Electroweak baryogenesis and beyond the SM (2)

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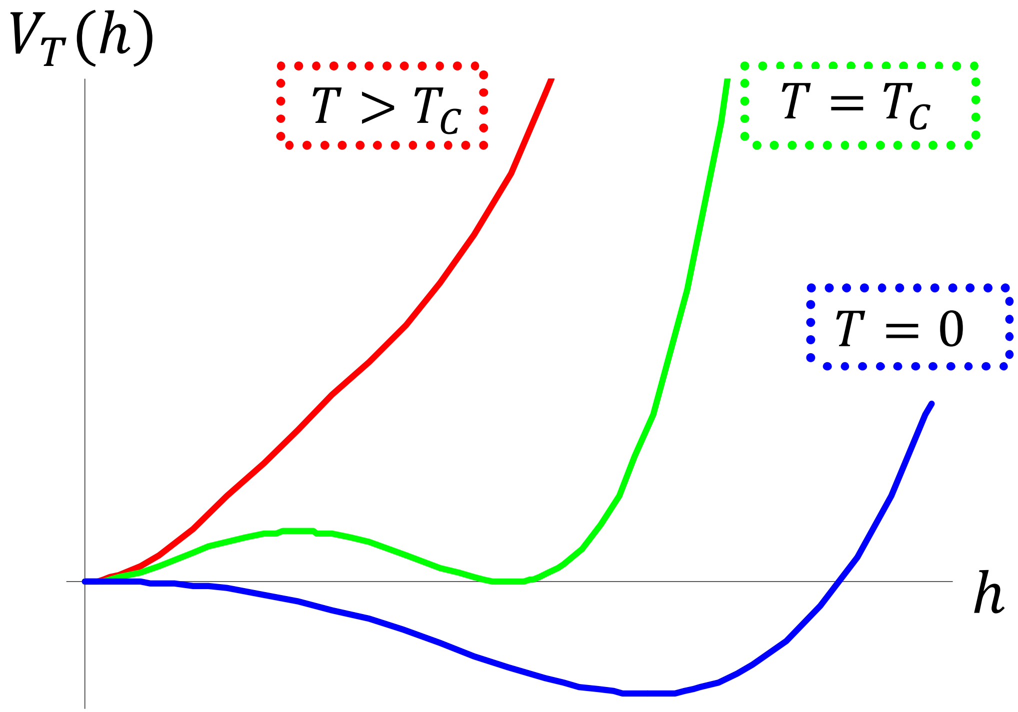
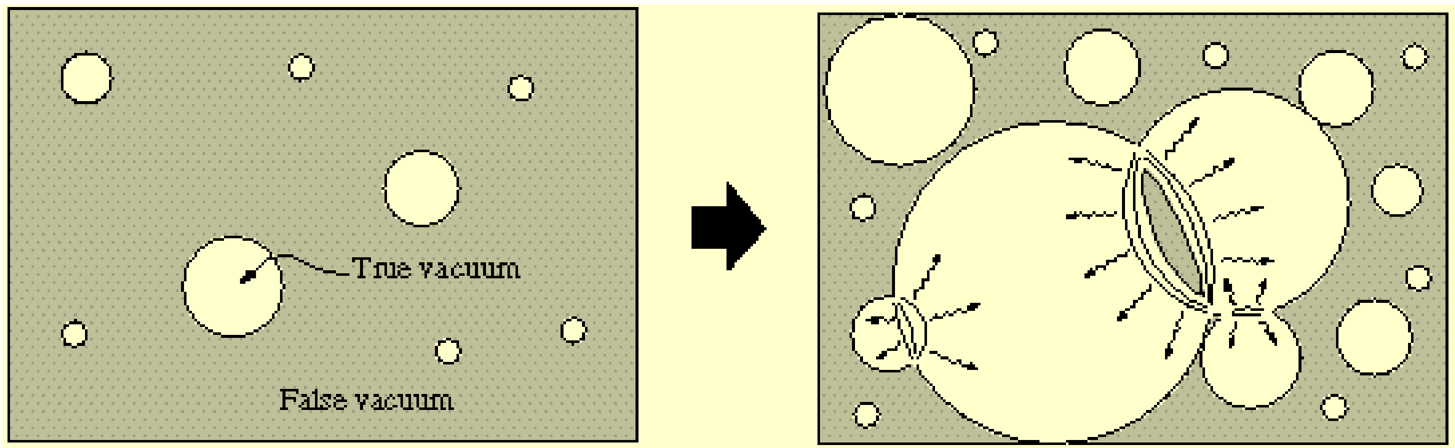
Electroweak baryogenesis (EWBG)

Baryon asymmetry of the Universe should be answered by physics beyond the SM. However, the Higgs still can play an important role for EWBG through electroweak phase transition (EWPT) in the early Universe





EWBG: Standard picture

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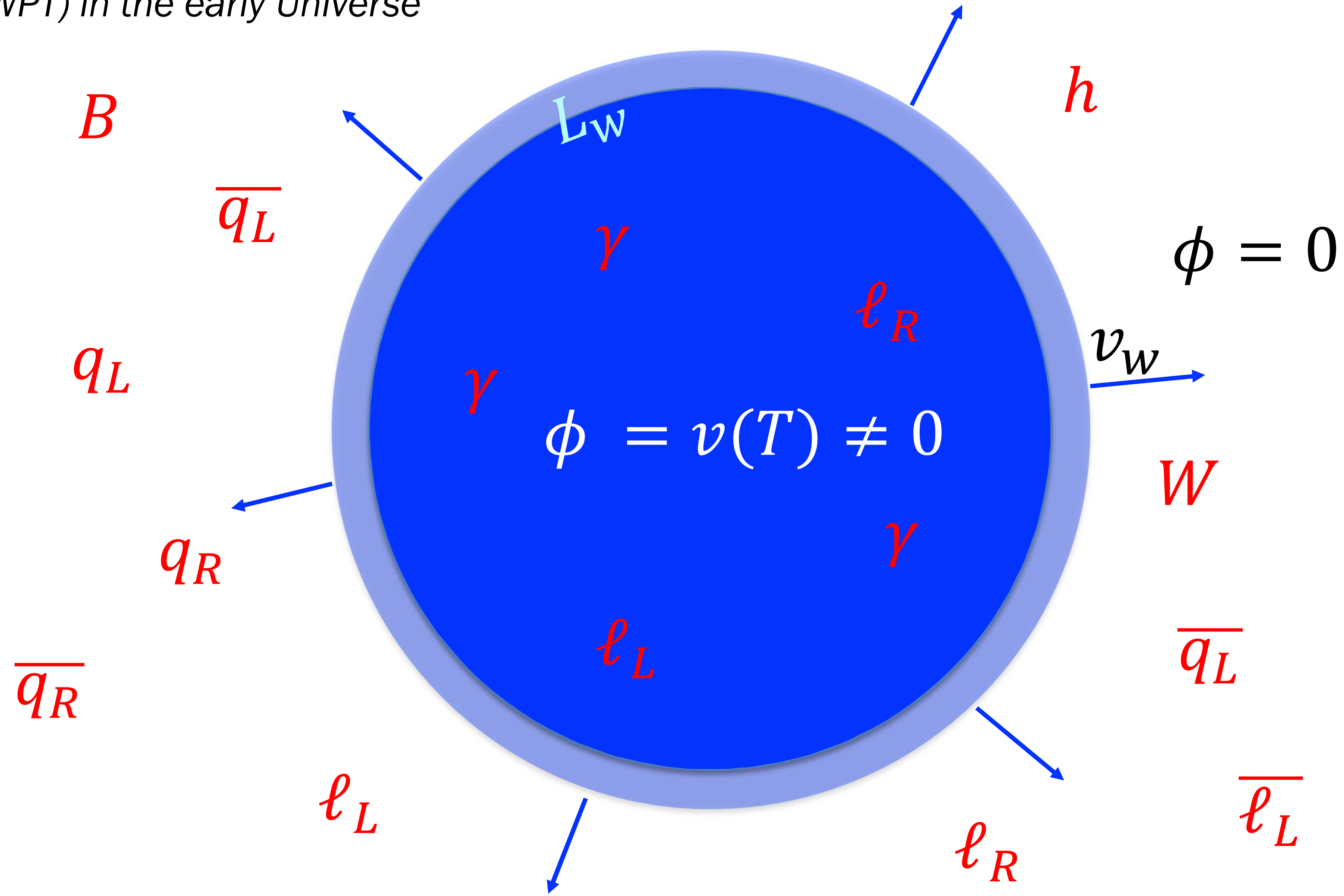
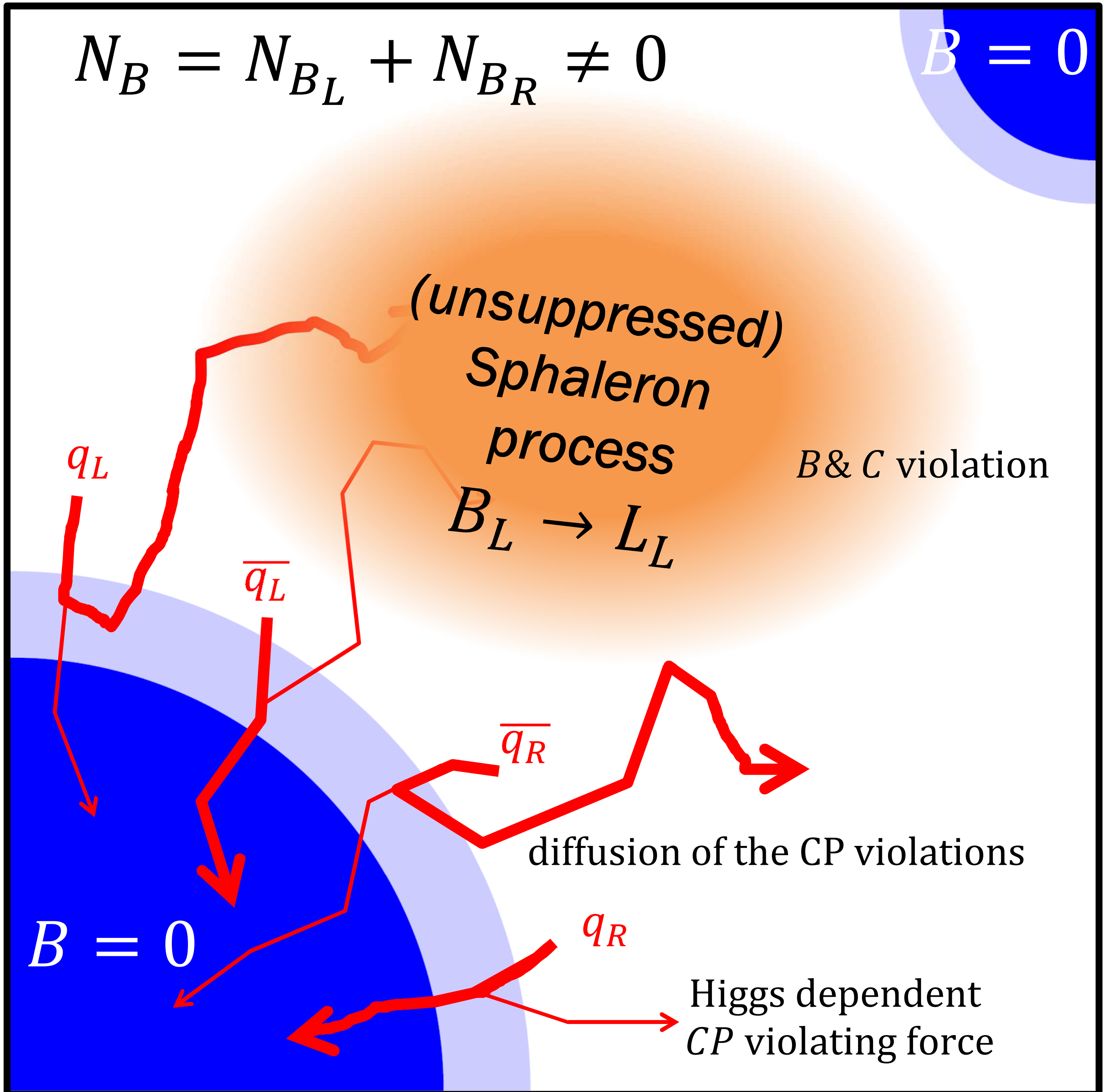


