Testing the Higgs sector with additional singlets with classical scale invariance by colliders and gravitational waves

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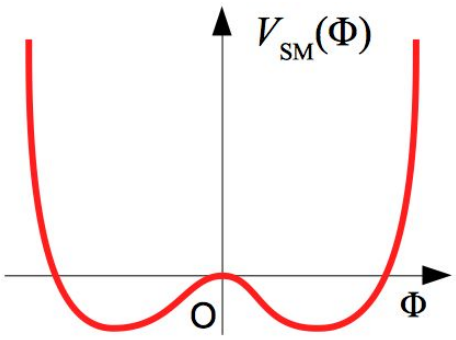
K. Hashino, S. Kanemura and Y. Orikasa, Phys. Lett. B 752, 217 (2016)

K. Hashino, M. Kakizaki, S. Kanemura and T. Matsui, Phys. Rev. D 94. no. 1, 015005 (2016)

Workshop on Multi-Higgs Models 4th of September of 2018

Introduction



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

$(\mu^2 < 0)$

- ❖ Higgs boson which is predicted in the Standard Model(SM) was detected at the Large Hadron Collider(LHC).

- ❖ But, the Higgs sector is still vague.

What is dynamics of the electroweak symmetry breaking (EWSB) ?

$\rightarrow$ The SM require that $\mu^2 < 0$ to realize EWSB.

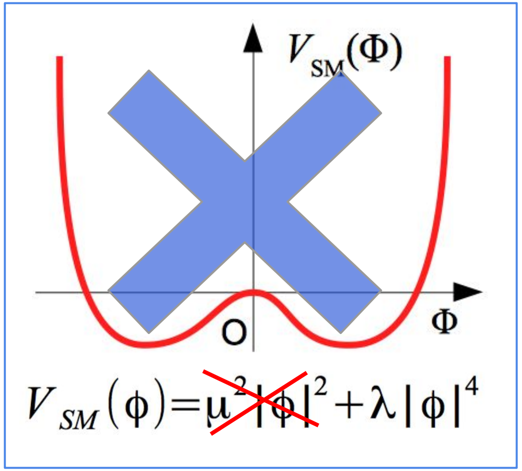
- ❖ The massless model is based on chiral symmetry, classically scale invariance(CSI), and so on. [W.A. Bardeen, FERMILAB-CONF-95-391-T]

We focus on the model based on CSI.

The model based on CSI for EWSB

$$x \to e^{-\alpha} x, \quad \partial_\mu \to e^{\alpha} \partial_\mu, \quad \Phi \to e^{\alpha} \Phi, \quad \int d^4x \sqrt{-g} \to e^{-4\alpha} \int d^4x \sqrt{-g}$$

EWSB cannot occur at the tree-level.



- EWSB can occur by Coleman and Weinberg mechanism.

[S. R. Coleman and E. J. Weinberg, PRD7, 1888(1973)]

- The model imposing CSI on the SM cannot explain the mass of Higgs boson (125 GeV).

($m_h^2 \sim$ the loop effects for the SM particles)

- We consider non-minimal Higgs model with CSI and analyze the model by the Gildener and Weinberg method.

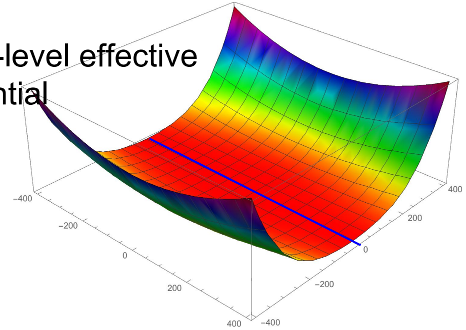
[E. Gildener and S. Weinberg, PRD13, 3333(1976)]

The model based on CSI for EWSB

❖ The method by Gildener and Weinberg

[E. Gildener and S. Weinberg, PRD13, 3333(1976)]

- There is flat direction in the tree-level effective potential.
- On the flat direction, EWSB occurs by Coleman and Weinberg mechanism.



❖ The effective potential

$$V_{\mathrm{eff}}(\varphi, T=0) = A\varphi^4 + B\varphi^4 \ln\frac{\varphi^2}{Q^2}$$

$$A = \frac{1}{64\pi^2 v^4}\left[3\,\mathrm{Tr}\left(M_V^4 \ln\frac{M_V^2}{v^2}\right) - 4\,\mathrm{Tr}\left(M_f^4 \ln\frac{M_f^2}{v^2}\right) + \mathrm{Tr}\left(M_S^4 \ln\frac{M_S^2}{v^2}\right)\right]$$

$$B = \frac{1}{64\pi^2 v^4}\left[3\,\mathrm{Tr}\left(M_V^4\right) - 4\,\mathrm{Tr}\left(M_f^4\right) + \mathrm{Tr}\left(M_S^4\right)\right]$$

All masses in the model are proportional to the vacuum expectation value.

❖ The models have characteristic features :

the triple Higgs boson coupling (hhh) Γ_{hhh}^{CSI}

The deviation in hhh coupling Γ_{hhh}^{CSI}

❖ The hhh coupling in the massive model with O(N) singlet scalar field without CSI is

$$\Gamma_{hhh} \equiv \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v}$$

$$\Gamma_{hhh}^{O(N)} = \frac{3m_h^2}{v}\left\{1 \underbrace{- \frac{1}{\pi^2}\frac{m_t^4}{v^2m_h^2} + \frac{N}{12\pi^2}\frac{m_S^4}{v^2m_h^2}\left(1-\frac{\mu_S^2}{m_S^2}\right)^3}_{\text{Loop effects}}\right\}.$$

$$\vec{S} = (S_1, \cdots, S_N)^{\rm T}$$

❖ In the models based on CSI for EWSB, Γ_{hhh}^{CSI} is universally

$$\Gamma_{hhh}^{CSI} \equiv \left.\frac{\partial^3 V_{\rm eff}}{\partial\varphi^3}\right|_{\varphi=v} = \underbrace{40vB}_{\text{Loop effects}} = \frac{5m_h^2}{v} = \frac{5}{3}\times\Gamma_{hhh}^{SM\,tree}.$$

$$B = \frac{1}{64\pi^2v^4}\left[3\,{\rm Tr}\left(M_V^4\right) - 4\,{\rm Tr}\left(M_f^4\right) + {\rm Tr}\left(M_S^4\right)\right]$$

$$m_h^2 \equiv \left.\frac{\partial^2 V_{\rm eff}}{\partial\varphi^2}\right|_{\varphi=v} = 8Bv^2$$

The loop effects in the model are renormalized in the SM-like Higgs mass m_h.

