EW baryogenesis and gravitational waves from a composite Higgs

A novel model with high dimensional fermion representations

Ke-Pan Xie (谢柯盼)

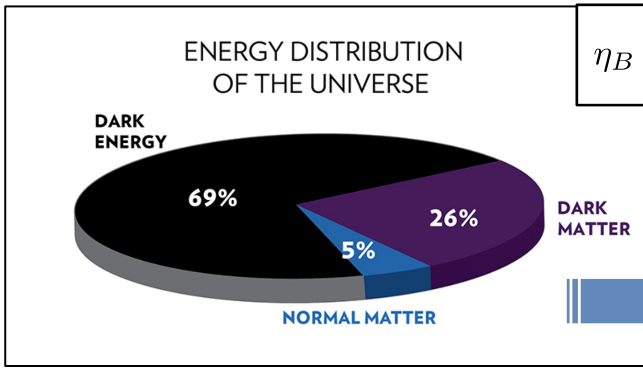
Seoul National University

2020.7.31 @Workshop on EWPT & Higgs physics, IHEP (remotely)

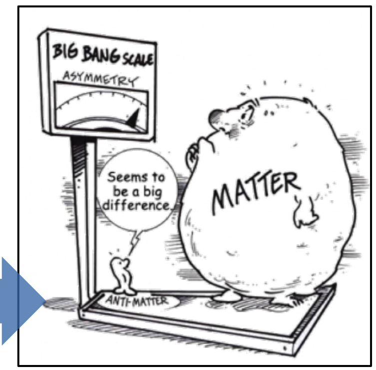
In collaboration with Ligong Bian and Yongcheng Wu, 2005.13552

Explaining the baryon-antibaryon asymmetry

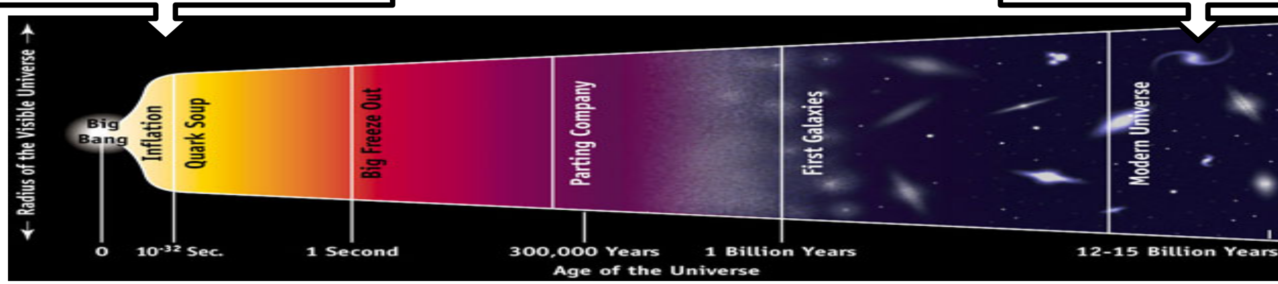
- Matter-antimatter asymmetry



$$\eta_B = \frac{n_B - n_{\bar{B}}}{s}$$



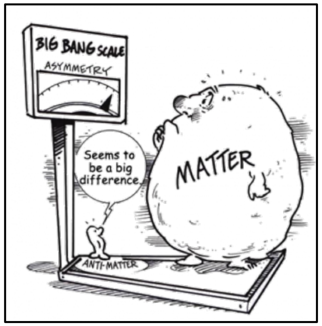
After inflation $\eta_B = 0$ --(Baryogenesis mechanism)-- Current $\eta_B \approx 10^{-10}$



- Conditions for baryon asymmetry

Sakharov conditions[Sakharov,1967]:

❑ Baryon number violation
❑ C/CP violation
❑ Departure from equilibrium



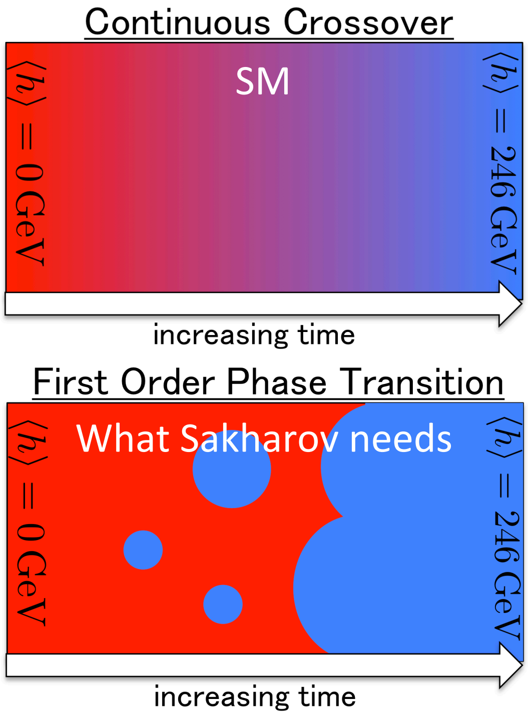
The Standard Model:

☑ Baryon number violation: EW sphaleron (non-perturbative)

☑ C/CP violation: from CKM matrix, however too small

☒ Out-of-equilibrium: EW phase transition is a smooth crossover

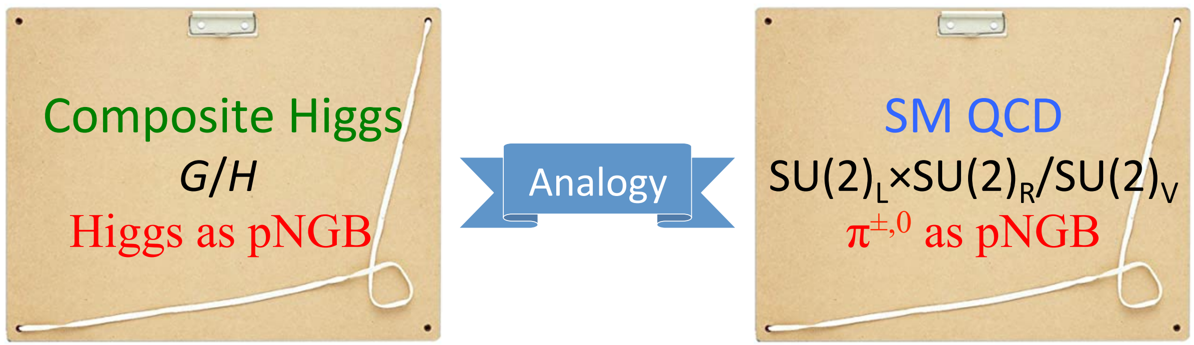
Calling for NEW physics!!



Firgure from Lian-Tao Wang's talk

- # The composite Higgs as a solution

What's the composite Higgs[Kaplan *et al* (1984), Agashe *et al* (2005)]?



✓ Hierarchy problem solved (Goldstone theorem)

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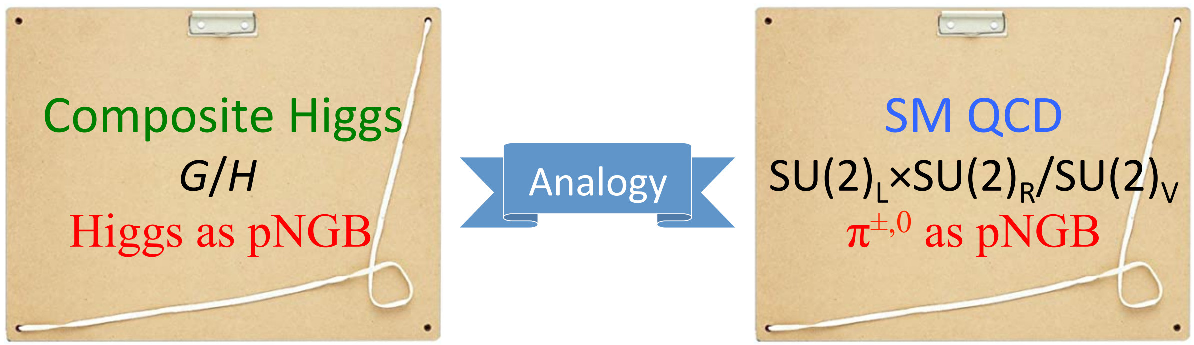

✓ Hierarchy problem solved (Goldstone theorem)

Composite Higgs v.s. Sakharov conditions

✓ The enlarged scalar sector

SO(6)/SO(5): Higgs + singlet;
SO(7)/SO(6): Higgs + 2 singlets;
SU(5)/SO(5): Higgs + 2 triplets + singlet;
SO(8)/SO(7): twin Higgs; ..., *etc*

⇒ Triggering strong 1st-order EW phase transition (departure from equilibrium)

✓ The new CP phase associated with new scalars & fermions

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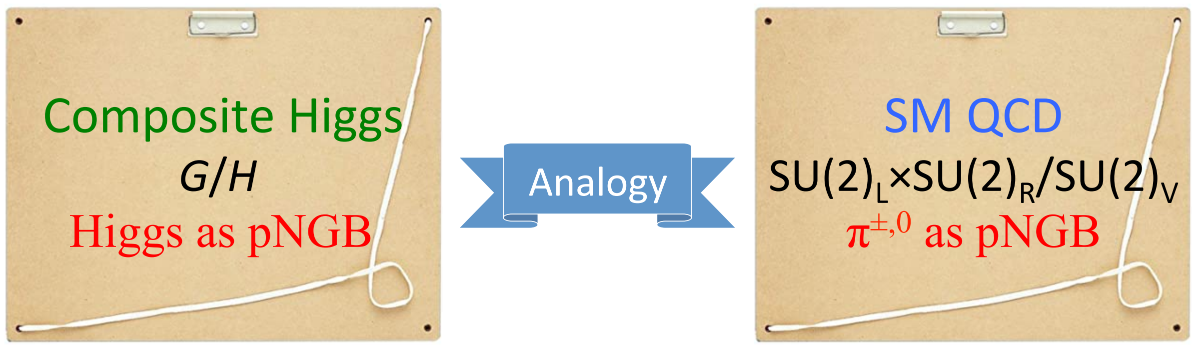

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This talk

⇒ Triggering strong 1st-order EW phase transition (departure from equilibrium)

✓ The new CP phase associated with new scalars & fermions

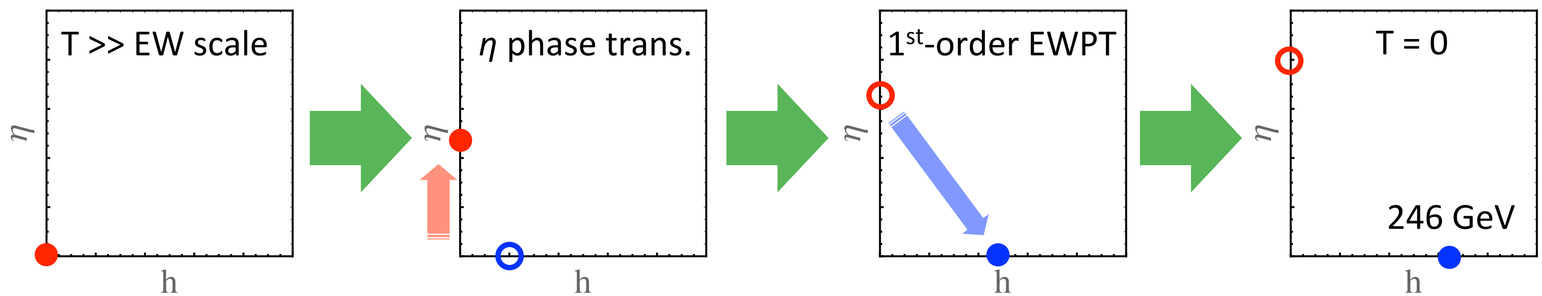
- Realizing baryogenesis with Higgs + singlet

The scalar potential is crucial. At finite temperature:

$$V_T(h,\eta) = \frac{\mu_h^2 + c_h T^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_\eta^2 + c_\eta T^2}{2} \eta^2 + \frac{\lambda_\eta}{4} \eta^4 + \frac{\lambda_{h\eta}}{2} h^2 \eta^2$$

$$c_h = \frac{3g^2 + g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda_h}{2} + \frac{\lambda_{h\eta}}{12}, \quad c_\eta = \frac{\lambda_\eta}{4} + \frac{\lambda_{h\eta}}{3},$$

The departure from equilibrium can be achieved by



-- the 1st-order EWPT (only in some specific parameter space!)

CP violating phase comes from the *η-relevant* interactions.

