

# Non-decoupling effects and the nearly aligned Higgs EFT

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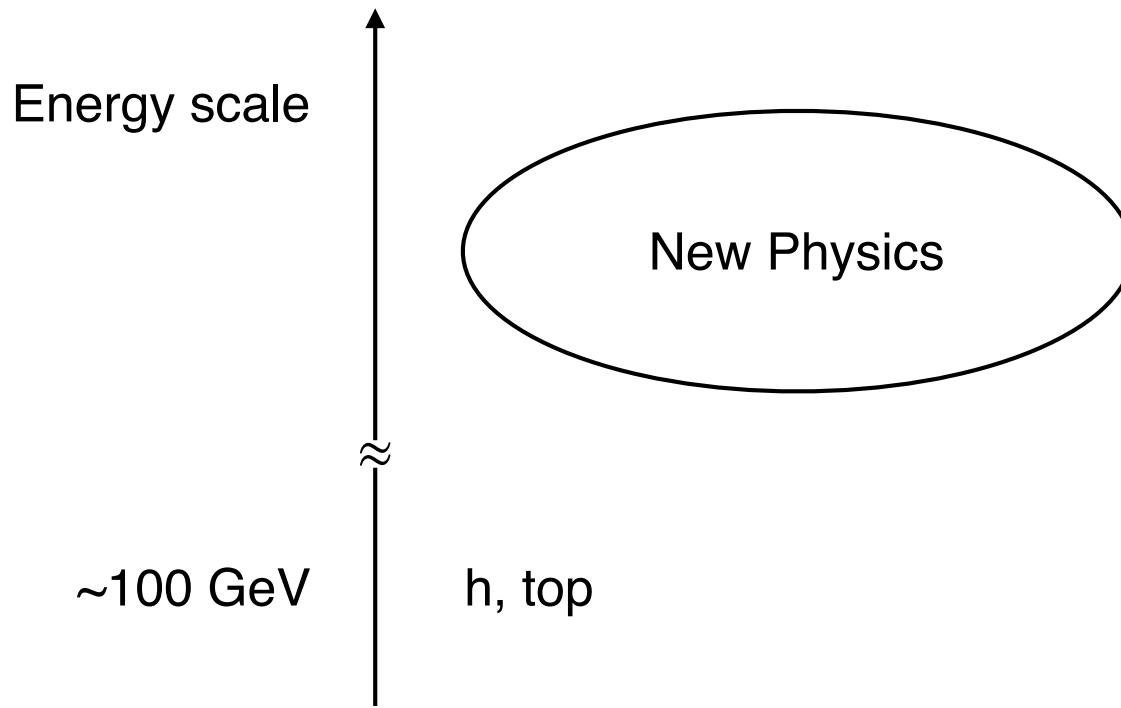
S. Kanemura, R. Nagai and M. Tanaka: JHEP 06 (2022) 027

IDT-WG3-Phys Open Meeting (Online) 13/10/2022

# Introduction

Standard Model (SM) is consistent with the result in LHC

Unsolved problems: baryon asymmetry of the Universe, dark matter etc...



Contributions from heavy new particles can be described by EFT frameworks

e.g., Standard Model Effective Field Theory (SMEFT), Higgs EFT (HEFT)

[Buchmuller and Wyler: Nucl. Phys. B268 (1986)]

[Grzadkowski et al.: JHEP 10 (2010)]

[Feruglio: Int. J. Mod. Phys. A 8 (1993)]

# Introduction

- The framework of the SMEFT is often used
  - SMEFT is a good EFT for the decoupling new physics
- Heavy particles can arise large quantum effects (non-decoupling effects)
  - SMEFT does not work well in such the case
- Higgs EFT can describe the new physics with the large quantum effects

[Buchmuller and Wyler: Nucl. Phys. B268 (1986)]  
[Grzadkowski et al.: JHEP 10 (2010)]

[Appelquist and Carazzone, PRD 11 (1975)]

[Kanemura et al.: PRD 70 (2004)]

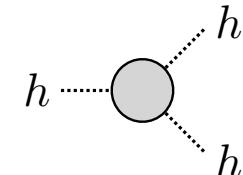
[Falkowski, Rattazzi, JHEP 10 (2019), Cohen et. al, JHEP 03 (2021)]

[Feruglio: Int. J. Mod. Phys. A 8 (1993)]

**We develop the HEFT to discuss the non-decoupling effects**

# Non-decoupling effects in hhh coupling

$$\left. \frac{\partial^3 V_{\text{eff}}(\varphi)}{\partial \varphi^3} \right|_{\varphi=v} = \lambda_{hhh}^{\text{SM}} \left( 1 + \frac{\Delta \lambda_{hhh}^{\text{new}}}{\lambda_{hhh}^{\text{SM}}} \right), \quad \Delta \lambda_{hhh}^{\text{new}} = \lambda_{hhh}^{\text{new}} - \lambda_{hhh}^{\text{SM}}$$



