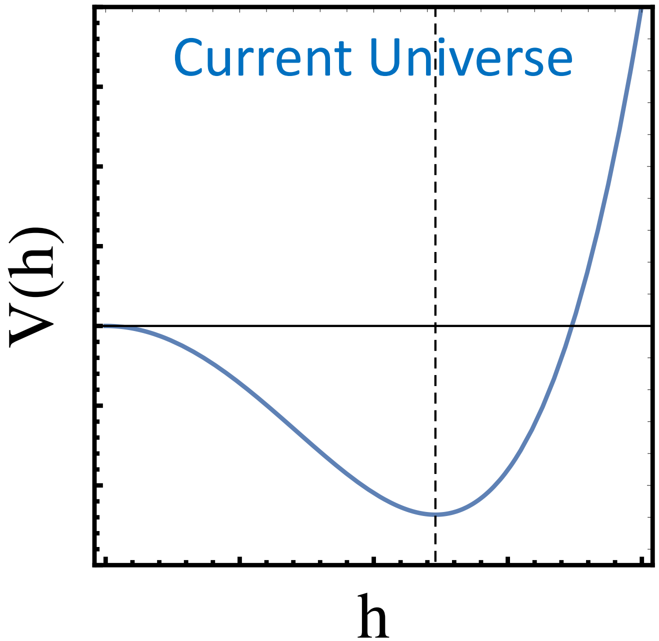
Probing first-order electroweak phase transitions at the LHC and future colliders

Ke-Pan Xie (谢柯盼)
Beihang University

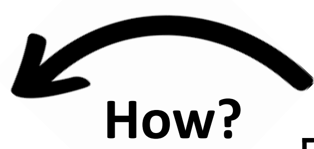
2024.11.14 @ Qingdao CLHCP2024

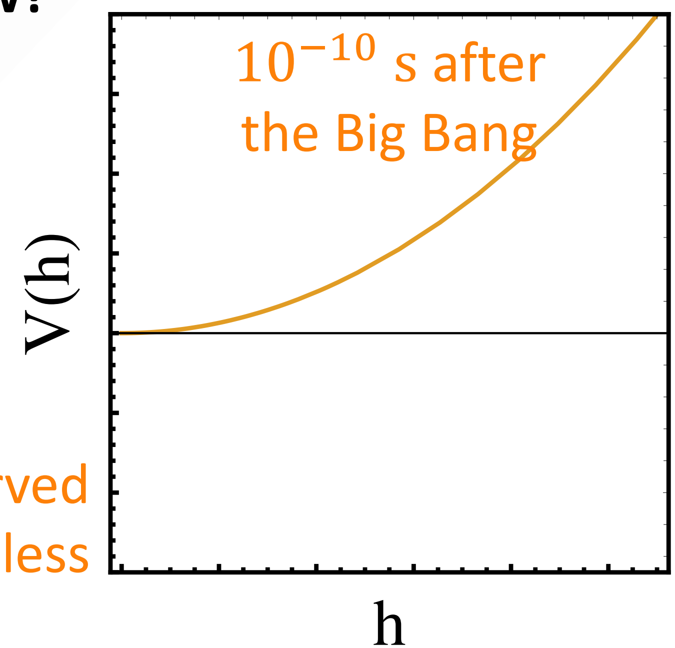
The electroweak phase transition

The evolution of Higgs potential & vacuum expectation value



EW gauge bosons & fermions are massive

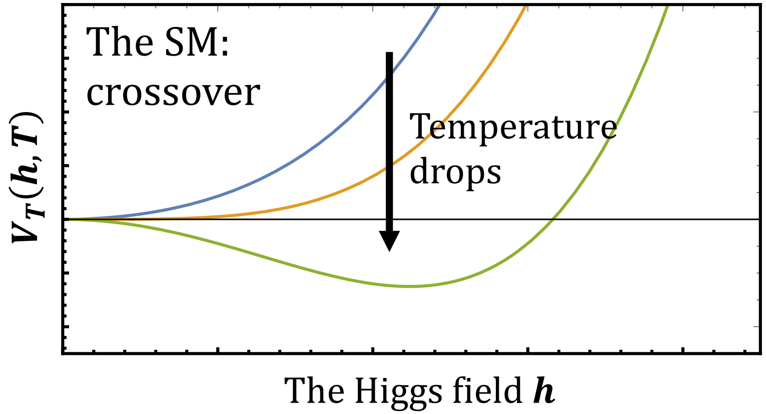


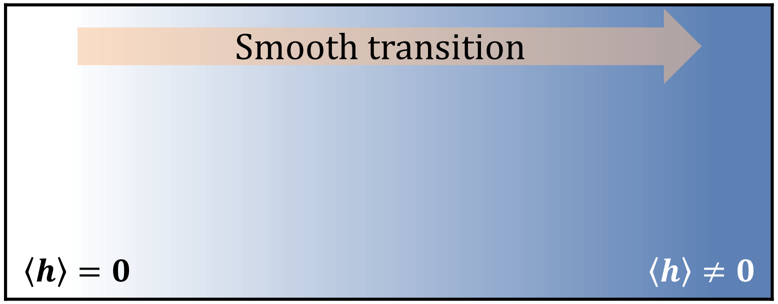


$SU(2)_L \times U(1)_Y$ preserved
Particles are massless

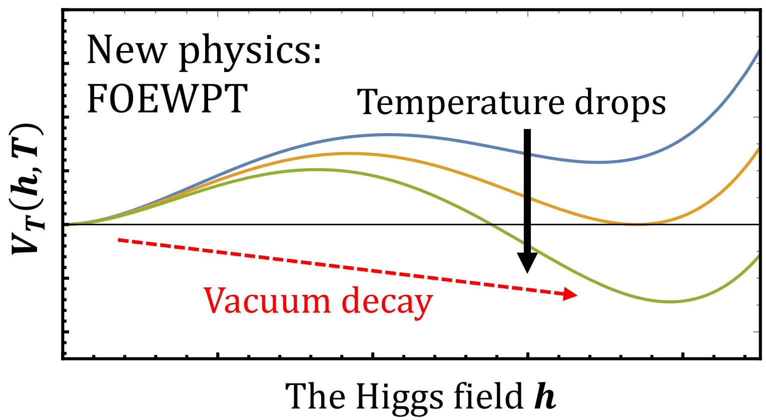
The feature of electroweak phase transition

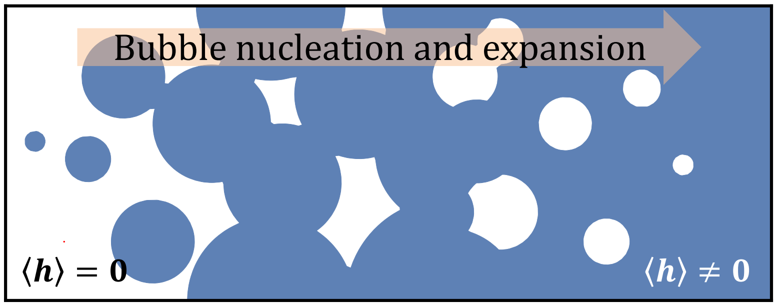
Which pattern?





First-order EWPT

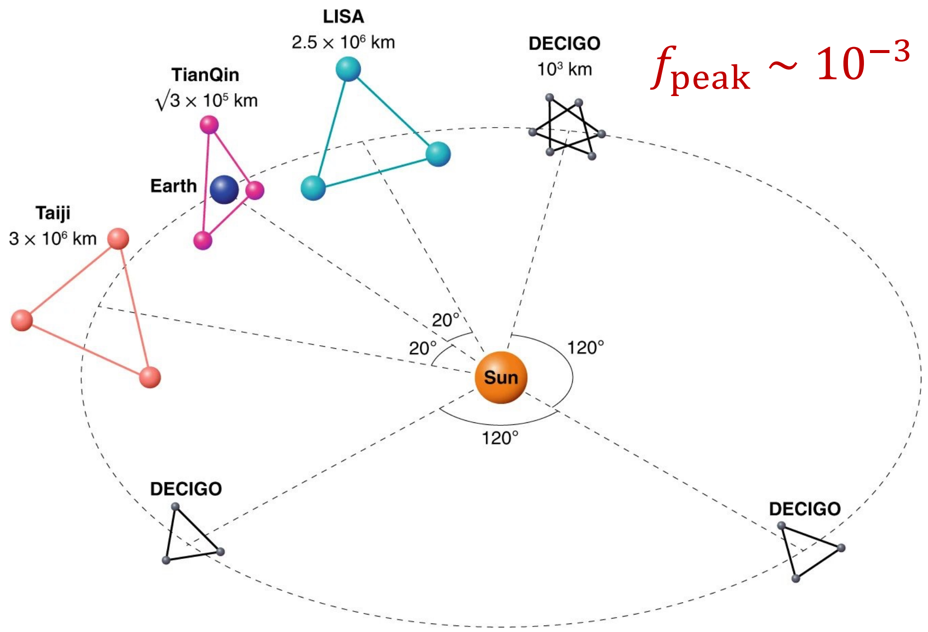




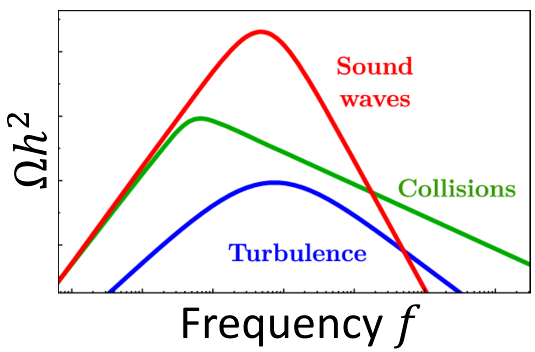
New physics is needed for FOEWPT

3 main reasons for studying FOEWPT

- ***If*** it has occurred, we may detect its stochastic *gravitational waves* in the next decade Caprini *et al*, JCAP 04 (2016) 001; JCAP 03 (2020) 024; Athron, Wu *et al*, Prog.Part.Nucl.Phys. 135 (2024) 104094



$$f_{\rm peak} \sim 10^{-3}\ {\rm Hz} \times \left(\frac{1}{v_w}\right)\left(\frac{\beta/H_*}{100}\right)\left(\frac{T_*}{100\ {\rm GeV}}\right)$$



- It is the *consequence* of many BSM models
- It is the *essential* condition of many BSM mechanisms solving the puzzles in the SM

Why we like FOEWPTs

Very **classic** motivation: explaining the matter-antimatter asymmetry via EW baryogenesis: since 1980s, still active

Joyce *et al*, PRL 75 (1995) 1695-1698; PRD 53 (1996) 2958-2980;
Ramsey-Musolf *et al*, New J.Phys. 14 (2012) 125003 [review]
Cline *et al*, PRD 101 (2020) 6, 063525; **KPX**, JHEP 02 (2021) 090;
KPX, Bian, Wu, JHEP 12 (2020) 047; …

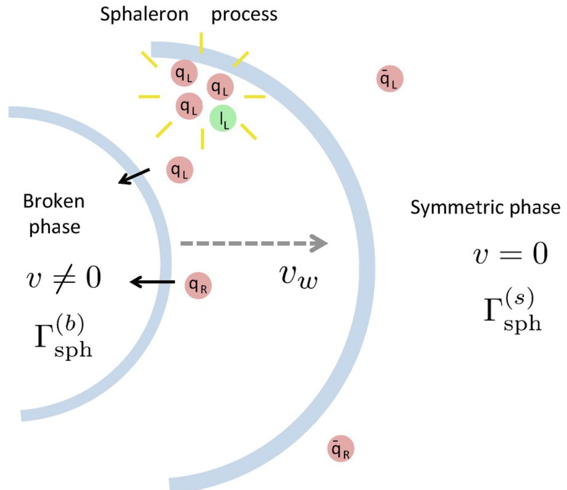
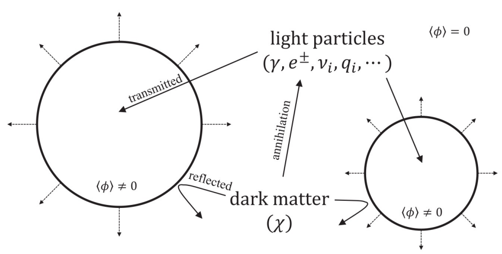


Figure from Fuyuto, PhD thesis (2016)