❖ Γ_{hhh}^{CSI} universally enhances about 67% from the SM values. [K.H, S. Kanemura and Y. Orikasa, Phys. Lett. B 752, 217 (2016)]

If the hhh coupling is large, the electroweak phase transition(EWPT) is strongly 1st order phase transition. [S. Kanemura, Y. Okada and E. Senaha, Phys. Lett. B 606, 361 (2005) [C. Grojean, G. Servant, and J. D. Wells, Phys. Rev. D 71, 036001 (2005).]

The model realizes the strongly 1st order electroweak phase transition(EWPT).

Gravitational waves from 1st order phase transition

❖ If EWPT is 1st order, gravitational waves(GWs) occur from the phase transition.

❖ The GWs from 1st order EWPT can be produced at bubble collisions in the early Universe.

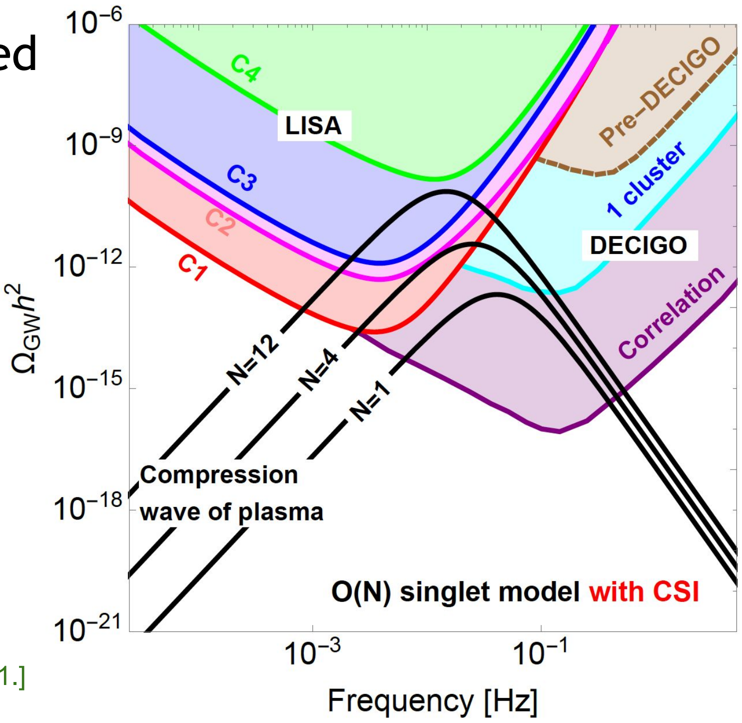
Sources of GWs

1. Collision of wall
2. Plasma turbulence
3. Compression wave of plasma

❖ For example, GW spectra in O(N) singlet model with CSI are described in right figure.

The GW spectra [C. Caprini, et al., J.Cosmol. Astropart. Phys. 1604(04)(2016) 01.]

The sensitivity regions
- LISA: [JCAP 1604, no. 04, 001 (2016)]
- DECIGO: [Class. Quant. Grav. 28, 094011(2011)]



(N is the number of additional singlet fields.)

GW spectra from phase transition for O(N) singlet models with and without CSI

LISA: [JCAP 1604, no. 04, 001 (2016)]
DECIGO: [Class. Quant. Grav. 28, 094011(2011)]

❖ We described the peak of GW spectra from compression wave of plasma for the following models.

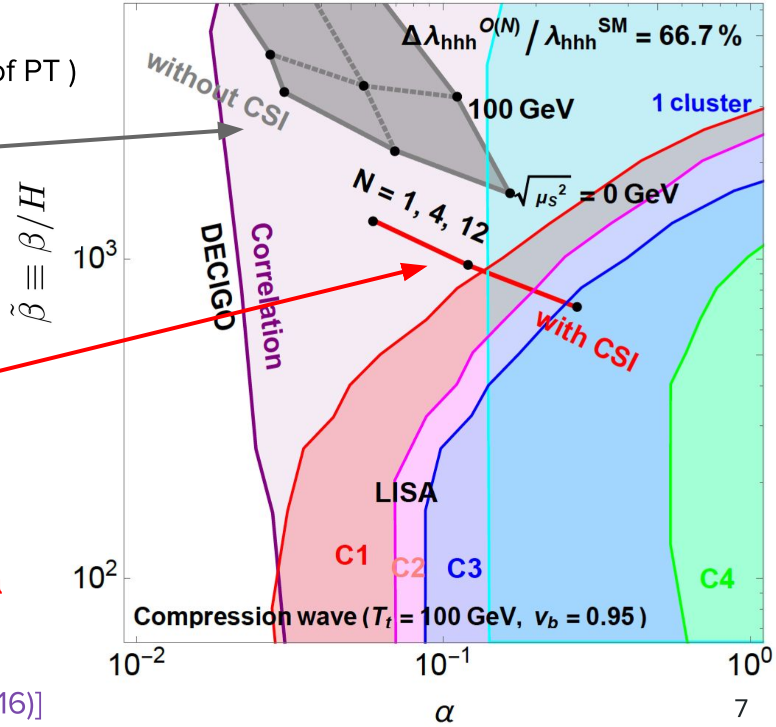
(α ≃ Normalized latent heat released by PT, β ≃ 1 / The duration of PT)

- O(N) singlet model without CSI (Massive model)

$$\left(\Delta\lambda_{hhh}^{O(N)}/\lambda_{hhh}^{SM} = 2/3 \simeq 67\,\%\right)$$

- O(N) singlet model with CSI

$$\left(\Delta\lambda_{hhh}^{CSI}/\lambda_{hhh}^{SM} = 2/3 \simeq 67\%\right)$$



❖ We can distinguish the models with and without CSI, and it will be possible to observe GW spectra in the future!

