Probing phase transition keeping the symmetry

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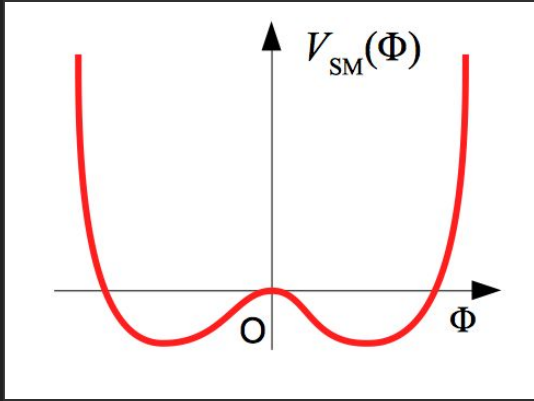
(1. CHEP at PKU, 2. ITP at PKU, 3. ITP at CAS)

[In preparation]

Introduction

★ The shape of Higgs potential is still undetermined.

$$V_{SM}(\phi)=\mu^2|\phi|^2+\lambda|\phi|^4$$ (The SM case)



It is important to explore the shape of the Higgs potential.

★ The dynamics of electroweak phase transition (EWPT) is governed by the shape of the Higgs potential.

If the model realize the first-order EWPT,

- Baryon asymmetry of the universe may be explained by electroweak baryogenesis scenario.
- The model may be tested by the gravitational wave (GW) observation experiment.

How can we realize the first-order EWPT?

First-order EWPT

★ First-order EWPT is that the electroweak symmetry breaking is produced by the bubble dynamics.

★ Effective potential for first-order EWPT

$$V_{\mathrm{eff}}(\varphi,T) = D(T^2 - T_0^2)\varphi^2 + (e - ET)\varphi^3 + \frac{\lambda(T)}{4}\varphi^4$$

(Under high temperature approximation)

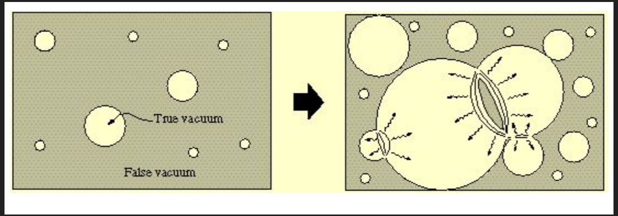
e : Mixing effects at the tree level

E : Loop effects of bosons

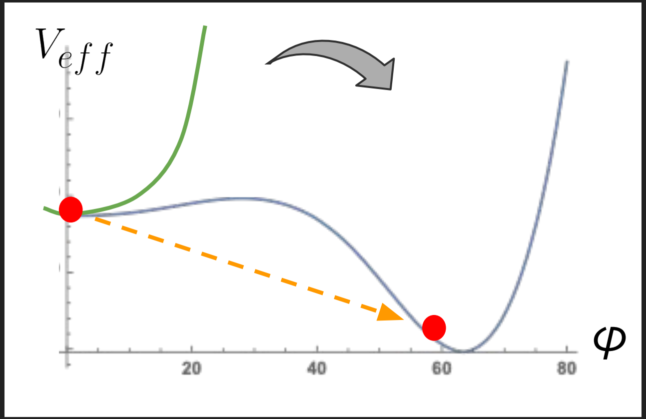
The SM cannot realize the first-order EWPT.

[Y. Aoki, F. Csikor, Z. Fodor and A. Ukawa, Phys. Rev. D 60, 013001 (1999)]

The model beyond the SM, especially the extended Higgs model, can realize the first-order EWPT.



Maya Fishbach's slide

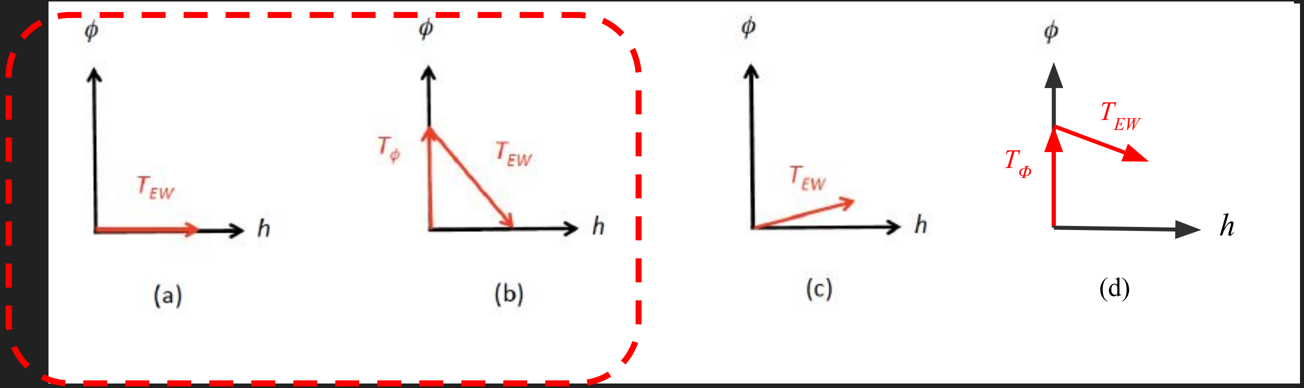


Motivation

★ Multi-step phase transition (PT) could be produced in some extended Higgs models.

[D. Land and E. D. Carlson, Phys. Lett. B 292 (1992), 107, A. Hammerschmitt, J. Kripfganz and M. G. Schmidt, Z. Phys. C 64 (1994), 105]

[M. J. Ramsey-Musolf, JHEP 09 (2020), 179]



h: The SM Higgs boson

φ: Additional scalar boson

★ A symmetry in the Higgs potential at zero temperature can be assured, that depends on the model parameters.

$$V = \mu_h^2 h^2 + \mu_\phi^2 \phi^2 + \lambda_h h^4 + \lambda_\phi \phi^4 + \lambda_{h\phi} h^2 \phi^2$$

$$h \to h, \quad \phi \to -\phi$$

In this potential case, the potential keep Z_2 symmetry when the PT realizes by (a) and (b).

→ We could explore a symmetry in the potential by the sign of (a) and (B) PT...

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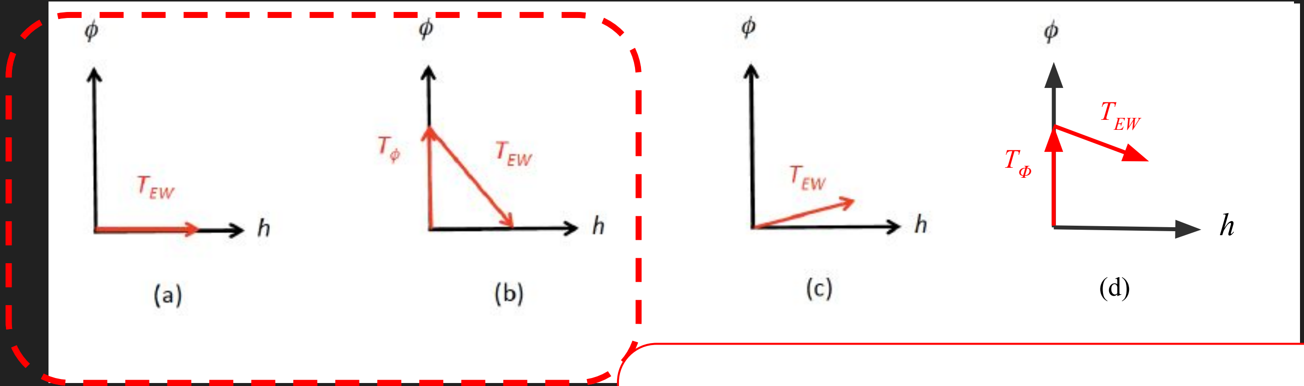

h: The SM Higgs boson
φ: Additional scalar boson

★ A symmetry in the Higgs potential at … e model parameters.

$$V = \mu_h^2 h^2+\mu_\phi^2\phi^2+\lambda_h h^4+\lambda_\phi\phi^4 \cdots$$

By using this symmetry, we may explain
1) Existence of DM,
2) Neutrino oscillation (radiative seasaw model).

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Motivation

★ Multi-step phase transition (PT) could be produced in some extended Higgs models.

