Gravitational waves from first order electroweak phase transition in models with the $U(1)_X$ gauge symmetry

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JHEP **1806**, 088 (2018) [arXiv:1802.02947]

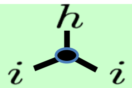
Physics behind EWSB

- Although SM has been established as a low-energy eff. theory, we have not yet understood the structure of Higgs sector.

$$\mathcal{L}_{\rm SM}^{\Phi} = |D_\mu \Phi|^2 - V_{\rm SM}(\Phi) - \overline{\psi}_i y_{ij} \psi_j \Phi + {\rm h.c.} \qquad V_{\rm SM}(\Phi) = \mu^2|\Phi|^2 + \frac{\lambda}{2}|\Phi|^4$$

- **Higgs boson couplings might be deviated from the prediction in SM.**

Zero temp.

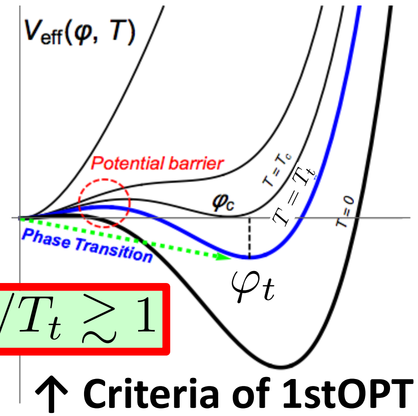


***hVV*, *hff*, *hhh*, …**

Future colliders can measure precisely.

- BSM phenomena might be described by extended Higgs sector.
  - *Dark matter* (DM) → **Higgs portal DM** : Higgs sector is extended from SM.
  - *BAU* → ***EW baryogenesis*** : Strongly 1stOPT for EWSB is required.
    [SM (m_h=125GeV) →1stOPT is not realized. →Extension is needed.]
  - **Gravitational waves (GWs) is produced from 1stOPT**

Finite temp.



Exploring the dynamics of EWSB is important. $\varphi_t / T_t \gtrsim 1$

↑ **Criteria of 1stOPT**

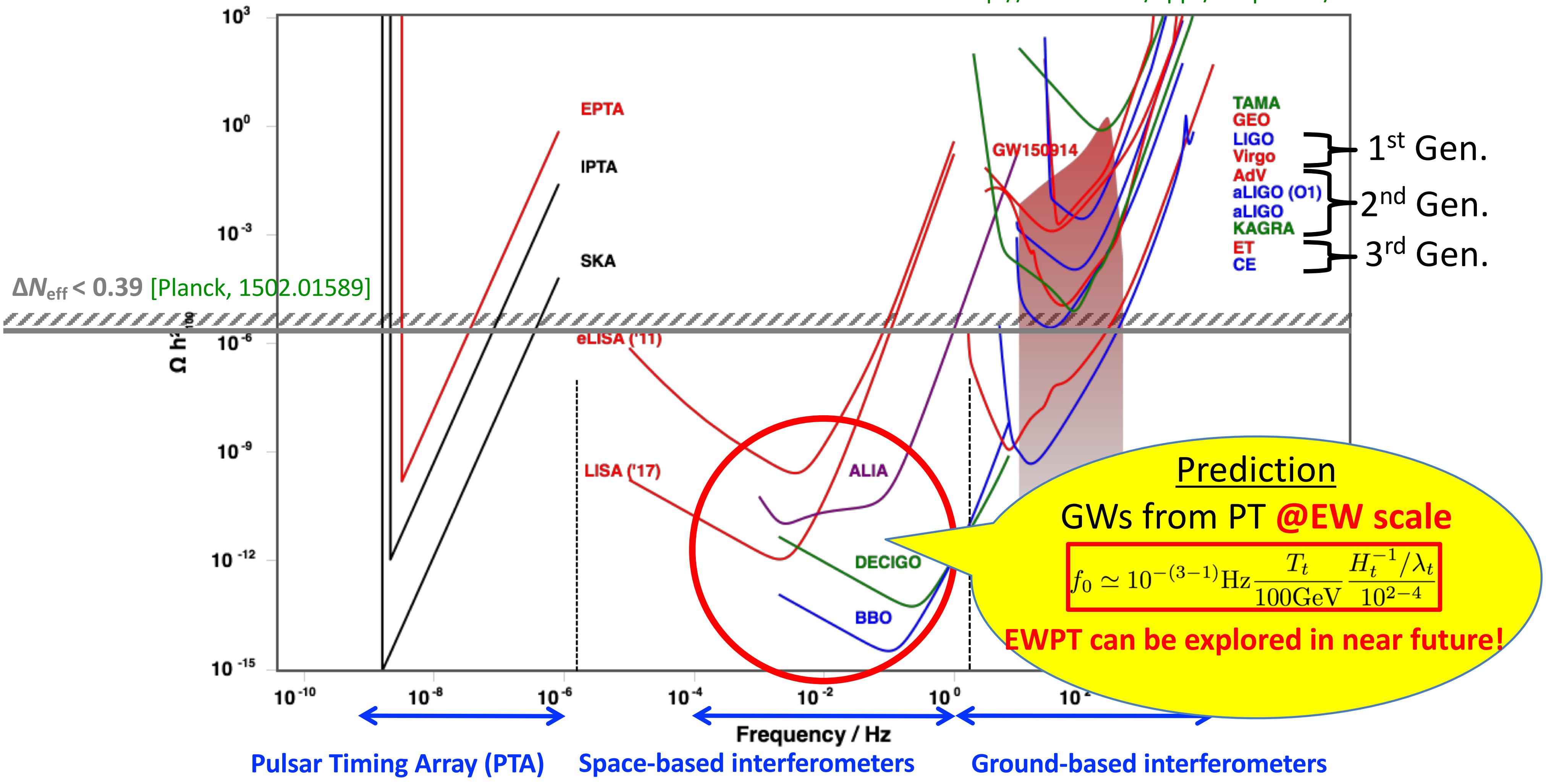
Classification of models w/1stOPT

Type	(hVV, hff) κ_V, κ_F	$h\gamma\gamma$	$\Delta\lambda_{hhh}/\lambda_{hhh}^{SM}$	GW	Minimal models		
I	○	○	○	○	2HDM	: $\Phi_{SM}+\Phi'$	(A)
II	[Light stops excluded at LHC]				MSSM		(A)
III	○	-	○	○	rHSM (real singlet scalar)	: $\Phi_{SM}+S$	(B)
IV	○	○	○	○	NMSSM		(B)
V	-	-	○	○	ISM (singlet scalar w/Z_2)	: $\Phi_{SM}+S$	(A) &(B)
VI	-	○	○	○	IDM (doublet scalar w/Z_2)	: $\Phi_{SM}+\Phi'$	(A) &(B)

We propose GWs as a new technique to explore BSM, in addition to collider experiments!

