Electroweak Phase Transition at CEPC: A cosmologist's perspective

(DR.) ANDREW LONG
UNIVERSITY OF CHICAGO, KICP

@ IHEP BEIJING
WORKSHOP ON CEPC PHYSICS
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Based on

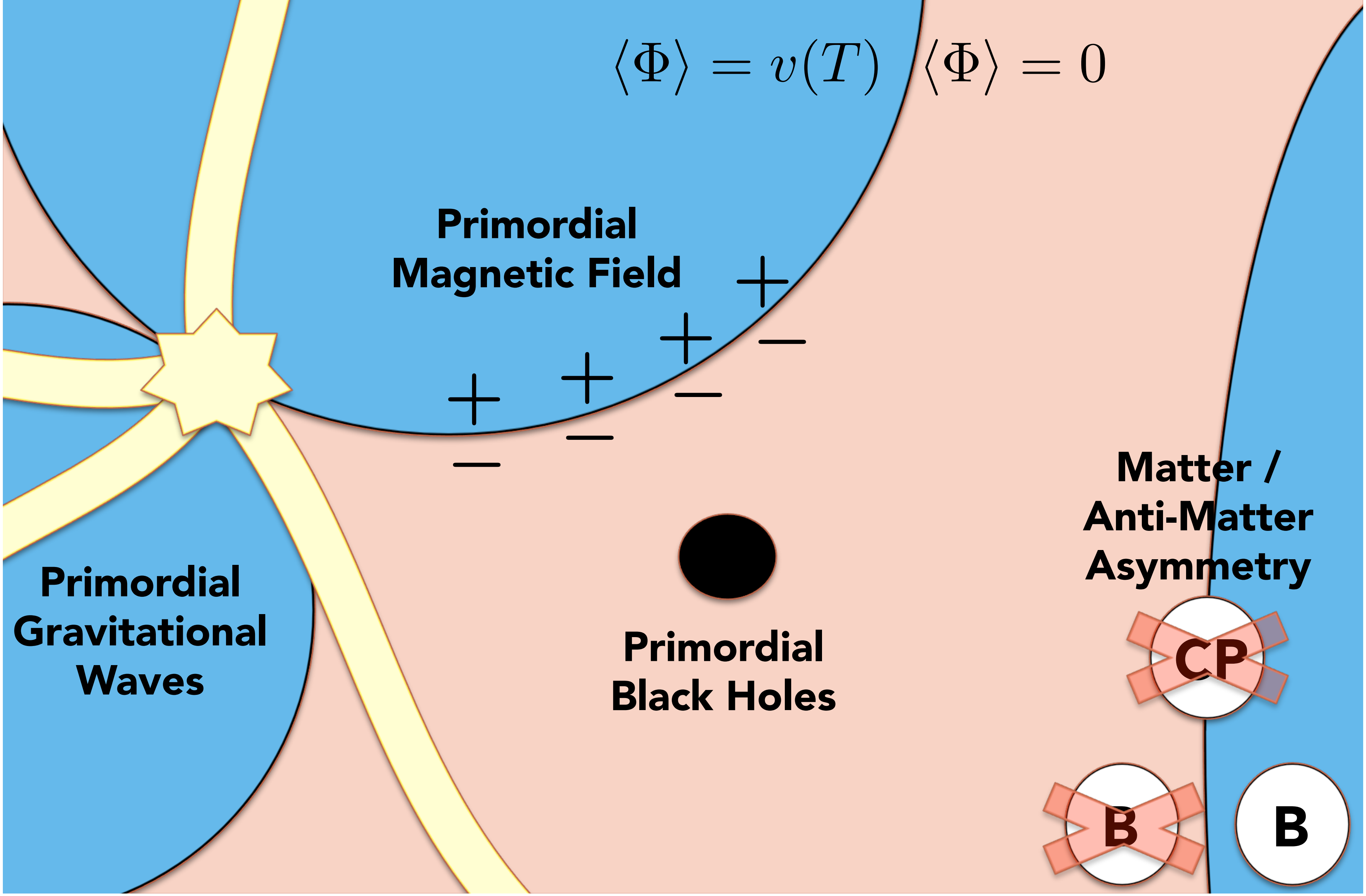
… 1608.06619 (PRD) with Peisi Huang & Lian-Tao Wang.
… 1708.03061 with Xucheng Gan & Lian-Tao Wang.

… see also Barger, Chung, AL, Wang [1112.5460]
and Chung, AL, Wang [1209.1819].

Thought experiment: heating a box of photons

Does the Higgs (condensate) melt? Or does it boil?

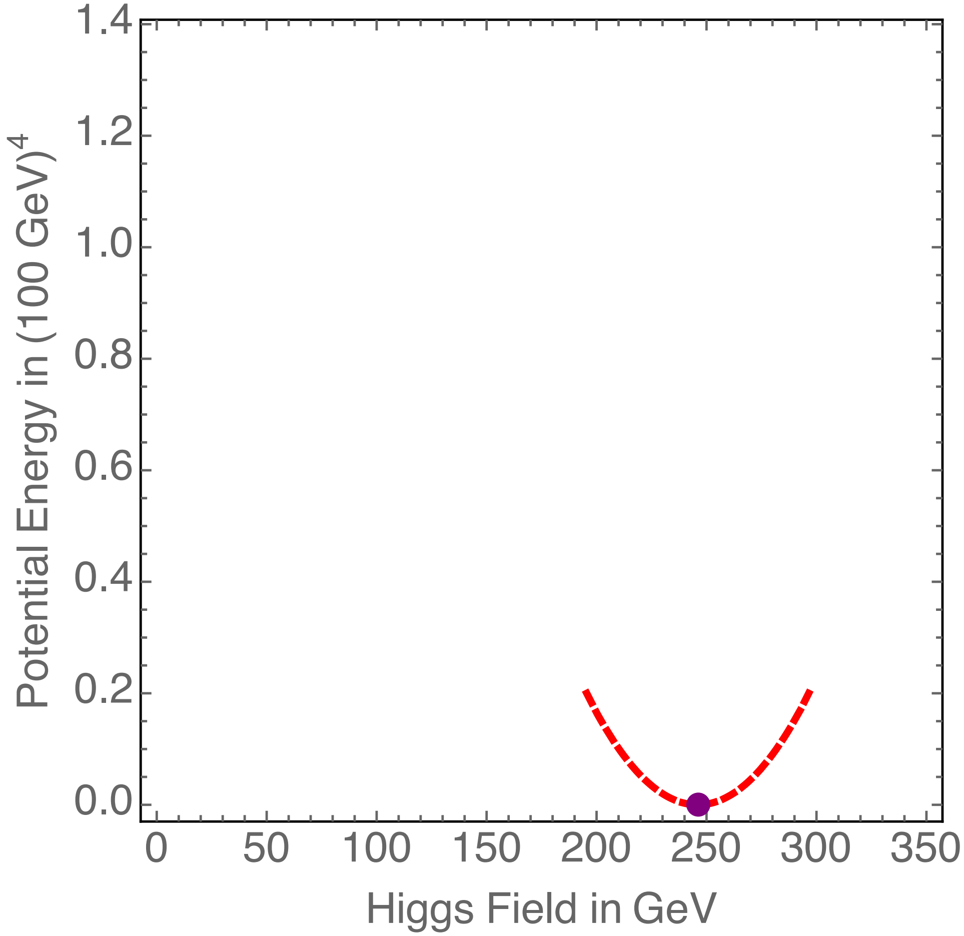
(Possible) Cosmological Relics of the EW Epoch



We discovered the Higgs!

We know that it's responsible for EW symmetry breaking!

Isn't that enough information to let us study the EW phase transition?