[K. H, M. Kakizaki, S. Kanemura and T. Matsui, RRD. 94, no 1, 015005(2016)]

Summary

- ❖ We discussed the phenomenological features for the models based on classical scale invariance for electroweak symmetry breaking.

  - ★ The triple Higgs boson coupling is universally enhanced. $\boxed{\Gamma_{hhh}^{CSI} = \frac{5}{3} \times \Gamma_{hhh}^{SM\ tree}}$

- ❖ If electroweak phase transition is 1st order, the gravitational waves occur from phase transition. We can use the gravitational wave spectra to distinguish between the models with and without classical scale invariance.

- ❖ We can test the models based on classical scale invariance for electroweak symmetry breaking by collider and gravitational wave observation experiments.

Backup

Gravitational waves interferometers

❖ If electroweak phase transition(EWPT) is 1st order, gravitational waves (GWs) occur from EWPT.

★ Ground-based GWs interferometers (LIGO, KAGRA, Advanced Virgo, …)

→ These experiments can detect the GWs from astronomical origin such as the binary of neutron star, black hole, and so on.

LIGO detected GWs directly. [PRL.116, no. 6,061102(2016), PRL.116, no. 24, 241103(2016), PRL. 118, no. 22, 221101 (2017), PRL. 119, no. 14, 141101 (2017), PRL 119, no. 16, 161101 (2017)]

★ Future space-based GWs interferometers (LISA, DECIGO, …)

LISA is scheduled to launch into space in 2034.

→ These experiments can detect the GWs from the early universe such as electroweak 1stOPT, cosmic inflation, and so on.

❖ It is a possibility that extended Higgs models can be tested not only by accelerator experiment but also by GW observation experiment.

O(N) singlet model without CSI

The model in which the loop effects of bosons is mainly related to 1stOPT

❖ The model have N additional singlet scalar fields $\vec{S} = (S_1, S_2, ..., S_N)^T$

For simplicity, these field obey a global O(N) symmetry.

❖ Tree-level potential

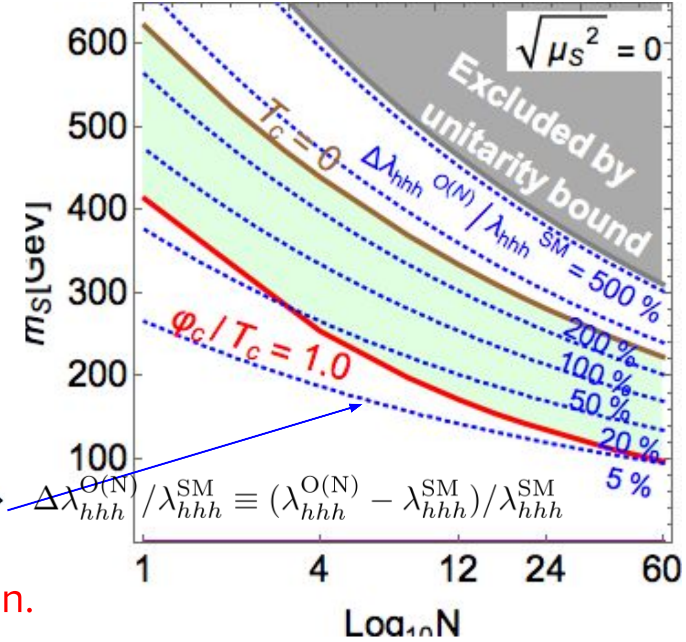
$$V_0(\Phi, \vec{S}) = -\mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4 + \frac{\mu_S^2}{2}|\vec{S}|^2 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$$

❖ The masses of singlet scalar fields

$$m_S^2 = \mu_S^2 + \frac{\lambda_{\Phi S}}{2}v^2$$

❖ 3 point Higgs boson coupling

$$\lambda_{hhh}^{O(N)} = \left.\frac{\partial^3 V_{\rm eff}(\varphi, T=0)}{\partial\varphi^3}\right|_{\varphi=v} = \frac{3m_h^2}{v}\left\{1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2} + \frac{N}{12\pi^2}\frac{m_S^4}{v^2 m_h^2}\left(1 - \frac{\mu_S^2}{m_S^2}\right)^3\right\}$$



❖ The model can realize strongly first order phase transition.

→ Detectable GWs from electroweak 1stOPT might be able to occur.

[M. Kakizaki, S. Kanemura and T. Matsui, PRD 92, no.11, 115007 (2015)]

O(N) singlet model with CSI

The model in which the loop effects of bosons is mainly related to 1stOPT

- ❖ We impose O(N) singlet model based on classically scale invariance(CSI).

(EWSB can occur by Coleman and Weinberg mechanism.)

[S. R. Coleman and E. J. Weinberg, PRD 7, 1888(1973)]

- ❖ Tree-level potential

$$V_0(\Phi, \vec{S}) = \frac{\lambda}{2}|\Phi|^4 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2$$

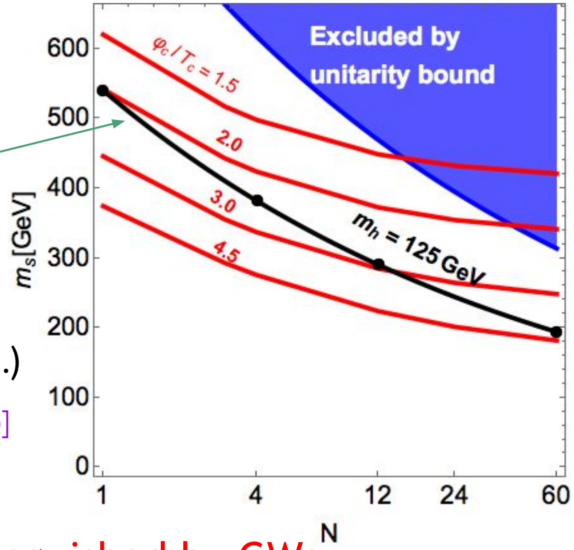
- ❖ The masses of singlet scalar fields

$$N m_S^2 = 8\pi^2 v^2 m_h^2 - 3m_Z^4 - 6m_W^4 + 12m_t^4$$

- ❖ 3 point Higgs boson coupling

$$\frac{\Delta\lambda_{hhh}}{\lambda_{hhh}^{SM(tree)}} = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM(tree)}} - 1 = \frac{2}{3} \simeq 67\%$$ (It doesn't depend on N.)