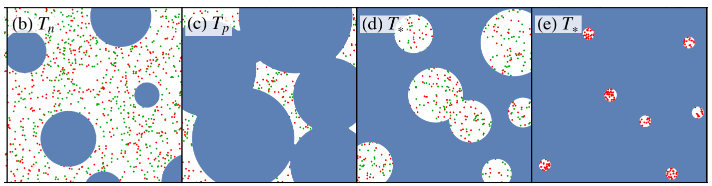
Recent progress

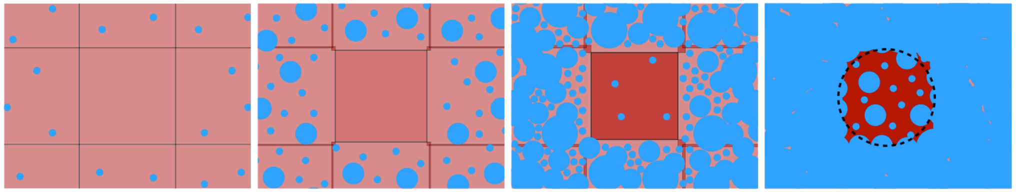
Novel dark matter and/or baryogenesis scenarios based on FOPTs

Filtered dark matter
Baker *et al*, PRL 125 (2020) 15, 151102
Chway *et al*, PRD 101 (2020) 9, 095019



Solitons Hong, Jung, **KPX**, PRD 102 (2020) 7, 075028





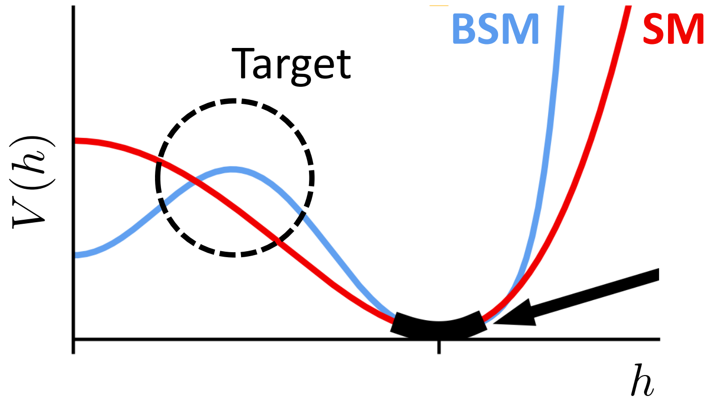
Primordial black holes
Liu *et al*, PRD 105 (2022) 2, L021303; Kanemura, Tanaka, **KPX**, JHEP 06 (2024) 036;
Cai *et al*, SCPMA 67 (2024) 9, 290411

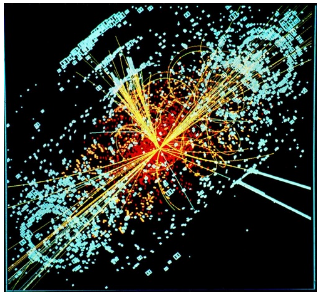
Probing FOEWPT at colliders

Searching for the underlying physics of the **potential barrier**

In general, this is

- *Challenging*, attempting to probe the global feature of the potential via phenomenology around vacuum
- *Model-dependent*, various signal channels



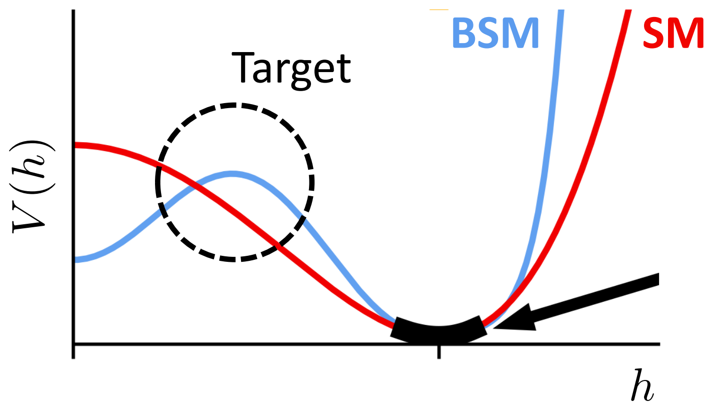


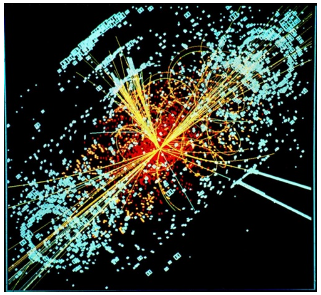
LHC → HL-LHC
HE-LHC? LHeC?
CEPC? ILC? FCC?
Muon collider?

Probing FOEWPT at colliders

Searching for the underlying physics of the **potential barrier**
In general, this is

- *Challenging*, attempting to probe the global feature of the potential via phenomenology around vacuum
- *Model-dependent*, various signal channels



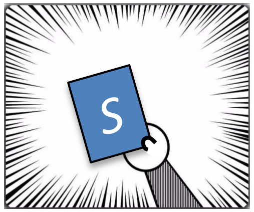


LHC → HL-LHC
HE-LHC? LHeC?
CEPC? ILC? FCC?
Muon collider?

However, it also has

- General and representative features, can be systematically summarized and classified
- Complementarity and crosscheck with the GW astronomy

A prototype model



Scalar sector: Higgs (h) + scalar (s)

- **Prototype** of many well-motivated models

Singlet-extended SM Cline *et al*, JCAP 01 (2013) 012; Alanne *et al*, NPB 889 (2014) 692; Chiang *et al*, PLB 789 (2019) 154; Jiang *et al*, PRD 93 (2016) 6, 065032; Alves *et al*, JHEP 04 (2019) 052, JHEP 12 (2018) 070, JHEP 03 (2020) 053, PLB 818 (2021) 136377; Carena *et al*, JHEP 08 (2020) 107; Liu, **KPX**, JHEP 04 (2021) 015; Huang, **KPX**, PRD 105 (2022) 11, 115033, Liu *et al*, PRD 105 (2022) 11, 115040; etc

2HDM Cline *et al*, JHEP 11 (2011) 089; Dorsch *et al*, JHEP 10 (2013) 029; Basler *et al*, JHEP 02 (2017) 121; Dorsch *et al*, JHEP 12 (2017) 086; Bian, Jiang *et al*, JHEP 05 (2018) 151; Wang *et al*, PLB 788 (2019) 519; Wang *et al*, PRD 101 (2020) 015015; Su *et al*, JHEP 04 (2021) 219; etc

Left-right model Brdar *et al*, JCAP 12 (2019) 027; Li *et al*, JHEP 03 (2021) 267; etc

Georgi-Machacek model Bian *et al*, JHEP 01 (2019) 216; Chen *et al*, PRD 106 (2022) 5, 055019; etc

Supersymmetry Lee *et al*, PRD 71 (2005) 075010; Balazs *et al*, PRD 71 (2005) 075002; Huang *et al*, PRD 91 (2015) 2, 025006; Bi *et al*, PRD 92 (2015) 023507; Bian, Guo, Shu, CPC 42 (2018) 9, 093106; Athron *et al*, JHEP 11 (2019) 151; Wang, **KPX**, Wu, Yang, EPJC 82 (2022) 12, 1120; etc

Composite Higgs Espinosa *et al*, JCAP 01 (2012) 012; Bian, Wu, **KPX**, JHEP 12 (2019) 028, JHEP 12 (2020) 047; De Curtis *et al*, JHEP 12 (2019) 149; Angelescu *et al*, JHEP 10 (2022) 019; etc

and more…

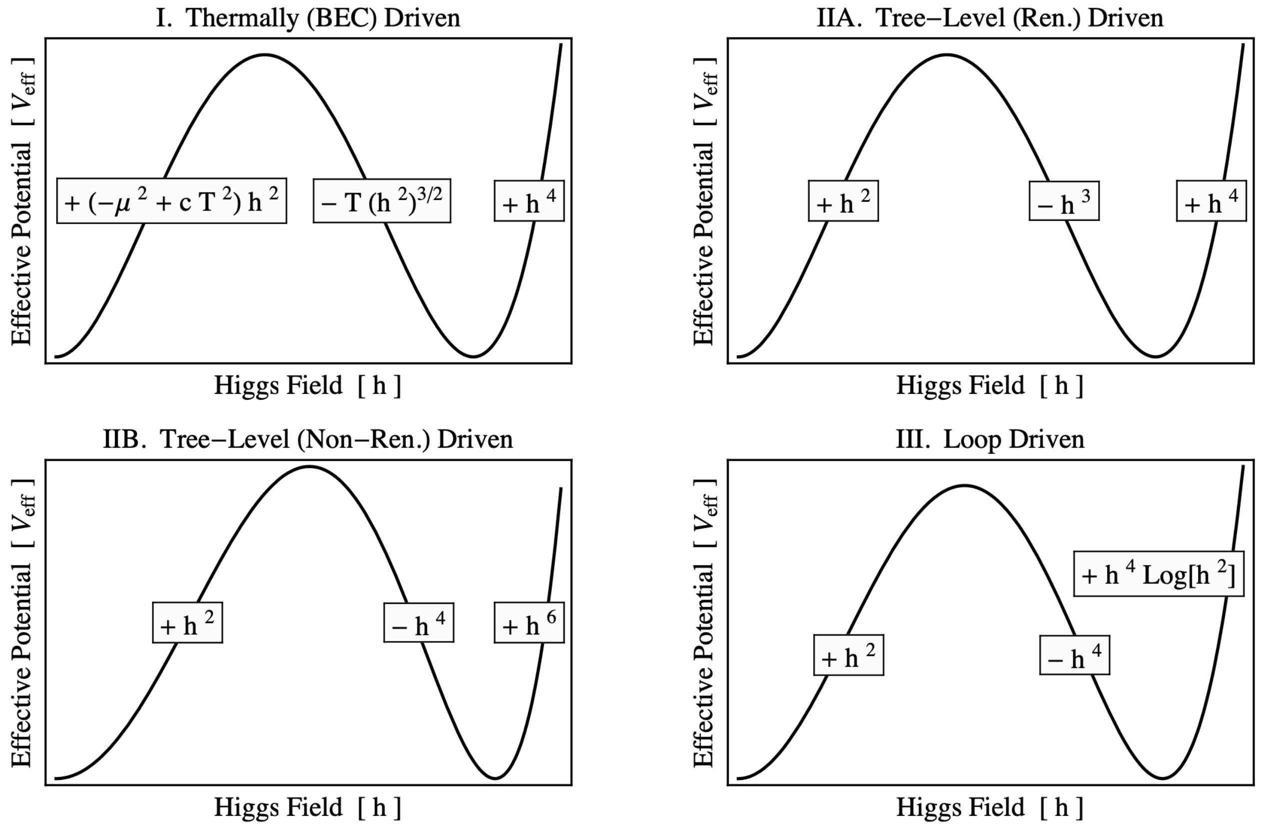
Underlying physics of the barrier

The full one-loop finite-temperature potential [Quiros, hep-ph/9901312]

$$V_T(h,T) = V_0(h) + V_1(h) + V_{1,T}(h,T) + V_{\text{daisy}}(h,T)$$

Tree level 1-loop CW 1-loop thermal Daisy resummation

A seminal classification [Chung, Long, and Wang, PRD 87 (2013) 2, 023509]



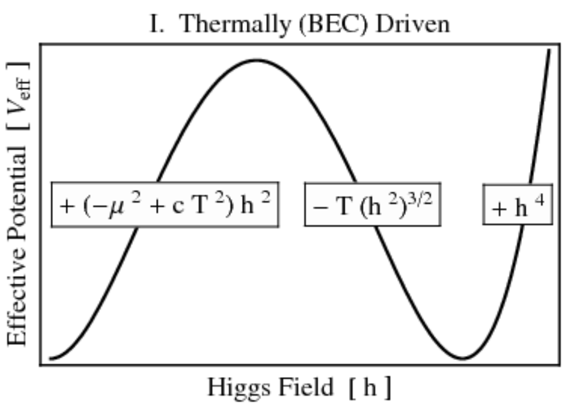
Type I: thermally loop-driven

Relevant $\mathcal{L} \supset -m_s^2 s^2/2 - \lambda_{hs} h^2 s^2/4$

IF $m_s^2 \ll \lambda_{hs} h^2/2 \lesssim T^2$,

$$V_T \approx \frac{-\mu^2 + cT^2}{2} h^2 - \frac{T}{12\pi}\left(\frac{\lambda_{hs}}{2}\right)^{3/2} h^3 + \frac{\lambda}{4} h^4$$

otherwise Boltzmann suppression $e^{-m_s/T}$



A strong FOEWPT requires

$$\frac{v_c}{T_c} \approx \frac{1}{6\pi\lambda}\left(\frac{\lambda_{hs}}{2}\right)^{3/2} \gtrsim 1$$