- # Realizing baryogenesis with Higgs + singlet

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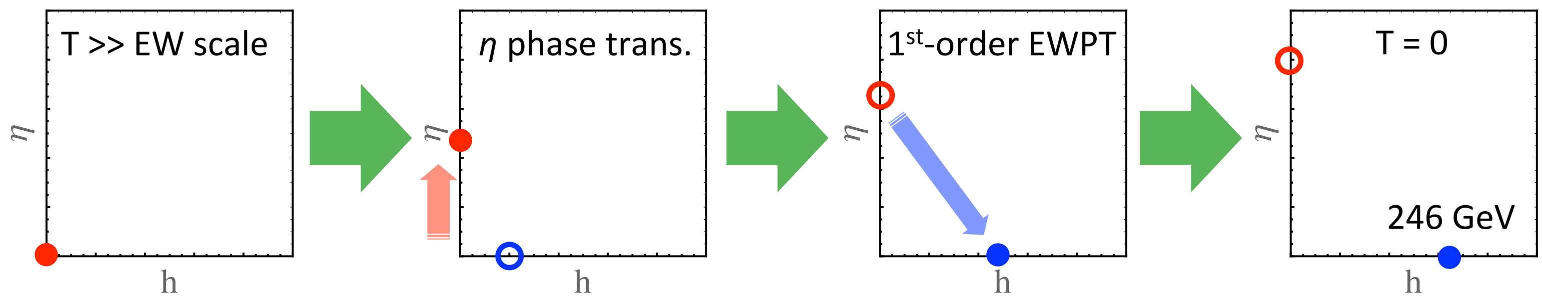

-- the 1st-order EWPT (only in some specific parameter space!)

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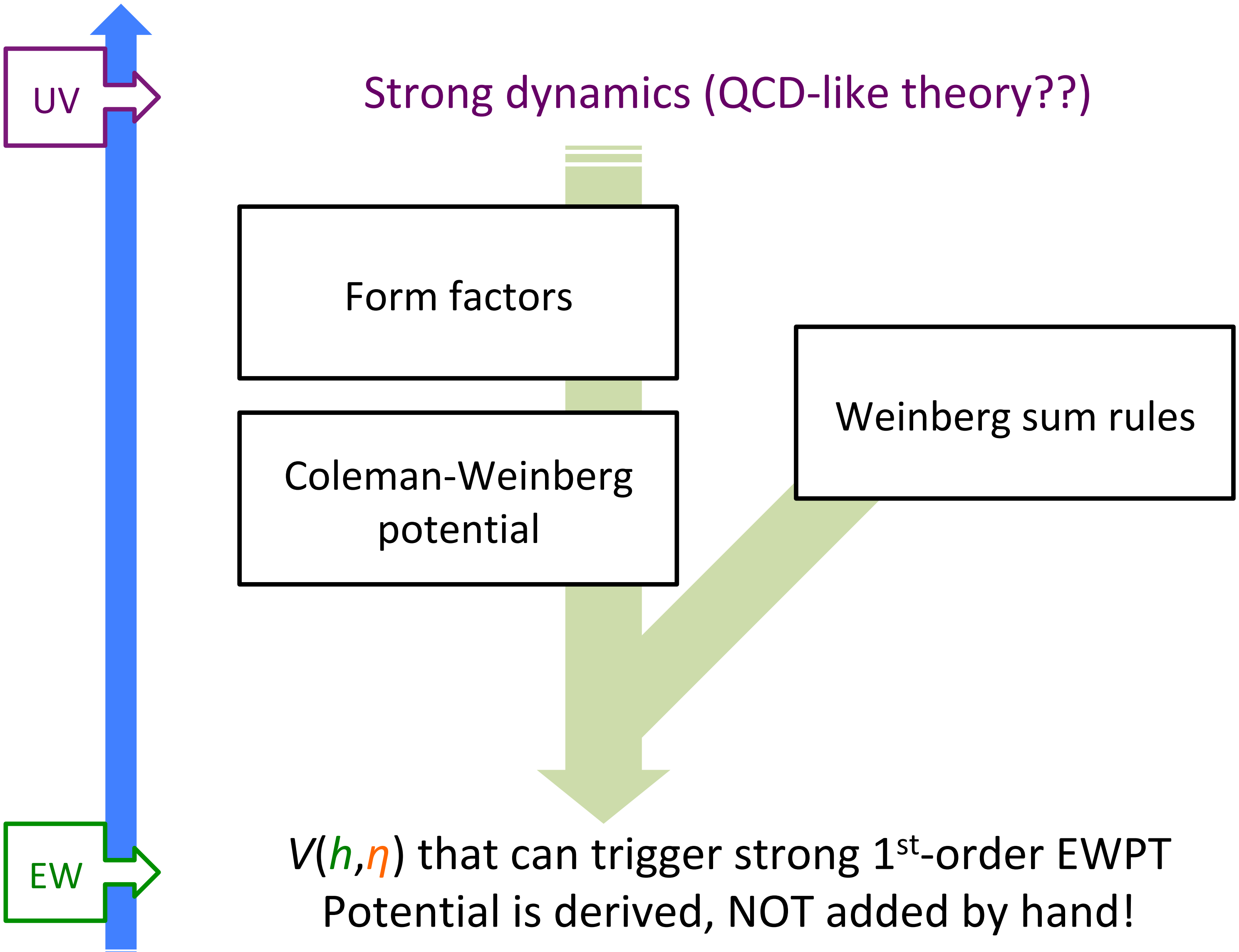
The central task of this talk: generating such a potential in the SO(6)/SO(5) composite Higgs model

- # Logic of our work



This talk!

Baryogenesis in SO(6)/SO(5) composite Higgs

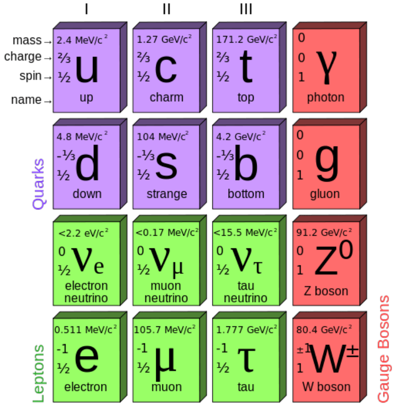
- Two sectors

Composite sector: SO(6)/SO(5)[Gripaios *et al*, JHEP 0904 (2009) 070]

✓ 15 – 10 = 5 pNGBs: Higgs doublet (4) + real singlet (1)

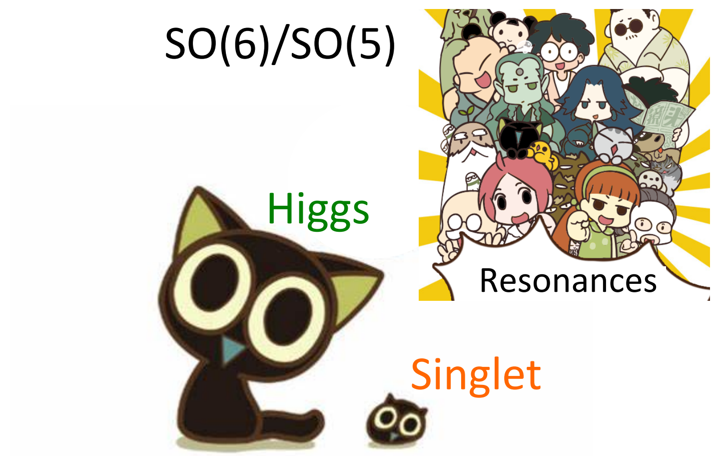
✓ Composite resonances: spin-1, spin-1/2, etc

$SU(2)_L \times U(1)_Y$



The elementary sector
(SM without Higgs)

SO(6)/SO(5)



The composite sector
(New strong dynamics)

This talk!

Baryogenesis in SO(6)/SO(5) composite Higgs

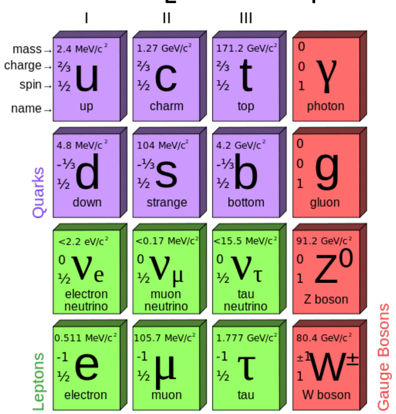
- Interplay between two sectors

Interactions break the SO(6) symmetry

✓ Making scalars pseudo-NGBs;

✓ Generating the scalar potential.

$SU(2)_L \times U(1)_Y$



SO(6)-breaking Interactions

SO(6)/SO(5)

The elementary sector
(SM without Higgs)

The composite sector
(New strong dynamics)

• Generating the scalar potential

Potential source 1: gauge interactions

SM gauge bosons

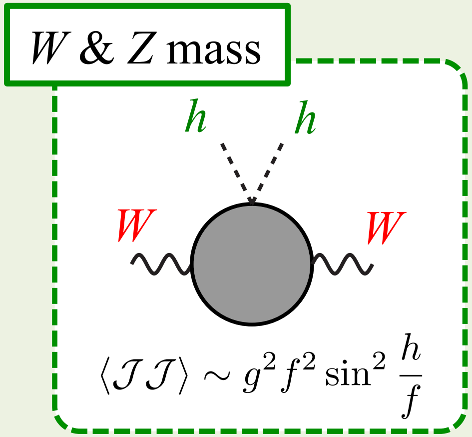
$$\mathcal{L}_{\text{int}} \supset \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu$$

Strong currents

Gauging a subgroup of SO(6) --

$$SO(6) \xrightarrow[\text{breaking}]{\text{explicit}} SU(2)_L \times U(1)_Y \times \underline{U(1)_\eta},$$

Higgs potential *V*(*h*) is generated !!



• Generating the scalar potential

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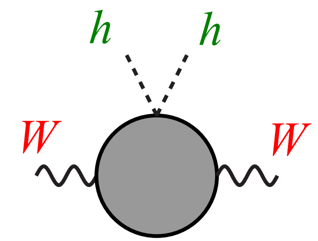
W & Z mass



$$\langle \mathcal{J}\mathcal{J} \rangle \sim g^2 f^2 \sin^2 \frac{h}{f}$$

Potential source 2: fermion interactions

SM quarks

$$\mathcal{L}_{\text{int}} \supset \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + \text{h.c.}$$

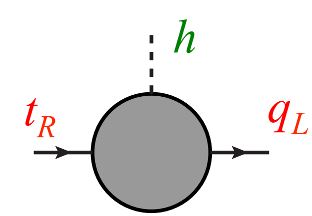
Strong operators

Symmetry breaking –

$$SO(6) \times U(1)_X \xrightarrow[\text{breaking}]{\text{explicit}} SU(2)_L \times U(1)_Y$$

Joint potential *V*(*h*,*η*) is generated !!

Top mass



$$\langle \mathcal{O}_L \mathcal{O}_R \rangle \sim \frac{y_L y_R}{g_\rho} f \sin \frac{h}{f}$$

* $U(1)_X$ is introduced: $Y = X + T_R^3$

• Generating the scalar potential

The crucial source: fermion interactions

$$\mathcal{L}_{\rm int} \supset \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + {\rm h.c.}$$

SM quarks -- in incomplete reps of SO(6)

Strong operators in reps of SO(6)

$V(h,\eta)$ depends on the q_L and t_R embeddings in SO(6).
Previous studies:

References on EW phase transition & baryogenesis	$q_L=(t_L, b_L)^T$ & t_R embedding
J. R. Espinosa *et al*, JCAP 1201 (2012) 012	6+6
L. Bian, Y. Wu and **K.-P. Xie**, JHEP 12 (2019) 028	6+6, 15+6, 15+15
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New!