Sensitivity of GW detectors

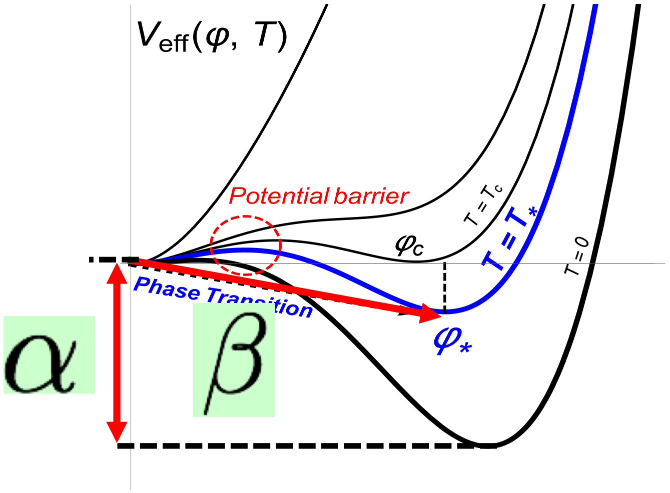
http://rhcole.com/apps/GWplotter/



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

GWs from 1stOPT

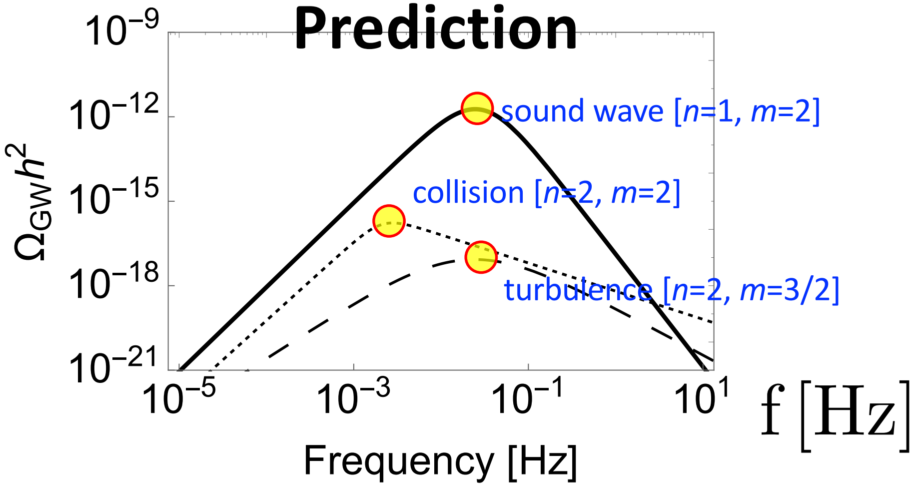
Model



α ~ Normalized difference of the potential minima

β^{-1} ~ Transition time ∝ Bubble size

Prediction



$$\Omega_{\rm GW} \propto \left(\frac{H_t}{\beta}\right)^n \left(\frac{\kappa\alpha}{1+\alpha}\right)^m$$

C. Caprini *et al.*, 1512.06239 (JCAP)

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

$U(1)_X$ model

- Particle contents
  - $U(1)_X$ gauge field (dark photon) X_μ
  - Complex scalar (dark Higgs) S with $U(1)_X$-charge Q_S =1
- Lagrangian

$$\mathcal{L} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}X_{\mu\nu}B^{\mu\nu} + |D_\mu S|^2 - V_0(\Phi, S)$$ [B. Holdom, PLB**166**, 196 (1986)]

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

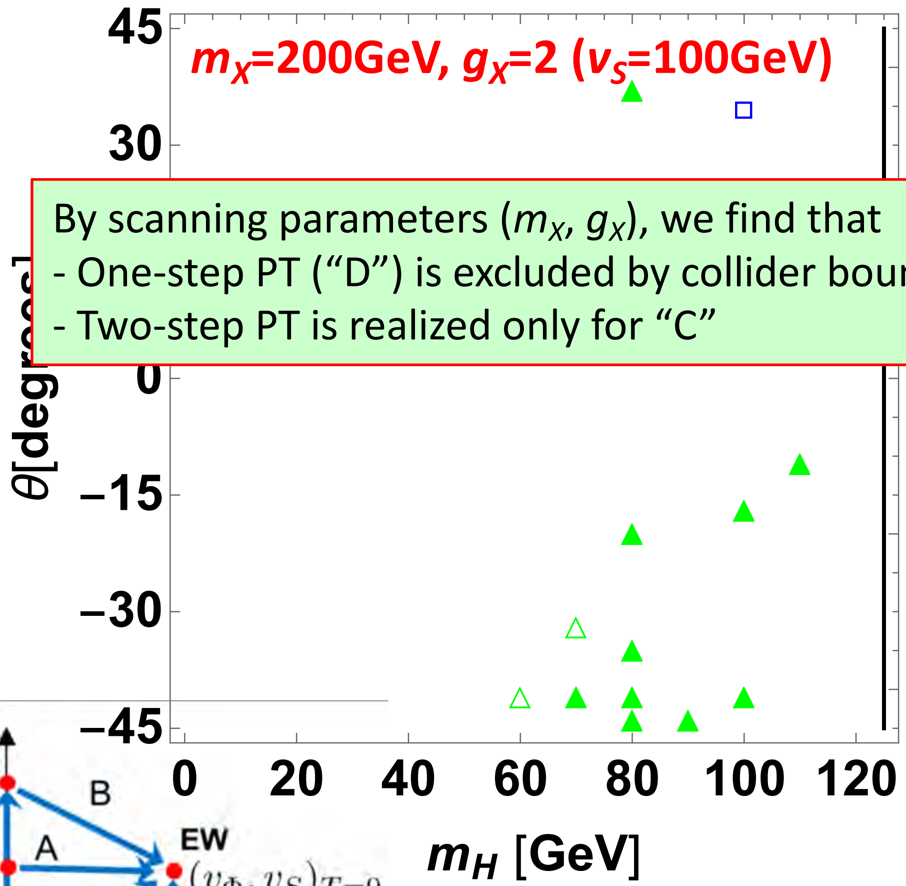
  - $U(1)_X$ gauge symmetry is spontaneously broken by nonzero VEV of S

$$D_\mu S = (\partial_\mu + i g_X Q_S X_\mu)S \rightarrow m_X \equiv g_X|Q_S|v_S$$ (Dark Higgs mechanism)