EWBG: Standard picture



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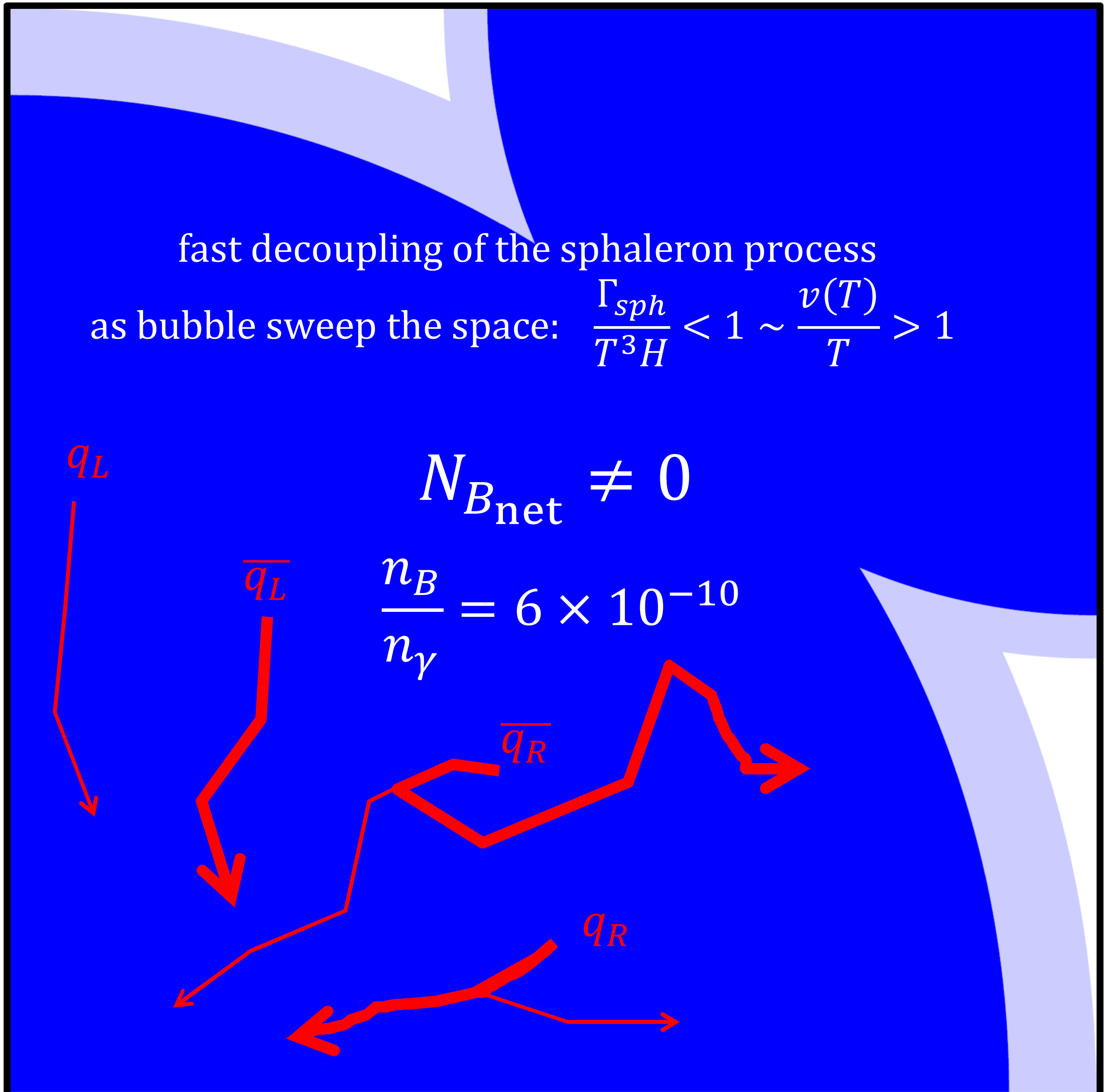
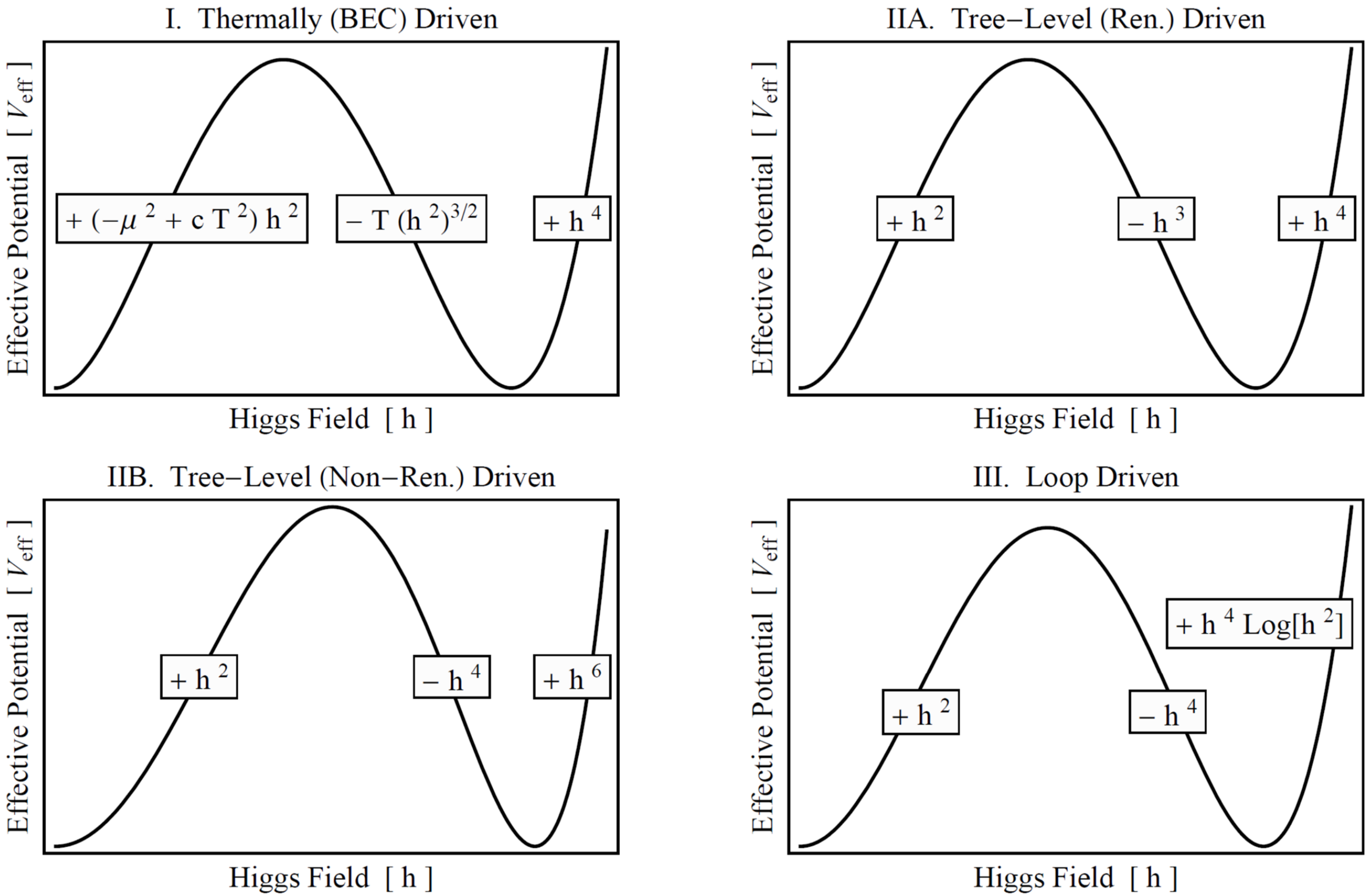
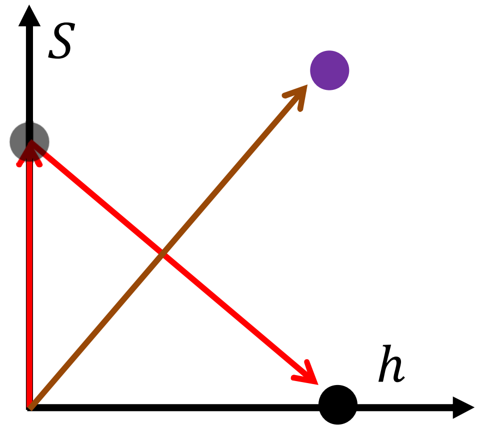


Extension for first order phase transition

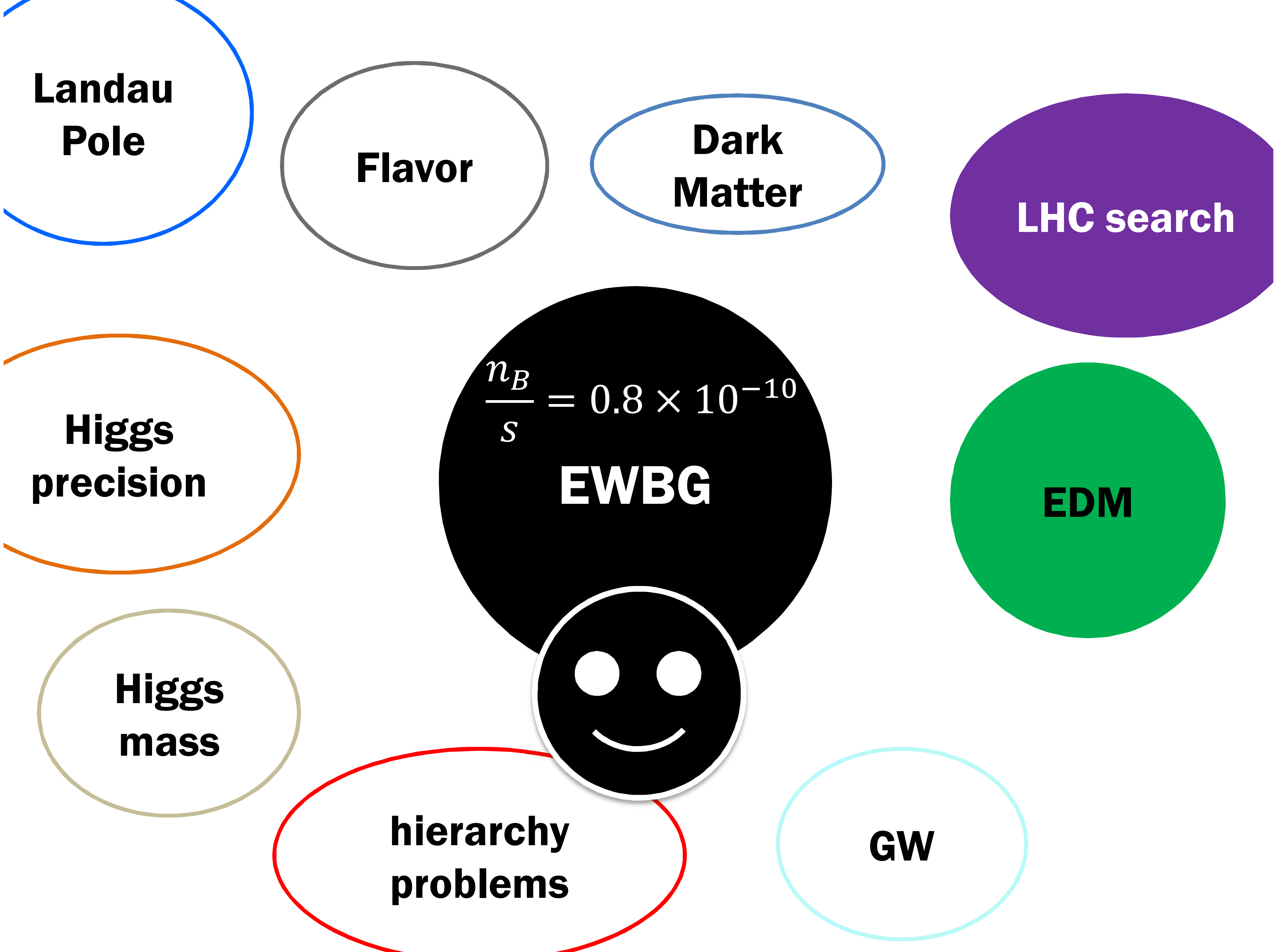
Most of extensions beyond the SM to realize strong 1st order EWPT needs strong couplings

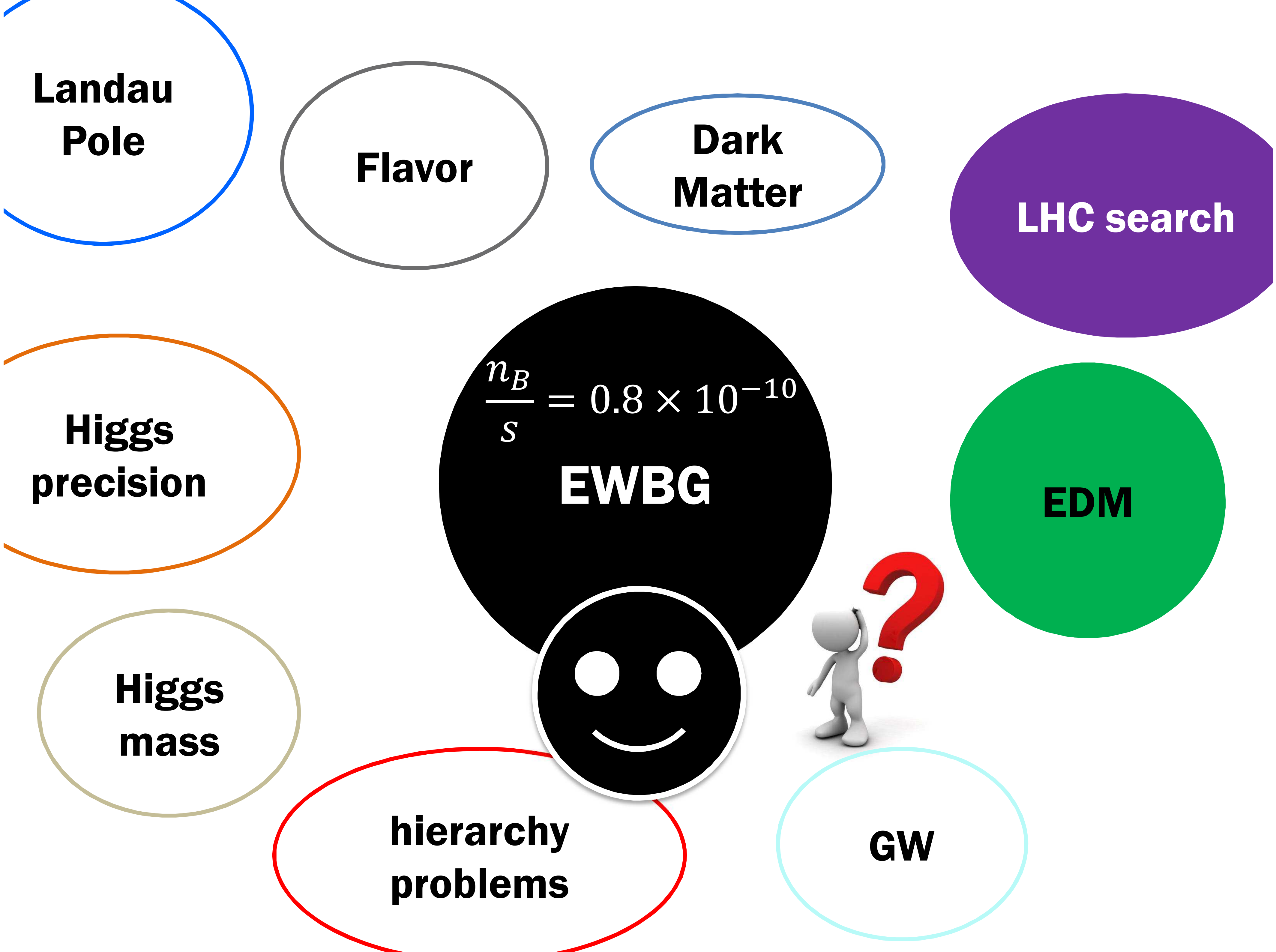
(single field description) *(multi field description)*





[Chung, Long, Wang 12]


Landau Pole
Flavor
Dark Matter
LHC search
$\frac{n_B}{s} = 0.8 \times 10^{-10}$
EWBG
EDM
Higgs precision
Higgs mass
hierarchy problems
GW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EW phase transition

Effect of thermal plasma

In order to describe the evolution of the early Universe, we have to take into account the effect of thermal plasma. First of all, equilibrium dynamics can be described by energy $U = \rho V$, *entropy* $S = sV$, *and free energy* $F = fV = U - TS = (\rho - Ts)V$.

