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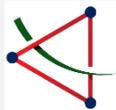
Baryogenesis Revisited: CP Violation and the Dynamics of the Higgs Phase Transition

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中山大学物理与天文学院天琴中心

味物理前沿研讨会

暨味物理讲座100期特别活动@三亚, 2026.1.31

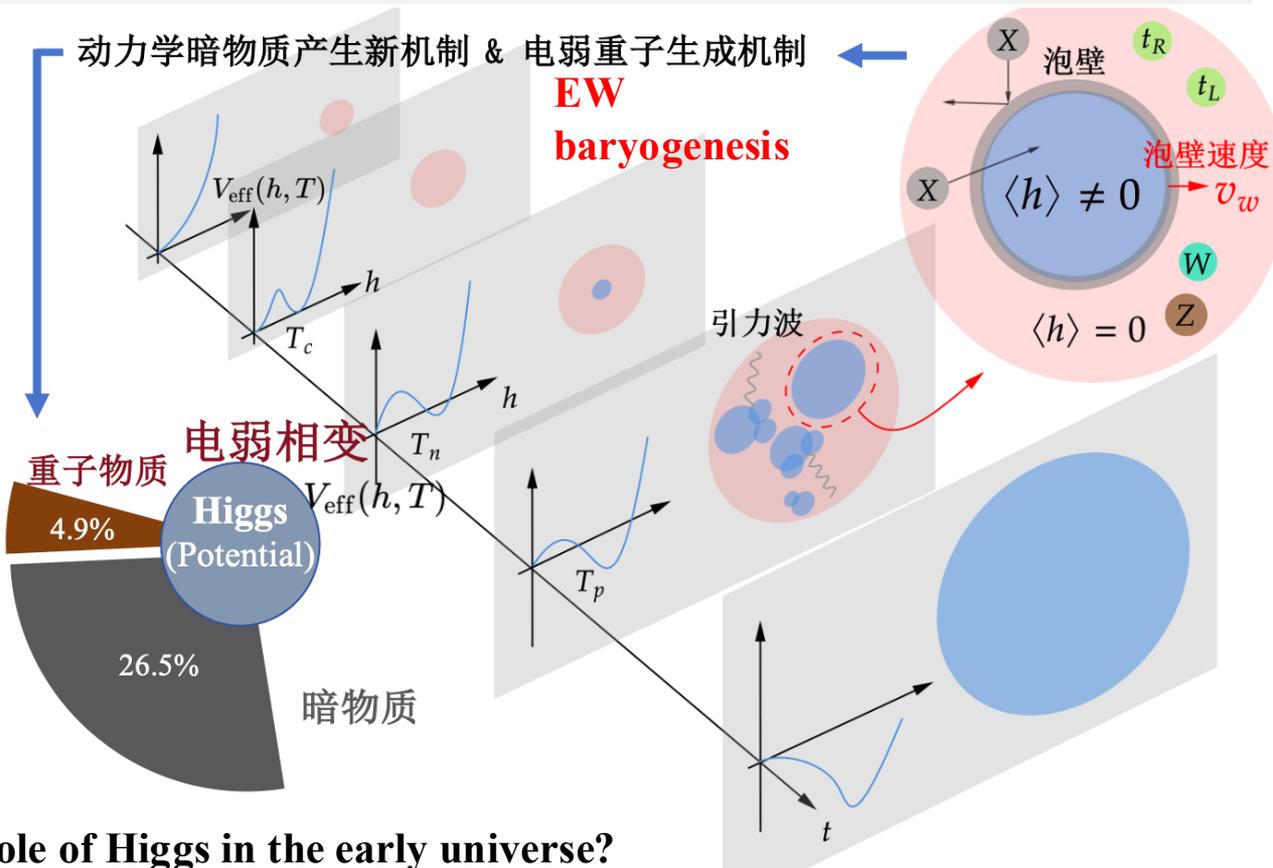


Baryogenesis in post-Higgs and GW Era

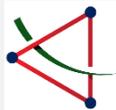
The observation of Higgs@LHC and GW@LIGO initiates a new era of exploring baryogenesis. SFOPT by Higgs could provide a necessary condition for EW baryogenesis.

Higgs' deep connections to cosmology, such as Higgs inflation, dark matter, and

EW baryogenesis testable by particle physics experiments and GW signals.

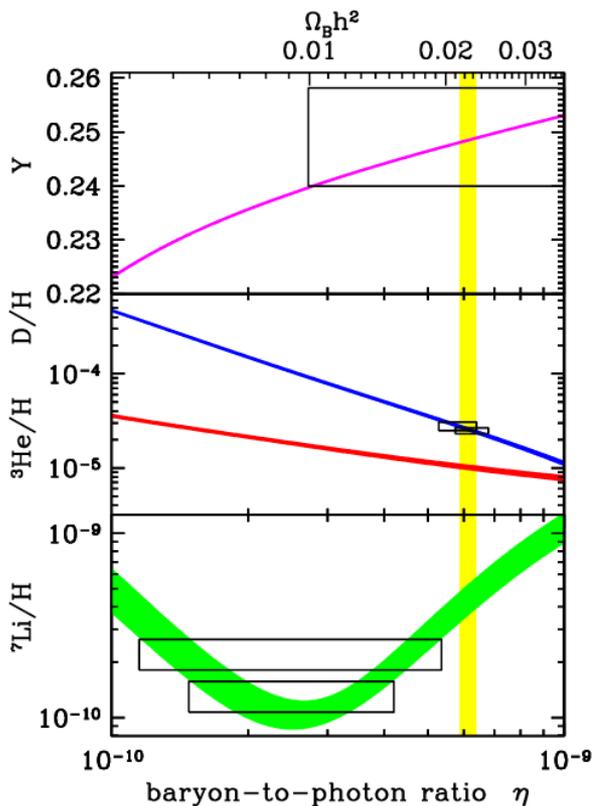


What is the role of Higgs in the early universe?

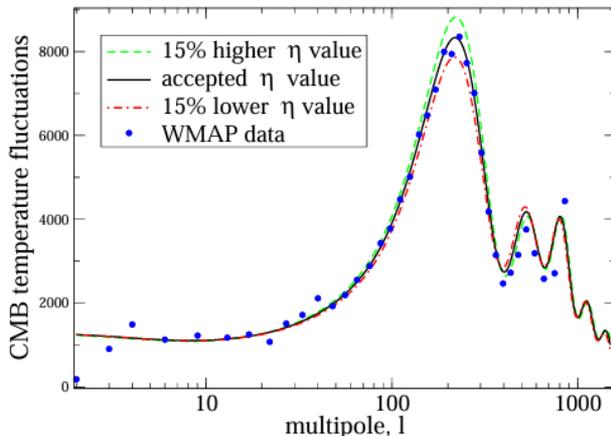


宇宙正反物质不对称的天文和宇宙学证据

BBN



CMB



$$\eta = n_B/n_\gamma \approx 6.10^{-10}$$

- 狄拉克方程对正反粒子是对称的
- 宇宙主要由物质组成
- 反物质只存在于宇宙射线和实验中

什么导致了正反物质不对称?
baryogenesis
需要超出标准模型新物理

One beautiful dream:
电弱重子数生成机制(EW Baryogenesis)



The first particles

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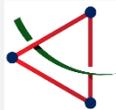


The first particles

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Sakharov (1967): three conditions for baryogenesis

- 重子数破坏
- C (电荷共轭)和 CP (电荷-宇称联合变换) 破坏
- 偏离热平衡的过程
- 如果模型的哈密顿量 (拉氏量) 不破坏重子数, 则不会有重子数的产生;

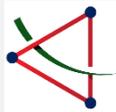
$$[H, B] = 0$$

- 若系统维持 CP 守恒, 破坏重子数的反应过程将产生等量的重子与反重子, 无法实现正反重子的不对称;

$$\Gamma(X \rightarrow YB) = \Gamma(\bar{X} \rightarrow \bar{Y}\bar{B})$$

- 热平衡将导致被产生的重子数不对称将立刻被逆过程冲刷 (wash-out) 掉;

$$\Gamma(X \rightarrow YB) = \Gamma(YB \rightarrow X)$$



EW baryogenesis

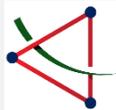
A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe.

After discovery of Higgs@LHC & GW @aLIGO, EW baryogenesis becomes a testable scenario.

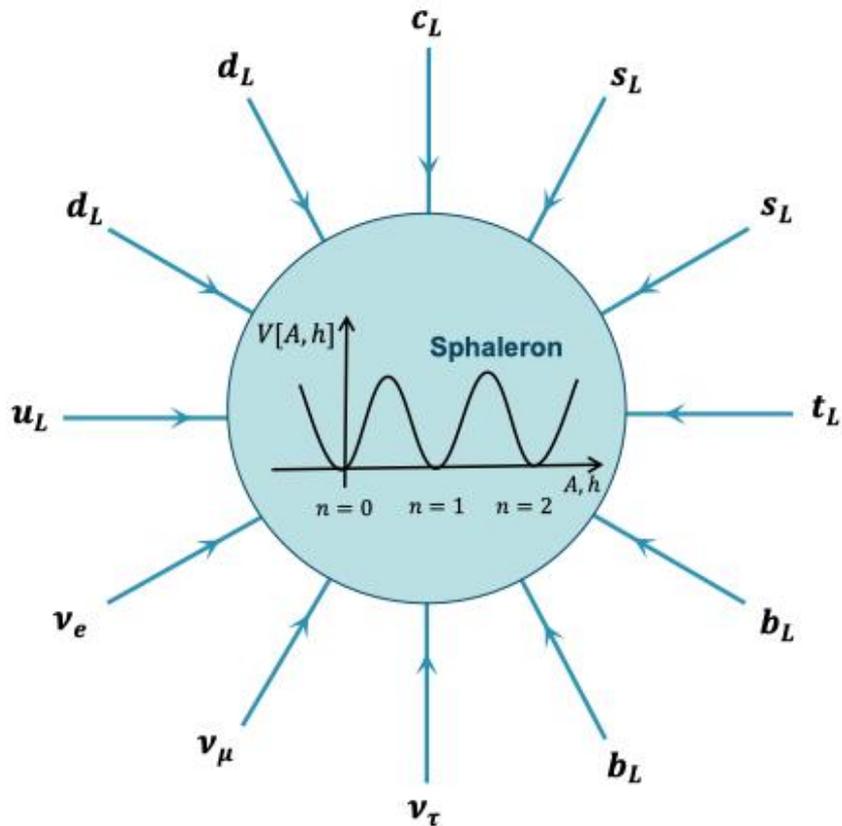
One beautiful dream:
电弱重子数生成 机制
(EW Baryogenesis)

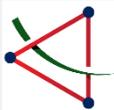
SM technically has all the 3 elements for baryogenesis (Sakharov conditions)

- B violation from anomaly in B+L current;
- C and CP-violation: CKM matrix, but too weak, need new CP-violating sources;
- Departure from thermal equilibrium: SFOPT with expanding Higgs bubble wall



标准模型中的重子数破坏过程Sphaleron





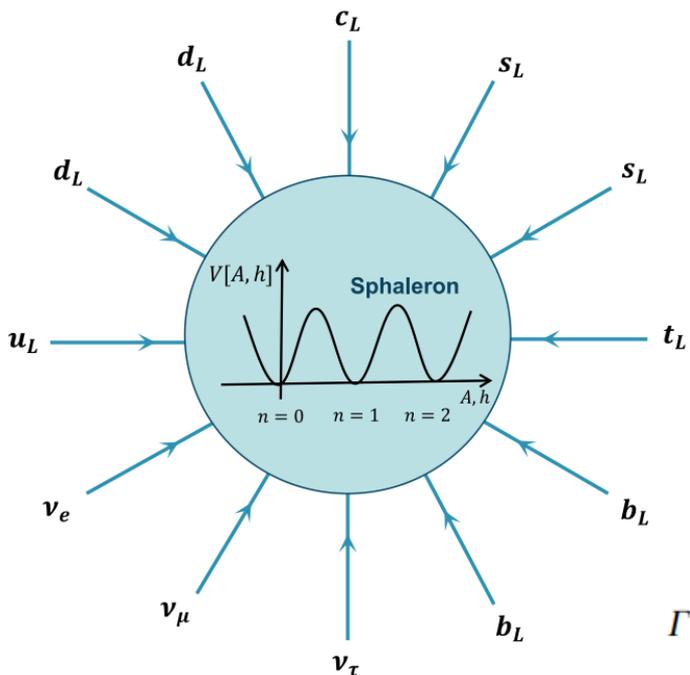
Sphaleron

- Adler-Bell-Jackiw 反常: 经典下守恒的对称性, 在量子水平下失效

$$\tilde{F}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$$

- 手征规范理论提供了重子数和轻子数破坏

$$\partial_\mu j_B^\mu = \partial_\mu j_L^\mu = N_f \left(\frac{g^2}{32\pi^2} W_{\mu\nu}^a \tilde{W}^{a\mu\nu} - \frac{g'^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$



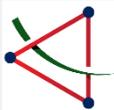
$$\Delta B(t) = \Delta L(t) = \Delta N_{CS} \equiv N_f [N_{CS}(t) - N_{CS}(0)]$$

$$N_{CS}(t) = \frac{g_2^3}{96\pi^2} \int d^3x \epsilon^{ijk} \epsilon_{abc} W_i^a W_j^b W_k^c(t)$$