This talk: q_L & t_R in 20’+20’ **K.-P.Xie**, Y.Wu and L.Bian, 2005.13552

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Motivations:

☒ We love group theory and representations

☑ The 20’ embedding has its own advantage

- Fermion sector: q_L and t_R in 20' of SO(6)

Dim-20 reps of SO(6): 20, 20', 20''

$$\mathbf{6}\otimes\mathbf{6}=\mathbf{1}\oplus\mathbf{15}\oplus\mathbf{20'}$$

$$SO(6)\times U(1)_X \to SO(5)\times U(1)_X \to SO(4)\times U(1)_X \to SU(2)_L\times U(1)_Y$$

$$(Y=X+T_R^3)$$

$$\begin{aligned}\mathbf{20'}_{2/3} &\to \mathbf{14}_{2/3}\oplus\mathbf{5}_{2/3}\oplus\mathbf{1}_{2/3}\\ &\to (\mathbf{9}_{2/3}\oplus\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus(\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus\mathbf{1}_{2/3}\\ &\to [(\mathbf{3}_{5/3}\oplus\mathbf{3}_{2/3}\oplus\mathbf{3}_{-1/3})\oplus(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}]\oplus[(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}]\oplus\underline{\mathbf{1}_{2/3}}.\end{aligned}$$

Two/three ways to embed q_L/t_R, respectively

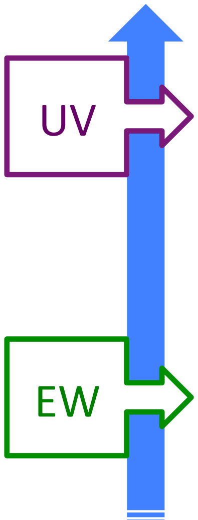
$$q_L^{\mathbf{20'}} = q_L^{\mathbf{20'}_A} e^{i\phi_L}\cos\theta_L + q_L^{\mathbf{20'}_B}\sin\theta_L,$$

$$t_R^{\mathbf{20'}} = e^{i\phi_{R1}}\cos\theta_{R1} t_R^{\mathbf{20'}_A} + e^{i\phi_{R2}}\sin\theta_{R1}\cos\theta_{R2} t_R^{\mathbf{20'}_B} + \sin\theta_{R1}\sin\theta_{R2} t_R^{\mathbf{20'}_C}$$

Due to Zb_Lb_L constraint(details in our paper):

$$q_L^{\mathbf{20'}} = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 0 & ib_L & 0\\ 0 & 0 & 0 & 0 & b_L & 0\\ 0 & 0 & 0 & 0 & it_L & 0\\ 0 & 0 & 0 & 0 & -t_L & 0\\ ib_L & b_L & it_L & -t_L & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\end{pmatrix}, \quad t_R^{\mathbf{20'}} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & t_R\\ 0 & 0 & 0 & 0 & t_R & 0\end{pmatrix}$$

• Lagrangian: fermion sector



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm strong} + \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu + \bar{q}_L^{\mathbf{20}'} \mathcal{O}_R^{\mathbf{20}'} + \bar{t}_R^{\mathbf{20}'} \mathcal{O}_L^{\mathbf{20}'} + {\rm h.c.}$$

------ Integrating out the strong dynamics ------

$$\begin{aligned}\mathcal{L}_\Psi \to\ & {\rm tr}\left[\bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'}\right] \Pi_0^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'} \Sigma\right) \Pi_1^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T q_L^{\mathbf{20}'} \Sigma\right) \Pi_2^q \\ & + {\rm tr}\left[\bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'}\right] \Pi_0^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'} \Sigma\right) \Pi_1^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) \Pi_2^t \\ & + {\rm tr}\left[\bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\right] M_0^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'} \Sigma\right) M_1^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) M_2^t + {\rm h.c.},\end{aligned}$$

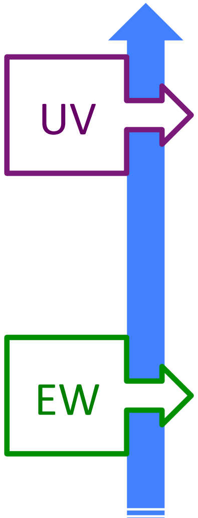
- ❑ p^2-dependent form factors $\Pi^{q,t}_{0,1,2}(p^2),\ M^t_{0,1,2}(p^2)$ (strong dynamics)

- ❑ Goldstone matrix $U(\vec{\pi}) = e^{i\frac{\sqrt{2}}{f}\pi_r \hat{T}_2^r}, \quad \Sigma = U \cdot (0,0,0,0,0,1)^T$
- ❑ Goldstone decay constant: $f > 1$ TeV [LEP & LHC]

- ❑ SM doublet & singlet $H = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi_2 + i\pi_1 \\ \pi_4 - i\pi_3 \end{pmatrix}; \quad \pi_5.$
- ❑ Unitary gauge

$$\pi_{1,2,3} = 0, \quad \frac{h}{f} = \frac{\pi_4}{\sqrt{\pi_4^2 + \pi_5^2}} \sin\frac{\sqrt{\pi_4^2+\pi_5^2}}{f}, \quad \frac{\eta}{f} = \frac{\pi_5}{\sqrt{\pi_4^2 + \pi_5^2}} \sin\frac{\sqrt{\pi_4^2+\pi_5^2}}{f}$$

- Lagrangian: fermion sector



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- ❑ p^2-dependent form factors $\Pi^{q,t}_{0,1,2}(p^2),\ M^t_{0,1,2}(p^2)$ (strong dynamics)

- ❑ Composite operator decomposed; Top partners excited by the operators

$$SO(6) \to SO(5) \qquad \langle 0 | \mathcal{O}^{\mathbf{14}}_{R,L} | \Psi_{\mathbf{14}} \rangle = y_{L,R} f, \quad \cdots$$

$$\mathcal{O}^{\mathbf{20}'} \to \mathcal{O}^{\mathbf{14}} \oplus \mathcal{O}^{\mathbf{5}} \oplus \mathcal{O}^{\mathbf{1}}$$

- ❑ Determining the form factors ($Q^2 = -p^2$)[Pomarol *et al*, JHEP 08 (2012) 135]

$$\Pi_0^{q,t} = 1 + \langle \mathcal{O}^{\mathbf{14}}_{R,L} \mathcal{O}^{\mathbf{14}}_{R,L} \rangle = 1 + \sum_{n=1}^{N_{\mathbf{14}}} \frac{|y^{\mathbf{14}(n)}_{L,R}|^2 f^2}{Q^2 + M^2_{\mathbf{14}(n)}}$$

Sum over the whole tower of top partners

- # From form factors to scalar potential

Form factors as functions of top partner masses & couplings

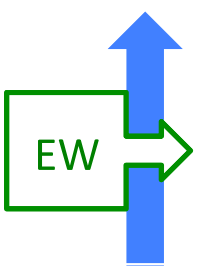
$$\Pi_0^{q,t} = 1 + \sum_{n=1}^{N_{\mathbf{14}}} \frac{|y_{L,R}^{\mathbf{14}(n)}|^2 f^2}{Q^2 + M_{\mathbf{14}(n)}^2}, \quad \Pi_1^{q,t} = 2\left(\sum_{n=1}^{N_{\mathbf{5}}} \frac{|y_{L,R}^{\mathbf{5}(n)}|^2 f^2}{Q^2 + M_{\mathbf{5}(n)}^2} - \sum_{n=1}^{N_{\mathbf{14}}} \frac{|y_{L,R}^{\mathbf{14}(n)}|^2 f^2}{Q^2 + M_{\mathbf{14}(n)}^2}\right),$$

$$\Pi_2^{q,t} = \frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}} \frac{|y_{L,R}^{\mathbf{1}(n)}|^2 f^2}{Q^2 + M_{\mathbf{1}(n)}^2} - 2\sum_{n=1}^{N_{\mathbf{5}}} \frac{|y_{L,R}^{\mathbf{5}(n)}|^2 f^2}{Q^2 + M_{\mathbf{5}(n)}^2} + \frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}} \frac{|y_{L,R}^{\mathbf{14}(n)}|^2 f^2}{Q^2 + M_{\mathbf{14}(n)}^2},$$

$$M_0^t = \sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2},$$

$$M_1^t = 2\left(\sum_{n=1}^{N_{\mathbf{5}}} \frac{y_L^{\mathbf{5}(n)} y_R^{\mathbf{5}(n)*} f^2 M_{\mathbf{5}(n)}}{Q^2 + M_{\mathbf{5}(n)}^2} - \sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2}\right),$$

$$M_2^t = \frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}} \frac{y_L^{\mathbf{1}(n)} y_R^{\mathbf{1}(n)*} f^2 M_{\mathbf{1}(n)}}{Q^2 + M_{\mathbf{1}(n)}^2} - 2\sum_{n=1}^{N_{\mathbf{5}}} \frac{y_L^{\mathbf{5}(n)} y_R^{\mathbf{5}(n)*} f^2 M_{\mathbf{5}(n)}}{Q^2 + M_{\mathbf{5}(n)}^2} + \frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2},$$



$$\begin{aligned}\mathcal{L}_\Psi \to\ & \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'}\right] \Pi_0^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \gamma^\mu p_\mu q_L^{\mathbf{20}'} \Sigma\right) \Pi_1^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T q_L^{\mathbf{20}'} \Sigma\right) \Pi_2^q \\ & + \mathrm{tr}\left[\bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'}\right] \Pi_0^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \gamma^\mu p_\mu t_R^{\mathbf{20}'} \Sigma\right) \Pi_1^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'} \Sigma\right) \gamma^\mu p_\mu \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) \Pi_2^t \\ & + \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\right] M_0^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'} \Sigma\right) M_1^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} \Sigma\right) \left(\Sigma^T t_R^{\mathbf{20}'} \Sigma\right) M_2^t + \mathrm{h.c.},\end{aligned}$$

- # From form factors to scalar potential

Coleman-Weinberg mechanism

$$
\begin{aligned}
V_f(h,\eta) \approx &- 2N_c \int \frac{d^4Q}{(2\pi)^4}\left[\ln\left(1+\frac{\Pi_1^q}{2\Pi_0^q}\frac{\eta^2}{f^2}\right)+\ln\left(1+\frac{\Pi_1^q}{4\Pi_0^q}\frac{h^2+2\eta^2}{f^2}+\frac{\Pi_2^q}{\Pi_0^q}\frac{h^2\eta^2}{f^4}\right)\right] \\
&- 2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{\Pi_1^t}{2\Pi_0^t}\left(1-\frac{h^2}{f^2}\right)+\frac{2\Pi_2^t}{\Pi_0^t}\frac{\eta^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\right] \\
&- 2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{1}{8Q^2\Pi_0^q\Pi_0^t}\frac{h^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\left|M_1^t+4M_2^t\frac{\eta^2}{f^2}\right|^2\right],
\end{aligned}
$$

$$
\Sigma = \left(0,0,0,\frac{h}{f},\frac{\eta}{f},\sqrt{1-\frac{h^2+\eta^2}{f^2}}\right)^T
$$

------ Integrating out the q_L and t_R ------

EW

$$
\begin{aligned}
\mathcal{L}_\Psi \to\ & \mathrm{tr}\left[\bar{q}_L^{\mathbf{20'}}\gamma^\mu p_\mu q_L^{\mathbf{20'}}\right]\Pi_0^q+\left(\Sigma^T\bar{q}_L^{\mathbf{20'}}\gamma^\mu p_\mu q_L^{\mathbf{20'}}\Sigma\right)\Pi_1^q+\left(\Sigma^T\bar{q}_L^{\mathbf{20'}}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T q_L^{\mathbf{20'}}\Sigma\right)\Pi_2^q \\
&+\mathrm{tr}\left[\bar{t}_R^{\mathbf{20'}}\gamma^\mu p_\mu t_R^{\mathbf{20'}}\right]\Pi_0^t+\left(\Sigma^T\bar{t}_R^{\mathbf{20'}}\gamma^\mu p_\mu t_R^{\mathbf{20'}}\Sigma\right)\Pi_1^t+\left(\Sigma^T\bar{t}_R^{\mathbf{20'}}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T t_R^{\mathbf{20'}}\Sigma\right)\Pi_2^t \\
&+\mathrm{tr}\left[\bar{q}_L^{\mathbf{20'}}t_R^{\mathbf{20'}}\right]M_0^t+\left(\Sigma^T\bar{q}_L^{\mathbf{20'}}t_R^{\mathbf{20'}}\Sigma\right)M_1^t+\left(\Sigma^T\bar{q}_L^{\mathbf{20'}}\Sigma\right)\left(\Sigma^T t_R^{\mathbf{20'}}\Sigma\right)M_2^t+\mathrm{h.c.},
\end{aligned}
$$

- From form factors to scalar potential

Coleman-Weinberg mechanism

$$\begin{aligned} V_f(h,\eta) \approx & -2N_c \int \frac{d^4Q}{(2\pi)^4}\left[\ln\left(1+\frac{\Pi_1^q}{2\Pi_0^q}\frac{\eta^2}{f^2}\right)+\ln\left(1+\frac{\Pi_1^q}{4\Pi_0^q}\frac{h^2+2\eta^2}{f^2}+\frac{\Pi_2^q}{\Pi_0^q}\frac{h^2\eta^2}{f^4}\right)\right] \\ & -2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{\Pi_1^t}{2\Pi_0^t}\left(1-\frac{h^2}{f^2}\right)+\frac{2\Pi_2^t}{\Pi_0^t}\frac{\eta^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\right] \\ & -2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{1}{8Q^2\Pi_0^q\Pi_0^t}\frac{h^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\left|M_1^t+4M_2^t\frac{\eta^2}{f^2}\right|^2\right], \end{aligned}$$

Convergence condition $\Pi_{1,2}^{q,t}/\Pi_0^{q,t} \sim Q^{-6}$;

recall $\Pi_0^{q,t} = 1+\sum_{n=1}^{N_{\mathbf{14}}}\frac{|y_{L,R}^{\mathbf{14}(n)}|^2 f^2}{Q^2+M^2_{\mathbf{14}(n)}}, \quad \Pi_1^{q,t} = 2\left(\sum_{n=1}^{N_{\mathbf{5}}}\frac{|y_{L,R}^{\mathbf{5}(n)}|^2 f^2}{Q^2+M^2_{\mathbf{5}(n)}}-\sum_{n=1}^{N_{\mathbf{14}}}\frac{|y_{L,R}^{\mathbf{14}(n)}|^2 f^2}{Q^2+M^2_{\mathbf{14}(n)}}\right),$

achieved by Weinberg sum rules

$$\sum_{n=1}^{N_{\mathbf{14}}}|y_{L,R}^{\mathbf{14}(n)}|^2=\sum_{n=1}^{N_{\mathbf{5}}}|y_{L,R}^{\mathbf{5}(n)}|^2=\sum_{n=1}^{N_{\mathbf{1}}}|y_{L,R}^{\mathbf{1}(n)}|^2,$$

$$\sum_{n=1}^{N_{\mathbf{14}}}|y_{L,R}^{\mathbf{14}(n)}|^2M^2_{\mathbf{14}(n)}=\sum_{n=1}^{N_{\mathbf{5}}}|y_{L,R}^{\mathbf{5}(n)}|^2M^2_{\mathbf{5}(n)}=\sum_{n=1}^{N_{\mathbf{1}}}|y_{L,R}^{\mathbf{1}(n)}|^2M^2_{\mathbf{1}(n)}.$$

Potential is a function of top partner masses & couplings!