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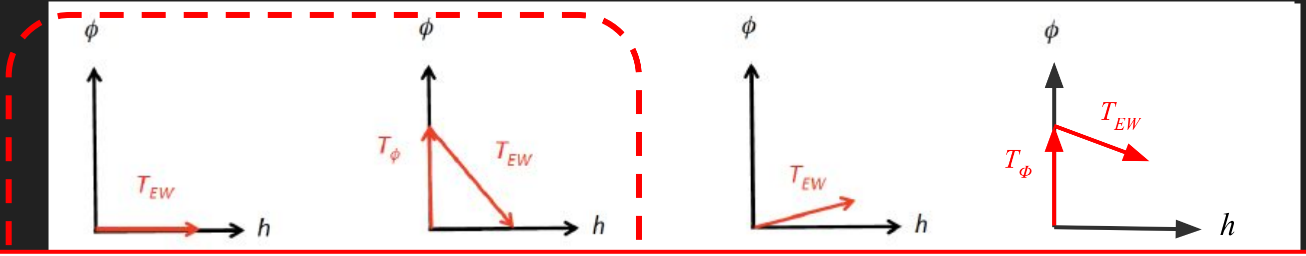


h: The SM Higgs boson
φ: Additional scalar boson

In our work, we focus on the extended Higgs model with Z_2 symmetry and an isospin N-plet scalar field and discuss the possibility of the PT, especially (b).

★ model parameters.

$$V = \mu_h^2 h^2 + \mu_\phi^2 \phi^2 + \lambda_h h^4 + \lambda_\phi \phi^4 + \lambda_{h\phi} h^2 \phi^2$$

$$h \to h, \quad \phi \to -\phi$$

In this potential case, the potential keep Z_2 symmetry when the PT realizes by (a) and (b).

→ We could explore a symmetry in the potential by the sign of (a) and (B) PT...

Extended Higgs model

$$Q = I^3 + \frac{1}{2}Y$$

★ Higgs potential with Z_2 symmetry

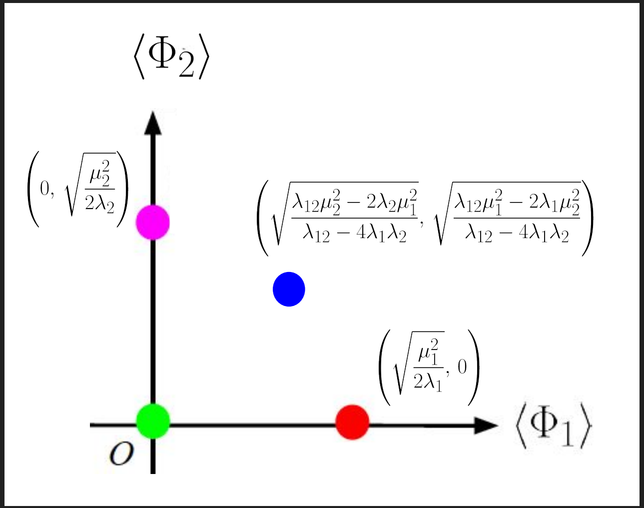
$$V(\Phi_1,\Phi_2) = -\mu_1^2|\Phi_1|^2 - \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_{12}|\Phi_1|^2|\Phi_2|^2$$

$$\Phi_1 = \left(G^\pm, \frac{1}{\sqrt{2}}\left(h + iG^0\right)\right)^T \qquad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi^1 + i\phi^{1,i} \\ \phi^2 + i\phi^{2,i} \\ \vdots \\ \phi^N + i\phi^{N,i} \end{pmatrix}$$

$$\Phi_1 \to \Phi_1, \quad \Phi_2 \to -\Phi_2$$

★ Stationary points of the potential

$$\frac{\partial V(\langle\Phi_1\rangle, \langle\Phi_2\rangle)}{\partial\langle\Phi_1\rangle} = \frac{\partial V(\langle\Phi_1\rangle, \langle\Phi_2\rangle)}{\partial\langle\Phi_2\rangle} = 0$$



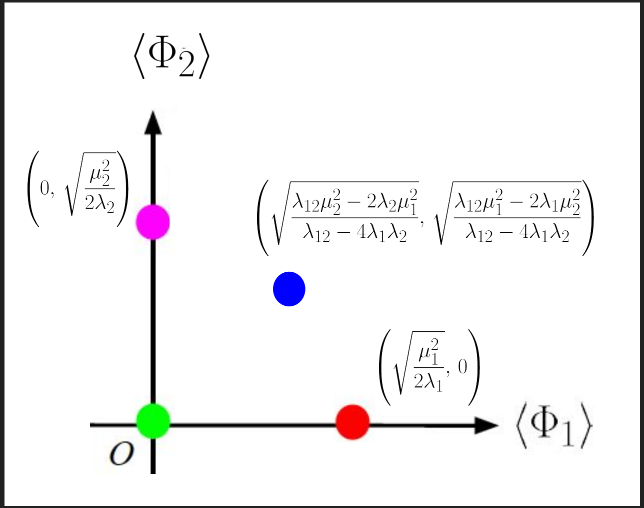
The condition of minimum points at red point could be obtained by Hesse matrix analysis.

Extended Higgs model

★ Tree-level results for Hesse matrix

$$\det[\mathcal{H}_{red}] = \mu_1^2\left(\frac{\lambda_{12}\mu_1^2}{\lambda_1} - 2\mu_2^2\right), \quad \det[\mathcal{H}_{mag}] = \mu_2^2\left(\frac{\lambda_{12}\mu_2^2}{\lambda_2} - 2\mu_1^2\right)$$

$$\det[\mathcal{H}_{blue}] = -4\frac{\left(\lambda_{12}\mu_2^2 - 2\lambda_2\mu_1^2\right)\left(\lambda_{12}\mu_1^2 - 2\lambda_1\mu_2^2\right)}{\lambda_{12}^2 - 4\lambda_1\lambda_2},$$



$$\Rightarrow \quad \frac{\lambda_{12}\mu_1^2}{\lambda_1} > 2\mu_2^2, \quad \frac{\lambda_{12}\mu_2^2}{\lambda_2} > 2\mu_1^2.$$

(Blue point is a saddle point)

Pink and red points are minimum values.

← These are the conditions of stability of a potential.

★ The condition of height of potential at tree-level

$$V\left(0, \sqrt{\mu_2^2/\lambda_2}\right) = -\mu_2^4/4\lambda_2, \quad V\left(\sqrt{\mu_1^2/\lambda_1}, 0\right) = -\mu_1^4/4\lambda_1 \quad \Rightarrow \quad \mu_2^4/\lambda_2 < \mu_1^4/\lambda_1$$

$$-\mu_2^4/4\lambda_2 \text{ (magenta)} < \frac{\lambda_1\mu_2^4 + \lambda_2\mu_1^4 - \lambda_{12}\mu_1^2\mu_2^2}{\lambda_{12}^2 - 4\lambda_1\lambda_2} \text{ (blue)}, \quad \rightarrow \quad 0 < \frac{1}{4\lambda_2}(\lambda_{12}\mu_2^2 - 2\lambda_2\mu_1^2)^2$$

Extended Higgs model

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$$\Rightarrow \quad \frac{\lambda_{12}\mu_1^2}{\lambda_1} > 2\mu_2^2, \quad \frac{\lambda_{12}\mu_2^2}{\lambda_2} > 2\mu_1^2.$$

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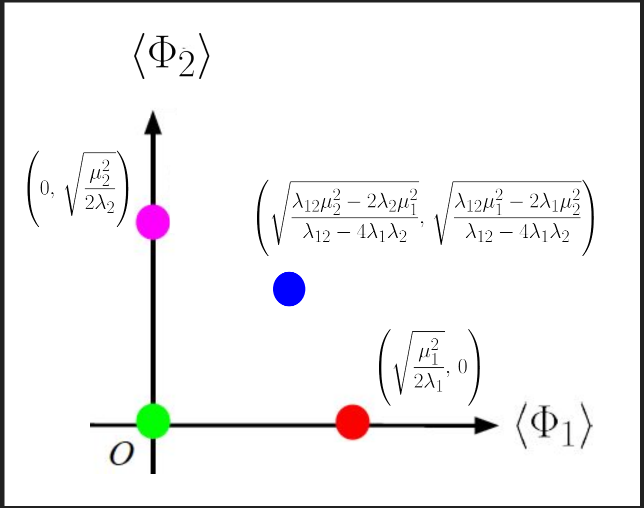


Pink ar

There are three conditions of the PT at zero temperature.