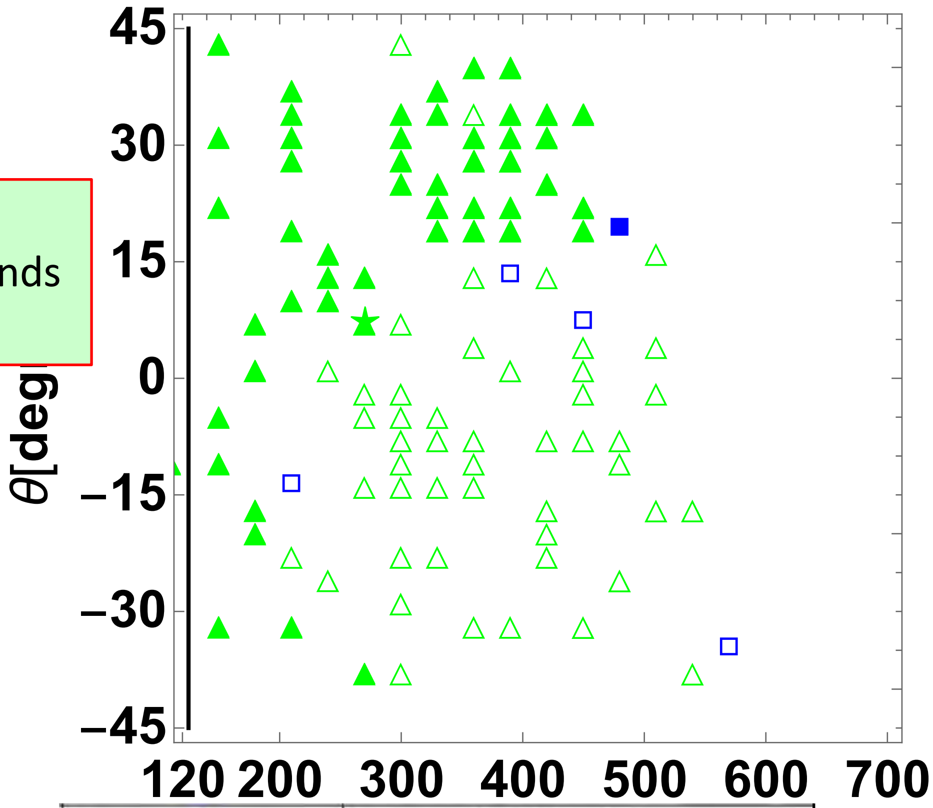
  - Scalar mixing: $(\phi_\Phi, \phi_S) \rightarrow (h, H)$ with the mixing angle θ
  - Parameters (m_h = 125 GeV, v_Φ = 246 GeV; m_H, θ; m_X, g_X; ε)

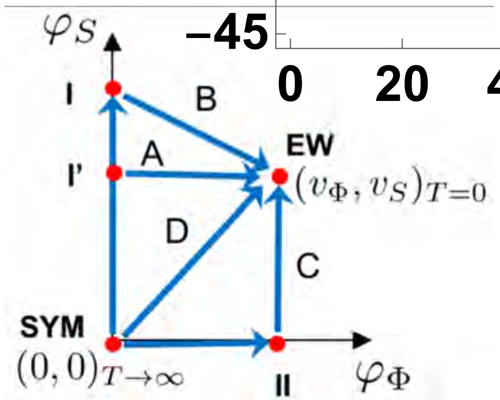
Multi-step phase transition

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



By scanning parameters (m_X, g_X), we find that
- One-step PT ("D") is excluded by collider bounds
- Two-step PT is realized only for "C"