- From form factors to scalar potential

Coleman-Weinberg mechanism

$$V_f(h,\eta) \approx -2N_c \int \frac{d^4Q}{(2\pi)^4}\left[\ln\left(1+\frac{\Pi_1^q}{2\Pi_0^q}\frac{\eta^2}{f^2}\right)+\ln\left(1+\frac{\Pi_1^q}{4\Pi_0^q}\frac{h^2+2\eta^2}{f^2}+\frac{\Pi_2^q}{\Pi_0^q}\frac{h^2\eta^2}{f^4}\right)\right]$$
$$-2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{\Pi_1^t}{2\Pi_0^t}\left(1-\frac{h^2}{f^2}\right)+\frac{2\Pi_2^t}{\Pi_0^t}\frac{\eta^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\right]$$
$$-2N_c \int \frac{d^4Q}{(2\pi)^4}\ln\left[1+\frac{1}{8Q^2\Pi_0^q\Pi_0^t}\frac{h^2}{f^2}\left(1-\frac{h^2+\eta^2}{f^2}\right)\left|M_1^t+4M_2^t\frac{\eta^2}{f^2}\right|^2\right],$$

Convergence condition $\Pi^{q,t}_{1,2}/\Pi^{q,t}_0 \sim Q^{-6}$;

recal

achiev

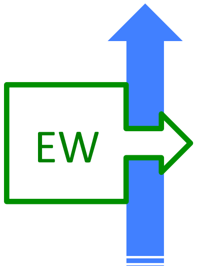
Matching to a polynomial (since f >1 TeV)

$$V_f(h,\eta) = \frac{\mu_h^2}{2}h^2+\frac{\mu_\eta^2}{2}\eta^2+\frac{\lambda_h}{4}h^4+\frac{\lambda_\eta}{4}\eta^4+\frac{\lambda_{h\eta}}{2}h^2\eta^2,$$

$$\sum_{n=1}^{N_{14}}|y_{L,R}^{\mathbf{14}(n)}|^2=\sum_{n=1}^{N_5}|y_{L,R}^{\mathbf{5}(n)}|^2=\sum_{n=1}^{N_1}|y_{L,R}^{\mathbf{1}(n)}|^2,$$
$$\sum_{n=1}^{N_{14}}|y_{L,R}^{\mathbf{14}(n)}|^2M^2_{\mathbf{14}(n)}=\sum_{n=1}^{N_5}|y_{L,R}^{\mathbf{5}(n)}|^2M^2_{\mathbf{5}(n)}=\sum_{n=1}^{N_1}|y_{L,R}^{\mathbf{1}(n)}|^2M^2_{\mathbf{1}(n)}.$$

Potential is a function of top partner masses & couplings!

- Potential: vector contribution



$$\mathcal{L}_{\rm EW} \supset \frac{1}{2} P_T^{\mu\nu} \Big\{ \left(-p^2 + \frac{g_0'^2}{g_0^2} \Pi_0(p^2) \right) B_\mu B_\nu + \left(-p^2 + \Pi_0(p^2)\right) W_\mu^a W_\nu^a$$
$$+ \frac{\Pi_1(p^2)}{4} \frac{h^2}{f^2} \left[W_\mu^1 W_\nu^1 + W_\mu^2 W_\nu^2 + \left(W_\mu^3 - \frac{g_0'}{g_0} B_\mu \right) \left(W_\nu^3 - \frac{g_0'}{g_0} B_\nu \right) \right] \Big\}$$

Form factors determined by vector resonances ρ and a

$$\Pi_0 = g^2 Q^2 \sum_{n=1}^{N_\rho} \frac{f_{\rho(n)}^2}{Q^2 + M_{\rho(n)}^2},$$
$$\Pi_1 = g^2 f^2 + 2 g^2 Q^2 \left(\sum_{n=1}^{N_a} \frac{f_{a(n)}^2}{Q^2 + M_{a(n)}^2} - \sum_{n=1}^{N_\rho} \frac{f_{\rho(n)}^2}{Q^2 + M_{\rho(n)}^2} \right)$$

Coleman-Weinberg mechanism

$$(\Pi_W = Q^2 + \Pi_0,\ \Pi_B = Q^2 + (g'^2/g^2)\Pi_0)$$

$$V_g(h) \approx \frac{3}{2} \int \frac{d^4Q}{(2\pi)^4} \left\{ 2 \ln \left(1 + \frac{\Pi_1}{4\Pi_W} \frac{h^2}{f^2} \right) + \ln \left[1 + \left(\frac{g'^2}{g^2} \frac{\Pi_1}{4\Pi_B} + \frac{\Pi_1}{4\Pi_W} \right) \frac{h^2}{f^2} \right] \right\},$$

Convergence condition $\Pi_1 \sim Q^{-4}$, hence Weinberg sum rules

$$\sum_{n=1}^{N_\rho} f_{\rho(n)}^2 = \frac{f^2}{2} + \sum_{n=1}^{N_a} f_{a(n)}^2; \quad \sum_{n=1}^{N_\rho} f_{\rho(n)}^2 M_{\rho(n)}^2 = \sum_{n=1}^{N_a} f_{a(n)}^2 M_{a(n)}^2,$$

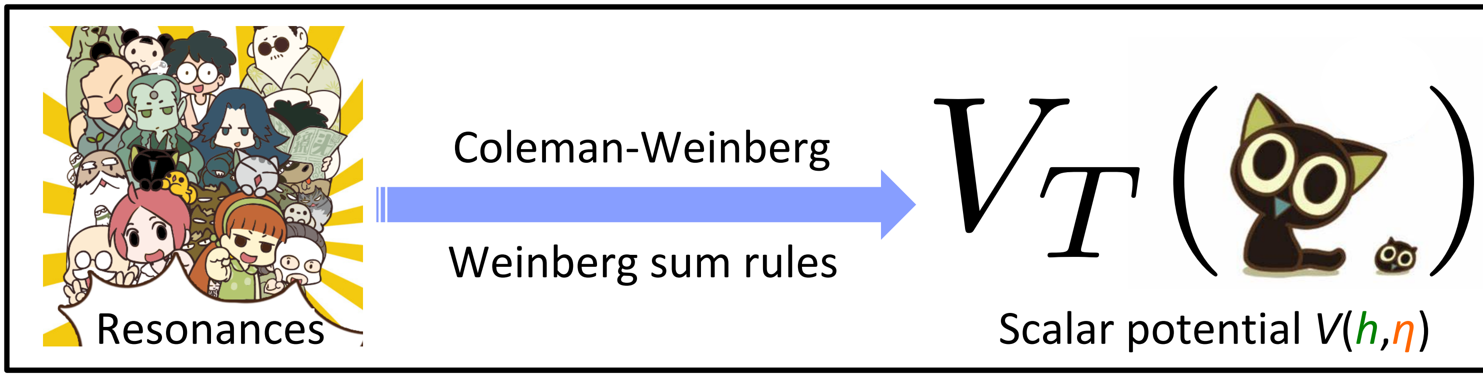
Potential is a function of vector resonances masses & couplings!

- Back to the cosmological study...

The scalar potential is still written as

$$V_T(h,\eta) = \frac{\mu_h^2 + c_h T^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_\eta^2 + c_\eta T^2}{2} \eta^2 + \frac{\lambda_\eta}{4} \eta^4 + \frac{\lambda_{h\eta}}{2} h^2 \eta^2$$

But now all the coefficents are determined by the *resonance mass and couplings*.

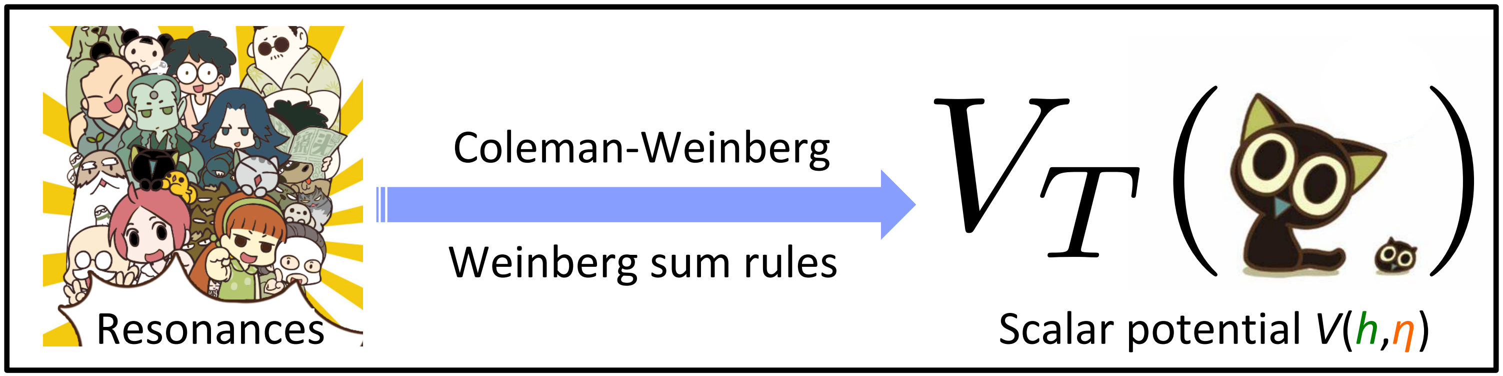


- Back to the cosmological study...

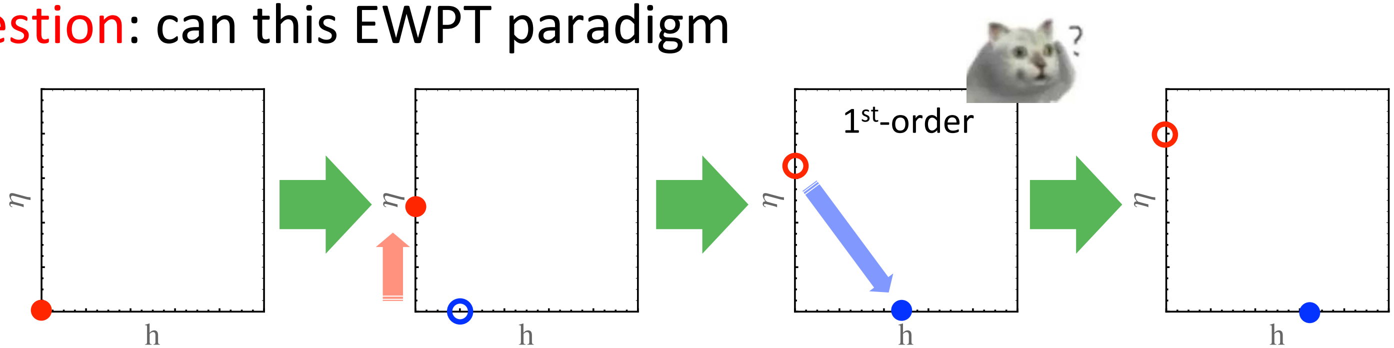
The scalar potential is still written as

$$V_T(h,\eta) = \frac{\mu_h^2 + c_h T^2}{2} h^2 + \frac{\lambda_h}{4} h^4 + \frac{\mu_\eta^2 + c_\eta T^2}{2} \eta^2 + \frac{\lambda_\eta}{4} \eta^4 + \frac{\lambda_{h\eta}}{2} h^2 \eta^2$$

But now all the coefficents are determined by the *resonance mass and couplings*.



