Gravitational waves from first order phase transition in Higgs portal dark matter models

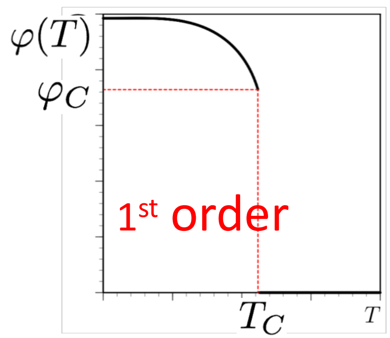
Toshinori Matsui (松井 俊憲)[1]

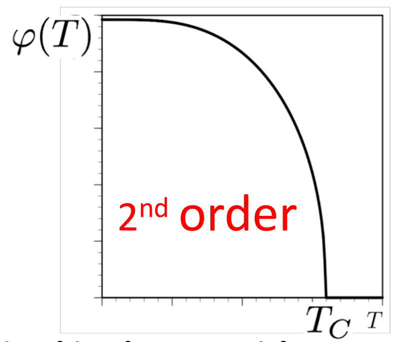
arXiv:1609.00297 [hep-ph] (PLB), K. Hashino[1], M. Kakizaki[1], S. Kanemura[1], P. Ko[2], TM[2]
arXiv:1706.09721 [hep-ph] (JHEP), Z. Kang[2,3], P. Ko[2], TM[2]
arXiv:1802.02947 [hep-ph] (JHEP), K. Hashino[1,4], M. Kakizaki[1], S. Kanemura[4], P. Ko[2], TM[2]

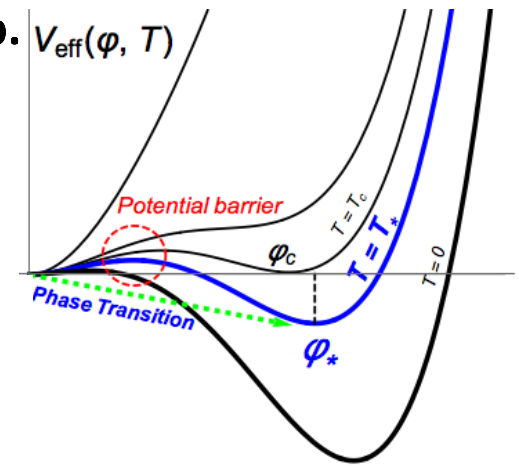
[1]U. of Toyama, [2]KIAS, [3]Huazhong Univ. of Science and Technology, [4]Osaka U.

Physics behind the EW symmetry breaking

- **No principle in the SM Higgs sector** $\mathcal{L}_{\rm SM}^{\Phi} = |D_\mu \Phi|^2 - V_{\rm SM}(\Phi) - \overline{\psi}_i y_{ij} \psi_j \Phi + {\rm h.c.}$
  - Higgs boson couplings might be deviated from the SM. → ***hVV*** → ***hhh*** → ***hff***
- **Physics behind the EW symmetry breaking @finite temp.**





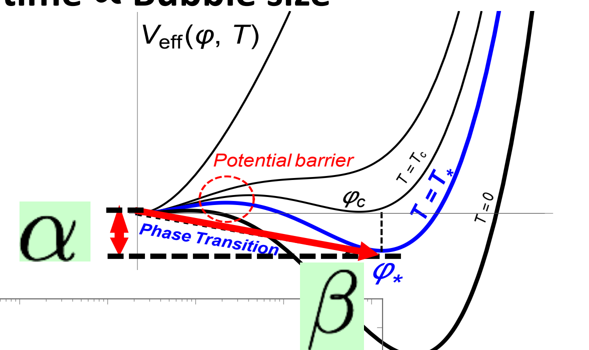


  - **1st order phase transition is not realized in the SM with m_h = 125 GeV.**
  - **If 1st order phase transition is realized, gravitational waves is produced in extended Higgs sector!**
- **New physics is required to solve beyond the SM (BSM) phenomena.**
  - *Existence of dark matter, Baryon asymmetry of the Universe, Neutrino oscillations, Cosmic inflation,…*
- **Extended Higgs sectors are required in several BSM models.**
  - Higgs portal DM is the simplest WINP DM scenario which is related to Higgs physics at EW scale.
  - Electroweak baryogenesis requires strongly 1stOPT (sphaleron decoupling criterion): $\varphi_*/T_* \gtrsim 1$.
- **Gravitational waves can be a new technique to explore BSM!**