They are related with the partition function, $Z = \mathrm{Tr}(e^{-\beta \hat{H}})$, *as* ($for\ \mu_i = 0$)

$$f = -\frac{T}{V}\ln Z = -p, \qquad s = -\frac{df}{dT}, \qquad \rho = f + Ts = f - T\frac{df}{dT}$$

(semiclassical) There are free (thermalized) particles with energy $E_k = \sqrt{k^2 + m_i^2}$, *its contribution to* Z *is*

$$Z_B = \prod_k \sum_{n_k} \exp(-\beta n_k E_k) = \prod_k \sum_{n_k=0}^{\infty} \exp(-\beta n_k E_k) = \prod_k \frac{1}{1 - \exp(-\beta E_k)}$$

$$Z_F = \prod_k (1 + \exp(-\beta E_k))$$

and contribution to the free energy density

$$\Delta f = -\frac{T}{V}\sum_{i=B,F} \ln Z_i = T\sum_{i=B}\int \frac{d^3k}{(2\pi)^3}\ln\left[1 - \exp\left(-\beta\sqrt{k^2 + m_i^2}\right)\right]$$
$$-T\sum_{i=F}\int \frac{d^3k}{(2\pi)^3}\ln\left[1 + \exp\left(-\beta\sqrt{k^2 + m_i^2}\right)\right]$$

free energy density $f(T,\phi)$

If the mass of the particle depends on the Higgs value, $m_i \to m_i(\phi) = y_i\phi$*, free energy density gives the additional temperature dependent effective potential for the Higgs.*

$$f(T,\phi) \equiv V_T(\phi) = V_0(\phi) + \Delta f = -\frac{1}{2}m^2\phi^2 + \frac{\lambda}{4}\phi^4 + \text{radiative corrections}$$

$$+ \sum_{n_B=1, n_F=-1} \int \frac{d^3k}{(2\pi)^3}(-1)^{n_i} T \ln\left[1-(-1)^{n_i}\exp\left(-\beta\sqrt{k^2+m_i^2(\phi)}\right)\right]$$

$$= -\frac{g_*\pi^2}{90}T^4 + \frac{1}{2}\left(\left(\frac{y_B^2}{12}+\frac{y_F^2}{24}\right)T^2 - m^2\right)\phi^2 - \frac{y_B^3}{12\pi}T\,\phi^3 + \frac{\lambda_{eff}(T)}{4}\phi^4 + \cdots \text{ for } T \gg y_i\phi$$

$$= V_0(\phi) - \sum_i T^4\left(\frac{y_i\phi}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{y_i\phi}{T}} + \cdots \text{ for } y_i\phi \gg T$$

free energy minimizing principle gives $\frac{\partial f(T,\phi)}{\partial\phi} = 0$ *at* $\phi = \langle\phi\rangle_T$

** In high temperature expansion, the coefficient of the cubic term,* y_B^3*, is only given by bosonic contribution (*$k \to 0, m_i(\phi) \to 0$*)*

free energy density $f(T,\phi)$

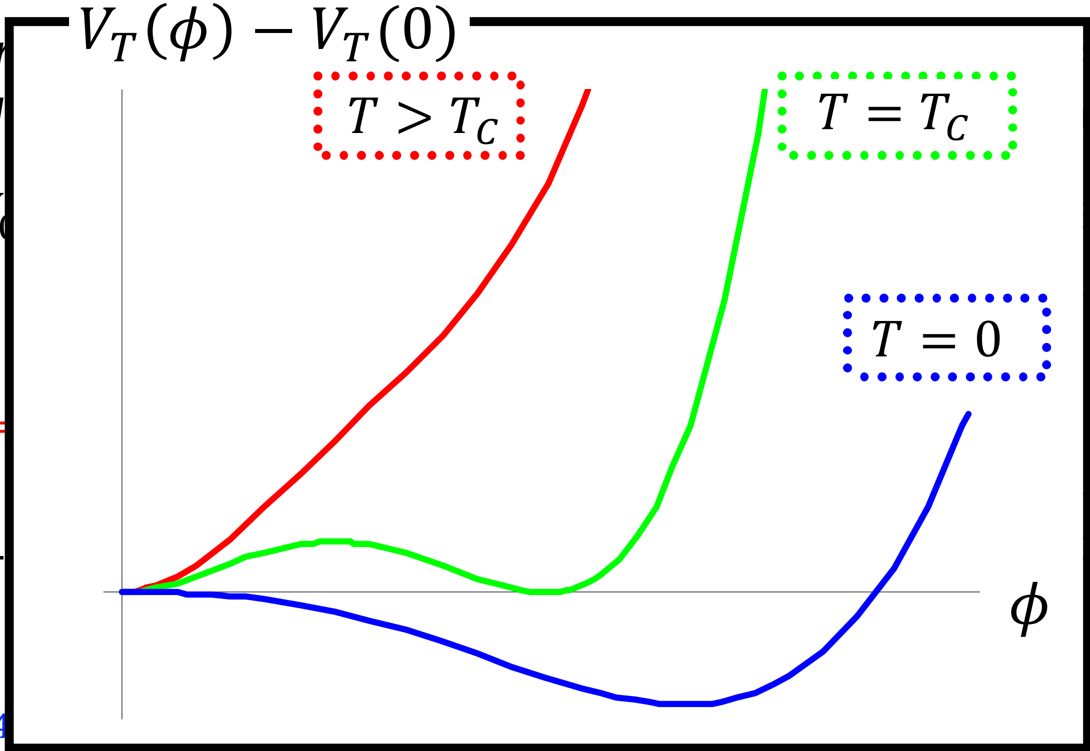
If the mass of the par ... $= y_i\phi$*, free energy density gives the add* ... *l for the Higgs.*

$f(T,\phi) \equiv V_T(\phi) = V_0$ ... ctions

$$+ \sum_{n_B=1,n_F=} \cdots + m_i^2(\phi)\Big)\Big]$$

$$= -\frac{g_*\pi^2}{90}T^4 + \frac{1}{2} \cdots \phi^4 + \cdots \text{ for } T \gg y_i\phi$$

$$= V_0(\phi) - \sum_i T^4 \cdots \left(2\pi T\right) \cdots$$



free energy minimizing principle gives $\frac{\partial f(T,\phi)}{\partial\phi} = 0$ *at* $\phi = \langle\phi\rangle_T$

** In high temperature expansion, the coefficient of the cubic term,* y_B^3*, is only given by bosonic contribution (*$k \to 0, m_i(\phi) \to 0$*). At* $T = T_c$*, the new minimum is developed at*

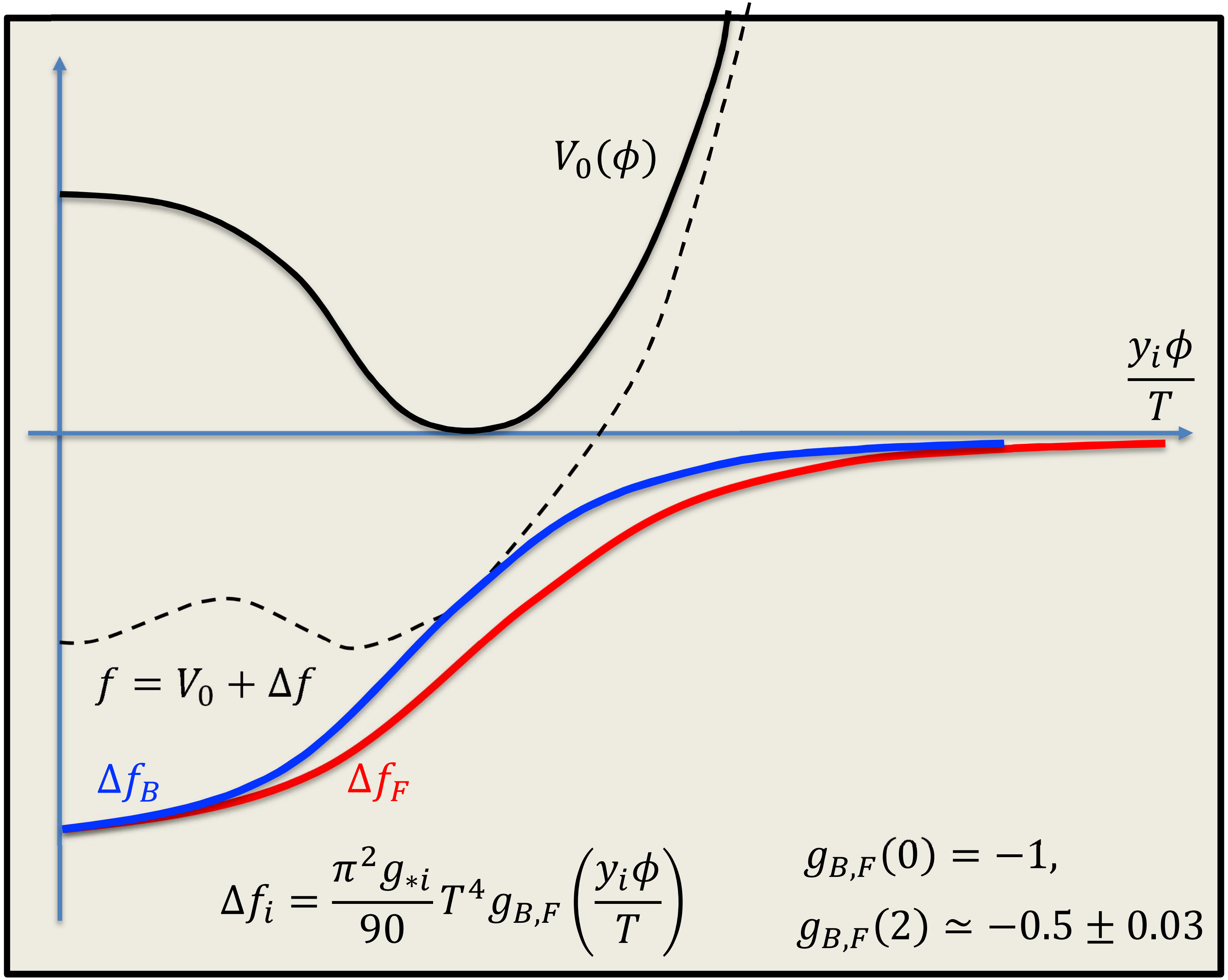
$$\frac{\phi_{new}(T_c)}{T_c} \simeq \frac{y_B^3}{6\pi\,\lambda_{eff}(T_c)}.$$

Then is the fermion contribution always useless for the first order phase transition?

1) Radiative corrections : decreasing λ_{eff} *2) Go beyond hight T expansion*

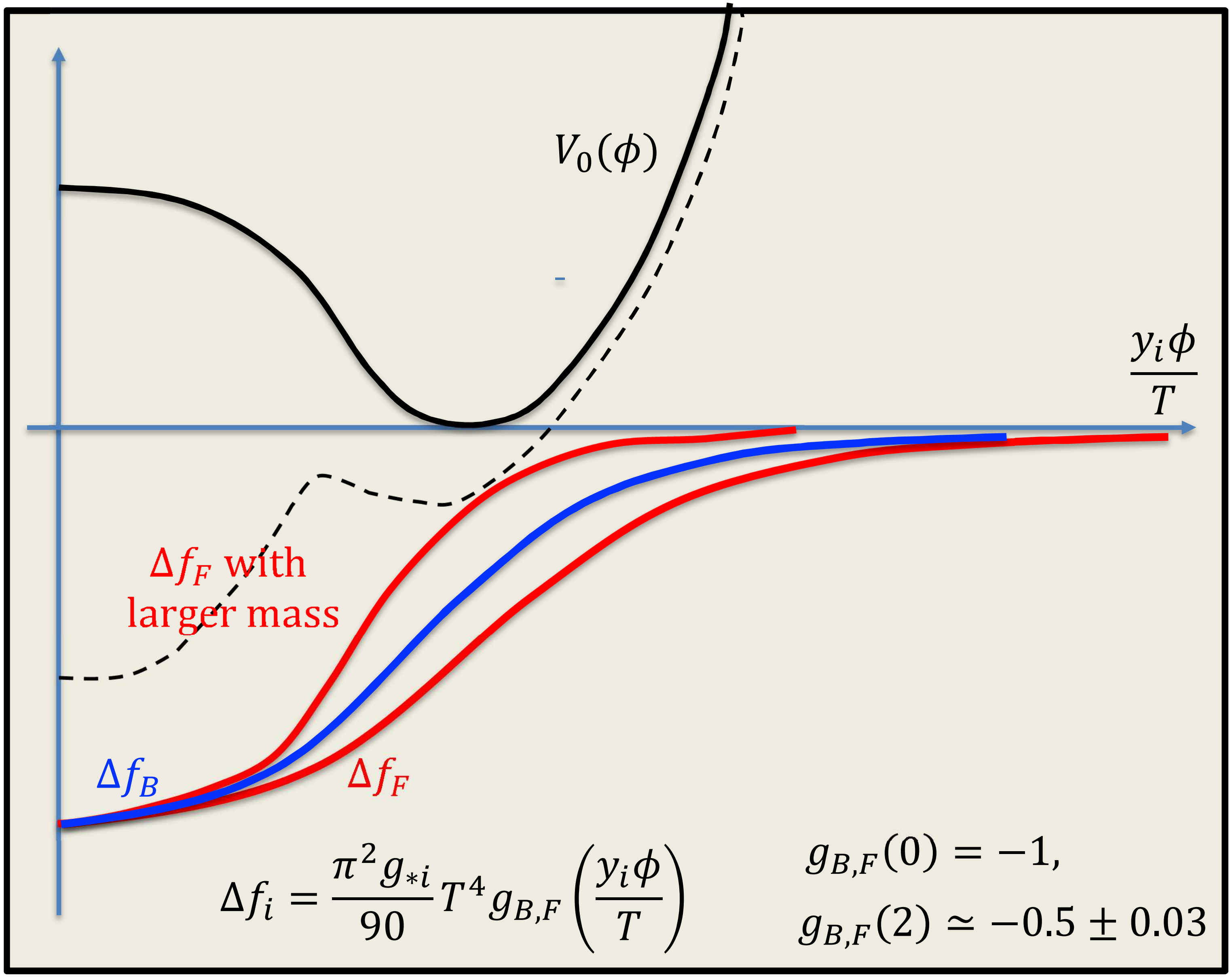
Beyond high T expansion

For given mass ($m = y\phi$), Δf_B shows more rapid increasing/saturating behavior compared to that of Δf_F as ϕ increases, whose effect can be captured by negative cubic term of ϕ