Eg) Two Higgs doublet model (2HDM)

[Kanemura et al.: PRD 70 (2004)]

$$m_\Phi^2 \simeq M^2 + \lambda_\Phi v^2$$

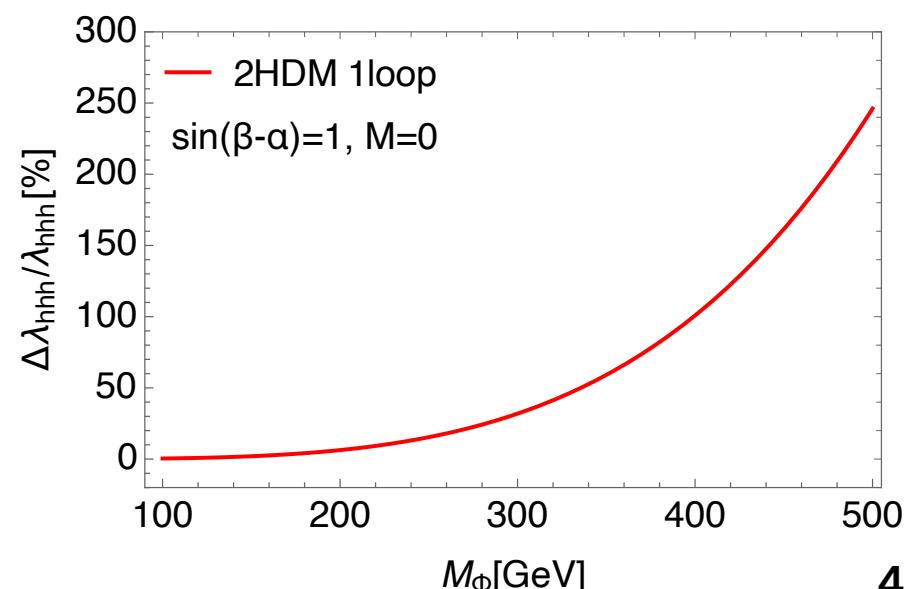
$$\frac{\Delta \lambda_{hhh}^{\text{2HDM}}}{\lambda_{hhh}^{\text{SM}}} \simeq \sum_{\Phi=H,A,H^\pm} \frac{n_\Phi m_\Phi^4}{12\pi^2 m_h^2 v^2} \left( 1 - \frac{M^2}{m_\Phi^2} \right)^3 \simeq \begin{cases} \sum_\Phi \frac{n_\Phi \lambda_\Phi^3 v^4}{12\pi^2 m_h^2 \cancel{m_\Phi^2}} & (\lambda_\Phi v^2 \ll M^2) \text{ Decoupling} \\ \boxed{\sum_\Phi \frac{n_\Phi \cancel{m_\Phi^4}}{12\pi^2 m_h^2 v^2}} & (\lambda_\Phi v^2 \gtrsim M^2) \text{ Non-decoupling} \end{cases}$$

Large hhh coupling is required to realize the strong 1st order EW phase transition

[Kanemura, Okada and Senaha, PLB606 (2005)]

$$\frac{\Delta \lambda_{hhh}^{\text{2HDM}}}{\lambda_{hhh}^{\text{SM}}} > 20 - 30 \%$$

The non-decoupling effect is very important



# Non-decoupling effects and new EFT

- Loop corrections to the effective potential [Coleman and Weinberg: PRD 7 (1973)]

$$V_{\text{CW}}(\varphi) = \frac{[M^2(\varphi)]^2}{64\pi^2} \ln \frac{M^2(\varphi)}{Q^2}$$

Important to describe the non-decoupling effects

- Assuming  $M^2(\varphi) = M^2 + \lambda_\Phi \varphi^2$  with  $M^2 \gg \lambda_\Phi v^2$

[Appelquist and Carazzone, PRD 11 (1975)]

$$V_{\text{CW}}(\varphi) \ni \frac{\lambda_\Phi^3}{64\pi^2 M^2} \varphi^6 = \frac{1}{\Lambda^2} \varphi^6 \Rightarrow \text{SMEFT is a good approximation}$$

- In the case with  $M^2 \lesssim \lambda_\Phi v^2$ , we cannot expand  $V_{\text{CW}}$  in terms of  $\varphi$

⇒ SMEFT is not appropriate to describe the non-decoupling effects

[Falkowski, Rattazzi, JHEP 10 (2019), Cohen et. al, JHEP 03 (2021)]