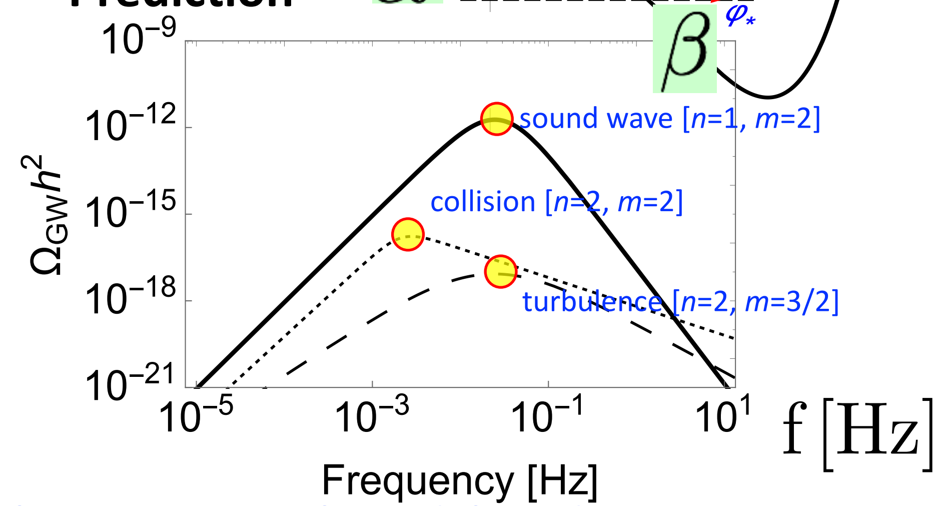
GWs from 1stOPT

- **GW is predicted in the general relativity.**
  - Weak field approximation
    $$g_{\mu\nu}(x) = \eta_{\mu\nu} + h_{\mu\nu}(x) \quad |h_{\mu\nu}| \ll 1$$
  - Wave eq. from Einstein eq.
    $$-\Box\left(h_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}h^{\alpha}{}_{\alpha}\right) = 16\pi G T_{\mu\nu}$$
- **Stochastic backgrounds of GWs**
  $$\rho_{\rm GW} = \frac{1}{32\pi G} < \dot{h}_{\alpha\beta}\dot{h}^{\alpha\beta} >$$
  - Energy density of GWs
    $$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}\ln f}$$
    M. Kamionkowski, astro-ph/9310044 (PRD)
  - Numerical simulation
    $$\Omega_{\rm GW}^{\rm peak} \propto \left(\frac{H_t}{\beta}\right)^n \left(\frac{\kappa\alpha}{1+\alpha}\right)^m$$
    C. Caprini *et al.*, 1512.06239 (JCAP)

- **Particle physics models w/1stOPT**
  - **α ~ Normalized difference of potential minima**
  - **β^{-1} ~ Transition time ∝ Bubble size**