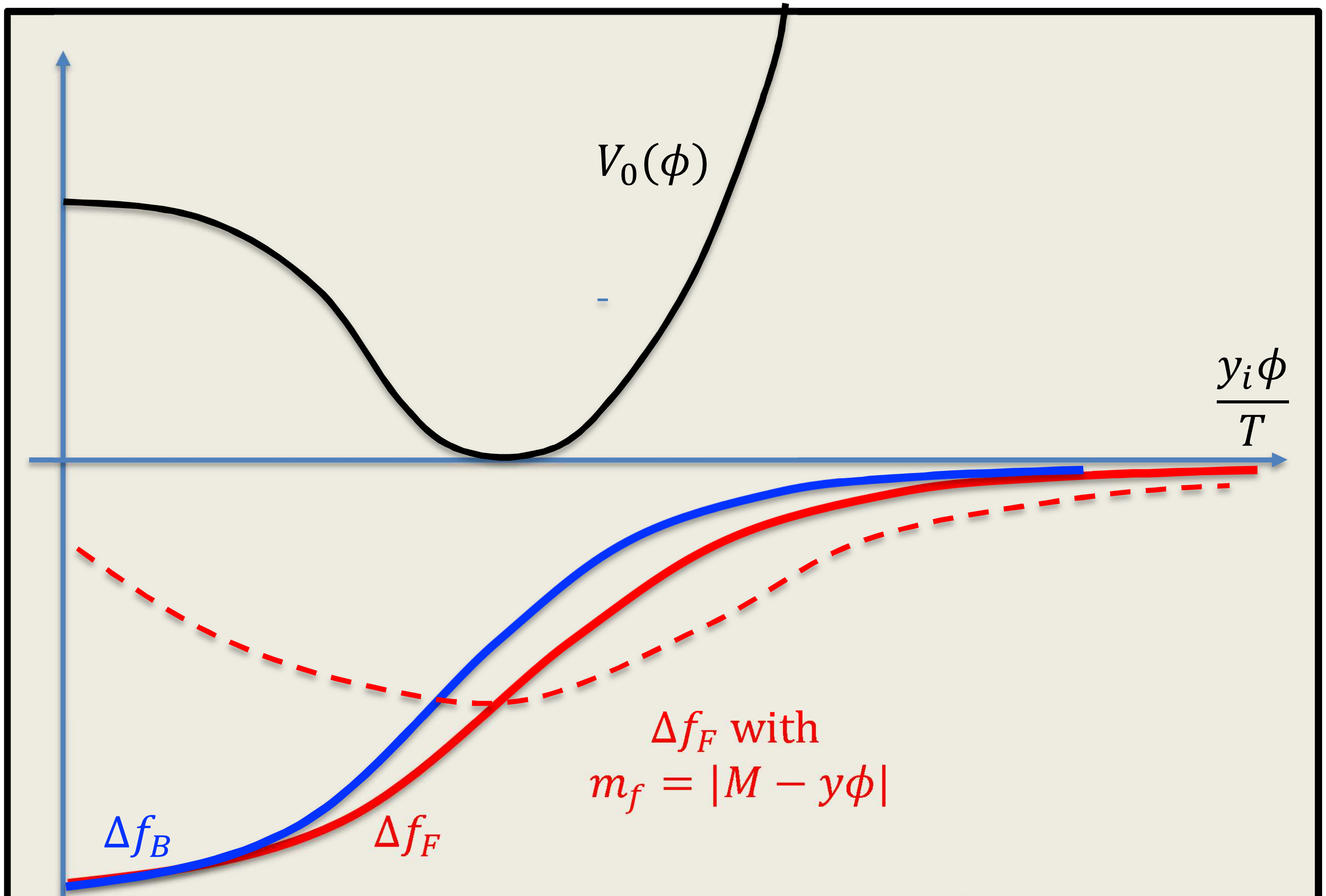
Beyond high T expansion

If $m_f = y\phi \rightarrow 2y\phi$ (strong coupling), because of the larger mass, as ϕ increases, the thermal effect is decoupled faster than that for the case with the smaller mass: leads to the first order phase transition. Carena, Megevand, Quiros, Wagner, hep-ph/0410352



Beyond high T expansion

Add fermions with $m_f = y\phi \to |M - y\phi|$, *which gives additional large negative contribution around* $\phi \sim M/y$ *(mimic the cubic term): could lead to the first order phase transition.*



$$\Delta f_i = \frac{\pi^2 g_{*i}}{90} T^4 g_{B,F}\left(\frac{|M - y\phi|}{T}\right) \quad g_{B,F}(0) = -1, \quad g_{B,F}(2) \simeq -0.5 \pm 0.03$$

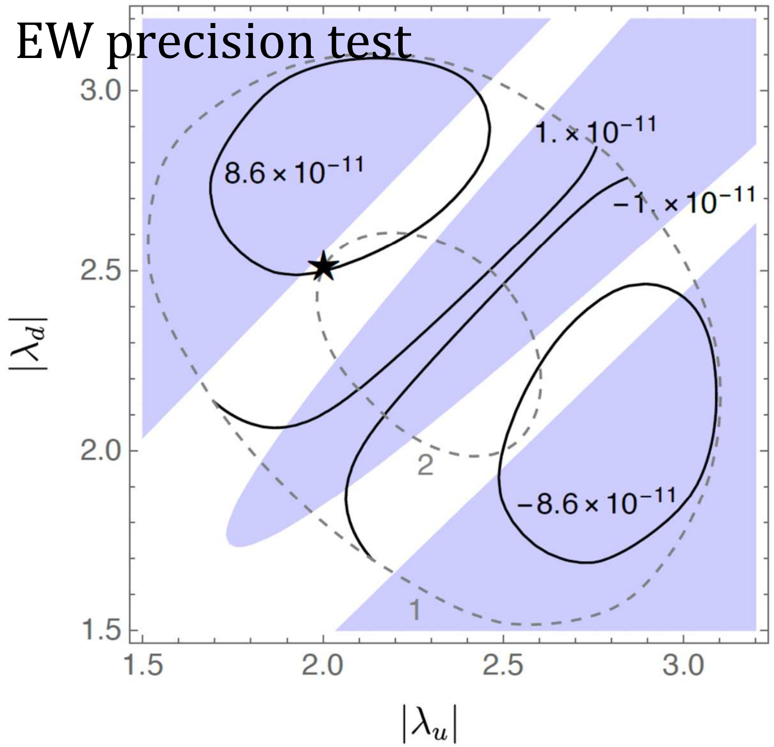
Beyond high T expansion

Minimal Model for baryogenesis with only fermions Egana-Ugrinovic, 1707.02306

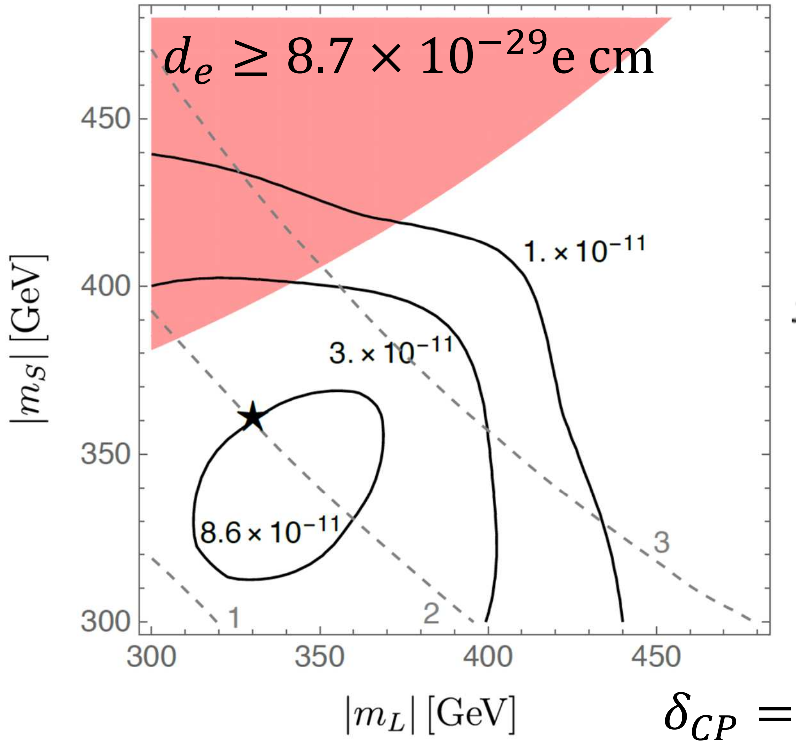
$$\Delta\mathcal{L} = \underbrace{-\frac{1}{2} m_S \chi_S \chi_S - m_L L_4 \bar{L}_4 - \left(\lambda_d L_4 H^c - \lambda_u \bar{L}_4 H\right)\chi_S + h.c.}_{\text{Mass mixing, and CPV source}} \underbrace{- \frac{(H^+ H)^3}{\Lambda^2}}_{\text{For Higgs stability}}$$

$$\delta_{CP} = \mathrm{Arg}(\lambda_u \lambda_d m_S^* m_L^*)$$

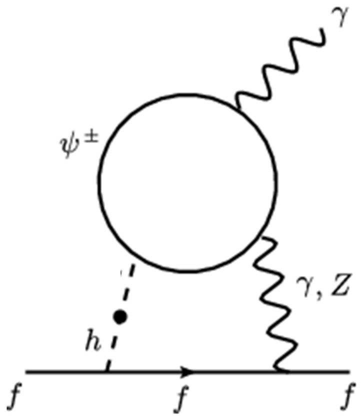
baryogenesis $n_B/s = 8.6 \times 10^{-11}$. *strong coupling is required:* $\Lambda \leq 1.1$ TeV



$|m_L| = 360$ GeV, $|m_S| = 360$ GeV



$|\lambda_u| = 2, |\lambda_d| = 2.5$



$\delta_{CP} = -4 \times 10^{-2}$

More correct treatment for strong couplings

Previous f is just a leading order contribution. Using path integral formalism

$$Z = \mathrm{Tr}\left(e^{-\beta\hat{H}}\right) = \sum_n \left\langle n \middle| e^{-\beta\hat{H}} \middle| n \right\rangle = \int_{\Phi(\tau)=(-1)^{n_i}\Phi(\tau+\beta)} D\Phi \exp\left(-\int_0^\beta d\tau\, d^3\vec{x}\ \mathcal{L}_E(\Phi(\tau,\vec{x}))\right)$$

$$\boxed{\begin{aligned}&\mathcal{L}_E(\Phi(\tau,\vec{x}))\\ &= -\mathcal{L}\big(\Phi(t,\vec{x})\big)\Big|_{t\to -i\tau}\end{aligned}}$$

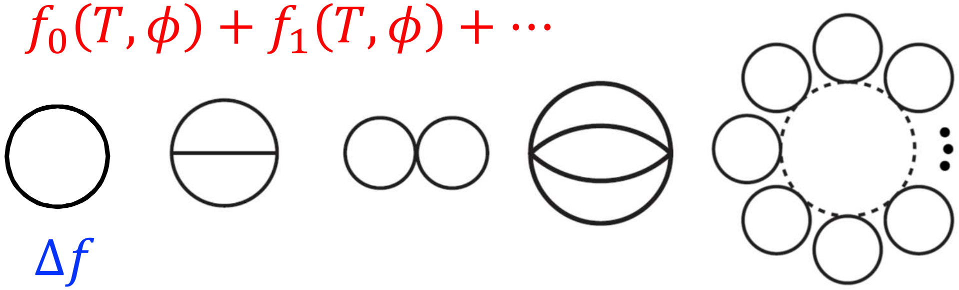
For the Higgs field, taking $H = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \phi\end{pmatrix} + \Delta H(\tau,\vec{x})$

$$f(T,\phi) = -\frac{T}{V}\ln\int D\Phi \exp\left(-\int_0^\beta d\tau\, d^3\vec{x}\ \mathcal{L}_E(\Phi(\tau,\vec{x}),\phi)\right)$$

$$\boxed{\begin{aligned}(k_n)_B &= 2n\pi T\\ (k_n)_F &= (2n+1)\pi T\\ \text{poles of } n_{B,F}(E) &= \frac{1}{e^{\beta E}\pm 1}\end{aligned}}$$

periodicity: $\Phi(\tau,\vec{x}) = T\sum_{n\in\mathbb{Z}}\int d^3k\ \tilde{\Phi}(k_n,\vec{k})\ e^{i\,(k_n\tau+\vec{k}\cdot\vec{x})}$

$$f(T,\phi) = V_0(\phi) + f_0(T,\phi) + f_1(T,\phi) + \cdots$$



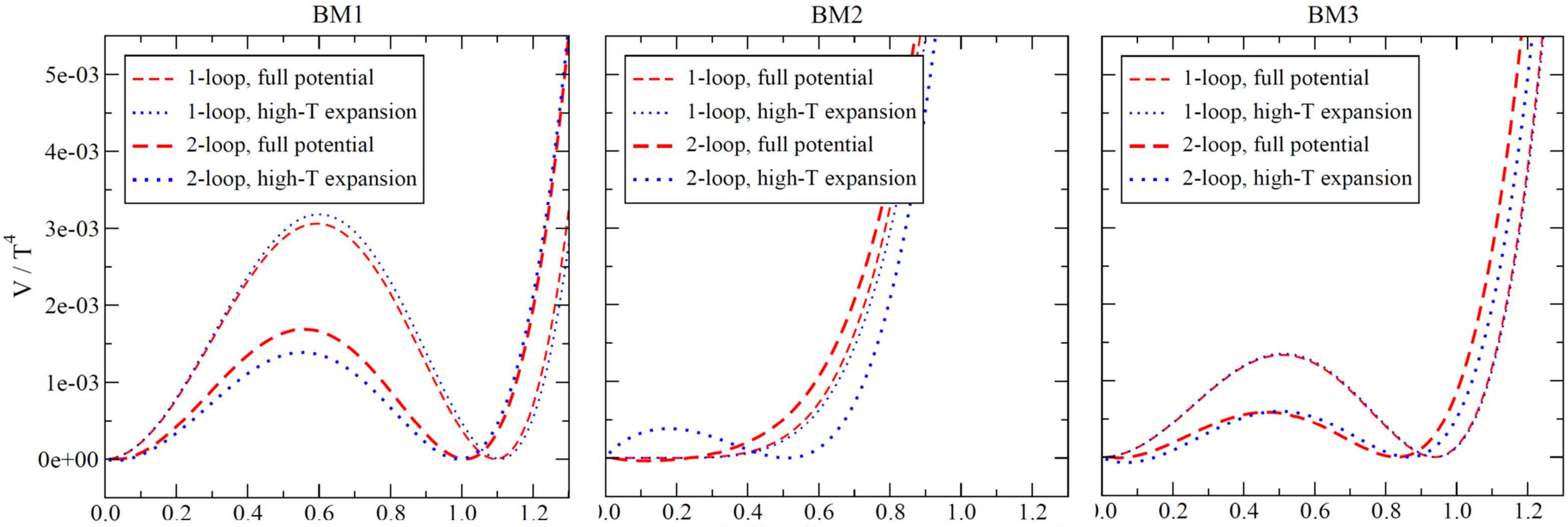
Strong couplings provide large thermal masses for loop fields ($\Delta_T m^2 \sim y^2T^2$), which make cubic terms for bosonic contribution regular around $\phi \sim 0$. Including thermal masses, the expansion parameter ($y^2T/\pi m_{eff}(T)$) becomes $O(y^2/\pi^2)$ for fermions, $O(y/\pi)$ for bosons.