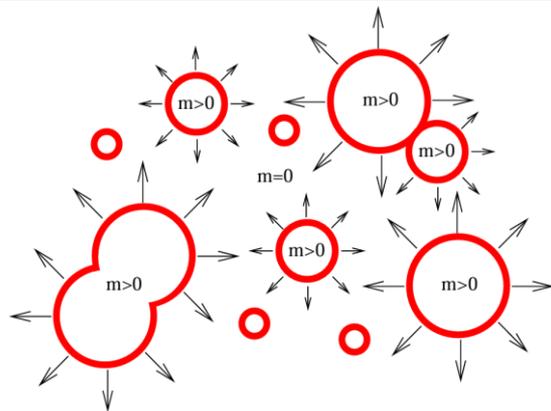
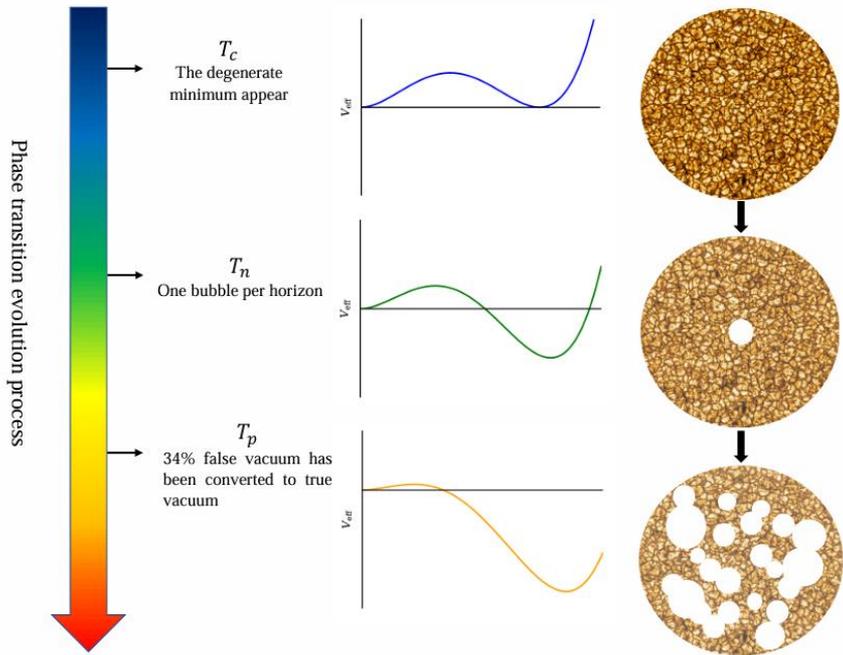
重子数 B 和轻子数 L 均被 Sphaleron 破坏, 但是 **B-L 守恒** → Leptogenesis (see **Chao and Han's** talks this morning)

$$\Gamma_S(T) = \mu \left(\frac{M_W}{\alpha_W T} \right)^3 M_W^4 \exp\left(-\frac{E_{\text{sph}}(T)}{T}\right)$$

Sphaleron 在对称相有效, 在破缺相被玻尔兹曼压低



宇宙一级相变



- 一级相变：伪真空与真真空存在势垒，真空从亚稳态通过量子隧穿或热隧穿到达能量更低的稳态
- 温度降低至核合成温度后，宇宙中将凝结大量泡泡
- 泡泡壁附近的物理过程强烈偏离热平衡



Electroweak Baryogenesis

泡泡壁对正反粒子施加不同的作用力，产生手征不对称

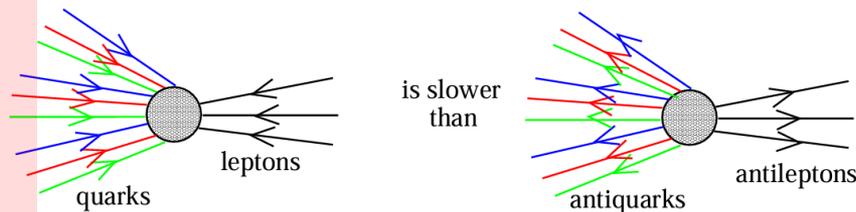
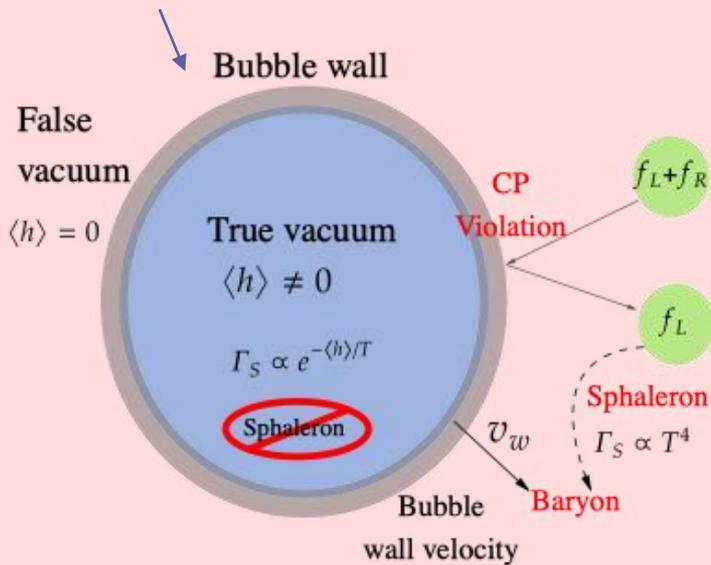
$$\mathcal{L}_Y = Y_{ij} \bar{\psi}_{Ri} \chi_{Lj} \phi + Y_{ij}^\dagger \bar{\chi}_{Lj} \psi_{Ri} \phi^\dagger,$$

$$[CP] \mathcal{L}_Y [CP]^\dagger = Y_{ij} \bar{\chi}_{Lj} \psi_{Ri} \phi^\dagger + Y_{ij}^\dagger \bar{\psi}_{Ri} \chi_{Lj} \phi.$$

$$P_{t_L \rightarrow t_R} \neq P_{t_L^c \rightarrow t_R^c}$$

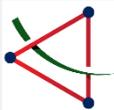
$$\Delta = n_{t_L} - n_{t_L^c} = -(n_{t_R} - n_{t_R^c}) \neq 0$$

只有左手的费米子和右手的反费米子参与 Sphaleron



$$\frac{dn_B}{dt} = -n_F \frac{\hat{\Gamma}_{sph}}{2T} \sum_{generations} (3\hat{\mu}_{U_L} + 3\hat{\mu}_{D_L} + \hat{\mu}_{\ell_L} + \hat{\mu}_{\nu_L})$$

手征不对称被 Sphaleron 转化为重子不对称



标准模型 CP 破坏

标准模型 CP 破坏

$$-\frac{g_2}{\sqrt{2}}\bar{u}_L\gamma^\mu d_L W_\mu^+ + h.c. = -\frac{g_2}{\sqrt{2}}\bar{u}_L^{(m)}(U_L^\dagger D_L)\gamma^\mu d_L^{(m)}W_\mu^+ + h.c..$$

CKM matrix

$$V_{CKM} \equiv U_L^\dagger D_L.$$

$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}c_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}.$$

CKM matrix provides the source of CP violation

$$-\frac{g_2}{\sqrt{2}}\bar{u}_L V_{CKM}\gamma^\mu d_L W_\mu^+ - \frac{g_2}{\sqrt{2}}\bar{d}_L V_{CKM}^\dagger\gamma^\mu u_L W_\mu^- \\ \xrightarrow{CP} -\frac{g_2}{\sqrt{2}}\bar{d}_L V_{CKM}^T\gamma^\mu u_L W_\mu^- - \frac{g_2}{\sqrt{2}}\bar{u}_L V_{CKM}^*\gamma^\mu d_L W_\mu^+.$$

$$V_{CKM}^* \neq V_{CKM}.$$

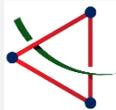
Jarlskog invariant

$$\Delta_{CP} \sim (M_W^6 T^6)^{-1} \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) J$$

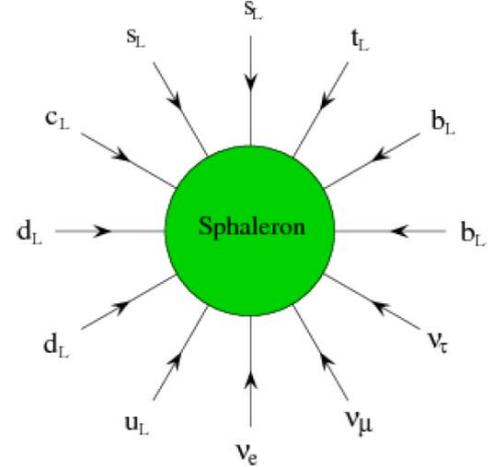
$$J = \text{Im}(V_{ud}V_{cs}V_{us}^*V_{cd}^*) \sim 3 \times 10^{-5}$$

标准模型的 CP 破坏不足以实现 baryogenesis!

Phys. Rev. Lett. 70 (1993) 2833–2836;
Phys. Rev. D50 (1994) 774; Mod. Phys.
Lett. A9 (1994) 795–810; Phys. Rev. D51
(1995) 379–394



EW baryogenesis



$$\Gamma_S \sim \text{Exp}(-\phi_C/T_C)$$

CP
Violation

$$f_L + f_R$$

$$f_L$$

$$\Gamma_S \sim T^4$$



Credit:
T. Cohen



EW baryogenesis

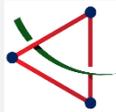
$$\Delta(n_B - \bar{n}_B) = 0$$



$$\Delta(n_B - \bar{n}_B) \neq 0$$

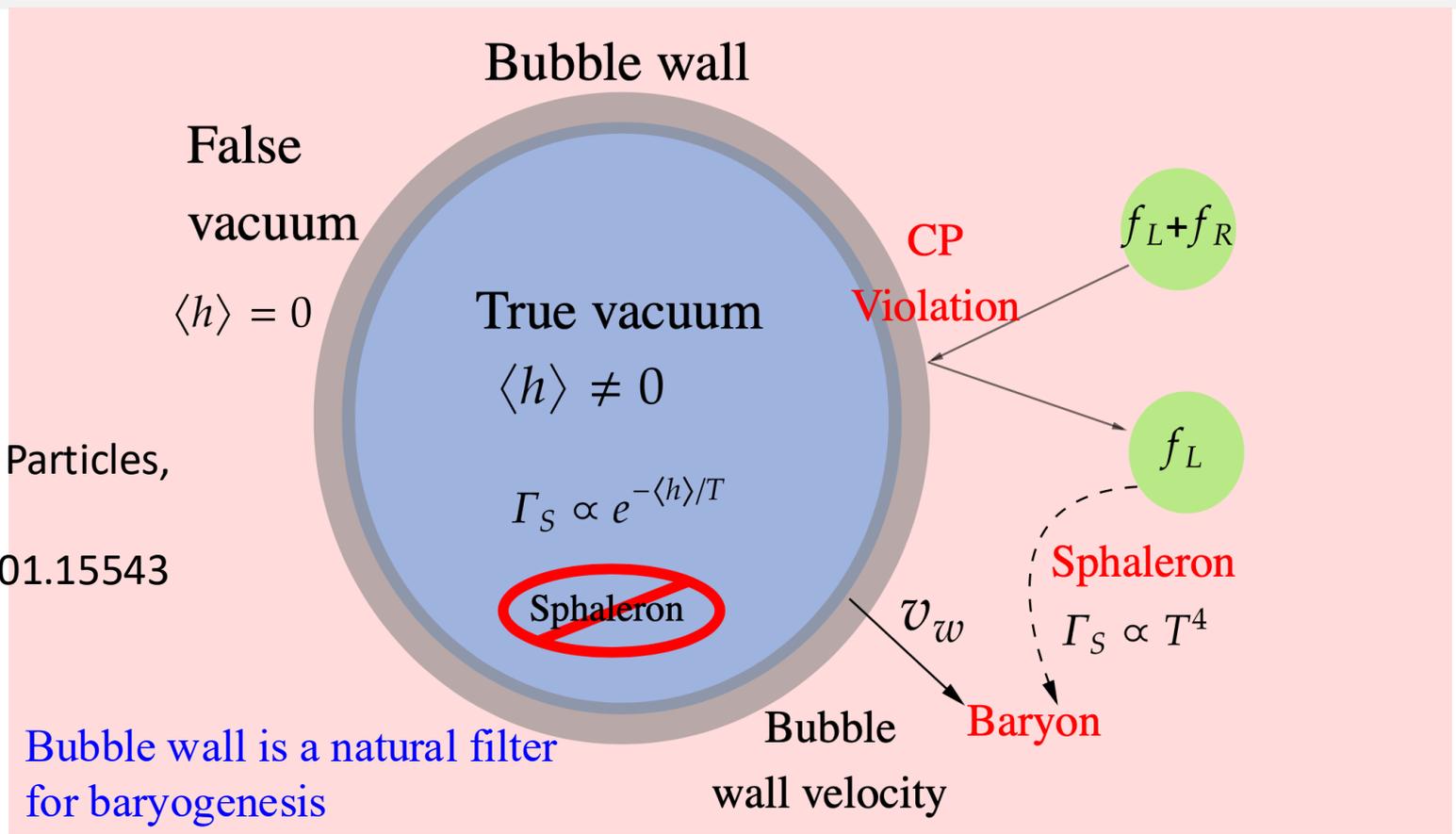


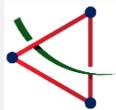
Credit:
T. Cohen



EW baryogenesis

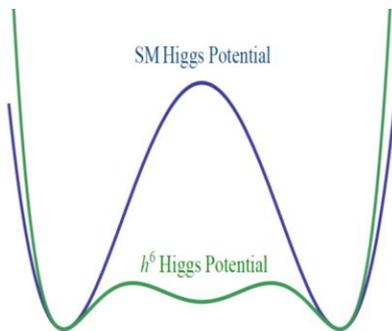
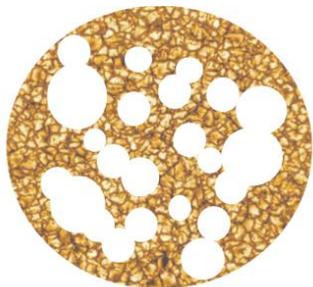
The First Particles,
FPH,
arXiv: 2501.15543



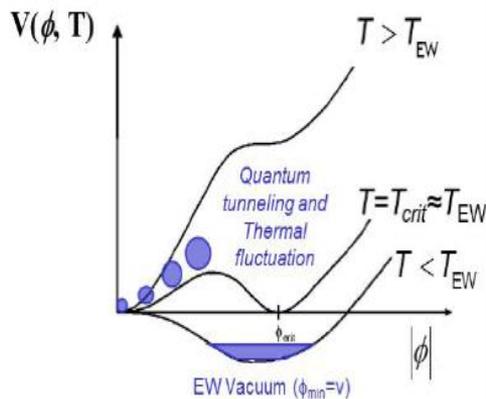


偏离热平衡条件

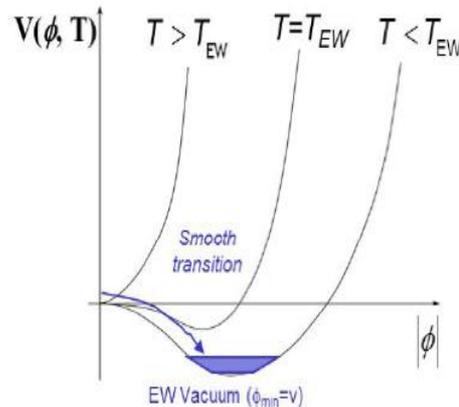
From
lattice
simulation



SFOPT for $m_H < 75$ GeV



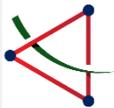
Cross over for $m_H > 75$ GeV



Extension of the Higgs sector is needed to SFOPT for 125 GeV Higgs boson.