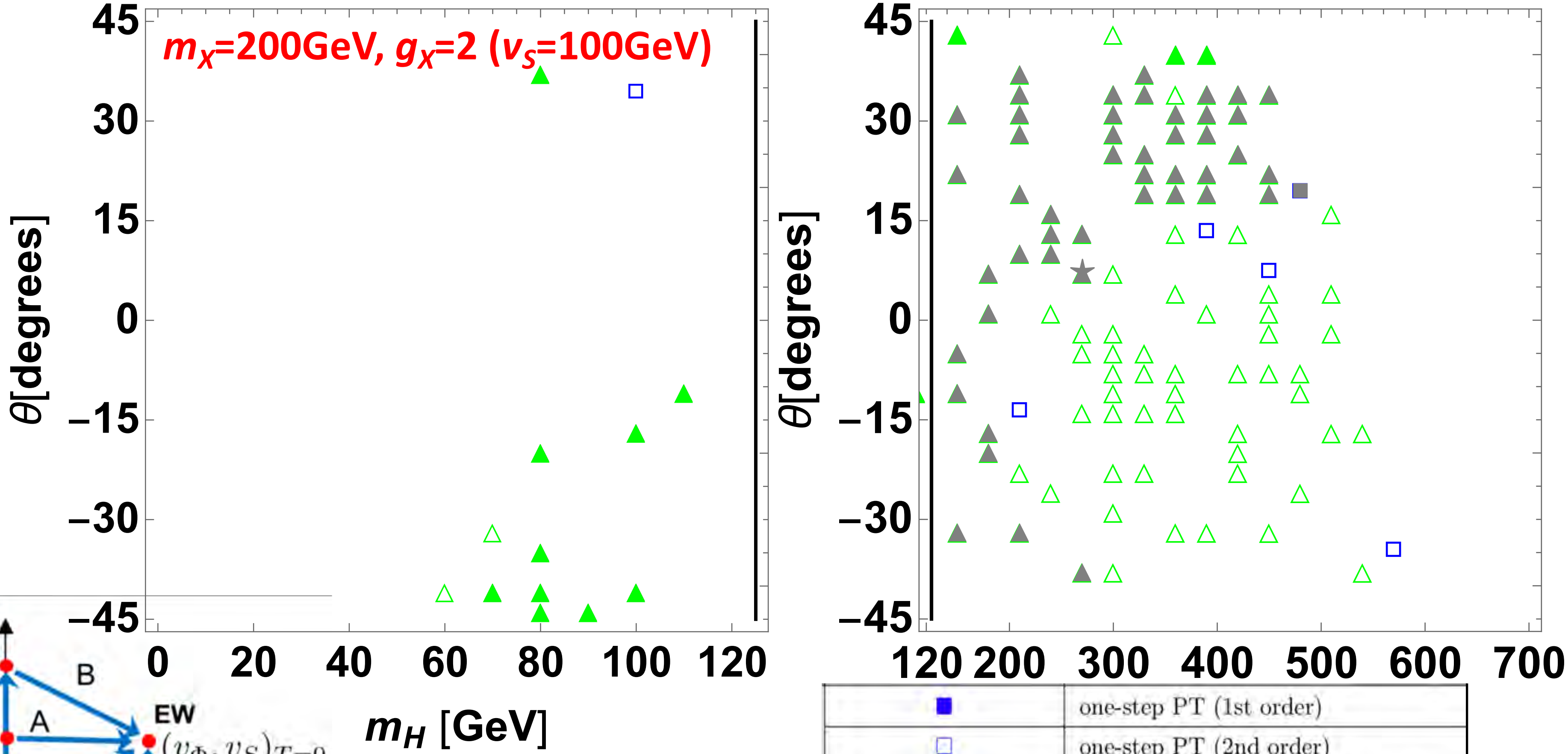


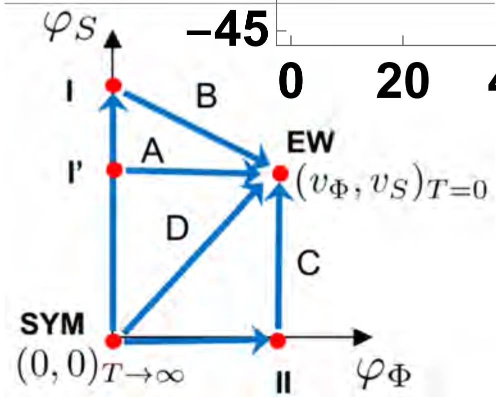


■	one-step PT (1st order)
□	one-step PT (2nd order)
★	two-step PT (1st order → 1st order)
▲	two-step PT (2nd order → 1st order)
△	two-step PT (1st order → 2nd order)

① Detectability at GW observations

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



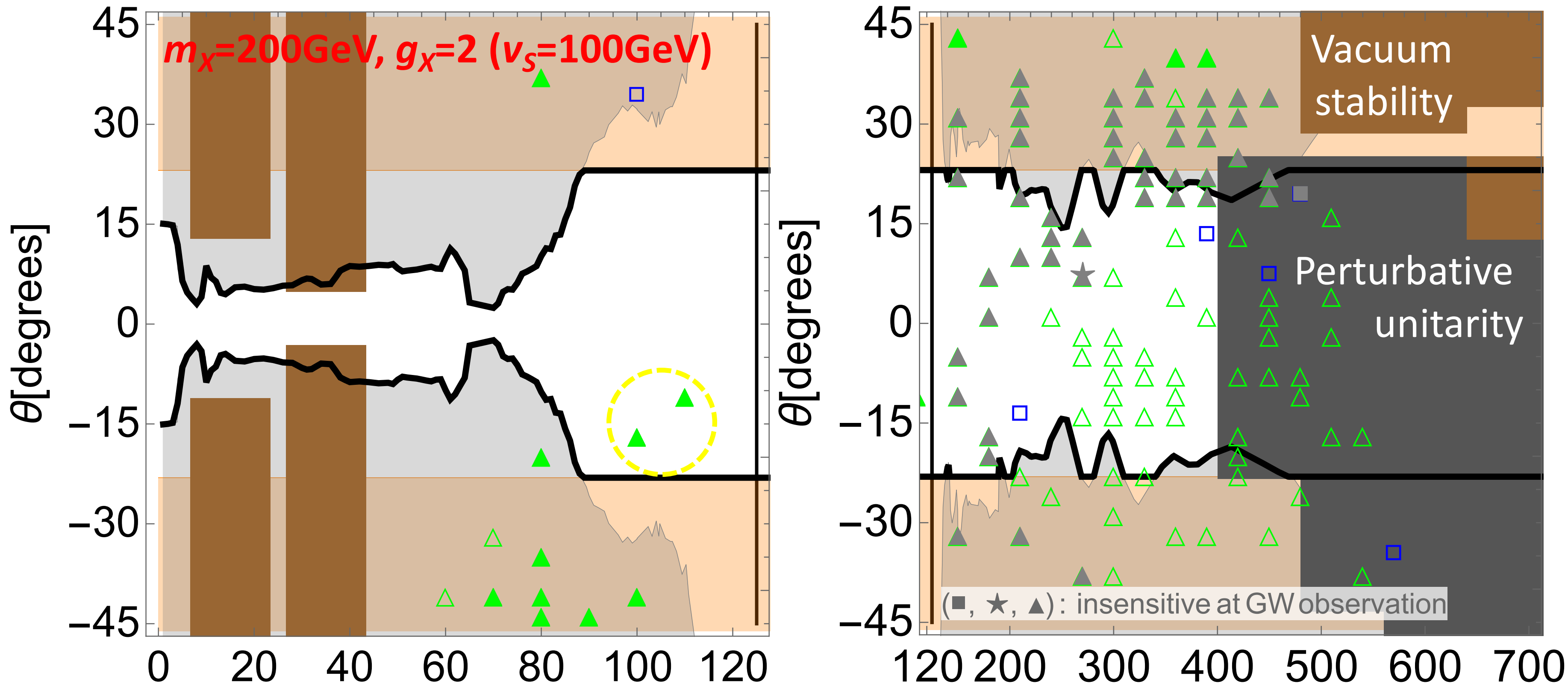


■ (blue)	one-step PT (1st order)
□ (blue)	one-step PT (2nd order)
★ (green)	two-step PT (1st order → 1st order)
▲ (green)	two-step PT (2nd order → 1st order)
△ (green)	two-step PT (1st order → 2nd order)
(■, ★, ▲) in (m_H, θ)	insensitive at GW observation