Usually, $\lambda = m_h^2/2v^2 \approx 0.13$ fixed

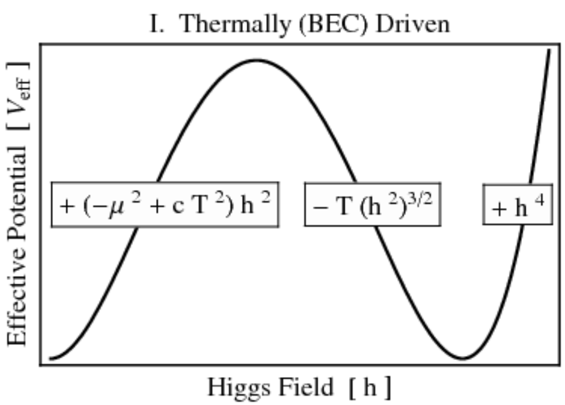
$\Rightarrow$ need a sizable λ_{hs}

Type I: thermally loop-driven

Relevant $\mathcal{L} \supset -m_s^2 s^2/2 - \lambda_{hs} h^2 s^2/4$
IF $m_s^2 \ll \lambda_{hs} h^2/2 \lesssim T^2$,

$$V_T \approx \frac{-\mu^2 + cT^2}{2} h^2 - \frac{T}{12\pi}\left(\frac{\lambda_{hs}}{2}\right)^{3/2} h^3 + \frac{\lambda}{4} h^4$$

otherwise Boltzmann suppression $e^{-m_s/T}$



A strong FOEWPT requires

$$\frac{v_c}{T_c} \approx \frac{1}{6\pi\lambda}\left(\frac{\lambda_{hs}}{2}\right)^{3/2} \gtrsim 1$$

Usually, $\lambda = m_h^2/2v^2 \approx 0.13$ fixed
$\Rightarrow$ needs a sizable λ_{hs}

Collider signal: a light scalar with significant coupling to the Higgs

- Candidates: stop (SUSY), h_2 (2HDM), etc
- Severely constrained by $\sigma(gg \to h)$, $h \to \gamma\gamma$, etc, but still rooms for model-building [Cao *et al*, JHEP 01 (2022) 001]

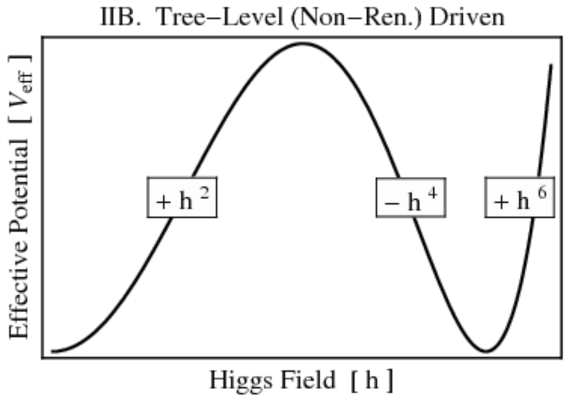
Type IIB: tree-level non-renormalizable operator

Relevant $\mathcal{L} \supset -m_s^2 s^2/2 - \lambda_{hs} h^2 s^2/4$

IF $m_s \gg 100\ \text{GeV}$, EFT

$$V_T \approx \frac{\mu^2 + cT^2}{2} h^2 - \frac{\lambda}{4} h^4 + \frac{\lambda_{hs}^3}{48 m_s^2} h^6$$

Barrier exists at tree-level at $T = 0$ via operator $\mathcal{O}_6 \equiv |H|^6/\Lambda^2$



A strong FOEWPT requires

$$0.55\ \text{TeV} < \Lambda < 0.89\ \text{TeV}$$

Huang *et al*, PRD93, 103515 (2016)

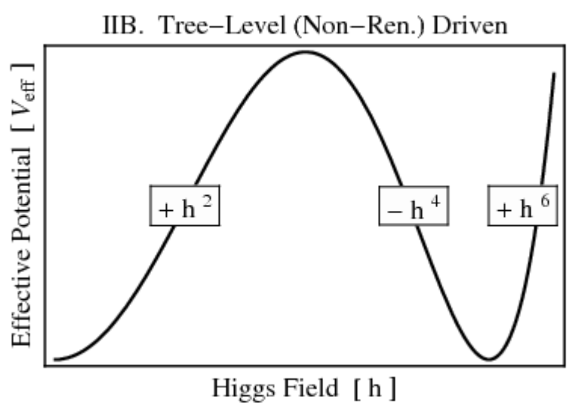
Type IIB: tree-level non-renormalizable operator

Relevant $\mathcal{L} \supset -m_s^2 s^2/2 - \lambda_{hs} h^2 s^2/4$

IF $m_s \gg 100$ GeV, EFT

$$V_T \approx \frac{\mu^2 + cT^2}{2} h^2 - \frac{\lambda}{4} h^4 + \frac{\lambda_{hs}^3}{48 m_s^2} h^6$$

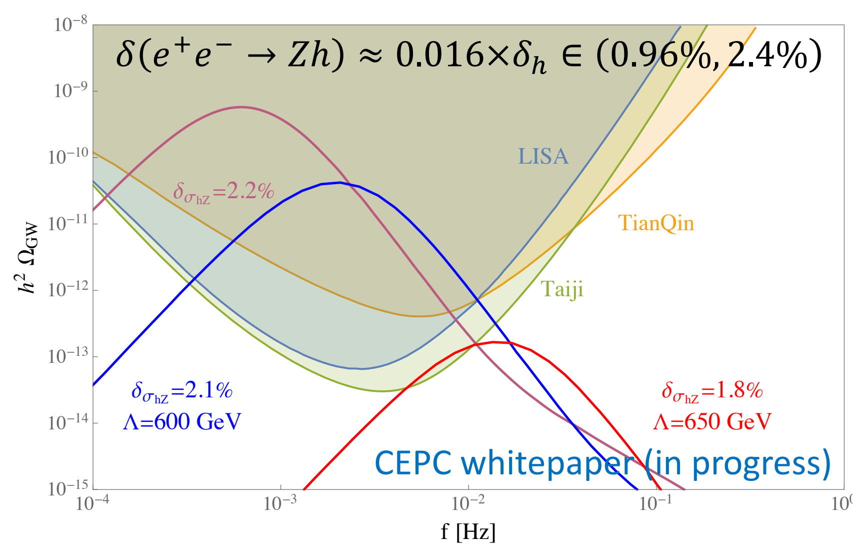
Barrier exists at tree-level at $T = 0$ via operator $\mathcal{O}_6 \equiv |H|^6/\Lambda^2$



A strong FOEWPT requires

$$0.55 \text{ TeV} < \Lambda < 0.89 \text{ TeV}$$

Huang *et al*, PRD93, 103515 (2016)



Collider signal: h^3 deviation

- $\delta_h = \left|\lambda_{h^3}/\lambda_{h^3}^{\rm SM} - 1\right| \approx 0.468 \times ({\rm TeV}/\Lambda)^2$

Type IIA: tree-level renormalizable operator

The most general case

$$V=-\frac{\mu^2}{2}h^2+\frac{\lambda}{4}h^4+\frac{a_1}{4}h^2s+\frac{a_2}{4}h^2s^2+\frac{b_2}{2}s^2+\frac{b_3}{3}s^3+\frac{b_4}{4}s^4$$

Fixing Higgs mass & VEV, 5 free parameters

$$\begin{pmatrix} h \\ s \end{pmatrix}=\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

h_1: Higgs-like, 125 GeV
h_2: Singlet-like

Type IIA: tree-level renormalizable operator

The most general case

$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_1}{4}h^2 s + \frac{a_2}{4}h^2 s^2 + \frac{b_2}{2}s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

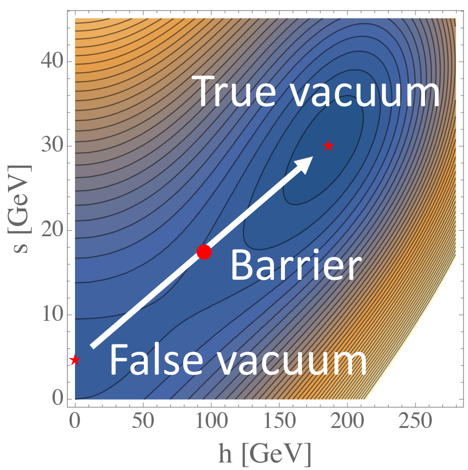
Fixing Higgs mass & VEV, 5 free parameters

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

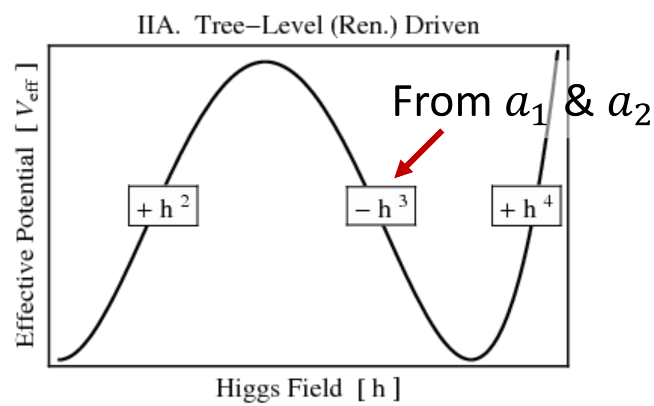
h_1: Higgs-like, 125 GeV
h_2: Singlet-like

Thermal corrections

$$\Delta V_T = \frac{c_h T^2}{2}h^2 + m_1 T^2 s + \frac{c_s T^2}{2}s^2$$



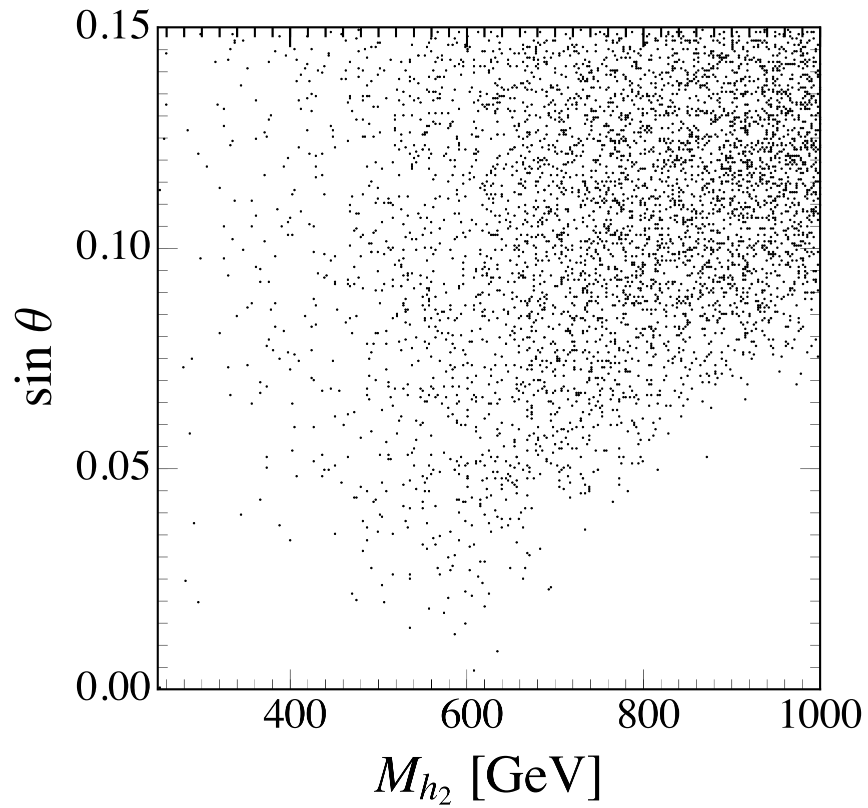
Effectively



FOEWPT parameter space

Varying the 5 free input parameters [Liu and **KPX**, JHEP 04 (2021) 015]