More correct treatment for strong couplings

Example: Inert Higgs model ($\langle\Phi\rangle_{T=0} = 0$) Laine, Meyer, Nardini, 1702.07479

$$V(H,\Phi) = \mu_1|H|^2 + \mu_2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4$$
$$+\lambda_3|H|^2|\Phi|^2 + \lambda_4|H\Phi|^2 + \left(\frac{\lambda_5}{2}(H\Phi)^2 + h.c.\right)$$

$$\frac{v_{\rm phys}}{\sqrt{2}} \equiv Z_{\mu_1^2}\langle|H|^2\rangle$$
relevent for sphaleron rate



full effective potential

	T_c/GeV		L/T_c^4		$v_{\rm phys}/T_c$		$v_{\rm min}/T_c$	
	1-loop	2-loop	1-loop	2-loop	1-loop	2-loop	1-loop	2-loop
BM1	139(14)	155(21)	0.44(1)	0.34(1)	1.14(12)	0.98(4)	1.15(12)	0.98(3)
BM2	159(13)	181(22)	0.07(7)	0.03(3)	0.39(28)	0.16(16)	0.39(28)	0.17(17)
BM3	138(8)	167(19)	0.35(3)	0.20(1)	0.96(10)	0.84(6)	0.98(10)	0.81(2)

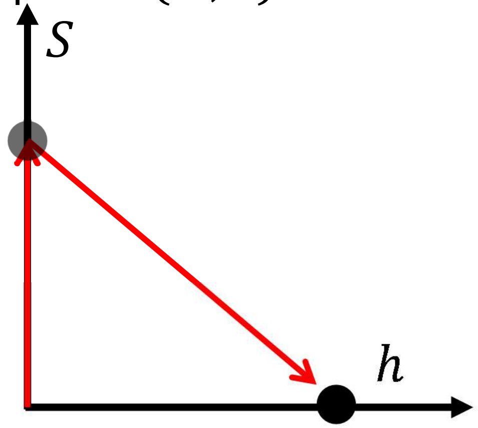
Multi step Phase transition

Squark-Higgs system, Two Higgs doublet model, (complex) singlet extension…

Here let us consider simple singlet extension.

In order to avoid large mixing between Higgs and the singlet e.g. $\lambda S\,|H|^2 \in V(H,S)$

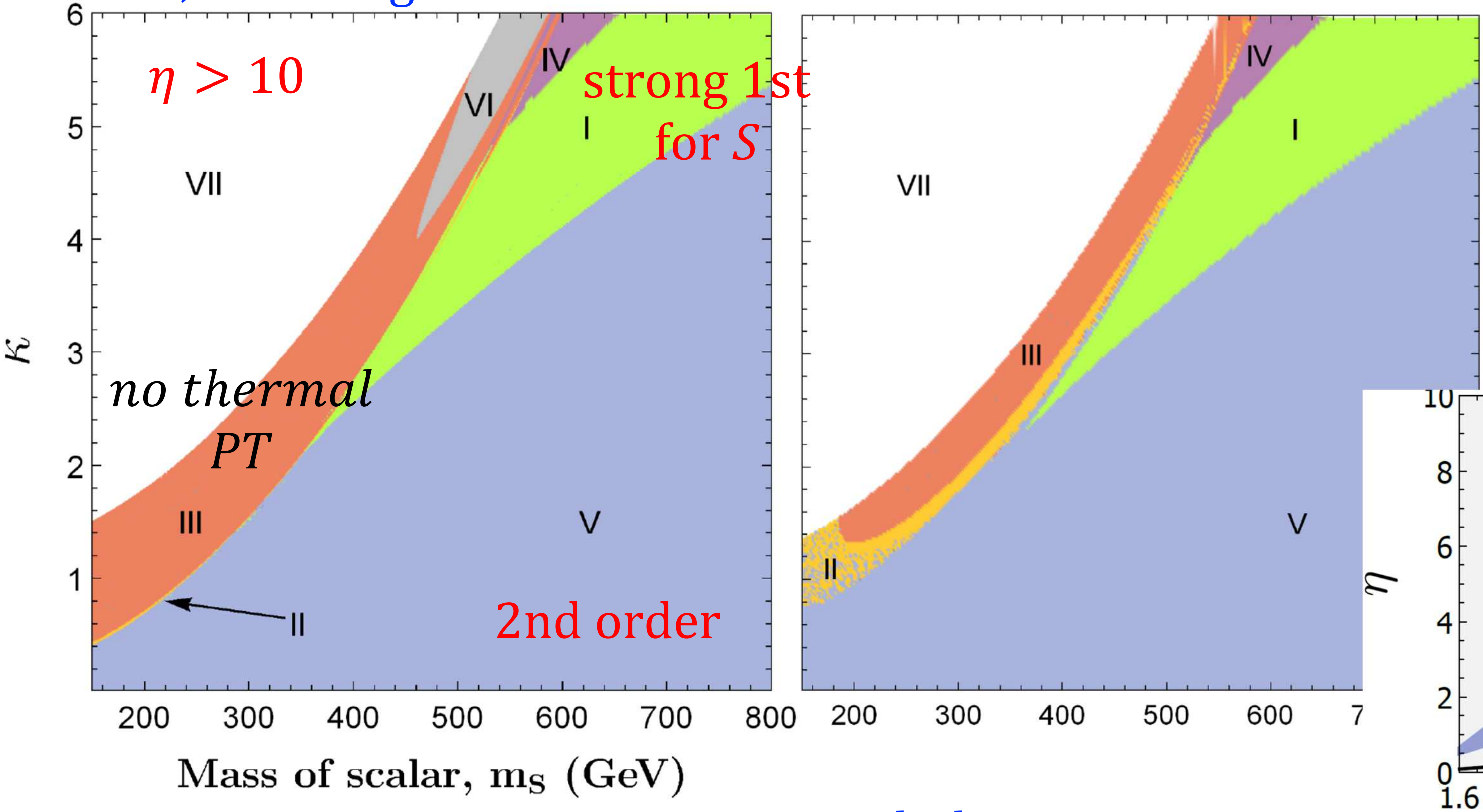
Z_2 symmetry for the singlet sector is introduced.

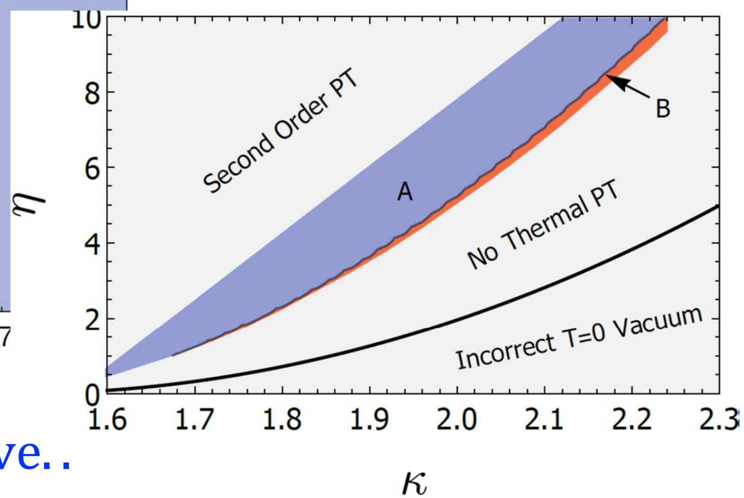


$$V(H,S) = -\mu^2|H|^2 + \lambda|H|^4 + \frac{1}{2}m_0^2 S^2 + \frac{\eta}{4}S^4 + \kappa|H|^2 S^2$$

II, A: strong 1st order $EWPT$

Kurup, Perelstein, 1704.03381

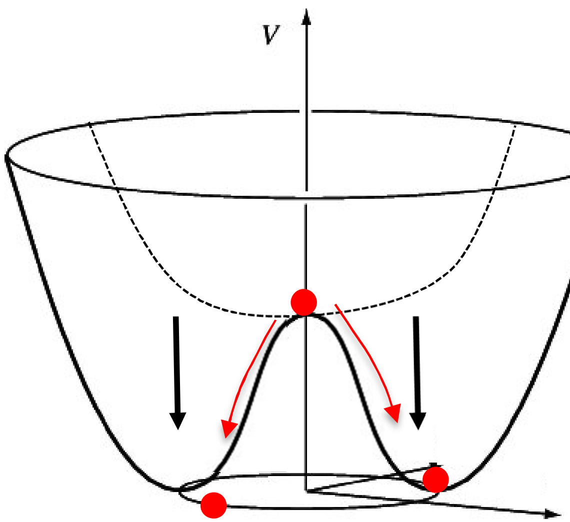




might be too conservative. .

Quenching?

Sudden change of the Higgs potential after inflation : super-cooling, and low reheating temp.



At the top of the potential, there is the exponential growth of soft Higgs modes via parametric resonances and or tachyonic transition:

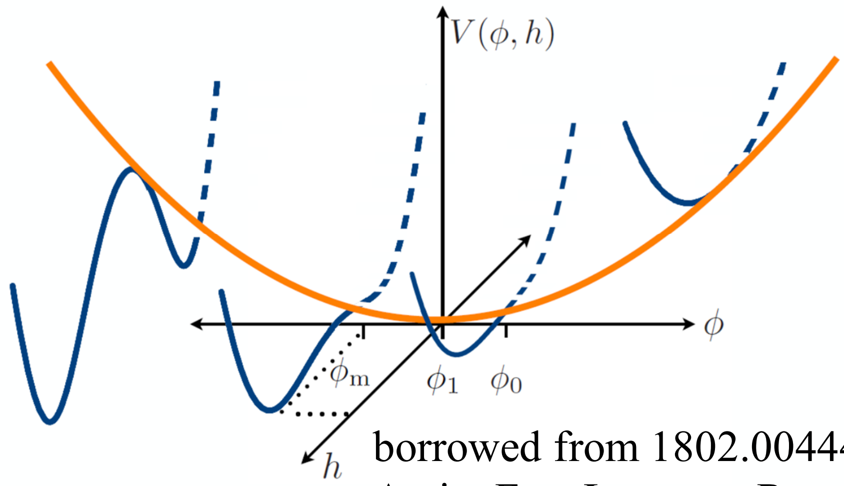
$$\delta\ddot{h}(t,\vec{k}) + (k^2 - m^2 + 3\lambda\phi^2 + g^2\sigma_{\rm inf}^2(t))\delta(t,\vec{k}) = 0$$

(preheating stage: strong out-of-equilibrium)

large inhomogeneity: defects are generated,

which could be relevant for baryogenesis

: Cold baryogenesis



borrowed from 1802.00444
Amin, Fan, Lozanov, Reece

Garcia-Bellido, Grigoriev, Kusenko, Shaposhinikov, hep-ph/9902449

Strong first order PT with only weak couplings

There is the way to obtain strong first order phase transition with only weak couplings between the Higgs and new fields in a controllable way! Jeong, Jung, CSS 1806.02591

Considering the singlet (the axion-like field, a) whose interaction is suppressed by $f \gg m_W$.

$$V(H,a) = \Lambda^4 \left(1 - \cos\frac{a}{f}\right) + \left(m_1^2 + m_2^2 \cos\left(\frac{a}{f} + \alpha\right)\right)|H|^2 + \lambda|H|^4$$