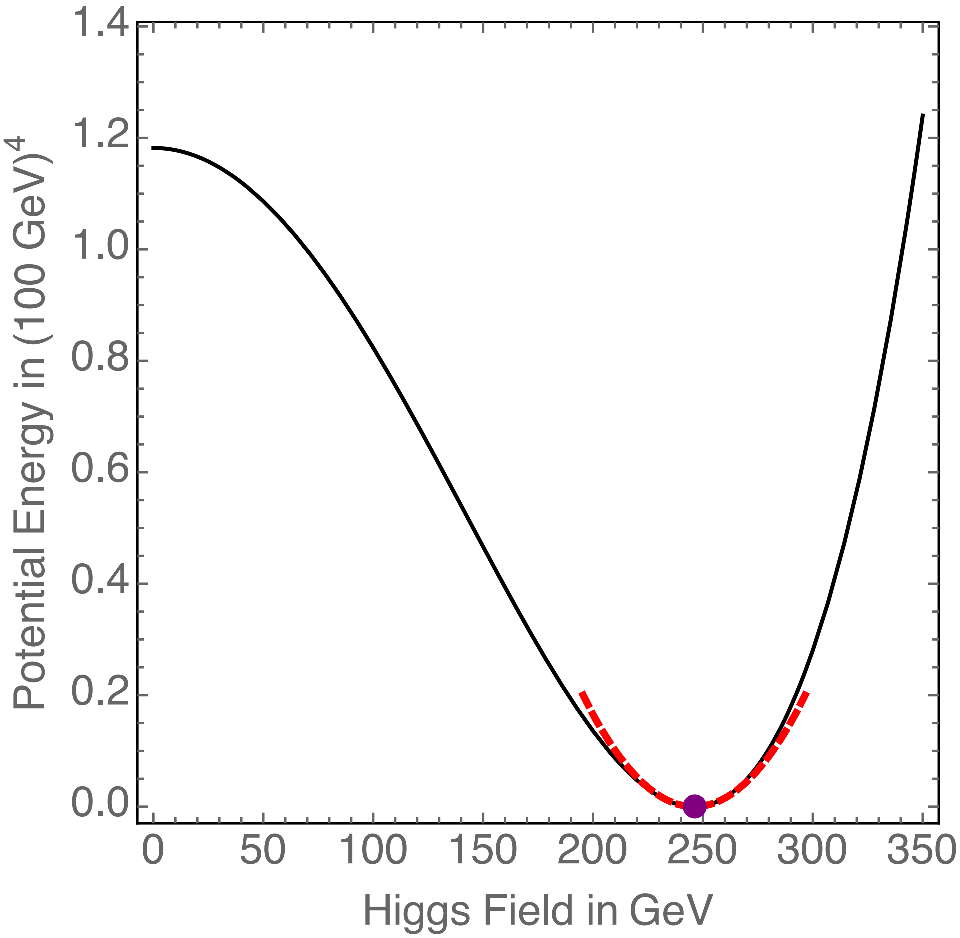


Measured Directly:

$$v \simeq 246 \text{ GeV}$$

$$M_h \simeq 125 \text{ GeV}$$

Assuming SM particle content & interactions



$$V = -\mu^2 H^\dagger H + \lambda_h (H^\dagger H)^2$$

$$\begin{cases} \mu^2 = M_h^2/2 \simeq (88\ \mathrm{GeV})^2 \\ \lambda_h = M_h^2/(2v^2) \simeq 0.13 \end{cases}$$

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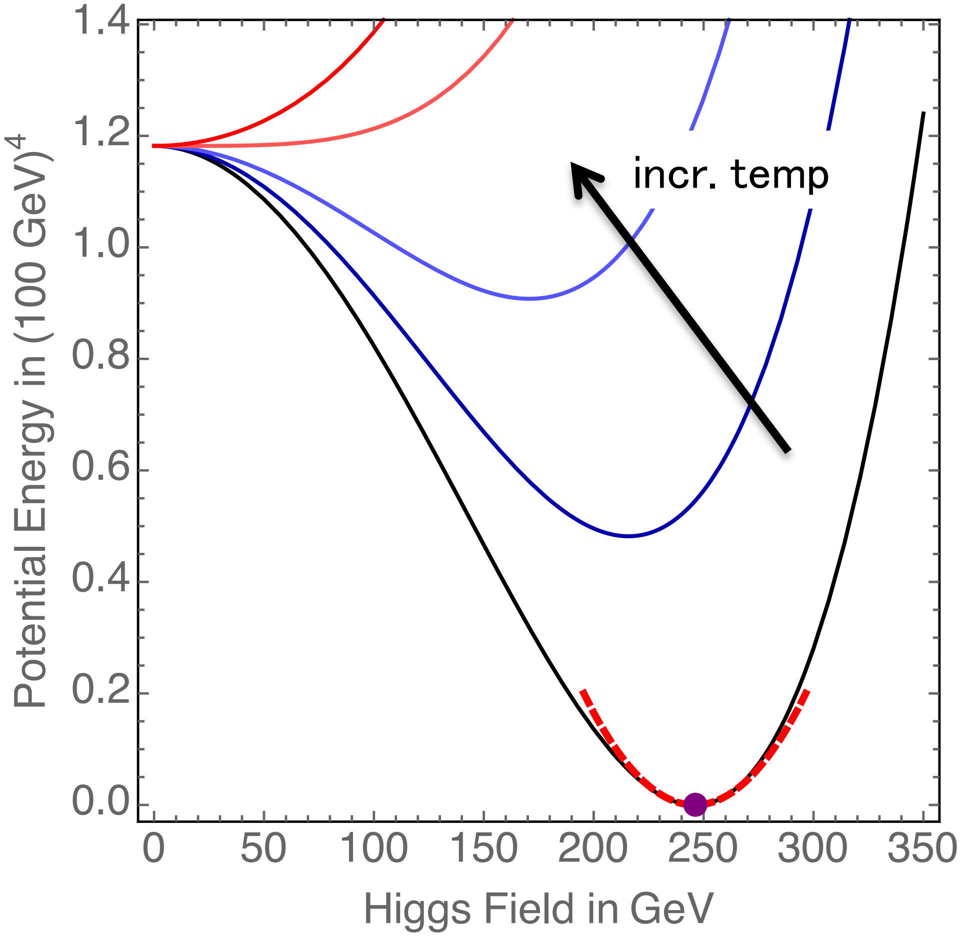

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$$\begin{cases} \mu^2 = M_h^2/2 \simeq (88\ \mathrm{GeV})^2 \\ \lambda_h = M_h^2/(2v^2) \simeq 0.13 \end{cases}$$

Thermal support from Higgs interactions with W, Z, t, …

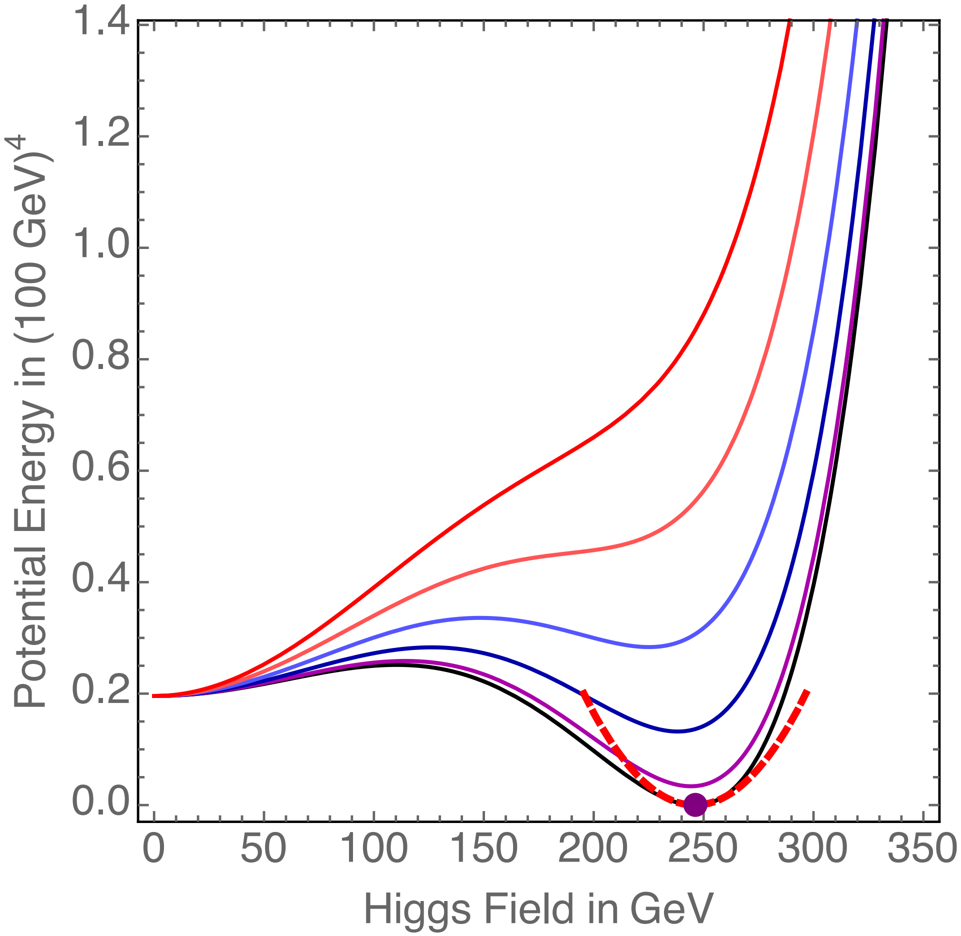
- EWPT is continuous crossover
- v(T) changes smoothly
- No energy barrier; no bubbles; no cosmological relics

Measured Directly: $v \simeq 246\ \mathrm{GeV}$

$M_h \simeq 125\ \mathrm{GeV}$

Variant –SM with low cutoff

Recently studied by
P. Huang, Jokelar, Li, Wagner (2015)
F.P. Huang, Gu, Yin, Yu, Zhang (2015)
F.P. Huang, Wan, Wang, Cai, Zhang (2016)
Cao, F.P. Huang, Xie, & Zhang (2017)



$$V = \mu^2 H^\dagger H - \lambda_h (H^\dagger H)^2 + \Lambda^{-2} (H^\dagger H)^3$$

$$\begin{cases} \mu^2 \simeq (44\ \mathrm{GeV})^2 \\ \lambda_h \simeq 0.19 \\ \Lambda \simeq 530\ \mathrm{GeV} \end{cases}$$

Energy barrier may be present already at T=0.