[K.H, S. Kanemura and Y. Orikasa, PLB 752, 217 (2016)]



- ❖ The model realize strongly first order phase transition.

→ O(N) singlet models with and without CSI may be distinguished by GWs.

[K. H, M.Kakizaki, S.Kanemura and T.Matsui, RRD. 94, no 1, 015005(2016)]

(We discuss that in next section.)

The measurements of the deviations

❖ The measurement of κ_γ

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%

[Snowmass Higgs Working Group Report, S. Dawson et al., arXiv:1310.8361]

- ILC 250GeV 2000fb^{-1} (+LHC) can measure the κ_γ at 1% accuracy.

[Slide : Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory]

❖ The measurement of $\Delta\lambda_{hhh}$

- HL-LHC 14 TeV 3000fb^{-1} can measure the λ_{hhh} at 50% accuracy.

[Snowmass Higgs Working Group Report, S. Dawson et al., arXiv:1310.8361]

- ILC 500GeV(1TeV) 4000fb^{-1}(2000fb^{-1},5000fb^{-1}) can measure the λ_{hhh} at 27%(16%,10%) accuracy. [K.Fujii et al., arXiv:1506.05992]

The measurements of the deviations

Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

Snowmass Higgs Working Group Report (1310.8361)

The measurements of the deviations

Parameter	ATLAS+CMS Measured
κ_Z	1.00 [0.92, 1.00]
κ_W	0.90 [0.81, 0.99]
κ_t	$1.43^{+0.23}_{-0.22}$
$\lvert\kappa_\tau\rvert$	$0.87^{+0.12}_{-0.11}$
$\lvert\kappa_b\rvert$	$0.57^{+0.16}_{-0.16}$
$\lvert\kappa_g\rvert$	$0.81^{+0.13}_{-0.10}$
$\lvert\kappa_\gamma\rvert$	$0.90^{+0.10}_{-0.09}$

[“ATLAS and CMS Collaborations” JHEP 1608, 045 (2016)]

The measurements of the deviations

coupling $\Delta g/g$	500 fb-1	2000 fb-1
HZZ	1.1%	0.63%
HWW	1.1%	0.63%
Hbb	1.7%	0.89%
Hcc	3.5%	1.8%
Hgg	3.1%	1.6%
$H\tau\tau$	2.0%	1.0%
$H\gamma\gamma$	1.5%	1.1%
$H\mu\mu$	27%	13%
Γ_H	4.1%	2.1%
BR(H->inv.) (95% CL)	0.61%	0.31%

[ILC 250 ヒッグスファクトリーの物理意義を検証する委員会]

The measurements of the deviations

❖ The measurement of κ

- LHC Run-I results : $\kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10}$

  [The ATLAS and CMS Collaborations, ATLAS-CONF-2015-044.]

- HL-LHC 14 TeV 3000fb^{-1} can reach the precision of 2% accuracy.

  [CMS Collaboration, arXiv:1307.7135.]

- ILC 250GeV 2000fb^{-1} can measure the κ_Z at 0.38% accuracy.

  [Slide : Report by the Committee on the Scientific Case of the ILC Operating at 250 GeV as a Higgs Factory]

- ILC 500GeV 500fb^{-1} can measure the κ_Z(κ_W) at 0.37%(0.51%) accuracy.

  [K.Fujii et al., arXiv:1506.05992]

❖ The measurement of $\Delta\lambda_{hhh}$

- HL-LHC 14 TeV 3000fb^{-1} can measure the λ_{hhh} at 50% accuracy.

  [S.Dawson et al.,arXiv:1310.8361]

- ILC 500GeV(1TeV) 4000fb^{-1}(2000fb^{-1},5000fb^{-1}) can measure the λ_{hhh} at 27%(16%,10%) accuracy. [K.Fujii et al., arXiv:1506.05992]

High temperature expansion

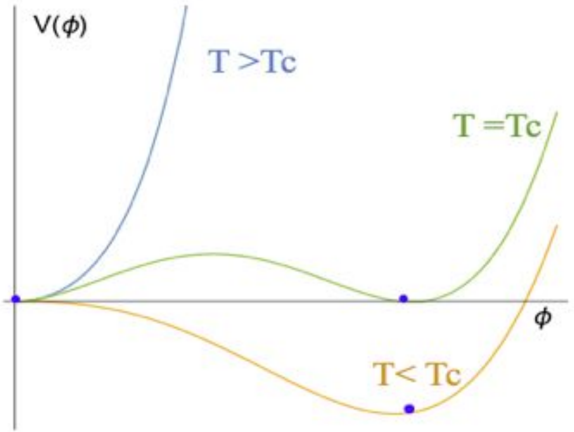
The loop effect of bosons and fermions

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

The loop effect of bosons

The effect of mixing Higgs fields

$$\frac{\varphi_c}{T_c} = \frac{2E}{\lambda}\left(1 - \frac{e\lambda}{ET}\right)$$



Gildener - Weinberg method

The GWM supposes that there is the f lat direction in the tree-level potential $V_0(\Phi)$.

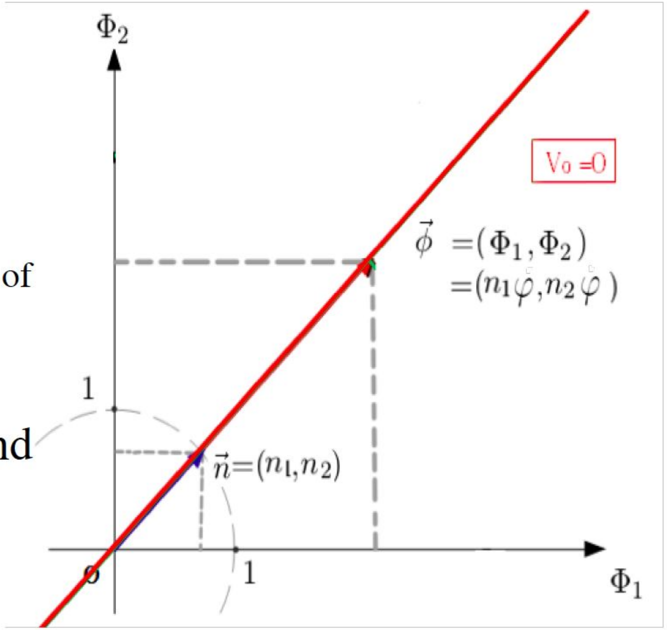
$$V_0(\Phi)=\frac{1}{24}f_{ijkl}\Phi_i\Phi_j\Phi_k\Phi_l\ , \quad f_{ijkl}\equiv\frac{\partial^4 V_0(\Phi)}{\partial\Phi_i\partial\Phi_j\partial\Phi_k\partial\Phi_l}$$

The f lat direction is decided by

$$\Phi_i=n_i\varphi.$$

The unit vector n_i represents the direction of f lat direction and φ is order parameter.