We discuss well-motivated extensions (baryogenesis) of Higgs section to realize strong first-order phase transition (SFOPT) with abundant cosmological effects.

EW phase transition and its GW signals becomes realistic after the discovery of Higgs by LHC and GW by LIGO.



偏离热平衡条件

标准模型的电弱相
变不是一级相变!

标准模型有效势

$$D = \frac{1}{8v^2} (2m_W^2 + m_Z^2 + 2m_t^2),$$

$$E = \frac{1}{4\pi v^3} (2m_W^3 + m_Z^3),$$

$$T_0^2 = \frac{1}{4D} (m_h^2 - 8Bv^2),$$

$$B = \frac{3}{64\pi^2 v^4} (2m_W^4 + m_Z^4 - 4m_t^4),$$

$$\lambda(T) = \lambda - \frac{3}{16\pi v^4} \left[2m_W^4 \log\left(\frac{m_W^2}{A_B T^2}\right) + m_Z^4 \log\left(\frac{m_Z^2}{A_B T^2}\right) - 4m_t^4 \log\left(\frac{m_t^2}{A_F T^2}\right) \right],$$

$$V_{\text{tree}} = \frac{\mu^2}{2} \phi_c^2 + \frac{\lambda}{4} \phi_c^4$$

$$V_{CW}(\phi_c) = \frac{1}{64\pi^2} \sum_{i=h,x,t,W,Z} (-1)^{F_i} g_i m_i^4(\phi_c) \left(\log \frac{m_i^2(\phi_c)}{\mu^2} - c_i \right)$$

$$V_T(\phi_c) = \frac{T^4}{2\pi^2} \left[\sum_{i=W,Z,h,x} g_i J_B \left(\frac{m_i^2(\phi_c)}{T^2} \right) - g_t J_F \left(\frac{m_t^2(\phi_c)}{T^2} \right) \right]$$

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

$$\frac{v(T_c)}{T_c} = \frac{2E}{\lambda(T_c)}$$

$$E = \frac{2m_W^3 + m_Z^3}{4\pi v^3} = 9.6 \times 10^{-3}$$

$$\frac{v(T_c)}{T_c} \geq 1.0 \longrightarrow m_h \lesssim 42 \text{ GeV}$$



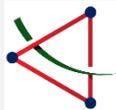
EW baryogenesis

Over the past several decades, many EW baryogenesis models have been ruled out by collider experiments, EDM searches, and related precision measurements. See Wei Chao and Chengcheng Han's talks for recent new progress on the new baryogenesis models.

To clearly show the general experimental predictions of the EW baryogenesis models, we take the following two models as benchmark models:

$$\delta\mathcal{L} = -x_u^{ij} \frac{H^\dagger H}{\Lambda^2} \bar{Q}_{Li} \tilde{H} u_{Rj} + \text{H.c.} - \frac{\kappa}{\Lambda^2} (H^\dagger H)^3$$

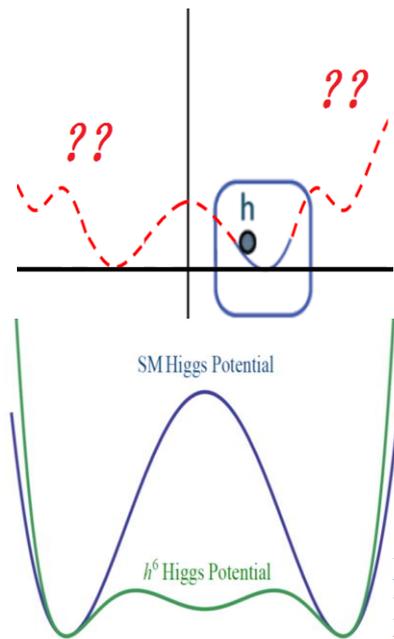
$$\mathcal{L} = \mathcal{L}_{\text{SM}} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{H} t_R + \text{H.c.} + \frac{1}{2} \partial_\mu S \partial^\mu S + \frac{1}{2} \mu^2 S^2 - \frac{1}{4} \lambda S^4 - \frac{1}{2} \kappa S^2 (H^\dagger H)$$



SFOPT and Higgs potential

What is the shape of Higgs potential?

Current data tells us nothing but the quadratic oscillation around the VEV 246 GeV with 125 GeV mass. **mass**



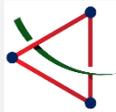
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4}h^4$$



or
$$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4}h^4 + \frac{1}{\Lambda^2}h^6$$

Produce a SFOPT, large deviation of Higgs trilinear coupling, and GW

Xinmin Zhang Phys.Rev. D47 (1993) 3065-3067; C. Grojean, G. Servant, J. Well PRD71(2005)036001
 D.J.H. Chung, A. J. Long, Lian-tao Wang Phys.Rev. D87(2013) 023509
FPH, et.al, Phys.Rev.D94(2016)no.4,041702 ; **FPH**, et.al, Phys.Rev.D93 (2016) no.10,103515
 arXiv:1511.06495, Nima Arkani-Hamed et. al.; PreCDR of CEPC; arXiv: [1811.10545](https://arxiv.org/abs/1811.10545), CDR of CEPC



SFOPT and Higgs potential

SM EFT

$$\mathcal{L} \supset -\mu^2 |H|^2 - \lambda |H|^4 + c_6 |H|^6$$

$$+ c_T \mathcal{O}_T + c_{WW} \mathcal{O}_{WW} + \text{other dimension-six operators}$$

$$\delta_{\sigma(hZ)} \approx (0.26c_{WW} + 0.01c_{BB} + 0.04c_{WB} - 0.06c_H - 0.04c_T + 0.74c_L^{(3)\ell}$$

$$+ 0.28c_{LL}^{(3)\ell} + 1.03c_L^\ell - 0.76c_R^e) \times 1 \text{ TeV}^2 + 0.016\delta_h,$$

SFOPT produces large modification of trilinear Higgs coupling

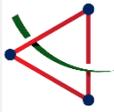
δ_h

c_6

dominates the hZ cross section deviation

Taking a general study of the scalar extended models and the composite Higgs model as examples, we find that the Higgs sextic scenario still works well after considering all the dim-6 operators and the precise measurements.

Qing-Hong Cao, FPH, Ke-Pan Xie, Xinmin Zhang, arXiv:1708.0473,



SFOPT and Higgs potential

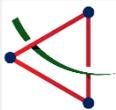
One examples

Qing-Hong Cao, **FPH**, Ke-Pan Xie, Xinmin Zhang, arXiv:1708.0473,

$$\begin{aligned} \delta\mathcal{L} = & D_\mu\Phi^\dagger D^\mu\Phi - M_\Phi^2\Phi^\dagger\Phi - \frac{\lambda_\Phi}{4}(\Phi^\dagger\Phi)^2 - \lambda_1\Phi^\dagger\Phi H^\dagger H - \lambda_2|\Phi \cdot H|^2 \\ & - \lambda_3[(\Phi \cdot H)^2 + h.c.] + (\eta_H|H|^2 + \eta_\Phi|\Phi|^2)(\Phi \cdot H + h.c.), \end{aligned}$$

Using **Covariant Derivative Expansion method**, the matched dim-6 operators and their coefficients in the doublet scalar models are obtained:

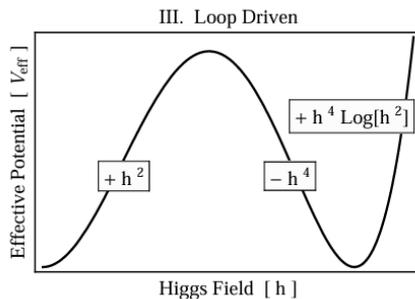
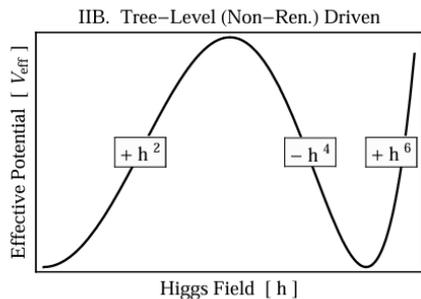
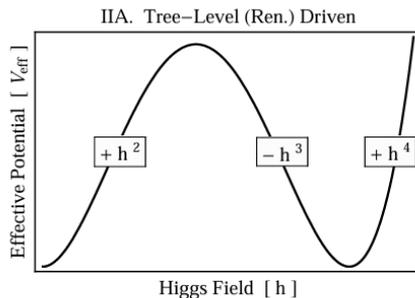
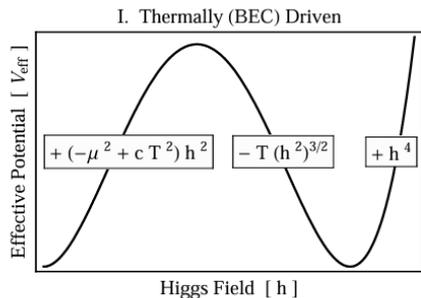
Dimension-six operator	Wilson coefficient
$\mathcal{O}_{WW} = g^2 H ^2 W_{\mu\nu}^a W^{a,\mu\nu}$	$c_{WW} = \frac{1}{(4\pi)^2} \frac{1}{48} (2\lambda_1 + \lambda_2) \frac{1}{M_\Phi^2}$
$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W_{\mu\nu}^a)^2$	$c_{2W} = \frac{1}{(4\pi)^2} \frac{g^2}{60} \frac{1}{M_\Phi^2}$
$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon^{abc} W_\rho^{a\mu} W_\mu^{b\nu} W_\nu^{c\rho}$	$c_{3W} = \frac{1}{(4\pi)^2} \frac{g^2}{60} \frac{1}{M_\Phi^2}$
$\mathcal{O}_{BB} = g'^2 H ^2 B_{\mu\nu} B^{\mu\nu}$	$c_{BB} = \frac{1}{(4\pi)^2} \frac{1}{48} (2\lambda_1 + \lambda_2) \frac{1}{M_\Phi^2}$
$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}$	$c_{WB} = \frac{1}{(4\pi)^2} \frac{\lambda_2}{24} \frac{1}{M_\Phi^2}$
$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B^{\mu\nu})^2$	$c_{2B} = \frac{1}{(4\pi)^2} \frac{g'^2}{60} \frac{1}{M_\Phi^2}$
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu H ^2)^2$	$c_H = \frac{1}{(4\pi)^2} [6\eta_\Phi\eta_H + \frac{1}{12}(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2 + 4\lambda_3^2)] \frac{1}{M_\Phi^2}$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$c_T = \frac{1}{(4\pi)^2} \frac{1}{12} (\lambda_2^2 - 4\lambda_3^2) \frac{1}{M_\Phi^2}$
$\mathcal{O}_r = H ^2 D_\mu H ^2$	$c_r = \frac{1}{(4\pi)^2} (6\eta_\Phi\eta_H + \frac{1}{6}(\lambda_2^2 + 4\lambda_3^2)) \frac{1}{M_\Phi^2}$
$\mathcal{O}_6 = H ^6$	$c_6 = \eta_H^2 + \frac{1}{(4\pi)^2} [\frac{3}{2}\lambda_\Phi\eta_H^2 + 6\eta_\Phi(\lambda_1 + \lambda_2) - \frac{1}{6}(2\lambda_1^3 + 3\lambda_1^2\lambda_2 + 3\lambda_1\lambda_2^2 + \lambda_2^3) - 2(\lambda_1 + \lambda_2)\lambda_3^2] \frac{1}{M_\Phi^2}$



SFOPT and new Higgs potential

电弱一级相变的实现: Modify the Higgs sector

Daniel J. H. Chung, Andrew J. Long, and Lian-Tao Wang, Phys.Rev.D 87 (2013) 2, 023509

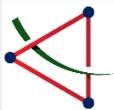


Type. I

$-\Delta C$	c	e
	$c_{\text{SM}} = \frac{6m_t^2 + 6m_W^2 + 3m_Z^2 + \frac{3}{2}m_H^2}{12v^2}$	$e_{\text{SM}} = \frac{6m_W^3 + 3m_Z^3}{v^3}$
	$c_{\text{SM}} + \frac{6m_t^2}{12v^2} \left(1 - \frac{A_t^2}{m_t^2}\right)$	$e_{\text{SM}} + \frac{6m_t^3}{v^3} \left(1 - \frac{A_t^2}{m_t^2}\right)^{3/2}$
$M_X^2 X ^2 + \frac{\kappa}{6} X ^4 + Q H ^2 X ^2$	$c_{\text{SM}} + \frac{6}{24} \frac{Q}{\kappa^2}$	$e_{\text{SM}} + 6 \left(\frac{Q}{\kappa}\right)^{3/2}$
$M^2 S ^2 + \lambda_S S ^4 + 2C^2 H ^2 S ^2$	$c_{\text{SM}} + \frac{g_S^2}{24} \frac{C^2}{\lambda_S^2}$	$e_{\text{SM}} + g_S C^3$
$\mu_S^2 S ^2 + \lambda_S S ^4 + \lambda_{H_S} H ^2 S ^2 + \frac{1}{2} y_i S \nu_i \nu_i + \text{h.c.}$	$c_{\text{SM}} + \frac{2\lambda_S}{24} \frac{\lambda_{H_S}}{\lambda_S^2}$	$e_{\text{SM}} + 2 \left(\frac{\lambda_{H_S}}{\lambda_S}\right)^{3/2}$
$\mu_D^2 D^\dagger D + \lambda_D (D^\dagger D)^2 + \lambda_3 H^\dagger H D^\dagger D + \lambda_4 H^\dagger D ^2 + (\lambda_5/2)[(H^\dagger D)^2 + \text{h.c.}]$	$c_{\text{SM}} + \frac{2\lambda_3 + \lambda_4}{12}$	$e_{\text{SM}} + 2 \left(\frac{\lambda_3}{2}\right)^{3/2} + \left(\frac{\lambda_3 + \lambda_4 - \lambda_5}{2}\right)^{3/2} + \left(\frac{\lambda_3 + \lambda_4 + \lambda_5}{2}\right)^{3/2}$