② Collider measurements

~ Current bounds ~

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



Direct searches for *H* @LEP&LHC Run-II (2σ exclusion)
[Robens, Stefaniak, 1501.02234 (EPJ); 1601.07880 (EPJ)]

Interactions@LHC Run-I results (1σ) [ATLAS and CMS, ATLAS-CONF-2015-044]

$\kappa_Z = 1.03^{+0.11}_{-0.11}, \kappa_W = 0.91^{+0.10}_{-0.10}$ → $|\theta| \leq 23.1°$

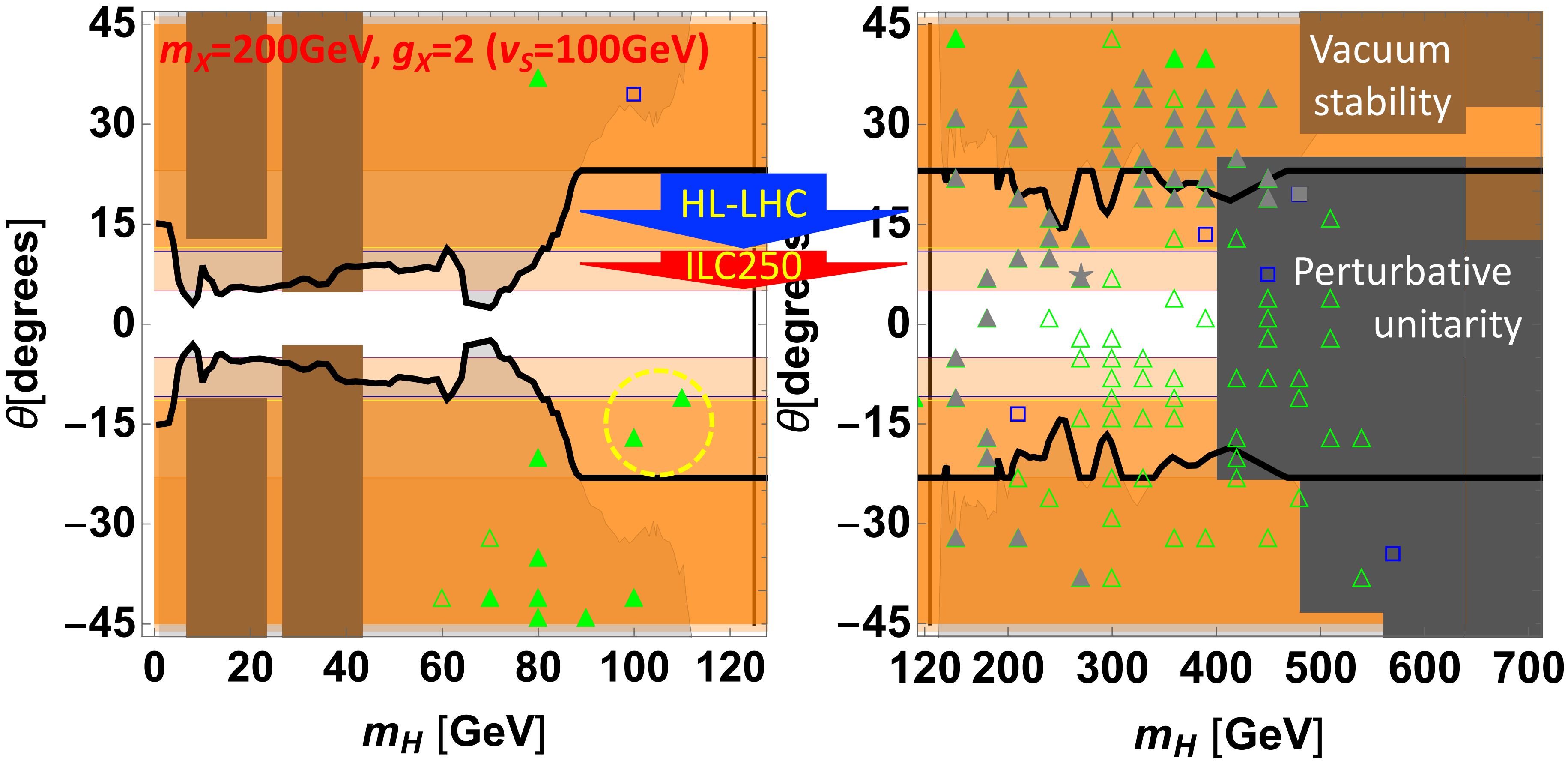
Model Prediction

$$\kappa \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = \frac{g_{hff}}{g_{hff}^{\rm SM}} = \cos\theta$$

