기초과학연구원
Institute for Basic Science

Electroweak Baryogenesis driven by an Axion-Like Particle

Chang Sub Shin (IBS-CTPU)

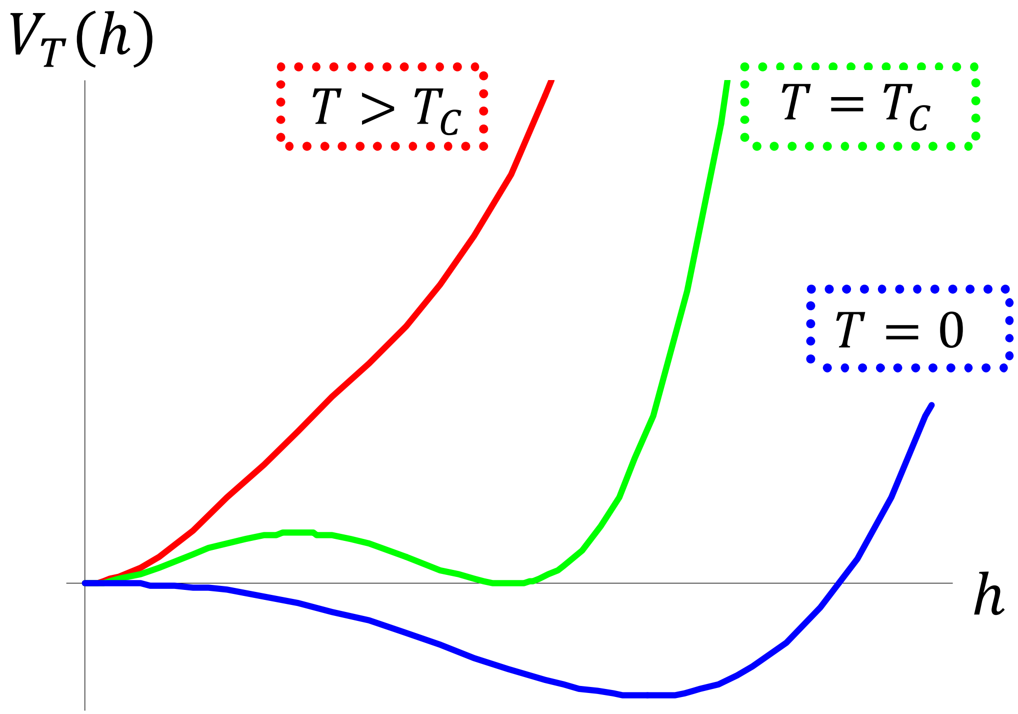
Based on work [arXiv:1806.02591, 1811.03294 [hep-ph]]
with Kwang Sik Jeong (PNU) and Tae Hyun Jung (IBS-CTPU)

at the 5th international workshop on
DM, DE, and Matt-antimatt Asymmetry
Dec. 28, 2018

Idea of EWBG

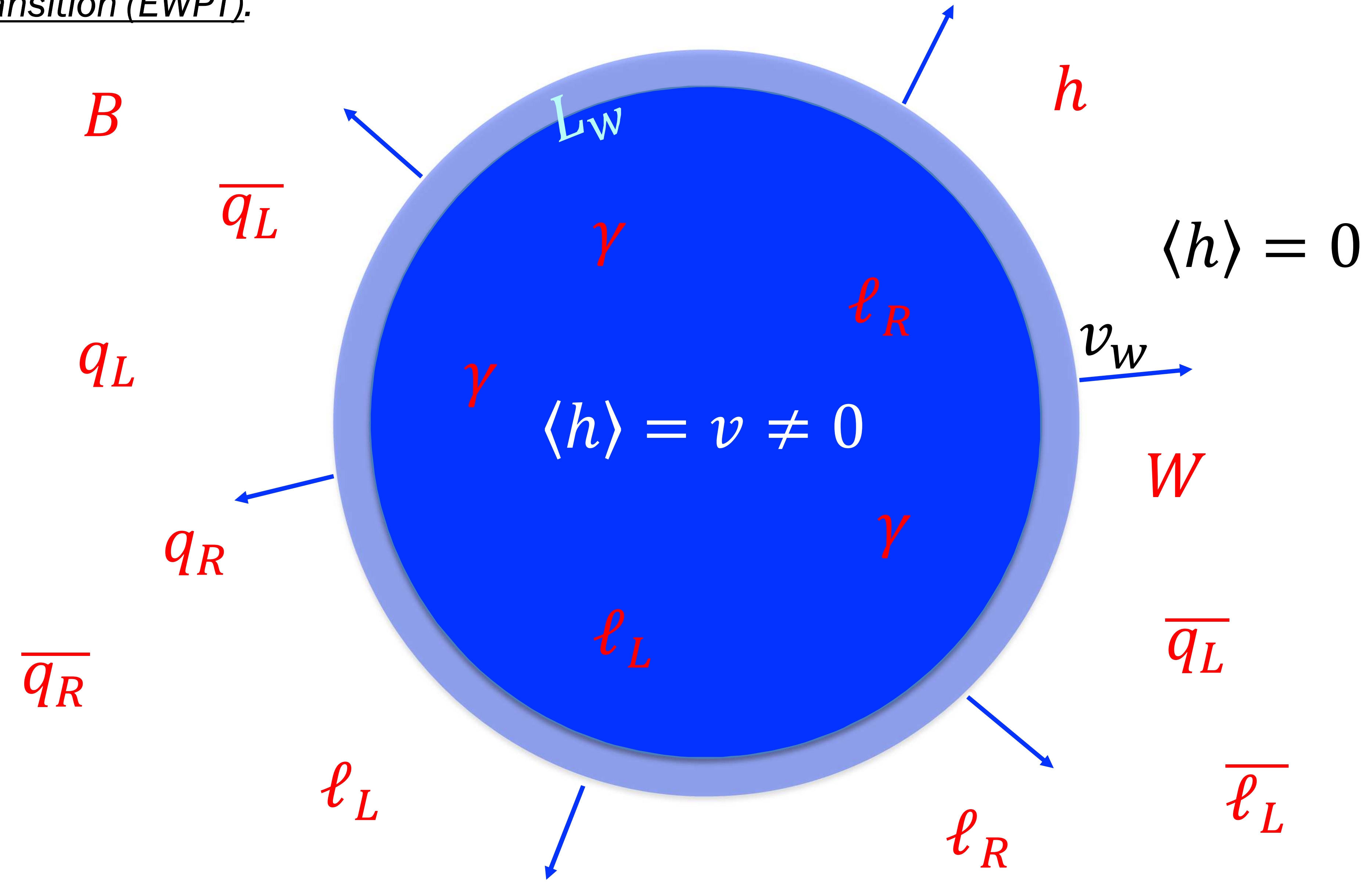
Electroweak baryogenesis (EWBG)

Baryon asymmetry of the Universe should be answered by physics beyond the SM. However, the Higgs still can play an important role to trigger ***EWBG by first order electroweak phase transition (EWPT)****.*

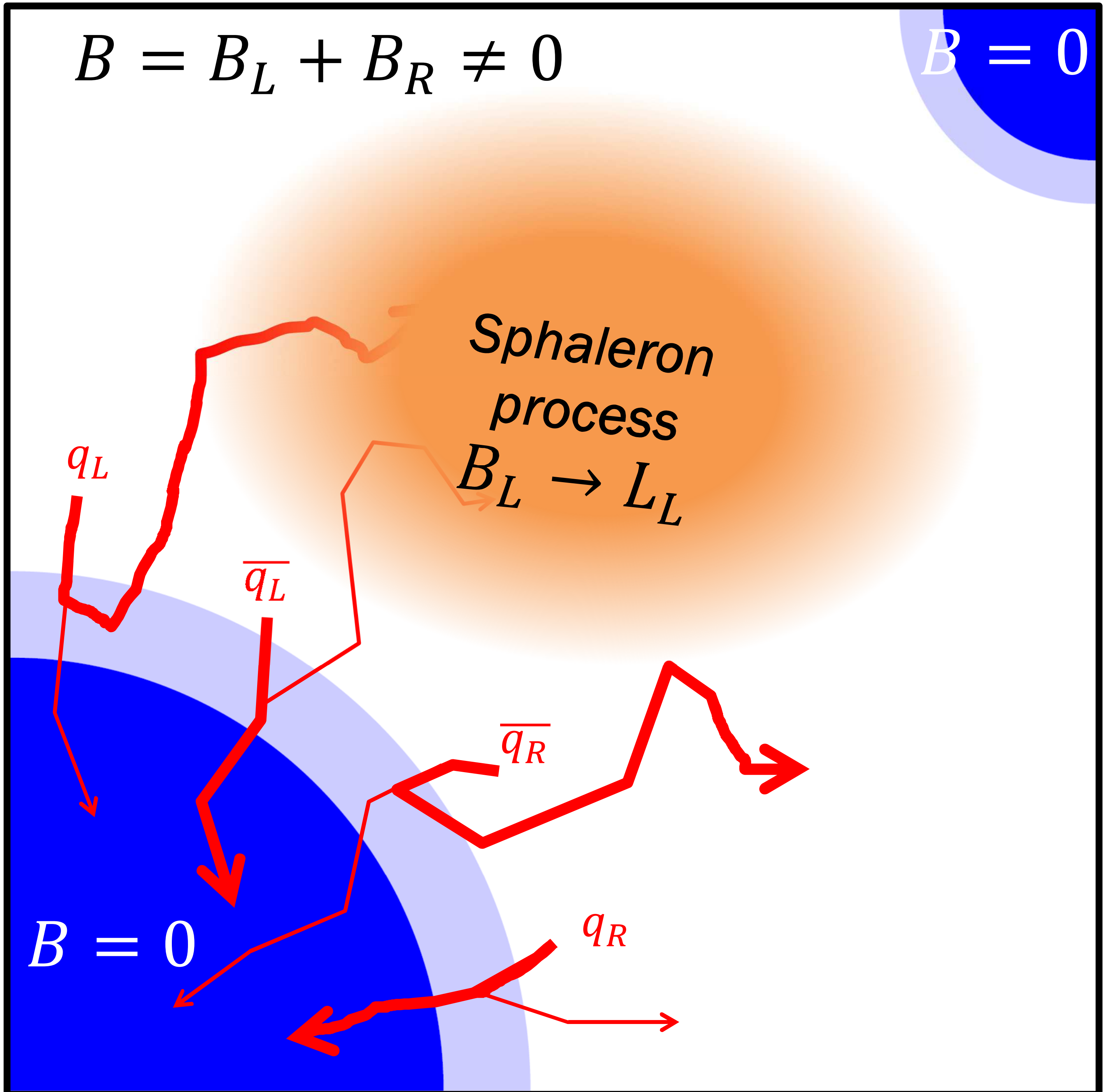


Electroweak baryogenesis (EWBG)

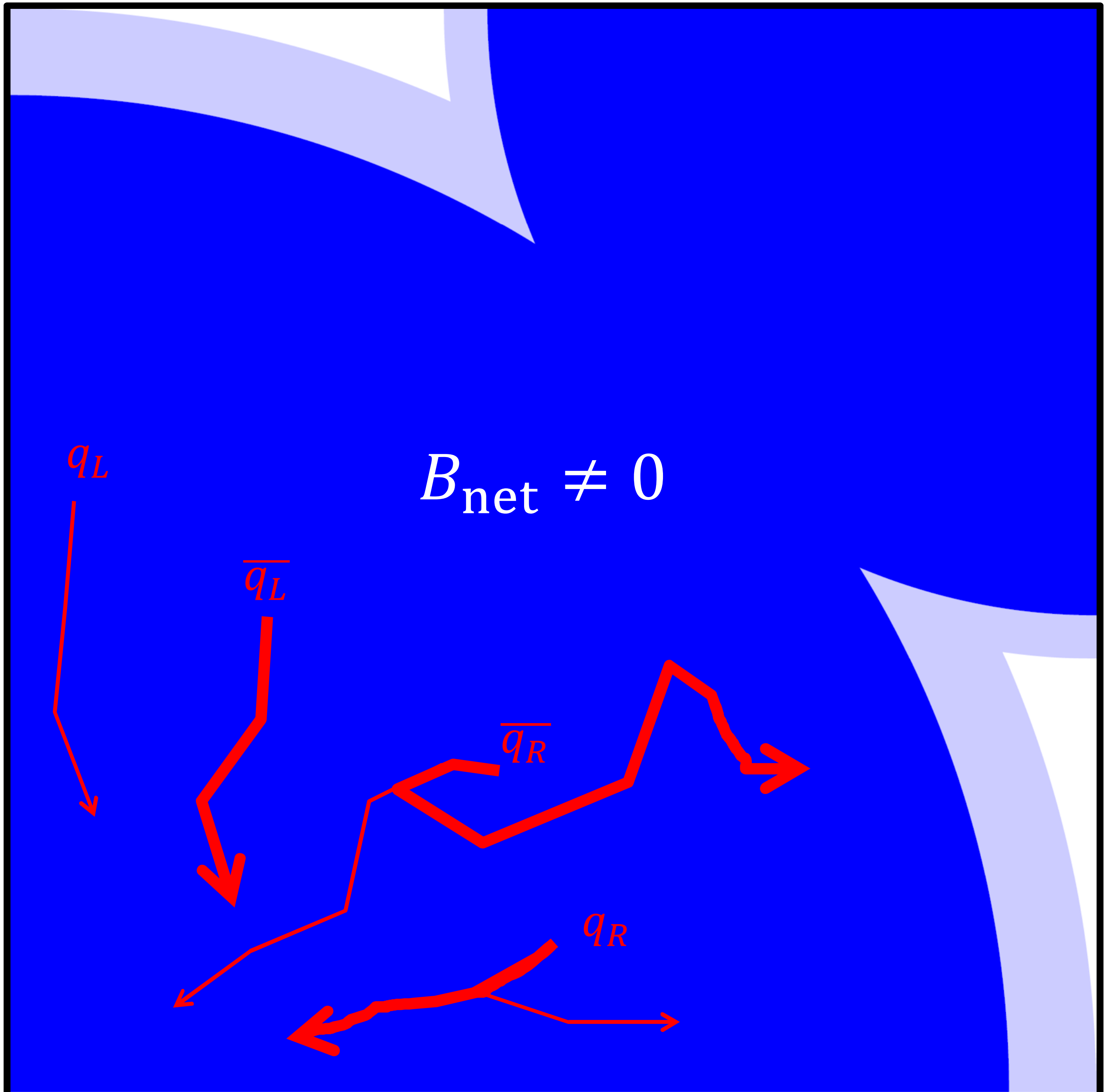
Baryon asymmetry of the Universe should be answered by physics beyond the SM. However, the Higgs still can play an important role to trigger <u>EWBG by first order electroweak phase transition (EWPT)</u>.