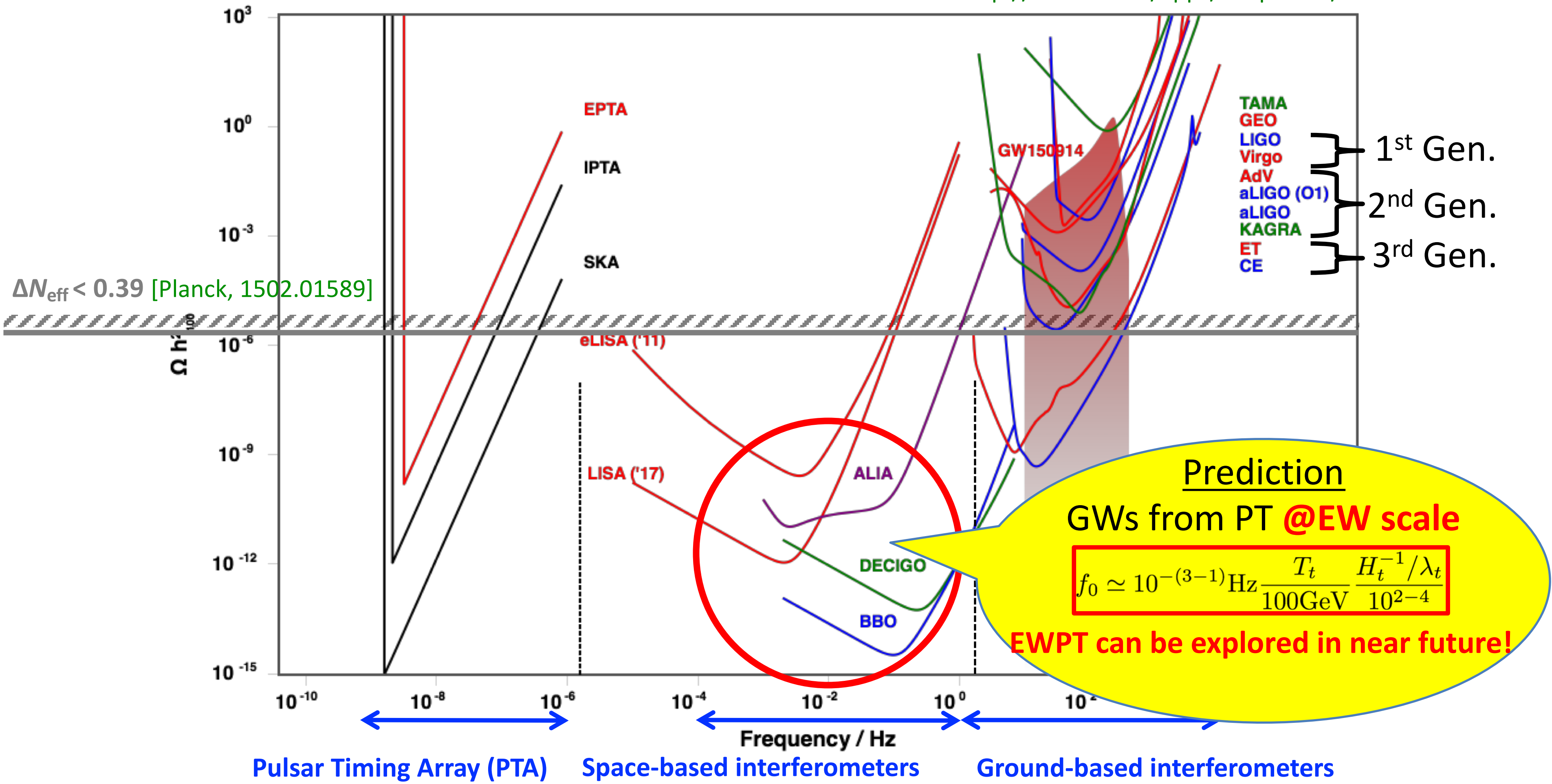
- **Prediction**



We can discuss the detectability at GW observations with model predictions.

Sensitivity of GW detectors

http://rhcole.com/apps/GWplotter/



L=O(10^6)km (LISA), 1000km (DECIGO), 4km (LIGO), 3km (Virgo, KAGRA)

Higgs portal DM w/1stOPT

- **Singlet scalar DM** (m_S, λ_{HS} , λ_S) 1210.4196, 1409.0005, 1611.02073, 1702.06124, 1704.03381, …

$$\mathcal{L}_{\rm SSDM} = -V_0(\Phi, S)$$

$$V_0(\Phi,S) = -\mu_\Phi^2|\Phi|^2 + \frac{1}{2}\mu_S^2 S^2 + \lambda_\Phi|\Phi|^4 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{\Phi S}|\Phi|^2 S^2$$

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  - Scalar potential is imposed unbroken Z_2 symmetry.

- **Singlet Fermion DM** (m_H, θ, v_S, $\mu_{\Phi S}$, μ_S, μ'_S; m_ψ, λ)

1112.1847, 1209.4163, 1305.3452, 1402.3087, …

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- **Vector DM** (m_H, θ; m_X, g_X) 1212.2131, 1412.3823, …