- EWPT is first order
- Possibly interesting cosmological relics!

Measured Directly:

$$v \simeq 246\ \mathrm{GeV}$$

$$M_h \simeq 125\ \mathrm{GeV}$$

A short aside on dim-6 ops & EWBG washout

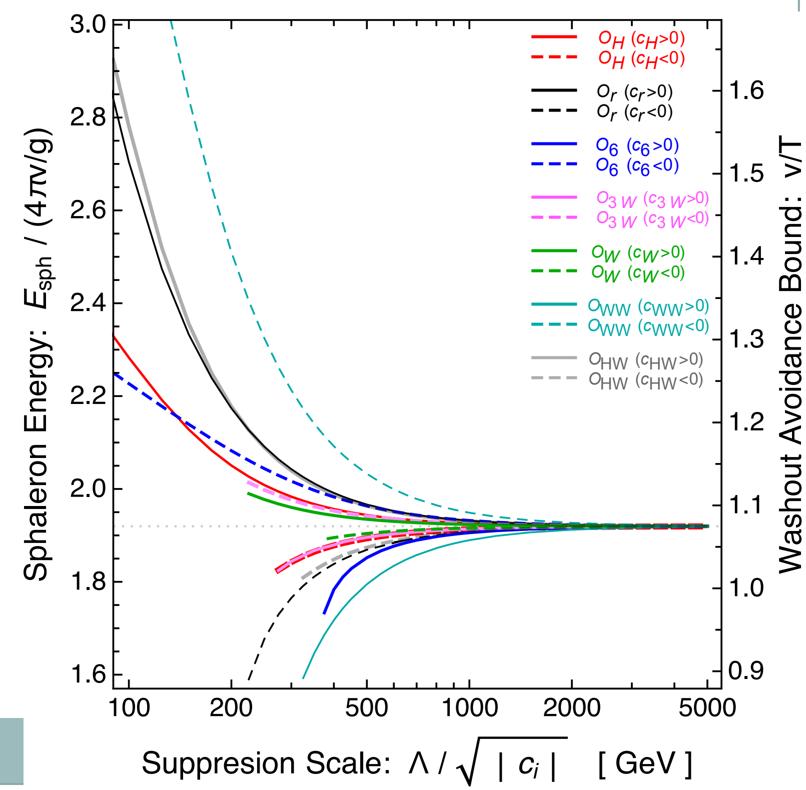
Successful EW baryogenesis requires the sphaleron to be out of equilibrium inside of Higgs-phase bubbles. This implies

$$\frac{v(T)}{T} \gtrsim 1.07$$

The “1” is weakly model-dependent.

In the Higgs-EFT framework, we calculate the new washout criterion for 7 different dimension-6 operators:

Gan, AL, Wang (1708.03061)
see also: Spannowsky & Tamarit (2016)



What can future colliders teach us about the electroweak phase transition?

In models with a first order EW phase transition, there must be new physics coupled to the Higgs.

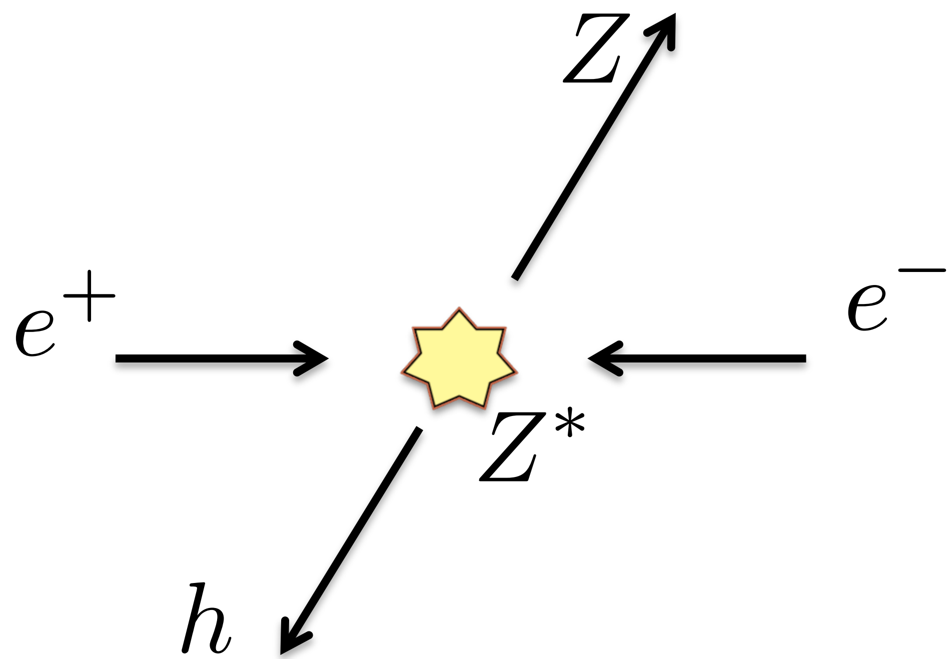
It is reasonable to expect that this NP may also induce deviations in the Higgs couplings with other SM fields.

Precision Measurements w/ Higgs Factories

Lepton colliders provide “clean” environment for studying Higgs physics.

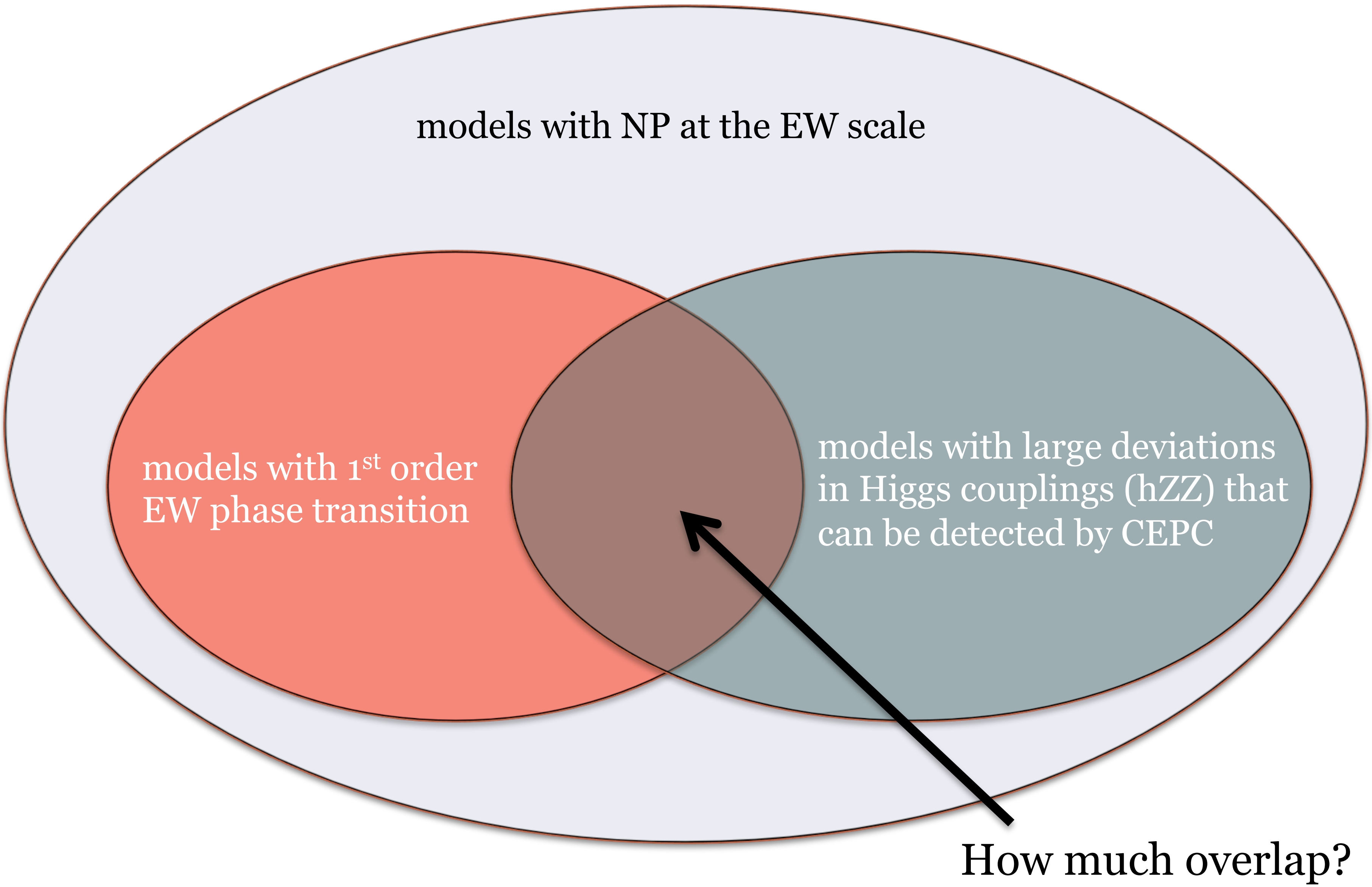
At E ~ 250 GeV, the production of Higgs + Z-boson is optimized.