EWBG 1 (2)


$B = B_L + B_R \neq 0$
$B = 0$
Sphaleron process
$B_L \to L_L$
q_L
$\overline{q_L}$
$\overline{q_R}$
q_R
$B = 0$

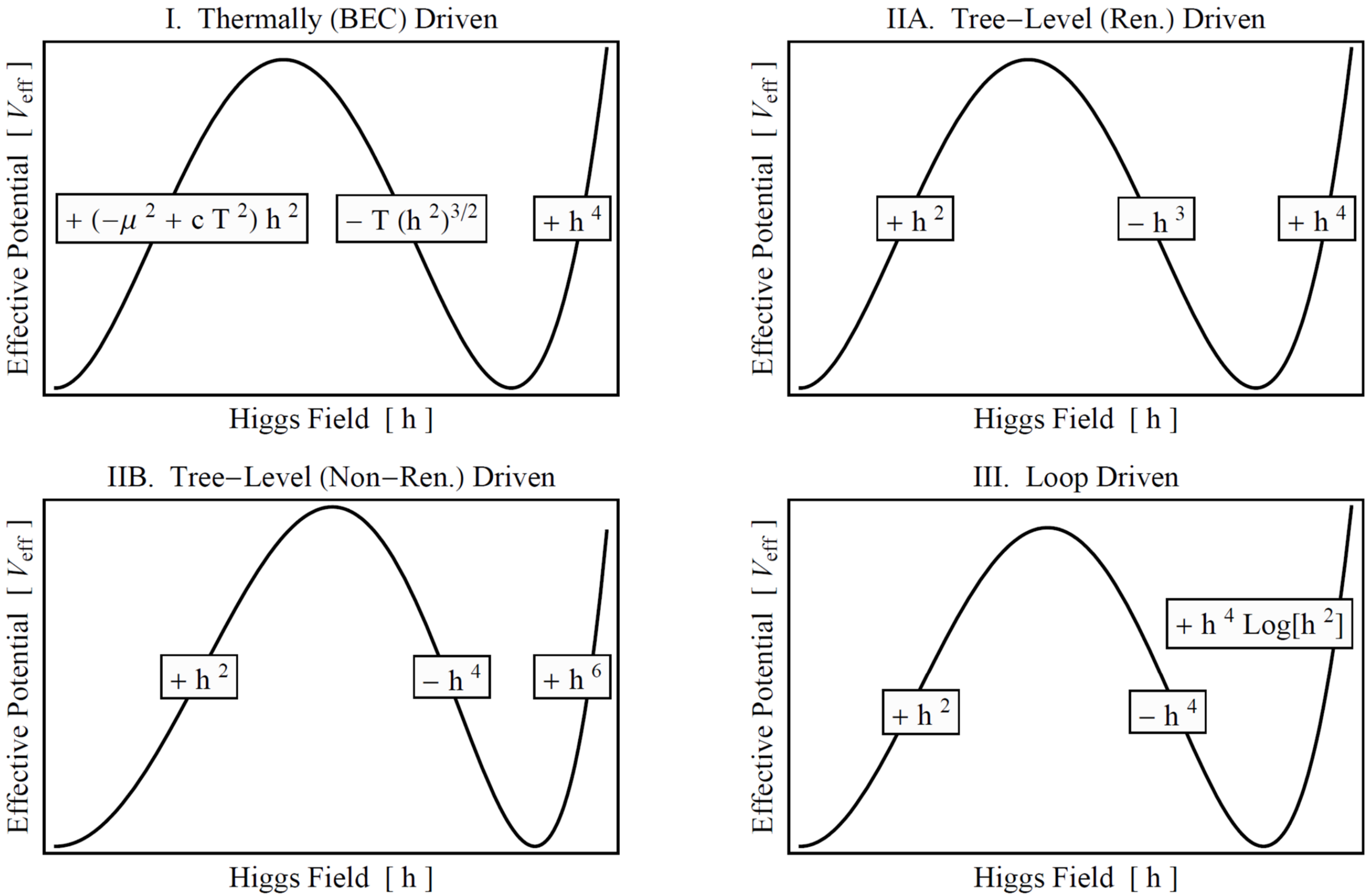
EWBG 2 (2)

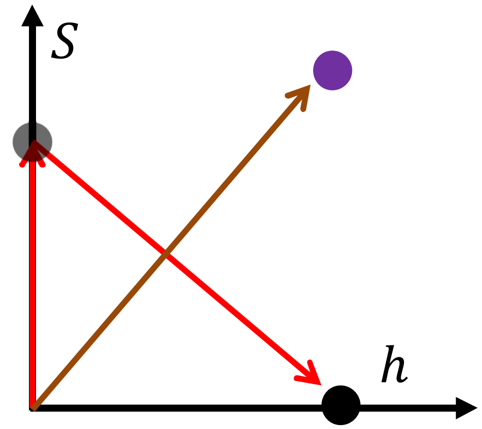


Extension for first order phase transition

Most of extensions beyond the SM focuses on realizing strong 1st order EWPT

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



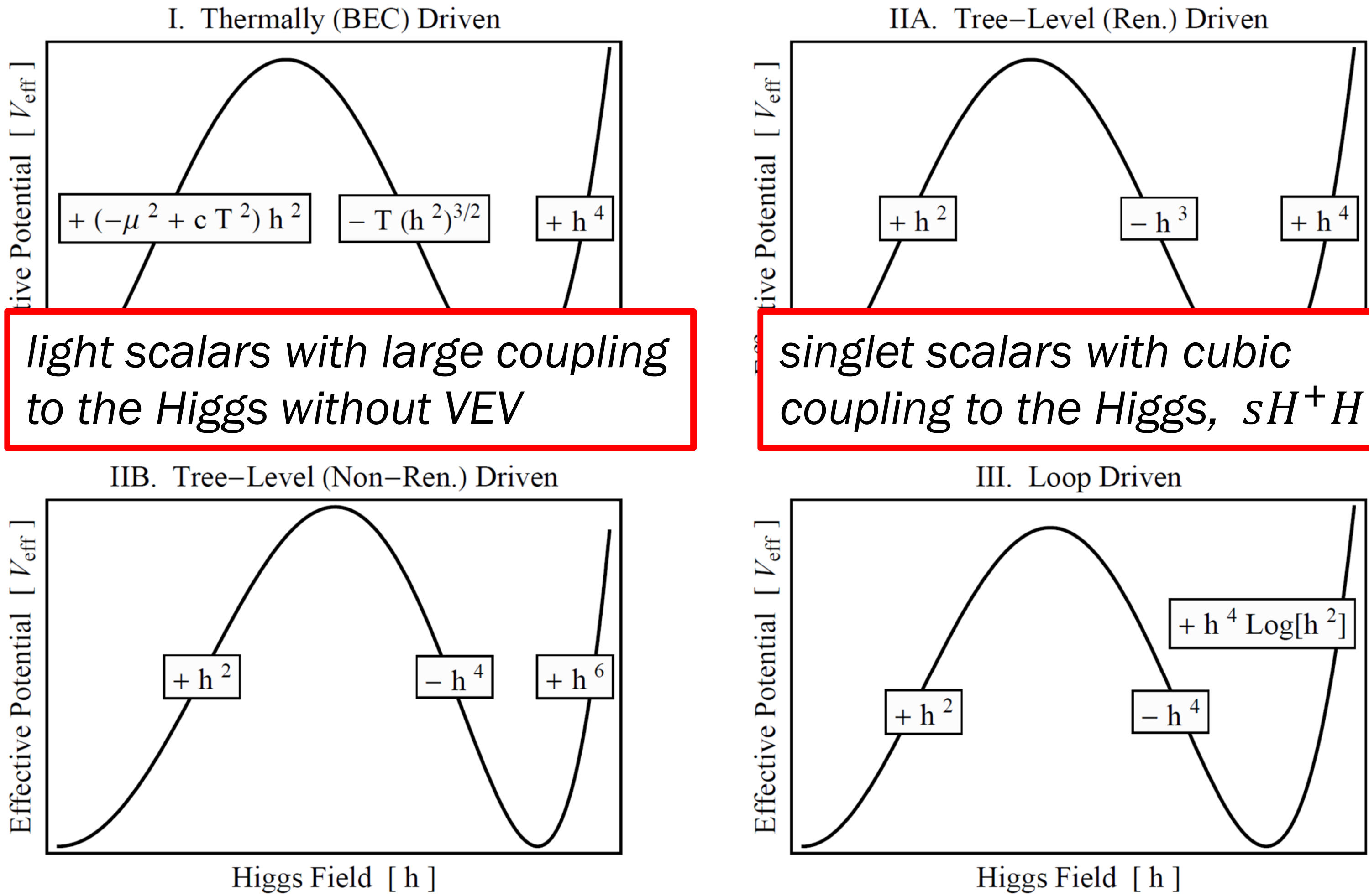


[Chung, Long, Wang 12]

Extension for first order phase transition

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

(single field description)



[Chung, Long, Wang 12]

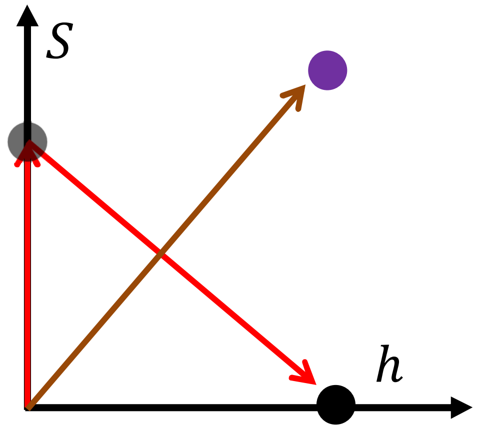
light scalars with large coupling to the Higgs without VEV