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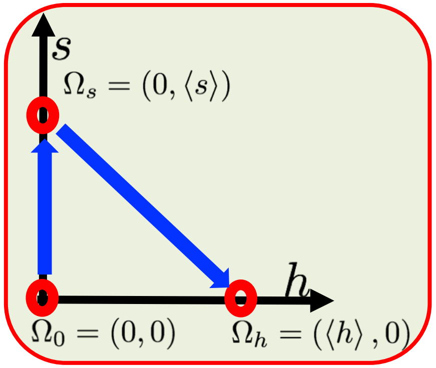
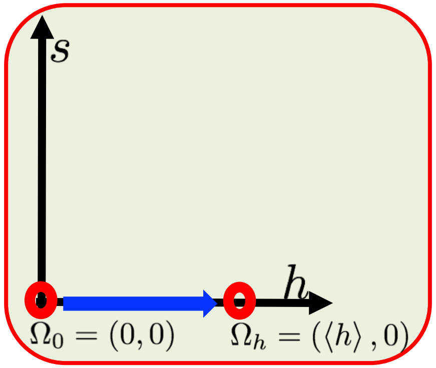
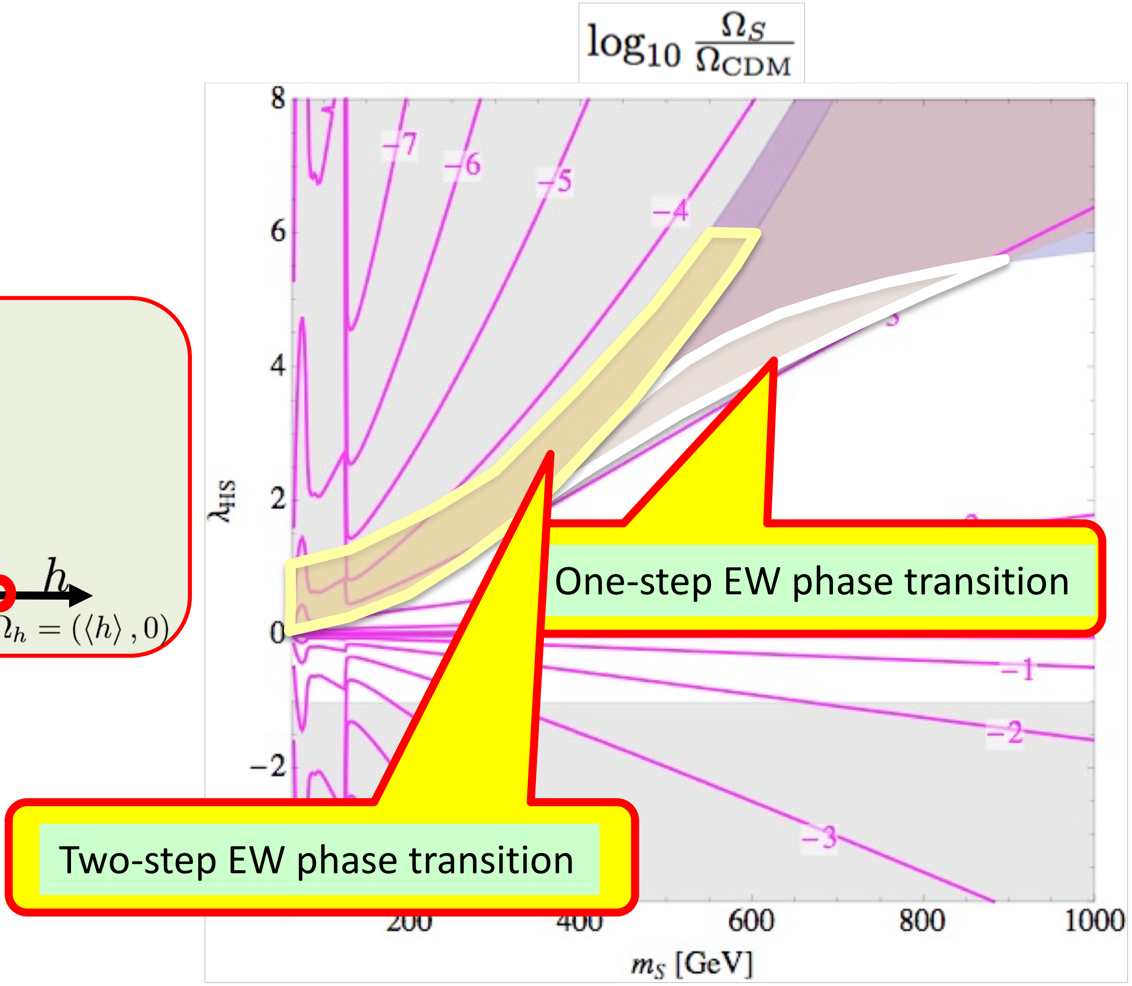
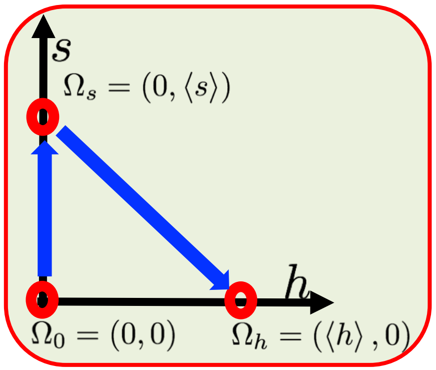


