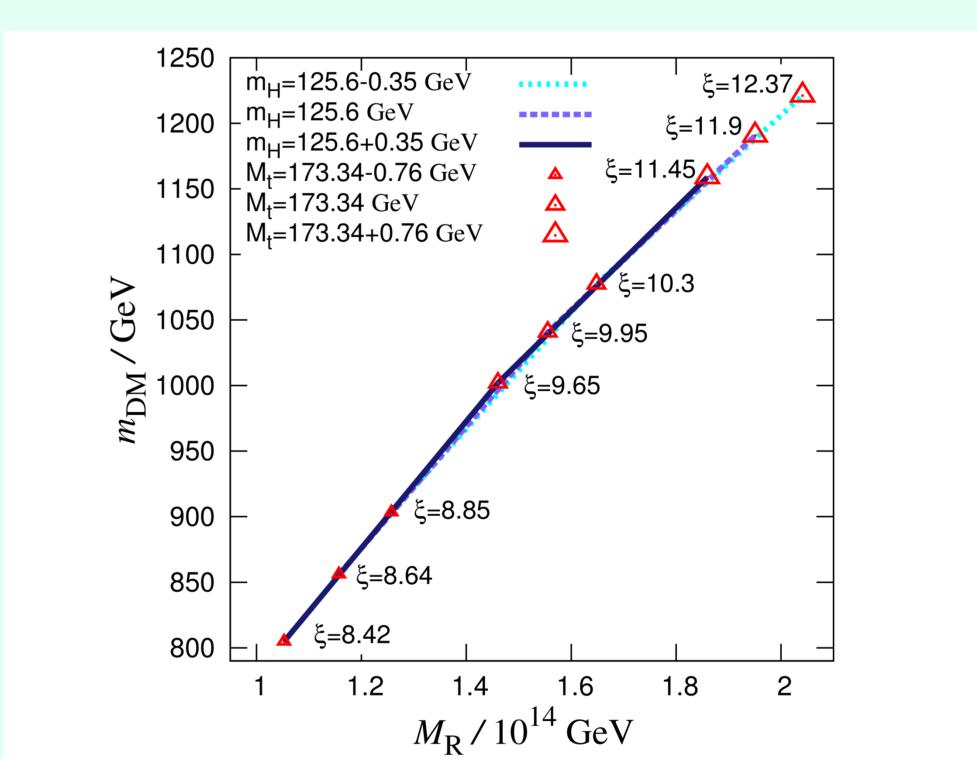$$r = 0.2^{+0.07}_{-0.05} \quad \text{:Tensor-to-scalar ratio}$$ [BICEP2 Collaboration]

$$50 < N < 60 \quad \text{:e-foldings}$$ [Planck Collaboration]

$$n_s = 0.9600 \pm 0.0071 \quad \text{:Scalar spectral index}$$

> Can this model explain not only cosmological parameters but also dark matter abundance and neutrino mass within the experimental values of top and Higgs masses

5.RESULTS

Constraints on RHν and DM masses

6.CONCLUSIONS

We discuss a possibility of Higgs inflation in the SM expanding RHν and scalar

• Right-handed neutrino : neutrino masses

• Real singlet scalar : DM candidate

Previous works conclude that top mass should be light

• Higgs quartic coupling goes to negative before inflation scale

For precise analysis, we solve RGEs @ 2-loop order

• Results of DM and RHν masses and non-minimal coupling

$$805 \text{ GeV} \lesssim m_{\rm DM} \lesssim 1220 \text{ GeV}$$

$$1.05 \times 10^{14} \text{ GeV} \lesssim M_R \lesssim 2.04 \times 10^{14} \text{ GeV}$$

$$8.42 \lesssim \xi \lesssim 12.4$$

Detectability @future direct detection experiments

Comment on recent report from the joint analysis of BICEP, Keck array and Planck

$$r = 0.048^{+0.035}_{-0.032} \quad \Rightarrow \quad \text{This result changes only non-minimal coupling into}$$
$$9.43 \lesssim \xi \lesssim 13.5 \quad \text{(DM and RHν masses are not changed at all)}$$