★ The condition of hei

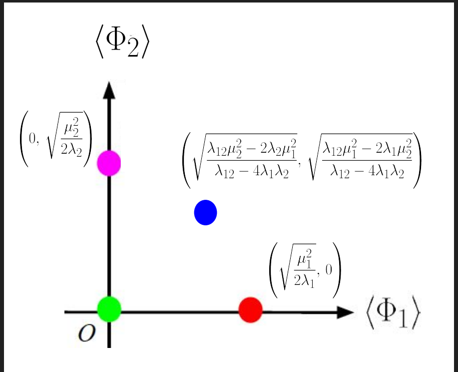
$$V\left(0, \sqrt{\mu_2^2/\lambda_2}\right) = -\mu_2^4/4\lambda_2, \quad V\left(\sqrt{\mu_1^2/\lambda_1}, 0\right) = -\mu_1^4/4\lambda_1 \quad \Rightarrow \quad \mu_2^4/\lambda_2 < \mu_1^4/\lambda_1$$

$$-\mu_2^4/4\lambda_2 \text{ (magenta)} < \frac{\lambda_1\mu_2^4 + \lambda_2\mu_1^4 - \lambda_{12}\mu_1^2\mu_2^2}{\lambda_{12}^2 - 4\lambda_1\lambda_2} \text{ (blue)}, \quad \rightarrow \quad 0 < \frac{1}{4\lambda_2}(\lambda_{12}\mu_2^2 - 2\lambda_2\mu_1^2)^2$$

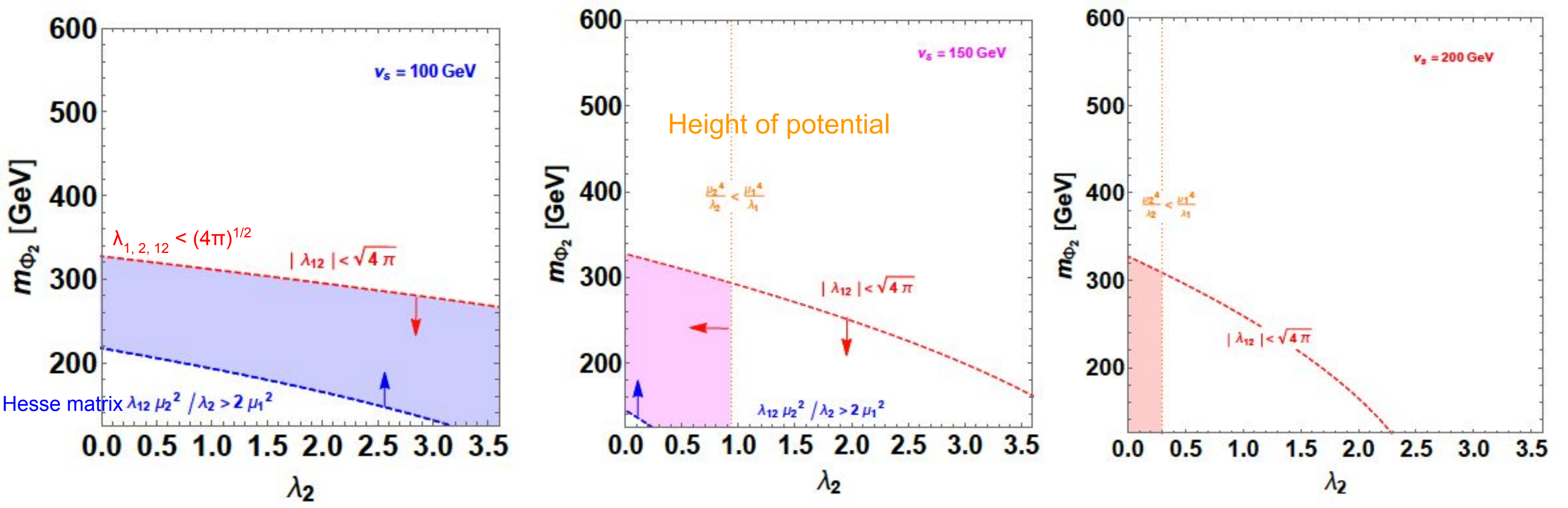
The conditions

★ Model parameters

$$(\mu_1^2, \mu_2^2, \lambda_1, \lambda_2, \lambda_{12}) \to (v, v_s, m_h, \lambda_2, m_{\Phi_2}^2).$$



★ Three conditions at tree-level



The conditions at one-loop level

★ The results with one-loop level

In the cyan parameter region,

Numerical conditions

・The height of potential at red point is the lowest.

$$V_{eff}(v, 0) < V_{eff}(0, v_S) \qquad (V_{eff} = V_0 + V_{1\text{-}loop})$$

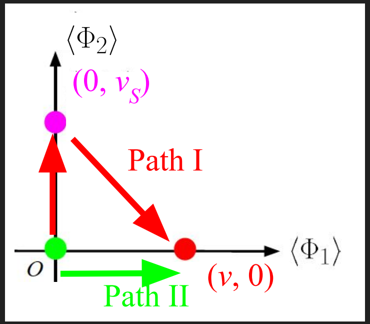
・Red and magenta points are minimum values.

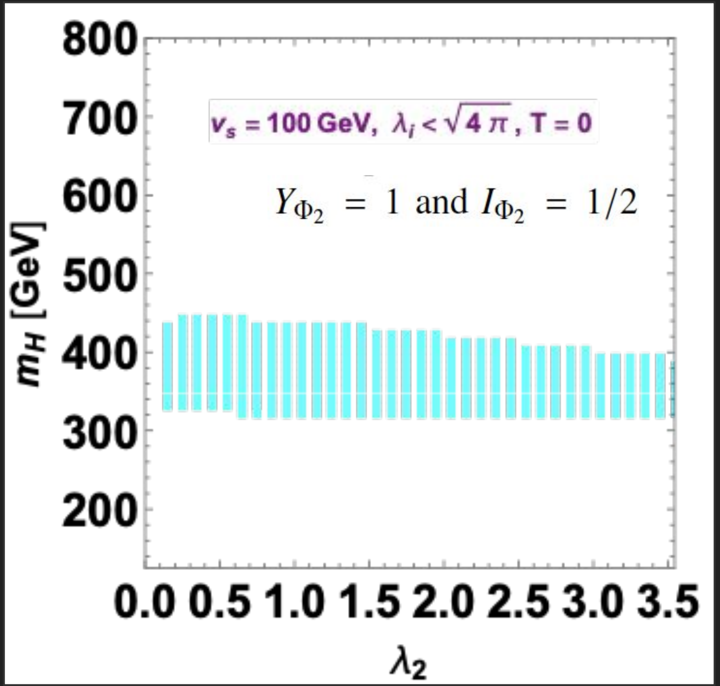
$$V_{eff}(v, 0) < V_{eff}(v, \pm 10^{-1}), V_{eff}(v \pm 10^{-1}, 0)$$

$$V_{eff}(0, v_S) < V_{eff}(\pm 10^{-1}, v_S), V_{eff}(0, v_S \pm 10^{-1})$$

・Condition of perturbative expansion

$$\lambda_i < (4\pi)^{1/2}$$





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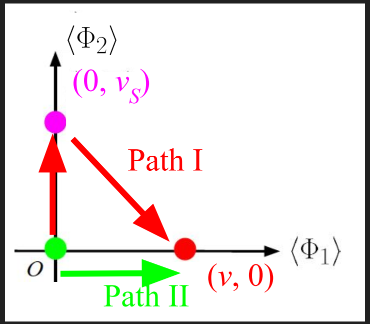

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- The height of potential at red point is the lowest.

$$V_{eff}(v, 0) < V_{eff}(0, v_S) \qquad (V_{eff} = V_0 + V_{1\text{-}loop})$$

We cannot clarify the possibility of the pattern of PT by the zero temperature analysis.