singlet scalars with cubic coupling to the Higgs, sH^+H

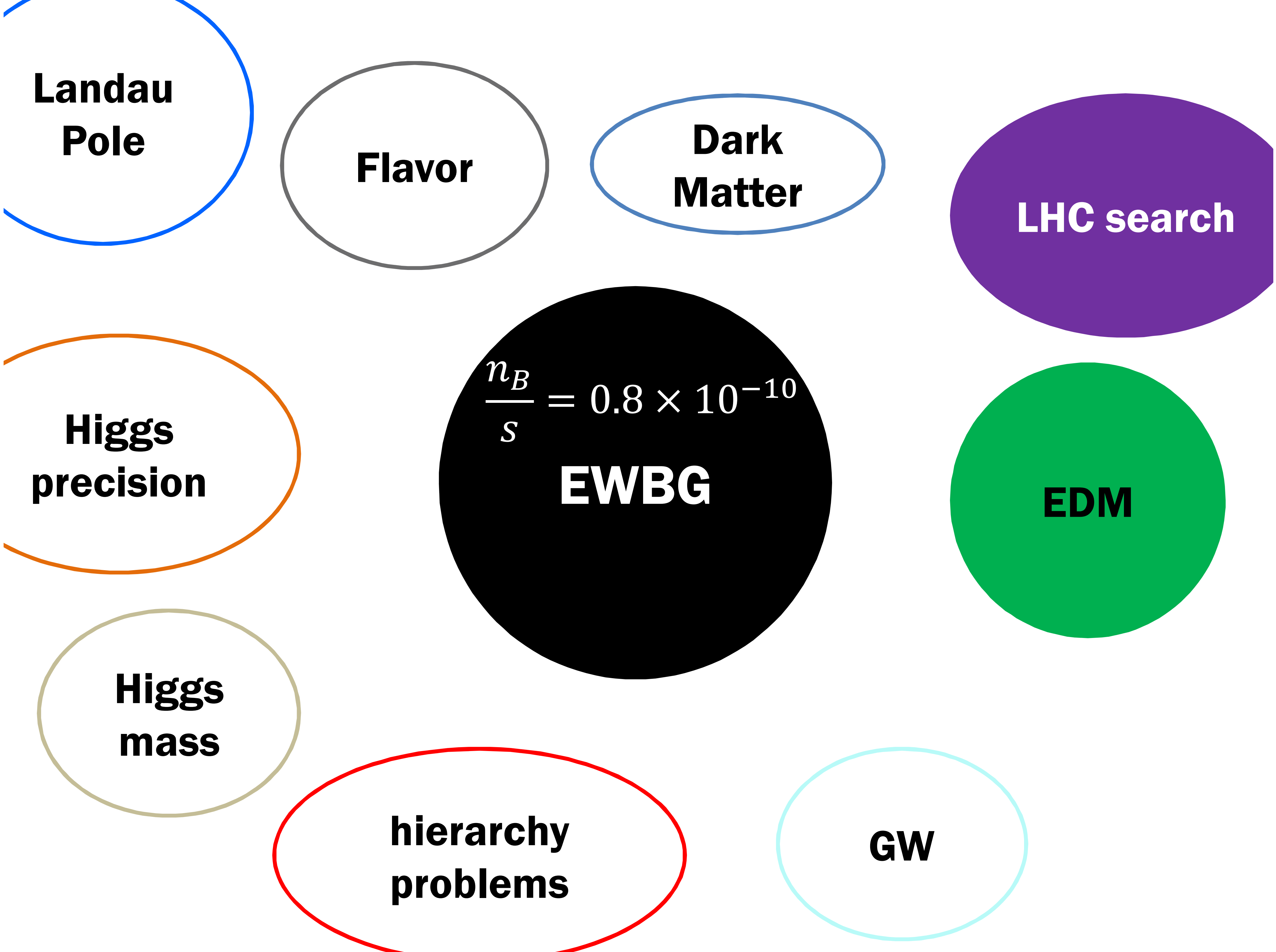
Strong dynamics to give a low cutoff

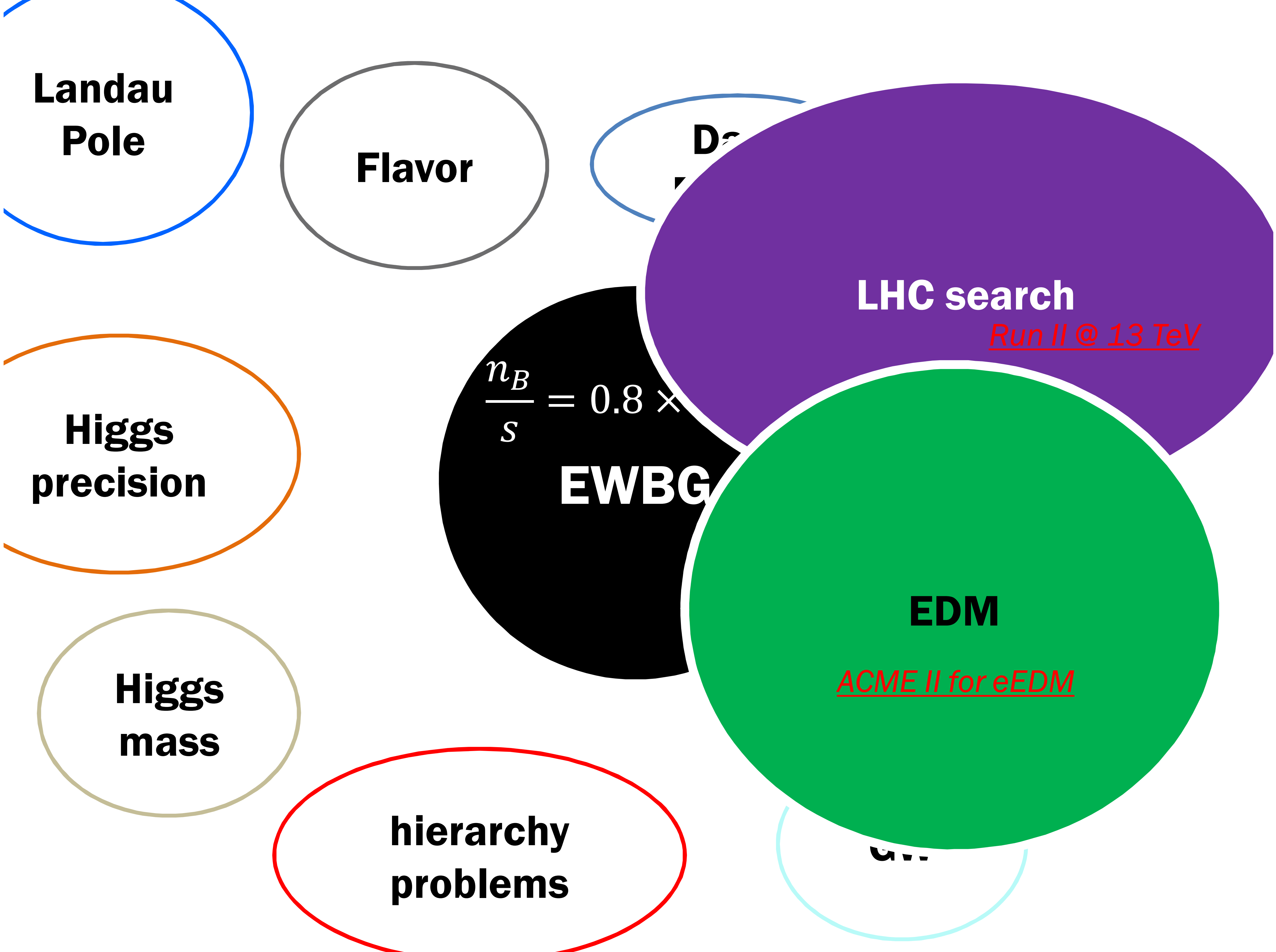
(charged) light fermions with large couplings to the Higgs

(multi field description)

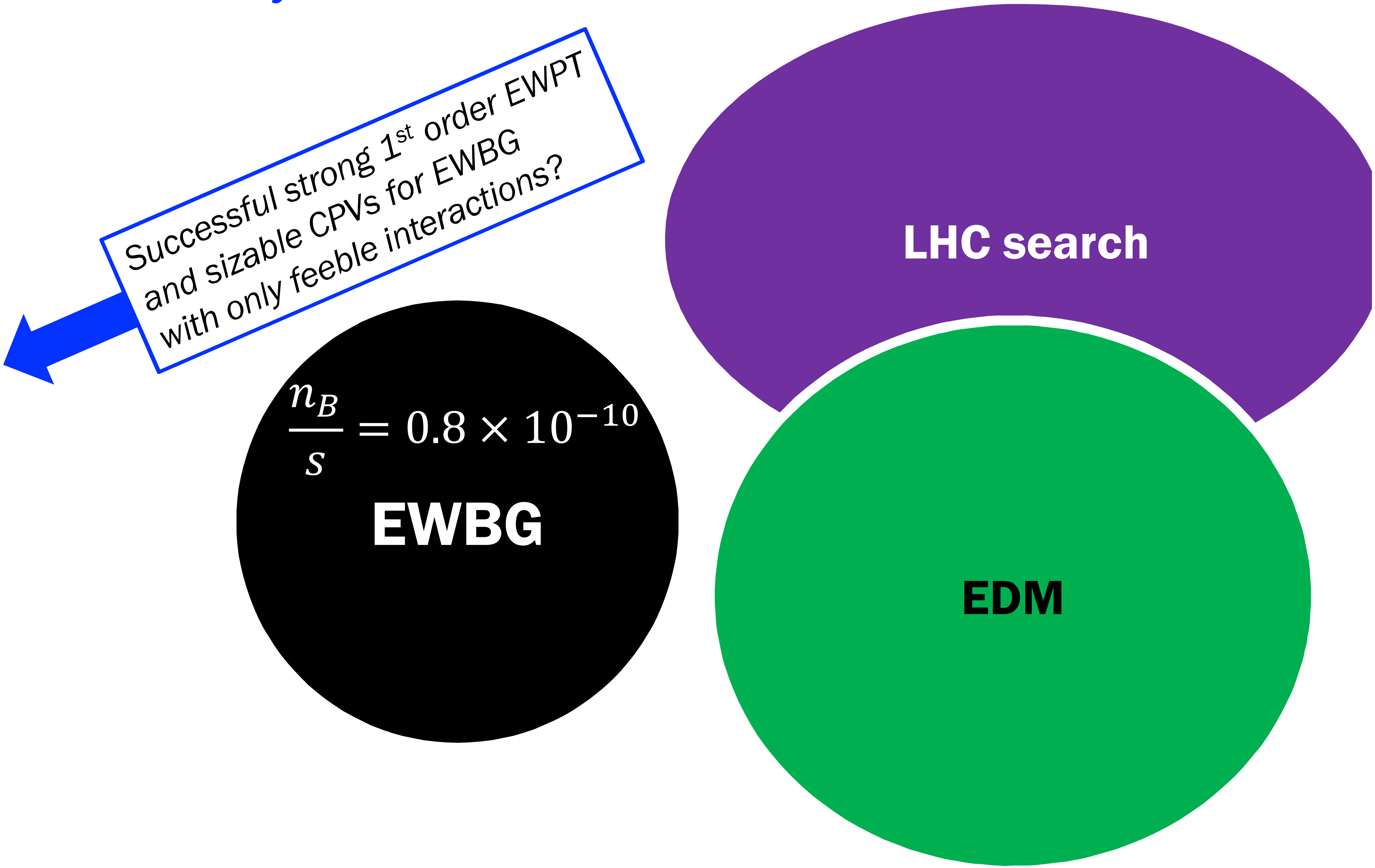


multi step PT with strong couplings (for Z_2 symmetric case: [Kurup, Perelstein 17])


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

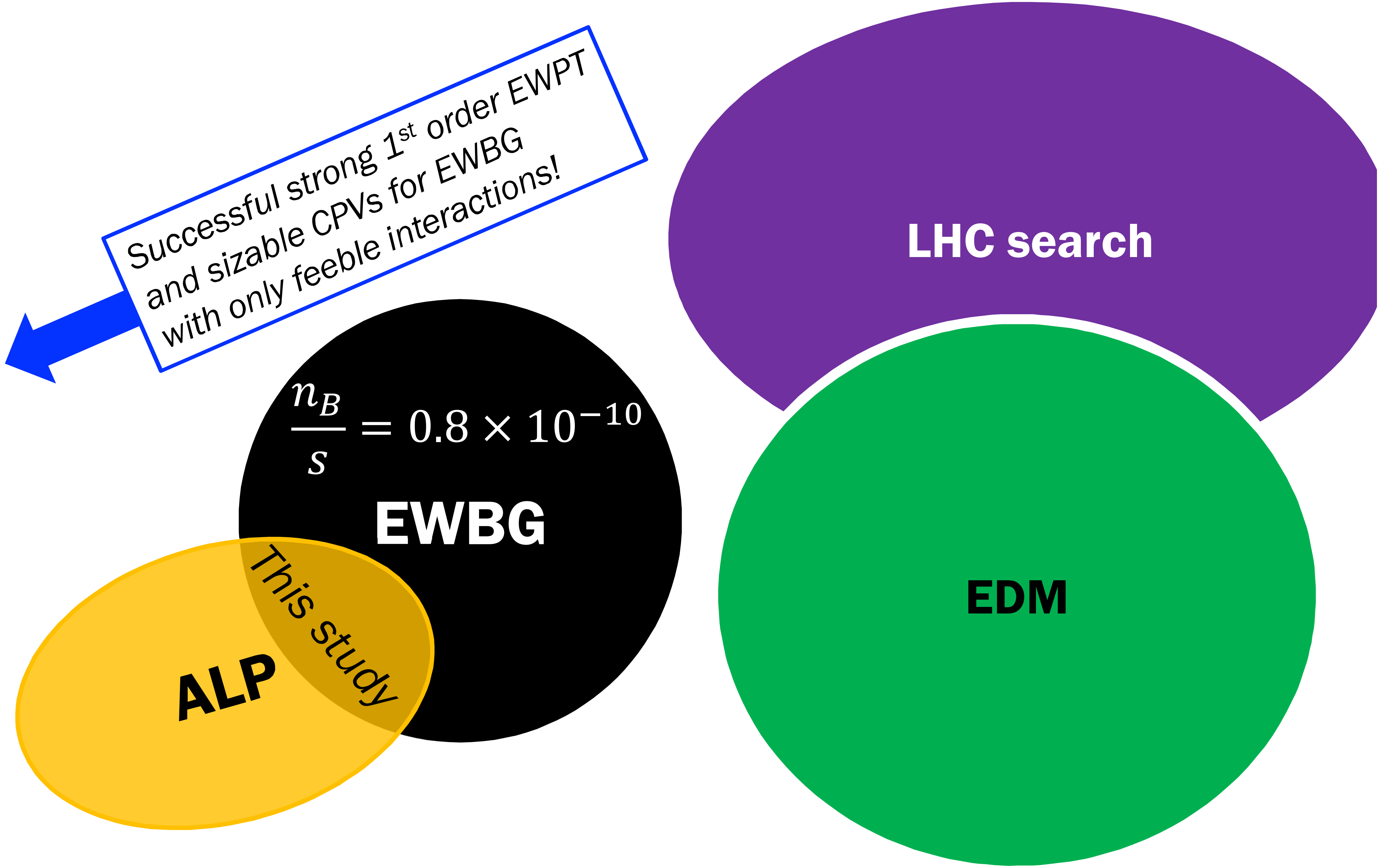

Landau Pole
Flavor
LHC search
Run II @ 13 TeV
$\frac{n_B}{s} = 0.8 \times$
EWBG
Higgs precision
EDM
ACME II for eEDM
Higgs mass
hierarchy problems