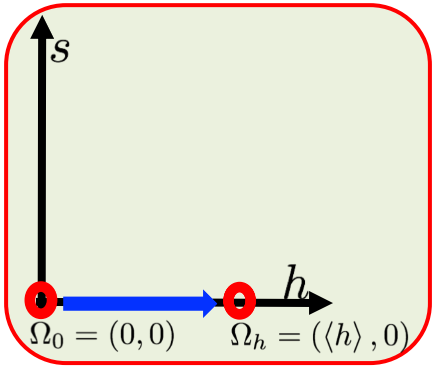


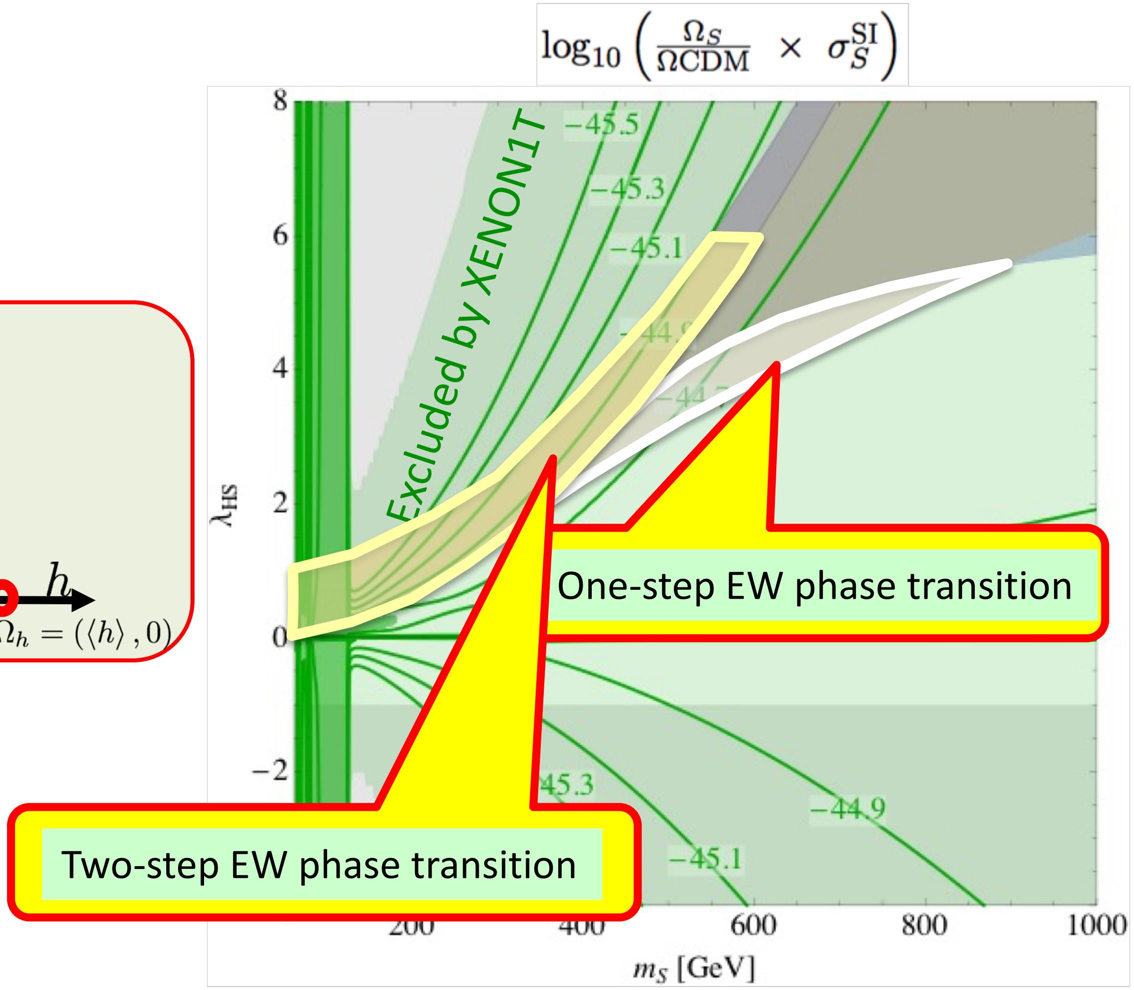


Curtin, Meade, Yu, 1409.0005 (JHEP)
See also Beniwal, Lewicki, Wells, White, Williams, 1702.06124 (JHEP)