Nume

conditions

$$V_{eff}(0, v_S) < V_{eff}(\pm 10^{-1}, v_S), V_{eff}(0, v_S \pm 10^{-1})$$

- Condition of perturbative expansion

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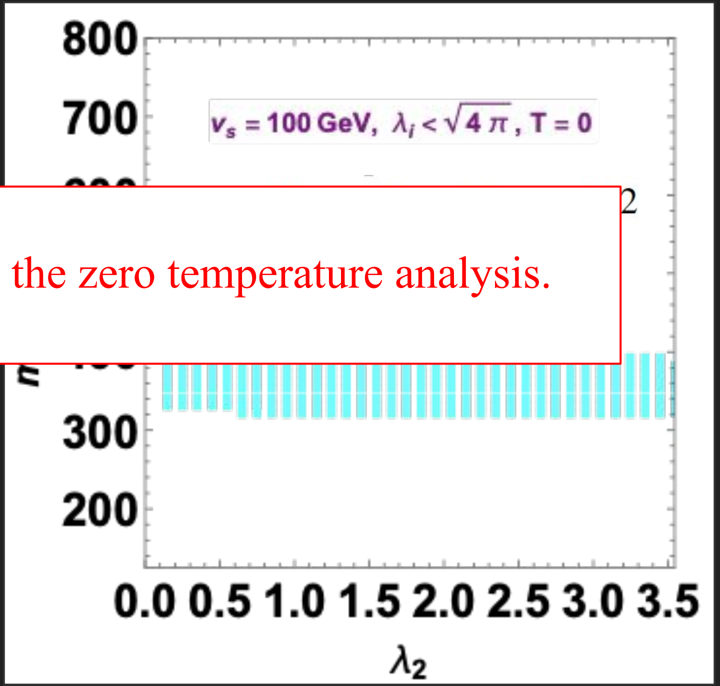


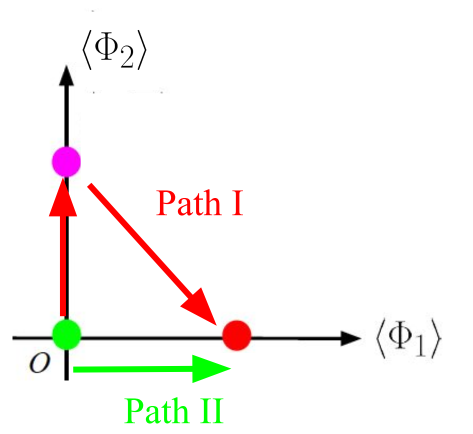
The condition of PT

★ Potential with high temperature approximation

$$V_{\rm eff}(\langle\Phi_1\rangle,\langle\Phi_2\rangle,T) \sim D_{EW}(T^2-T_{EW}^2)\langle\Phi_1\rangle^2 + D_\phi(T^2-T_\phi^2)\langle\Phi_2\rangle^2$$

$$T_{EW}^2 \sim \frac{12m_h^2}{3g'^2/2+9g^2/2+6y_t^2+2(3+n_1)\lambda_1+(1+n_2)\lambda_{12}}$$

$$T_\phi^2 \sim \frac{24\lambda_2 v_s^2}{3Y_{\Phi_2}^2 g'^2/2+3(Y_{\Phi_2}^2+2I_W^2)g^2/2+2(3+n_2)\lambda_2+(1+n_1)\lambda_{12}},$$



$$I_W^2 = 2\left(I_{\Phi_2}(I_{\Phi_2}+1)-(I^3)^2\right)$$

The PT occurs through Path I, when $T_\Phi > T_{EW}$.

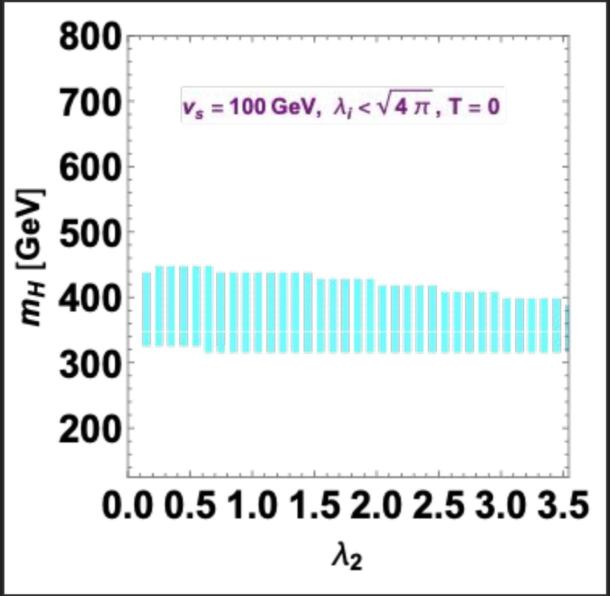
[D. Land and E. D. Carlson, Phys. Lett. B 292 (1992), 107, M. J. Ramsey-Musolf, JHEP 09 (2020), 179]

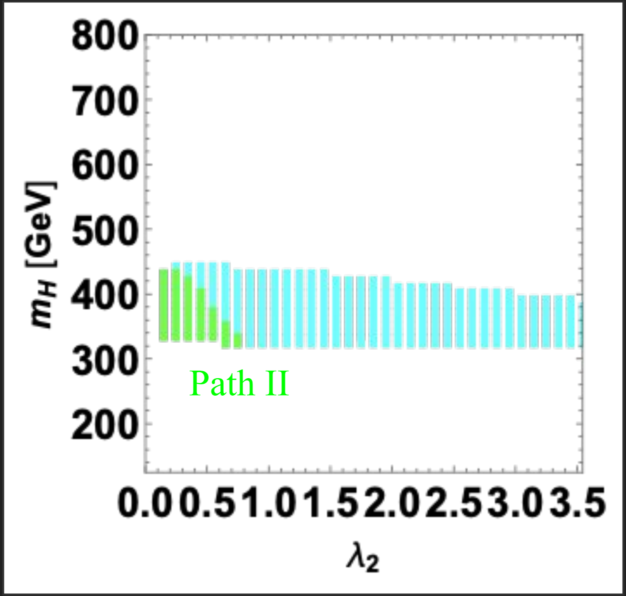
Especially, the multi-step PT for Path I could be produced by large λ_2 and v_s .

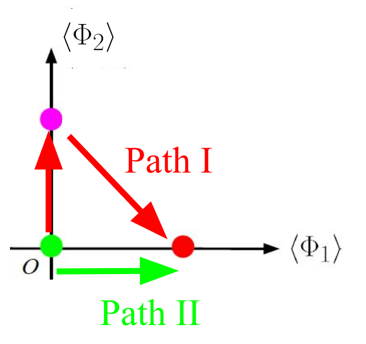
We will show the results without high temperature approximation.

Numerical results

★ Without high temperature approximation





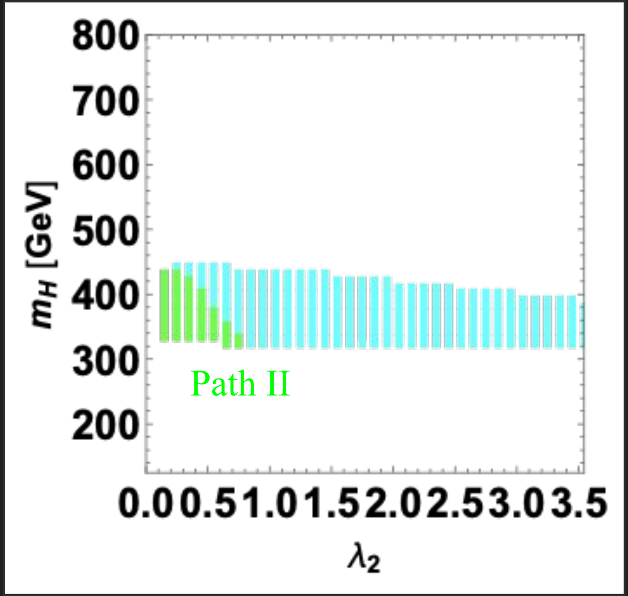


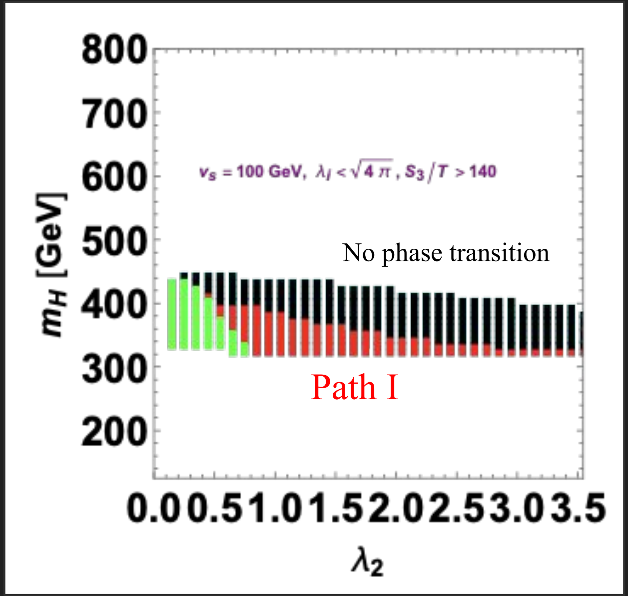
Parameter region where PT for Path II can occur.