1. Naturally safe from EDM and LHC constraints



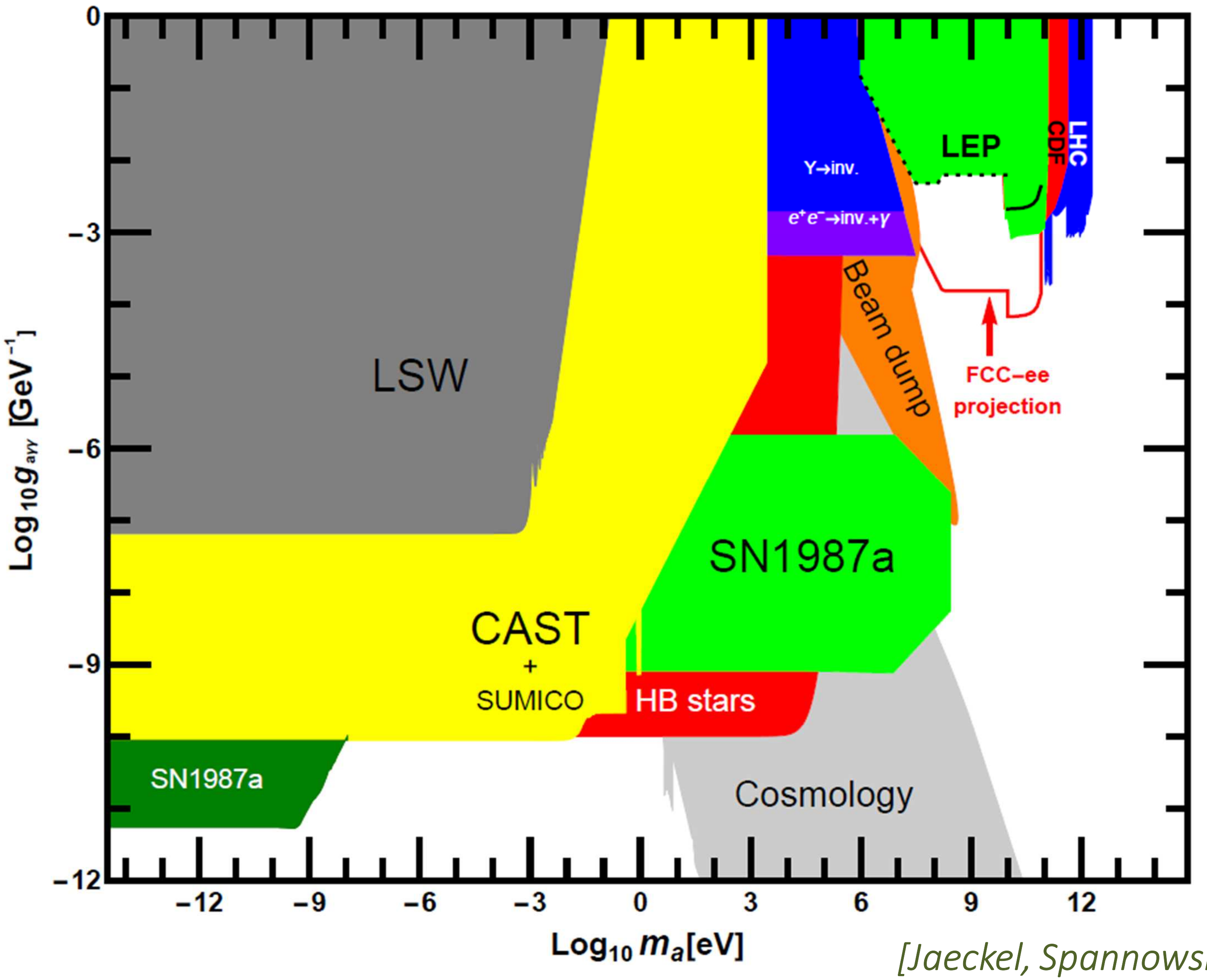
2. New experimental searches for the evidence of EWBG?

With Axion-Like Particles (ALPs)



2. New experimental searches for the evidence of EWBG!

ALP landscapes



[Jaeckel, Spannowsky 15]

Theoretical motivations of ALP for various ranges of its mass and decay constant

Axionic EWBG

[Jeong, Jung, CSS 18]

Outline

ALP intro

- *compact, light, suppressed by a large axion decay constant*

Strong first order phase transition

- *With only feeble interactions independently from a decay constant*

Generation of baryon asymmetry

- *Non-local, local electroweak baryogenesis depending on a decay constant*

CP violating sources

- *Dynamical Top Yukawa, Electroweak theta term*

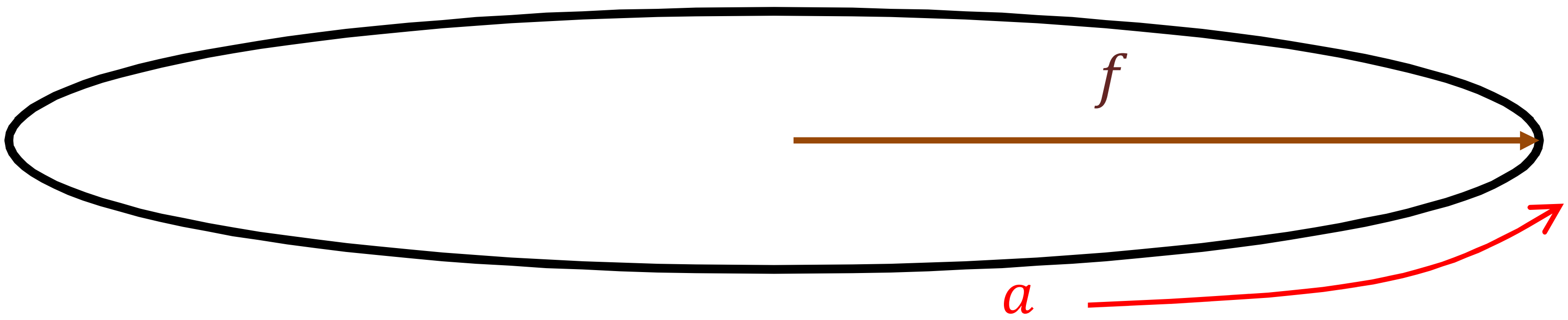
Experimental constraints

- *Natural suppression of EDM.*
- *ALP searches (LHC, meson rare decays, Supernova cooling)*

ALP intro (1)

ALP, $a(x)$, is the scalar field in effective theories well below the scale f :

1) *The SM singlet, and compact with a period: $2\pi f$*



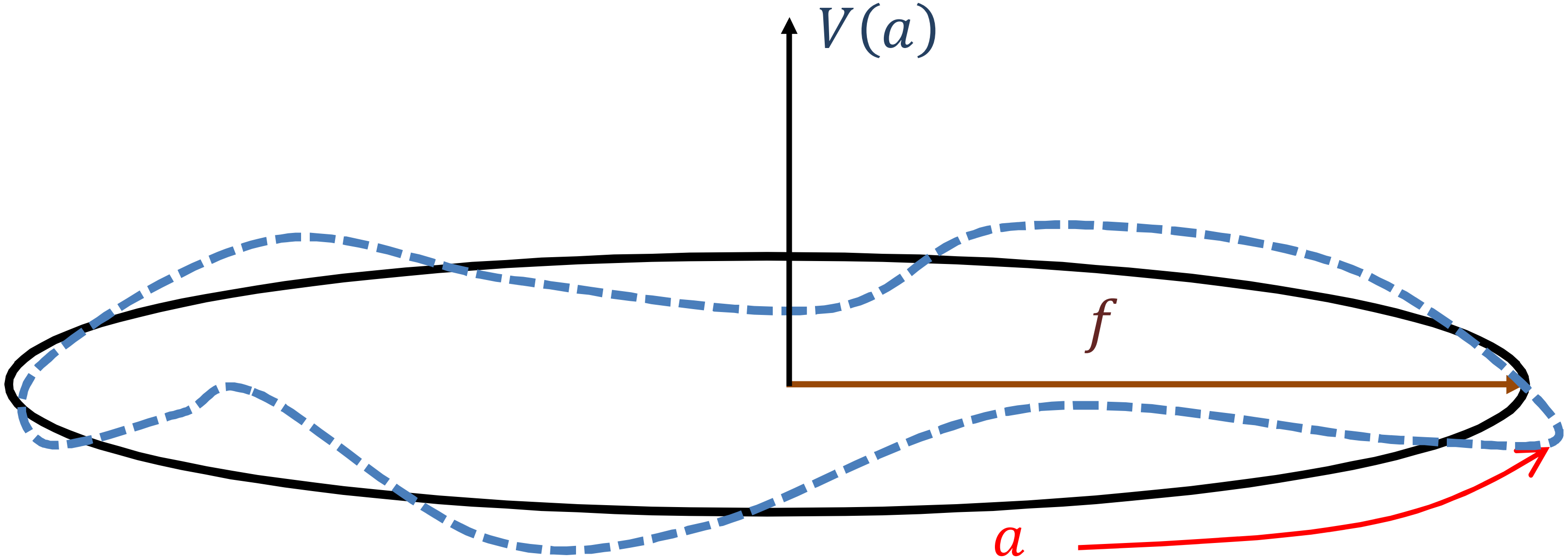
$$S[a] = S[a + 2\pi\mathbb{N}f]$$

ALP intro (2)

ALP, $a(x)$*, is the scalar field in effective theories well below the scale* f *:*

2) Approximate continuous shifty symmetry $U(1)_{PQ}$

($a \to a + 2\pi f \beta$, *where* $\beta \in \mathbb{R}$)



The potentials and interactions to explicitly break shift symmetry are generated at a scale (μ*) much lower than* f *(*$\mu \ll f$*)*

ALP intro (3)

All interactions between ALP and matters can be given by the combination of

$$\frac{a}{f}$$

A natural way to introduce higher dim. operators, weak couplings, and small mass of ALP

E.g. for $\Lambda \ll f$

$$V(a) = -\Lambda^4 \cos\frac{a}{f} = \Lambda^4 + \frac{\Lambda^4}{2f^2}a^2 - \frac{\Lambda^4}{24f^4}a^4 + \frac{\Lambda^4}{720f^6}a^6 + \cdots$$

the ALP mass,

$$m_a = \frac{\Lambda^2}{f} \ll f,\ \Lambda$$

the self coupling,

$$\lambda_{\mathrm{quartic}} = \frac{\Lambda^4}{6f^4} \ll O(1)$$

Axion couplings to matters

$$\mathcal{L} \ni \frac{a}{16\pi^2 f}\left(c_G G\tilde{G} + c_W W\widetilde{W} + c_B B\tilde{B}\right) + x_q e^{ia/f} H Q_L q_R + h.c. + \cdots$$

The energy scale that we concern: $E \ll f \rightarrow \ \Gamma_{\mathrm{int}} \propto (E/f)^2$

Axionic extension of the Higgs potential

A scalar potential is constructed by the Higgs and the angular field, $\theta(x) \equiv a(x)/f$

$$V(H,a) = V(H^{+}H, \sin\theta\,, \cos\theta)\,.$$

As an simple example with $\mu_1 \sim \mu_2 \sim \Lambda \sim O(m_W)$ *(a UV model will is presented later)*

$$V(H,a) = \mu_1^2|H|^2 + \lambda|H|^4 + \mu_2^2\cos(\theta+\alpha)\,|H|^2 - \Lambda^4\cos\theta\,.$$

Considering an expansion in terms of a/f*,*

$$V(h,a) = \frac{1}{2}\left(\mu^2 + c_1\frac{\mu^2}{f}a + c_2\frac{\mu^2}{f^2}a^2 + c_3\frac{\mu^2}{f^3}a^3 + \cdots\right)h^2 + \frac{\lambda}{4}h^4 + \frac{\Lambda^4}{2f^2}a^2 - \frac{\Lambda^4}{24f^4}a^4 + \frac{\Lambda^4}{720f^6}a^6 + \cdots.$$

The couplings between ALP and the Higgs are suppressed for $m_W \ll f$*.*

Tadpole, cubics and higher dimensional operators can be systematically introduced without worrying about stability of the scalar potential.