We need a new EFT framework → **Nearly aligned Higgs EFT (naHEFT)**

# Nearly aligned Higgs EFT (naHEFT)

- Lagrangian in the naHEFT

[Kanemura and Nagai, JHEP 03 (2022)]

$$\mathcal{L}_{\text{naHEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}},$$

$$\mathcal{M}^2(h), \mathcal{F}(h), \mathcal{K}(h), \mathcal{Y}_\psi^{ij}(h), \hat{\mathcal{Y}}_\psi^{ij}(h)$$

$$\begin{aligned} \mathcal{L}_{\text{BSM}} = & \xi \left[ -\frac{\kappa_0}{4} [\mathcal{M}^2(h)]^2 \ln \frac{\mathcal{M}^2(h)}{\mu^2} \right. \\ & + \frac{v^2}{2} \mathcal{F}(h) \text{Tr} [D_\mu U^\dagger D^\mu U] + \frac{1}{2} \mathcal{K}(h) (\partial_\mu h) (\partial^\mu h) \\ & \left. - v \left( \bar{q}_L^i U \left[ \mathcal{Y}_q^{ij}(h) + \hat{\mathcal{Y}}_q^{ij}(h) \tau^3 \right] q_R^j + h.c. \right) - v \left( \bar{l}_L^i U \left[ \mathcal{Y}_l^{ij}(h) + \hat{\mathcal{Y}}_l^{ij}(h) \tau^3 \right] l_R^j + h.c. \right) \right] \end{aligned}$$

: polynomial in terms of  $h$

$$\xi = \frac{1}{16\pi^2}$$

$$U = \exp \left( \frac{i}{v} \pi^a \tau^a \right) \quad \text{For simplicity, we take } \mathcal{M}^2(h) = M^2 + \frac{\kappa_p}{2} (h + v)^2$$

- 3 Free parameters in the naHEFT

$$\Lambda = \sqrt{M^2 + \frac{\kappa_p}{2} v^2}, \quad \kappa_0, \quad r = \frac{\kappa_p v^2}{2} / \Lambda^2$$

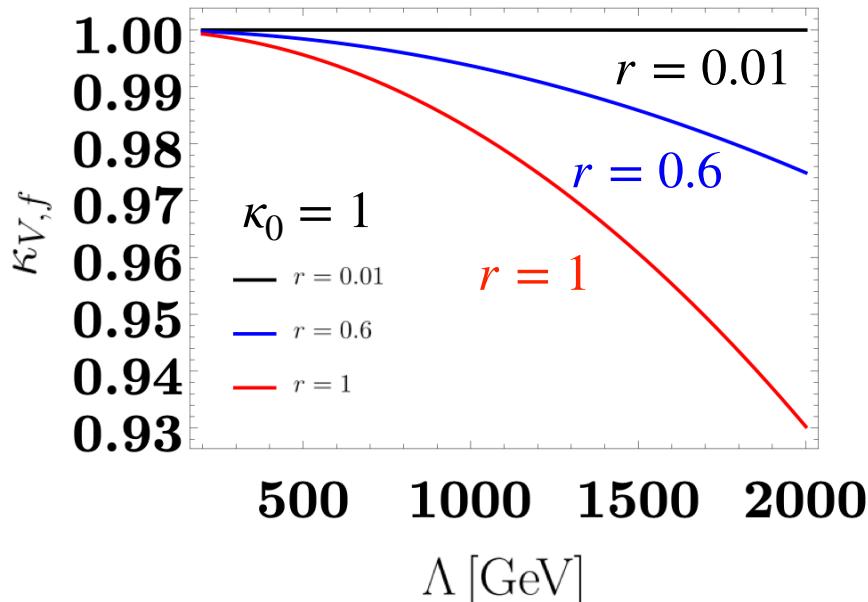
$$\begin{aligned} r \sim 0 & \Rightarrow M^2 \gg \frac{\kappa_p}{2} v^2 && \text{Decoupling} \\ r \sim 1 & \Rightarrow M^2 \ll \frac{\kappa_p}{2} v^2 && \text{Non-decoupling} \end{aligned}$$

# What is the meaning of “nearly aligned”?

- The naHEFT in the canonical basis

[Kanemura and Nagai, JHEP 03 (2022)]

$$\begin{aligned} \mathcal{L}_{\text{naHEFT}} = & -\frac{1}{4}W^{a\mu\nu}W_{\mu\nu}^a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ & + \frac{v^2}{4} \left( 1 + 2\kappa_V \frac{\hat{h}}{v} + \kappa_{VV} \frac{\hat{h}^2}{v^2} + \mathcal{O}(\hat{h}^3) \right) \text{Tr} [D_\mu U^\dagger D^\mu U] \\ & + \frac{1}{2} \left( \partial_\mu \hat{h} \right) \left( \partial^\mu \hat{h} \right) - \frac{1}{2} M_h^2 \hat{h}^2 - \frac{1}{3!} \frac{3M_h^2}{v} \kappa_3 \hat{h}^3 - \frac{1}{4!} \frac{3M_h^2}{v^2} \kappa_4 \hat{h}^4 + \mathcal{O}(h^5) \\ & - \sum_{f=u,d,e} m_{f^i} \left[ \left( \delta^{ij} + \kappa_f^{ij} \frac{h}{v} + \mathcal{O}(h^2, \pi^2) \right) \bar{f}_L^i f_R^j + h.c. \right], \end{aligned}$$