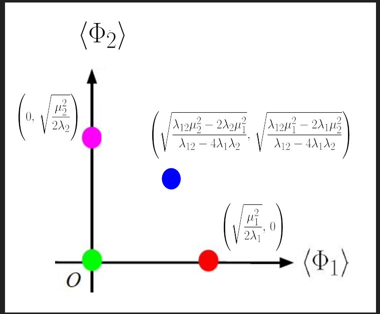
We compared the critical temperatures between (Green and red) and (Green and Magenta).

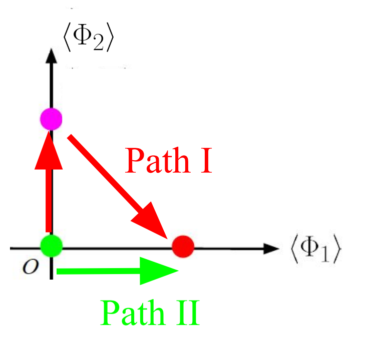
Numerical results

★ Without high temperature approximation







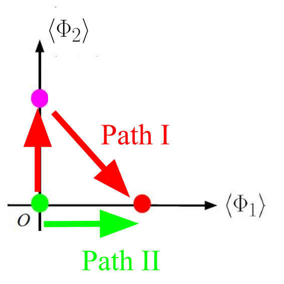


There is a barrier between magenta and red points at zero temperature, therefore we need to make sure that the PT has been completed at the current university.

We used “Anybubble” to analyze multi-step PT.

[A. Masoumi, K. D. Olum and B. Shlaer, JCAP 01 (2017), 051]

Gravitational wave from PT

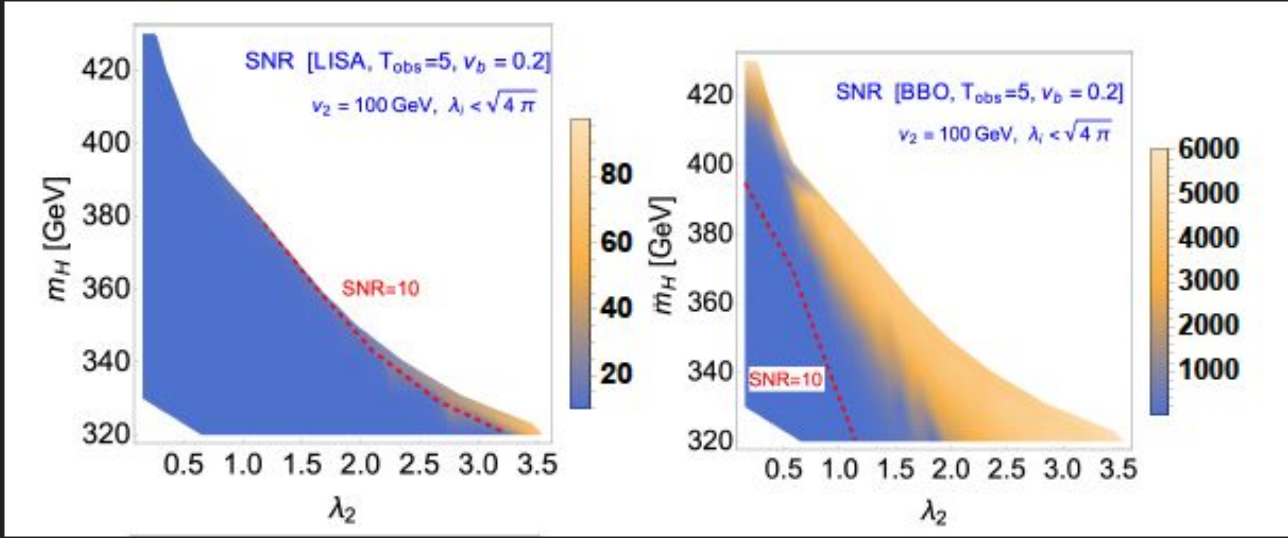


★ The gravitational wave could be produced from first-order PT.

★ We estimate the S/N ratio for measurements of GW spectrum.

S/N ratio :
$$\mathrm{SNR} = \sqrt{\delta \times \mathcal{T} \int_{f_{min}}^{f_{max}} df \left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm exp}(f)}\right]^2},$$

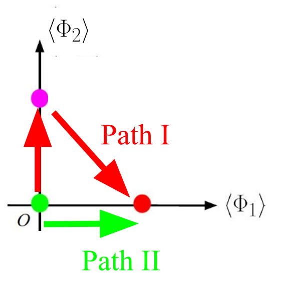
[E. Thrane and J. D. Romano, Phys. Rev. D 88 (2013) 12, 124032, C. Caprini, M. Hindmarsh, S. Huber, T. Konstandin, J. Kozaczuk, G. Nardini, J. M. No, A. Petiteau, P. Schwaller and G. Servant, et al.,JCAP 04 (2016), 001]



[LISA Collaboration, P. Amaro-Seoane et al., Laser Interferometer Space Antenna, arXiv:1702.00786]

[Yagi and N. Seto, Phys. Rev. D83 (2011) 044011]

Two first-order PTs



★ Both PTs for (Green to magenta) and (magenta to red) may be first-order.

Potential along $<\Phi_2>$ under high temperature approximation.

$$V_{eff}(0,\langle\Phi_2\rangle,T)=\Sigma_{\Phi_2}T^2\langle\Phi_2\rangle^2-E_2T\langle\Phi_2\rangle^3+\lambda_2\langle\Phi_2\rangle^4$$

$$\frac{\langle\Phi_2\rangle_C}{T_C}=\frac{E_2}{2\lambda_2}$$

First-order PT at first step can be realized by Small λ_2 .

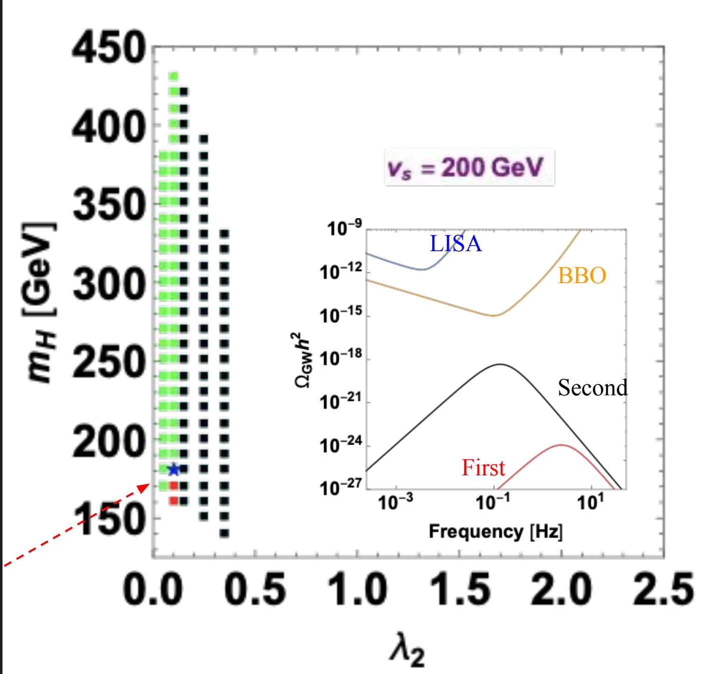
But...

$$T_{EW}^2\sim\frac{12m_h^2}{3g'^2/2+9g^2/2+6y_t^2+2(3+n_1)\lambda_1+(1+n_2)\lambda_{12}}$$

$$T_\phi^2\sim\frac{24\lambda_2v_s^2}{3Y_{\Phi_2}^2g'^2/2+3(Y_{\Phi_2}^2+2I_W^2)g^2/2+2(3+n_2)\lambda_2+(1+n_1)\lambda_{12}},$$

The PT for Path I could be realized by large λ_2 value or large v_S.

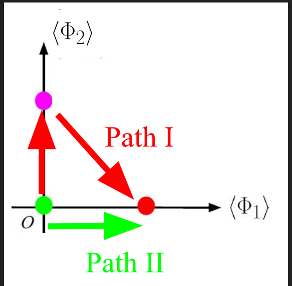
At a blue star mark, two first-order PTs can be realized, however, the spectra couldn't be tested at future experiments.



GW spectrum: C. Caprini, et al., J.Cosmol. Astropart. Phys. 1604(04)(2016) 01.

[Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu]

Two first-order PTs



★ Both PTs for (Green to magenta) and (magenta to red) may be first-order.