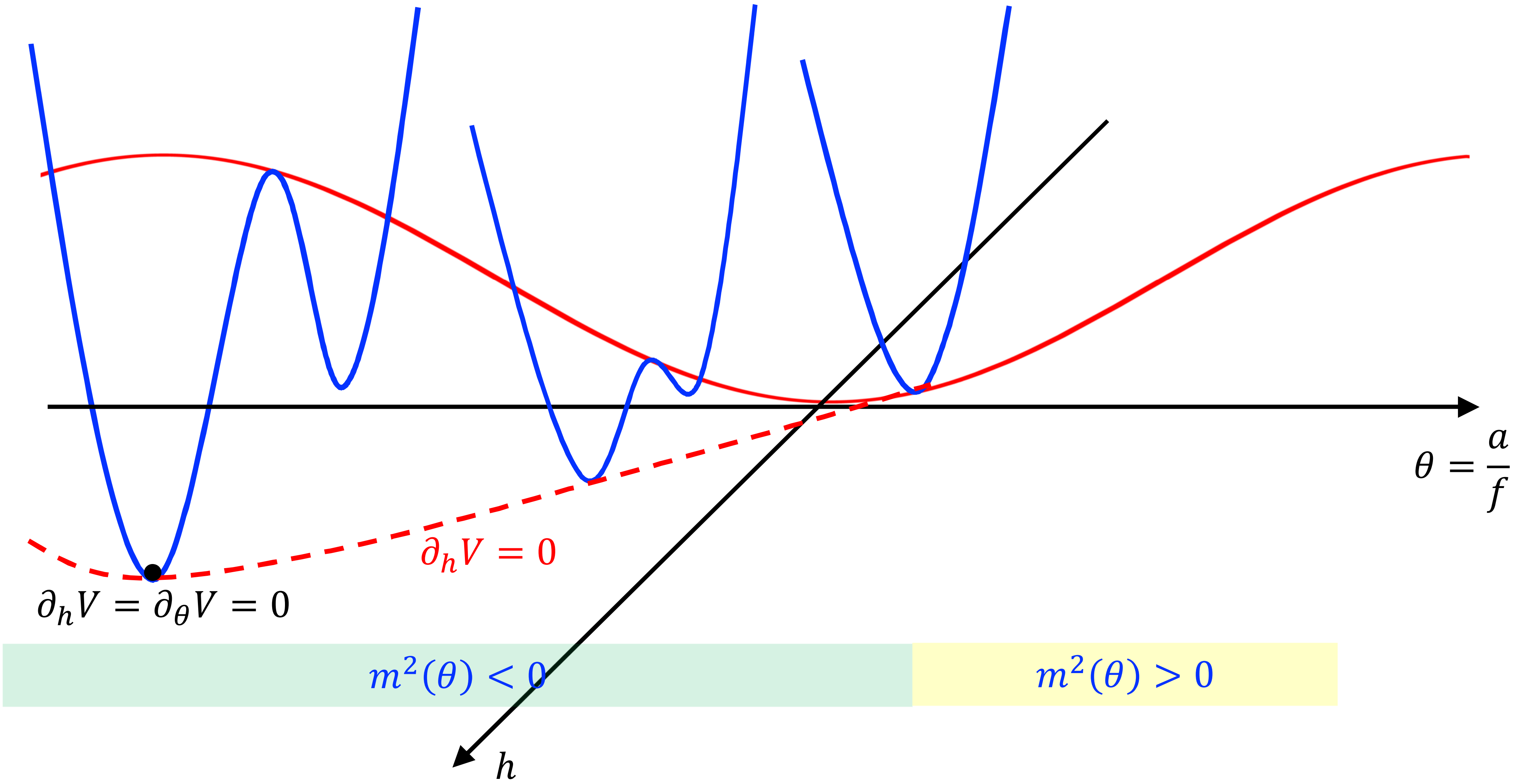
A strong 1st order EWPT can be realized!

Schematic description of the potential

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

Schematic description of the potential

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



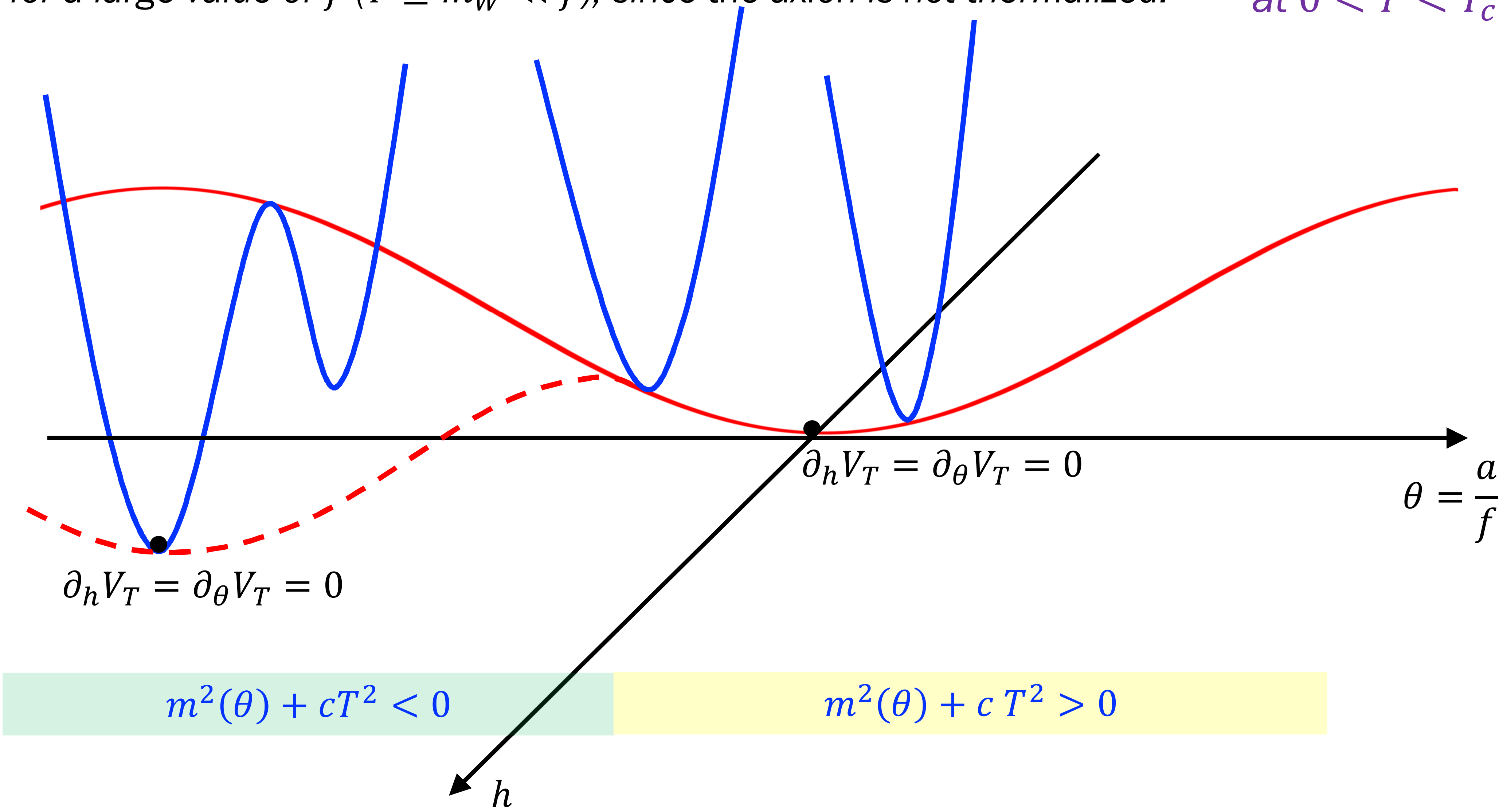
The potential is bounded from below due to the periodicity of the axion dependence