② Collider measurements

~ Precision measurements of κ @ILC 250GeV 2ab^{-1} ~

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

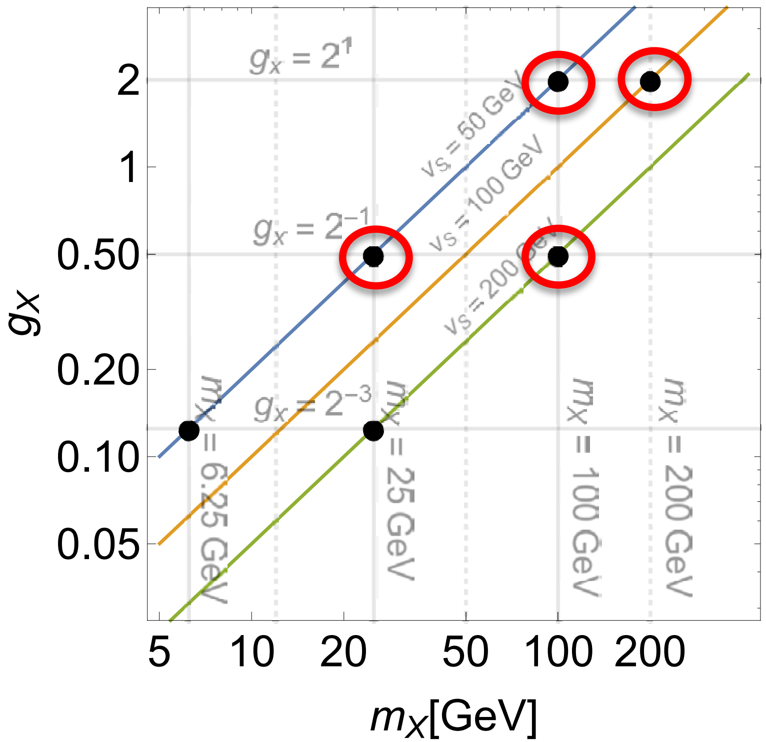


Δκ$_V$: **2**%@HL-LHC 14TeV 3ab^{-1} [CMS, 1307.7135]

Δκ$_{Z(W)}$: **0.38** (1.8)%@ILC250GeV 2ab^{-1} [Fujii et al., 1710.07621]

③ Dark photon searches

- **Prediction: Detectable GW signal → $m_X \gtrsim 25\mathrm{GeV},\ g_X \gtrsim 0.5$**



Current bound

- **LHCb** [1710.02867 (PRL)]
  $\varepsilon < 2 \times 10^{-7}$ - 6×10^{-3} for m_X = [20, 70]GeV
- **EW precision tests** [Hook, Izaguirre, Wacker, 1006.0973]
  $\varepsilon < O(10^{-2})$ for m_X = [70, 150]GeV
- **LHC** 13TeV, 36.1fb^{-1} [1707.02424 (JHEP)]
  $\varepsilon < 8.3 \times 10^{-3}$ for m_X = [150, 300]GeV

Future exclusion

- **$e^+ e^-$ colliders** (CEPC/ILC/FCC-ee)
  [M. He, X. He, C. Huang, G. Li, 1712.09095]
  $\varepsilon < 10^{-2}$ - 10^{-3} for m_X = [20, 330]GeV
- **HL-LHC** 14TeV, 0.3(3)ab^{-1} [1412.0018 (JHEP)]
  $\varepsilon < 4.8(2.7) \times 10^{-3}$ for m_X = [150, 300]GeV

- **Constraint on Kinetic mixing ε**

We can explore the model by complementarity of collider measurements and GW observations!

$U(1)_X$ model w/1stOPT

Prediction

① **・Gravitational waves**
(LISA/DECIGO)

② **・Direct searches for *H***
(HL-LHC)
・Higgs coupling measurements
(HL-LHC/e^+e^- coliders)

③ **・Dark photon searches**
(HL-LHC/e^+e^- coliders)

Conclusions

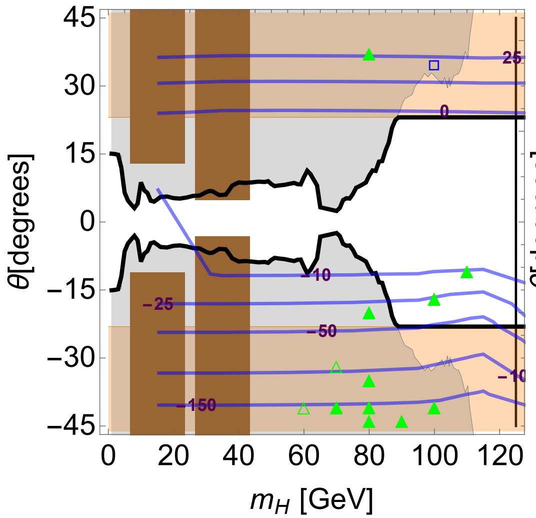
- We have investigated models with $U(1)_X$ gauge symmetry.
  - Mass of a dark photon (X_μ), which can be vector DM by imposing Z_2, is generated by spontaneous breaking of a dark Higgs field (S).
- We have explored comprehensively the patterns of PT and the detectability of GWs from 1stOPT as well as various collider and theoretical bounds.
- **We expect the model with 1stOPT will be tested by the complementarity of GW observations and (in)direct searches for 2^{nd} Higgs boson and dark photon (or DM).**
  - We have found that GW signals are detectable only for larger dark photon mass region ($m_X \gtrsim 25$ GeV with $g_X \gtrsim 0.5$).

Back Up

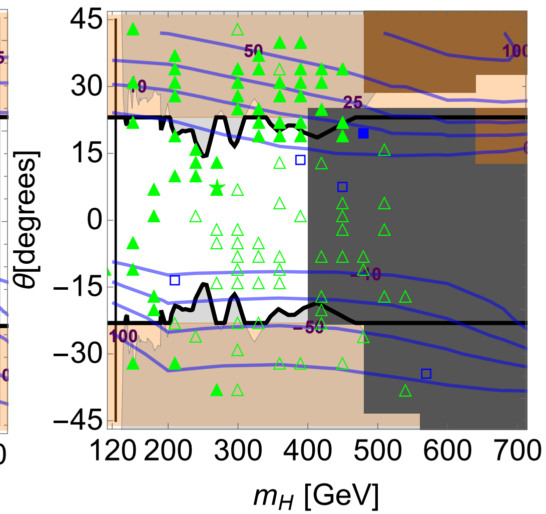
A numerical result on (m_H, θ) by fixing (m_X, g_X)