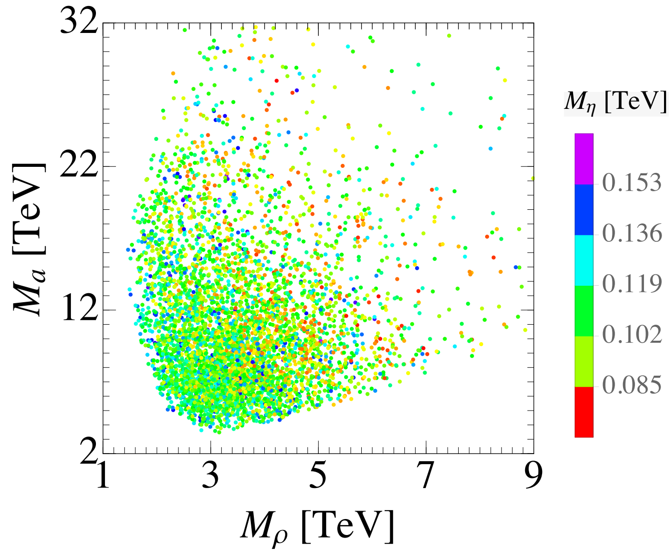
Question: can this EWPT paradigm

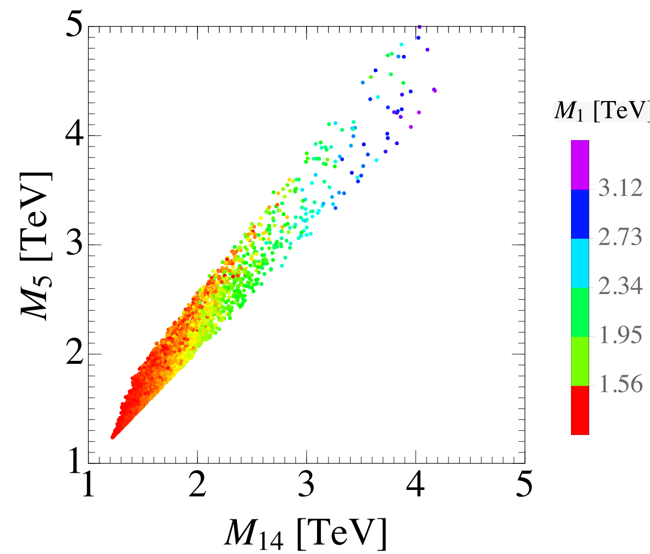


be realized in the mass & couplings parameter space??

to the cosmological study...

Reproducing SM particle spectrum & triggering strong 1[st]-order EWPT





- ✧ Embeddings lower than 20: quartic couplings too small
- ✧ In 20', $\lambda_{\eta,h\eta}$ is enhanced!

$$\begin{aligned}\mathcal{L}_\Psi \to\ & \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\right]\Pi_0^q + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\Sigma\right)\Pi_1^q + \boxed{\left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T q_L^{\mathbf{20}'}\Sigma\right)\Pi_2^q} \\ & + \mathrm{tr}\left[\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\right]\Pi_0^t + \left(\Sigma^T\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\Sigma\right)\Pi_1^t + \boxed{\left(\Sigma^T\bar{t}_R^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)\Pi_2^t} \\ & + \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'}t_R^{\mathbf{20}'}\right]M_0^t + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}t_R^{\mathbf{20}'}\Sigma\right)M_1^t + \left(\Sigma^T\bar{q}_L^{\mathbf{20}'}\Sigma\right)\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)M_2^t + \mathrm{h.c.},\end{aligned}$$

The first composite Higgs model that succeeds to trigger the strong 1[st]-order EWPT via Coleman-Weinberg potential

- Phase transition is OK, then next...

CP violating phase

$$\mathcal{L}_\Psi \to \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\right]\Pi_0^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\gamma^\mu p_\mu q_L^{\mathbf{20}'}\Sigma\right)\Pi_1^q + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu \left(\Sigma^T q_L^{\mathbf{20}'}\Sigma\right)\Pi_2^q$$
$$+ \mathrm{tr}\left[\bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\right]\Pi_0^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'}\gamma^\mu p_\mu t_R^{\mathbf{20}'}\Sigma\right)\Pi_1^t + \left(\Sigma^T \bar{t}_R^{\mathbf{20}'}\Sigma\right)\gamma^\mu p_\mu \left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right)\Pi_2^t$$
$$+ \mathrm{tr}\left[\bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\right] M_0^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'} t_R^{\mathbf{20}'}\Sigma\right) M_1^t + \left(\Sigma^T \bar{q}_L^{\mathbf{20}'}\Sigma\right)\left(\Sigma^T t_R^{\mathbf{20}'}\Sigma\right) M_2^t + \mathrm{h.c.},$$

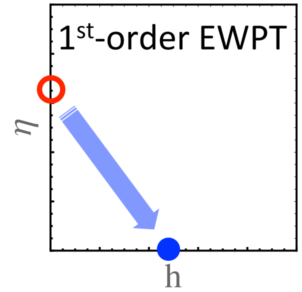
$$M_0^t = \sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2},$$
$$M_1^t = 2\left(\sum_{n=1}^{N_{\mathbf{5}}} \frac{y_L^{\mathbf{5}(n)} y_R^{\mathbf{5}(n)*} f^2 M_{\mathbf{5}(n)}}{Q^2 + M_{\mathbf{5}(n)}^2} - \sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2}\right),$$
$$M_2^t = \frac{6}{5}\sum_{n=1}^{N_{\mathbf{1}}} \frac{y_L^{\mathbf{1}(n)} y_R^{\mathbf{1}(n)*} f^2 M_{\mathbf{1}(n)}}{Q^2 + M_{\mathbf{1}(n)}^2} - 2\sum_{n=1}^{N_{\mathbf{5}}} \frac{y_L^{\mathbf{5}(n)} y_R^{\mathbf{5}(n)*} f^2 M_{\mathbf{5}(n)}}{Q^2 + M_{\mathbf{5}(n)}^2} + \frac{4}{5}\sum_{n=1}^{N_{\mathbf{14}}} \frac{y_L^{\mathbf{14}(n)} y_R^{\mathbf{14}(n)*} f^2 M_{\mathbf{14}(n)}}{Q^2 + M_{\mathbf{14}(n)}^2},$$

$$\mathcal{L}_\Psi \supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R h\left[\frac{M_{1,0}^t}{|M_{1,0}^t|}\left(1 - \frac{h^2 - v^2}{2f^2}\right) + \frac{\eta^2}{2f^2}\left(\frac{8M_{2,0}^t}{|M_{1,0}^t|} - \frac{M_{1,0}^t}{|M_{1,0}^t|}\right)\right] + \mathrm{h.c.}$$
$$\supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R h\left[e^{i\phi_1}\left(1 - \frac{h^2 + \eta^2 - v^2}{2f^2}\right) + \rho_t e^{i\phi_2}\frac{\eta^2}{2f^2}\right] + \mathrm{h.c.}$$

Novelty: CPV from dimension-6 operator $ih\eta^2 t\gamma^5 t$!

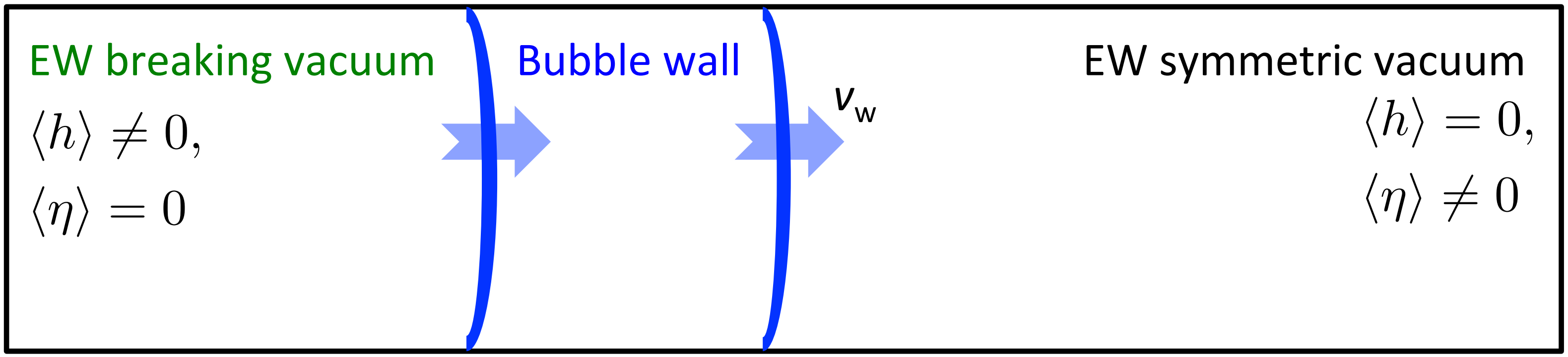
- Towards the baryogenesis

In the field space:



This is the departure from thermal equilibrium!

In the spacetime:



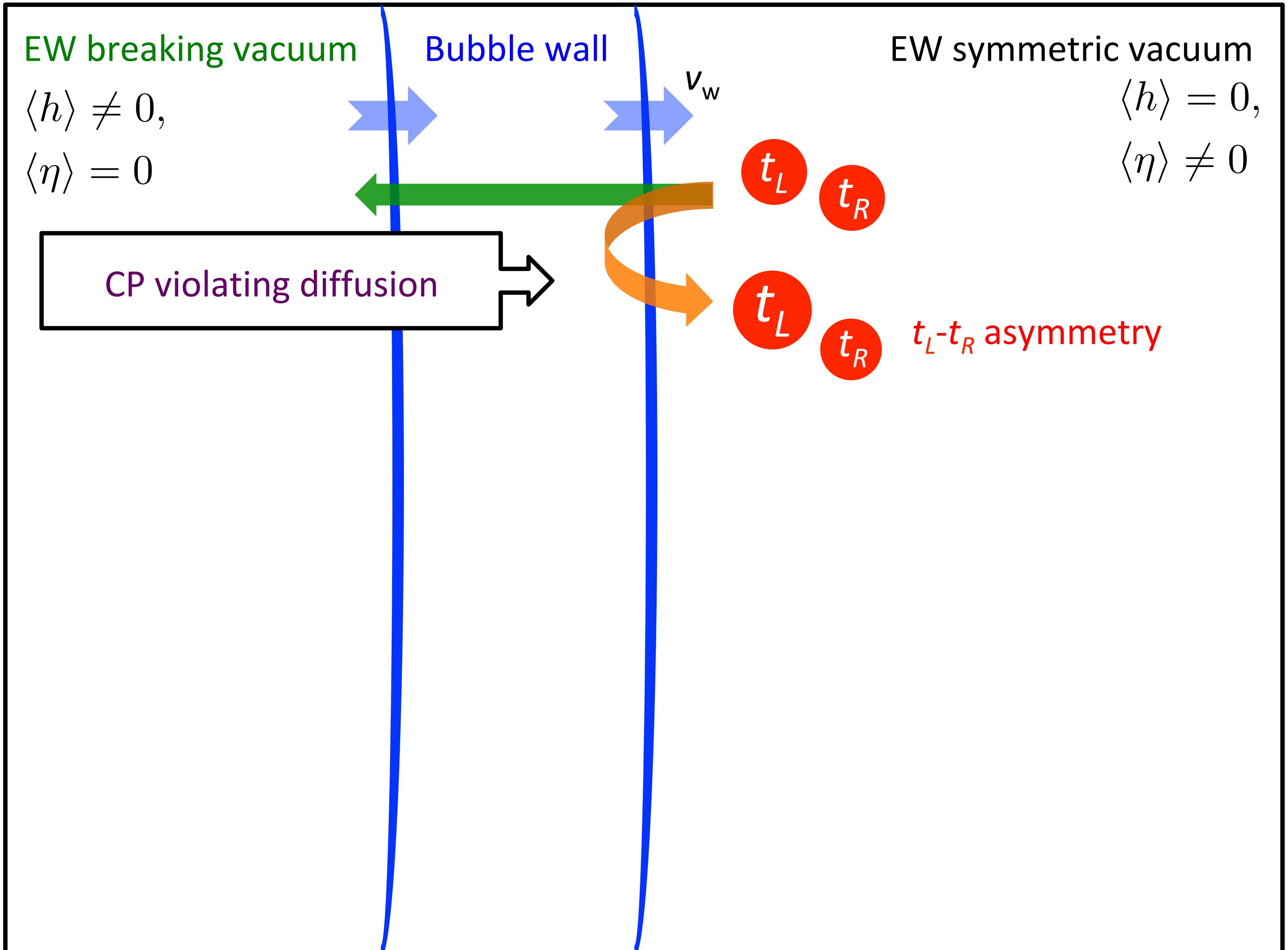
Top quarks experience a force when crossing the bubble wall

$$\mathcal{L}_\Psi \supset -\frac{y_t}{\sqrt{2}}\bar{t}_L t_R h\left[e^{i\phi_1}\left(1-\frac{h^2+\eta^2-v^2}{2f^2}\right)+\rho_t e^{i\phi_2}\frac{\eta^2}{2f^2}\right]+\text{h.c.}$$