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.*

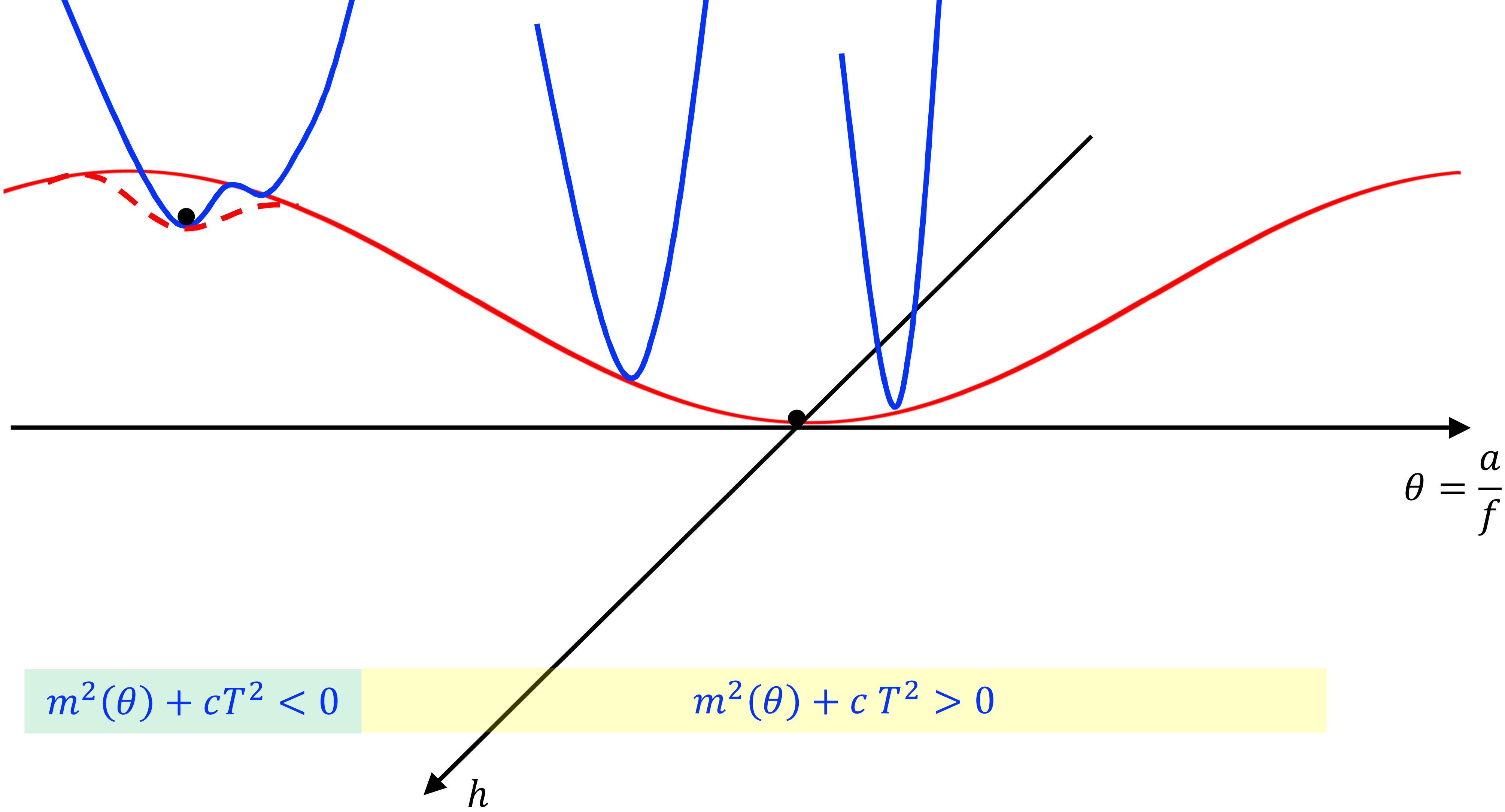
at $0 < T < T_c$



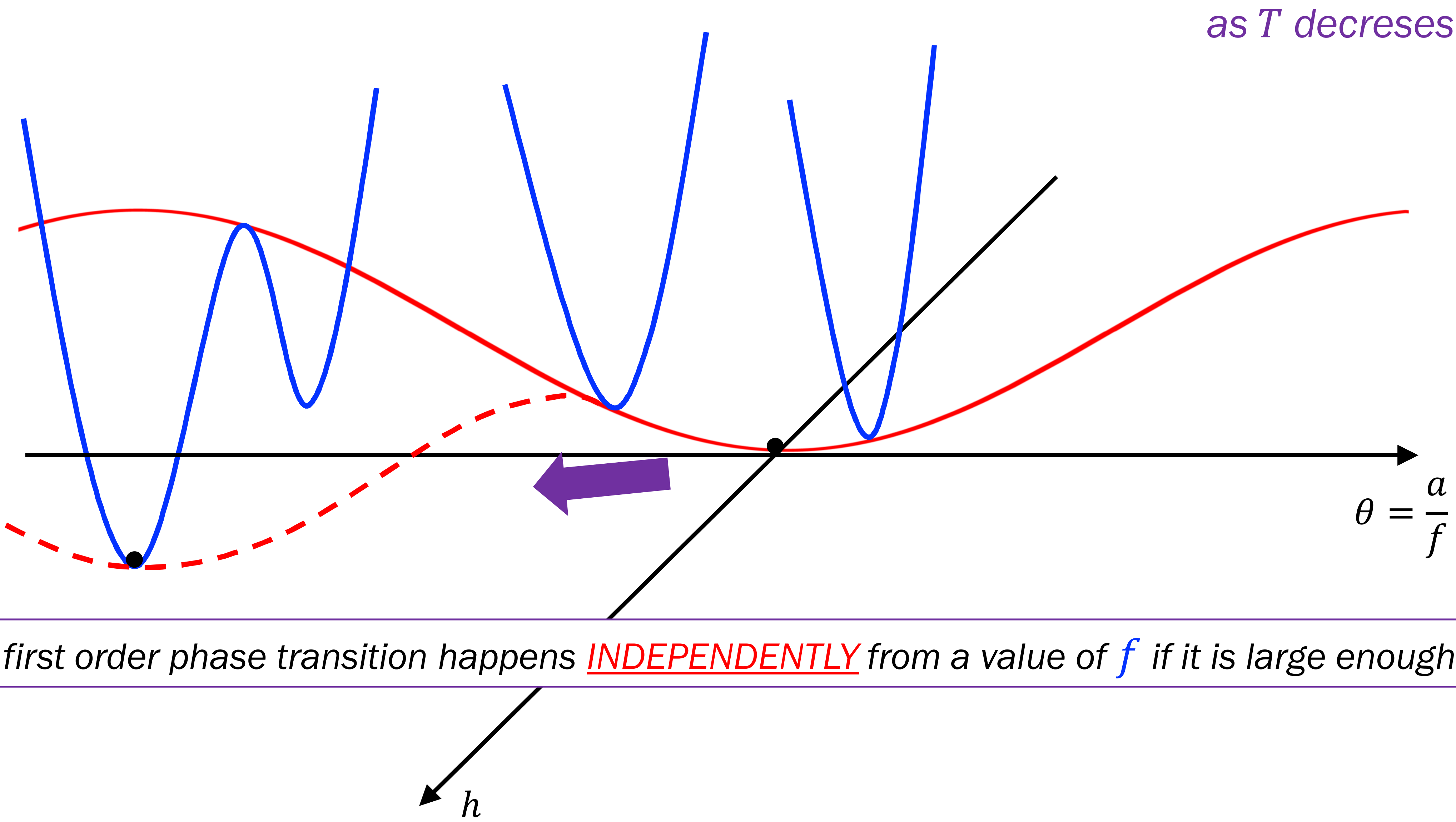
Schematic description of EWPT

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

at $T_c < T$



Schematic description of EWPT



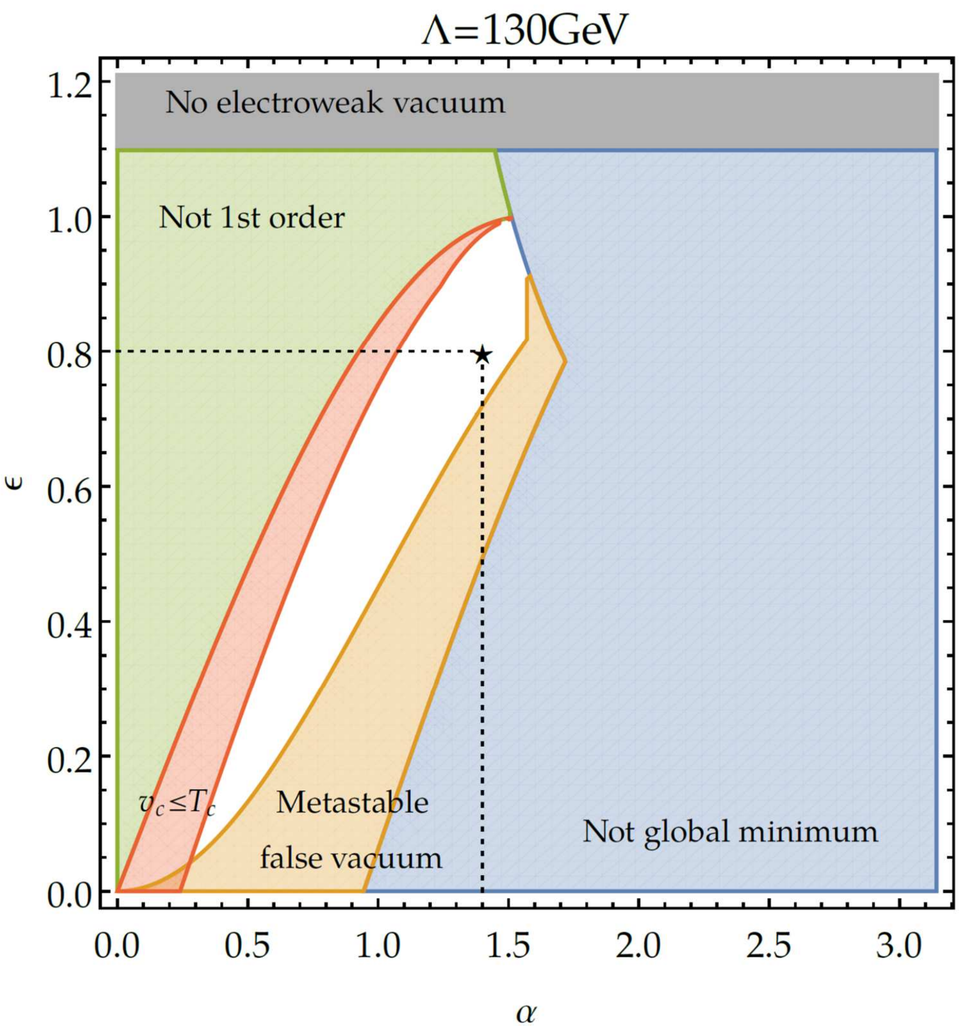
first order phase transition happens INDEPENDENTLY from a value of f if it is large enough

Strong first order EWPT

After fixing parameters by the Higgs mas and the Higgs VEV from (with $\mu_1^2 > 0, \mu_2^2 < 0$)

$$V_{tree}(h,a) = \frac{\mu_1^2}{2}\, h^2 + \frac{\lambda}{4} h^4 + \frac{\mu_2^2}{2} \cos(\theta+\alpha)\; h^2 - \Lambda^4 \cos\theta$$

the free parameters are $\boxed{\Lambda, \alpha, \epsilon = \sqrt{2\lambda}\Lambda^2/(-\mu_2^2) \quad (\text{not } f)}$

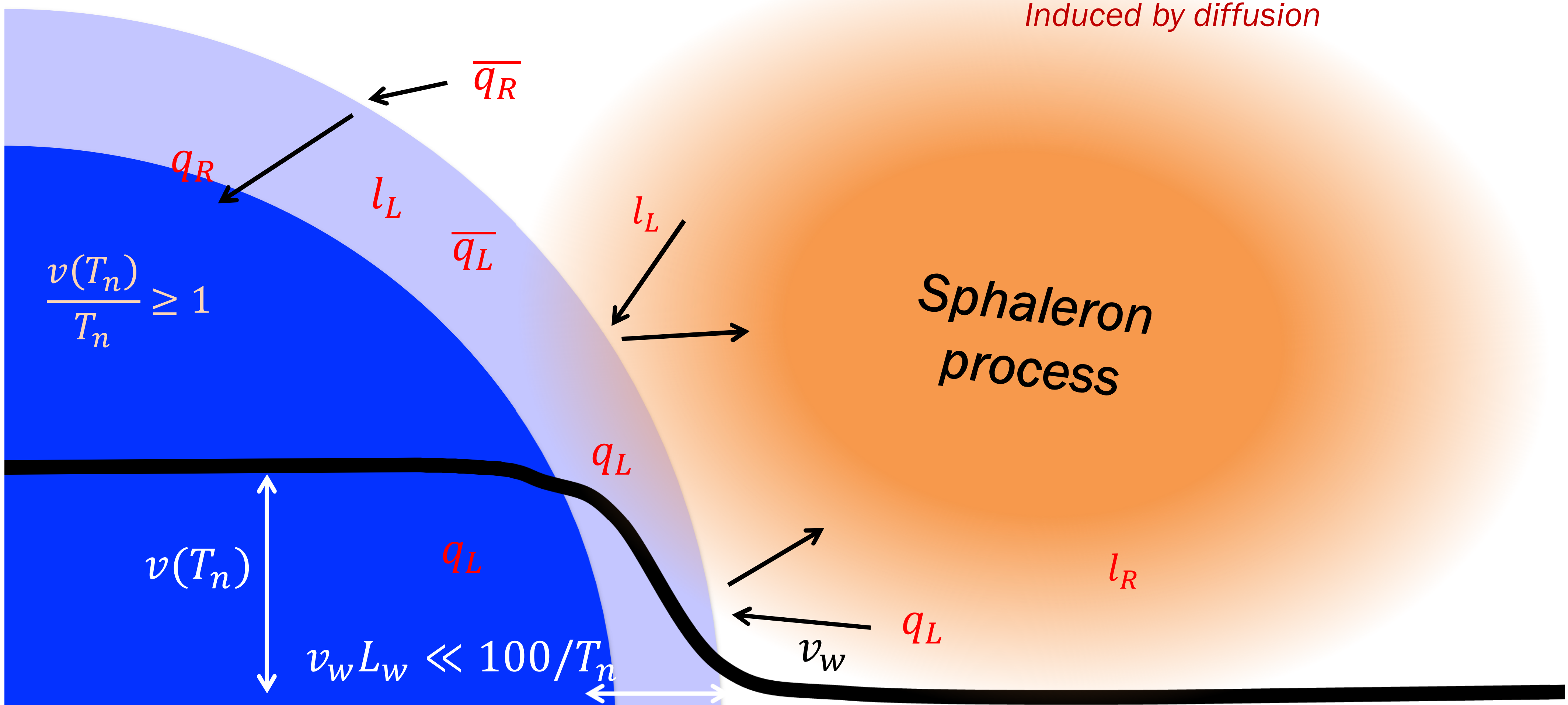


Non-local generation of baryon asymmetry

Most of baryons are generated at symmetric phase after CP violating diffusion

$$\frac{dn_B}{dt} + 3Hn_B = \frac{\Gamma_{sph}(\text{sym})}{T}\left(\mu_B(\text{sym}) - c_0\frac{n_B}{T^2}\right)$$

chemical potential Induced by diffusion

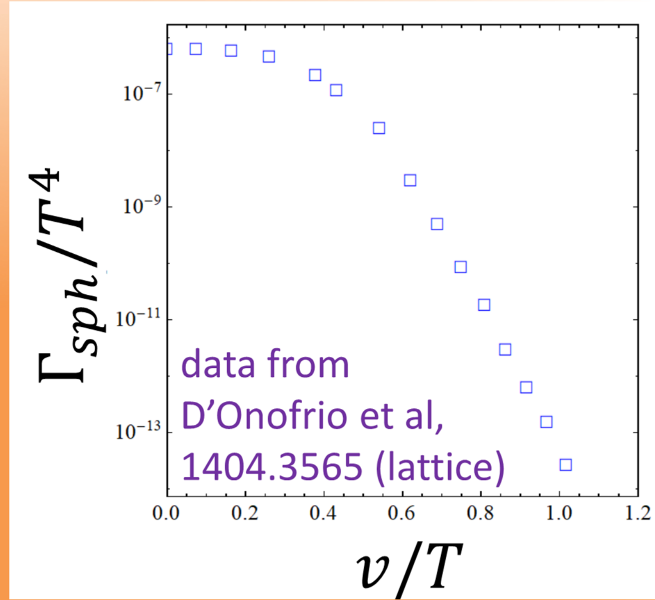


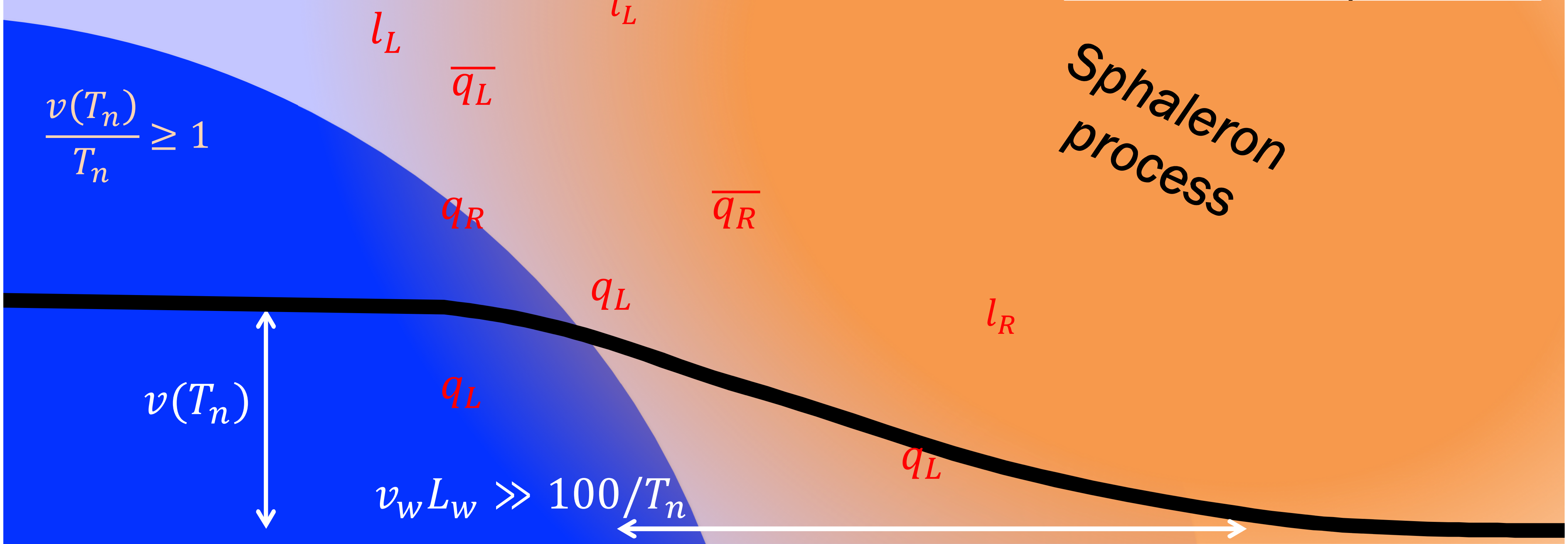
Local generation of baryon asymmetry

Adiabatically generated inside the bubble wall by Higgs dependent chemical potential

$$\frac{dn_B}{dt} + 3Hn_B = \frac{\Gamma_{sph}(h)}{T}\left(\mu_B(h) - c_0\frac{n_B}{T^2}\right)$$