Hashino, Kakizaki, Kanemura, Ko, TM, 1802.02947

↓m_H<m_h



↓ m_h<m_H



m_X=200GeV, g_X=2 (v_S=100GeV) as an example

Categories	Symbols	Legends
Theory		excluded by perturbative unitarity
		excluded by vacuum stability
Collider		contours of $\Delta\lambda_{hhh}/\lambda_{hhh}^{SM}$ (%)
		constraint by the κ_Z measurement (see Eq. (4.3))
		constraint by the direct searches for the H-boson (see Ref. [119])
		combined exclusion limit (+)
PT	■	one-step PT (1st order)
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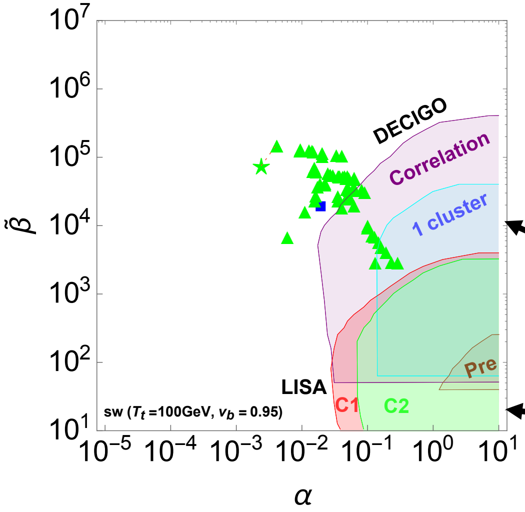
GW		DECIGO (Correlation)
		DECIGO (1 cluster)
		DECIGO (Pre)
		LISA (C1)
		LISA (C2)



Sensitivities

- DECIGO
  [S.Kawamura, et al., Class. Quant. Grav. **28**, 094011 (2011)]
- eLISA
  [C.Caprini *et al.*, arXiv:1512.06239 (JCAP)]

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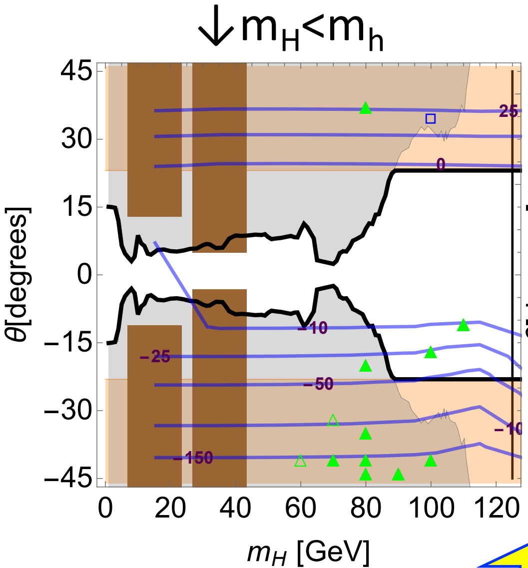

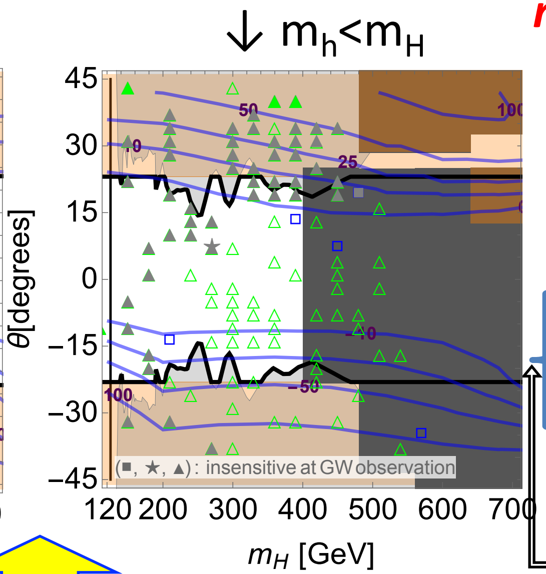

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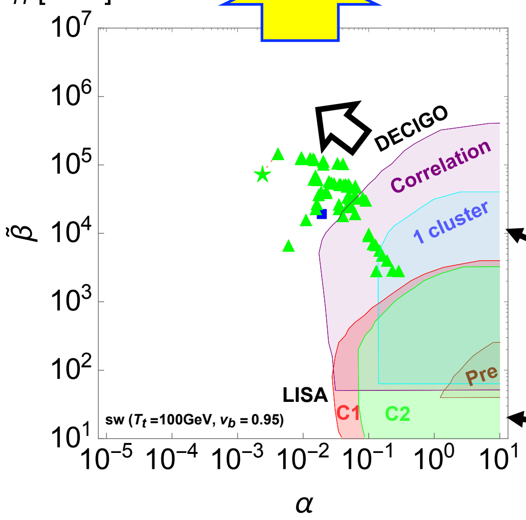

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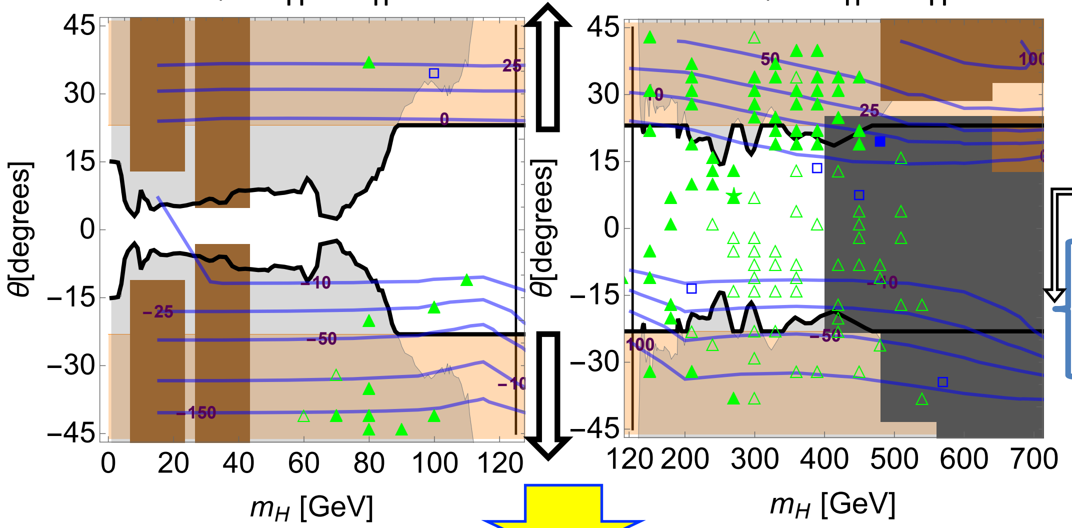