Singlet mass & mixing angle

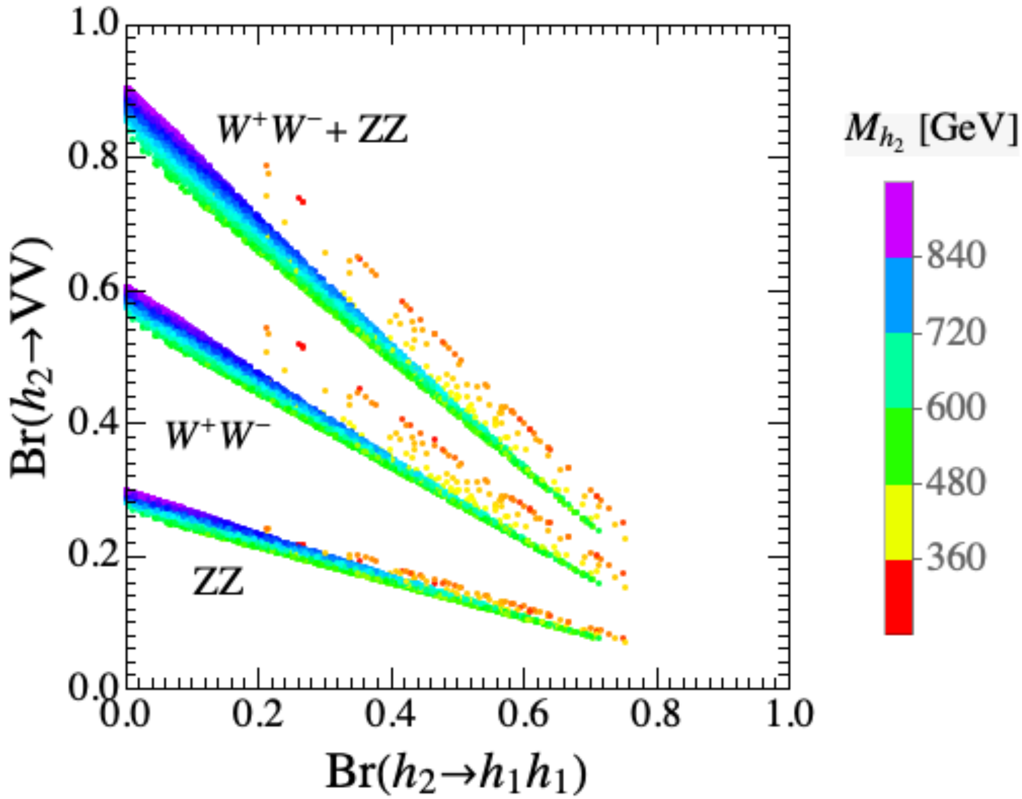


Sizable mixing required for a FOEWPT

Resonant heavy h_2 search

FOEWPT parameter space

- Produced via mixing, e.g. $gg \to h_2$, cross section $\propto \sin^2\theta$



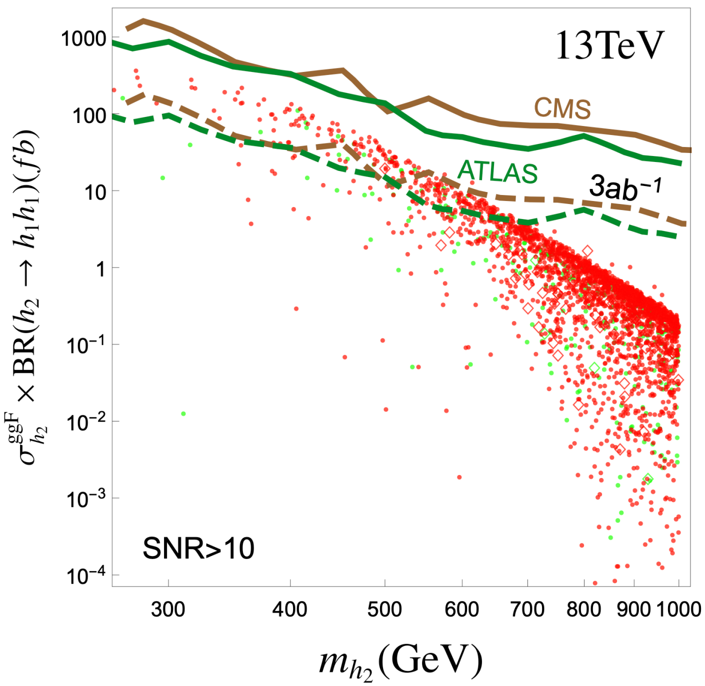
- Dominant decays $h_2 \to h_1 h_1$ and $h_2 \to W^+W^-$ or ZZ
- $\mathrm{Br}(h_2 \to t\bar{t}) \lesssim 20\%$ subdominant

Resonant heavy h_2 search

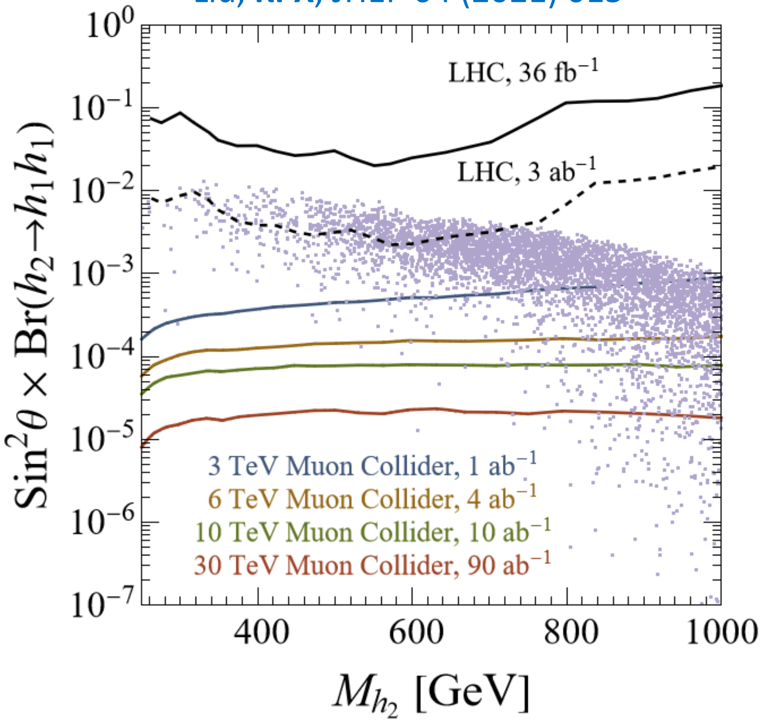
FOEWPT parameter space

- HL-LHC or multi-TeV muon colliders
- Complementary to gravitational wave search

Alves, Guo, *et al*, JHEP 04 (2019) 052



Liu, **KPX**, JHEP 04 (2021) 015



Recent progress [Biermann *et al*, 2408.08043; Aboudonia *et al*, 2410.22700, etc]

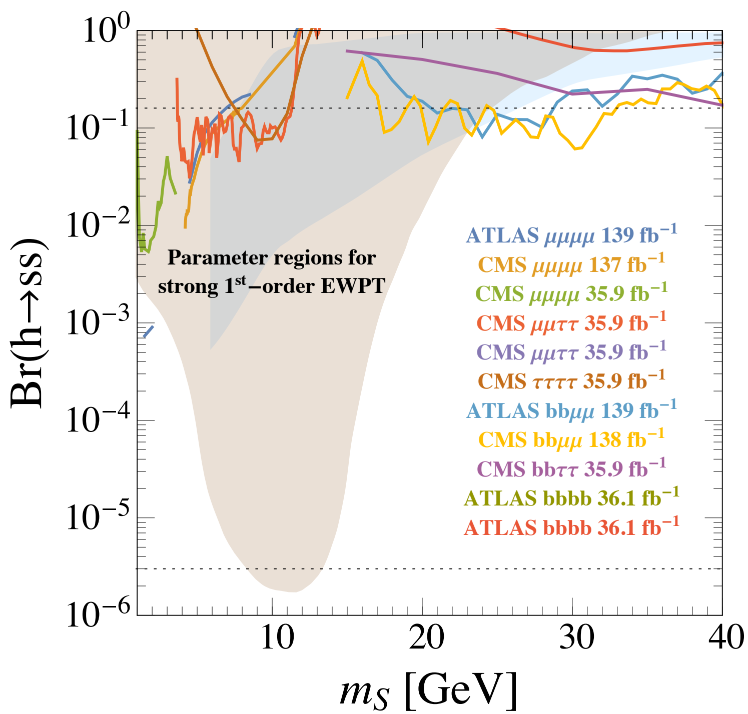
Light h_2 search

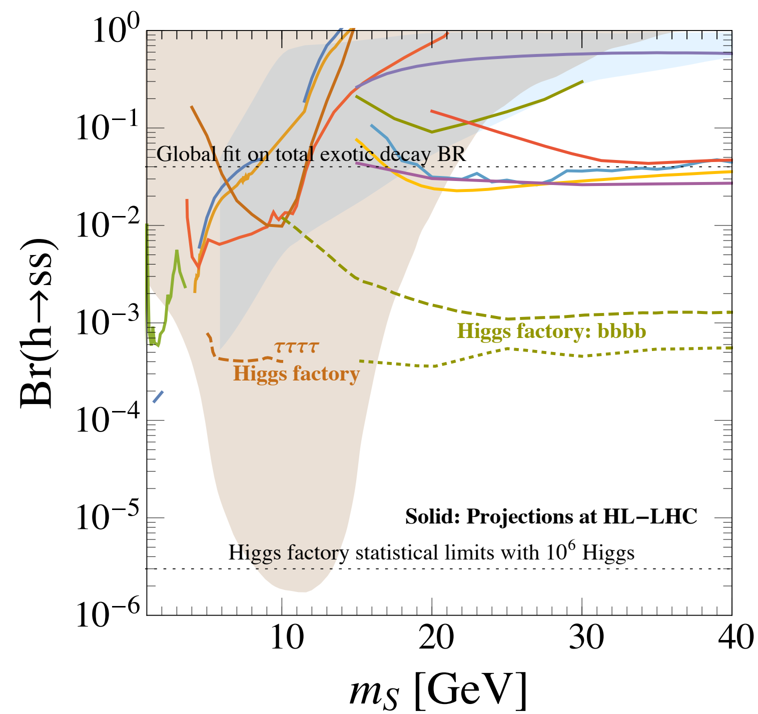
Higgs exotic decay $h_1 \to h_2 h_2 \to XXYY$ [SM light particles]

Carena, **KPX**, *et al*, LHEP 2023 (2023) 432

FOEWPT parameter space

- Light blue: fixing mixing angle $\sin\theta = 0.01$ — Kozaczuk *et al*, PRD 101 (2020) 11, 115035
- Brown: spontaneous broken Z_2 of S — Carena *et al*, JHEP 08 (2020) 107



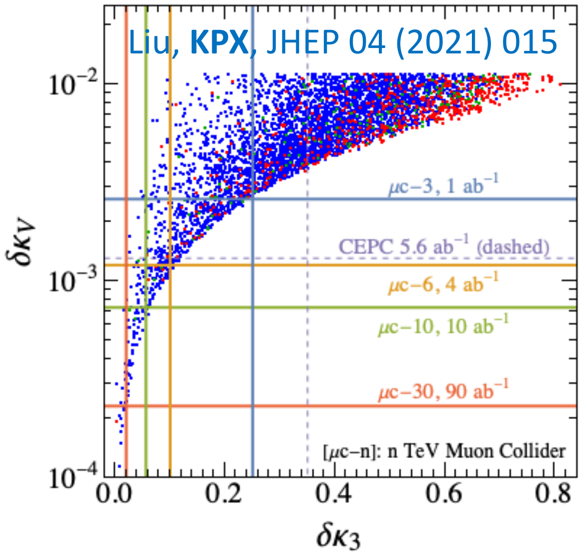


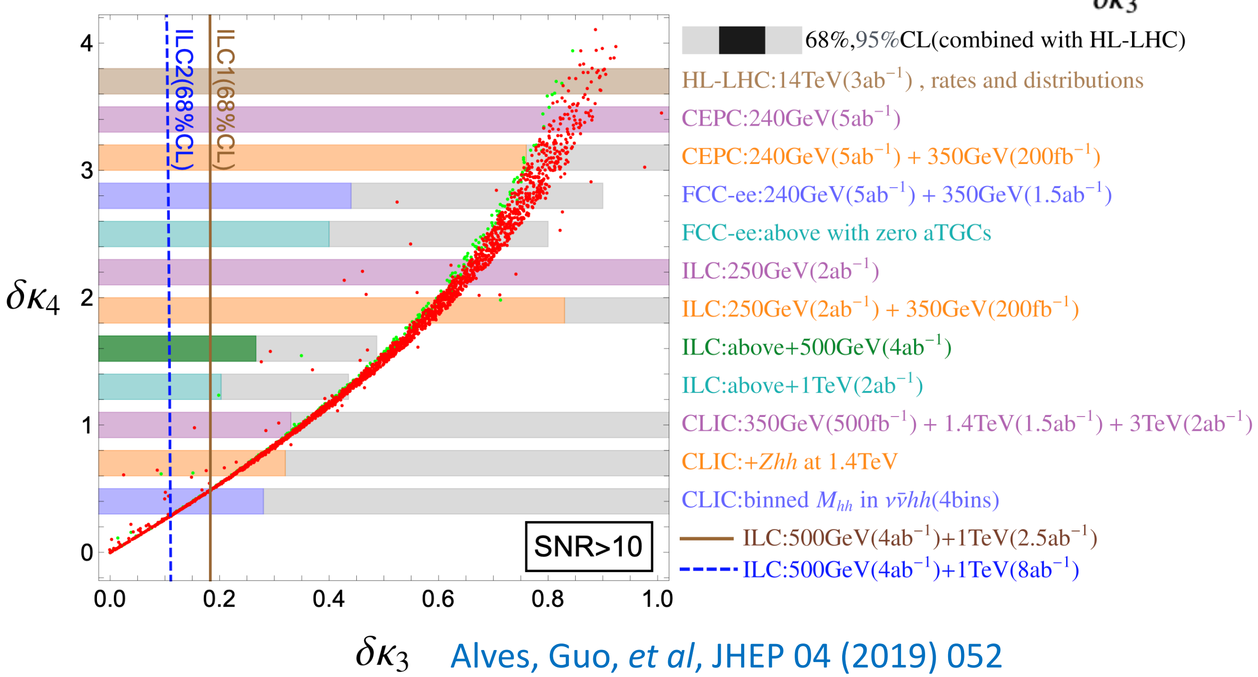
Higgs precision measurement

Higgs coupling deviations

$$\delta\kappa = |g/g_{\rm SM} - 1|$$

- $\delta\kappa_V \to h_1 VV \propto |1-\cos\theta|$
- $\delta\kappa_3 \to h_1^3$ and $\delta\kappa_4 \to h_1^4$
- CEPC, ILC, FCC-ee, CLIC, or muon colliders