Expect to achieve precision Higgs-Z-Z measurements at the sub-percent level!



Projected Sensitivities to various Higgs couplings at different future colliders:

	current	HL-LHC	CEPC-250	ILC-500	FCC-ee	FCC-hh
hZZ	27%	7%	0.25%	0.25%	0.15%	-
$\Gamma(h \to \gamma\gamma)$	20%	8%	4%	-	1.5%	-
hhh	N/A	-	-	27%	-	10%


models with NP at the EW scale
models with 1st order EW phase transition
models with large deviations in Higgs couplings (hZZ) that can be detected by CEPC
How much overlap?

What Kinds of Models?

Model	References
SM + Scalar Singlet	Espinosa & Quiros, 1993; Benson, 1993; Choi & Volkas, 1993; McDonald, 1994; Vergara, 1996; Branco, Delepine, Emmanuel-Costa, & Gonzalez, 1998; Ham, Jeong, & Oh, 2004; Ahriche, 2007; Espinosa & Quiros, 2007; Profumo, Ramsey-Musolf, & Shaughnessy, 2007; Noble & Perelstein, 2007; Espinosa, Konstandin, No, & Quiros, 2008; Ashoorioon & Konstandin, 2009; Das, Fox, Kumar, & Weiner, 2009; Espinosa, Konstandin, & Riva, 2011; Chung & AL, 2011; Wainwright, Profumo, & Ramsey-Musolf, 2012; Barger, Chung, AL, & Wang, 2012; Huang, Shu, Zhang, 2012; Katz & Perelstein, 2014; Jiang, Bian, Huang, Shu, 2015; Huang & Li 2015; Cline, Kainulainen, Tucker-Smith, 2017; Kurup & Perelstein, 2017; Chen, Kozaczuk, & Lewsis, 2017
SM + Scalar Doublet	Davies, Froggatt, Jenkins, & Moorhouse, 1994; Huber, 2006; Fromme, Huber, & Seniuch, 2006; Cline, Kainulainen, & Trott, 2011; Kozhushko & Skalozub, 2011;
SM + Scalar Triplet	Patel, Ramsey-Musolf, 2012; Patel, Ramsey-Musolf, Wise, 2013; Huang, Gu, Yin, Yu, Zhang 2016
SM + Chiral Fermions	Carena, Megevand, Quiros, Wagner, 2005
MSSM	Carena, Quiros, & Wagner, 1996; Delepine, Gerard, Gonzales Felipe, & Weyers, 1996; Cline & Kainulainen, 1996; Laine & Rummukainen, 1998; Cohen, Morrissey, & Pierce,; Carena, Nardini, Quiros, & Wagner, 2012;
NMSSM / nMSSM / μνSSM	Pietroni, 1993; Davies, Froggatt, & Moorhouse, 1995; Huber & Schmidt, 2001; Ham, Oh, Kim, Yoo, & Son, 2004; Menon, Morrissey, & Wagner, 2004; Funakubo, Tao, & Toyoda, 2005; Huber, Kontandin, Prokopec, & Schmidt, 2006; Chung, AL, 2010, Huang, Kang, Shu, Wu, Yang, 2014; Bian, Guo, Shu (2017)
EFT-like Approach (H^6 operator)	Grojean, Servant, Wells, 2005; Huang, Gu, Yin, Yu, Zhang 2015; Huang, Joglekar, Li, Wagner, 2015; Huang, Wan, Wang, Cai, Zhang 2016; Huang, Gu, Yin, Yu, Zhang 2016; Cao, F.P. Huang, Xie, Zhang (2017)

Can we systematize the calculation?

Chung, AL, Wang [1209.1819].
(similar concerns raised in:
Damgaard, Haarr, O'Connell, Tranberg 2015)

There is **no systematic formalism** for studying BSM models that give rise to a first order electroweak phase transition *and* associated collider phenomenology.

Can we use *effective field theory*?
➔ Not if there are EW-scale particles present in the plasma.
➔ Not if the particles get their mass from the Higgs (light in symmetric phase).

Can we use *phase transition model classes*? Chung, AL, Wang (2012)
➔ This framework organizes the PT-side of the calculation, but it is ignorant of the particle physics (phenomenology). E.g., from the PT perspective

SM + 1 colored scalar = SM + 3 singlet scalars with SO(3)

Models with very different collider phenomenology can have similar phase transition dynamics.

Models are typically studied on a case-by-case basis.

A Survey of Simplified Models

Model #1 – SM + chiral fermions (like MSSM gauginos)

Model #2 – SM + scalar doublet (like MSSM stops)

Model #3 – SM + real scalar singlet (like NMSSM singlet)

In the simplified / minimal models, the new degrees of freedom are responsible for *both* the 1PT and hZZ

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SM + Scalar Doublet ("stops")

In the MSSM, the stops play a critical role in making the EWPT first order. Here we considered a simplified version of the SUSY stop sector.

$$\tilde{Q} \sim (\mathbf{1}, \mathbf{2}, 1/3) \times 3 \text{ flavor}$$

$$\tilde{U} \sim (\mathbf{1}, \mathbf{1}, 4/3) \times 3 \text{ flavor}$$

four model parameters

The full Lagrangian is

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} &+ \big(D_\mu \tilde{Q}\big)^\dagger \big(D^\mu \tilde{Q}\big) + \big(D_\mu \tilde{U}\big)^* \big(D^\mu \tilde{U}\big) - \big[a_{hQU} \tilde{Q} \cdot H \tilde{U}^* + \text{h.c.}\big] \\ &- m_Q^2 \tilde{Q}^\dagger \tilde{Q} - m_U^2 \tilde{U}^* \tilde{U} - \lambda_Q \big(\tilde{Q}^\dagger \tilde{Q}\big)^2 - \lambda_U \big(\tilde{U}^* \tilde{U}\big)^2 \\ &- \lambda_{QU} \big(\tilde{Q}^\dagger \tilde{Q}\big)\big(\tilde{U}^* \tilde{U}\big) - \lambda_{hU} \big(H^\dagger H\big)\big(\tilde{U}^* \tilde{U}\big) \\ &- \lambda_{hQ} \big(H^\dagger H\big)\big(\tilde{Q}^\dagger \tilde{Q}\big) - \lambda'_{hQ} \big(\tilde{Q} \cdot H\big)^* \big(\tilde{Q} \cdot H\big) - \lambda''_{hQ} \big(\tilde{Q}^\dagger H\big)^* \big(\tilde{Q}^\dagger H\big)\end{aligned}$$

and for simplicity we focus on

$$\langle \tilde{Q} \rangle = (0\,,\,0) \qquad \text{and} \qquad \langle \tilde{U} \rangle = 0$$

$$\lambda_Q = \lambda_U = \lambda_{QU} = \lambda_{hU} = \lambda_{hQ} = \lambda'_{hQ} = \lambda''_{hQ} \equiv \lambda$$