In general, it can be represented as

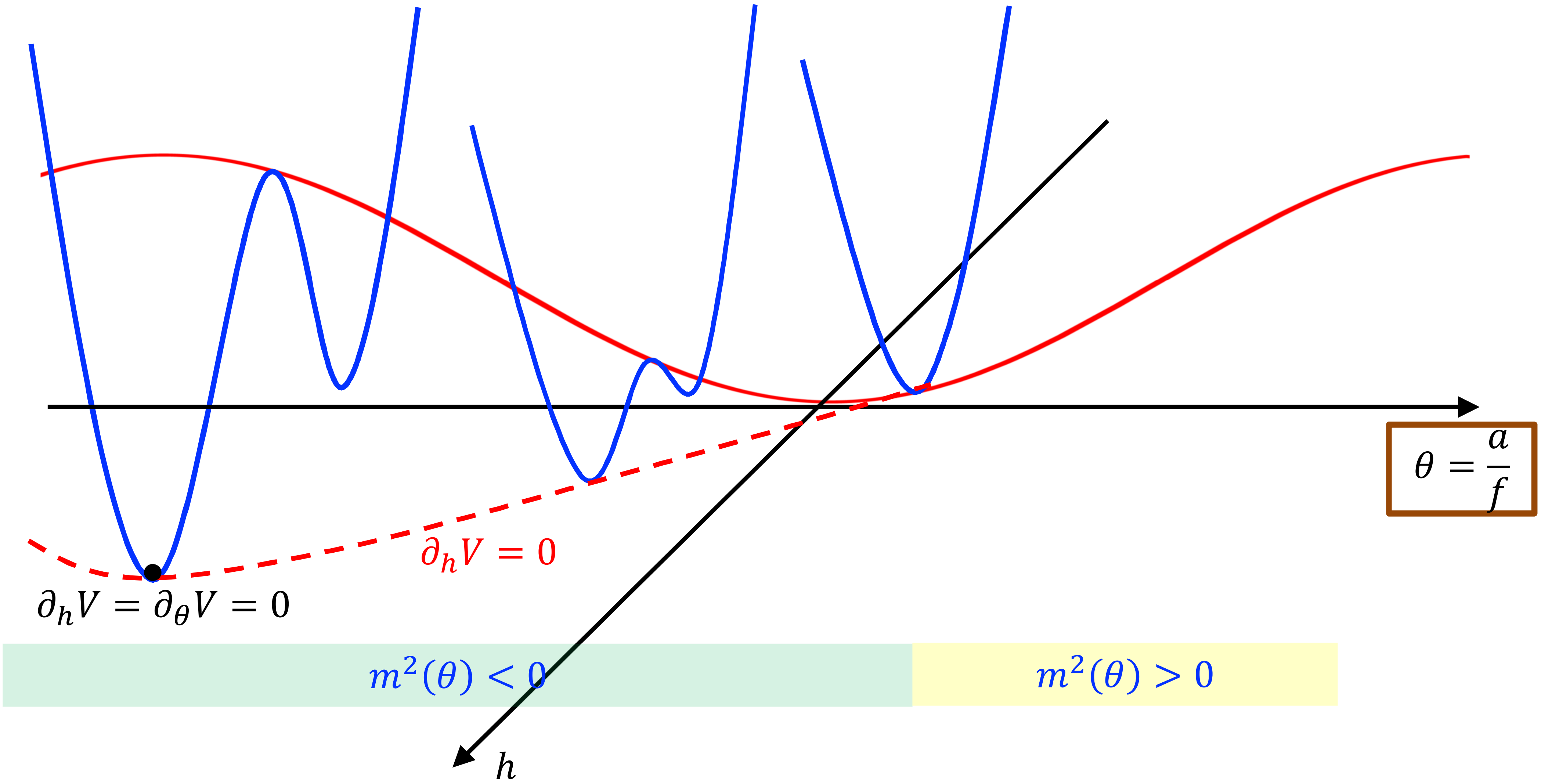
$$V(h,\theta) = \tilde{V}(\theta) + \frac{1}{2}m^2(\theta)h^2 + \frac{\lambda}{4}h^4$$

where $\theta \equiv a/f$.

At $T \ll f$, *the thermal contribution of the axion loop is suppressed by the power of* (T/f). *Dominant contribution is coming from the coupling of the Higgs and SM particles.*

Schematic description of the potential

The scalar potential can be written as $V(h,\theta) = \tilde{V}(\theta) + \frac{1}{2}m^2(\theta)h^2 + \frac{\lambda}{4}h^4.$



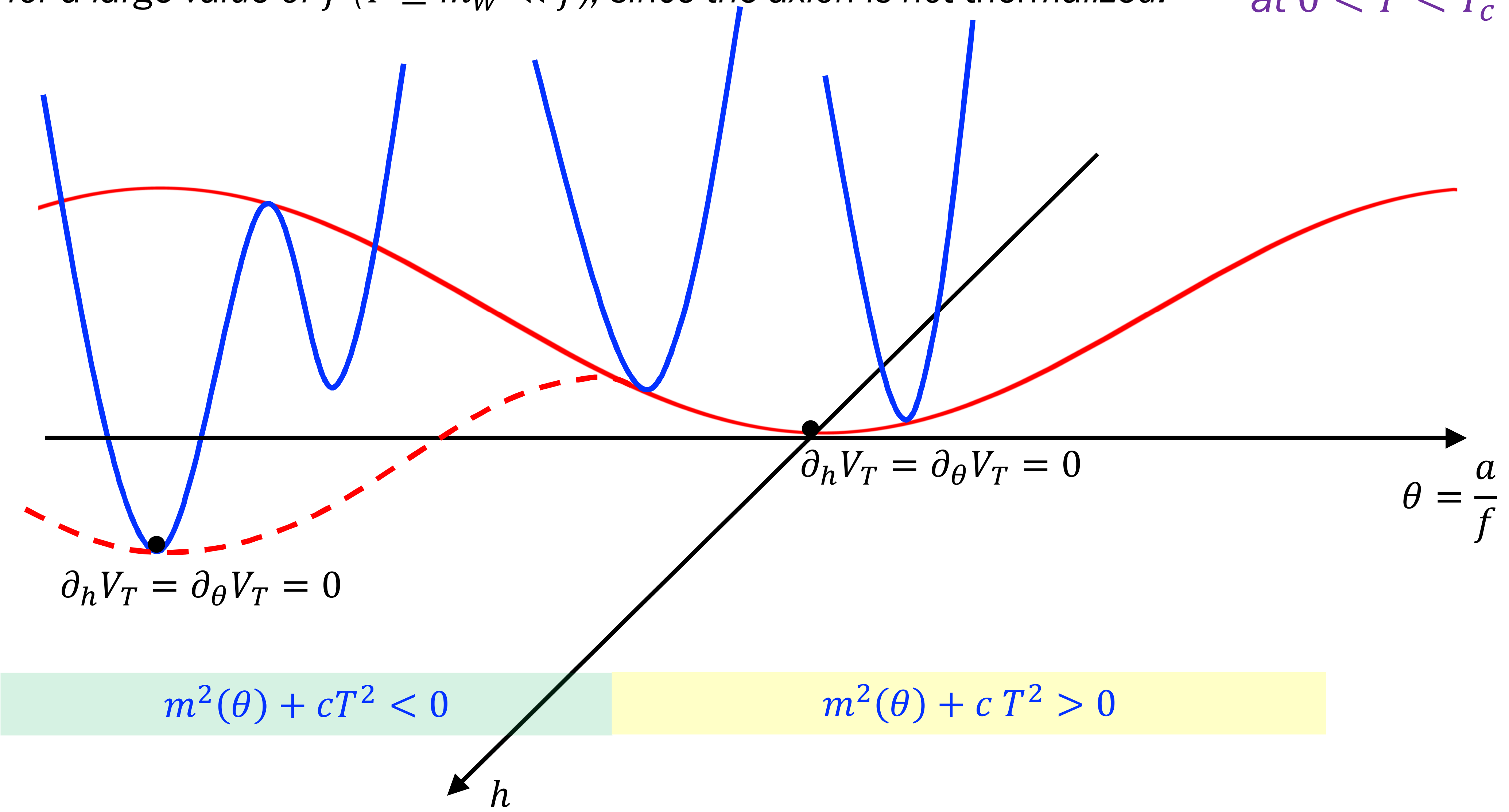
The potential is bounded from below due to the periodicity of the axion dependence

Schematic description of EWPT

The scalar potential can be written as $V_T(h,\theta) = \tilde{V}(\theta) + \frac{1}{2}(m^2(\theta) + cT^2)h^2 + \frac{\lambda}{4}h^4$

for a large value of f $(T \leq m_W \ll f)$*, since the axion is not thermalized.*

at $0 < T < T_c$



Schematic description of EWPT

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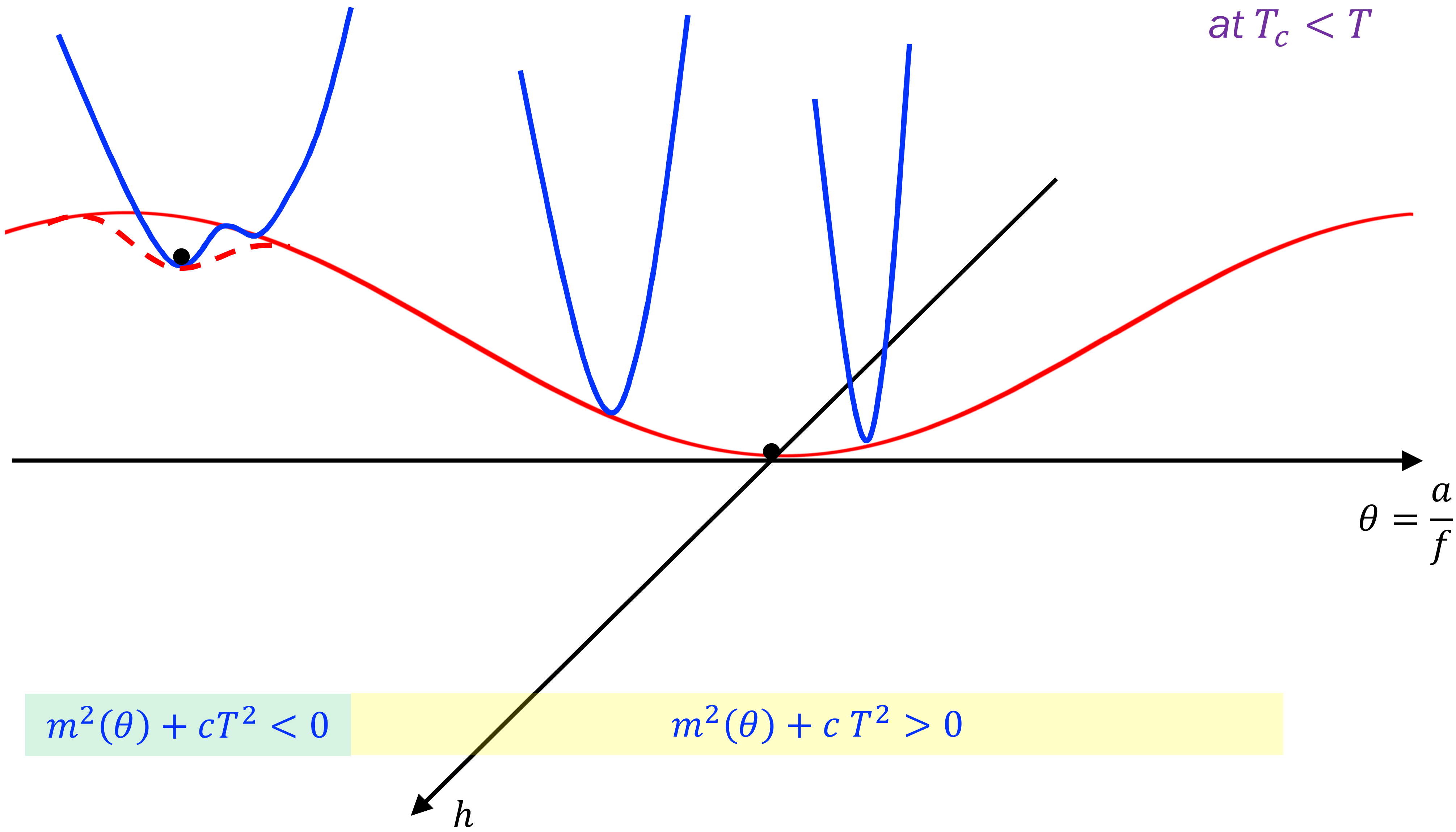
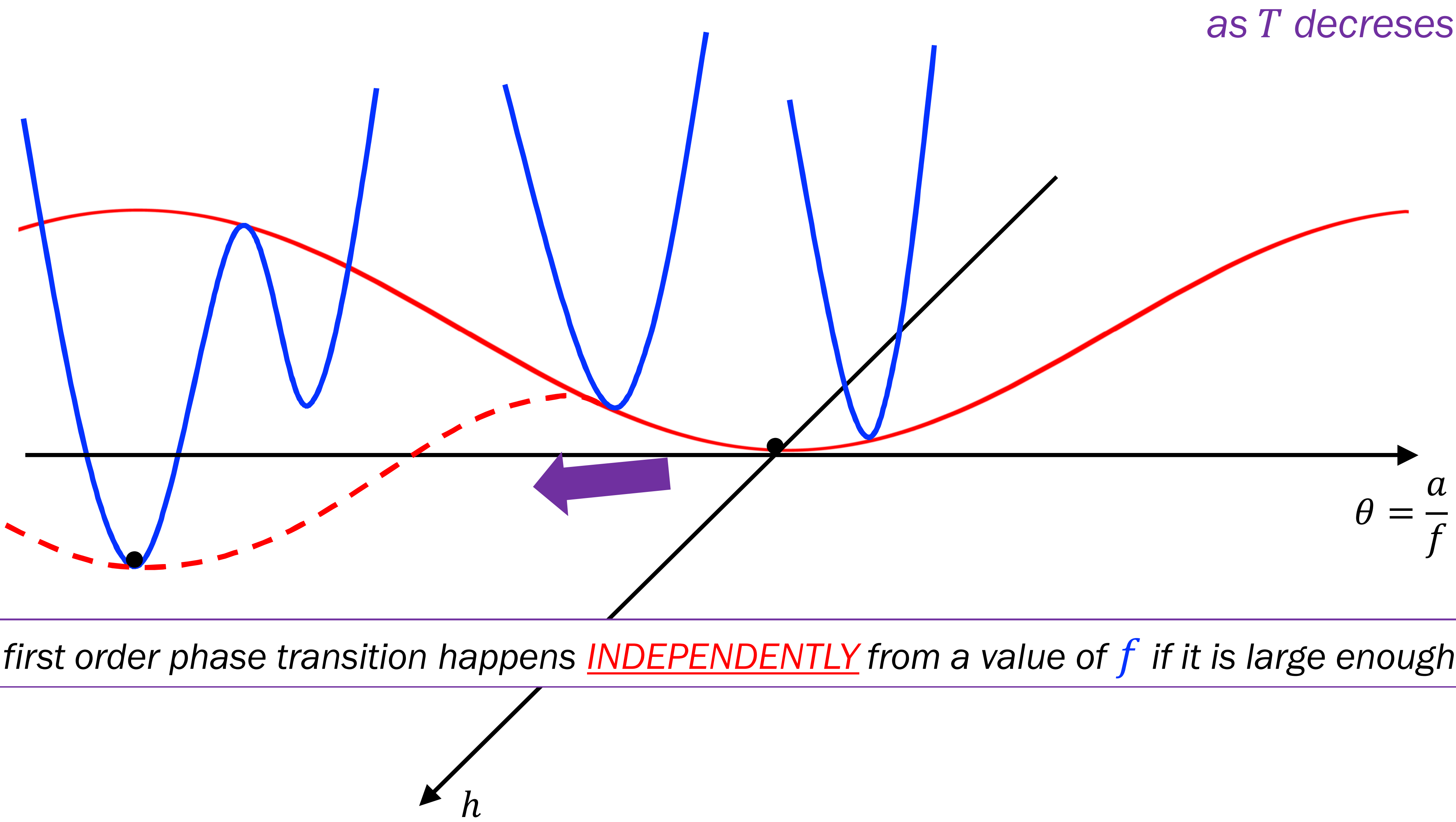
at $T_c < T$