On the f lat direction, $V_0(n_i\varphi)=0$, and EWSB occurs by CWM.



General upper bound on the mass m_1^{CSI}

$$V_{\rm eff}(\varphi, T=0) = A\varphi^4 + B\varphi^4 \ln\frac{\varphi^2}{Q^2}$$

$$A = \frac{1}{64\pi^2 v^4}\left[3\,\mathrm{Tr}\left(M_V^4 \ln\frac{M_V^2}{v^2}\right) - 4\,\mathrm{Tr}\left(M_f^4 \ln\frac{M_f^2}{v^2}\right) + \mathrm{Tr}\left(M_S^4 \ln\frac{M_S^2}{v^2}\right)\right]$$

$$B = \frac{1}{64\pi^2 v^4}\left[3\,\mathrm{Tr}\left(M_V^4\right) - 4\,\mathrm{Tr}\left(M_f^4\right) + \mathrm{Tr}\left(M_S^4\right)\right]$$

- The Higgs mass m_h : $m_h^2 \equiv \left.\frac{\partial^2 V_{\rm eff}}{\partial\varphi^2}\right|_{\varphi=v} = 8Bv^2 \simeq (125\ \mathrm{GeV})^2$

$$\boxed{\mathrm{Tr}\, M_S^4 = 8\pi^2 v^2 m_h^2 - 3m_Z^4 - 6m_W^4 + 12m_t^4 \sim (543\mathrm{GeV})^4}$$

- We consider the model with N extra scalar bosons : $m_1^{CSI} \le m_2^{CSI} \le \ldots \le m_N^{CSI}$

$$\mathrm{Tr}\, M_s^4 = \sum_{n=1}^{N} (m_n^{CSI})^4 \ge N (m_1^{CSI})^4 \longrightarrow m_1^{CSI} \le \frac{C}{\sqrt[4]{N}} \le 543\,(GeV)$$

- m_1^{CSI} is generally less than 543 GeV!

Upper bound on the mass m_1^{CSI} in 2HDM

For a specific model

- We rewrite N as $N_{I,Y}$ which is the number of scalar fields with isospin I and hypercharge Y.

$$N = N_{0,0} + 2\mathrm{N}_{0,1} + 4\mathrm{N}_{\frac{1}{2},\frac{1}{2}} + 3\mathrm{N}_{1,0} + 6\mathrm{N}_{1,1} + s \quad s \quad s$$

$$m_1^{\mathrm{CCI}} \leq \frac{C}{\sqrt[4]{N_{0,0} + 2N_{0,1} + 4N_{\frac{1}{2},\frac{1}{2}} + 3N_{1,0} + 6N_{1,1} + \cdots}}$$

- When we consider the extensions for doublets($I=\frac{1}{2}, Y=\frac{1}{2}$), this upper bound is stronger!

$$\boxed{m_1^{\mathrm{CCI}} \leq \frac{C}{\sqrt[4]{4N_{\frac{1}{2},\frac{1}{2}}}} \sim \frac{1}{\sqrt[4]{N_{\frac{1}{2},\frac{1}{2}}}} \times 383\mathrm{GeV}}$$

The scaling factor κ_γ^{CSI} of the hγγ coupling

$$\kappa_\gamma^{CSI} \equiv \sqrt{\frac{\Gamma^{(n,m)}_{h\to\gamma\gamma}}{\Gamma^{SM}_{h\to\gamma\gamma}}} \sim \sqrt{\left|1+\frac{1}{2}\frac{\sum_{i=1}^{n}(v/m^2_{\phi_i^\pm})\lambda_{h\phi_i^+\phi_i^-}A_0(\tau_{\phi_i^\pm})+4\sum_{j=1}^{m}(v/m^2_{\phi_j^{\pm\pm}})\lambda_{h\phi_j^{++}\phi_j^{--}}A_0(\tau_{\phi_j^{\pm\pm}})}{A_1(\tau_W)+\frac{4}{3}A_{\frac{1}{2}}(\tau_t)}\right|^2}$$

n(m) is the number of singly-(doubly-) charged scalar bosons and $\tau_x = 4m_\tau^2/m_h^2$.

top quark	$A_{1/2}(\tau_t) = -1.4$
W boson	$A_1(\tau_W) = 8.4$
Charged scalar boson ($m_h \ll m_i$)	$A_0(\tau_i) = -1/3$

The loop effects

$$m^2_{\phi_i^\pm} = \frac{1}{2}\left(\frac{\lambda_{h\phi_i^+\phi_i^-}}{v}\right)v^2$$

$$m^2_{\phi_i^{\pm\pm}} = \frac{1}{2}\left(\frac{\lambda_{h\phi_i^{++}\phi_i^{--}}}{v}\right)v^2$$

Charged scalar masses

All masses are proportional to VEV.

- The scaling factor κ_γ^{CSI} depends on n and m.