1stOPT in scalar DM model → Excluded by XENON1T







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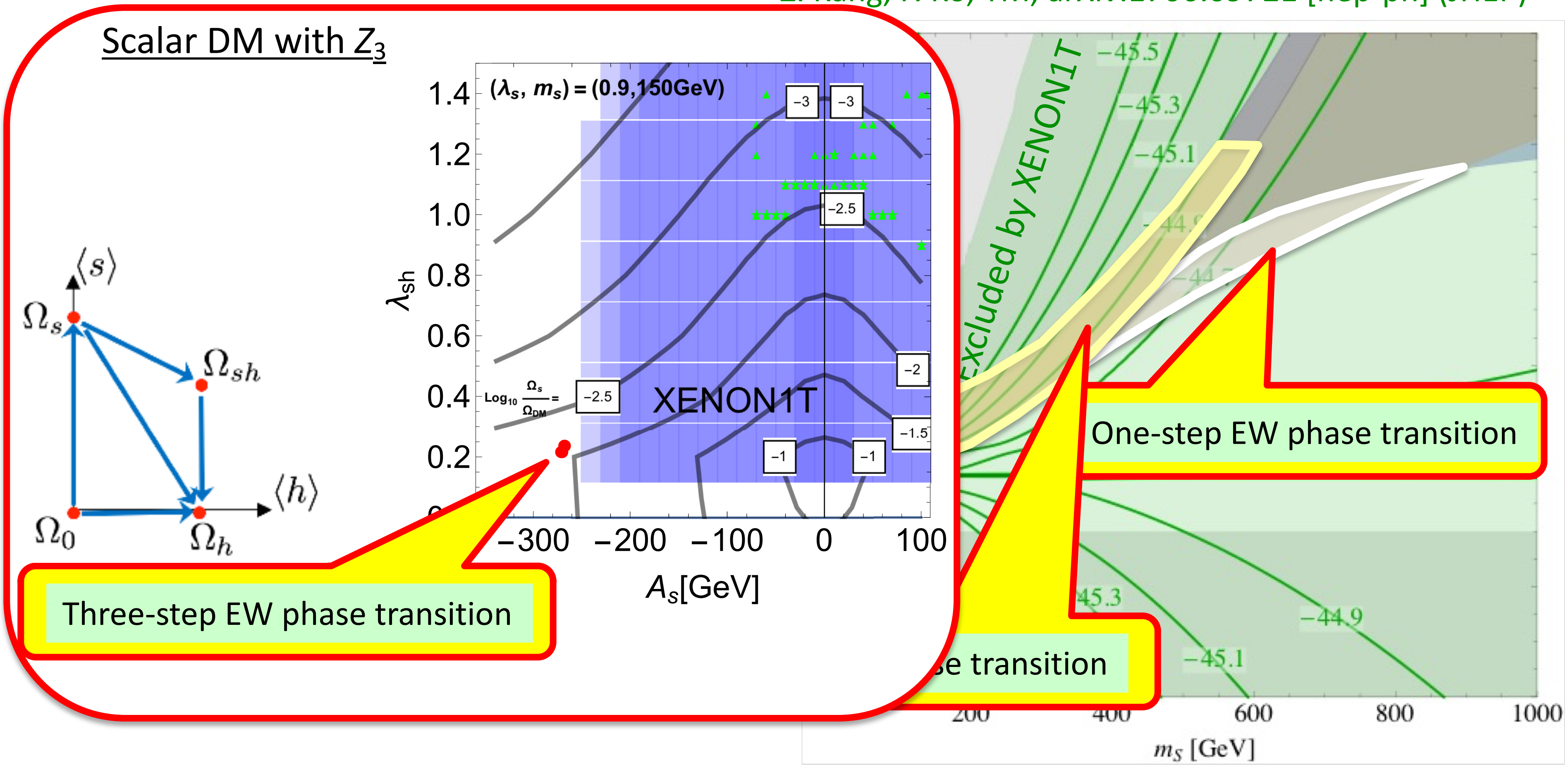
Z_3 extension: S^3 term is allowed (extra parameter A_S)

→ It is possible to satisfy the DM direct search bound!

Z. Kang, P. Ko, TM, arXiv:1706.09721 [hep-ph] (JHEP)



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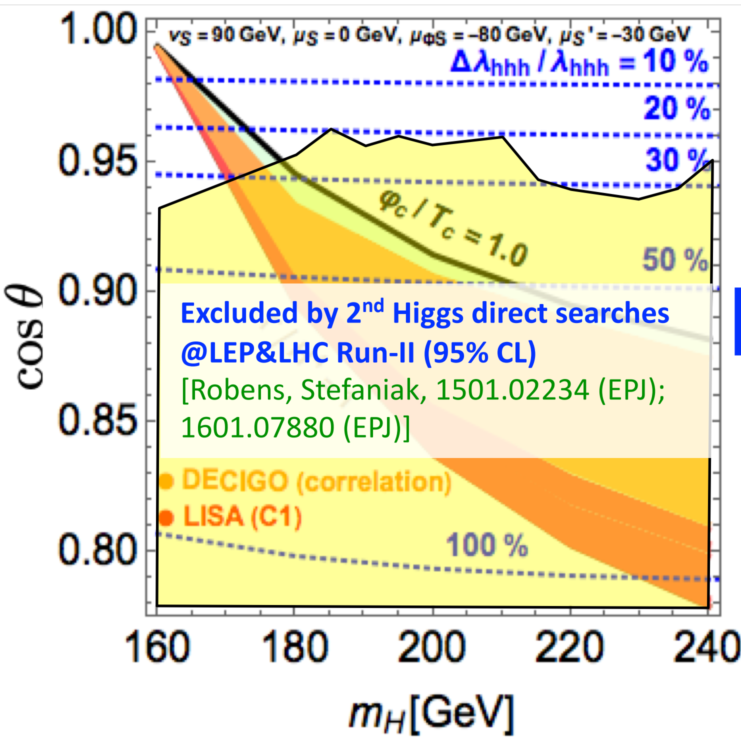
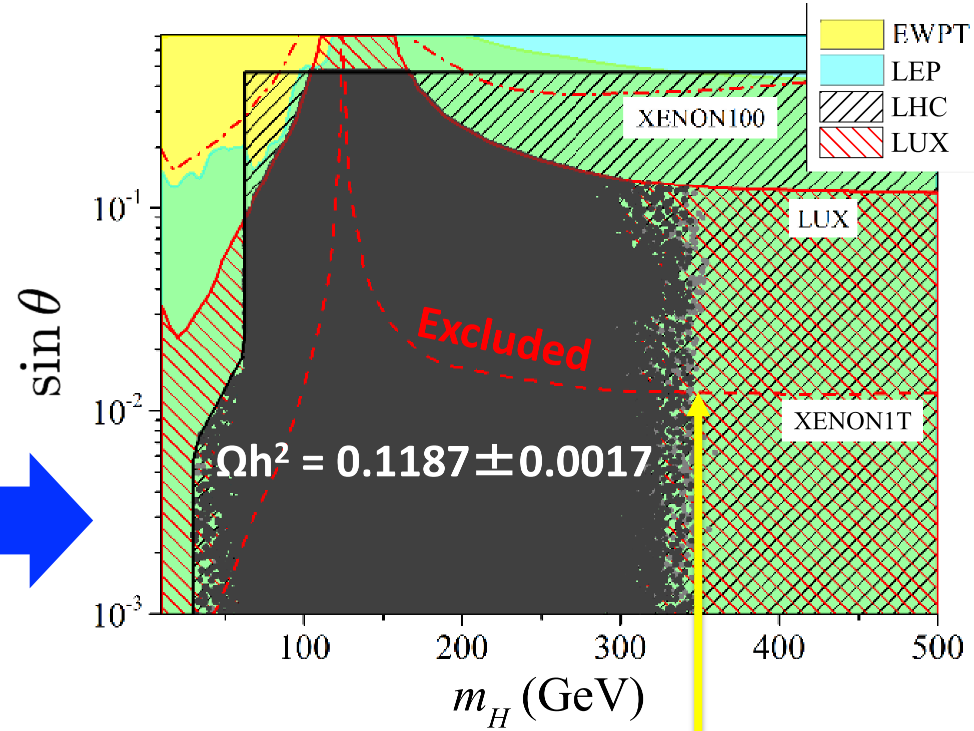
1stOPT in Fermion DM model