Potential along $\langle\Phi_2\rangle$ under high temperature approximation.

$$V_{eff}(0,\langle\Phi_2\rangle,T) = \Sigma_{\Phi_2}T^2\langle\Phi_2\rangle^2 - E_2T\langle\Phi_2\rangle^3 + \lambda_2\langle\Phi_2\rangle^4$$

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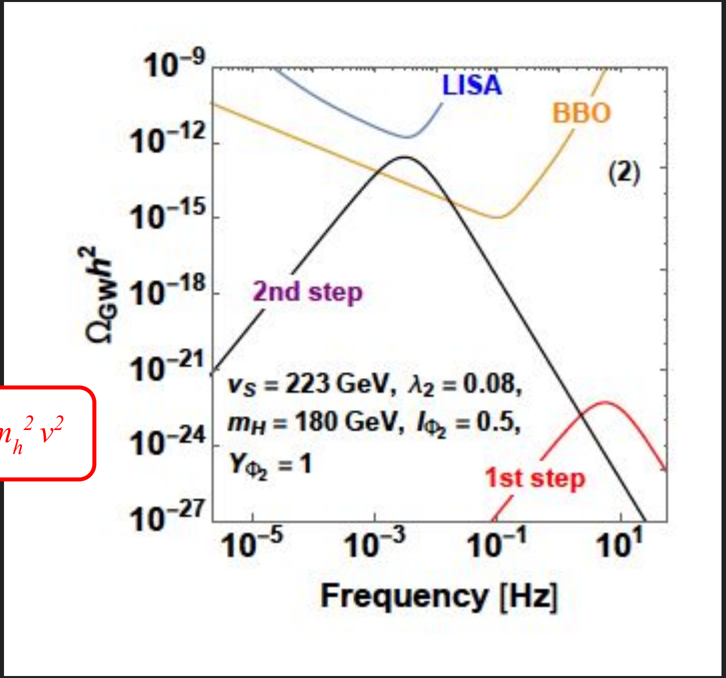
First-order PT at first step can be realized by Small λ_2 .

But...

$$T_{EW}^2 \sim \frac{12m_h^2}{3g'^2/2 + 9g^2/2 + 6y_t^2 + 2(3+n_1)\lambda_1 + (1+n_2)\lambda_{12}}$$

$$T_\phi^2 \sim \frac{24\lambda_2 v_s^2}{3Y_{\Phi_2}^2 g'^2/2 + 3(Y_{\Phi_2}^2 + 2I_W^2)g^2/2 + 2(3+n_2)\lambda_2 + (1+n_1)\lambda_{12}}$$

$\lambda_2 v_S^4 < m_h^2 v^2$



The PT for Path I could be realized by large λ_2 value or large v_S.

At least, one peak of Gw spectrum can be detected by future experiments: S/N (LISA) ~ 58.0, S/N (BBO) ~ 238.

GW spectrum: C. Caprini, et al., J.Cosmol. Astropart. Phys. 1604(04)(2016) 01.

[Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu]

Summary

★ The shape of Higgs potential is still undetermined.

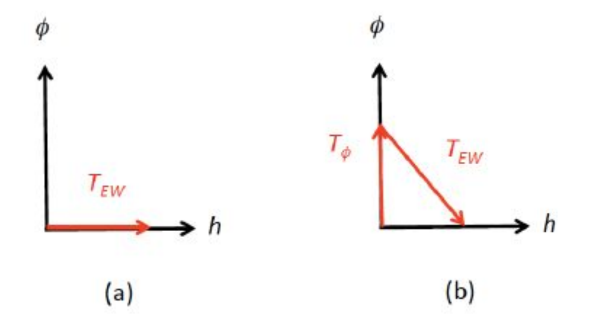
The Higgs potential may have the symmetry.

★ In this time, we discussed the possibility of phase transitions keeping the symmetry at zero temperature.

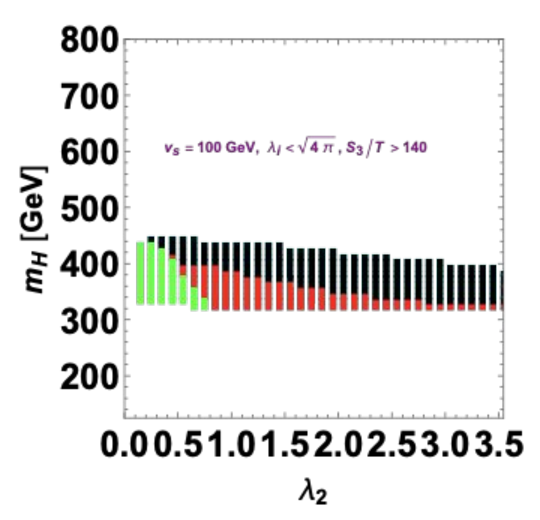
★ As an example, we focused on the extended Higgs model with Z_2 symmetry and an isospin N-plet scalar field and discuss the possibility of the phase transitions.

★ Especially, the multi-step phase transition could be realized by large λ_2 value.

★ The potential being able to realize such phase transitions could be tested by the gravitational wave observastion.

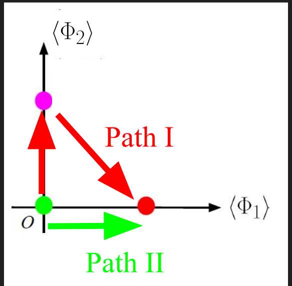


$$\langle h \rangle \neq 0, \langle \phi \rangle = 0$$



Backup

Isospin dependence

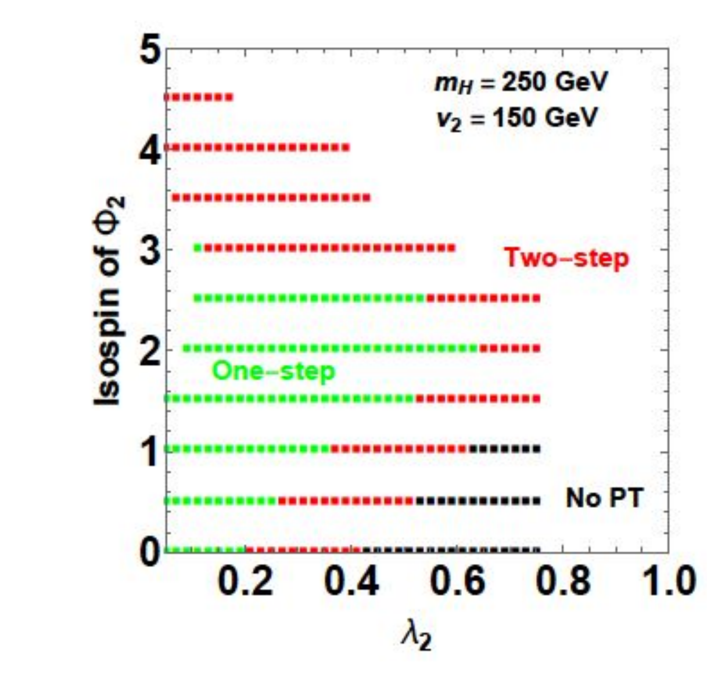


★ We examine the isospin dependence for the possibility of the path of PT.

★ For large isospin of Φ_2, the ratio of T_2 and T_{EW} is

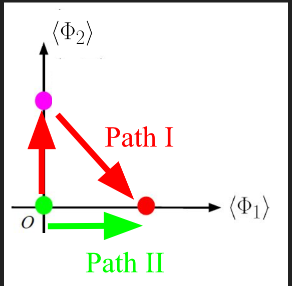
$$\frac{T_2^2}{T_{EW}^2} \sim \frac{2\lambda_2(m_H^2+\lambda_2 v_2^2)v_2^2\left(1+\frac{3I_{\Phi_2}\lambda_2}{\pi^2}\left(\ln\frac{T_2^2\alpha_B}{Q^2}-\frac{3}{2}\right)\right)}{3I_{\Phi_2}m_W^2 m_h^2}$$

When the value of $\lambda_2 I_{\Phi 2}$ is large, multi-step PT could be generated.



[Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu]

Isospin dependence



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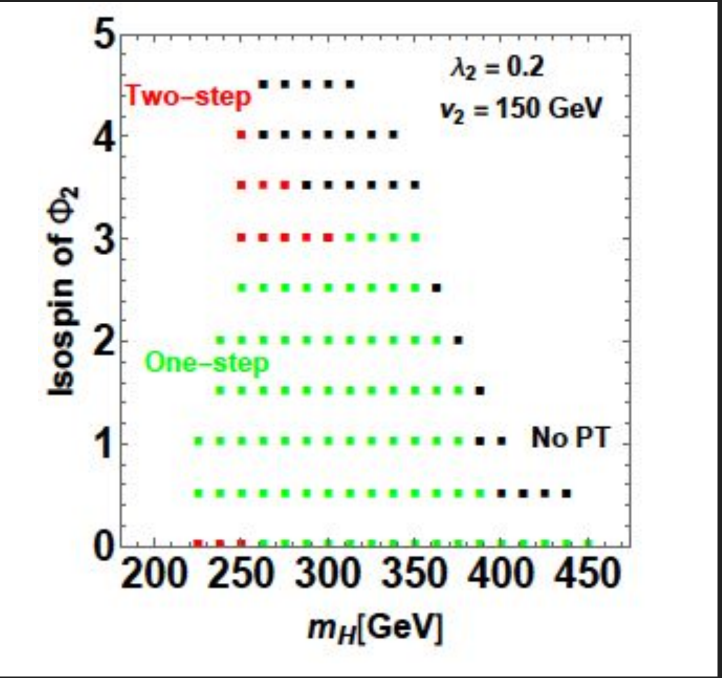
When the value of $\lambda_2 I_{\Phi 2}$ is large, multi-step PT could be generated.

★ For heavy m_H, the ratio is

$$\frac{T_2^2}{T_{EW}^2} \sim \frac{\lambda_2 v_2^2(1+2I_{\Phi_2})+\frac{3m_h^2}{2\pi^2}\left(\ln\frac{T_2^2\alpha_B}{Q^2}-\frac{3}{2}\right)}{m_h^2}$$

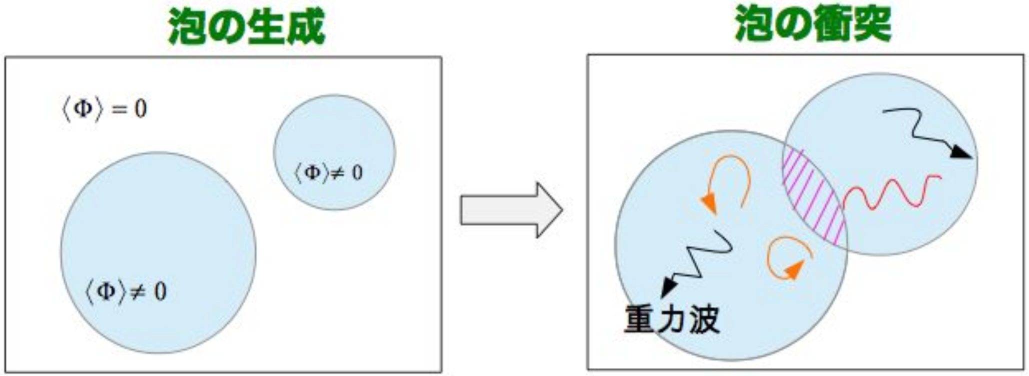
The mass parameter m_H does not much affect the possibility of the path of PT.



[Qing-Hong Cao, Katsuya Hashino, Xu-Xiang Li, Jiang-Hao Yu]

Gravitational wave

重力波



重力波の起源

- 壁の衝突
- プラズマの音波
- プラズマの乱流

➢ 真空泡の核生成率Γ：$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$

➢ 3次元ユークリッド作用S_3：$S_3(T) = \int dr^3 \left\{ \frac{1}{2} \left(\vec{\nabla}\varphi \right)^2 + V_{\rm eff}(\varphi, T) \right\}$

➢ 相転移温度T_t：$\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1 \longrightarrow \frac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$

$$\alpha = \frac{\epsilon(T_t)}{\rho_{rad}(T_t)}, \quad \beta \simeq \frac{1}{\Gamma}\frac{d\Gamma}{dT}$$

潜熱：$\epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$

輻射エネルギー密度：ρ_{rad}

重力波スペクトル [C. Caprini et al., JCAP 1604, no. 04, 001 (2016)]

壁の衝突

$$\widetilde{\Omega}_{\rm env}h^2 \simeq 1.67\times 10^{-5}\times\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\tilde{\beta}^{-2}\left(\frac{\kappa_\varphi\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$

エネルギー密度のピーク

$$\tilde{f}_{\rm env}\simeq 1.65\times 10^{-5}\ {\rm Hz}\times\left(\frac{0.62}{1.8-0.1v_b+v_b^2}\right)\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

振幅のピーク

プラズマの音波

$$\widetilde{\Omega}_{\rm sw}h^2\simeq 2.65\times 10^{-6}v_b\tilde{\beta}^{-1}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$

$$\tilde{f}_{\rm sw}\simeq 1.9\times 10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

プラズマの乱流

$$\widetilde{\Omega}_{\rm turb}h^2\simeq 3.35\times 10^{-4}v_b\tilde{\beta}^{-1}\left(\frac{\epsilon\kappa_v\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*^t}\right)^{1/3}$$

$$\tilde{f}_{\rm turb}\simeq 2.7\times 10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

$\kappa_\varphi, \kappa_v, \epsilon$： efficiency factors　　v_b： wall velocity

Phase transition

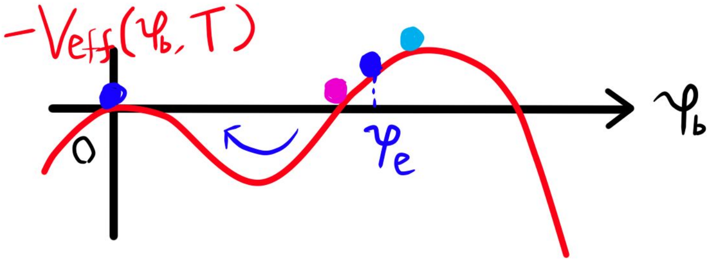
❖ The bubble nucleation rate per unit volume per unit time:

$$\left(S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\text{eff}}(\varphi_b, T) \right] \right)$$

❖ The bounce solution φ_b is obtained by equation of motion.

$$\frac{d^2\varphi_b}{dr^2} + \frac{2}{r}\frac{d\varphi_b}{dr} - \frac{\partial V_{\text{eff}}}{\partial \varphi_b} = 0$$

(Boundary condition $\left.\frac{d\varphi_b}{dr}\right|_{r=0} = 0, \quad \lim_{r\to\infty} \varphi_b = 0$)



The spectrum of the stochastic GWs

[C. Caprini, et al., J. Cosmol. Astropart. Phys. 1604 (04) (2016) 001.]

- Compression wave of plasma

$$\widetilde{\Omega}_{\rm sw}h^2 \simeq 2.65\times 10^{-6} v_b \tilde{\beta}^{-1}\left(\frac{\kappa_v \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$ the peak of energy dencity

$$\tilde{f}_{\rm sw} \simeq 1.9\times 10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$ the peak frequency

$$\Omega_{\rm sw}(f)h^2 = \widetilde{\Omega}_{\rm sw}h^2 \times (f/\tilde{f}_{\rm sw})^3\left(\frac{7}{4+3(f/\tilde{f}_{\rm sw})^2}\right)^{7/2}$$

In this talk, we use only the GW spectrum from compression wave pf plasma.

- Collision of wall

$$\widetilde{\Omega}_{\rm env}h^2 \simeq 1.67\times 10^{-5}\times\left(\frac{0.11 v_b^3}{0.42+v_b^2}\right)\tilde{\beta}^{-2}\left(\frac{\kappa_\varphi \alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$

$$\tilde{f}_{\rm env} \simeq 1.65\times 10^{-5}\ {\rm Hz}\times\left(\frac{0.62}{1.8-0.1v_b+v_b^2}\right)\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

- Plasma turbulence

$$\widetilde{\Omega}_{\rm turb}h^2 \simeq 3.35\times 10^{-4} v_b \tilde{\beta}^{-1}\left(\frac{\epsilon\kappa_v \alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*^t}\right)^{1/3}$$