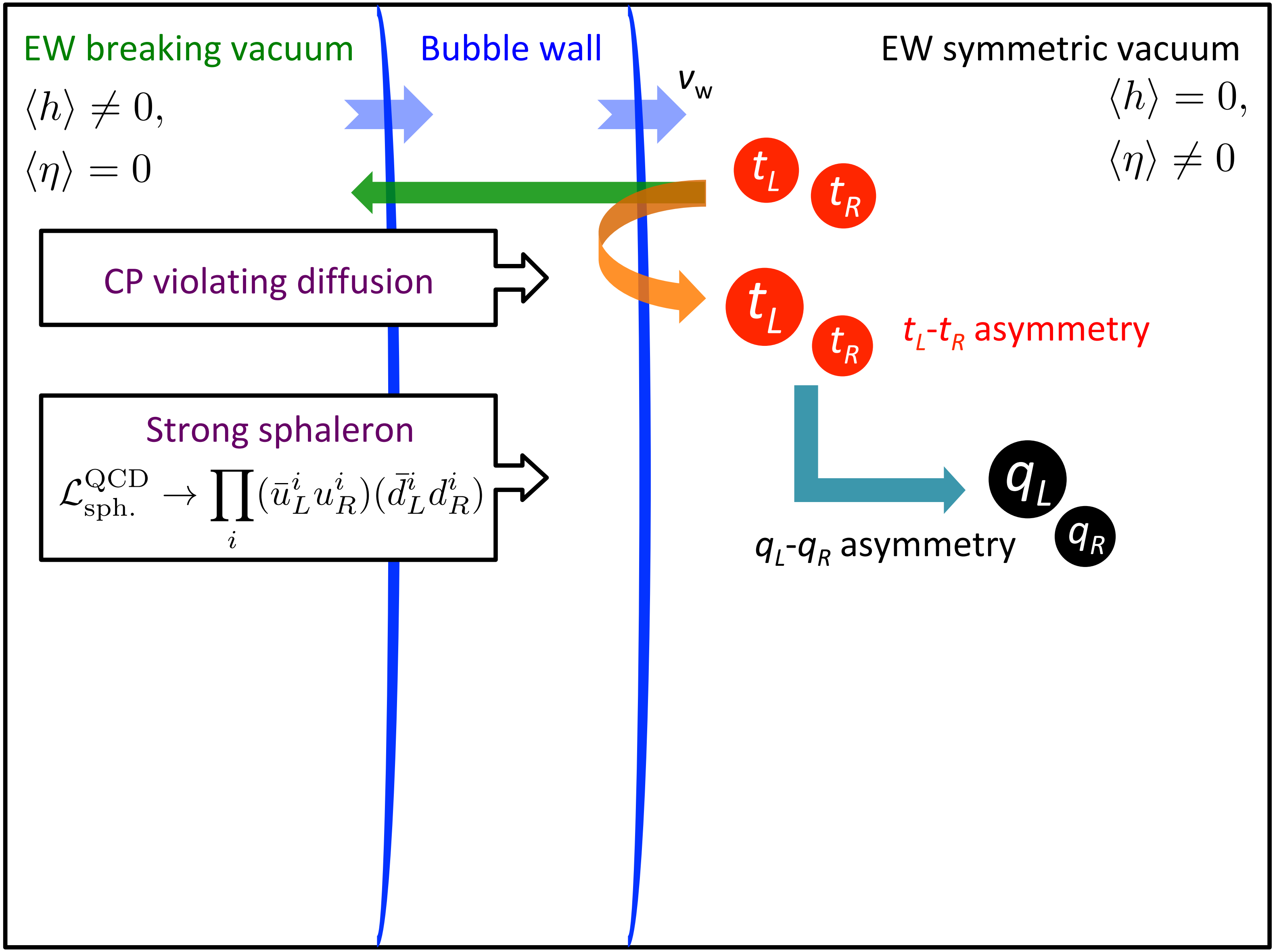
$$\to -m_t\,\bar{t}\,e^{i\gamma^5\theta_t}t$$

$$m_t=\frac{y_t}{\sqrt{2}}\hat{h}\left[1-\frac{\hat{h}^2-v^2}{2f^2}-\frac{\hat{\eta}^2}{2f^2}\left(1-\rho_t\cos\phi_2\right)\right], \quad \tan\theta_t=\frac{\hat{\eta}^2}{2f^2}\rho_t\sin\phi_2.$$