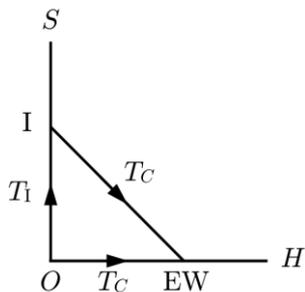
Type. IIA

ΔC
$\frac{1}{2} (\partial S)^2 - \left[\frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4 + \frac{a_1}{2} H^\dagger H S^2 + \frac{a_2}{2} H^\dagger H S^2 \right]$
$\frac{1}{2} (\partial S)^2 - \left[\frac{b_2}{2} S^2 + \frac{b_4}{4} S^4 + \frac{a_2}{2} H^\dagger H S^2 \right]$
$\mu_D^2 D ^2 + \lambda_D D ^4 + \lambda_3 H ^2 D ^2 + \lambda_4 H^\dagger D ^2 + (\lambda_5/2)[(H^\dagger D)^2 + \text{h.c.}]$
ΔW
$\lambda H_1 H_2 N - \frac{\kappa}{3} N^3 + r N$
$\lambda H_1 H_2 S + \frac{m_{12}^2}{\lambda} S$
$-\lambda_i H_1 H_2 \nu_i^c + \frac{\kappa_{ijk}}{3} \nu_i^c \nu_j^c \nu_k^c + Y_\nu^{ij} H_2 L_i \nu_j^c$

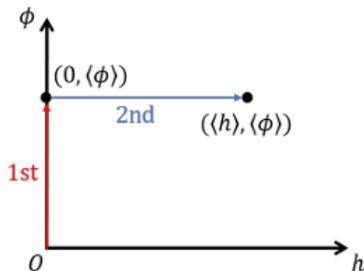
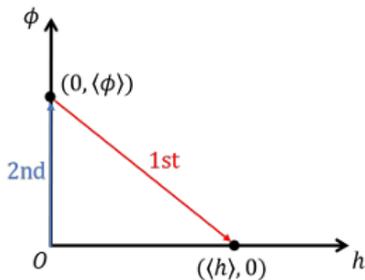


EW SFOPT

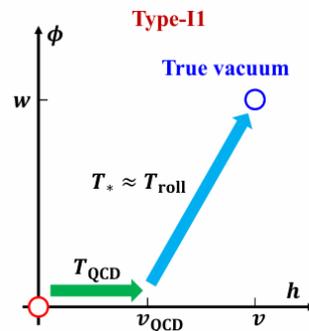
Multi-step phase transition



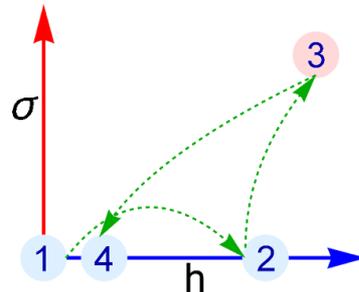
$$V_0(H, S) = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \frac{\mu_S^2}{2} S^2 + \frac{\lambda_S}{4} S^4 + \frac{\lambda_{HS}}{2} H^\dagger H S^2$$



Zizhuo Zhao, Yuefeng Di, Ligong Bian, Rong-Gen Cai,
JHEP 10 (2023) 158



Wei Liu, Ke-Pan Xie,
Phys.Rev.D 110 (2024) 11, 115001



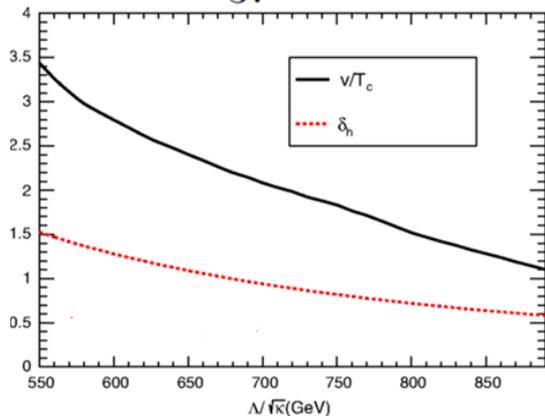
Wei Chao, Huai-Ke Guo, Xiu-fei Li,
Phys.Lett.B 849 (2024) 138430



SFOPT and Higgs potential

SFOPT leads to obvious deviation of the tri-linear Higgs coupling

$$\mathcal{L}_{hhh} = -\frac{1}{3!}(1 + \delta_h)A_h h^3$$

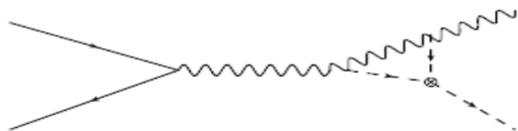


At one-loop level, deviation of the tri-linear Higgs coupling

$$\delta_h \in (0.6, 1.5)$$

The Circular Electron Positron Collider (CEPC), ILC, FCC-ee can precisely test this scenario by precise measurements of the hZ cross section ($e^- e^+ \rightarrow hZ$).

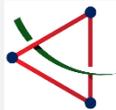
SM NNLO hZ cross section recently by Lilin Yang, et al 2016 \square Yu Jia et al 2016



$$\delta_\sigma = \frac{\sigma_{hz, \delta_h \neq 0}}{\sigma_{hz, SM}} - 1$$

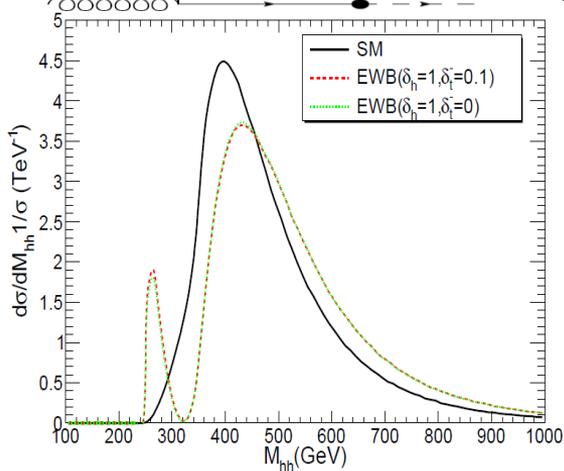
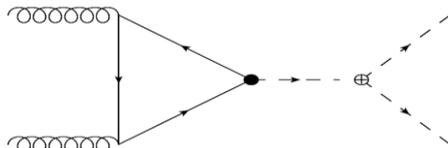
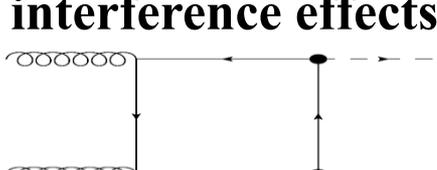
$$-x_u^{ij} \frac{H^\dagger H}{\Lambda^2} \bar{Q}_{Li} \tilde{H} u_{Rj} + \text{H.c.} - \frac{\kappa}{\Lambda^2} (H^\dagger H)^3$$

See the works of Lilin Yang, Zhao Li Yu Jia et.al,



SFOPT and Higgs potential

Hints at hadron collider: **Modify the invariant mass distribution of Higgs pair due to interference effects:**



Two peaks for the baryogenesis scenario, one peak for the SM.

Due to the difficulties to suppress backgrounds at the LHC, it will be difficult to completely pin down these anomalous coupling at 14 TeV LHC, even with 3000 ab^{-1} integrated luminosity.

Exploiting boosted tricks helps to increase ability to extract the anomalous couplings.

More precise information may come from future 100 TeV hadron collider, such as SppC, or future lepton collider, such as CEPC.

$$-x_u^{ij} \frac{H^\dagger H}{\Lambda^2} \bar{Q}_{Li} \tilde{H} u_{Rj} + \text{H.c.} - \frac{\kappa}{\Lambda^2} (H^\dagger H)^3$$

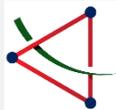
SFOPT requires

$$\kappa_3 \in (0.6, 1.5)$$

Current constraints from LHC

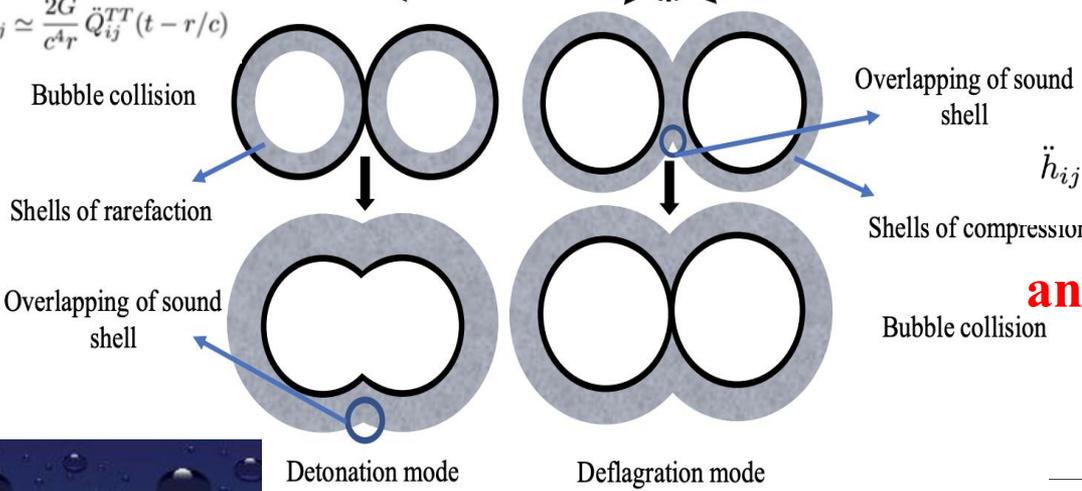
$$\kappa_3 \in [-0.4, 6.3]$$

实验探测能力的提升对检验电弱重子生成机制至关重要



Phase transition GW in a nutshell

$$h_{ij} \simeq \frac{2G}{c^4 r} \ddot{Q}_{ij}^{TT}(t - r/c)$$



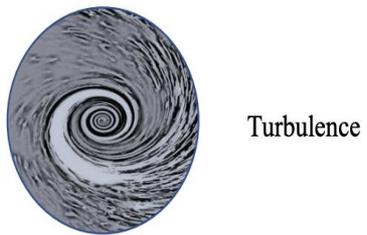
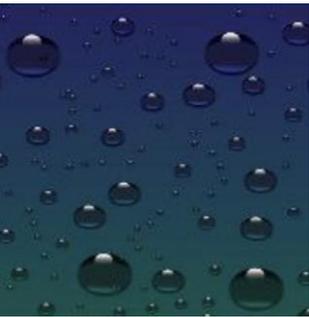
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\ddot{h}_{ij}(\mathbf{x}, t) + 3H \dot{h}_{ij}(\mathbf{x}, t) - \frac{\nabla^2}{a^2} h_{ij}(\mathbf{x}, t) = 16\pi G \Pi_{ij}(\mathbf{x}, t)$$

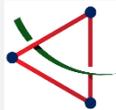
**anisotropic stress tensor:
source of GW**

E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983);
M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))
EW phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

General form Π_{ij}
$[\partial_i \phi \partial_j \phi]^{TT}$
$[\gamma^2(\rho + p)v_i v_j]^{TT}$
$[-E_i E_j - B_i B_j]^{TT}$
$\partial_i \Psi, \partial_i \Phi$



Xiao Wang, FPH, Xinmin Zhang, JCAP05(2020)045



Phase transition GW in a nutshell

characteristic frequency of the GW signal

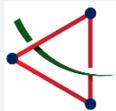
$$f_* = \frac{1}{\ell_*} \geq H_*$$

$$\epsilon_* = \ell_* H_*$$

Ratio of the typical length-scale of the GW sourcing process (size of the anisotropic stresses) and the Hubble scale at the generation time

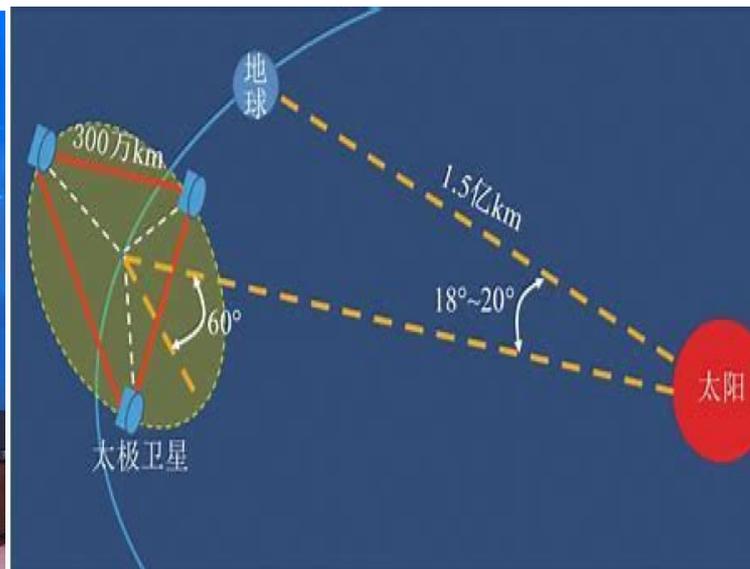
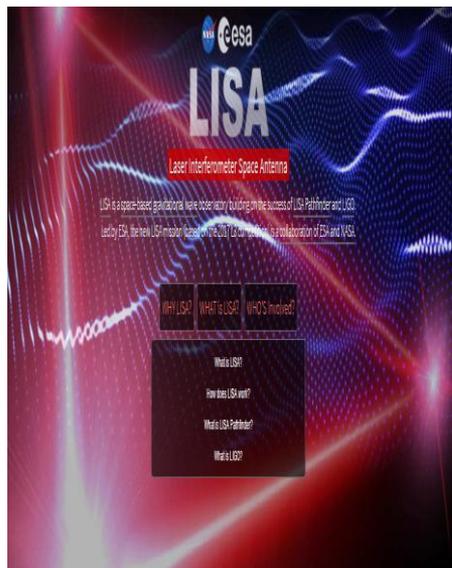
$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\epsilon_*} \left(\frac{g(T_*)}{100} \right)^{1/6} \frac{T_*}{\text{GeV}} \text{ Hz}$$

电弱相变对应的峰值频率在mHz附近，刚好也在空间引力波实验(LISA、天琴、太极)的探测区间



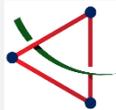
GW experiments

LISA/TianQin/Taiji ~2034



“天琴”

“Harpe in space”