Alves, Guo, *et al*, JHEP 04 (2019) 052

Type III: loop driven

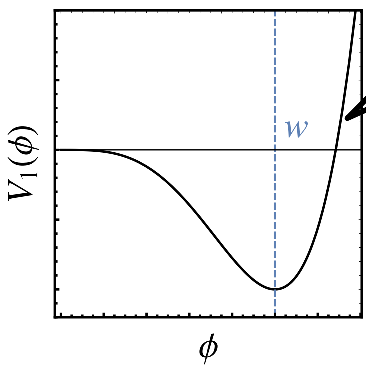
Based on **classically conformal principle**, tree-level

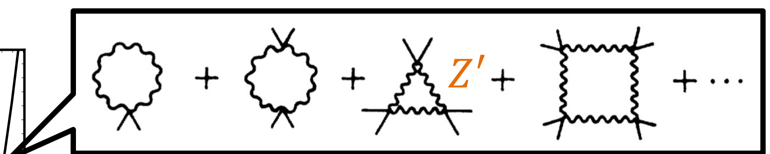
$$V_0(H,s) = \lambda_h|H|^4 + \lambda_s|s|^4 - \lambda'|H|^2|s|^2$$

$s = (\phi + i\eta)/\sqrt{2}$ is charged under a dark $U(1)_X$

One-loop level [Coleman and Weinberg, PRD 7 (1973) 1888-1910]

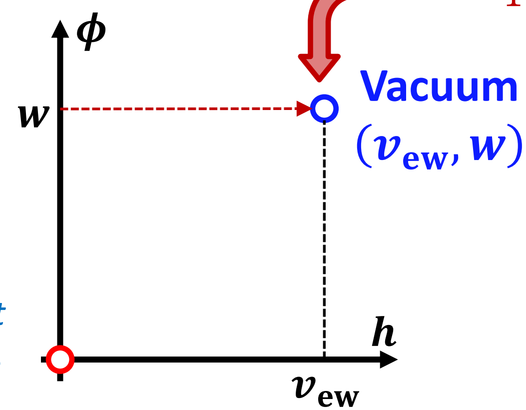
$$V_1(h,\phi) \approx \frac{3g_X^4}{32\pi^2}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right) - \frac{\lambda'}{4}h^2\phi^2 + \frac{\lambda_h}{4}h^4$$





After $\langle\phi\rangle \approx w$,

$$V_1 \to -\frac{\lambda' w^2}{4}h^2 + \frac{\lambda_h}{4}h^4$$



EWSB with

$$v_{\rm ew} \approx \sqrt{\frac{\lambda'}{\lambda_h}}\,w$$

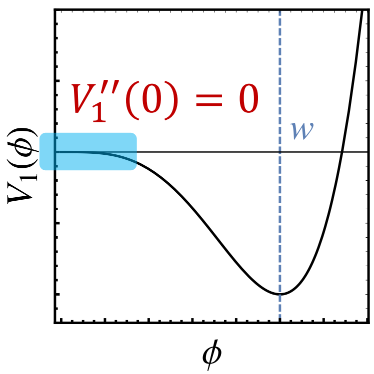
Motivated by the

hierarchy problem

Hempfling, PLB 379, 153 (1996); Iso *et al*, PLB 676, 81 (2009); Chun *et al*, PLB 725, 158 (2013), etc

FOEWPT in classically conformal model

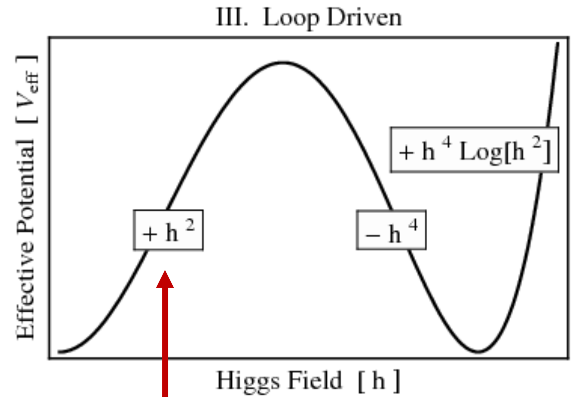
Very special feature of logarithmic potential



$$V_1(\phi) \sim \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

When $T > 0$

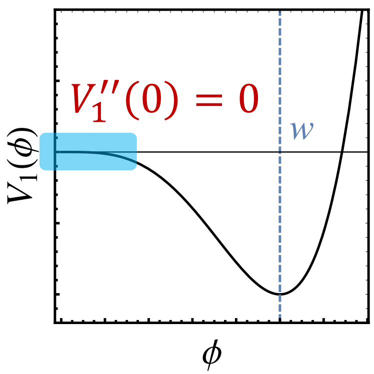
Effectively



$\sim \lambda' g_X^2 T^2 h^2$ generated by Z' in hidden sector

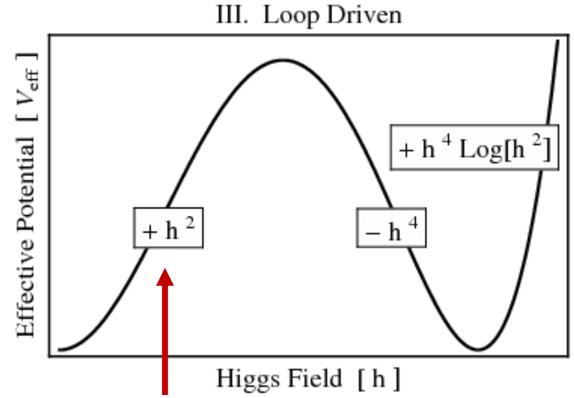
FOEWPT in classically conformal model

Very special feature of logarithmic potential



When $T > 0$

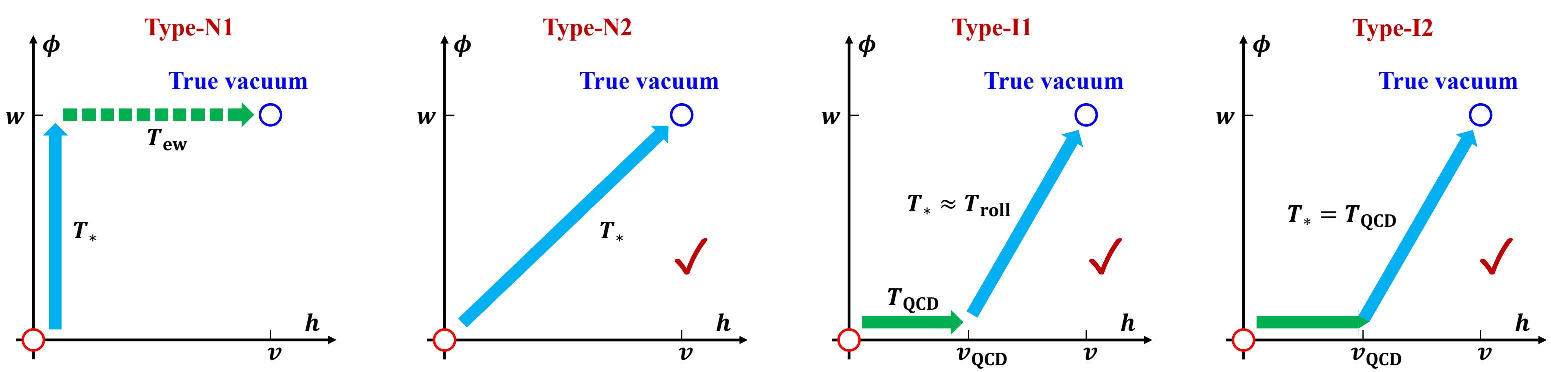
Effectively



$$V_1(\phi) \sim \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

$\sim \lambda' g_X^2 T^2 h^2$ generated by Z' in hidden sector

4 phase transition patterns (3 have FOEWPT) [Liu and **KPX**, 2408.03649]

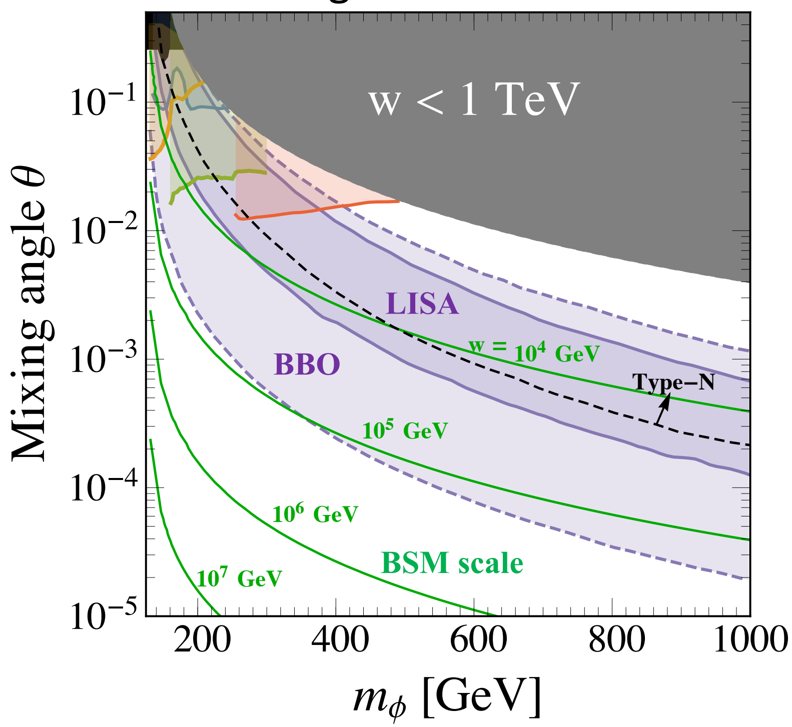


Collider signals: for a heavy singlet

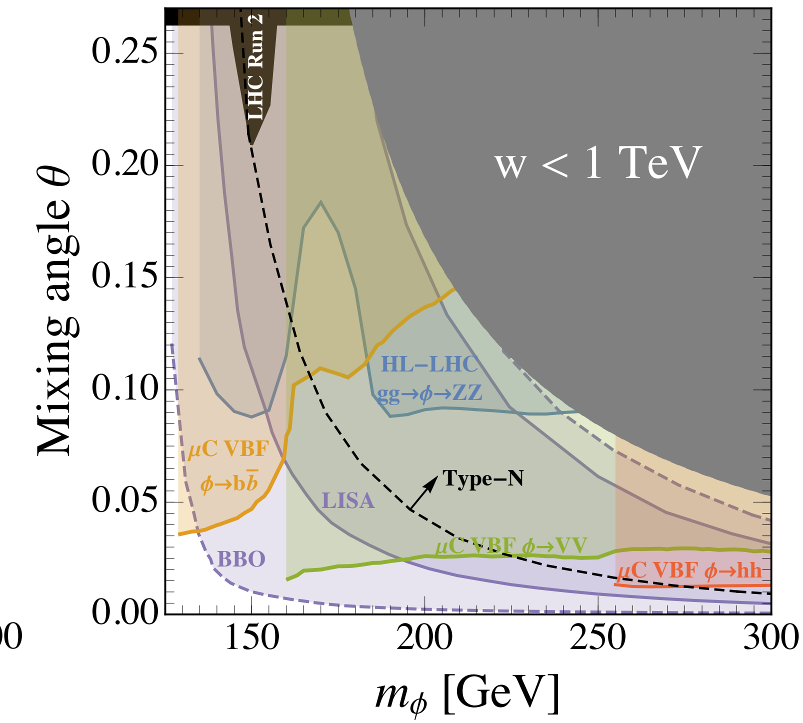
Collider search [Liu and **KPX**, 2408.03649]