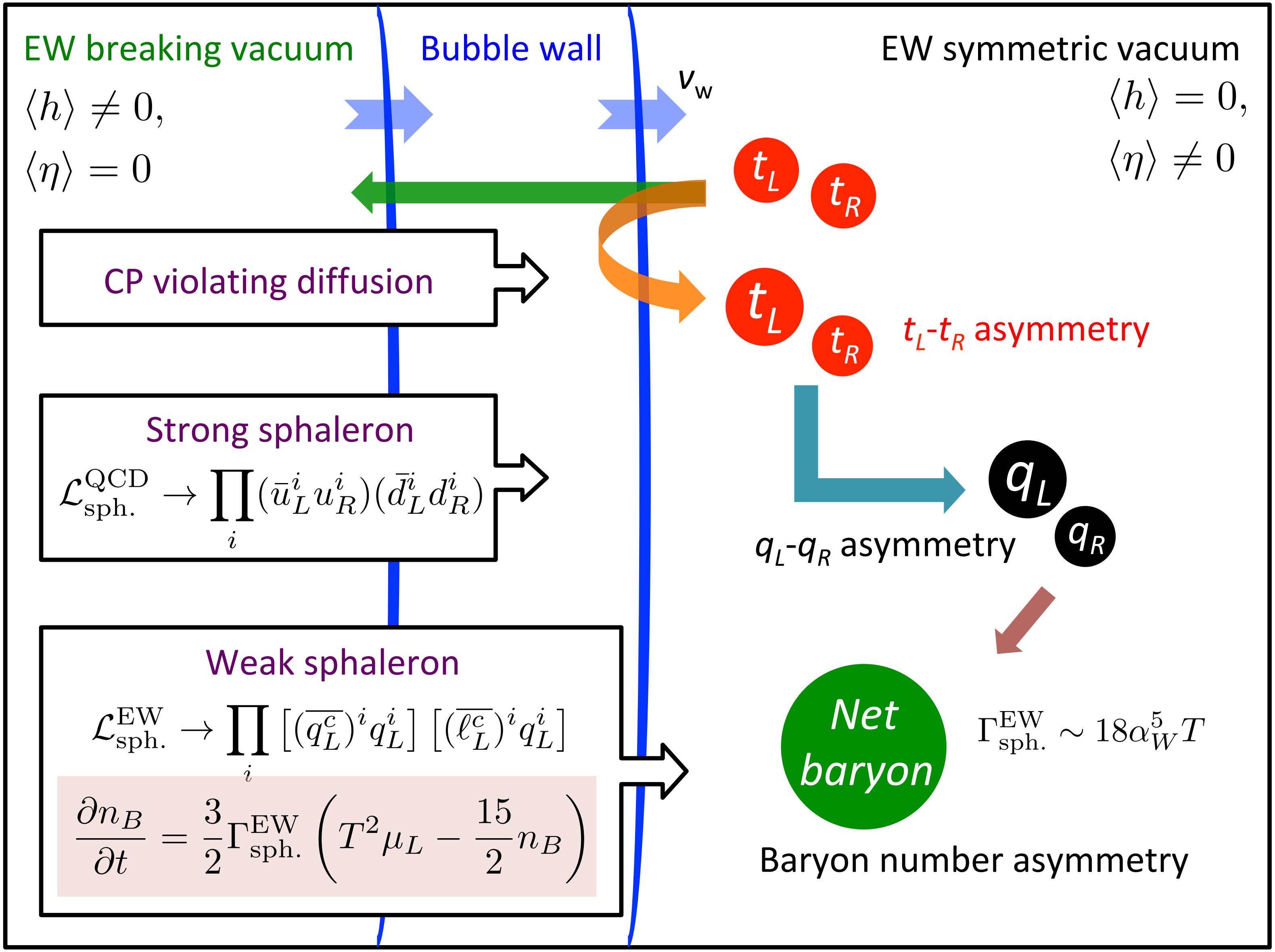
- EW baryogenesis



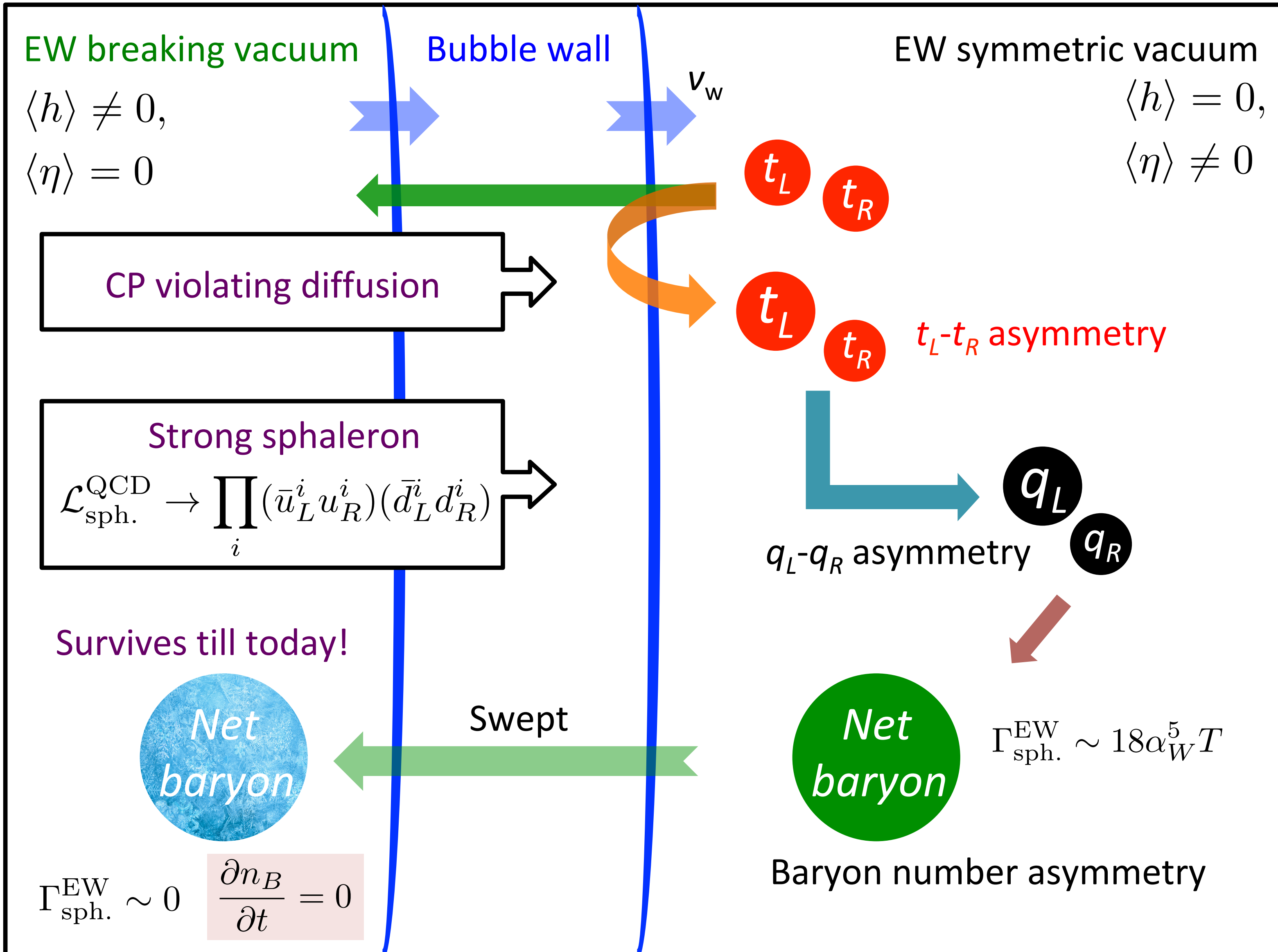
- EW baryogenesis



- EW baryogenesis



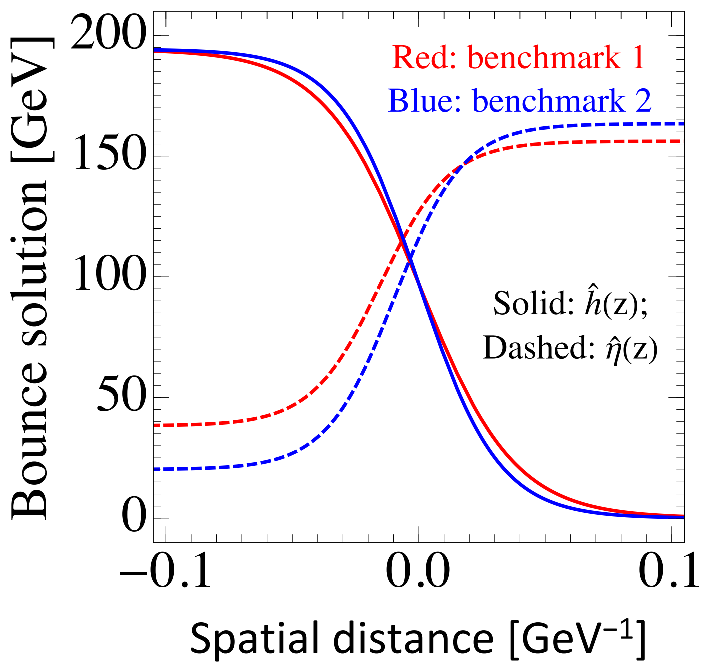
- EW baryogenesis

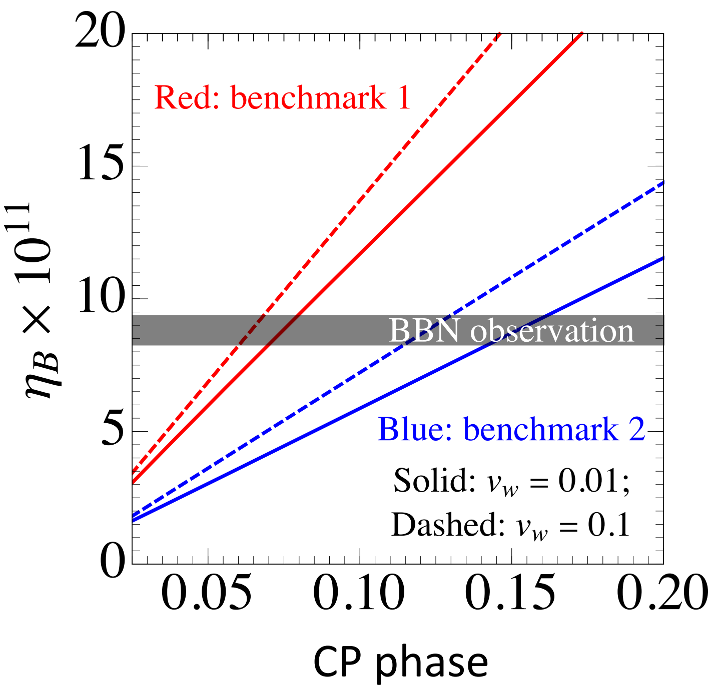


• EW baryogenesis

Mechanism proposed in [Joyce *et al*, PRL 75 (1995) 1695–1698].
Technically we adopt [Fromme *et al*, JHEP 03 (2007) 049] to calculate.

Two benchmarks for illustration:





The baryon asymmetry of the universe can be explained.

- Testing the scenario: gravitational waves

1st-order EWPT generates stochastic GWs:

✓ Collision of the bubbles

✓ Sound waves in plasma

✓ Turbulance in plasma

Typical spectrum ➡

Near-future space-based detectors:

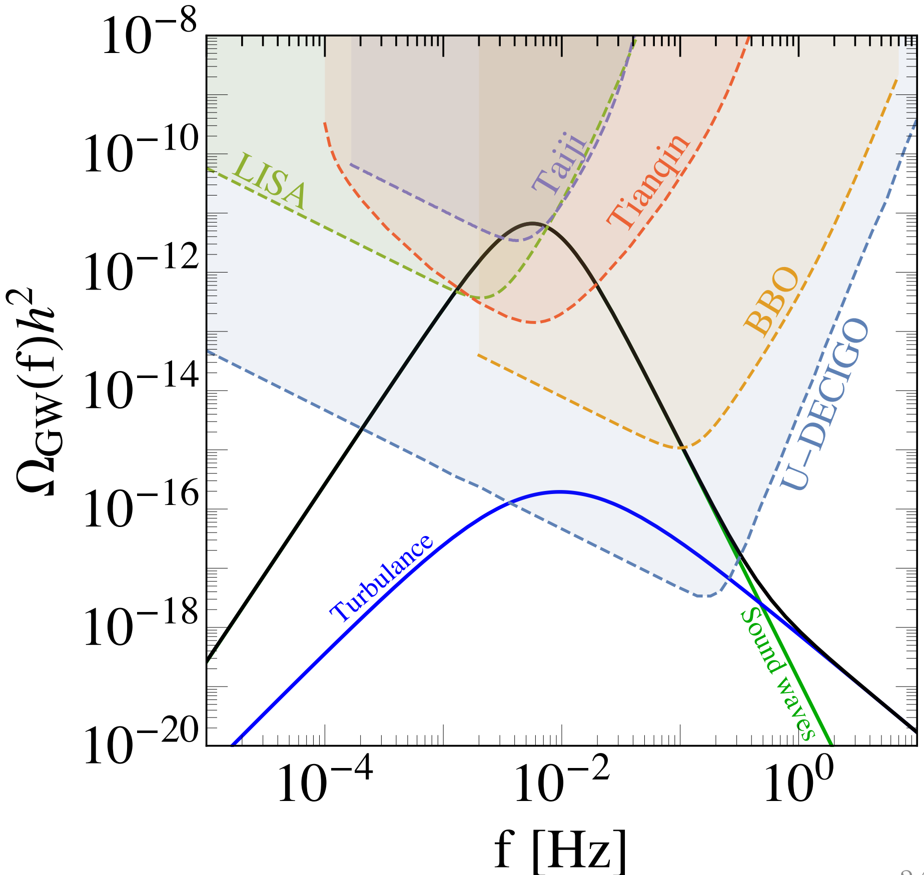
LISA (EU)

Taiji (China)

TianQin (China)

DECIGO (Japan)

......



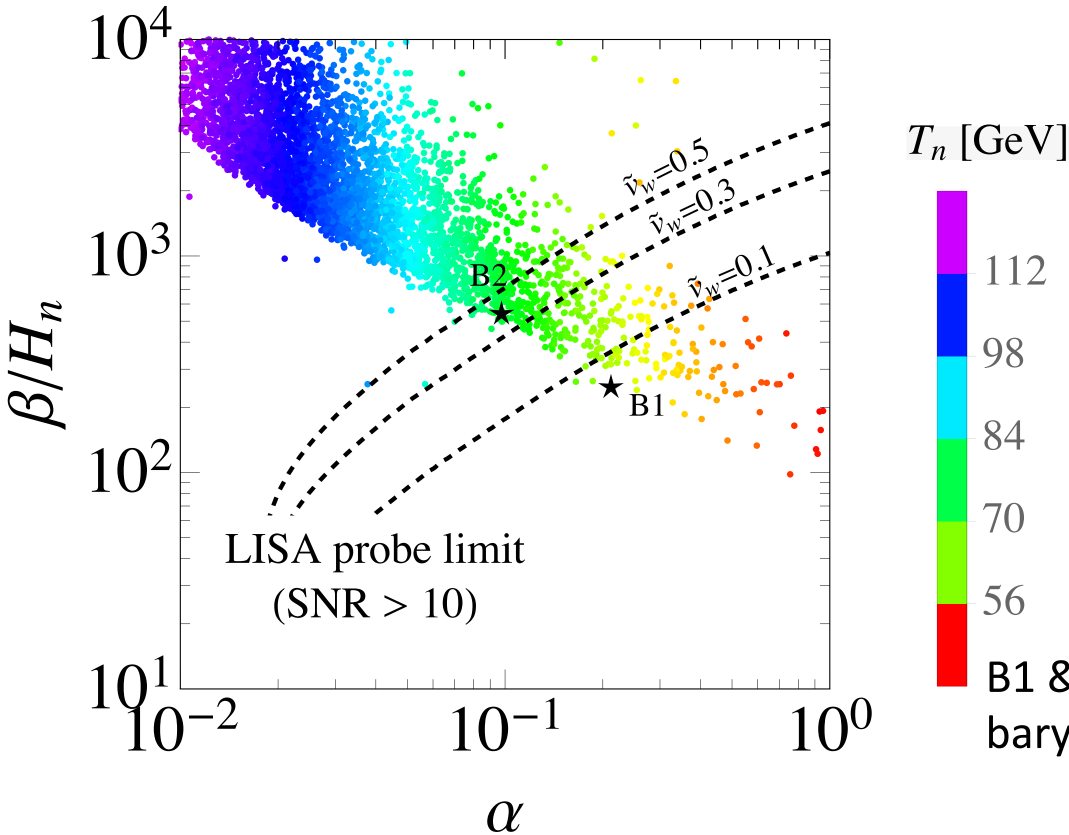
- Testing the scenario: gravitational waves

Signal-to-noise (SNR) study for the LISA detector

α: (EWPT latent heat)/(the universe energy density)

β/H_*: (Universe expansion time)/(EWPT time)

tilde v_w : wall velocity relative to plasma at infinte distance

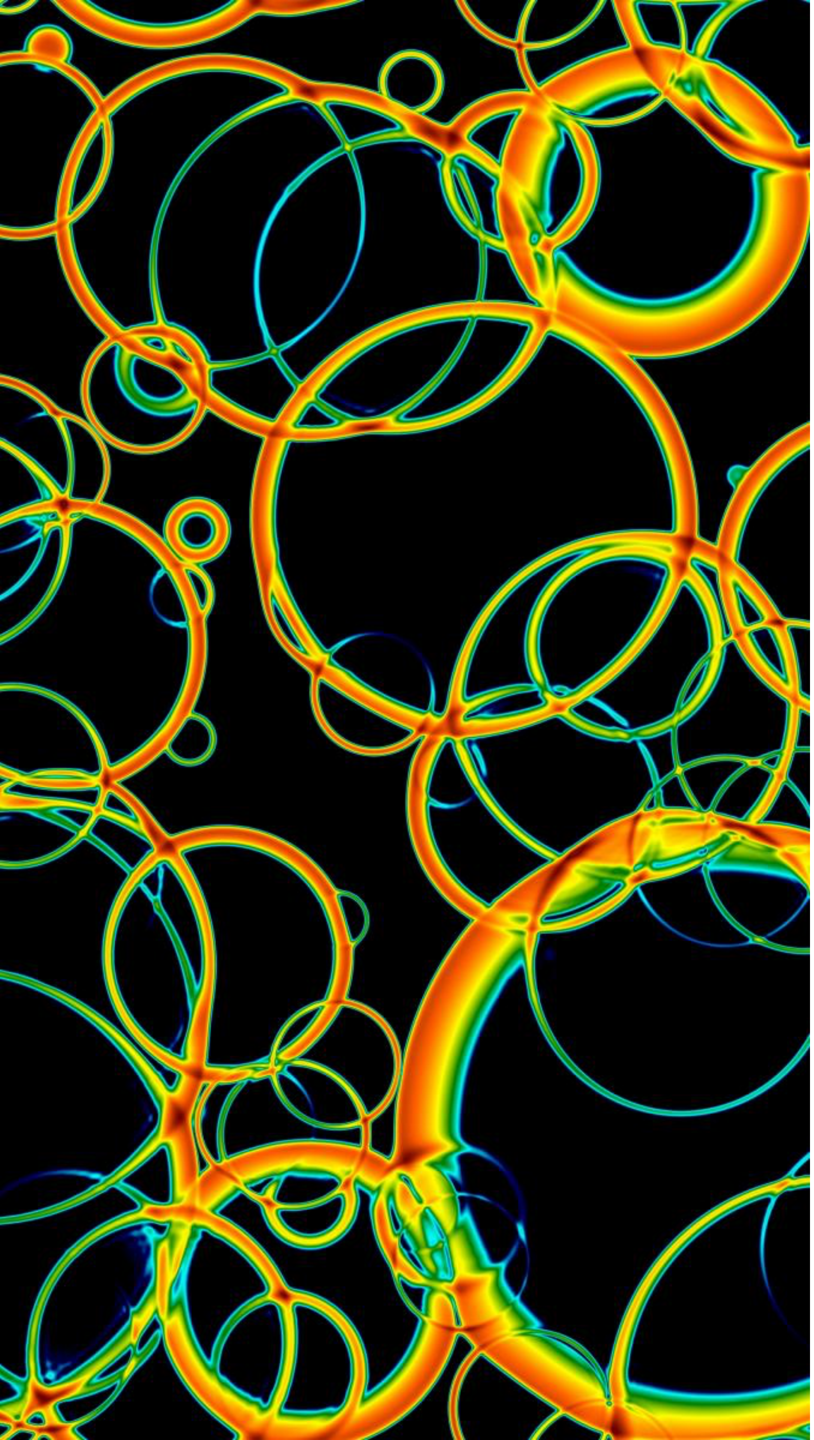


EWPT temperature

B1 & B2: benchmarks for EW baryogenesis in previous slides

Conclusion

- We build a SO(6)/SO(5) composite Higgs model with q_L and t_R both embedded in 20'
- New! This model is able to trigger a strong 1st-order EWPT with resonance masses O(1-10 TeV)
- CP violation comes from the dim-6 operator $ih\eta^2 t\gamma^5 t$
- EW baryogenesis is realized.
- Phase transition GWs can be tested at the near-future space-based detectors.



Thank you!