Phase transition dynamics

Theory: The most important and difficult phase transition parameter for GW, dynamical DM, baryogenesis is bubble wall velocity v_w

Experiment: GW experiment is most sensitive to bubble wall velocity v_w

arXiv: 2404.18703
Aidi Yang, **FPH**

Finite-temperature effective potential

$$V_{eff}(\phi, T)$$

α

T_p

$R_* H_*$

- (1). Daisy resummation problem: Pawani scheme vs. Arnold scheme
- (2). Gauge dependence problem: see Michael J. Ramsey-Musolf's works
- (3). No perturbative calculations: lattice calculations and dim-reduction method: by D. Weir, Michael J. Ramsey-Musolf et.al

Bubble wall velocity
this talk v_w

Energy budget
 κ

S. Hoche, J. Kozaczuk, A. J. Long, J. Turner and Y. Wang
, arXiv:2007.10343,
Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith, arXiv:2009.14295v2
Xiao Wang, **FPH**, Xinmin Zhang, arXiv:2011.12903
Siyu Jiang, **FPH**, xiao wang,
Phys.Rev.D 107 (2023) 9, 095005

F. Giese, T. Konstandin, K. Schmitz and J. van de
, arXiv:2010.09744
Xiao Wang, **FPH** and Xinmin Zhang,
Phys.Rev.D 103 (2021) 10, 103520
Xiao Wang, Chi Tian, **FPH**, JCAP 07 (2023) 006

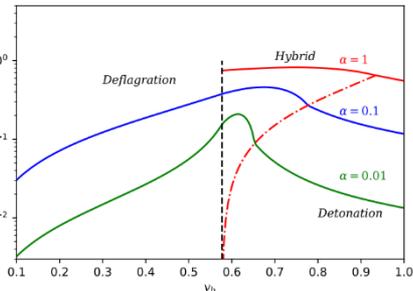
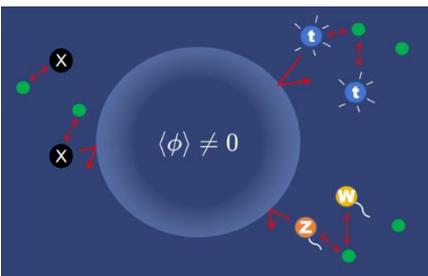
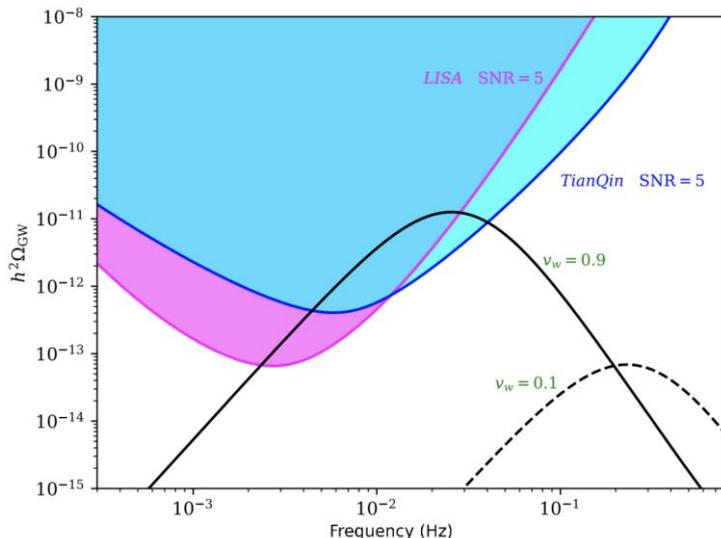


Bubble wall is essential (like a filter)

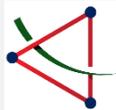
The most essential parameter for
 phase transition GW, phase
 transition DM, baryogenesis v_w

GW detection favor larger v_w
 EW baryogenesis favor smaller v_w
 Dynamical DM is sensitive to v_w

S. Hoche, J. Kozaczuk, A. J. Long, J. Turner and Y. Wang, arXiv:2007.10343,
 Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith,
 arXiv:2009.14295v2
 Xiao Wang, **FPH**, Xinmin Zhang, arXiv:2011.12903
 Siyu Jiang, **FPH**, xiao wang, Phys.Rev.D 107 (2023) 9, 095005

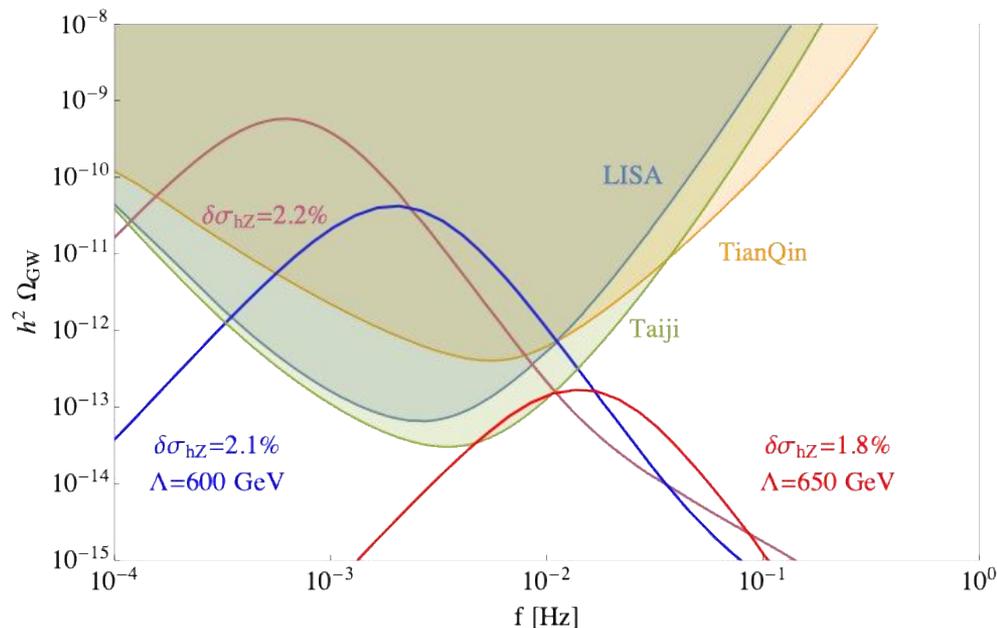


$$\eta_B = \frac{405 \Gamma_S}{4\pi^2 \gamma_w v_w g_* T} \int dz \mu_{BL}(z) f_{\text{sph}}(z) e^{-45 \Gamma_S |z| / (4 \gamma_w v_w)}$$



SFOPT and Higgs potential

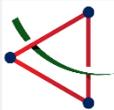
Correlate particle collider and GW signals: double test on Higgs potential from particle to wave



The cross section could be measured with an accuracy of 0.25 % at CEPC.
Chin.Phys.C 49
(2025) 123108

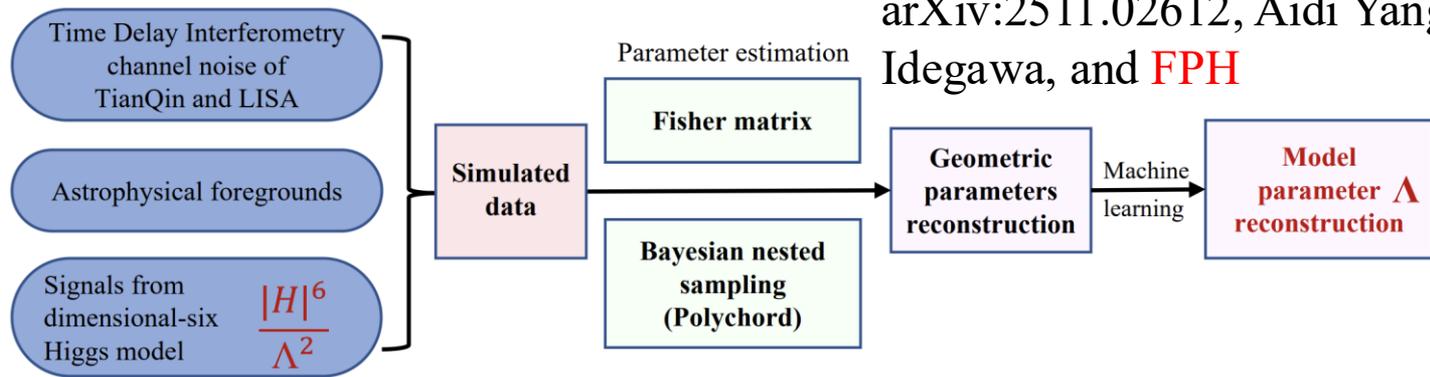
arxiv: [2502.20138](https://arxiv.org/abs/2502.20138)

FPH, et.al, Phys.Rev.D94(2016)no.4,041702 ; FPH, et.al, Phys.Rev.D93 (2016) no.10,103515

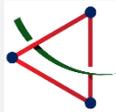


Model Parameter Reconstruction

arXiv:2511.02612, Aidi Yang, Chikako Idegawa, and **FPH**



Detector	Benchmark	Λ_{true} [GeV]	reconstructed Λ (Mean \pm Std) [GeV]	68% CI [GeV]	95% CI [GeV]
LISA	BP ₁	548.31	547.99 \pm 0.39	[547.54, 548.32]	[547.00, 548.57]
	BP ₂	549.02	549.39 \pm 0.22	[549.16, 549.57]	[549.01, 549.90]
	BP ₃	550.16	554.34 \pm 2.49	[551.36, 556.97]	[549.95, 558.69]
TianQin	BP ₁	548.31	548.07 \pm 0.30	[547.77, 548.33]	[547.31, 548.53]



EW baryogenesis

Extra CP violation source: Modify the phase of the Higgs sector

FPH,

Phys.Rev.D 93 (2016) 10, 103515

$$\delta\mathcal{L} = -x_u^{ij} \frac{\phi^\dagger \phi}{\Lambda^2} \bar{q}_{Li} \tilde{\phi} u_{Rj} + \text{H.c.} - \frac{\kappa}{\Lambda^2} (\phi^\dagger \phi)^3$$

$$\frac{v^2}{2\Lambda^2} h [\text{Re}(x_u^{ij}) \bar{t}t + i \text{Im}(x_u^{ij}) \bar{t}\gamma^5 t]$$

which can be rewritten as

$$\frac{v^2}{2\Lambda^2} h (a\bar{t}t + ib\bar{t}\gamma^5 t).$$

$$\mathcal{L} = -\frac{m_t}{v} h \bar{t} (1 + \delta_t^+ + i\delta_t^- \gamma^5) t$$

$$\delta_t^+ = \frac{av^3}{2\Lambda^2 m_t}$$

$$\delta_t^- = \frac{bv^3}{2\Lambda^2 m_t}$$

CP violation in baryogenesis (this CP violation source is strongly constrained by recent EDM data.)

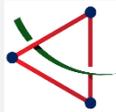
$$m_t(z) = \frac{m_t}{v} (1 + \delta_t^+ + i\delta_t^- \gamma^5) h(z) \equiv |m_t(z)| e^{i\Theta(z)}$$

See Meng Xiao's talk

Large theory uncertainty

$$\eta_B = \frac{405\Gamma_{\text{sph}}}{4\pi^2 v_{\text{wall}} g_* T} \int dz \mu_{BL} f_{\text{sph}} e^{-45\Gamma_{\text{sph}}|z|/(4v_{\text{wall}})}$$

$$\delta_t^- \sim \mathcal{O}(0.01)$$



Transport equations

Precise calculation of electroweak baryogenesis is difficult

$$\mathcal{L} \supset \frac{y_t}{\sqrt{2}} \phi \left(1 + c \frac{\phi^2}{\Lambda^2} \right) \bar{t}_L t_R + \text{h.c.} \longrightarrow m(\mathbf{x}, t) = \frac{y_t}{\sqrt{2}} v_b \left(1 + c \frac{v_b^2}{2\Lambda^2} \right) = |m| e^{i\theta}$$

Dirac equation for particle state

$$(i\not{\partial} - mP_L - m^*P_R)\psi = 0 \quad P_{L,R} = \frac{1}{2}(1 \mp \gamma_5)$$

$$\psi = \begin{pmatrix} q_L \\ q_R \end{pmatrix} = e^{-i\omega t} \begin{pmatrix} L_s \\ R_s \end{pmatrix} \otimes \chi_s$$

$$(\omega - is\partial_z)L_s = mR_s, \quad (\omega + is\partial_z)R_s = m^*L_s$$

$$\left[(\omega + is\partial_z) \frac{1}{m} (\omega - is\partial_z) - m^* \right] L_s = 0, \quad \left[(\omega - is\partial_z) \frac{1}{m^*} (\omega + is\partial_z) - m \right] R_s = 0$$

WKB approximation $L_s = \omega(z) e^{i \int^z p(z') dz'}$

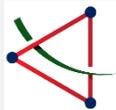
$$p = p_0 + \frac{s\omega + p_0}{2p_0} \theta' + \mathcal{O}(\partial_z^2), \quad p_0 = \text{sign}(p) \sqrt{\omega^2 - |m|^2} \Rightarrow \omega = \sqrt{(p + \theta'/2)^2 + |m|^2} - \frac{1}{2} s \theta'$$

Semi-classical force acting on particles

$$\dot{p} = - \left(\frac{\partial \omega}{\partial z} \right)_p = - \frac{(m^2)^2}{2\omega} + s s_c \frac{(m^2 \theta')'}{2\omega^2}$$

$$s_c = \pm 1$$

for particle/anti-particles



Transport equations

The distribution of particles follows the Boltzmann equations

$$(v_g \partial_z + F \partial_{p_z}) f = C[f]$$

$$f = \frac{1}{e^{\beta[\gamma_w(E_w + v_w p_z) - \mu]} \pm 1} + \delta f$$

$$v_g = \frac{p_z}{E} + s_h s_{k_0} \frac{m^2 \theta'}{2E^2 E_z}$$

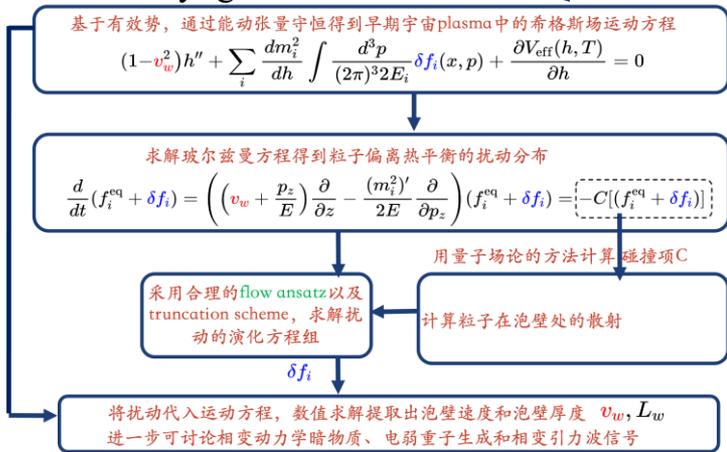
$$F = -\frac{(m^2)'}{2E} + s_h s_{k_0} \left(\frac{(m^2 \theta)'}{2E E_z} - \frac{m^2 (m^2)' \theta'}{4E^3 E_z} \right)$$