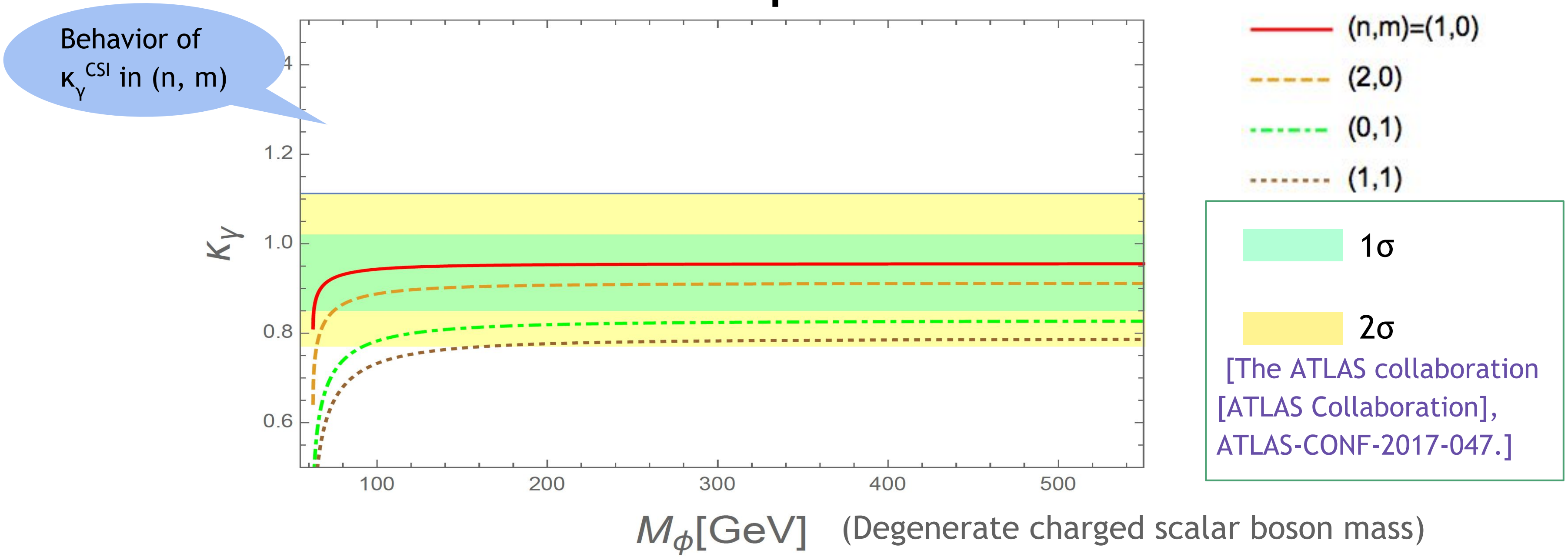
[K.H, S. Kanemura and Y. Orikasa, PLB 752, 217 (2016)]

$$\kappa_\gamma^{CSI} \simeq 1 - \frac{n}{16} - \frac{m}{4}$$

(Large mass limit)

Non-decoupling effects

The scaling factor κ_γ^{CSI} of the h$\gamma\gamma$ coupling



- ❖ HL-LHC can measure the κ_γ at 2-5% accuracy. [S. Dawson et al., arXiv:1310.8361]
- ❖ The number of the charged scalar bosons in the models will be predicted by experiments! [K.H, S. Kanemura and Y. Orikasa, PLB 752, 217 (2016)]

Discriminative phenomenological features for the models

- The models based on CSI for EWSB have three discriminative features.

[K. H, S. Kanemura and Y. Orikasa, PLB 752, 217(2016)]

  - A general upper bound on the additional lightest mass m_1^{CSI}

    $$\rightarrow m_1^{CSI} \leq 543\mathrm{GeV}$$

  - The scaling factor κ_γ^{CSI} of the hγγ coupling depends on numbers for singly- and doubly- charged scalar bosons

    $$\rightarrow \kappa_\gamma^{CSI} \simeq 1 - \frac{n}{16} - \frac{m}{4}$$

  - The deviation in hhh coupling Γ_{hhh}^{CSI} is universally predicted at the leading order

    $$\rightarrow \Gamma_{hhh}^{CSI} = \frac{5}{3} \times \Gamma_{hhh}^{SM\ tree}$$

Landau pole Λ (CSI O(N) models)

- We calculate the Landau pole Λ of the CSI O(N) models.

$$V_0(\Phi, \vec{S}) = \frac{\lambda}{2}|\Phi|^4 + \frac{\lambda_S}{4}|\vec{S}|^4 + \frac{\lambda_{\Phi S}}{2}|\Phi|^2|\vec{S}|^2 \qquad \vec{S} = (S_1, S_2, ..., S_N)^T$$

N	1	4	12
Q	381 GeV	257 GeV	188 GeV
$\Lambda(\lambda_S = 0)$	5.4 TeV	17 TeV	28 TeV
$\Lambda(\lambda_S = 0.1)$	5.3 TeV	16 TeV	23 TeV
$\Lambda(\lambda_S = 0.2)$	5.2 TeV	15 TeV	19 TeV
$\Lambda(\lambda_S = 0.3)$	5.0 TeV	14 TeV	15 TeV

TABLE : The energy scale of the Landau pole Λ in the CSI O(N) models for N = 1,4,12

- The renormalization scale Q is decided by the stationary condition.

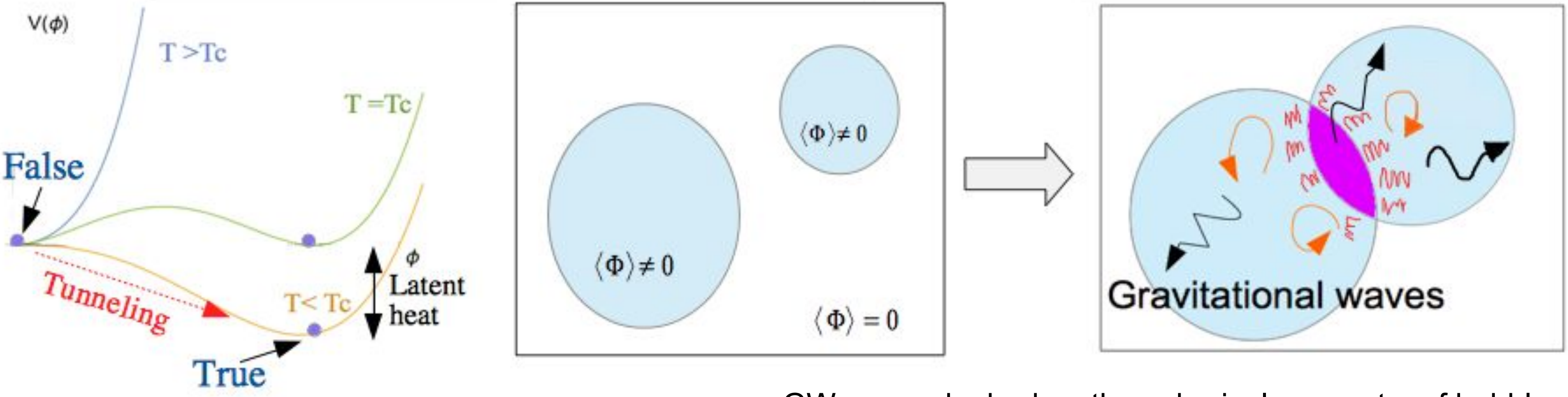
- The cutoff scale Λ is defined as the scale where any of the scalar couplings diverges.