- HL-LHC $gg \to \phi \to ZZ$
- 10 TeV muon collider VBF $\phi \to b\bar{b}, VV, hh$

Log θ coordinate



Zoom-in, linear θ coordinate



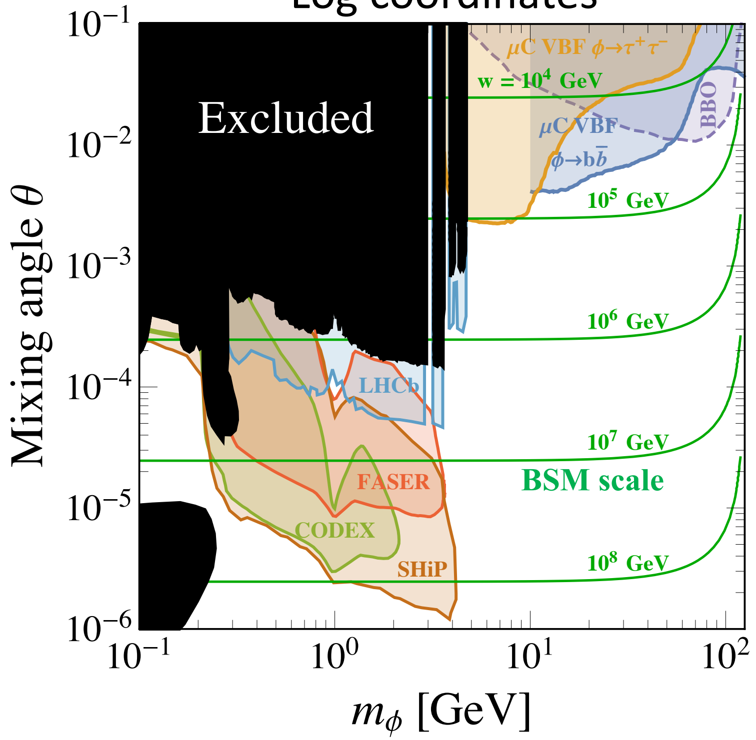
Gravitational wave search: LISA (also TianQin, Taiji) and BBO

Collider signals: for a light singlet

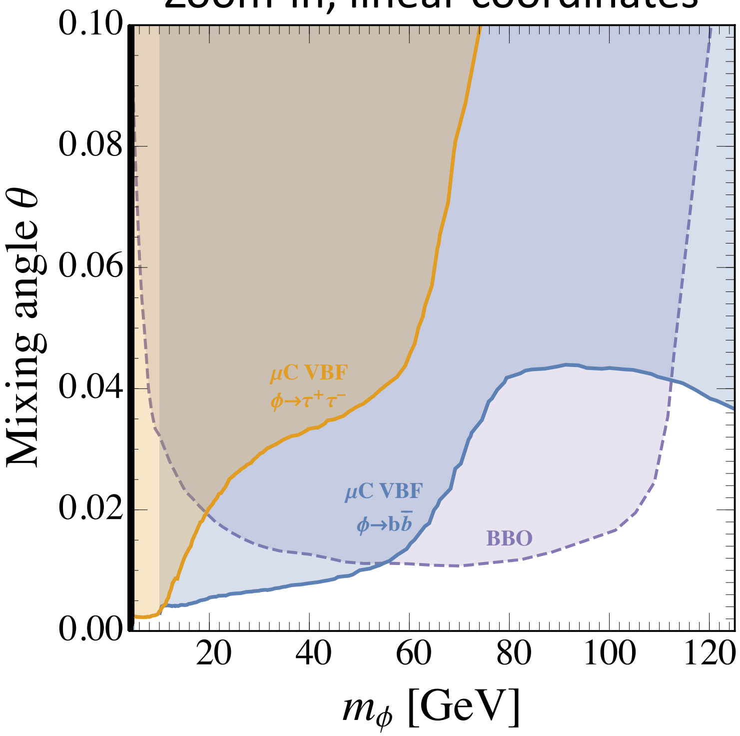
Collider search [Liu and **KPX**, 2408.03649]

- Long-lived particle search; muon collider
- NO Higgs exotic decay signal, as $\mathrm{Br}(h \to \phi\phi) < 10^{-10}$

Log coordinates



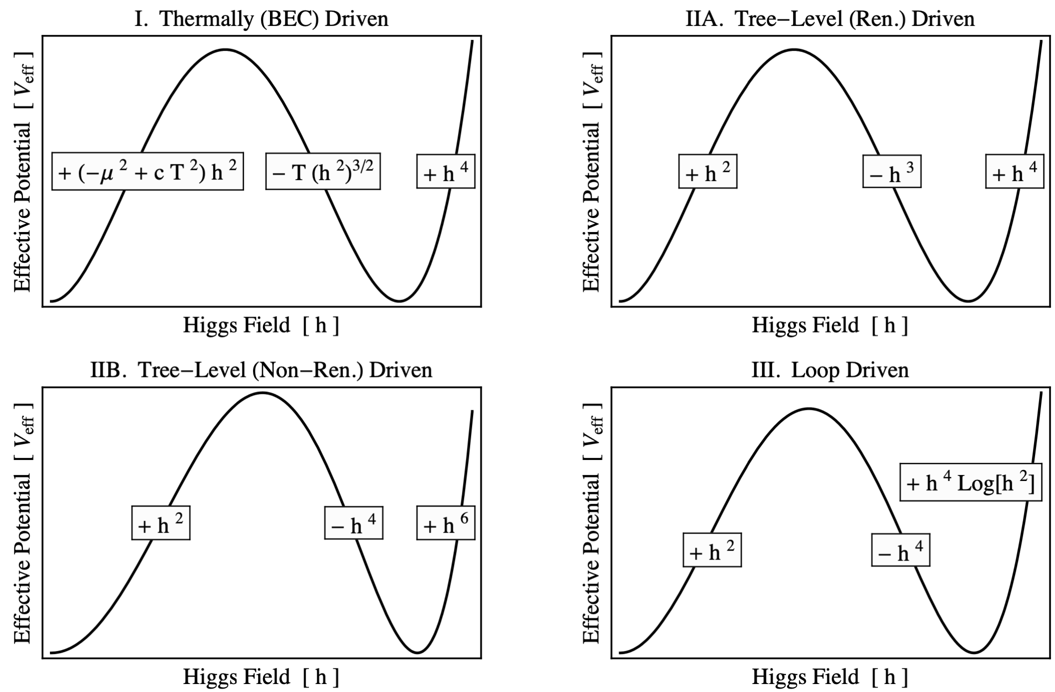
Zoom-in, linear coordinates



GW search NOT sensitive, as the FOPTs complete too fast

Summary

FOEWPT { A good probe for physics beyond the SM
A key ingredient for solving puzzles in the SM }



Origin of barrier:

1. Thermally driven
2. Tree-level ren.
3. Tree-level non-ren.
4. Loop driven

Chung, Wang *et al*, PRD 87 (2013) 2, 023509

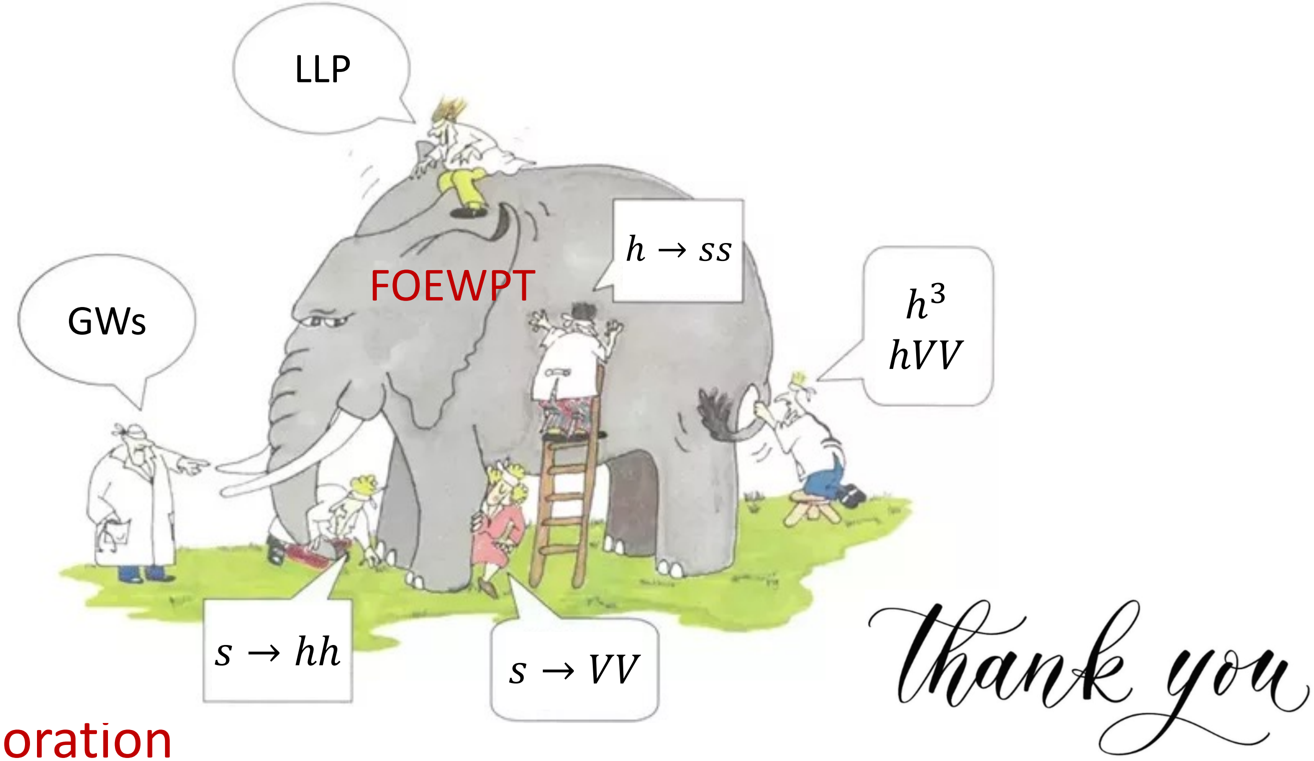
Typical signals

- Resonant $s \to hh$, $s \to W^+W^-/ZZ$, or $h \to ss \to XXYY$
- Higgs couplings deviation, especially h^3 or hVV

Hopefully we can detect something in the next decade!

Conclusion and outlook

It’s challenging to confirm what happened right after the Big Bang!