non-zero chemical potential inside a bubble wall

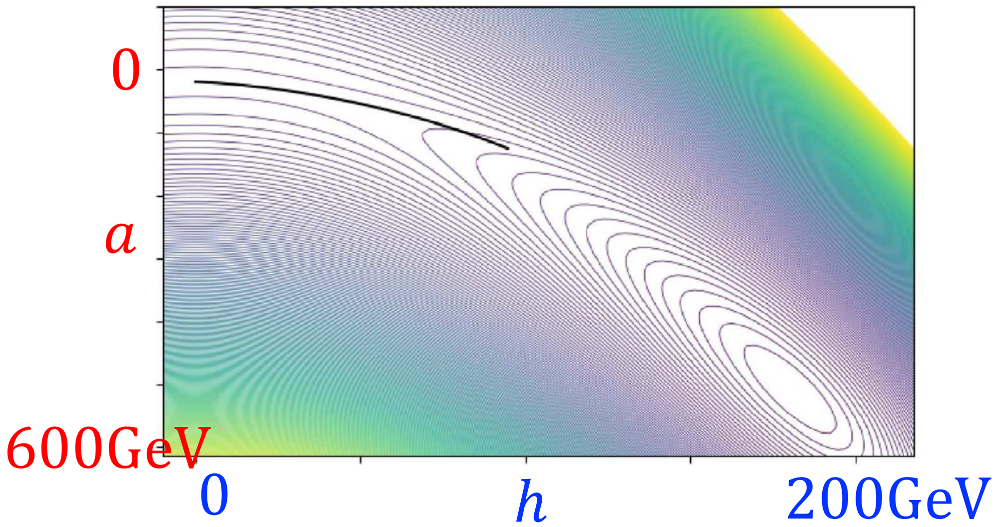


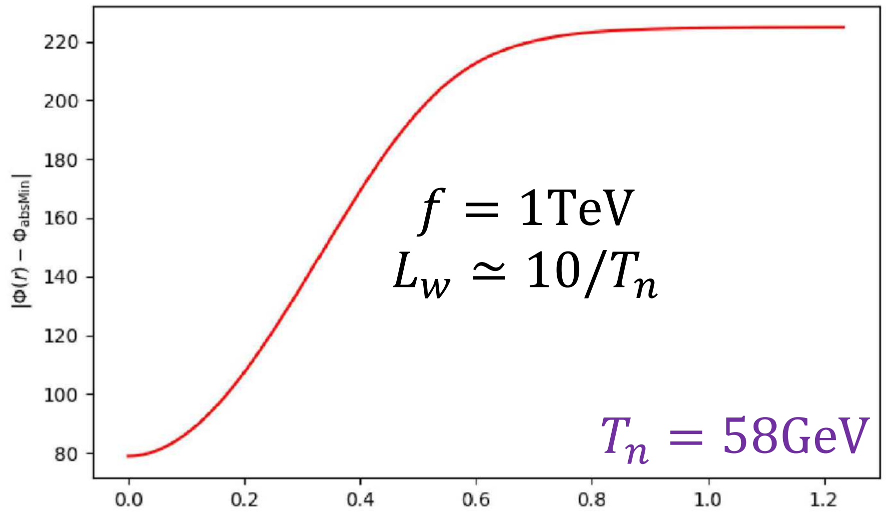


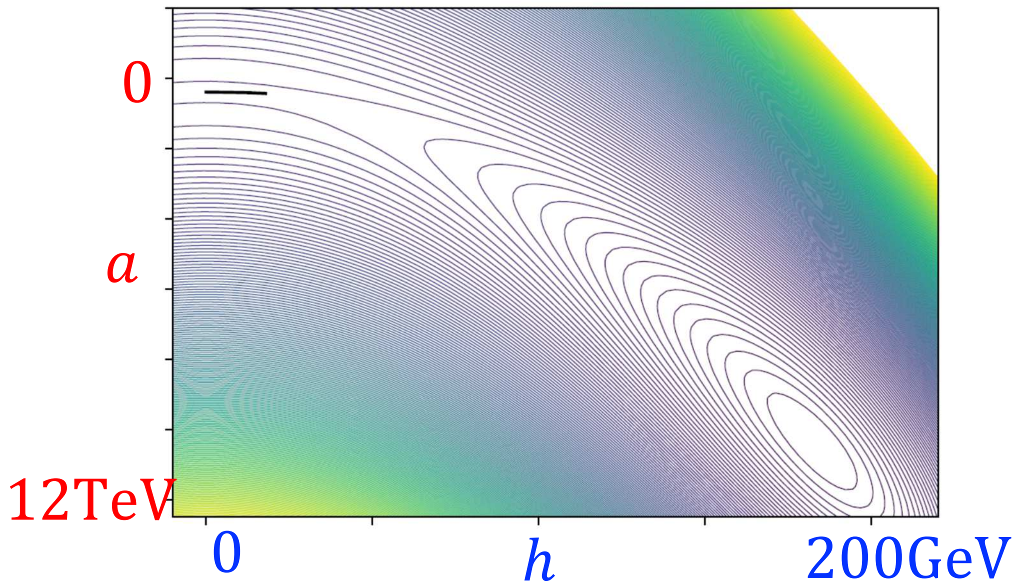
f determines the bubble wall width

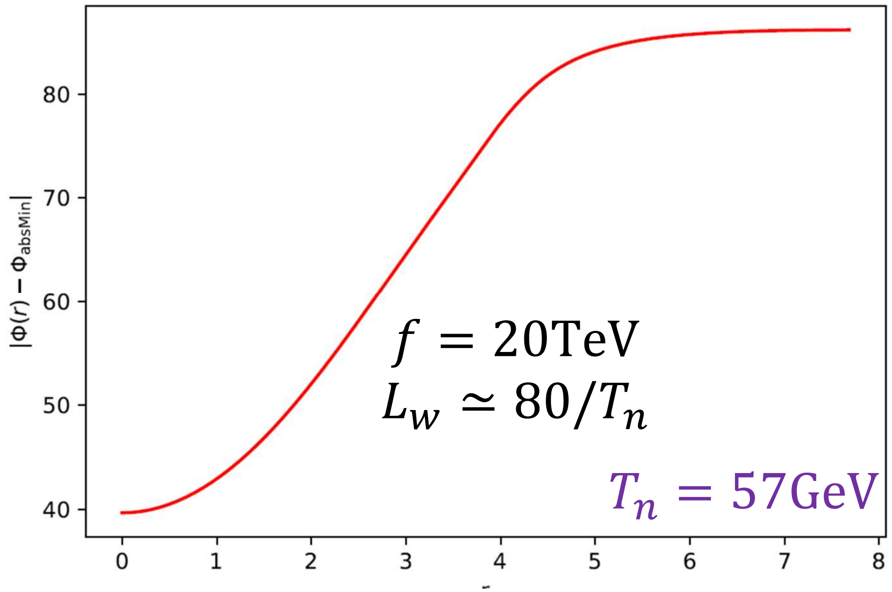
For large $f \gg m_W$, $\quad L_W \sim \dfrac{f}{m_W^2} \sim \dfrac{1}{T_n}\left(\dfrac{f}{m_W}\right)$

$f \lesssim O(10-100)$ TeV : *non-local gen.*
$f \gtrsim O(10-100)$ TeV : *local gen.*









CP violation

CP violating source (which depends on the bubble wall profile) from

$$\mathcal{L}_{CPV} \ni \frac{a}{f} O_{SM}(x)$$

During phase transition ($\Delta h \sim O(m_W)$), $\Delta\theta = \Delta a/f \sim O(1)$ even for a very large f

: <u>Enhancing CPV effects</u>

Examples:

1) *Dynamical top Yukawa coupling [1806.02591]*

$$Y_t(\theta)h\, t_L t_R + h.c., \qquad \text{where} \quad Y_t(\theta) = \left(y_t + x_t e^{i\theta}\right)$$

2) *Dynamical electroweak theta-term [1811.03294] ($\mu_B \propto \dot{\theta}$)*

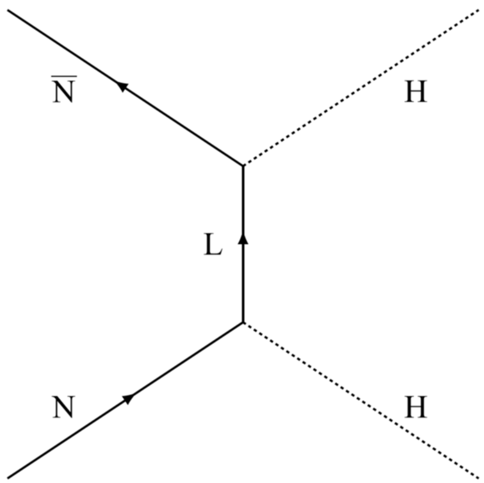
$$\frac{g_2^2\, \Theta(\theta)}{16\pi^2} \mathrm{Tr}\left[W_{\mu\nu}\, \widetilde{W}^{\mu\nu}\right], \qquad \text{where} \quad \Theta(\theta) = \theta$$

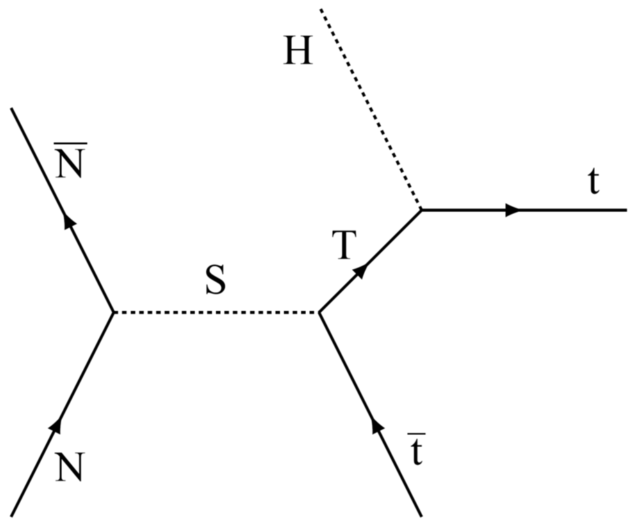
$$\boxed{\left(\partial_\mu J_B^\mu\right) = \frac{N_f}{8\pi^2}\left(W_{\mu\nu}\widetilde{W}^{\mu\nu} - B_{\mu\nu}\tilde{B}^{\mu\nu}\right)}$$

An UV example (1)

$$\left(y_t + x_t e^{i\theta}\right) h\, t_L t_R + h.c.$$

As a UV model, we can propose that the PQ symmetry is anomalously broken by hidden sector confining gauge symmetry.





$$\mathcal{L}_{eff}^{(1)} = -m_N\, N\overline{N} + \frac{yy'}{m_L} N\overline{N}\ |H|^2 + \frac{\kappa\, N\overline{N}}{m_S^2 m_T} H Q_L t_R + h.c.$$

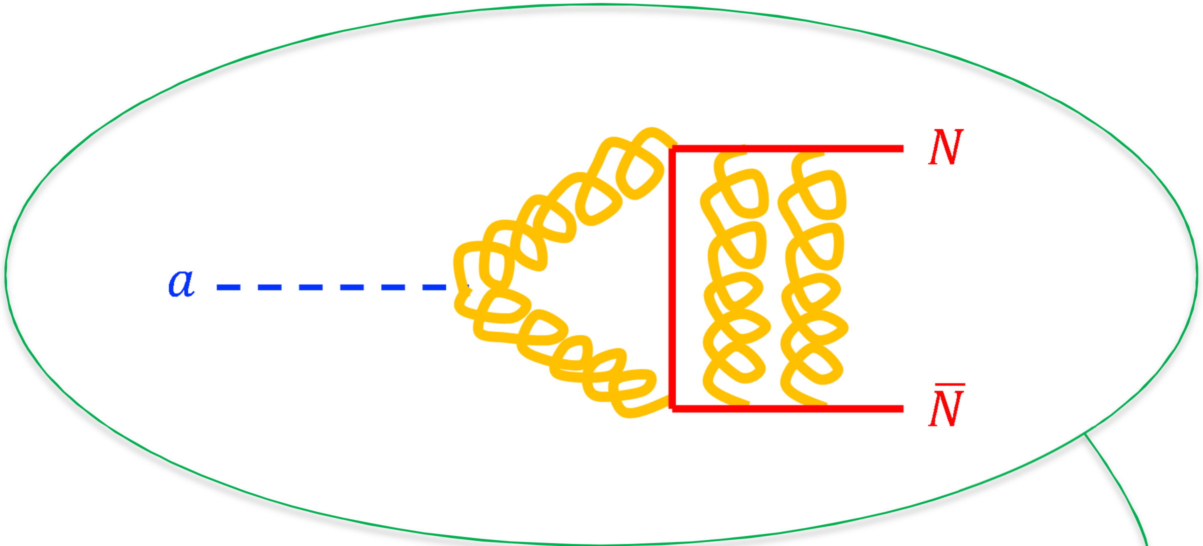
$N + \overline{N}$ *hidden quarks, condensate:* $\langle N\overline{N}\rangle = \Lambda_h^3\, e^{i\, a(x)/f}$ *from axion-hidden meson mixing*

$$\mathcal{L}_{eff}^{(2)} = -m_N \Lambda_h^3 \cos\theta + \frac{yy'\Lambda_h^3}{m_L} \cos(\theta + \alpha)\ |H|^2 + \frac{\kappa\, \Lambda_h^3}{m_S^2 m_T} e^{i(\theta+\beta)} H Q_L t_R + h.c.$$

An UV example (2)

$$(y_t + x_t e^{i\theta}) h\, t_L t_R + h.c.$$

As a UV model, we can propose that the PQ symmetry is anomalously broken by hidden sector confining gauge symmetry.