GW spectrum from 1stOPT

❖ The GWs from 1stOPT can be produced at bubble collisions in the early Universe.

Bubbles of broken phase nucleation

Collision of bubbles wall



GWs occur by broken the spherical symmetry of babble.

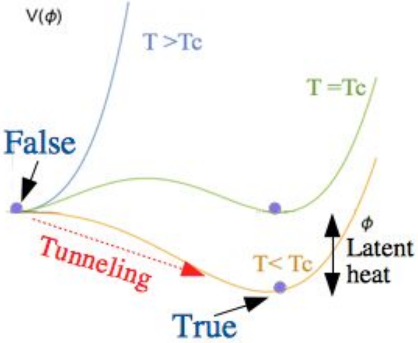
Sources of GWs

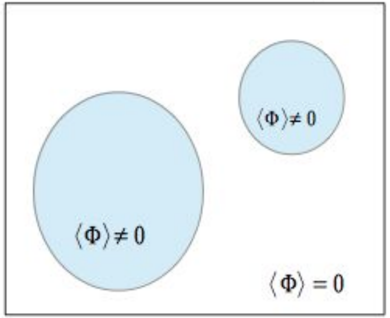
1.Collision of wall 2.Plasma turbulence 3.Compression wave of plasma

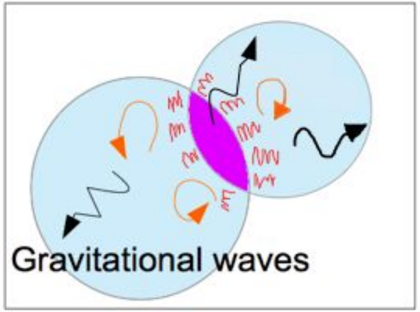
Gravitational waves

Bubbles of broken phase nucleation

Collision of bubbles wall







- Bubble nucleation rate per unit volume per unit time Γ : $\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}}$
- The three dimensional Euclidean action S_3 :

$$S_3(T) = \int dr^3 \left\{ \frac{1}{2} \left(\vec{\nabla}\varphi \right)^2 + V_{\rm eff}(\varphi, T) \right\}$$

- Transition temperature T_t : $\left.\frac{\Gamma}{H^4}\right|_{T=T_t} \simeq 1 \longrightarrow \frac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$

$$U = F + TS = F - T\frac{\partial F}{\partial T}$$

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

Latent heat : $\epsilon(T) = \Delta V_{\rm eff}(T) + T\Delta s = \Delta V_{\rm eff}(T) - T\frac{{\rm d}\Delta V_{\rm eff}(T)}{{\rm d}T}$

Radiative energy dencity : ρ_{rad}

Phase transition

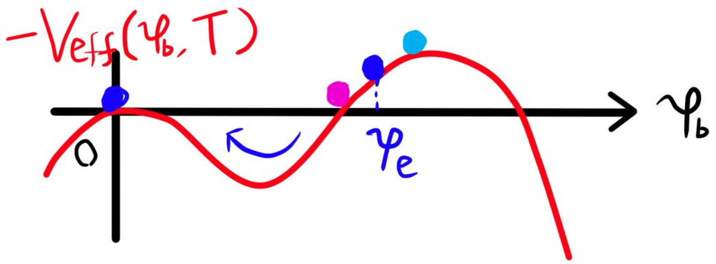
- The bubble nucleation rate per unit volume per unit time:

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}} \qquad \left(S_3 = \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi_b)^2 + V_{\rm eff}(\varphi_b, T) \right] \right)$$

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

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

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



Phase transition

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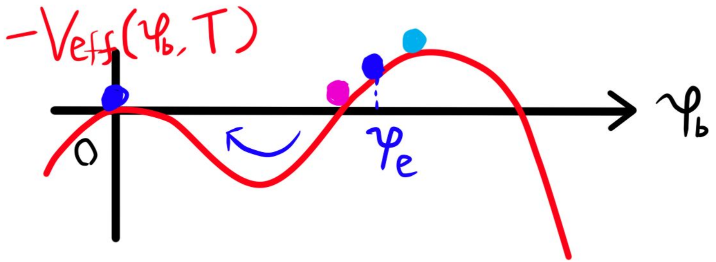
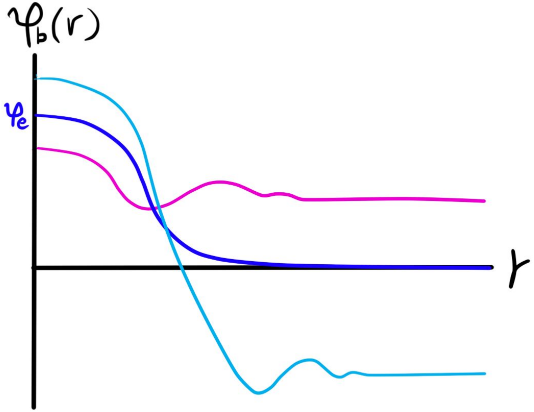




❖ We can obtain S_b by the bounce solution φ_b.

$$\rightarrow \quad \frac{S_3(T_t)}{T_t} = 4\ln(T_t/H_t) \simeq 140$$ (We can caluculate T_t.)

GW spectrum from 1st order phase transition

❖ The GW spectrum from 1stOPT need complicated numerical simulations.

→ We use apploximate fitting formula.