The CP-even perturbations can determine the bubble wall velocity which is also essential for baryogenesis.

$$\mu \equiv \mu_e + s_{k_0} \mu_o$$

$$\delta f \equiv \delta f_e + s_{k_0} \delta f_o$$

James M. Cline, Kimmo Kainulainen,
Phys.Rev.D 101 (2020) 6, 063525



Moment expansion

$$u_\ell \equiv \left\langle \left(\frac{p_z}{E} \right)^\ell \delta f \right\rangle$$

$$\left\langle \left(\frac{p_z}{E} \right)^\ell L \right\rangle = \left\langle \left(\frac{p_z}{E} \right)^\ell \left(S + \delta C \right) \right\rangle$$

CP-violating source

$$y_i h(z) \bar{t}_L \left(1 + i \frac{s(z)}{\Lambda} \right) t_R + \text{H.c.}$$

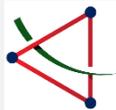
$$A_t w'_{tL} + m_t^2 B_t w_{tL} - \delta C_{tL} = S_t,$$

$$A_b w'_{bL} + m_b^2 B_b w_{bL} - \delta C_{bL} = S_b,$$

$$A_t w'_{tR} + m_t^2 B_t w_{tR} - \delta C_{tR} = -S_t,$$

$$A_h w'_h + m_h^2 B_h w_h - \delta C_h = 0,$$

$$w_i = (\mu_{oi}, u_{oi})^T$$



CP-violating source

理论困境: Bubble wall velocity is essential in EW baryogenesis

low/high bubble wall velocity, thin/thick wall, local/non-local

Precise calculation of EW baryogenesis requires to solve the transport equations

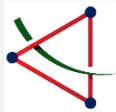
vacuum expectation value insertion approximation (VIA)

$$D_i n_i'' + v_w n_i' - C_i^{\text{VIA}} [n_j] = \boxed{S_{\text{VIA},i}}, \quad \int d^4 y \text{tr}(S^>(x,y)\Sigma^<(y,x) + \{x \leftrightarrow y\}) - \{\Sigma \leftrightarrow S\}. \quad \text{A.Riotto, Phys.Rev.D53, 5834(1996), Nucl.Phys.B518,339(1998).}$$

semiclassical (WKB) formalism

$$A_i \begin{pmatrix} \mu_i \\ u_i \end{pmatrix}' + (m_i^2)' B_i \begin{pmatrix} \mu_i \\ u_i \end{pmatrix} - C_i^{\text{WKB}} = \begin{pmatrix} v_w S_{\text{WKB},i} \\ S_{\text{WKB},i} \end{pmatrix}, \quad \begin{aligned} & -v_w \gamma_w h s_p \frac{(m^2 \theta)'}{2E E_z} f'_{v_w} \\ & + v_w \gamma_w h s_p \frac{m^2 (m^2)' \theta'}{4E^2 E_z} \left(\frac{f'_{v_w}}{E} - \gamma_w f''_{v_w} \right) \end{aligned} \quad \text{M. Joyce, T.Prokopec, and N.Turok, Phys.Rev.Lett.75,1695 (1995); J.M.Cline and K.Kainulainen, Phys.Rev.Lett.85,5519 (2000).}$$

In Phys.Rev.D 101 (2020) 6, 063525, James Cline and Kimmo Kainulainen make a comparison between the two methods in a given model, they found that the predictions typically differed by factors of 10-40.



Bubble wall velocity

Systematically calculation of bubble wall velocity in specific model:

Standard Model (small Higgs mass):

Guy D. Moore, Tomislav Prokopec, How fast can the wall move? A Study of the electroweak phase transition dynamics, *Phys.Rev.D* 52 (1995) 7182-7204

Minimal Supersymmetric Standard Model:

P. John, M.G. Schmidt, Do stops slow down electroweak bubble walls?, *Nucl.Phys.B* 598 (2001) 291-305

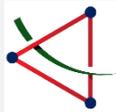
Higgs + scalar singlet:

Jonathan Kozaczuk, Bubble Expansion and the Viability of Singlet-Driven Electroweak Baryogenesis, *JHEP* 10 (2015) 135

Avi Friedlander, Ian Banta, James M. Cline, David Tucker-Smith, Wall speed and shape in singlet-assisted strong electroweak phase transitions, *Phys.Rev.D* 103 (2021) 5, 055020

Inert Doublet Model:

Siyu Jiang, **FPH**, Xiao Wang, Bubble wall velocity during electroweak phase transition in the inert doublet model, *Phys.Rev.D* 107 (2023) 9, 095005



Bubble wall velocity

The Guy Moore's method would be invalid at around sound velocity, there are some other solutions:

New ansatz:

[Benoit Laurent, James M. Cline, Phys.Rev.D 102 \(2020\) 6, 063516](#)

[James M. Cline, Avi Friedlander, Dong-Ming He, Kimmo Kainulainen, Benoit Laurent, Phys.Rev.D 103 \(2021\) 12, 123529](#)

[Marek Lewicki, Marco Merchand, Mateusz Zych, JHEP 02 \(2022\) 017](#)

[Benoit Laurent, James M. Cline, Phys.Rev.D 106 \(2022\) 2, 023501](#)

[Stefania De Curtis, Luigi Delle Rose, Andrea Guiggiani, Ángel Gil Muyor, Giuliano Panico, JHEP 03 \(2022\) 163](#)

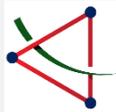
Higher order corrections in Guy Moore's ansatz

[Glauber C. Dorsch, Stephan J. Huber, Thomas Konstandin, JCAP 04 \(2022\) 04, 010](#)

[Glauber C. Dorsch, Daniel A. Pinto, arXiv:2312.02354](#)

Phenomenological parametrization of friction (friction= ηv_w)

[Ariel Megevand, et.al, Nucl.Phys.B 820 \(2009\) 47-74, Nucl.Phys.B 825 \(2010\) 151-176 ...](#)



Bubble wall velocity

Hydrodynamical backreaction:

Marc Barroso Mancha, Tomislav Prokopec, Bogumila Swiezewska, JHEP 01 (2021) 070

Wen-Yuan Ai, Bjorn Garbrecht, Carlos Tamarit, JCAP 03 (2022) 03, 015

Wen-Yuan Ai, Benoit Laurent, Jorinde van de Vis, JCAP 07 (2023) 002

Shao-Jiang Wang, Zi-Yan Yuwen, Phys.Rev.D 107 (2023) 2, 023501

Jun-Chen Wang, Zi-Yan Yuwen, Yu-Shi Hao, Shao-Jiang Wang, arXiv:2310.07691

Tomasz Krajewski, Marek Lewicki, Mateusz Zych, Phys.Rev.D 108 (2023) 10, 103523

Bubble wall velocity for ultra-relativistic bubble walls (run-away criterion):

Dietrich Bodeker, Guy D. Moore, JCAP 05 (2009) 009

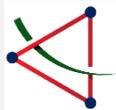
Dietrich Bodeker, Guy D. Moore, JCAP 05 (2017) 025

Stefan Höche, Jonathan Kozaczuk, Andrew J. Long, Jessica Turner, Yikun Wang, JCAP 03 (2021) 009

Aleksandr Azatov, Miguel Vanvlasselaer, JCAP 01 (2021) 058

Yann Gouttenoire, Ryusuke Jinno, Filippo Sala, JHEP 05 (2022) 004

Wen-Yuan Ai, JCAP 10 (2023) 052



CP-violating source

Semiclassical (WKB) formalism vs VEV insertion approximation (VIA)

WKB: The CP-violation source is accompanied by CP-violating force

CP even part:
determine the bubble
wall velocity

$$S_s^{\text{CP}} = \gamma_w v_w \frac{m^{2'}}{2\omega} f'_0,$$

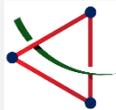
$$S_s^{\text{CPV}} = -s\gamma_w v_w \left(\frac{(m^2\theta)'}{2\omega\omega_z} f'_0 - \frac{m^2\theta'm^2'}{4\omega^3\omega_z} (f'_0 - \gamma_w\omega f''_0) \right)$$

CP odd part: source of
the CP-violation

VIA: The VIA treats the space-time-dependent mass term as a perturbation, which comes down to a Taylor expansion of the KB equations with the Higgs vev as expansion parameter.

However, recently, it has been shown that VIA source **vanishes** at leading order in the gradient expansion.

$$\begin{aligned} \bar{S} &= [M^2, \Delta^> + \Delta^<] + [\Pi^> + \Pi^<, \Delta^h] + \{\Pi^>, \Delta^<\} - \{\Pi^<, \Delta^>\} \\ &= 0 \end{aligned}$$



EW baryogenesis

Recently, it has been pointed out that the VIA source terms exactly **vanish** by performing correct resummation of 1PI self energy.

CP-violating transport theory for electroweak baryogenesis with thermal corrections

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Helsinki Institute of Physics, University of Helsinki,
PL 64, Helsinki 00014, Finland
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Published November 22, 2021

Abstract. We derive CP-violating transport equations for fermions for electroweak baryogenesis from the CTP-formalism including thermal corrections at the one-loop level. We consider both the VEV-insertion approximation (VIA) and the semiclassical (SC) formalism. We show that the VIA-method is based on an *assumption* that leads to an ill-defined source term containing a pinch singularity, whose regularisation by thermal effects leads to ambiguities including spurious ultraviolet and infrared divergences. We then carefully review the derivation of the semiclassical formalism and extend it to include thermal corrections. We present the semiclassical Boltzmann equations for thermal WKB-quasiparticles with source terms up to the second order in gradients that contain both dispersive and finite width corrections. We also show that the SC-method reproduces the current divergence equations and that a correct implementation of the Fick's law captures the semiclassical source term even with conserved total current $\partial_\mu j^\mu = 0$. Our results show that the VIA-source term is not just ambiguous, but that it does not exist. Finally, we show that the collisional source terms reported earlier in the semiclassical literature are also spurious, and vanish in a consistent calculation.

Keywords: baryon asymmetry, cosmological phase transitions, particle physics - cosmology connection

ArXiv ePrint: [2108.08336](https://arxiv.org/abs/2108.08336)

Resummation and cancellation of the VIA source in electroweak baryogenesis

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Notkestr. 85, 22607 Hamburg, Germany*

^c*Kavli IPMU (WPI), UTIAS, The University of Tokyo,
Kashiwa, Chiba 277-8583, Japan*

E-mail: mpostma@nikhef.nl, jorinde.van.de.vis@desy.de,
graham.white@ipmu.jp

ABSTRACT: We re-derive the vev-insertion approximation (VIA) source in electroweak baryogenesis. In contrast to the original derivation, we rely solely on 1-particle-irreducible self-energy diagrams. We solve the Green's function equations both perturbatively and resummed over all vev-insertions. The VIA source corresponds to the leading order contribution in the gradient expansion of the Kadanoff-Baym (KB) equations. We find that it vanishes both for bosons and fermions, both in the perturbative and in the resummed approach. The non-existence of the source is a result of a cancellation between different terms in the KB equations, and persists after resumming the masses.

KEYWORDS: Baryo- and Leptogenesis, Cosmology of Theories BSM, Early Universe Particle Physics

ARXIV EPRINT: [2206.01120](https://arxiv.org/abs/2206.01120)

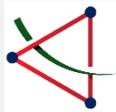
EW baryogenesis with high bubble wall velocity

P.Auclair, C.Caprini, D.Cutting, M.Hindmarsh,
K.Rummukainen, D.A.Steer and D.J.Weir,
[\[arXiv:2205.02588\]](https://arxiv.org/abs/2205.02588)
J.Dahl, M.Hindmarsh, K.Rummukainen and D.J.Weir,
[\[arXiv:2112.12013\]](https://arxiv.org/abs/2112.12013).

JHEP

2)121

JCAP11(2021)042



EW baryogenesis

实验困难:

**Large enough
CP-violating source
for successful
EW baryogenesis**

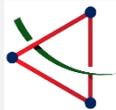
**Strong tension
in most cases**



**pretty small
CP-violation
to avoid strong EDM
constraints**
 $|d_e| < 4.1 \times 10^{-30} \text{ e cm}$

Science 381 (2023) 6653

How to alleviate this tension for successful baryogenesis?
Dynamical CP violation for baryogenesis ?



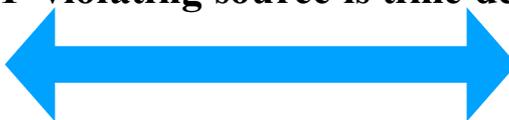
EW baryogenesis

Question: How to alleviate the tension for successful baryogenesis ?

Answer: Dynamical CP-violating source

**Large enough
CP-violating source
for successful
EW baryogenesis**

Alleviate by assuming the
CP-violating source is time dependent

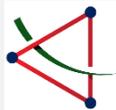


Dynamical/cosmological evolve

**Negligible
CP-violating source
at current time
to avoid strong EDM
constraints**

- **Effective field theory:** **FPH**, Zhuoni Qian, Mengchao Zhang, Phys.Rev. D98 (2018) no.1, 015014; **FPH**, Chong Sheng Li, Phys. Rev. D 92, 075014 (2015); lots of works
- **Renormalizable model:** Complex 2HDM, Xiao Wang, FPH, Xinmin Zhang, arXiv: 1909.02978, work in progress with Eibun Senaha, Xiao Wang in an extended IDM model
Baltes, T. Konstandin and G. Servant, arXiv:1604.04526; I. Baltes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016); S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)

See Matthew Reece's recent study on the dynamical CP-violation.