Spectrum

$$M_{\tilde{t}}^2 = \begin{pmatrix} m_Q^2 + \frac{1}{2}(\lambda_{hQ} + \lambda'_{hQ})v^2 & \frac{a_{hQU}v}{\sqrt{2}} \\ \frac{a_{hQU}v}{\sqrt{2}} & m_U^2 + \frac{1}{2}\lambda_{hU}v^2 \end{pmatrix}$$

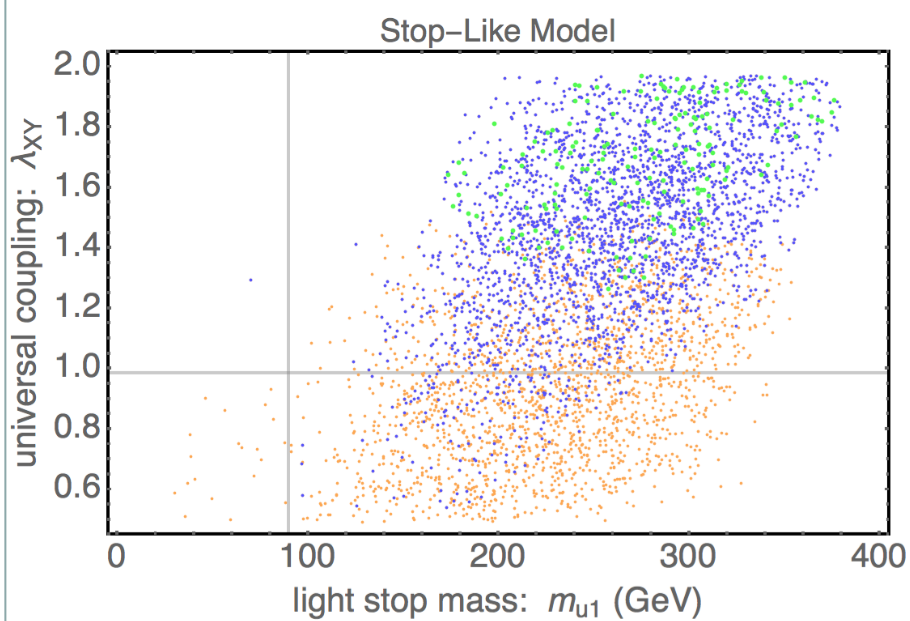
2 "stops"

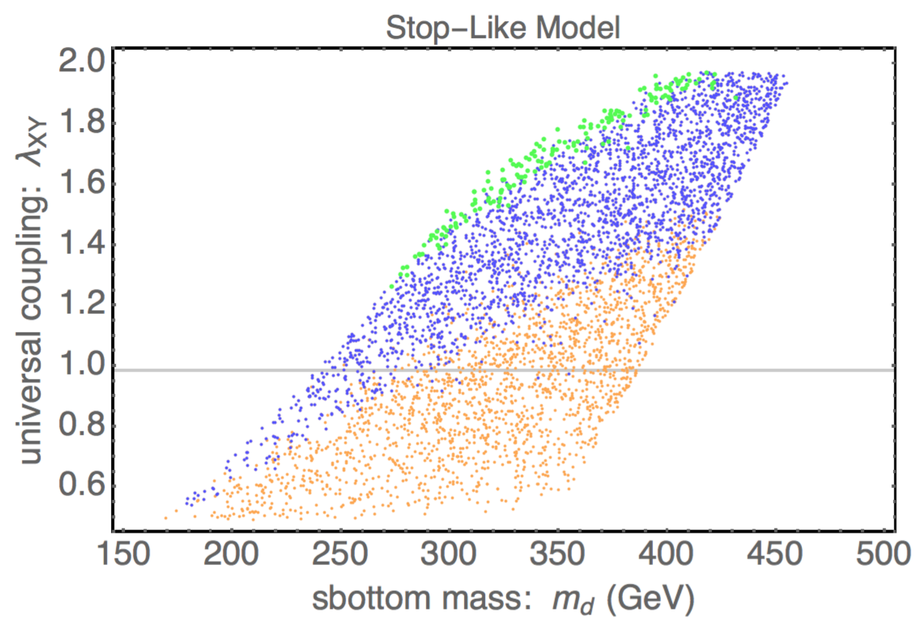
$$\tan 2\theta = \frac{\sqrt{2}a_{hQU}v}{m_Q^2 - m_U^2 + \frac{1}{2}(\lambda_{hQ} + \lambda'_{hQ} - \lambda_{hU})v^2}$$

(mixing)

$$M_{\tilde{b}}^2 = m_Q^2 + \frac{1}{2}(\lambda_{hQ} + \lambda''_{hQ})v^2$$

1 "sbottom"



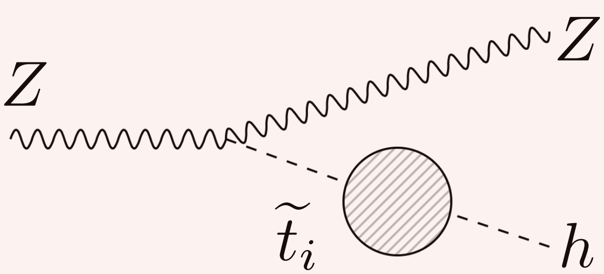


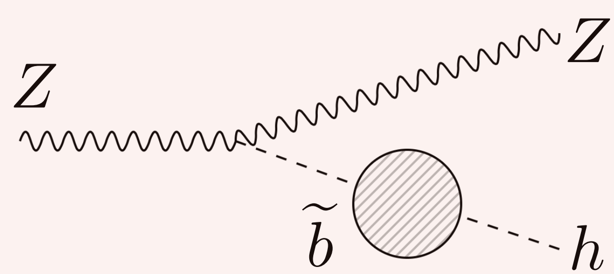
Effective hZZ coupling

(adapted from: Fan, Reece, Wang, 2014)

+vertex correction (suppressed by g/λ)

$$\delta Z_h = -n_f \sum_{i,j=1}^{2} \frac{|g_{h\tilde{t}_i\tilde{t}_j}|^2}{32\pi^2} I_B(M_h^2; M_{\tilde{t}_i}^2, M_{\tilde{t}_j}^2) - n_f \frac{|g_{h\tilde{b}\tilde{b}}|^2}{32\pi^2} I_B(M_h^2; M_{\tilde{b}}^2, M_{\tilde{b}}^2)$$





$$g_{h\tilde{t}_1\tilde{t}_1} = -\cos^2\theta\,(\lambda_{hQ} + \lambda'_{hQ})v - \sin^2\theta\,\lambda_{hU}v + \frac{a_{hQU}\sin 2\theta}{\sqrt{2}}$$

$$g_{h\tilde{t}_2\tilde{t}_2} = -\sin^2\theta\,(\lambda_{hQ} + \lambda'_{hQ})v - \cos^2\theta\,\lambda_{hU}v - \frac{a_{hQU}\sin 2\theta}{\sqrt{2}}$$

$$g_{h\tilde{t}_1\tilde{t}_2} = -\frac{\sin 2\theta}{2}(\lambda_{hQ} + \lambda'_{hQ})v + \frac{\sin 2\theta}{2}\lambda_{hU}v - \frac{a_{hQU}\cos 2\theta}{\sqrt{2}}$$

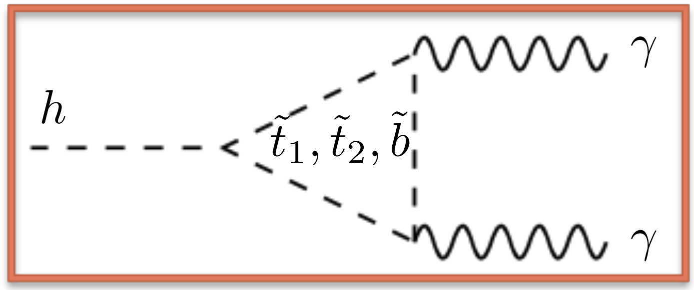
$$g_{h\tilde{b}\tilde{b}} = -(\lambda_{hQ} + \lambda''_{hQ})v$$