The naHEFT can describe extended Higgs models without alignment ( $\kappa_{V,f} \neq 1$ )

$$\kappa_V = \frac{g_{hVV}^{\text{new}}}{g_{hVV}^{\text{SM}}}, \quad \kappa_f = \frac{g_{hff}^{\text{new}}}{g_{hff}^{\text{SM}}}$$

# SMEFT and naHEFT

$$V_{\text{EFT}} = V_{\text{SM}} + \frac{\xi}{4} \kappa_0 \left[ \mathcal{M}^2(\phi) \right]^2 \ln \frac{\mathcal{M}^2(\phi)}{\mu^2}$$

$$\mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2} \phi^2,$$

Expand the logarithmic part in terms of  $\phi$

$$\mathcal{M}^2(v) \equiv \Lambda^2 \quad r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

$$\xi = \frac{1}{16\pi^2}$$

- Up to dimension six

$$V_{\text{BSM}}(\Phi) = \frac{1}{f^2} \left( |\Phi|^2 - \frac{v^2}{2} \right)^3, \quad \frac{1}{f^2} = \frac{2}{3} \xi \kappa_0 \frac{\Lambda^4}{v^6} \frac{r^3}{1-r}$$

- Up to dimension eight

$$|\Phi|^2 = \phi^2/2$$

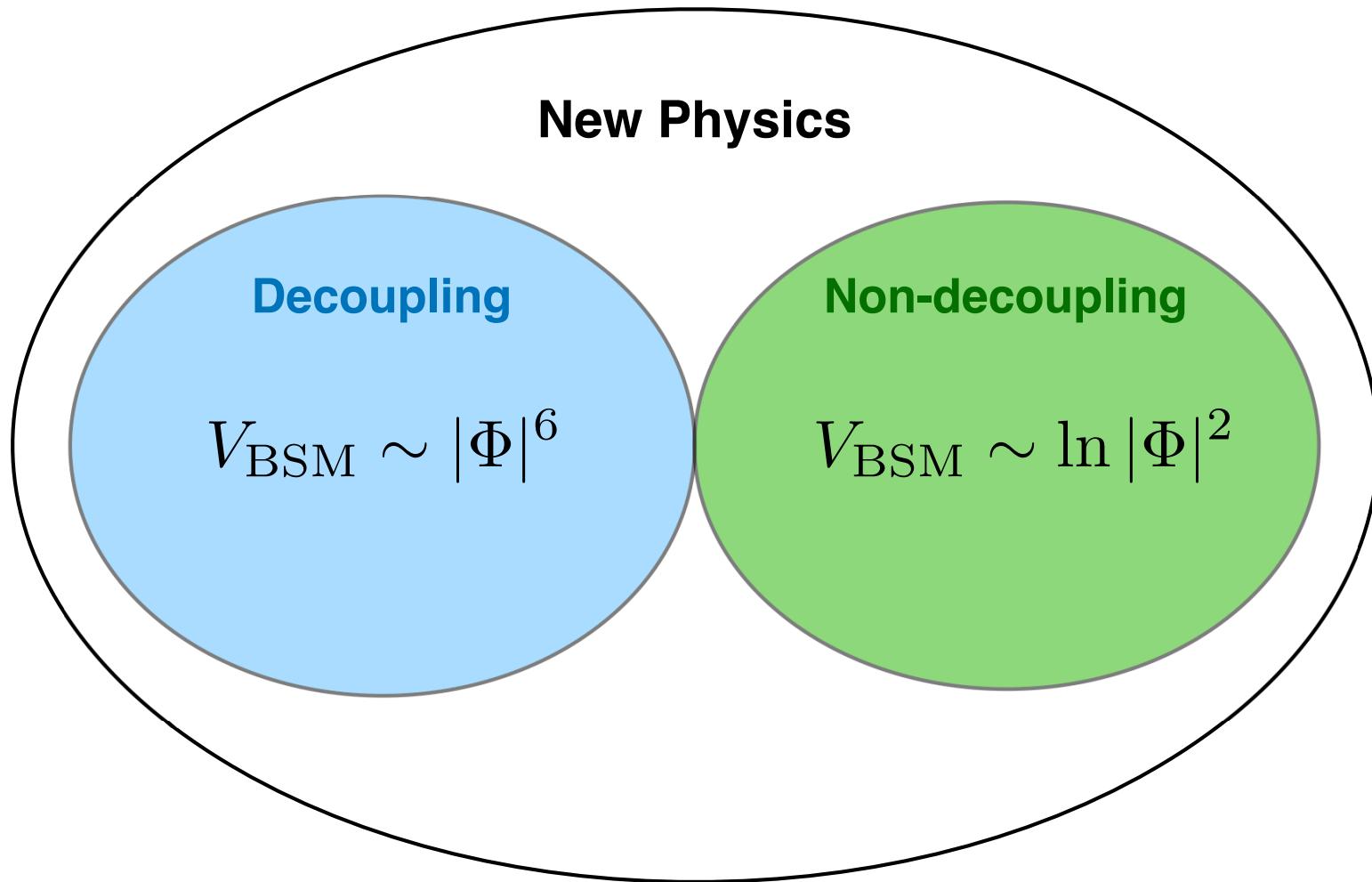
$$V_{\text{BSM}}(\Phi) = \frac{1}{f_6^2} \left( |\Phi|^2 - \frac{v^2}{2} \right)^3 - \frac{1}{f_8^4} \left( |\Phi|^2 - \frac{v^2}{2} \right)^4$$