Schematic description of EWPT



first order phase transition happens INDEPENDENTLY from a value of f if it is large enough

Local & nonlocal generation of asymmetry

generation of baryon asymmetry

As the Higgs changes its expectation value during phase transition $\phi(t,\vec{x}) = 0 \to v(T)$, *baryogenesis will be triggered by CP-violating interactions. Effectively we can write them as*

$$\Delta\mathcal{L}_{CPV} = \frac{g^2}{16\pi^2}\theta_W(\phi)\mathrm{Tr}\left[W\,\widetilde{W}\right] + y_q\phi\,\bar{\psi}\exp(i\gamma_5\theta_\psi(\phi))\;\psi + \cdots$$

For constant θ*s, we can always rotate them away: no physical effects during phase transition, or very suppressed even if we introduce several flavors.*

For $\dot{\theta}(t,\vec{x}) \neq 0$, *the CP asymmetry is generated during phase transition. Most of baryon asymmetry can be generated simultaneously at the same position (locally) or at different position (non-locally)*

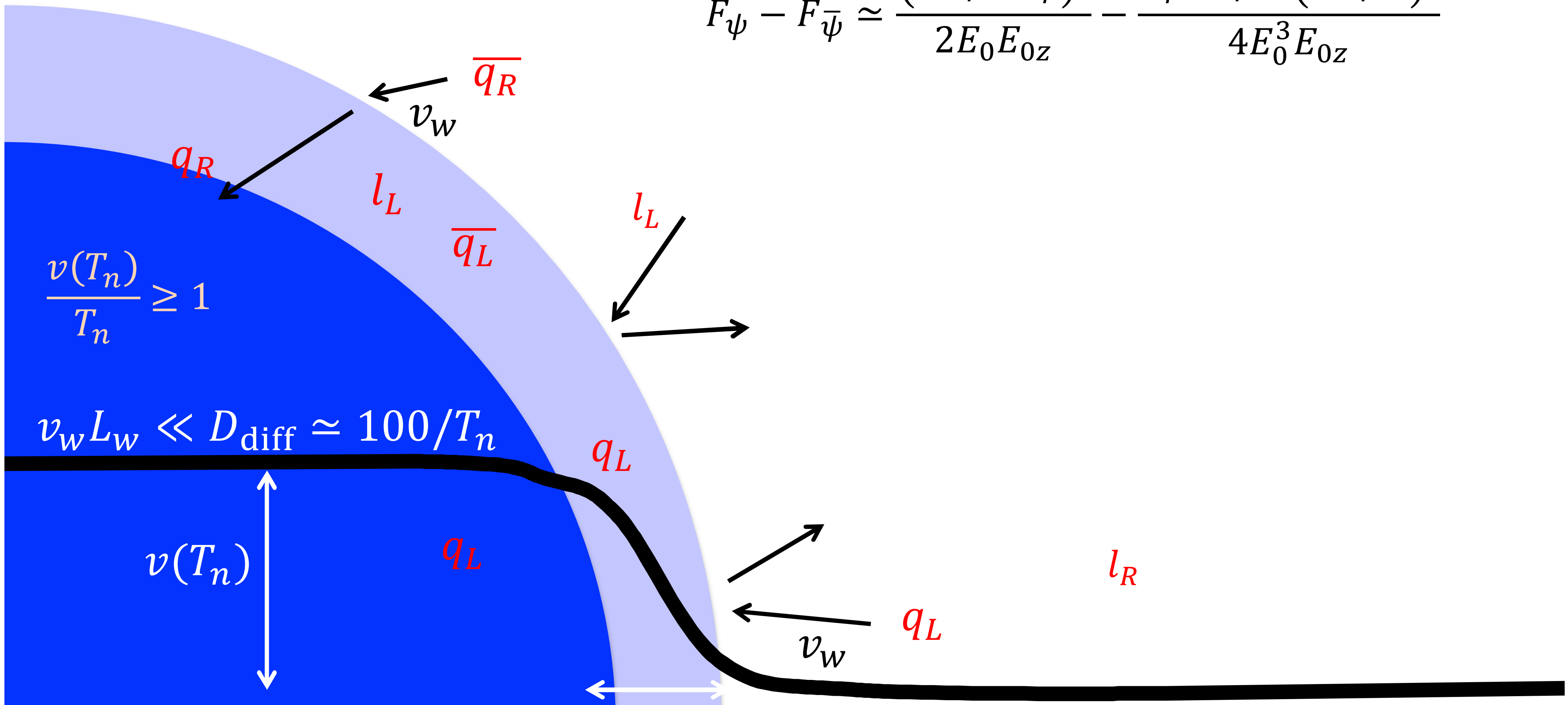
Non-local generation of baryon asymmetry

Assuming first order phase transition with bubble formation with following CPV term,

$$\Delta\mathcal{L}_{CPV} = y_q \phi\, \bar{\psi} \exp(i\gamma_5 \theta_\psi(\phi))\, \psi$$

With $L_w > 1/T$, *in the wall rest frame:* $m_\psi = |y_q|\phi(z)e^{\pm i\theta_\psi(z)}$ *, there is the flux from symmetric phase to broken phase. Then the semi-classical CPV force is given by*

$$F_\psi - F_{\bar{\psi}} \simeq \frac{\left(|m_\psi|^2 \theta'_\psi\right)'}{2E_0 E_{0z}} - \frac{\theta'_\psi |m_\psi|^2 \left(|m_\psi|^2\right)'}{4E_0^3 E_{0z}}$$

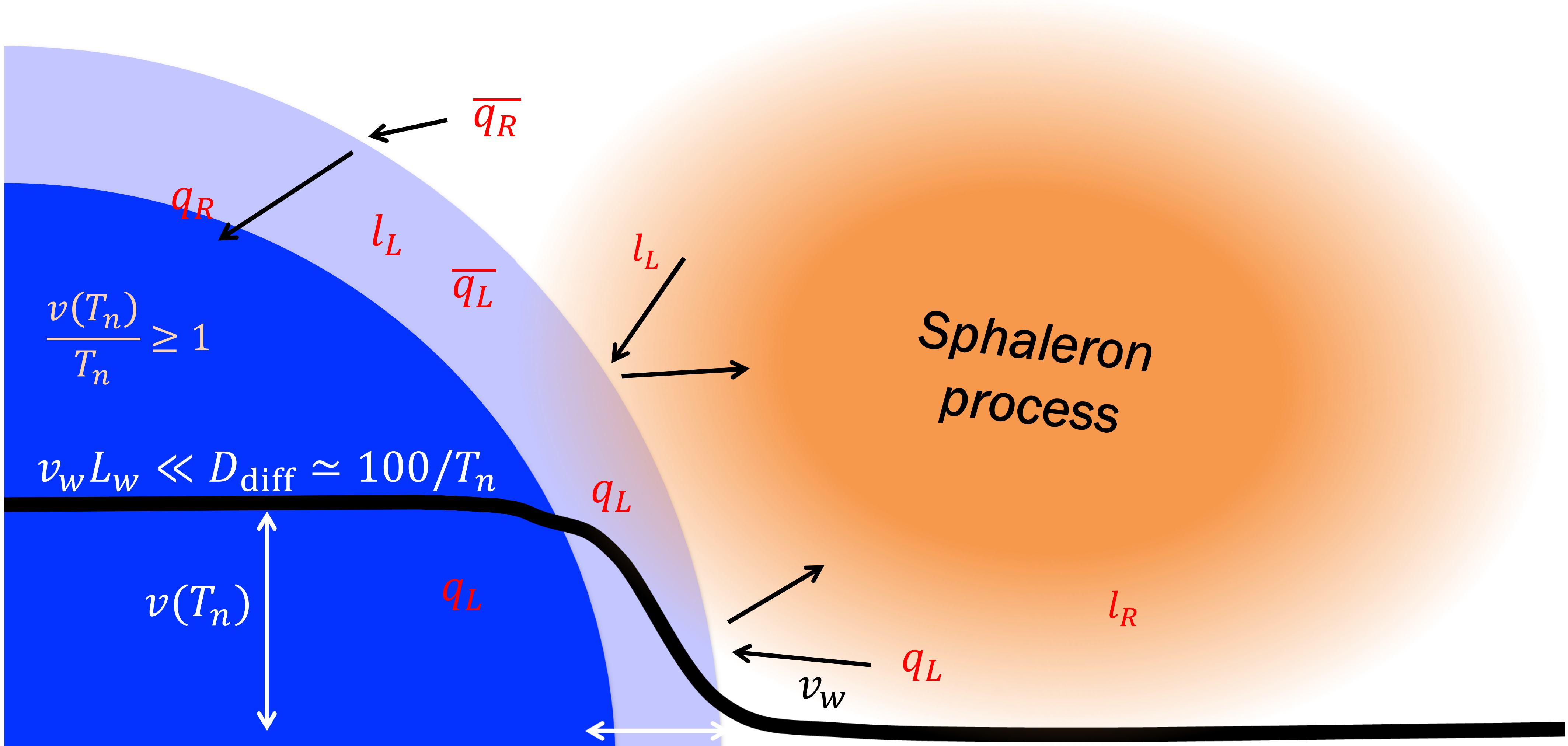


Non-local generation of baryon asymmetry

Around the bubble wall, diffusion happens through thermal interaction

$$\frac{dn_B}{dt} + 3Hn_B = \frac{3}{2}\frac{\Gamma_{sph}(\text{sym})}{T}\left(\mu_L(\text{sym}) - \frac{15}{2}\frac{n_B}{T^2}\right)$$

chemical potential
Induced by diffusion



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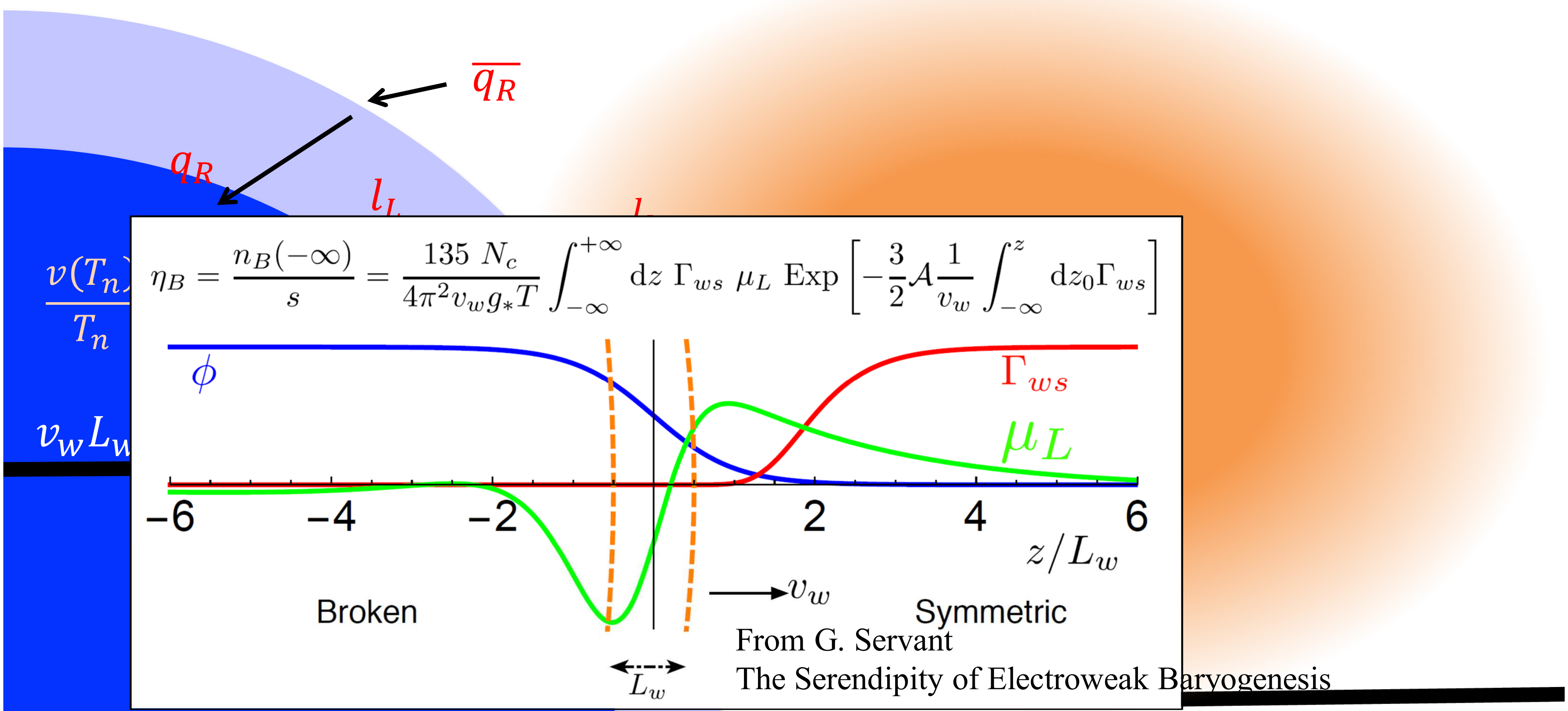
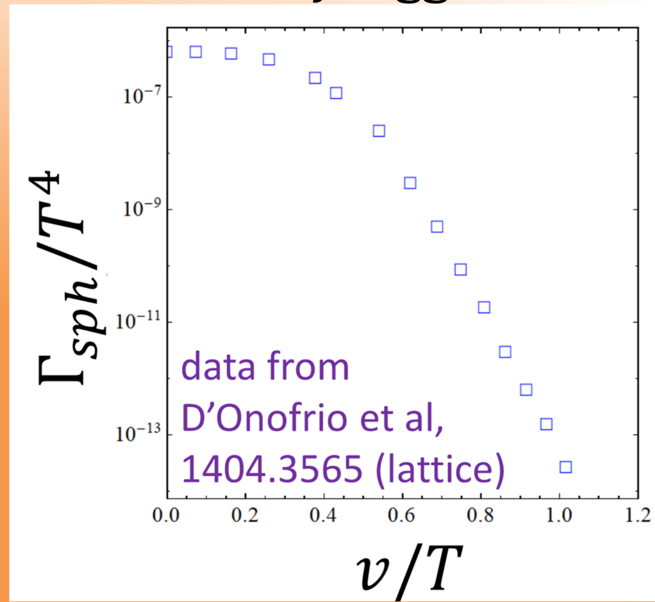