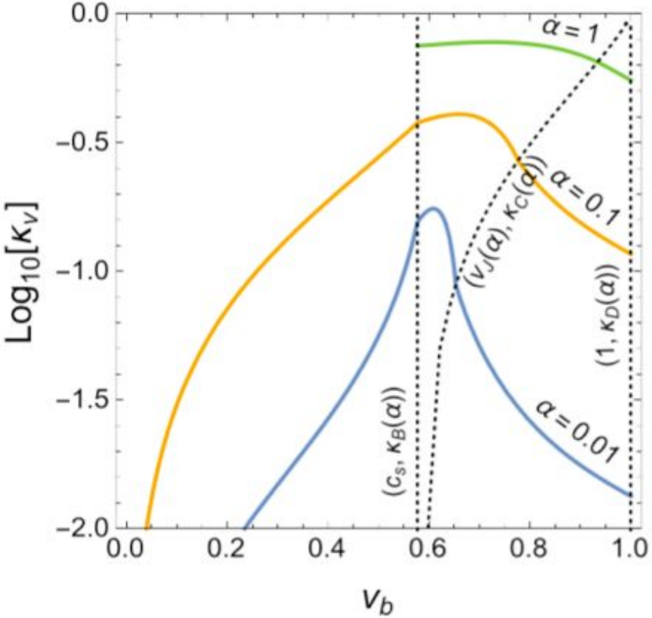
$$\tilde{f}_{\rm turb} \simeq 2.7\times 10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

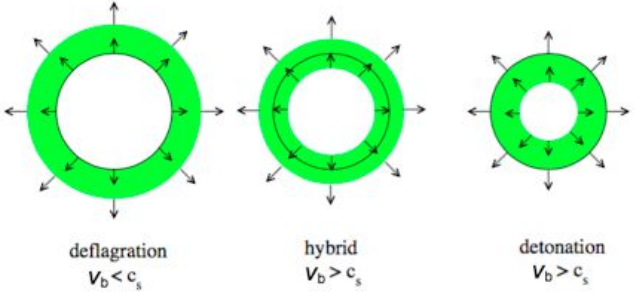
$\kappa_\varphi, \kappa_v, \epsilon$: efficiency factors $\quad v_b$: wall velocity

[J.R.Espinosa,T.Konstandin, J.M.No and G. Servant,JCAP 1006,028 (2010)]

Efficiency factors

[J. R. Espinosa, T. Konstandin, J. M. No and G. Servant, JCAP 1006, 028 (2010)]





黒い線は泡の壁を表しており、緑の領域は流体速度が0でない領域を表す

κ_φ： $\kappa_\varphi = 1 - \frac{\alpha_\infty}{\alpha}$ ， $\alpha_\infty \simeq \frac{30}{24\pi^2 g_*^t T_t^2} \sum_i c_i \left[M_i^2(\varphi_t) - M_i^2(0) \right]$.

[C. Caprini et al., arXiv:1512.06239 [astro-ph.CO], J. R. Espinosa et al.,JCAP 1006, 028 (2010)]

ϵ： 5-10%. (In our numerical analysis, we set ϵ = 0.05.)

[M.Hindmarsh et al.,Phys. Rev. D92, no. 12, 123009 (2015)]

電弱一次相転移由来の重力波

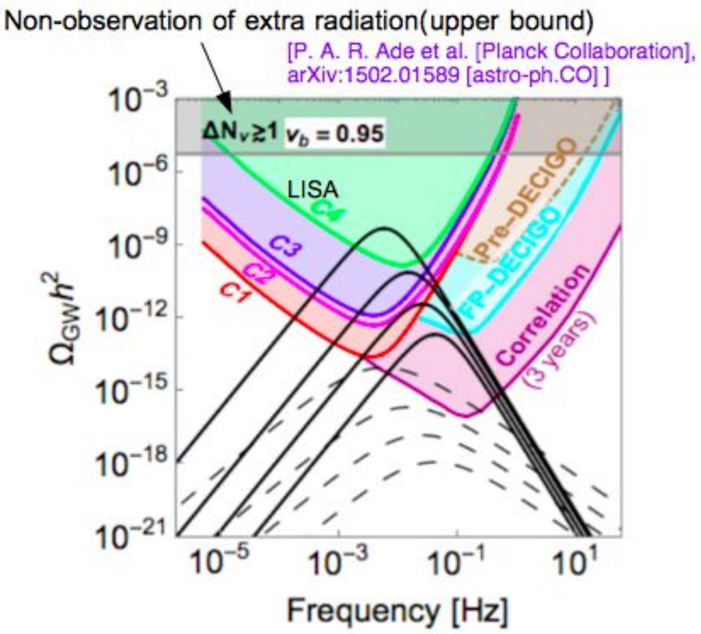
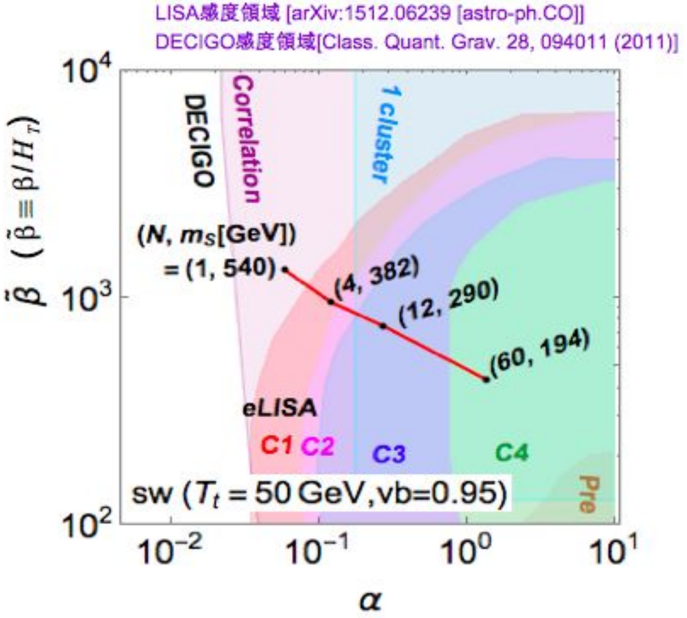


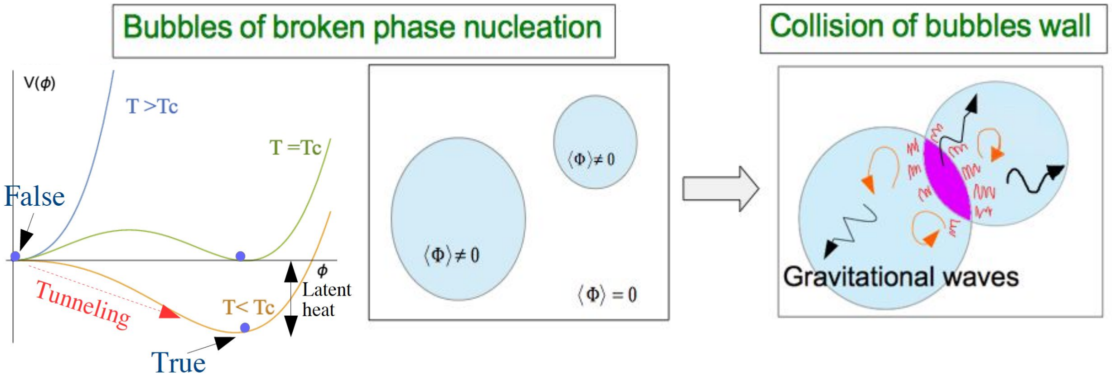
図:下からN=1,4,12,60での古典的スケール不変性を
課したO(N)一重項模型の重力波スペクトル
(実線が音波、破線が乱流による寄与)



図：左図の重力波スペクトルの音波の
ピークの位置（vbは泡の壁の速度、
Ttは相転移温度、H_Tは温度Tでの
ハッブルパラメータ）

次世代重力波干渉計のLISAやDECIGOで一次相転移由来の重力波を将来的に観測できる可能性がある

GW spectrum from 1stOPT



$$S_3 \equiv \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi)^2 + V_{\rm eff}(\varphi, T)\right]$$

- ❖ The bubble nucleation rate per unit volume per unit time: $\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$
- ❖ Transition temperature T_t : $\Gamma/H^4|_{T=T_t} = 1$

  (The temperature at which phase transition starts)

(S_3 : the three dimensional Euclidean action
H : the Hubble parameter)

- ❖ The GW spectrum is characterized by α and β : $\Omega_{\rm GW} \propto \left(\frac{H}{\beta}\right)^n \left(\frac{\kappa\alpha}{1+\alpha}\right)^m$

"Bubble collision(Envelope approximation) n=2, m=2" [M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994)]

α ≃ Normalized latent heat released by PT, β ≃ 1/(The duration of PT)

$$\alpha = \frac{\epsilon(T_t)}{\rho_{rad}(T_t)}, \quad \beta \simeq \frac{1}{\Gamma}\frac{d\Gamma}{dT}$$

Latent heat : $\epsilon(T) = -V_{\rm eff}(\varphi_B(T), T) + T\frac{\partial V_{\rm eff}(\varphi_B(T), T)}{\partial T}$

Radiative energy dencity : ρ_{rad}