Higgs di-photon decay width (adapted from: Djouadi, Driesen, Hollik, Illana, 2005)

$$\Gamma_{h\to\gamma\gamma} = \frac{1}{64\pi}\frac{\alpha^2 M_h^3}{16\pi^2}\left|\bar{A}_W + \bar{A}_t + \bar{A}_{\tilde{t}} + \bar{A}_{\tilde{b}}\right|^2$$

$$\bar{A}_W = \frac{g_{hWW}}{M_W^2} F_1\left(M_h^2/4M_W^2\right)$$

$$\bar{A}_t = 2N_c Q_t^2 \frac{g_{htt}}{M_t} F_{1/2}\left(M_h^2/4M_t^2\right)$$



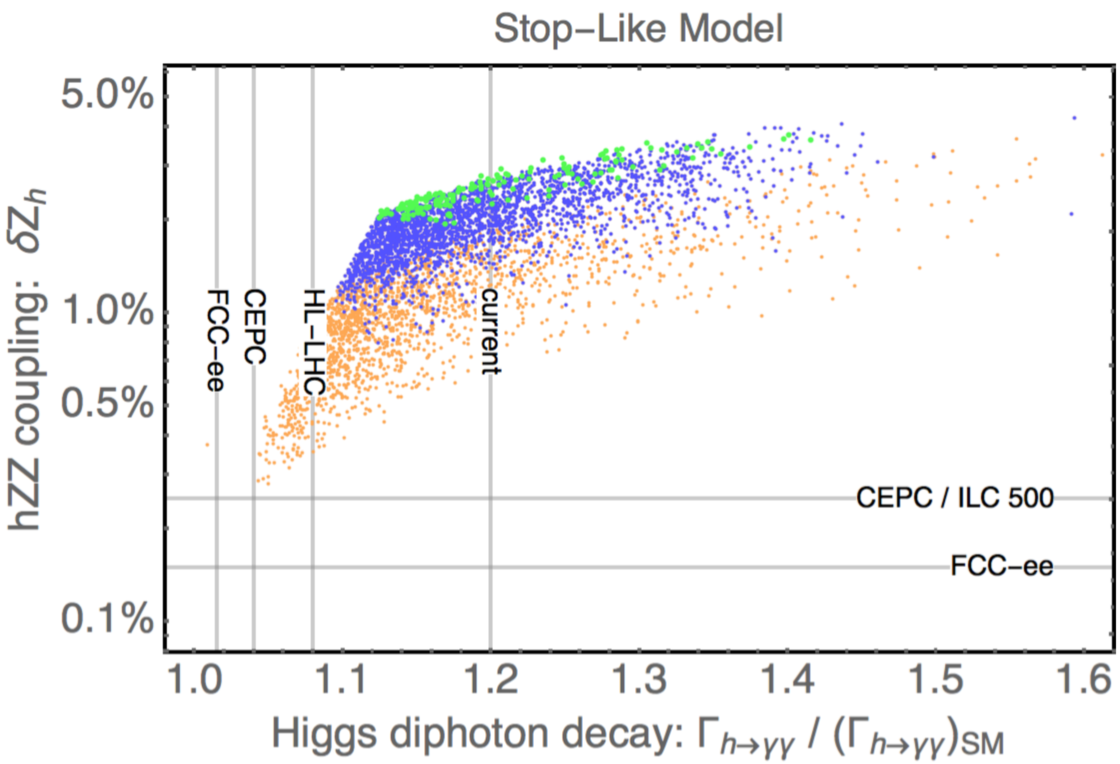
$$\bar{A}_{\tilde{t}} = \sum_{i=1}^{2} N_c Q_t^2 \frac{g_{h\tilde{t}_i\tilde{t}_i}}{M_{\tilde{t}_i}^2} F_0\left(M_h^2/4M_{\tilde{t}_i}^2\right)$$

$$\bar{A}_{\tilde{b}} = N_c Q_b^2 \frac{g_{h\tilde{b}\tilde{b}}}{M_{\tilde{b}}^2} F_0\left(M_h^2/4M_{\tilde{b}}^2\right)$$

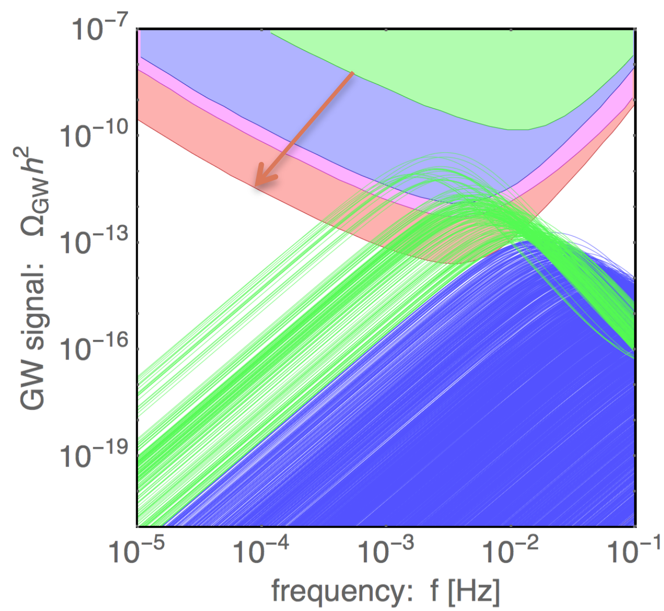
$$F_1(\tau) = \frac{2\tau^2 + 3\tau + 3(2\tau - 1)\arcsin(\tau^{1/2})^2}{\tau^2}$$

$$F_{1/2}(\tau) = -2\frac{\tau + (\tau - 1)\arcsin(\tau^{1/2})^2}{\tau^2}$$

$$F_0(\tau) = \frac{\tau - \arcsin(\tau^{1/2})^2}{\tau^2}$$



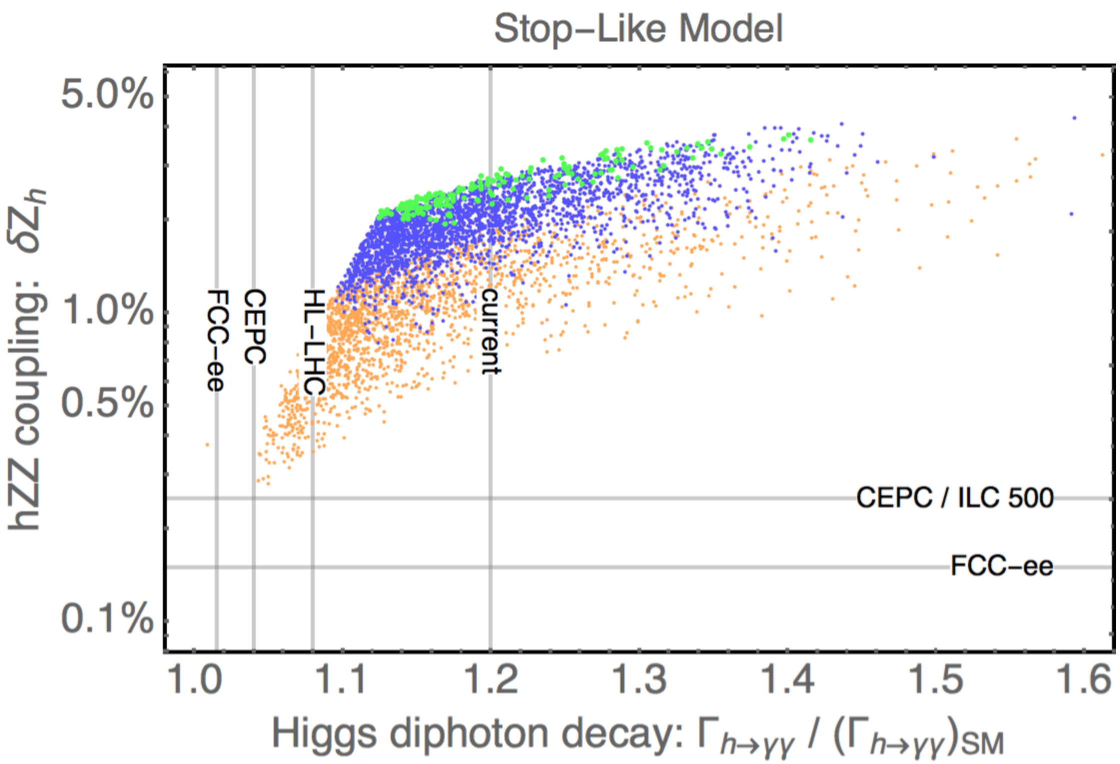
(sensitivities of four different proposed eLISA configurations)