For example… Compression wave of thermal plasma

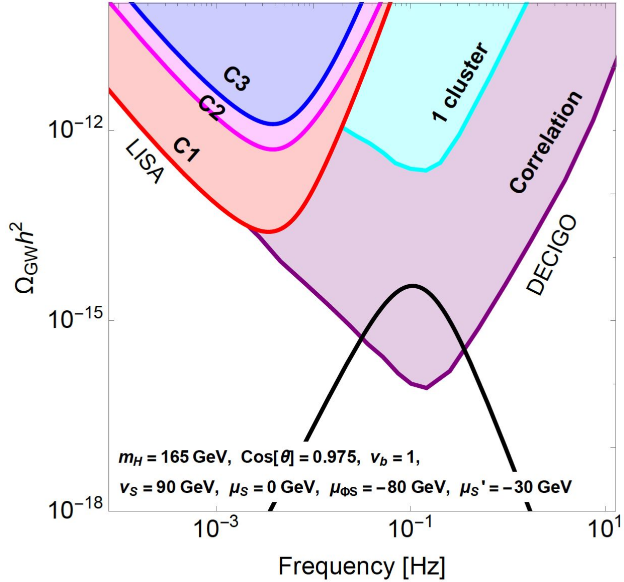
[C. Caprini, et al., J.Cosmol. Astropart. Phys. 1604(04)(2016) 01.]

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

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

$\tilde{\beta}\equiv\beta/H$ κ_v : efficiency factor v_b : wall velocity

The sensitivity regions
- LISA: [arXiv:1512.06239 [astro-ph.CO]]
- DECIGO: [Class. Quant. Grav. 28, 094011(2011)]



❖ α and β parameters are determined by effective potential.

→ Parameters in the model can be fixed by GW spectrum!

The spectrum of the stochastic GWs

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

➤ Compression wave of plasma

$$\widetilde{\Omega}_{\rm sw}h^2 \simeq 2.65\times10^{-6}v_b\tilde{\beta}^{-1}\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$ the peak of energy dencity

$$\tilde{f}_{\rm sw} \simeq 1.9\times10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$ 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

$$\widetilde{\Omega}_{\rm env}h^2 \simeq 1.67\times10^{-5}\times\left(\frac{0.11v_b^3}{0.42+v_b^2}\right)\tilde{\beta}^{-2}\left(\frac{\kappa_\varphi\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*^t}\right)^{1/3}$$

$$\tilde{f}_{\rm env} \simeq 1.65\times10^{-5}\ {\rm Hz}\times\left(\frac{0.62}{1.8-0.1v_b+v_b^2}\right)\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

➤ Plasma turbulence

$$\widetilde{\Omega}_{\rm turb}h^2 \simeq 3.35\times10^{-4}v_b\tilde{\beta}^{-1}\left(\frac{\epsilon\kappa_v\alpha}{1+\alpha}\right)^{3/2}\left(\frac{100}{g_*^t}\right)^{1/3}$$

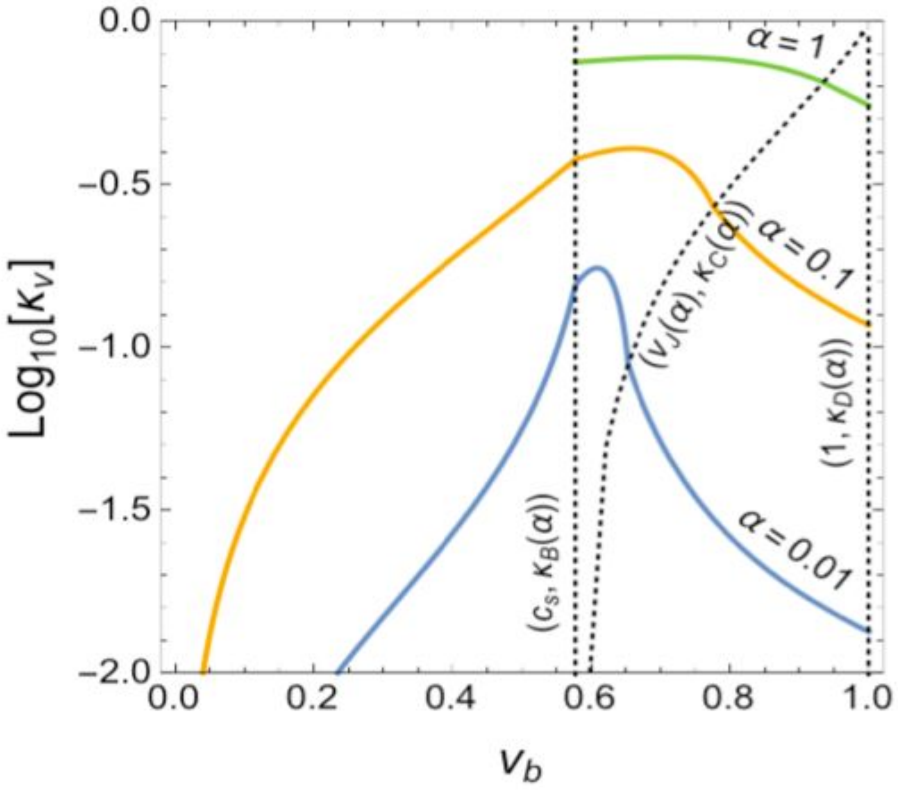
$$\tilde{f}_{\rm turb} \simeq 2.7\times10^{-5}\ {\rm Hz}\frac{1}{v_b}\tilde{\beta}\left(\frac{T_t}{100\ {\rm GeV}}\right)\left(\frac{g_*^t}{100}\right)^{1/6}$$

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

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

Efficiency factor

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



LISA design

[C.Caprini et al., JCAP 1604, no. 04, 001 (2016) arXiv:1512.06239]

Name	C1	C2	C3	C4
Full name	N2A5M5L6	N2A1M5L6	N2A2M5L4	N1A1M2L4
# links	6	6	4	4
Arm length [km]	5M	1M	2M	1M
Duration [years]	5	5	5	2
Noise level	N2	N2	N2	N1

[N.Bartolo et al., JCAP 1612, no. 12, 026 (2016) arXiv:1610.06481]

Name	A5M5	A5M2	A2M5	A2M2	A1M5	A1M2
Arm length [10^6 Km]	5	5	2	2	1	1
Duration [years]	5	2	5	2	5	2