(without fermion)



Hashino, Kakizaki, Kanemura, TM, Ko, 1609.00297 (PLB)



$\cos\theta \gtrsim 0.99995$ at $m_H = 350$ GeV

XENON1T gives stronger constraint to the Higgs mixing angle than collider bound.

$m_H \simeq 30 - 250$ GeV

$m_\psi = 15 - 350$ GeV (DM)

Li, Zhou, 1402.3087 (JHEP)

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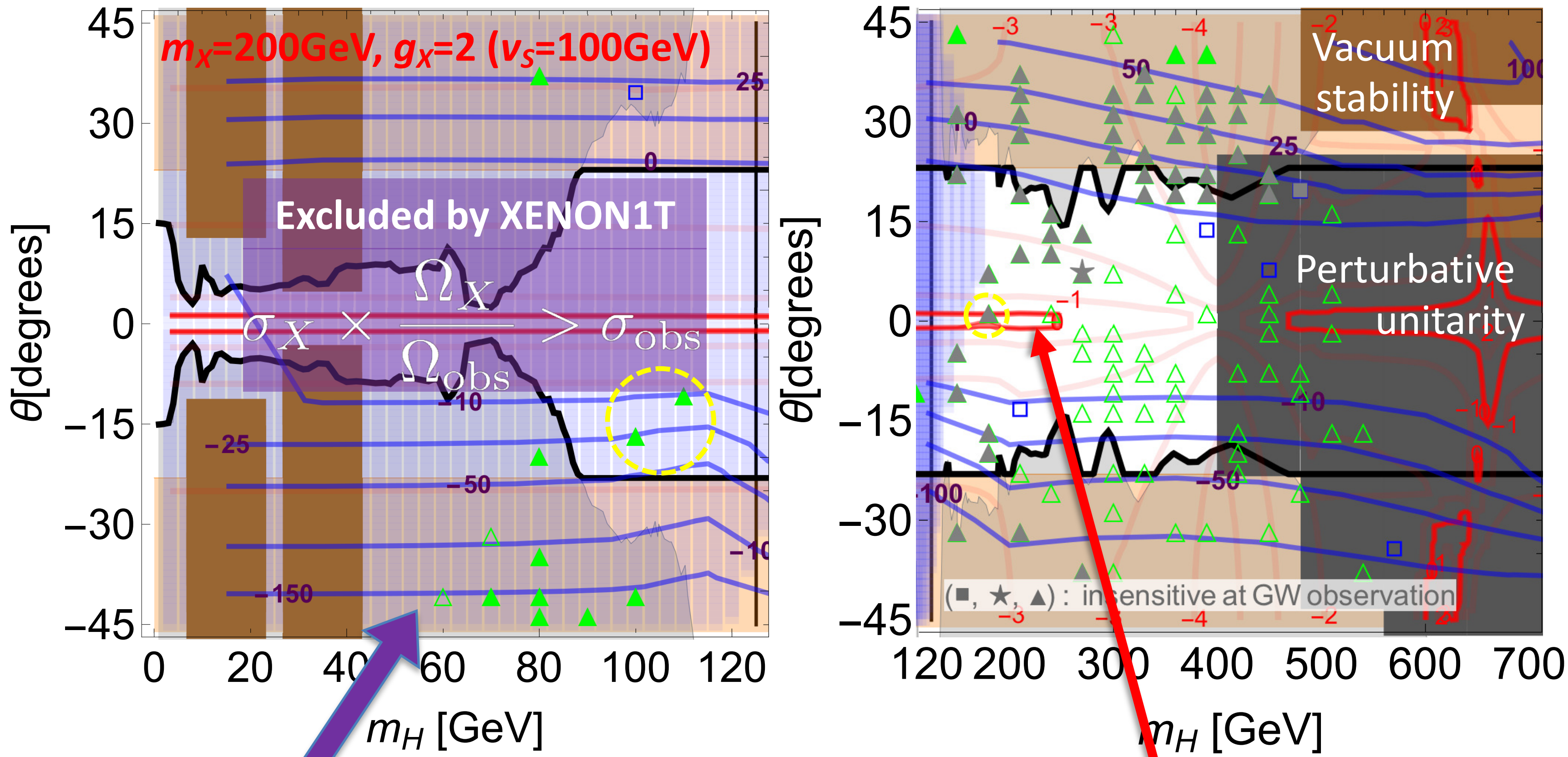
Hashino, Kakizaki, Kanemura, Ko, TM, 1802.02947 (JHEP)