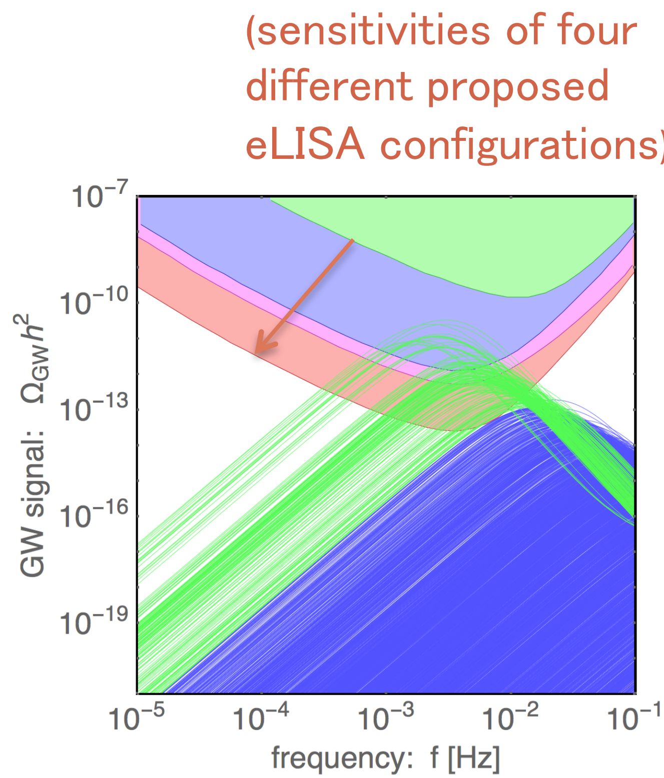


Orange = first order phase transition, $v(T_c)/T_c > 0$

Blue = “strongly” first order phase transition, $v(T_c)/T_c > 1.3$

Green = very strongly 1PT, could detect GWs at LISA





Models with a first order electroweak phase transition (orange, blue, or green) have large **deviation in hZZ** that can be probed by CEPC.

These models also have large enhancement to **Higgs diphoton decay** rate (b/c of charged particles) that can be probed by HL-LHC & CEPC.

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In the simplified / minimal models, the new degrees of freedom are responsible for *both* the 1PT and hZZ

SM + Real Scalar Singlet

five model parameters

Consider

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}(\partial\phi_s)^2 - \frac{m_s^2}{2}\phi_s^2 - \frac{a_s}{3}\phi_s^3 - \frac{\lambda_s}{4}\phi_s^4 - \underbrace{\lambda_{hs}H^\dagger H\phi_s^2 - 2a_{hs}H^\dagger H\phi_s}_{\text{Higgs portal}}$$

real scalar singlet

In the vacuum

$$\langle H \rangle = (0\,,\ v/\sqrt{2}) \qquad \text{and} \qquad \langle \phi_s \rangle = v_s$$

$$\sin 2\theta = \frac{4v(a_{hs} + \lambda_{hs}v_s)}{M_h^2 - M_s^2}$$ (mixing)

Effective hhh coupling

(adapted from: McCullough, 2014; Curtin, Meade, Yu, 2014)

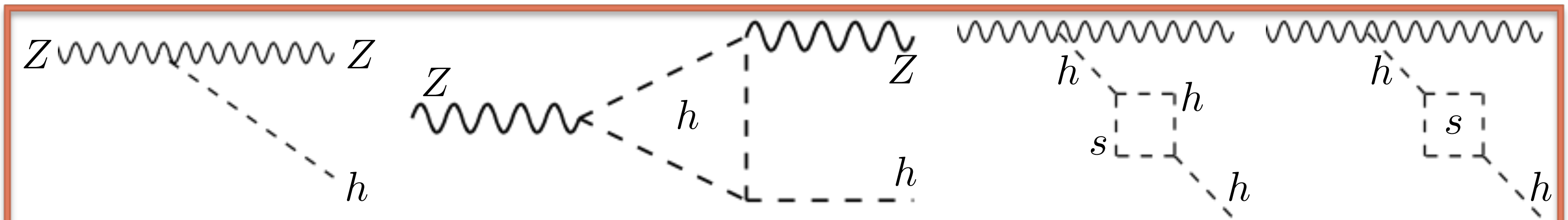
$$\lambda_3 = \left(6\lambda_h v\right)\cos^3\theta + \left(6a_{hs} + 6\lambda_{hs}v_s\right)\sin\theta\cos^2\theta + \left(6\lambda_{hs}v\right)\sin^2\theta\cos\theta$$
$$+ \left(2a_s + 6\lambda_s v_s\right)\sin^3\theta + 4\frac{|\lambda_{hs}|^3 v^3}{16\pi^2 M_s^2}$$

(one-loop)

Effective hZZ coupling

$$\delta Z_h \approx (1-\cos\theta) - 0.006\left(\frac{\lambda_3}{\lambda_{3,\mathrm{SM}}} - 1\right)$$
$$- \frac{1}{2}\frac{|\lambda_{hs}v_s + a_{hs}|^2}{16\pi^2} I(M_h^2; M_h^2, M_s^2) - \frac{1}{2}\frac{|\lambda_{hs}|^2 v^2}{16\pi^2} I(M_h^2; M_s^2, M_s^2)$$

(leading effect is from mixing)