Local generation of baryon asymmetry

If the wall width is very large, adiabatically generated inside the bubble wall by Higgs dependent chemical potential



$$\frac{dn_B}{dt} + 3Hn_B = \frac{3}{2}\frac{\Gamma_{sph}(\phi)}{T}\left(\mu_{eff}(\phi) - \frac{15}{2}\frac{n_B}{T^2}\right)$$

non-zero chemical potential inside a bubble wall

l_L l_L $\overline{q_L}$ q_R $\overline{q_R}$ q_L l_R q_L q_L

Sphaleron process

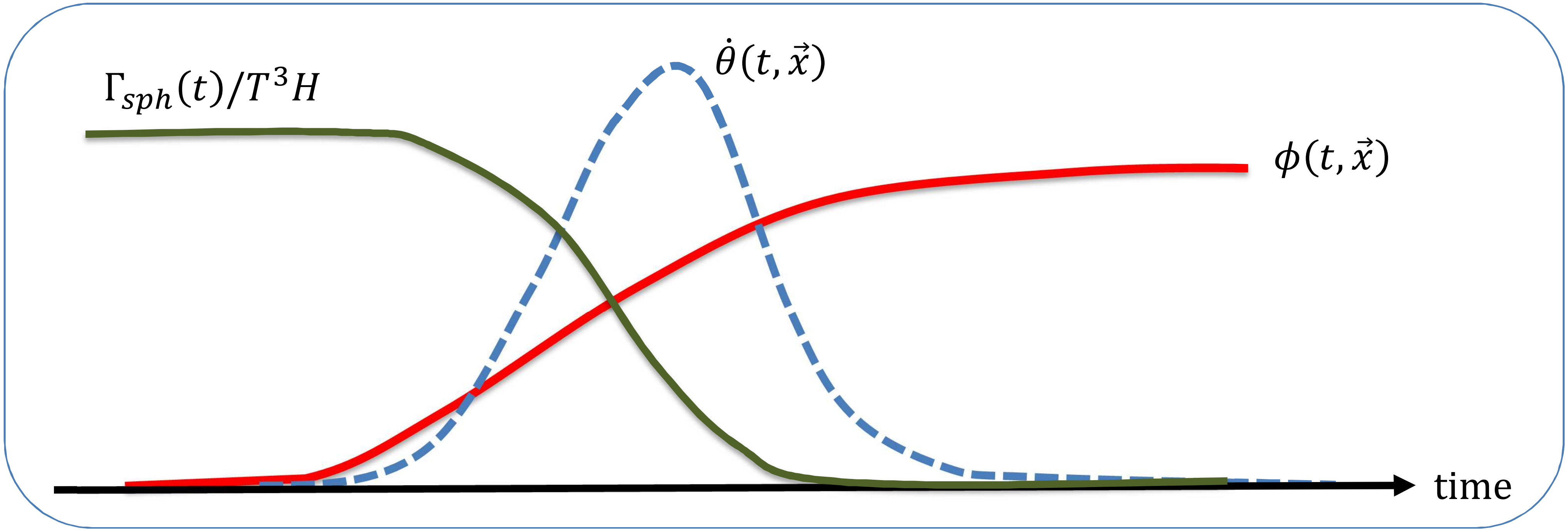
$$\frac{v(T_n)}{T_n} \geq 1$$

$$v_w L_w \gg D_{\rm diff} \simeq 100/T_n$$

$v(T_n)$

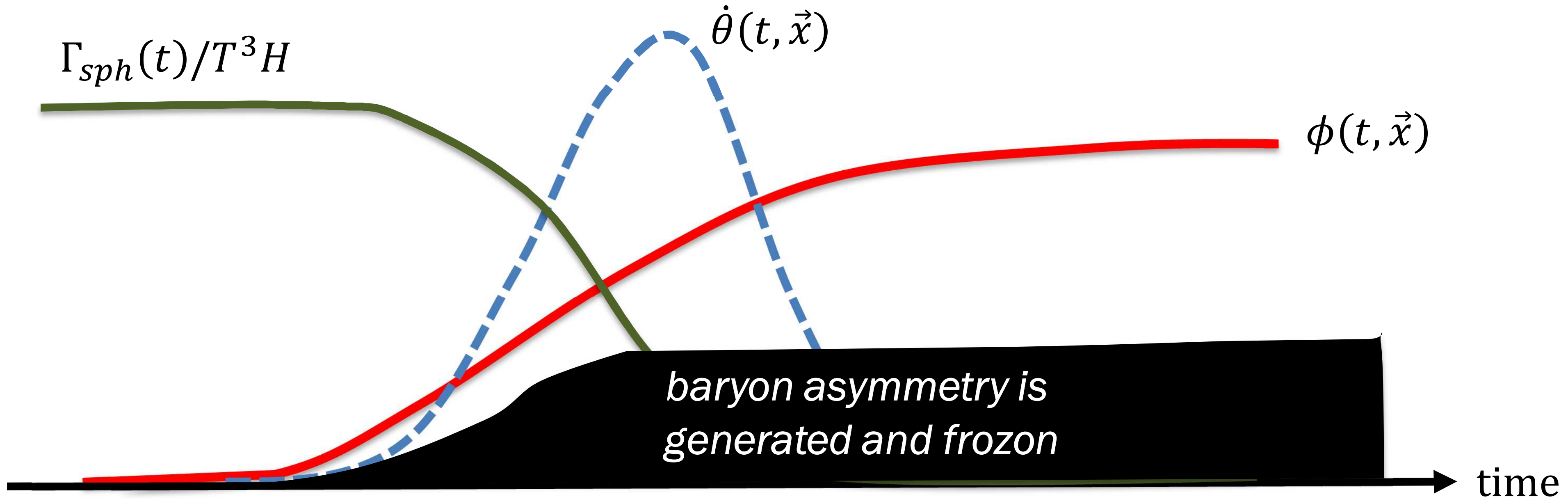
Local generation of baryon asymmetry

$$\Delta\mathcal{L}_{CPV} = \frac{g^2}{16\pi^2}\theta_W(\phi)\mathrm{Tr}\left[W\,\widetilde{W}\right] + y_q\phi\,\bar{\psi}\exp(i\gamma_5\theta_\psi(\phi))\;\psi + \cdots$$



Local generation of baryon asymmetry

$$\Delta\mathcal{L}_{CPV} = \frac{g^2}{16\pi^2}\theta_W(\phi)\mathrm{Tr}\left[W\,\widetilde{W}\right] + y_q\phi\,\bar{\psi}\exp(i\gamma_5\theta_\psi(\phi))\;\psi + \cdots$$



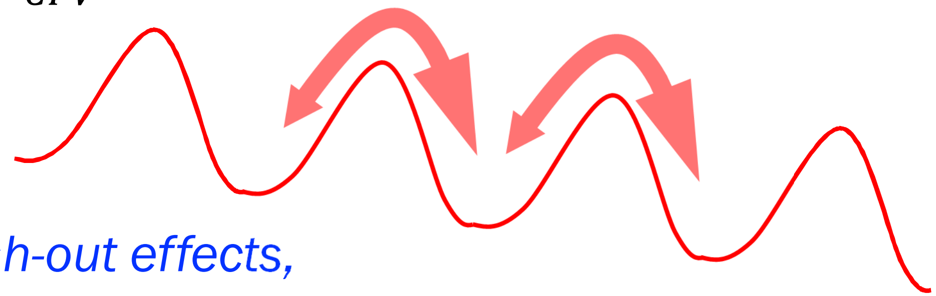
Local generation of baryon asymmetry

Example

$$\Delta\mathcal{L}_{CPV} = \frac{g^2}{16\pi^2}\theta_W(\phi)\mathrm{Tr}\left[W\,\widetilde{W}\right] \simeq -\dot{\theta}_W\, j^0_{CS}(x)$$

effective chemical potential for the CS number: gives the bias for the change of N_{CS}

$$\left(\frac{1}{V}\frac{dN_{CS}}{dt}\right)_{CPV} = \left\langle \partial_\mu j^\mu_{CS}\right\rangle_T \simeq \frac{\mathrm{Tr}\left[e^{-\beta H}\partial_\mu j^\mu_{CS}\right]}{\mathrm{Tr}\left[e^{-\beta H}\right]} \simeq \frac{\dot{\theta}_W}{2T}\Gamma_{sph} \qquad \left(H \simeq H_0 + \int d^3\vec{x}\,\frac{\theta_W}{4\pi^2}\mathrm{Tr}[\vec{\Pi}_A\cdot\vec{B}]\right)$$



Including the wash-out effects,

$$\frac{dn_B}{dt} + 3Hn_B \simeq \frac{3}{2}\frac{\Gamma_{sph}}{T}\left(\dot{\theta}_W - \frac{15}{2}c_1\frac{n_B}{T^2}\right) \Rightarrow \boxed{\frac{d(n_B/n_\gamma)}{dt} \simeq \frac{45c_1}{4}\frac{\Gamma_{sph}}{T^3}\left(\frac{\dot{\theta}_W}{c_2 T} - \frac{n_B}{n_\gamma}\right)}$$

Note that it does not require the bubble formation. However if it is 2nd order pT or cross-over, $\dot{\theta}_W \sim H$, *therefore*

$$\frac{n_B}{n_\gamma} \leq \left(\frac{n_B}{n_\gamma}\right)_{eq} = \left(\frac{\dot{\theta}_W}{c_2 T}\right)_{dec} \sim \frac{H(T_{EW})}{T_{EW}} \sim \frac{T_{EW}}{M_{Pl}} = O\left(10^{-15}\right) \ll 6\times 10^{-10}$$

The fast transition is still required.

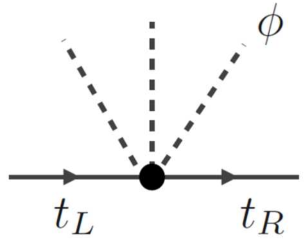
Minimal example

Within the SM field contents. Introducing high dimensional operators to give

$$\Delta\mathcal{L}_{CPV} = \frac{g^2}{16\pi^2}\theta_W(\phi)\mathrm{Tr}[W\,\widetilde{W}] + y_q\phi\,\bar{\psi}\exp(i\gamma_5\theta_\psi(\phi))\;\psi + \cdots$$

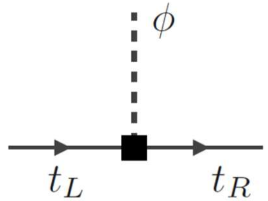
de Vries, Postma, van de Vis, White 1710.04061

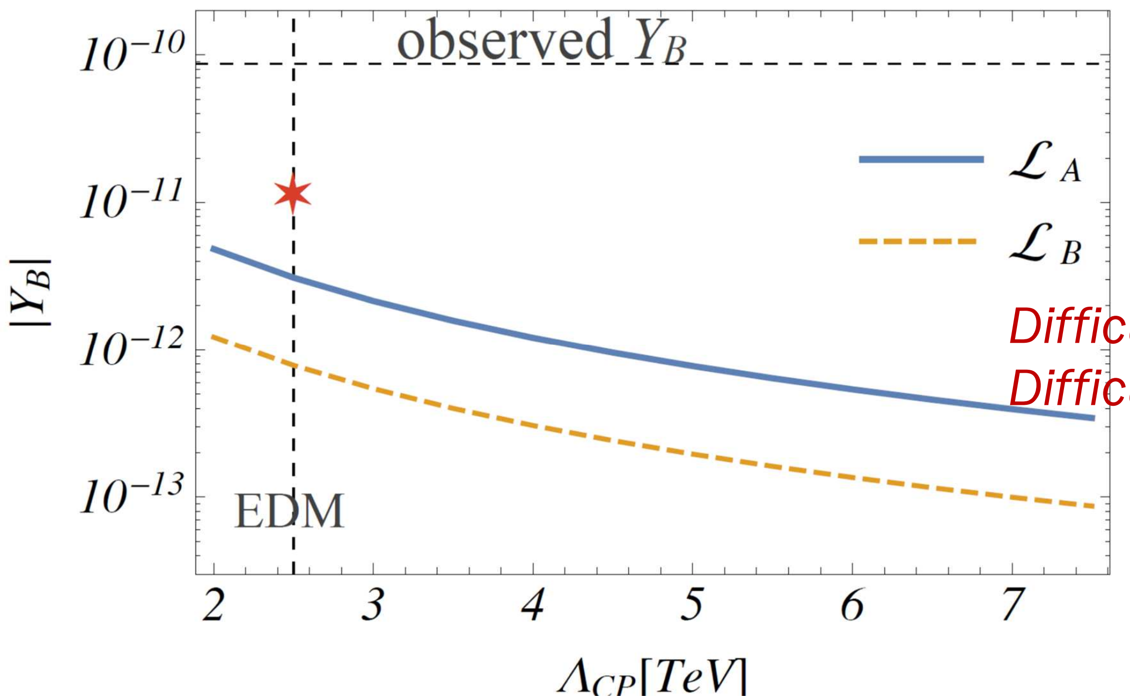
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} - \frac{|H|^6}{\Lambda^2} + \left(i\frac{|H|^2}{\Lambda_{CP}^2}y_t Q_L H t_R + h.c.\ \text{or}\ \frac{i\alpha}{\Lambda_{CP}^2}Q_L D^2 H\, t_R + \ h.c.\right)$$



for 1st order pT: $\Lambda \simeq 800\mathrm{GeV}$

for CPV source (scenario A or B)
related by classical e.o.m





Difficult to use effective theory description
Difficult to achieve a correct baryon abundance

Short summary

First order phase transition (or sudden change of Higgs expectation value at give space) is usually required to generate the sizable asymmetry.

In simple set-ups, they generally require strong couplings with the Higgs, which predict observable consequences. However, so far there is no hint from EDM and LHC. Such models are strongly constrained.

On one hand, first order phase transition can be realized with only weak couplings, which can lead to new possibility for baryogenesis and detectability.