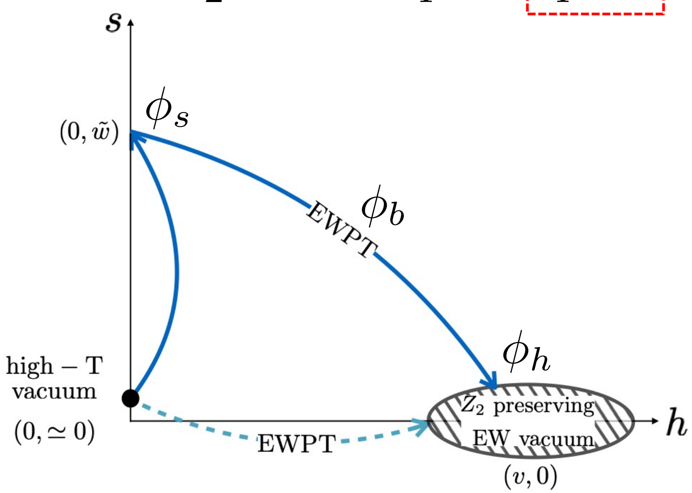
Future exploration

- More detailed simulations (e.g. boosted by AI)
- More sensitive channels (e.g. $h \to ss \to \mu^+\mu^-\mu^+\mu^-$@ CEPC)
- Distinguishing the 4 scenarios by combining all channels
- …

Backup: type IIA light singlet general case

The potential at finite temperature

$$V = -\frac{\mu^2 - c_h T^2}{2} h^2 + \frac{\lambda}{4} h^4 + \boxed{\frac{a_1}{4} h^2 S} + \boxed{\frac{a_2}{4} h^2 S^2} + b_1 S + \frac{b_2 + c_S T^2}{2} S^2 + \boxed{\frac{b_3}{3} S^3} + \frac{b_4}{4} S^4$$

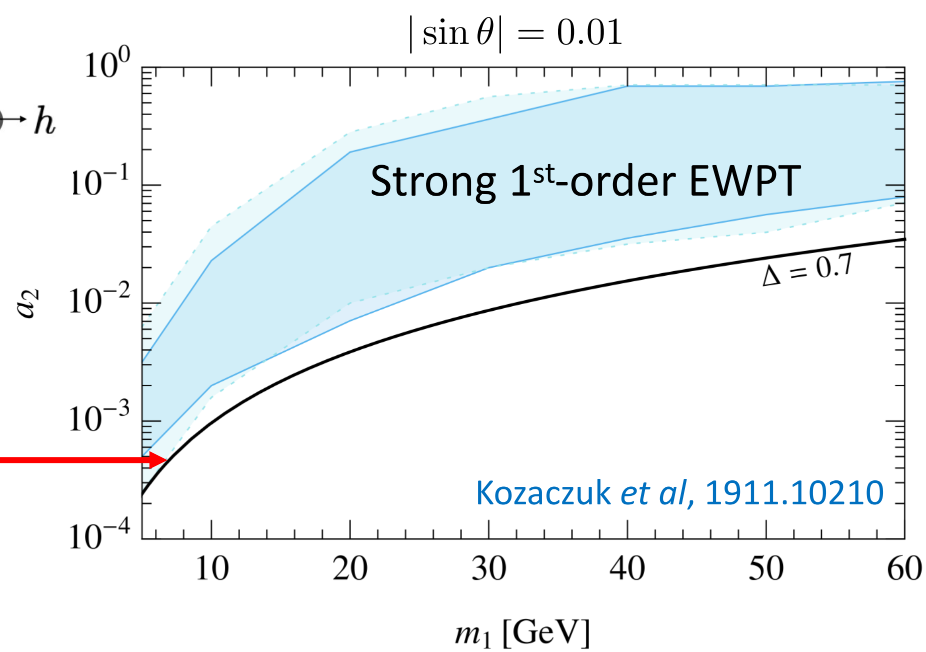


$$c_h = \frac{1}{48}\left(24a_2 + 9g^2 + 3g'^2 + 24\lambda + 12y_t^2\right),$$
$$c_S = \frac{1}{12}\left(2a_2 + 3b_4\right)$$

Analytical estimation

$$\frac{V(\phi_s, T_*) - V(\phi_h, T_*)}{V(\phi_b, T_*) - V(\phi_h, T_*)} > \Delta$$

$$a_2 \gtrsim \frac{m_1^2}{4v_{\rm EW}^2} \frac{\Delta}{1-\Delta}$$



Backup: type IIA Z_2 spontaneous breaking case

Motivated by dark symmetry breaking models [Carena *et al*, 1911.10206]

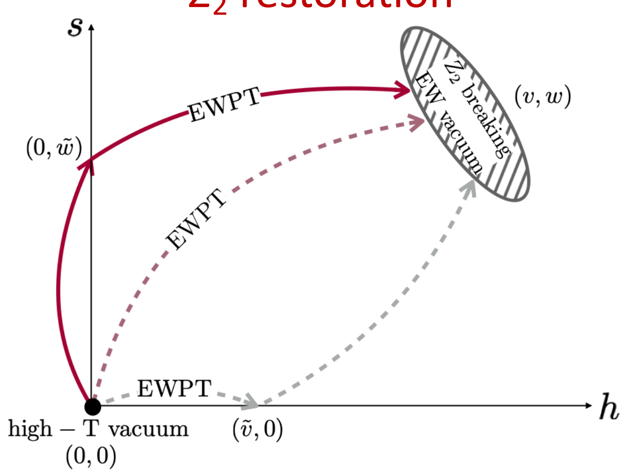
$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_2}{4}h^2S^2 + \frac{b_2}{2}S^2 + \frac{b_4}{4}S^4$$

A complete one-loop level analysis

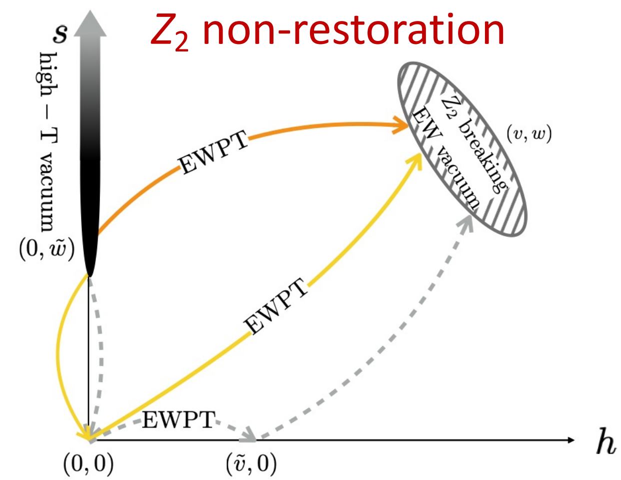
$$V_{\rm CW} = \frac{1}{64\pi^2}\left(\sum_B n_B m_B^4(h,S)\left[\ln\frac{m_B^2(h,S)}{Q^2} - c_B\right] - \sum_F n_F m_F^4(h,S)\left[\ln\frac{m_F^2(h,S)}{Q^2} - \frac{3}{2}\right]\right)$$

$$V^T(h,s,T) = \frac{T^4}{2\pi^2}\left[\sum_B n_B J_B\left(\frac{m_B^2(h,S)}{T^2}\right) + \sum_F n_F J_F\left(\frac{m_F^2(h,S)}{T^2}\right)\right] + \text{Daisy resummation}$$

Z_2 restoration



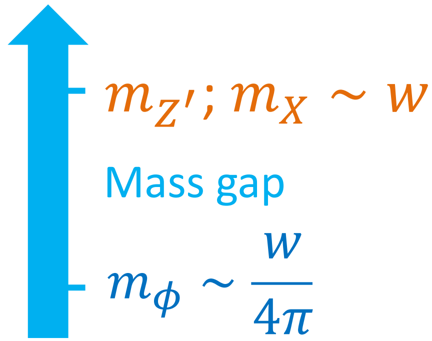
Z_2 non-restoration



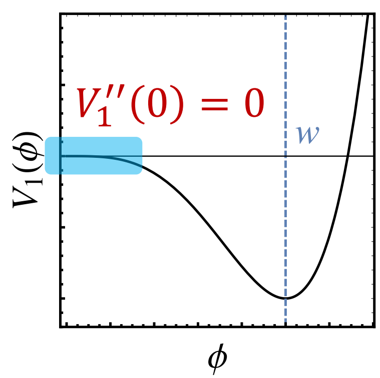
Backup: the classically conformal model

Particle content

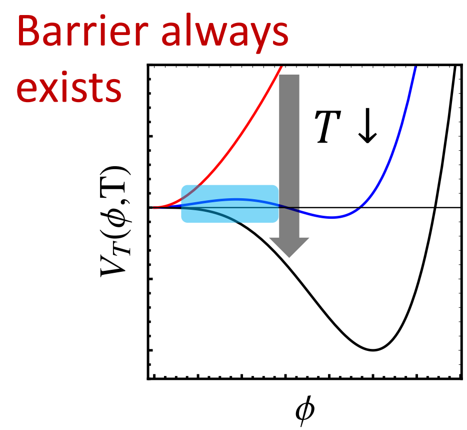
- A scalar ϕ mixing with the Higgs
- Heavy particle(s) that generates the Coleman-Weinberg potential



Early Universe evolution of the logarithmic-shaped potential



$$V_1(\phi) \sim \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$



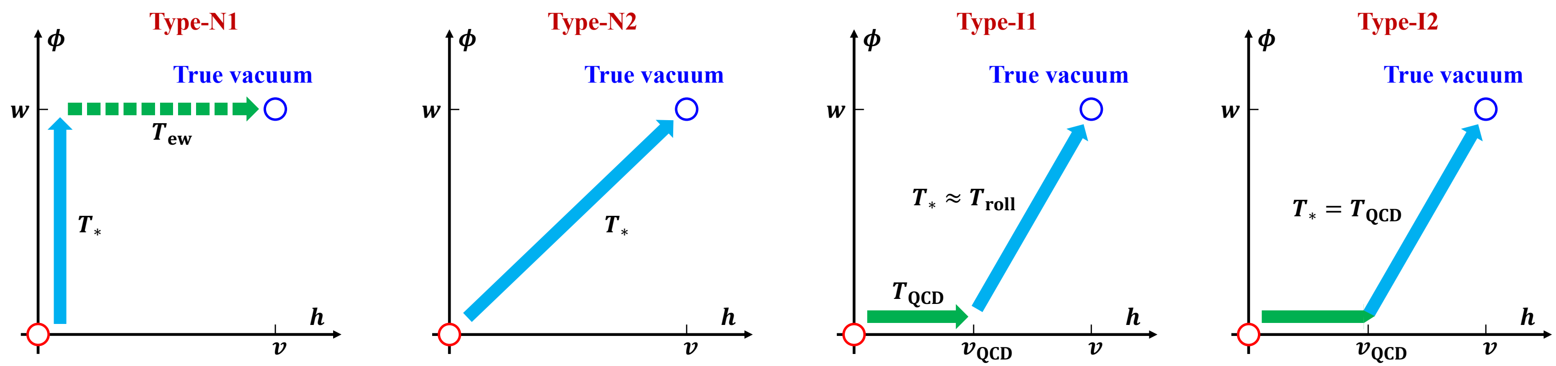
$$V_T(\phi, T) \sim \boldsymbol{g_X^2 T^2 \phi^2} + \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

First-order phase transition along the ϕ-direction guaranteed

Backup: thermal history patterns of CC theories

Normal pattern: high scale ϕ transition, then low scale h transition

- **N1**: ϕ-FOPT → EW crossover
- **N2**: joint ϕ-EW-FOPT



Inverted pattern: low scale h transition, then high scale ϕ transition

- **I1**: QCD-EW-FOPT → ϕ-FOPT
- **I2**: joint QCD-EW-ϕ-FOPT

Inverted pattern first proposed by Witten [NPB 177, 477 (1981)]

Transition rate $\Gamma(T) \sim e^{-S}$ with $S \propto g_X^{-3}$ [Iso *et al*, PRL 119 (2017) 14, 141301]

Small g_X → Universe trapped at $(h, \phi) = (0,0)$

QCD transition occurs first! A FOPT with 6 massless quarks

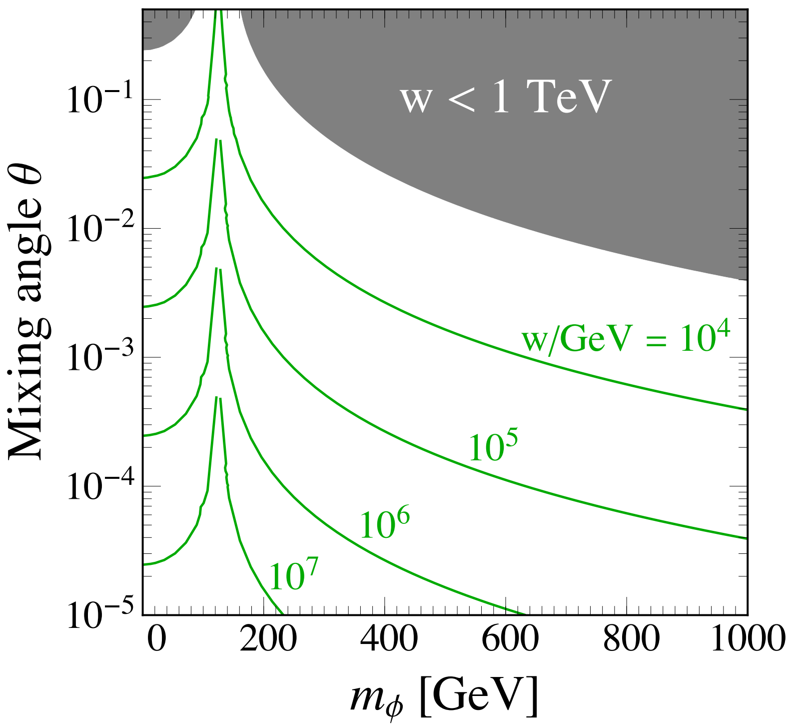
- $-y_t h\langle \bar{t}t \rangle$ yields an EWPT $h: 0 \mapsto v_{\rm QCD} \approx 100$ MeV