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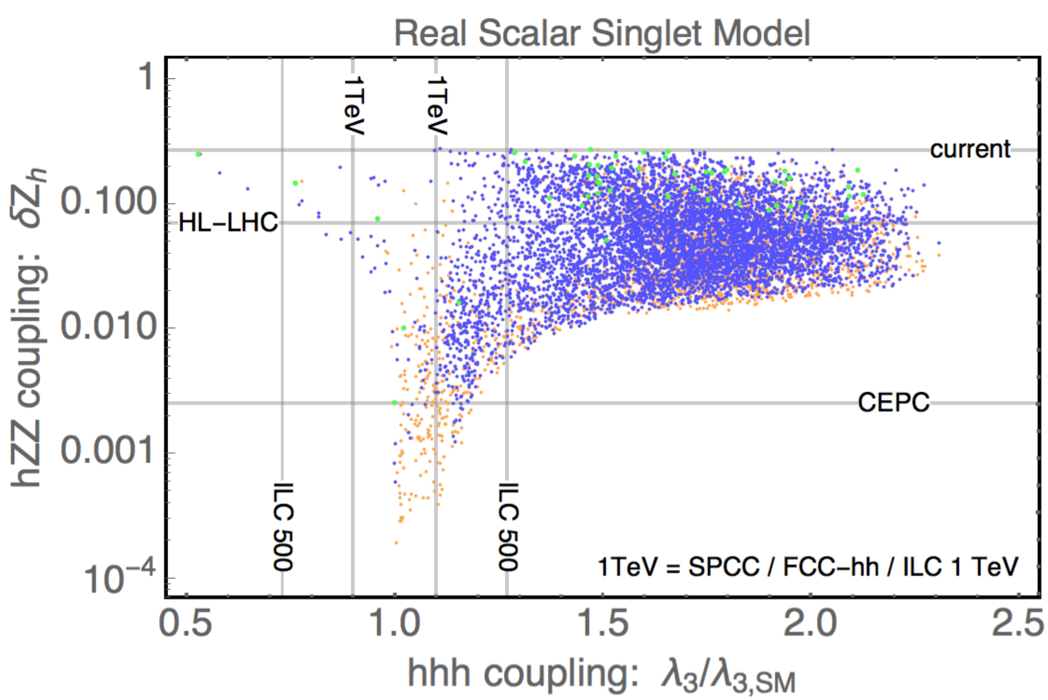
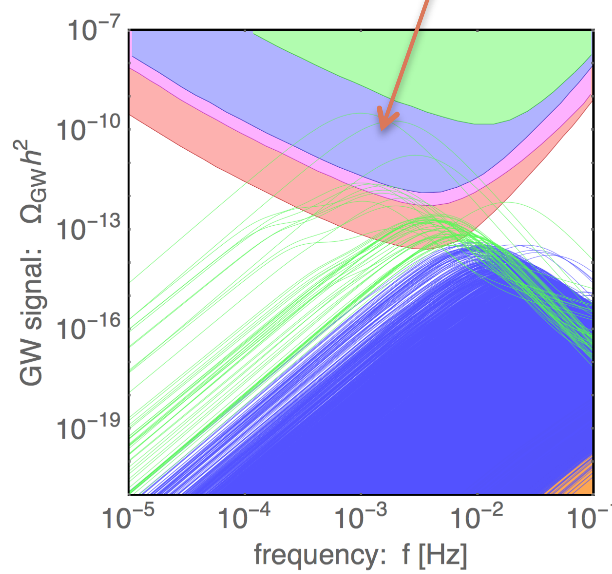
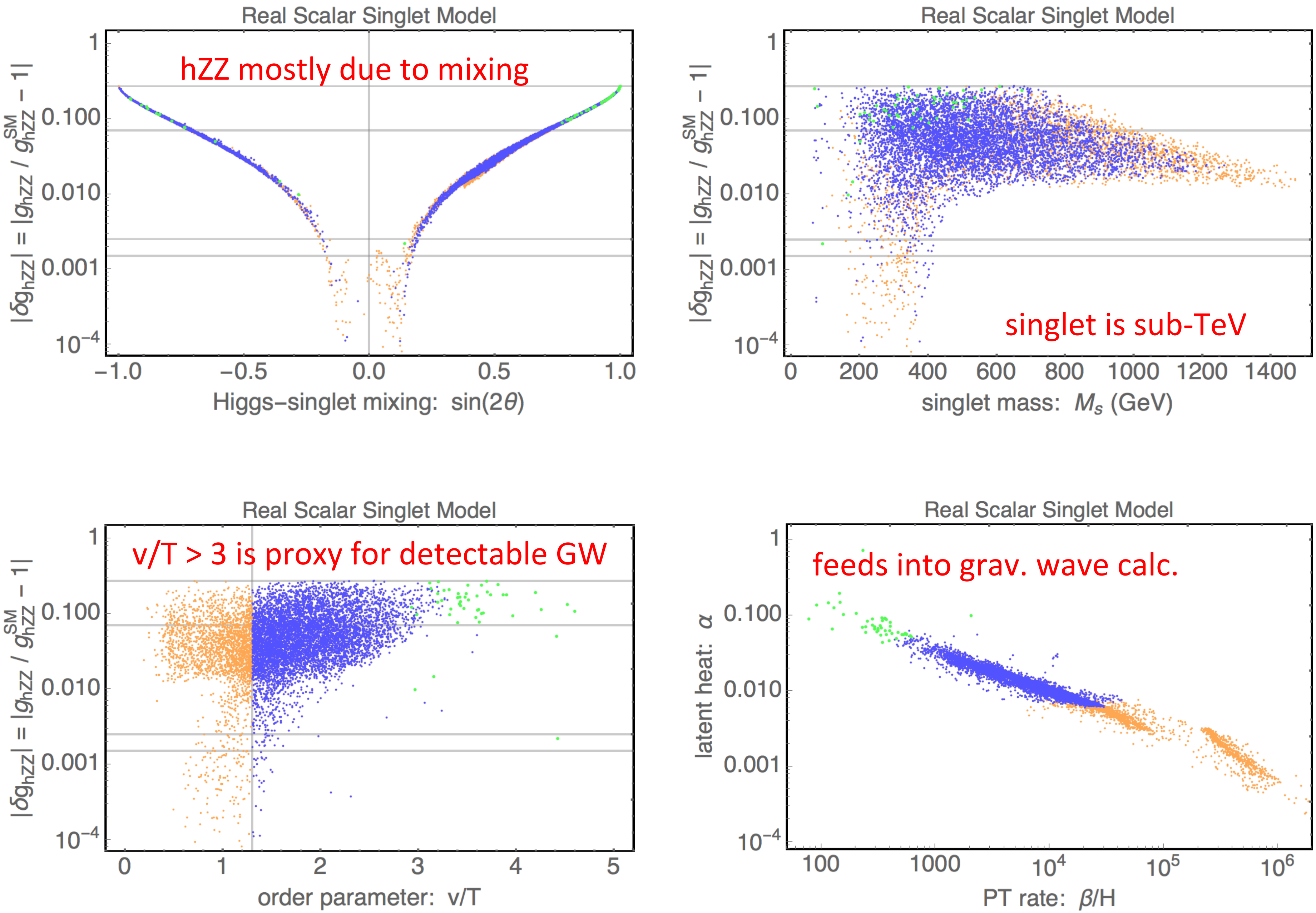


(sensitivities of four different proposed eLISA configurations)



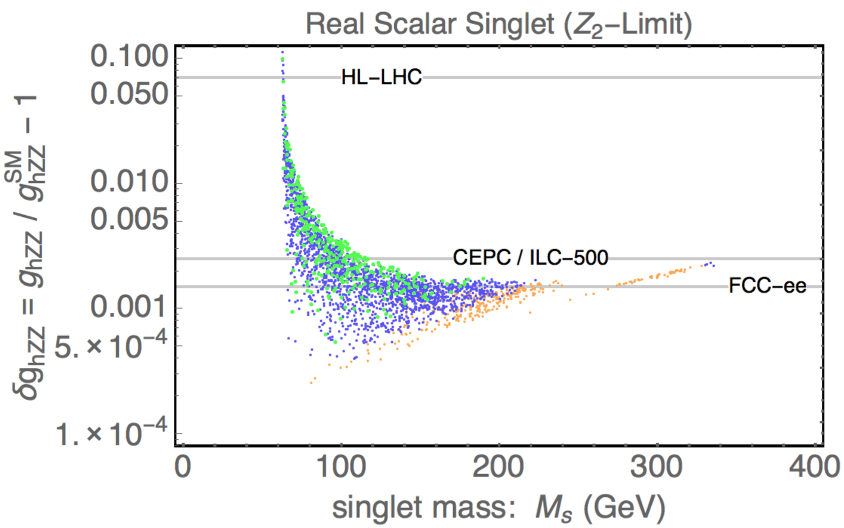
Parameter space with first order electroweak phase transition has large deviation in hZZ, which can be probed by CEPC


Real Scalar Singlet Model
hZZ mostly due to mixing
$|\delta g_{hZZ}| = |g_{hZZ} / g_{hZZ}^{SM} - 1|$
Higgs–singlet mixing: sin(2θ)
Real Scalar Singlet Model
singlet is sub-TeV
singlet mass: M_s (GeV)
Real Scalar Singlet Model
v/T > 3 is proxy for detectable GW
order parameter: v/T
Real Scalar Singlet Model
feeds into grav. wave calc.
latent heat: α
PT rate: β/H

Challenging Limits

Z2-Symmetric

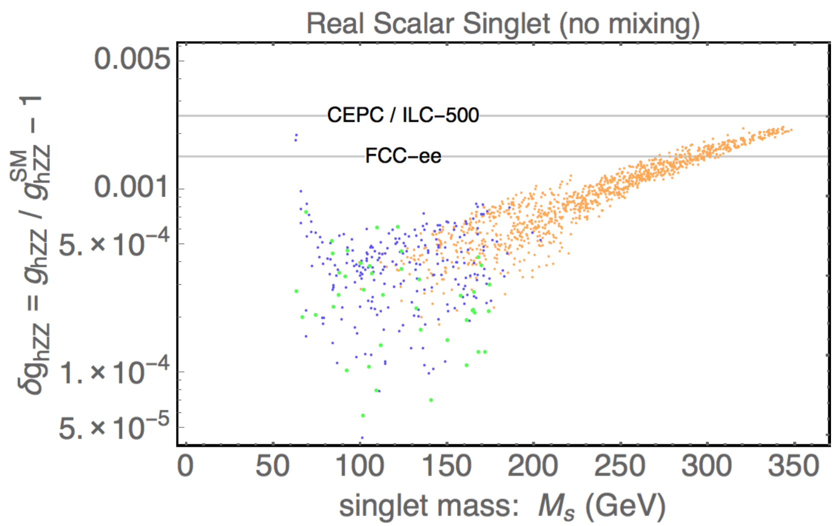
$$a_s = a_{hs} = v_s = 0$$



- Dubbed "nightmare scenario" by Curtin, Meade, & Yu (2014).
- No mixing & singlet is stable.

Tuned Zero Mixing

$$a_{hs} + \lambda_{hs} v_s = 0$$



- A new "nightmare scenario" / "blind spot"
- Can be probed by non-resonant pair production pp → ss and s→ visible.

see also : Chen, Kozaczuk, & Lewis (2017)

Summary

The Standard Model predicts a continuous electroweak crossover (no bubbles).

It is easy to extend the SM and find a first order phase transition (bubbles!).

Precision measurements of Higgs couplings may uncover new physics at the EW scale, and thereby indirectly probe the electroweak phase transition.

A large deviation in the hZZ coupling seems to be generic in models with first order EWPT, allowing these models to be tested by Higgs factories.

scalar singlet w/ Z2 (nightmare scenario)