Dynamical CP violation

Evading the EDM constraints \rightarrow Dynamical CP violation

FPH, Zhuoni Qian,
Mengchao Zhang,
Phys.Rev.D 98 (2018)
1, 015014

$$y_t \eta \frac{S^n}{\Lambda^n} \bar{Q}_L \tilde{\Phi} t_R + h.c.$$

Effective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + H.c + \frac{1}{2} \partial_\mu S \partial^\mu S + \frac{1}{2} \mu^2 S^2 - \frac{1}{4} \lambda S^4 - \frac{1}{2} \kappa S^2 (\Phi^\dagger \Phi).$$

$$V_{\text{tree}}(H, \sigma) = -\frac{1}{2} \mu_{SM}^2 H^2 - \frac{1}{2} \mu^2 \sigma^2 + \frac{1}{4} \lambda_{SM} H^4 + \frac{1}{4} \lambda \sigma^4 + \frac{1}{4} \kappa H^2 \sigma^2.$$

$$V(H, \sigma, T) = (D_H T^2 - \frac{\mu_{SM}^2}{2}) H^2 + (D_\sigma T^2 - \frac{\mu^2}{2}) \sigma^2 + \frac{1}{4} (\lambda_{SM} H^4 + \kappa H^2 \sigma^2 + \lambda \sigma^4)$$

$$D_H = \frac{1}{32} (8\lambda_{SM} + g'^2 + 3g^2 + 4y_t^2 + 2\kappa/3), \quad D_\sigma = \frac{1}{24} (2\kappa + 3\lambda),$$

$$\lambda = \left(\frac{\kappa}{2\lambda_{SM}}\right)^2 \lambda_{SM} (1 + \delta_\lambda), \quad \mu^2 = \mu_{SM}^2 \frac{\kappa}{2\lambda_{SM}} (1 + \delta_{\mu^2})$$



Dynamical CP violation

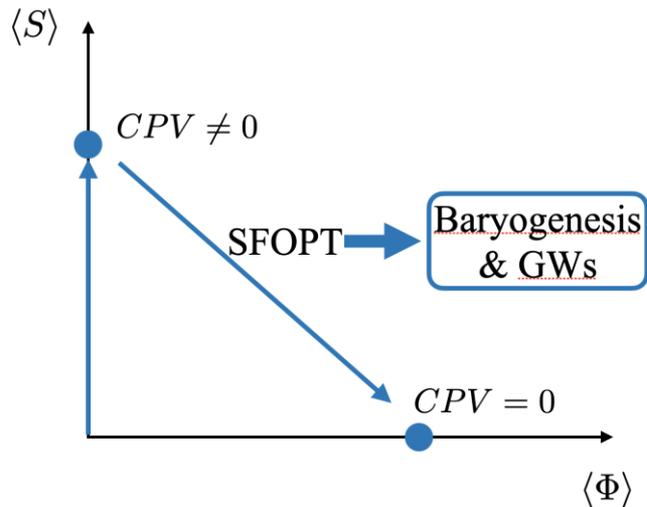
Taking the effective scenario as a representative example:

$$\mathcal{L}_{\text{SM}} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + \text{H.c.} + \frac{1}{2} \partial_\mu S \partial^\mu S + \frac{1}{2} \mu^2 S^2 - \frac{1}{4} \lambda S^4 - \frac{1}{2} \kappa S^2 (\Phi^\dagger \Phi)$$

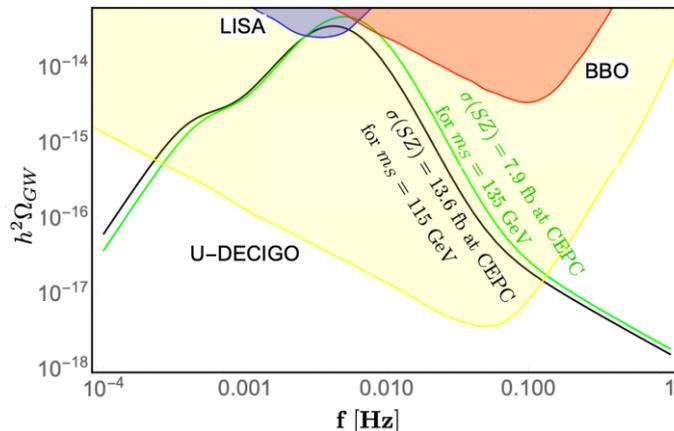
The singlet and the dim-5 operator can come from many types composite Higgs model, arXiv:0902.1483, arXiv:1703.10624, arXiv:1704.08911,

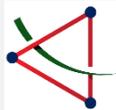
J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP **1201**, 012 (2012)

J. M. Cline and K. Kainulainen, JCAP **1301**, 012 (2013)



Phys.Rev. D98 (2018) no.1, 015014, **FPH**, Zhuoni Qian, Mengchao Zhang





Dynamical CP violation

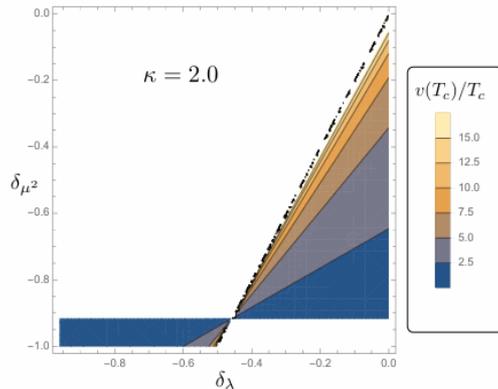
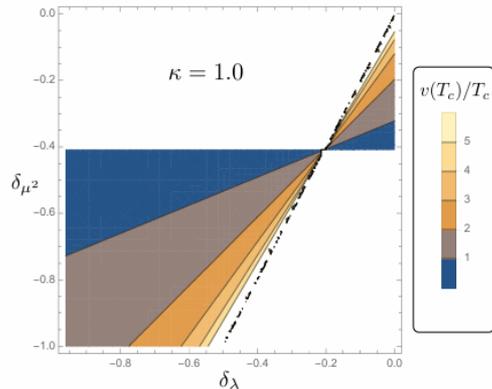
Symmetry breaking Pattern

$$(0, 0) \rightarrow (0, \langle S \rangle) \rightarrow (\langle \Phi \rangle, 0)$$

Constraints and predictions in particle physics experiments

$$\frac{v(T_c)}{T_c} \sim \frac{2v}{m_H} \sqrt{\frac{D_H - D_\sigma}{\delta_\lambda - 2\delta_{\mu^2}}}$$

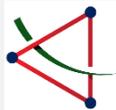
$$\mathcal{L}_{Stt} = - \left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v} \right) S (a\bar{t}t + ib\bar{t}\gamma_5 t)$$



$$\mathcal{L}'_{SVV} = \frac{a\alpha_S}{12\pi\Lambda} SG_{\mu\nu}^a G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} SG_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{2a\alpha_{EW}}{9\pi\Lambda} SF_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} SF_{\mu\nu} \tilde{F}^{\mu\nu}.$$

$$m_t(z) = \frac{y_t}{\sqrt{2}} H(z) \left(1 + (1+i) \frac{S(z)}{\Lambda} \right) \equiv |m_t(z)| e^{i\Theta(z)}$$

$$\eta_B = \frac{405\Gamma_{\text{sph}}}{4\pi^2 \tilde{v}_b g_* T} \int dz \mu_{BL} f_{\text{sph}} e^{-45\Gamma_{\text{sph}}|z|/(4\tilde{v}_b)}$$



Dynamical CP violation: C2HDM

Zero temperature

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.} \right] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \left[\frac{1}{2} \lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right],$$

Xiao Wang, **FPH***,
Phys.Rev.D 101 (2020)
 1, 015015

$$\Phi_1^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ v_1 + \zeta_1 + i\psi_1 \end{pmatrix} \quad \Phi_2^{(0)} = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ v_2 + \zeta_2 + i\psi_2 \end{pmatrix}$$

$$\delta_1 = \arg[(m_{12}^2)^2 \lambda_5^*],$$

$$\delta_2 = \arg[m_{12}^2 v_1 v_2^* \lambda_5^*],$$

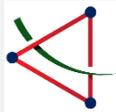
$$|m_{12}^2| \sin(\delta_1 - \delta_2) = v^2 \sin \Theta \cos \Theta | \lambda_5 | \sin(\delta_1 - 2\delta_2).$$

Finite temperature

$$\Phi_1^{(T)} = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \tilde{v}_1 + \zeta_1 + i\psi_1 \end{pmatrix} \quad \Phi_2^{(T)} = \frac{1}{\sqrt{2}} \begin{pmatrix} \tilde{v}_{CB} + \rho_2 + i\eta_2 \\ \tilde{v}_2 + i\tilde{v}_{CP} + \zeta_2 + i\psi_2 \end{pmatrix}$$

$$\tilde{v}_1(T=0) = v_1, \quad \tilde{v}_2(T=0) = v_2, \quad \tilde{v}_{CP}(T=0) = v_{CP} = 0, \quad \tilde{v}_{CB}(T=0) = v_{CB} = 0,$$

Evade the
 EDM
 constraints



Dynamical CP violation: C2HDM

$$v \equiv \sqrt{v_1^2 + v_2^2 + v_{CP}^2 + v_{CB}^2} = \sqrt{v_1^2 + v_2^2}, \quad \approx 246 \text{ GeV}$$

mass eigenstates

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \zeta_1 \\ \zeta_2 \\ \zeta_3 \end{pmatrix}, \quad R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -c_1 s_2 s_3 - s_1 c_3 & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -c_1 s_3 - s_1 s_2 c_3 & c_2 c_3 \end{pmatrix}$$

$$\lambda_1 = \frac{1}{v^2 \cos^2 \Theta} [m_1^2 c_1^2 c_2^2 + m_2^2 (c_3 s_1 + c_1 s_2 s_3)^2 + m_3^2 (c_1 c_3 s_2 - s_1 s_3)^2 - \mu^2 \sin^2 \Theta],$$

$$\lambda_2 = \frac{1}{v^2 \sin^2 \Theta} [m_1^2 s_1^2 c_2^2 + m_2^2 (c_1 c_3 - s_1 s_2 s_3)^2 + m_3^2 (c_3 s_1 s_2 + c_1 s_3)^2 - \mu^2 \cos^2 \Theta],$$

$$\lambda_3 = \frac{1}{v^2 \sin \Theta \cos \Theta} [(m_1^2 c_2^2 + m_2^2 (s_2^2 s_3^2 - c_3^2) + m_3^2 (s_2^2 c_3^2 - s_3^2)) c_1 s_1 + (m_3^2 - m_2^2) (c_1^2 - s_1^2) s_2 c_3 s_3] - \frac{\mu^2 - 2m_{H\pm}^2}{v^2},$$

$$\lambda_4 = \frac{m_1^2 s_2^2 + (m_2^2 s_3^2 + m_3^2 c_3^2) c_2^2 + \mu^2 - 2m_{H\pm}^2}{v^2},$$

$$\text{Re}(\lambda_5) = \frac{-m_1^2 s_2^2 - (m_2^2 s_3^2 + m_3^2 c_3^2) c_2^2 + \mu^2}{v^2},$$

$$\text{Im}(\lambda_5) = \frac{2c_2}{v^2 \sin \Theta} [(-m_1^2 + m_2^2 s_3^2 + m_3^2 c_3^2) c_1 s_2 + (m_2^2 - m_3^2) s_1 s_3 c_3],$$

$$\mu^2 = \frac{v^2}{v_1^2 v_2^2} \text{Re}(m_{12}^2)$$

The coupling parameters in the original Lagrangian can be written as



Dynamical CP violation: C2HDM

Effective
potential in the
C2HDM

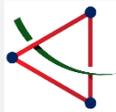
$$V_{eff}(\tilde{v}, T) \equiv V_{tree}(\tilde{v}) + V_{CW}(\tilde{v}) + V_{CT}(\tilde{v}) + V_T(\tilde{v}, T)$$

$$\begin{aligned}
 V_{tree}(\tilde{v}) = & \frac{1}{2}m_{11}^2\tilde{v}_1^2 + \frac{1}{2}m_{22}^2(\tilde{v}_2^2 + \tilde{v}_{CB}^2 + \tilde{v}_{CP}^2) - Re(m_{12}^2)\tilde{v}_1\tilde{v}_2 + Im(m_{12}^2)\tilde{v}_1\tilde{v}_{CP} + \frac{1}{8}\lambda_1\tilde{v}_1^4 \\
 & + \frac{1}{8}\lambda_2(\tilde{v}_2^2 + \tilde{v}_{CP}^2 + \tilde{v}_{CB}^2)^2 + \frac{1}{4}\lambda_3\tilde{v}_1^2(\tilde{v}_2^2 + \tilde{v}_{CB}^2 + \tilde{v}_{CP}^2) + \frac{1}{4}\lambda_4\tilde{v}_1^2(\tilde{v}_2^2 + \tilde{v}_{CP}^2) \\
 & + \frac{1}{4}Re(\lambda_5)\tilde{v}_1^2(\tilde{v}_2^2 - \tilde{v}_{CP}^2) - \frac{1}{2}Im(\lambda_5)\tilde{v}_1^2\tilde{v}_2\tilde{v}_{CP} .
 \end{aligned}
 \quad \tilde{v} \equiv \{\tilde{v}_1, \tilde{v}_2, \tilde{v}_{CP}, \tilde{v}_{CB}\}$$

$$V_{CW}(\tilde{v}) = \frac{1}{64\pi^2} \sum_s n_s m_s^4(\tilde{v}) \left[\log \frac{m_s^2(\tilde{v})}{\mu^2} - C_s \right]
 \quad C_s = \begin{cases} \frac{5}{6}, & s = W^\pm, Z, \gamma \\ \frac{3}{2}, & \text{others} \end{cases}$$

$$\begin{aligned}
 V_{CT} = & \delta m_{11}^2 \Phi_1^\dagger \Phi_1 + \delta m_{22}^2 \Phi_2^\dagger \Phi_2 - [(\delta Re(m_{12}^2) + i\delta Im(m_{12}^2))\Phi_1^\dagger \Phi_2 + \text{h.c.}] \\
 & + \frac{1}{2}\delta\lambda_1(\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\delta\lambda_2(\Phi_2^\dagger \Phi_2)^2 + \delta\lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \delta\lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
 & + \frac{1}{2}[(\delta Re(\lambda_5) + i\delta Im(\lambda_5))(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \\
 & + \delta T_1(\zeta_1 + \tilde{v}_1) + \delta T_2(\zeta_2 + \tilde{v}_2) + \delta T_{CP}(\psi_2 + \tilde{v}_{CP}) + \delta T_{CB}(\rho_2 + \tilde{v}_{CB}).
 \end{aligned}$$