- Embedding q_L and t_R into 20'

$$\mathbf{6}\otimes\mathbf{6}=\mathbf{1}\oplus\mathbf{15}\oplus\mathbf{20}'$$

Dimensional-20 representations of SO(6): 20, 20', 20''

$$SO(6)\times U(1)_X \to SO(5)\times U(1)_X \to SO(4)\times U(1)_X \to SU(2)_L\times U(1)_Y$$

$$(Y=X+T_R{}^3)$$

$$\begin{aligned}\mathbf{20}'_{2/3} &\to \mathbf{14}_{2/3}\oplus\mathbf{5}_{2/3}\oplus\mathbf{1}_{2/3}\\ &\to (\mathbf{9}_{2/3}\oplus\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus(\mathbf{4}_{2/3}\oplus\mathbf{1}_{2/3})\oplus\mathbf{1}_{2/3}\\ &\to \left[(\mathbf{3}_{5/3}\oplus\mathbf{3}_{2/3}\oplus\mathbf{3}_{-1/3})\oplus(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}\right]\oplus\left[(\mathbf{2}_{7/6}\oplus\underline{\mathbf{2}_{1/6}})\oplus\underline{\mathbf{1}_{2/3}}\right]\oplus\underline{\mathbf{1}_{2/3}}.\end{aligned}$$

Two/three ways to embed q_L/t_R, respectively

$$q_L^{\mathbf{20}'_A}=\frac{1}{2}\begin{pmatrix}0&0&0&0&ib_L&0\\0&0&0&0&b_L&0\\0&0&0&0&it_L&0\\0&0&0&0&-t_L&0\\ib_L&b_L&it_L&-t_L&0&0\\0&0&0&0&0&0\end{pmatrix},\quad q_L^{\mathbf{20}'_B}=\frac{1}{2}\begin{pmatrix}0&0&0&0&0&ib_L\\0&0&0&0&0&b_L\\0&0&0&0&0&it_L\\0&0&0&0&0&-t_L\\0&0&0&0&0&0\\ib_L&b_L&it_L&-t_L&0&0\end{pmatrix},$$

$$t_R^{\mathbf{20}'_A}=\frac{1}{2\sqrt{5}}\begin{pmatrix}-\mathbb{I}_{4\times4}t_R&0_{4\times2}\\0_{2\times4}&2\left(\mathbb{I}_{2\times2}+\tau^3\right)t_R\end{pmatrix},\quad t_R^{\mathbf{20}'_B}=\frac{1}{\sqrt{2}}\begin{pmatrix}0_{4\times4}&0_{4\times2}\\0_{2\times4}&\tau^1 t_R\end{pmatrix},$$

$$t_R^{\mathbf{20}'_C}=\frac{1}{\sqrt{30}}\begin{pmatrix}-\mathbb{I}_{5\times5}t_R&0_{5\times1}\\0_{1\times5}&5t_R\end{pmatrix},$$

$$q_L^{\mathbf{20}'}=q_L^{\mathbf{20}'_A}e^{i\phi_L}\cos\theta_L+q_L^{\mathbf{20}'_B}\sin\theta_L,$$

$$t_R^{\mathbf{20}'}=e^{i\phi_{R1}}\cos\theta_{R1}t_R^{\mathbf{20}'_A}+e^{i\phi_{R2}}\sin\theta_{R1}\cos\theta_{R2}t_R^{\mathbf{20}'_B}+\sin\theta_{R1}\sin\theta_{R2}t_R^{\mathbf{20}'_C}.$$

- Embedding q_L and t_R into 20'

WARNING: Dangerous mixing!

$$\mathcal{L} \supset -\frac{1}{\sqrt{2}} h y_L^{\mathbf{14}} \left(\frac{\eta e^{-i\phi_L} \cos\theta_L}{f + \sqrt{f^2 - h^2 - \eta^2}} + \sin\theta_L \right) (\bar{b}_L N_{-1/3} + \bar{b}_L Y_{-1/3})$$

$$q_L^{\mathbf{20}'} = q_L^{\mathbf{20}'_A} e^{i\phi_L} \cos\theta_L + q_L^{\mathbf{20}'_B} \sin\theta_L$$

$$\begin{bmatrix} \mathbf{14}_{2/3} & \rightarrow & \mathbf{3}_{5/3} & \oplus & \mathbf{3}_{2/3} & \oplus & \mathbf{3}_{-1/3} & \oplus & \mathbf{2}_{7/6} & \oplus & \mathbf{2}_{1/6} & \oplus & \mathbf{1}_{2/3} \\ \Psi_{\mathbf{14}} & \rightarrow & K & \oplus & N & \oplus & Y & \oplus & J_X & \oplus & J_Q & \oplus & T' \end{bmatrix},$$

$$Zf\bar{f} = \frac{g}{c_W}\left(T_L^3 - s_W^2 Q\right),$$

Zb_Lb_L is measured at the LEP accurately. Should not be modified!

Letting $\vartheta_L = 0$ and $\eta = 0$ at zero temeprature can avoid this problem.

- Embedding q_L and t_R into 20'

To get a top mass

$$t_R^{\mathbf{20'}_A} : \Pi_{LR}^t = -\frac{1}{2\sqrt{5}}\frac{h\eta}{f^2}\left(\frac{3M_1^t}{2} - M_2^t\frac{h^2-4\eta^2}{f^2}\right),$$

$$t_R^{\mathbf{20'}_B} : \Pi_{LR}^t = -\frac{1}{2\sqrt{2}}\frac{h}{f}\sqrt{1-\frac{h^2+\eta^2}{f^2}}\left(M_1^t + 4M_2^t\frac{\eta^2}{f^2}\right),$$

$$t_R^{\mathbf{20'}_C} : \Pi_{LR}^t = \frac{1}{\sqrt{30}}\frac{h\eta}{f^2}\left[M_1^t - M_2^t\left(5-6\frac{h^2+\eta^2}{f^2}\right)\right].$$

Only the second embedding provides a massive top when the VEV η = 0 at zero temeprature.

- EW baryogenesis benchmarks

Details of the parameters

	f [TeV]	M_ρ [TeV]	M_a [TeV]	$M_{\mathbf{14}}$ [TeV]	$M_{\mathbf{5}}$ [TeV]	$M_{\mathbf{1}}$ [TeV]	$M_{\mathbf{14}'}$ [TeV]	$M_{\mathbf{1}'}$ [TeV]
B1	2.17	4.57	6.49	1.61	1.89	1.05	8.57	13.9
B2	1.88	3.41	9.02	1.68	1.77	1.37	8.47	18.7

	$y_L^{\mathbf{14}}$	$y_R^{\mathbf{14}}$	$y_L^{\mathbf{5}}$	$y_R^{\mathbf{5}}$	$y_L^{\mathbf{1}}$	$y_R^{\mathbf{1}}$	$y_L^{\mathbf{14}'}$	$y_R^{\mathbf{14}'}$	$y_L^{\mathbf{1}'}$	$y_R^{\mathbf{1}'}$	M_η [GeV]
B1	1.90	0.676	-1.91	0.681	1.90	0.676	0.224	0.0798	0.216	0.0769	91.8
B2	2.11	0.574	2.12	-0.575	2.11	0.574	0.141	0.0383	0.126	0.0342	99.9

Table 1: The benchmarks used to evaluate the BAU. The T_n for B1 and B2 are respectively 59.2 GeV and 76.4 GeV; while v_n for B1 and B2 are respectively 222 GeV and 205 GeV.

• Generating the scalar potential

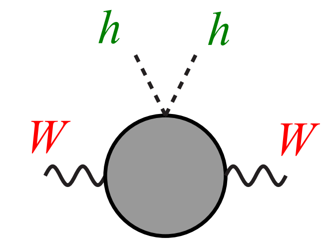
Potential source 1: gauge interactions

$$\mathcal{L}_{\text{int}} \supset \mathcal{J}^a_\mu W^\mu_a + \mathcal{J}_{Y\mu} B^\mu$$

SM gauge bosons: W^μ_a, B^μ

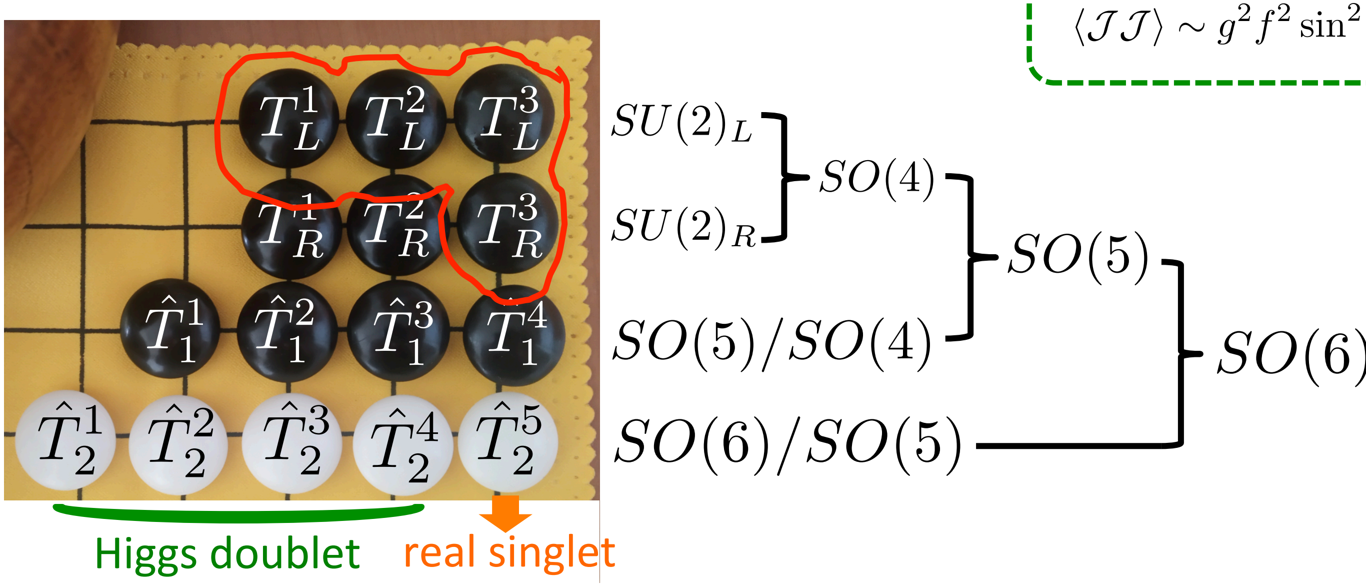
Strong currents: $\mathcal{J}^a_\mu$, $\mathcal{J}_{Y\mu}$

W & Z mass



$$\langle \mathcal{J}\mathcal{J} \rangle \sim g^2 f^2 \sin^2 \frac{h}{f}$$

Gauging a subgroup of SO(6) --



Breaks the symmetry down to $SO(6) \xrightarrow[\text{breaking}]{\text{explicit}} SU(2)_L \times U(1)_Y \times U(1)_\eta$,

Higgs potential $V(h)$ is generated !!

- # Generating the scalar potential

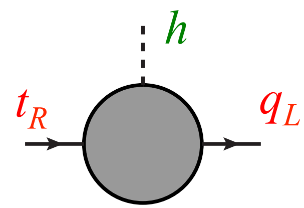
Potential source 2: fermion interactions

SM quarks

$$\mathcal{L}_{\rm int} \supset \bar{q}_L \mathcal{O}_R + \bar{t}_R \mathcal{O}_L + \text{h.c.}$$

Strong operators

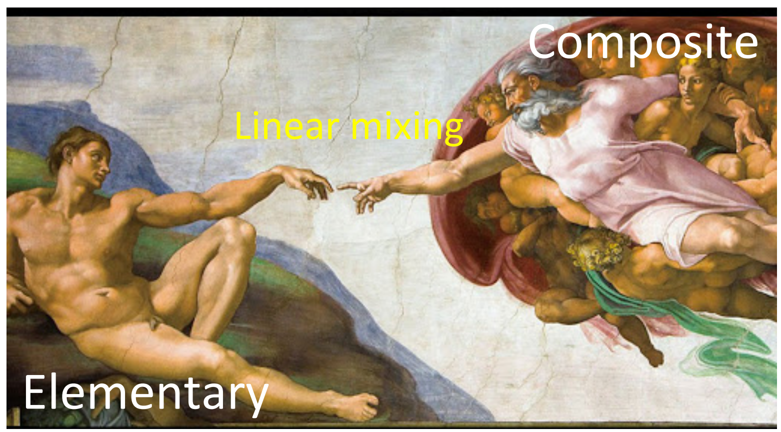
Top mass



$$\langle \mathcal{O}_L \mathcal{O}_R \rangle \sim \frac{y_L y_R}{g_\rho} f \sin\frac{h}{f}$$

Linear mixing:
so-called "*partial compositeness*"

SM quarks $q_L=(t_L, b_L)^T$, t_R in incomplete reps of SO(6)



Strong fermionic operators O_L & O_R

Agashe *et al* (2005)

Breaks the symmetry to $SO(6) \times U(1)_X \xrightarrow[\text{breaking}]{\text{explicit}} SU(2)_L \times U(1)_Y$

Joint potential $V(h,\eta)$ is generated !!

* $U(1)_X$ is introduced: $Y = X + T_R^3$