$$\frac{1}{f_6^2} = \frac{1}{f^2} \frac{1-2r}{1-r}, \quad \frac{1}{f_8^4} = \frac{1}{2f^2 v^2} \frac{r}{1-r}$$

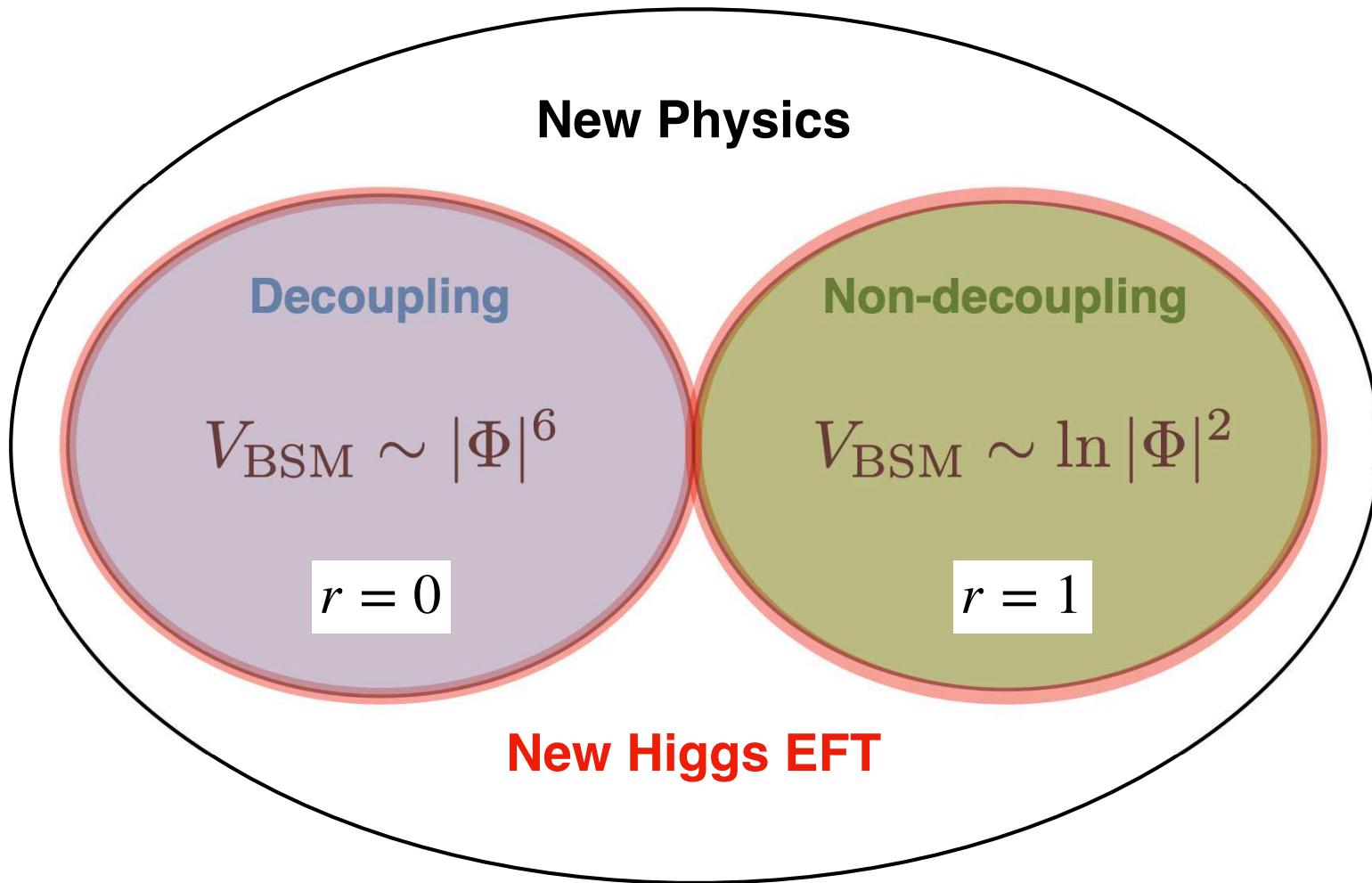
$$r \rightarrow 1/2 \Rightarrow 1/f_8 \gg 1/f_6$$