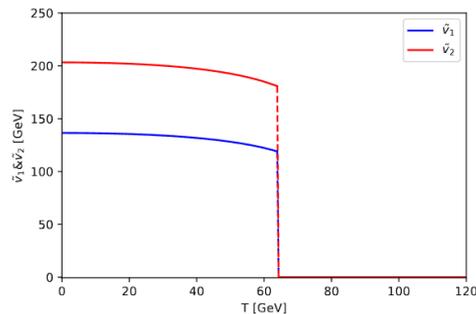
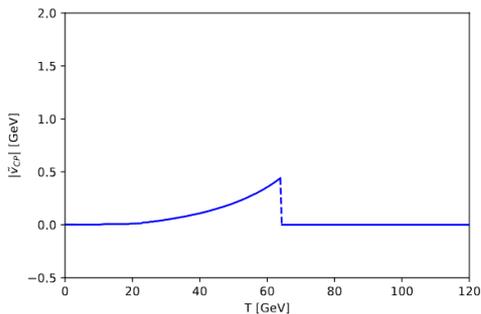
$$V_T = \sum_F \frac{T^4}{2\pi^2} n_F J_F \left(\frac{m_F^2}{T^2} \right) + \sum_B \frac{T^4}{2\pi^2} n_B J_B \left(\frac{m_B^2}{T^2} \right)
 \quad J_{B/F} = \int_0^\infty dx x^2 \log \left[1 \mp e^{-\sqrt{x^2 + m_i^2}/T} \right]$$



Dynamical CP violation: C2HDM

One-step strong FOPT

$$(0, 0, 0, 0) \xrightarrow{FOPT} (\tilde{v}_1, \tilde{v}_2, \tilde{v}_{CP}, \tilde{v}_{CB}) \xrightarrow{T \rightarrow 0} (v_1, v_2, 0, 0)$$



	v [GeV]	m_1 [GeV]	m_2 [GeV]	m_{H^\pm} [GeV]	$Re(m_{12}^2)$ [GeV ²]	θ_1	θ_2	θ_3	$\tan \Theta$
BP_1	246	125.09	356.779	581.460	29939	1.470	0.0223	-0.097	4.17
BP_2	246	125.09	603.699	629.564	73628	0.817	3.687×10^{-3}	-1.557	1.216
BP_3	246	125.09	455.834	685.479	85376	0.880	-0.0156	1.568	1.399
BP_4	246	125.09	458.834	683.679	85376	0.880	-0.0156	1.568	1.399
BP_5	246	125.09	490.698	525.220	20392	0.932	0.0101	-0.514	1.608
BP_6	246	125.09	485.698	530.220	20392	0.932	0.0101	-0.514	1.608
BP_7	246	125.09	495.698	525.220	20192	0.932	0.0101	-0.514	1.608
BP_8	246	125.09	481.698	533.220	20192	0.932	0.0101	-0.514	1.608

modification of Higgs trilinear coupling and ZH cross section

	pattern	T_n [GeV]	$\epsilon(T_n)$ [GeV ⁴]	v_b	α	$\tilde{\beta}$	δ_H @one-loop	$\delta(ZH)$
BP_1	1-step	59.653	6.892×10^7	0.825	0.192	648.048	1.135	1.816%
BP_2	1-step	45.291	4.493×10^7	0.875	0.376	630.773	1.338	2.141%
BP_3	1-step	25.964	2.771×10^7	0.964	2.149	471.699	1.677	2.684%
BP_4	1-step	23.644	2.714×10^7	0.974	3.060	414.956	1.723	2.737%
BP_5	1-step	40.912	2.954×10^7	0.874	0.372	915.233	1.652	2.643%
BP_6	1-step	36.639	2.61×10^7	0.895	0.510	313.287	1.672	2.674%
BP_7	1-step	26.529	2.121×10^7	0.952	1.509	100.33	1.720	2.752%
BP_8	1-step	27.621	2.188×10^7	0.947	1.325	81.825	1.680	2.687%



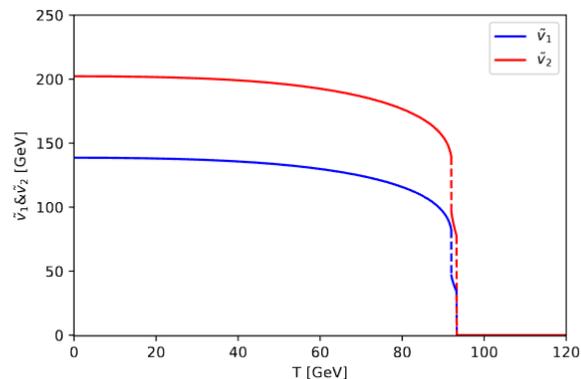
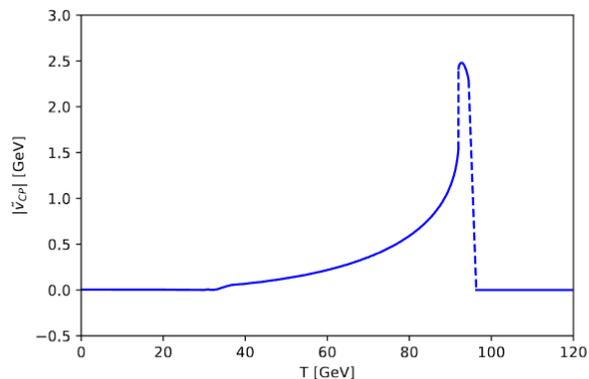
Dynamical CP violation: C2HDM

Two-step strong FOPT

$$(0, 0, 0, 0) \xrightarrow{FOPT} (\tilde{v}_1^{(1)}, \tilde{v}_2^{(1)}, \tilde{v}_{CP}^{(1)}, \tilde{v}_{CB}^{(1)}) \xrightarrow{FOPT} (\tilde{v}_1^{(2)}, \tilde{v}_2^{(2)}, \tilde{v}_{CP}^{(2)}, \tilde{v}_{CB}^{(2)}) \xrightarrow{T \rightarrow 0} (v_1, v_2, 0, 0)$$

	v [GeV]	m_1 [GeV]	m_2 [GeV]	$m_{H\pm}$ [GeV]	$Re(m_{12}^2)$ [GeV ²]	θ_1	θ_2	θ_3	$\tan \Theta$
BP_9	246	125.09	430.698	500.220	20192	0.832	0.0101	-0.514	1.458
BP_{10}	246	125.09	440.698	500.220	20092	0.832	0.0101	-0.514	1.458

	pattern	T_n [GeV]	$\epsilon(T_n)$ [GeV ⁴]	v_b	α	$\tilde{\beta}$	δ_H @one-loop	$\delta(ZH)$
BP_9	2-step	96.995	1.532×10^7	0.638	0.00610	107292.81	1.049	1.678%
		93.997	4.077×10^7	0.677	0.0184	1279659.55		
BP_{10}	2-step	93.462	2.56×10^7	0.659	0.0118	20542.25	1.104	1.766%
		91.920	4.892×10^7	0.690	0.0241	479401.89		





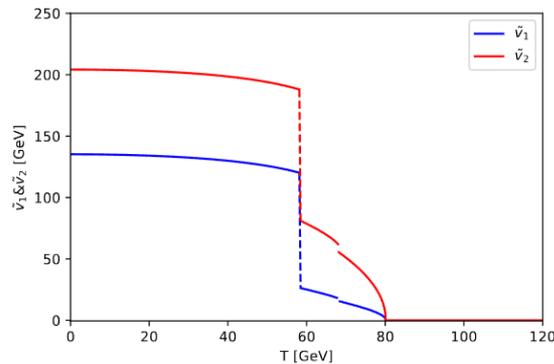
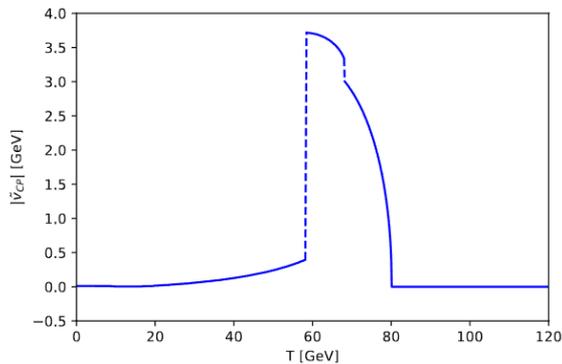
Dynamical CP violation: C2HDM

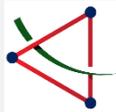
Three-step strong FOPT

$$(0, 0, 0, 0) \xrightarrow{SOPT} (\tilde{v}_1^{(1)}, \tilde{v}_2^{(1)}, \tilde{v}_{CP}^{(1)}, \tilde{v}_{CB}^{(1)}) \xrightarrow{FOPT} (\tilde{v}_1^{(2)}, \tilde{v}_2^{(2)}, \tilde{v}_{CP}^{(2)}, \tilde{v}_{CB}^{(2)}) \xrightarrow{FOPT} (\tilde{v}_1^{(3)}, \tilde{v}_2^{(3)}, \tilde{v}_{CP}^{(3)}, \tilde{v}_{CB}^{(3)}) \xrightarrow{T \rightarrow 0} (v_1, v_2, 0, 0)$$

	v [GeV]	m_1 [GeV]	m_2 [GeV]	m_{H^\pm} [GeV]	$Re(m_{12}^2)$ [GeV ²]	θ_1	θ_2	θ_3	$\tan \Theta$
BP_{11}	246	125.09	489.698	550.220	20392	0.832	0.0101	-0.514	1.508
BP_{12}	246	125.09	495.698	543.220	20292	0.832	0.0101	-0.514	1.508

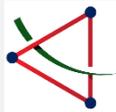
	pattern	T_n [GeV]	$\epsilon(T_n)$ [GeV ⁴]	v_b	α	$\tilde{\beta}$	δ_H @one-loop	$\delta(ZH)$
BP_{11}	3-step	68.046	2.15×10^6	0.624	0.00353	1457261.58	1.863	2.980%
		51.316	2.966×10^7	0.807	0.151	2235.16		
BP_{12}	3-step	69.380	2.864×10^6	0.629	0.00436	1225417.53	1.854	2.966%
		55.586	3.354×10^7	0.792	0.124	3142.96		





Dynamical CP violation: C2HDM

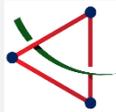
- Extra CP-violating source for electroweak baryogenesis can dynamically appear at finite temperature in the complex two-Higgs doublet model, which might help to alleviate the strong constraints from the EDM experiments.
- The extra CP-violation can be tested by GW signals in synergy with the collider signals.
- GW complementary to collider signals can help to pin down the underlying phase transition dynamics or different phase transition patterns.



Bubble assisted baryogenesis

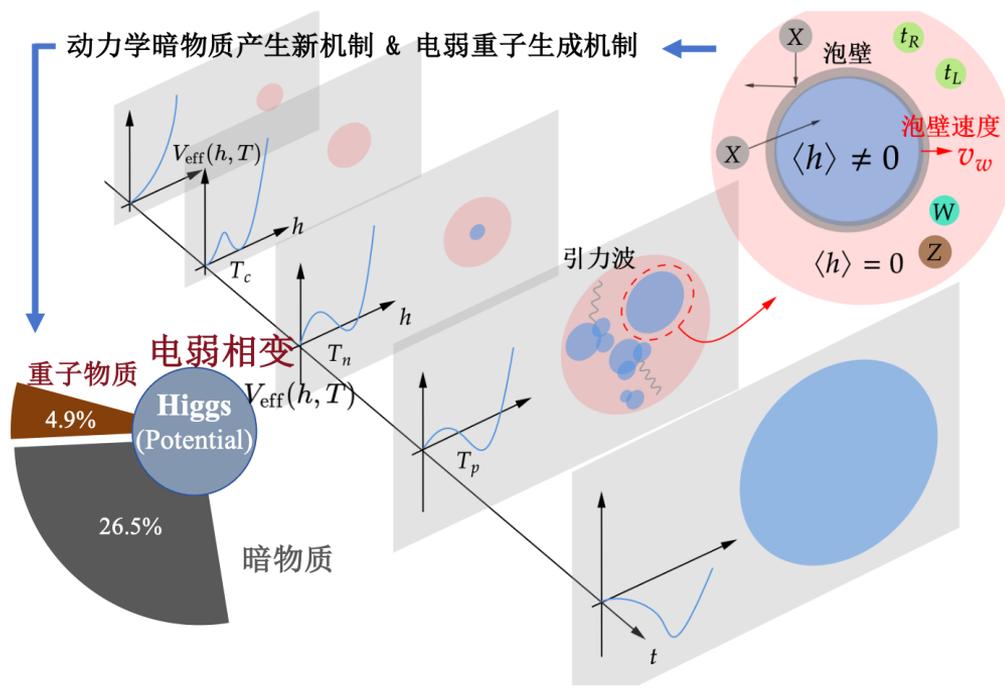
New baryogenesis (leptogenesis) models: Bubble assisted baryogenesis (leptogenesis)

- **Mass gain mechanism:** Particles gain mass after passing through the bubble wall, and the mass is much greater than the temperature, causing them to instantaneously deviate from thermal equilibrium, thus avoiding being washed out.
- **Bubble induced conversion or radiation:** During the process of particles passing through the relativistic bubble wall, they can convert into or radiates into superheavy particles, and the subsequent decays generate baryon asymmetry or lepton asymmetry.
- **Bubble collision:** Similar to the bubble second one, leptogenesis can be realized through the decays of sterile (right-handed) neutrinos produced from runaway bubble collisions, thereby enabling high scale leptogenesis without the need for high reheat temperatures while also naturally suppressing washout effects.
- **Filtered baryogenesis (leptogenesis):** Only a small fraction of dark matter particles are energetic enough to enter the true vacuum bubbles, while the rest are reflected and annihilate away quickly. In the false vacuum phase, a portal interaction quickly converts the dark sector chiral asymmetry into a Standard Model lepton asymmetry.



Summary and Outlook

- The correlation between GW and collider signals can make complementary test on the Higgs nature, baryogenesis and the cosmic evolution history around 100 GeV.
- More precise study are needed: resummation, non-perturbation, bubble dynamics (wall velocity), CP-violation source...
- Precise measurements of Higgs triple coupling and Yukawa coupling are urgent.





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THANK YOU

谢 谢 大 家