Backup: parametrization of the CC model

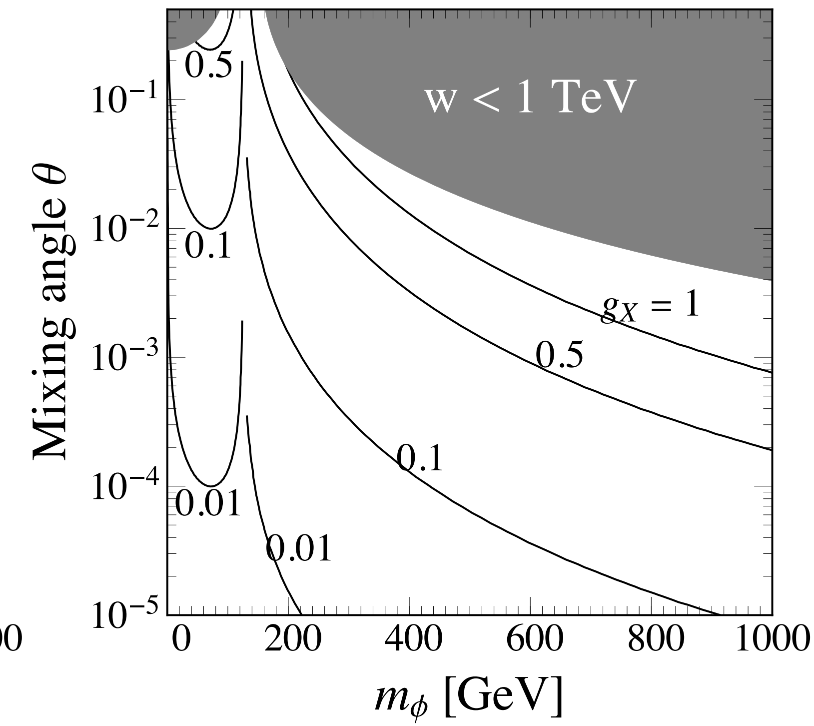
Fixing $m_h = 125$ GeV and $v_{\rm ew} = 246$ GeV --

- Only 2 free parameters
- First thorough and **rigorous** analysis in [Liu and **KPX**, 2408.03649]

New physics scale w



g_X in gauge-induced scenario



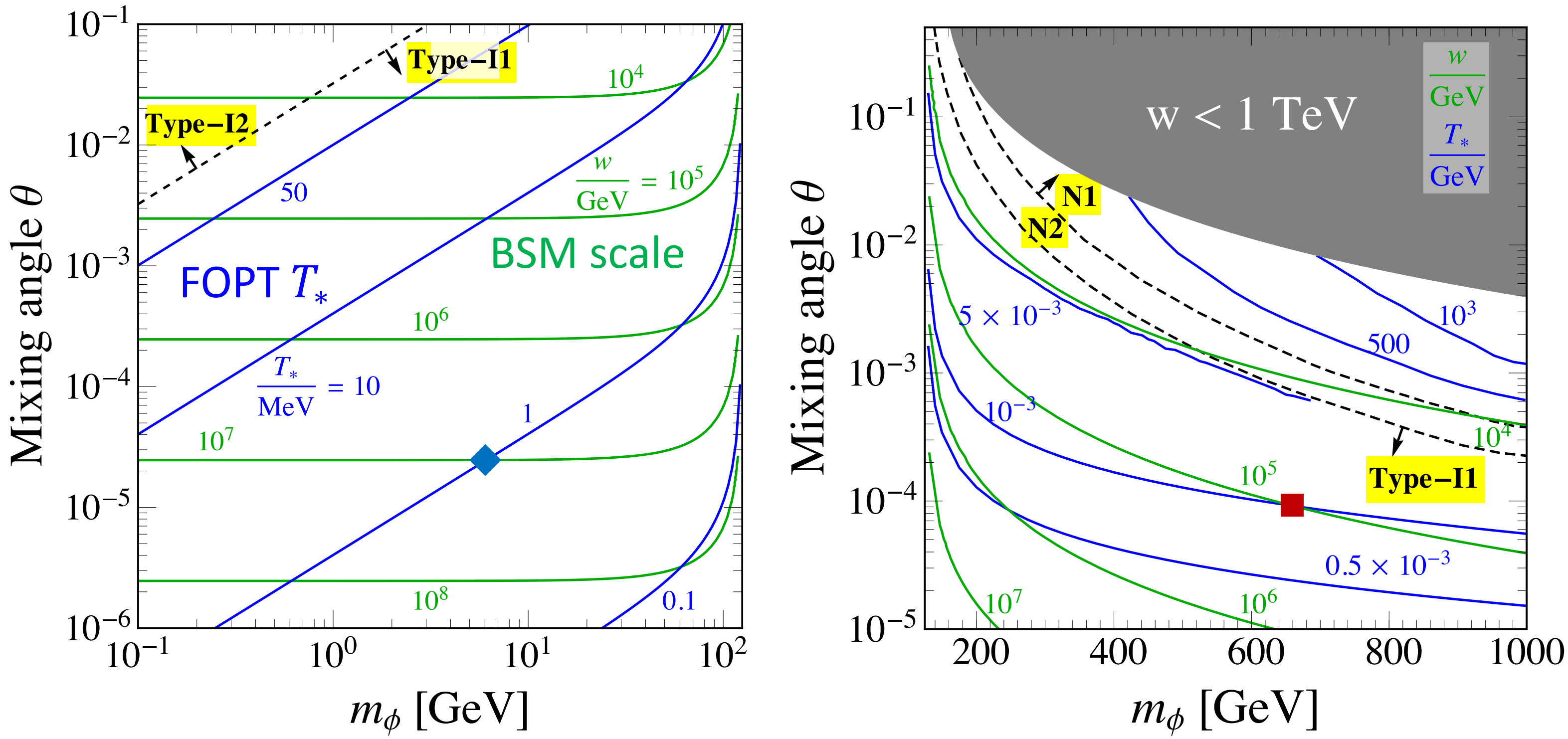
- $m_\phi \neq 125$ GeV: ϕ cannot be degenerate with the Higgs

Backup: phase diagram of the CC model

Full <u>one-loop</u> calculation & <u>completeness check</u> in [Liu and **KPX**, 2408.03649]

Type-N1: ϕ-FOPT → EW crossover **Type-N2**: joint ϕ-EW-FOPT

Type-I1: QCD-EW-FOPT → ϕ-FOPT **Type-I2**: joint QCD-EW-ϕ-FOPT



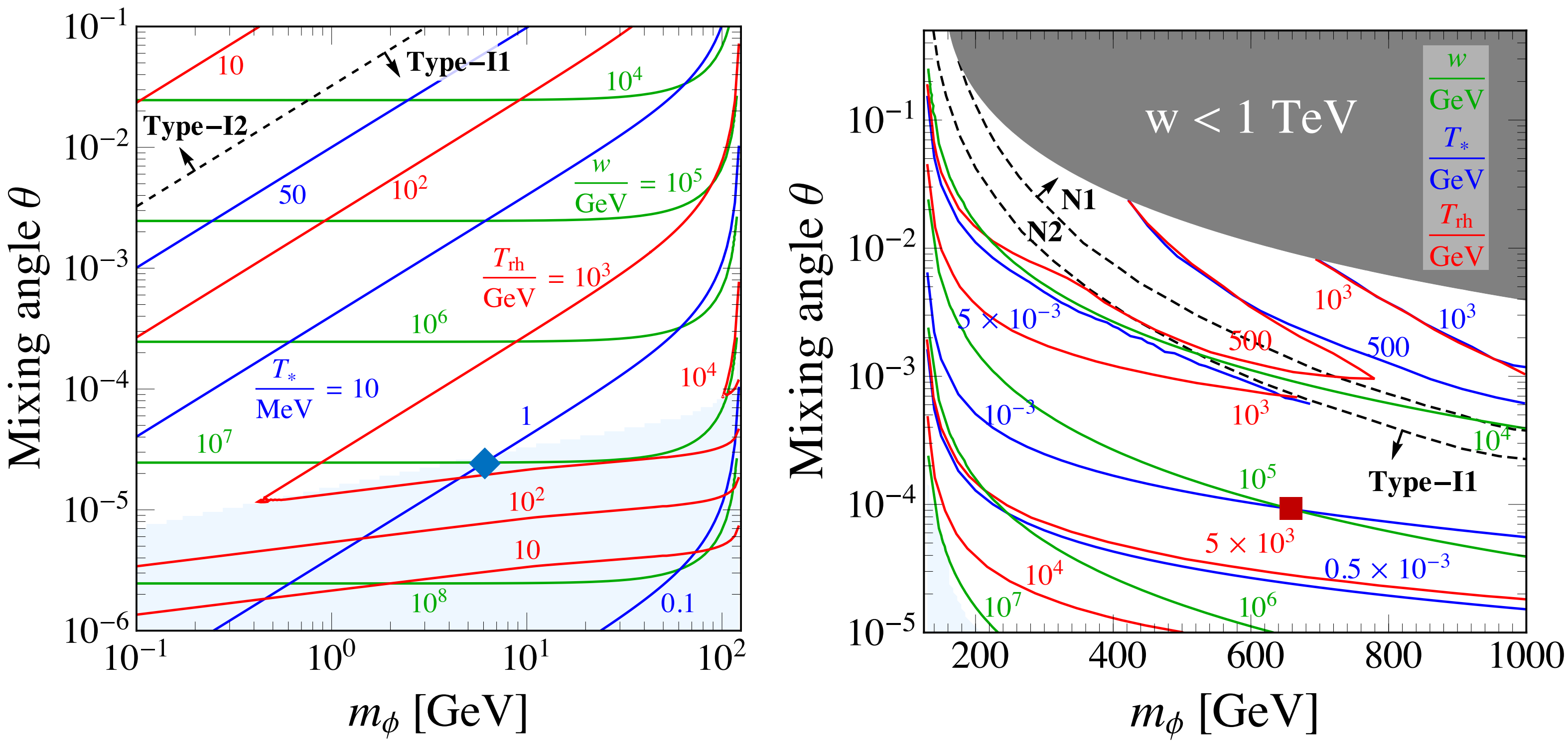
◆ $w = 10^7$ GeV, $T_* = 1$ MeV ■ $w = 10^5$ GeV, $T_* = 1$ MeV

- Ultra-supercooled phase transitions!

Backup: reheating in the CC model

The Universe is reheated to $T_{\rm rh} \gtrsim T_*$ [Liu and **KPX**, 2408.03649]

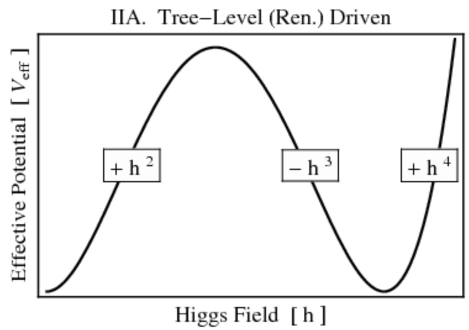
- Possible EW symmetry restoration and a second EWPT
- Early matter era, if reheating is slow

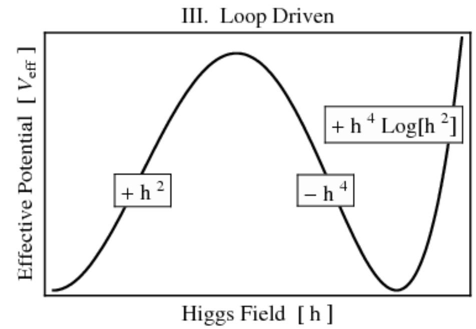


◆ $w = 10^7$ GeV, $T_* = 1$ MeV, $T_{\rm rh} \sim 1$ TeV

■ $w = 10^5$ GeV, $T_* = 1$ MeV, $T_{\rm rh} \sim 3$ TeV

Comparison between type IIA and type III





	Type IIA	Type III
Motivation	Prototype of many BSM models	Hierarchy problem
Potential	Polynomial with mass terms	Logarithmic
# of parameters	5	2
Origin of barrier	h-s interaction	Z' from $U(1)_X$
FOEWPT	In some parameter space	Almost guaranteed
PT strength	Moderate	Ultra-supercooling
Pheno of heavy s	Resonant $s \to hh, VV$	
Pheno of light s	Higgs exotic decay	Long-lived particle