DM direct detection bound
[XENON Collaboration, 1705.06655 (PRL)]

Relic abundance of DM
$\Omega_{obs}h^2$=0.1199±0.0027 → **contours of $\log_{10} (\Omega_X / \Omega_{obs})$**
[Planck Collaboration, 1502.01589 (Astron. Astrophys.)]

Higgs portal DM w/1stOPT

- **Singlet scalar DM (m_S, λ_{HS} , λ_S)** 1210.4196, 1409.0005, 1611.02073, 1702.06124, 1704.03381, …

$$\mathcal{L}_{\rm SSDM} = -V_0(\Phi, S)$$

$$V_0(\Phi,S) = -\mu_\Phi^2|\Phi|^2 + \frac{1}{2}\mu_S^2 S^2 + \lambda_\Phi|\Phi|^4 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\lambda_{\Phi S}|\Phi|^2 S^2$$

$$\langle S\rangle = 0 \qquad m_S^2 = \mu_S^2 + \lambda_{HS}v^2$$

  - Scalar potential is imposed unbroken Z_2 symmetry.
  - **PT can be caused by thermal loop effect, but excluded by DM direct searches.** [Curtin, Meade, Yu, 1409.0005 (JHEP)]

    → Z_3 extension allow to satisfy the constraint from DM direct searches but $\Omega_{DM}<\Omega_{obs}$ [Kang, Ko, TM, 1706.09721 (JHEP)]

- **Singlet Fermion DM (m_H, θ, v_S, $\mu_{\Phi S}$, μ_S, μ'_S; m_ψ, λ)**

  1112.1847, 1209.4163, 1305.3452, 1402.3087, …

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}(i\partial\!\!\!/ - m_{\psi_0})\psi - \lambda S\overline{\psi}\psi - V_0(\Phi,S)$$

$$V_0(\Phi,S) = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \frac{\lambda_{\Phi S}}{2}|\Phi|^2 S^2 + \mu_S^3 S + \frac{m_S^2}{2}S^2 + \frac{\mu'_S}{3}S^3 + \frac{\lambda_S}{4}S^4$$

$$S = v_S + \phi_2 \qquad m_\psi \equiv m_{\psi_0} + \lambda v_S$$

  - Scalar potential is general shape with a real Higgs singlet scalar field (HSM).
  - **PT is dominantly caused by tree level (scalar mixing) effect.** [Hashino, Kakizaki, Kanemura, Ko, TM, 1609.00297(PLB)]
  - **DM contributes as the thermal loop effect.** [Li, Zhou, 1402.3087 (JHEP)]

    → DM direct searches give stronger constraint. We expect that GW from PT will be detectable satisfying DM conditions.

- **Vector DM (m_H, θ; m_X, g_X)** 1212.2131, 1412.3823, …

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu S)^2 + V_0(\Phi,S)$$

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

$$D_\mu S = (\partial_\mu + ig_X Q_S X_\mu)S \qquad S = \frac{1}{\sqrt{2}}(v_S + \phi_2 + ix) \qquad m_X \equiv g_X|Q_S|v_S$$

  - Scalar potential is a case for the spontaneously broken Z_2 symmetry in HSM. (**dark Higgs mechanism**)
  - **PT is too weak to detect GWs.** [Hashino, Kakizaki, Kanemura, Ko, TM, 1802.02947 (JHEP)] → Extension is needed.