The expansion is not good at large  $r$

# Possibility of new physics



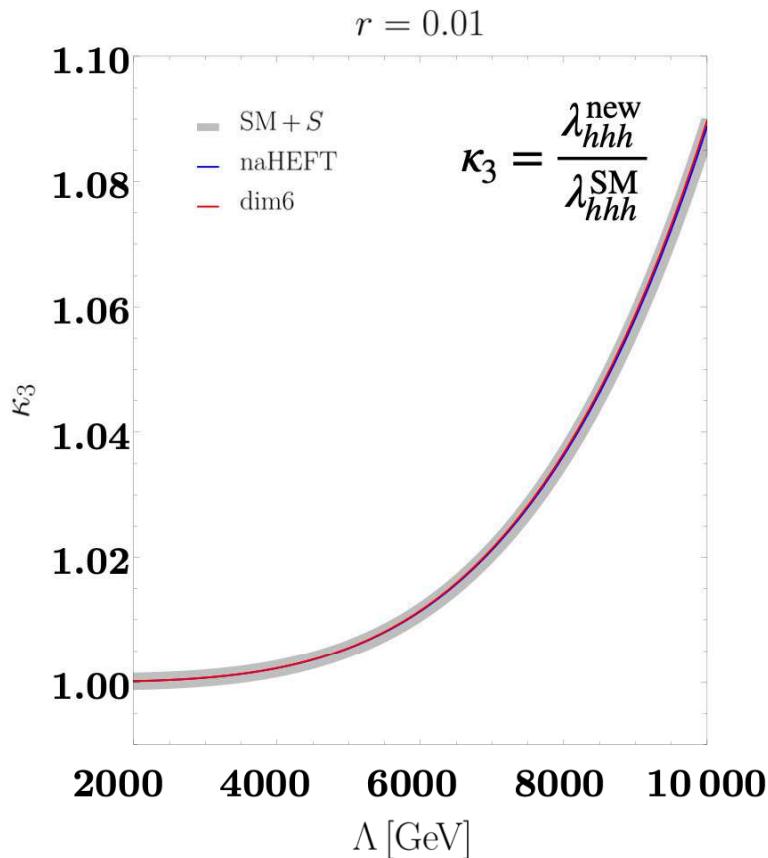
# Possibility of new physics



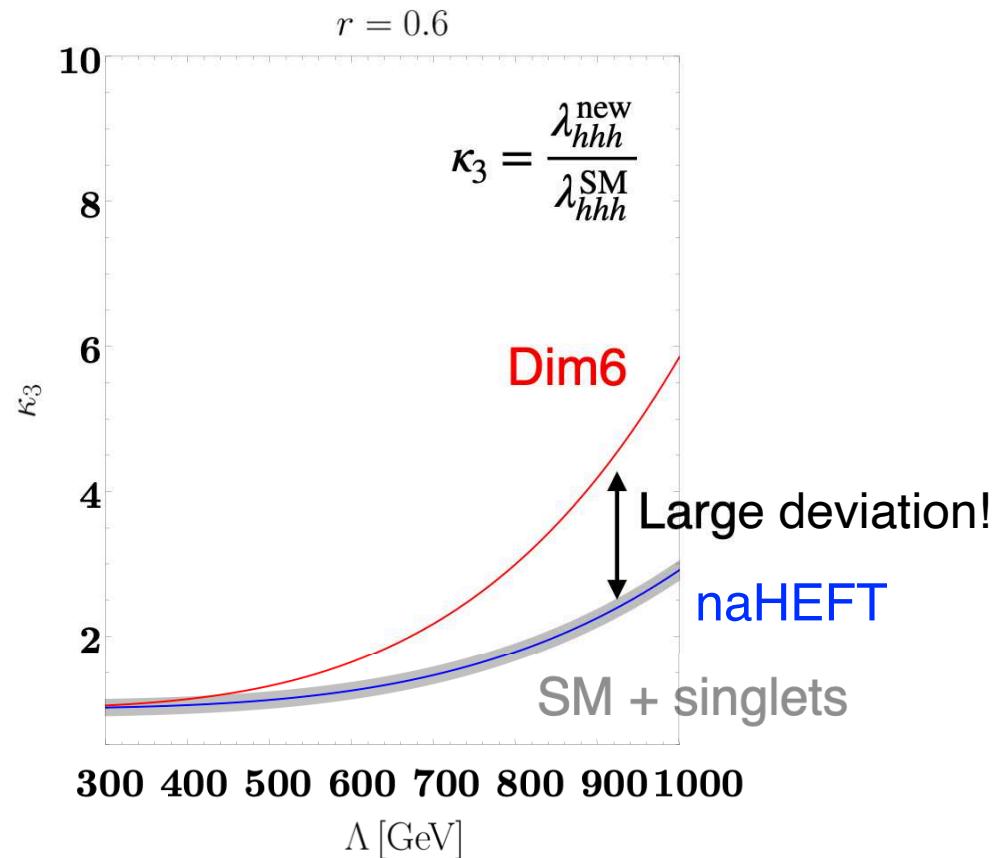
# SMEFT vs naHEFT: hhh coupling

[Kanemura and Nagai, JHEP 03 (2022)]

## Decoupling



## Non-decoupling



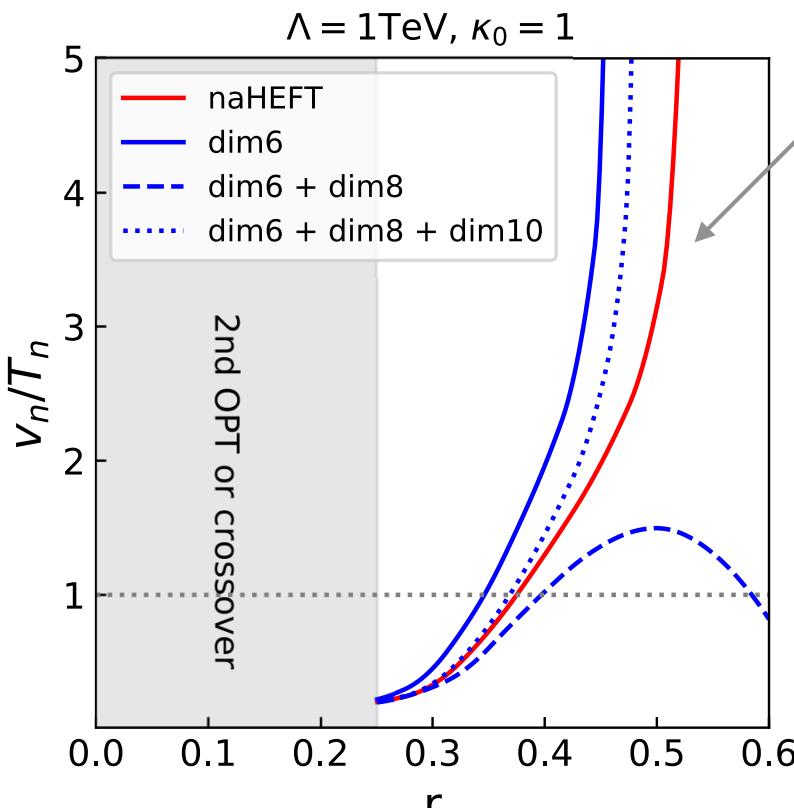
$$\mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2}\phi^2, \quad \mathcal{M}^2(v) \equiv \Lambda^2 \quad r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

# new Higgs EFT at the finite temperature

- We extend the new EFT at finite temperature [Kanemura, Nagai and Tanaka, JHEP 06 (2022)]

$$V_{\text{EFT}} = V_{\text{SM}} + \frac{\kappa_0}{64\pi^2} [\mathcal{M}^2(\phi)]^2 \ln \frac{\mathcal{M}^2(\phi)}{\mu^2} + \frac{\kappa_0}{2\pi^2} T^4 J_{\text{BSM}} \left( \frac{\mathcal{M}^2(\phi)}{T^2} \right)$$

$$J_{\text{BSM}}(a^2) = \int_0^\infty dk^2 k^2 \ln \left[ 1 - \text{sign}(\kappa_0) e^{-\sqrt{k^2+a^2}} \right] \quad \mathcal{M}^2(\phi) = M^2 + \frac{\kappa_p}{2} \phi^2$$



consistent with the result in the SM with a singlet scalar  
[Kakizaki et al., PRD 92 (2015), Hashino et al., PRD 94 (2016)]

There is a large discrepancy b/w the prediction  
for  $\nu_n/T_n$  in the new EFT and the SMEFT