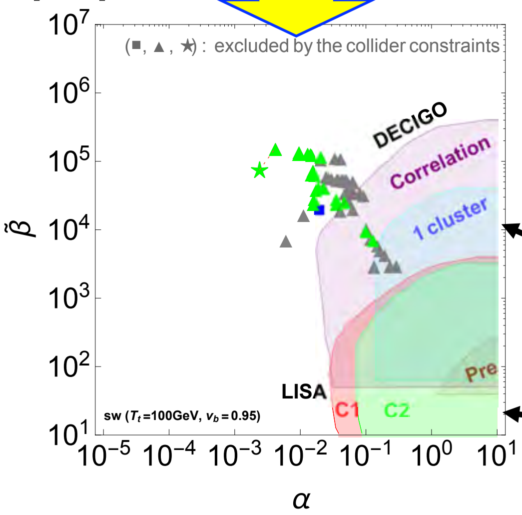

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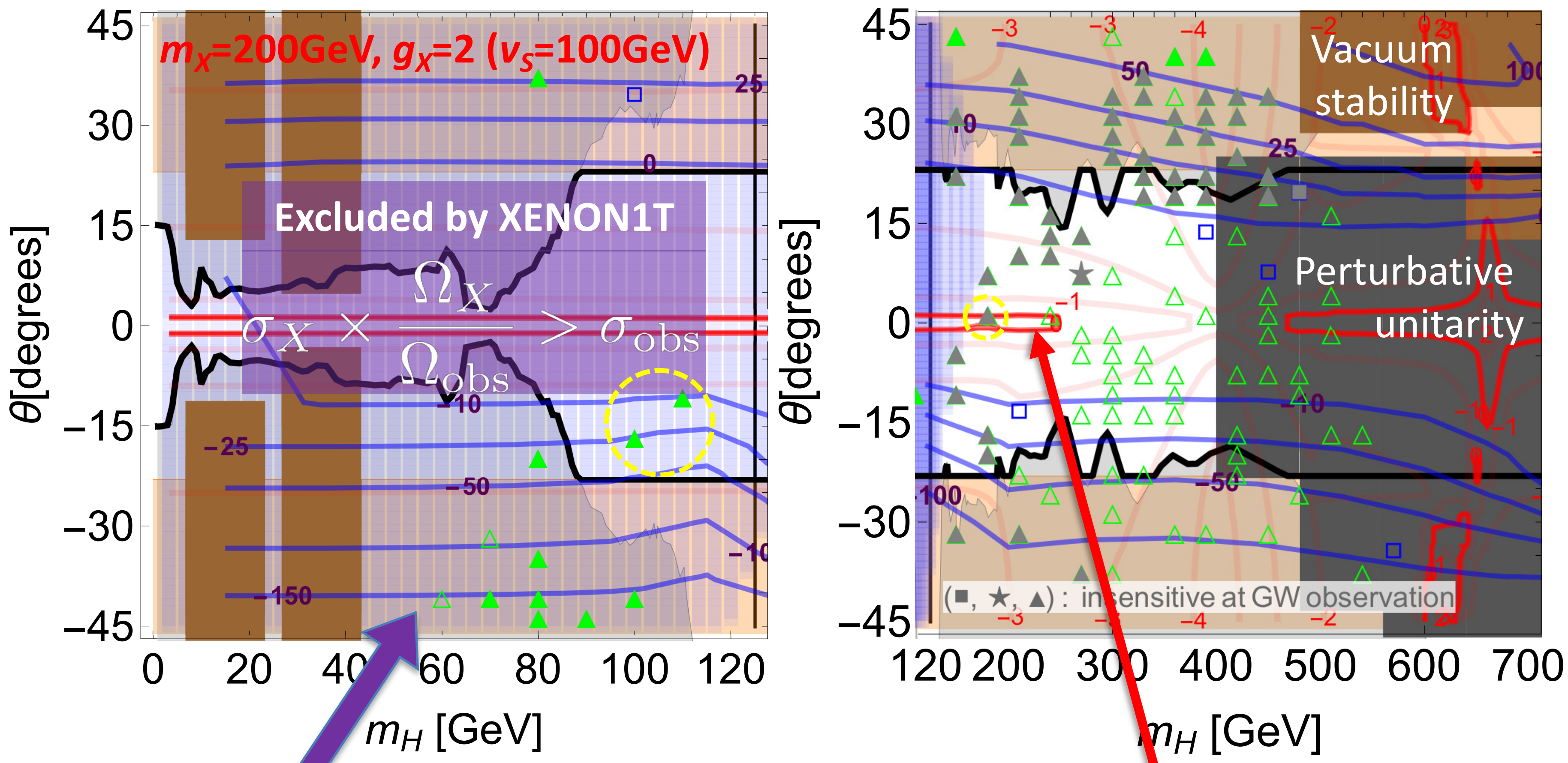
Two cases in $U(1)_X$ model

- <u>Model A</u> (A general case for nonzero ε)
  - The parameter space (m_X, ε) is constrained by various experiments of **dark photon search**.
  - We investigate the **complementarity of dark photon searches and GW observations.** [Addazi and Marciano, 1703.03248 (CPC)]
- <u>Model B</u> (An optional case for ε → 0)
  - X_μ^0 boson can be a DM candidate if we assume it to be odd under the Z_2 sym. (**Vector DM**) [cf. Baek, Ko, Park, Senaha, 1212.2131 (JHEP)]
  - The Z_2 symmetry removes the kinetic mixing term, making X_μ^0 stable; ε → 0 limit.
  - We consider current DM constraints as a scenario.

A case for dark photon as Vector DM

~ Z_2 symmetry is imposed in the model ($\varepsilon \to 0$) ~

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 (5 parameters)** 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 [Z. Kang, P. Ko, TM, 1706.09721 (JHEP)]

- **Singlet Fermion DM (10 parameters)** 1112.1847, 1209.4163, 1305.3452, 1402.3087, …

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

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

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

  - 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 loop effect. [Li, Zhou, 1402.3087 (JHEP)]

- **Vector DM (6 parameters)** 1212.2131, 1412.3823, …

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

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

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

  - Scalar potential is a case for the spontaneously broken Z_2 symmetry in HSM.