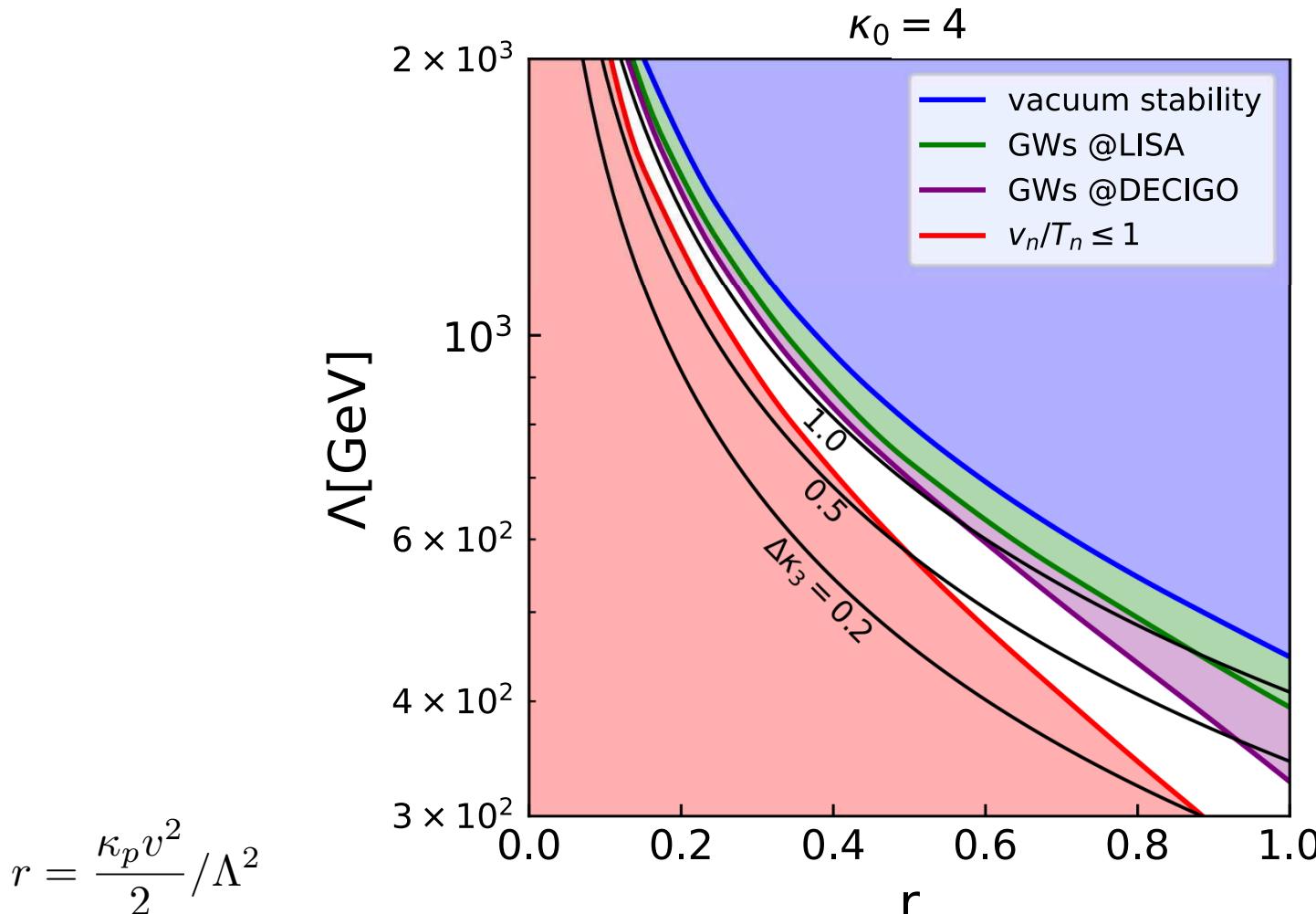


SMEFT may not be appropriate when we  
discuss the strong first order phase transition

$$r = \frac{\frac{\kappa_p v^2}{2}}{\Lambda^2}$$

# Phenomenology in the new HEFT

We can test the extended Higgs models with the non-decoupling effects by using the GW observations and the measurement of  $hhh$  coupling



$\Lambda$ : masses of new particles

[Kanemura, Nagai and Tanaka,  
JHEP 06 (2022)]

$$\Delta\kappa_3 = \frac{\lambda_{hhh}^{\text{new}} - \lambda_{hhh}^{\text{SM}}}{\lambda_{hhh}^{\text{SM}}}$$

# Summary

- We proposed the nearly aligned Higgs EFT

$$V_{\text{EFT}} = V_{\text{SM}} + \frac{\kappa_0}{64\pi^2} [\mathcal{M}^2(\phi)]^2 \ln \frac{\mathcal{M}^2(\phi)}{\mu^2} + \frac{\kappa_0}{2\pi^2} T^4 J_{\text{BSM}} \left( \frac{\mathcal{M}^2(\phi)}{T^2} \right)$$

→ The naHEFT can describe models with the non-decoupling effects

- We discussed  $hhh$  coupling and EW phase transition in the naHEFT
  - SMEFT may not be appropriate when we discuss phenomena related to the non-decoupling quantum effects
- We can test extended models with the non-decoupling effects via  $hhh$  coupling measurements and gravitational wave observations

Colliders: ILC, HL-LHC      GW observations: DECIGO, LISA, etc...