$$\mathcal{L}_{eff}^{(1)} = -m_N\, N\bar{N} + \frac{yy'}{m_L} N\bar{N}\, |H|^2 + \frac{\kappa\, N\bar{N}}{m_S^2 m_T} H Q_L t_R + h.c.$$

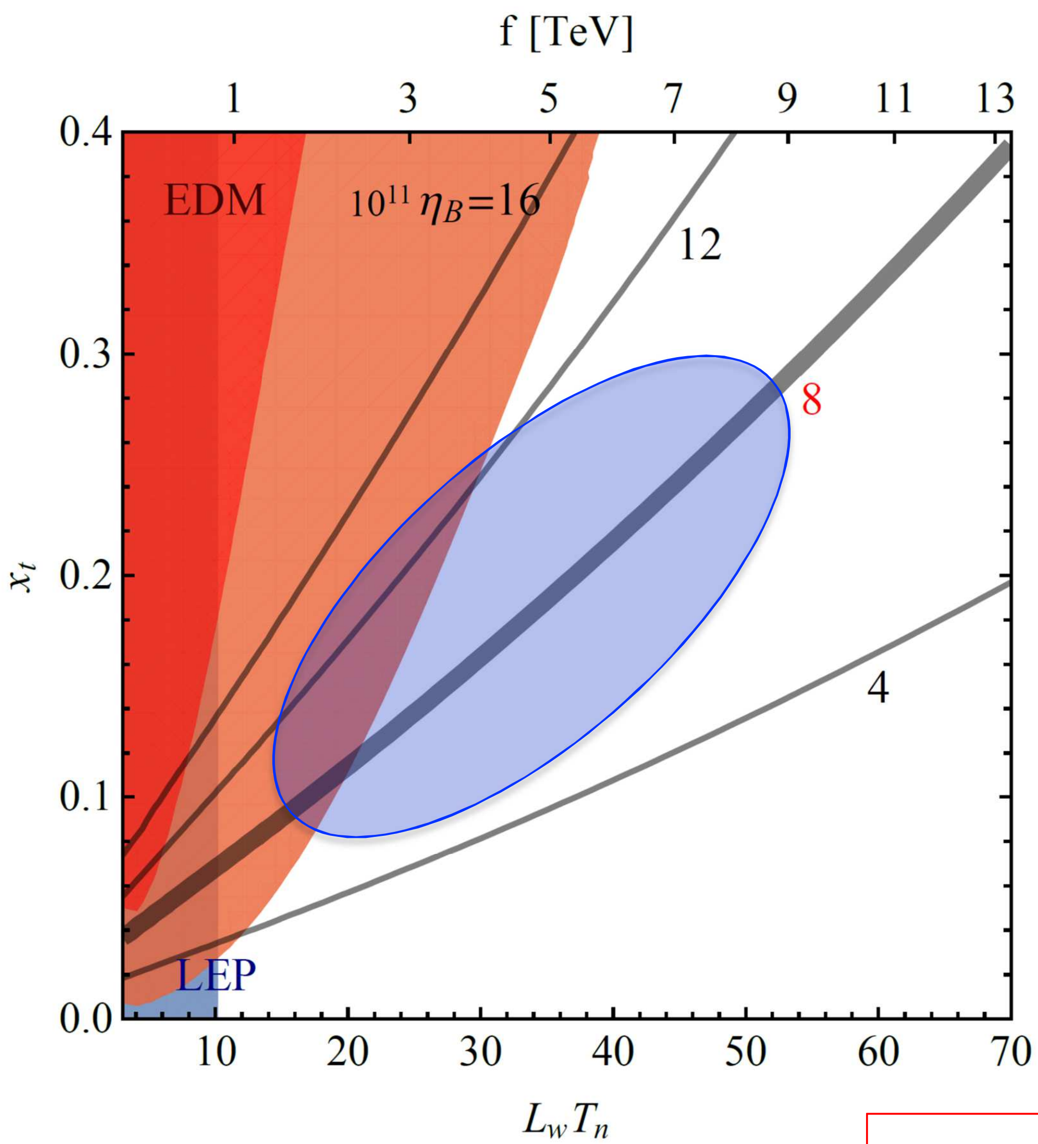
$N + \bar{N}$ *hidden quarks, condensate:* $\langle N\bar{N} \rangle = \Lambda_h^3\, e^{i\, a(x)/f}$ *from axion-hidden meson mixing*

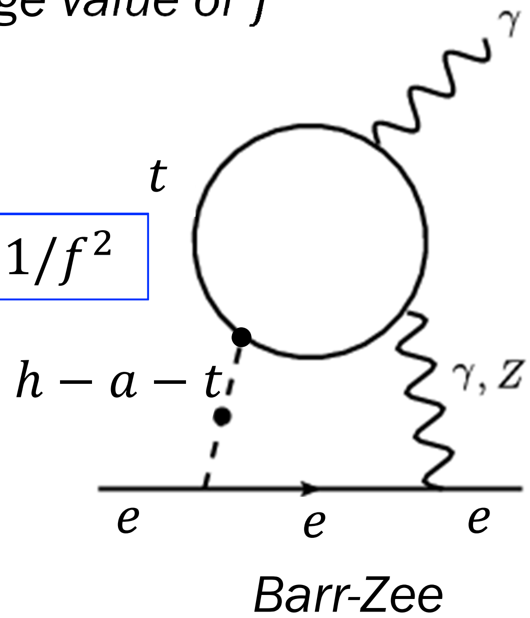
$$\mathcal{L}_{eff}^{(2)} = -m_N \Lambda_h^3 \cos\theta + \frac{yy'\Lambda_h^3}{m_L} \cos(\theta + \alpha)\, |H|^2 + \frac{\kappa\, \Lambda_h^3}{m_S^2 m_T} e^{i(\theta+\beta)} H Q_L t_R + h.c.$$

Results

For $f \sim O(1-10)$ TeV $(y_t + x_t e^{i\theta}) h\, t_L t_R$

EDM and collider constraints are easily evaded for a sufficiently large value of f





EDM $\propto 1/f^2$

$$\mathcal{L}_{eff} = -\frac{\mu_0^4}{2}\frac{(\delta a)^2}{f^2} + \mu_1^3 \frac{\delta a}{f}\delta h + \mu_2^3 \frac{(\delta a)^2}{f^2}\delta h + i\frac{\delta a}{f} x_t m_t \bar{t}\gamma_5 t + h.c.$$

New! $|d_e| < 1.1\times 10^{-29}$ cm $\cdot\, e$ at 90% C.L

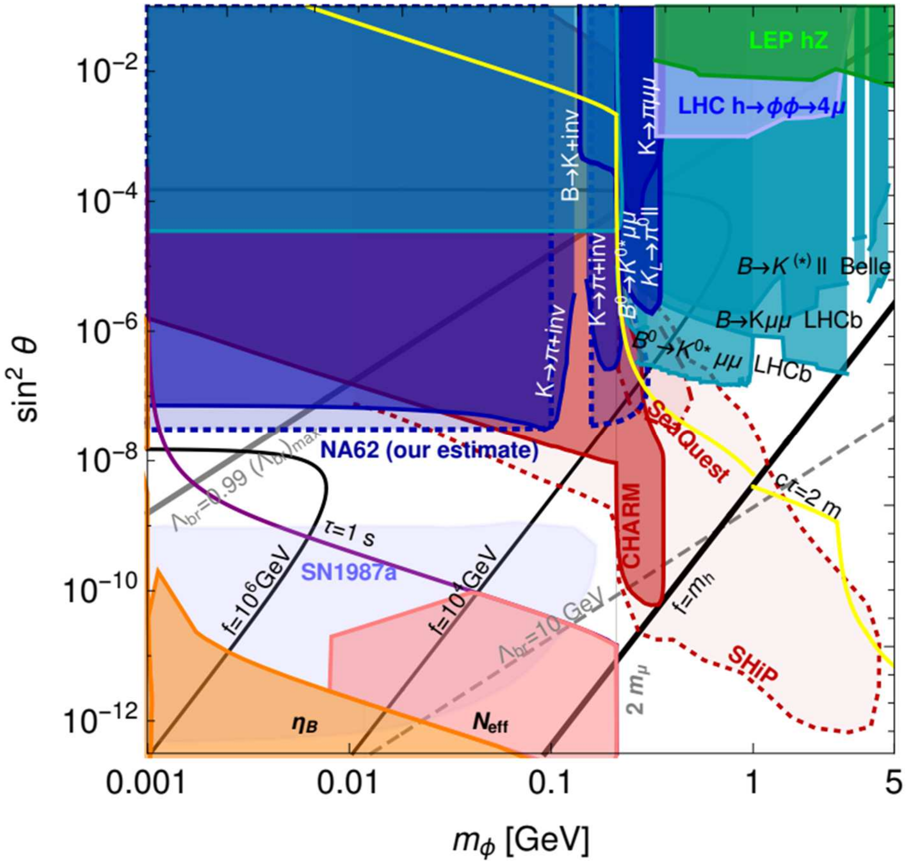
$$\boxed{m_a \sim m_w\left(\frac{m_w}{f}\right) \rightarrow\ m_a \sim O(0.1-10)\ \text{GeV}}$$

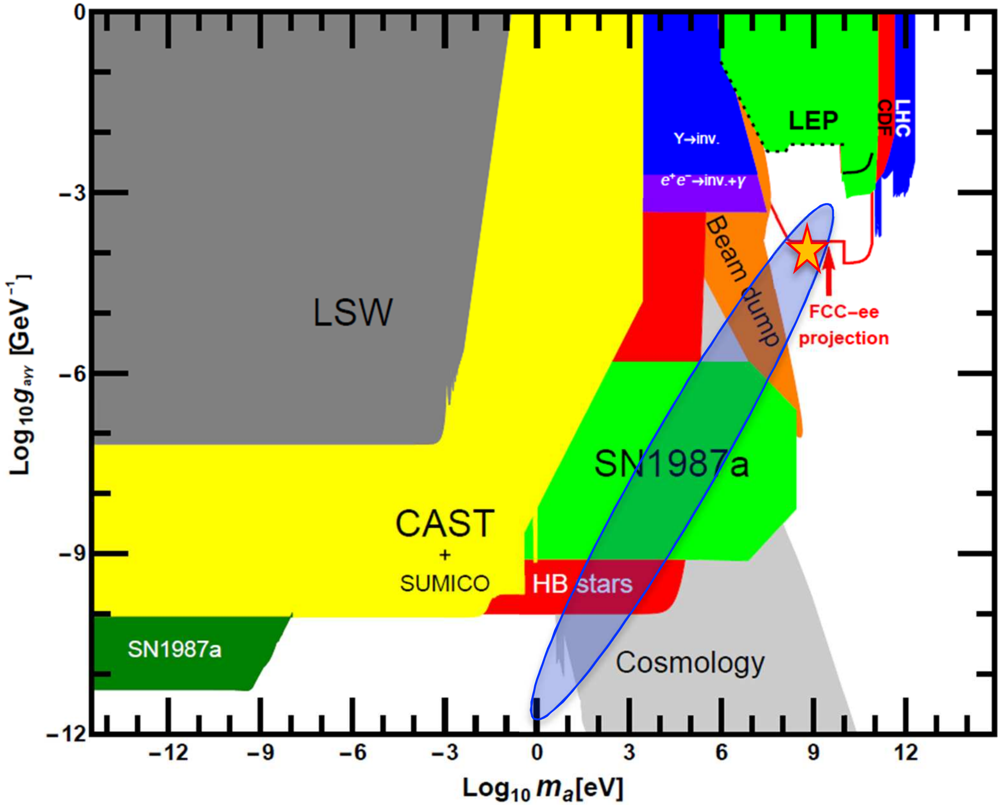
ALP searches

After integrating out top and Higgs, ALP couplings to <gluon, photon, light quark and lepton> are generated. Model dependent (axion decay channels) constraints are applied

$$\mathcal{L}_{eff} = \frac{1}{16\pi^2}\frac{(\delta a)}{f}\left(c_1 G_{\mu\nu}\tilde{G}^{\mu\nu} + c_2 F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots\right) + \frac{\delta a}{f}\delta_{\mathrm{mix}} m_q \bar{q} q + \frac{\delta a}{f}\delta_{\mathrm{mix}} m_\ell \bar{\ell}\ell$$

Axion with mass around $(5-10)\mathrm{GeV}$ *is model independently safe.*





[Flacke, Frugiuele, Fuchs, Gupta, Perez 16]
[Choi, Im 16]

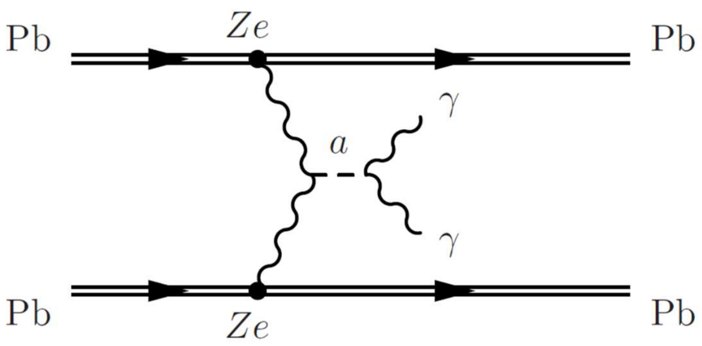
[Jaeckel, Spannowsky 15]

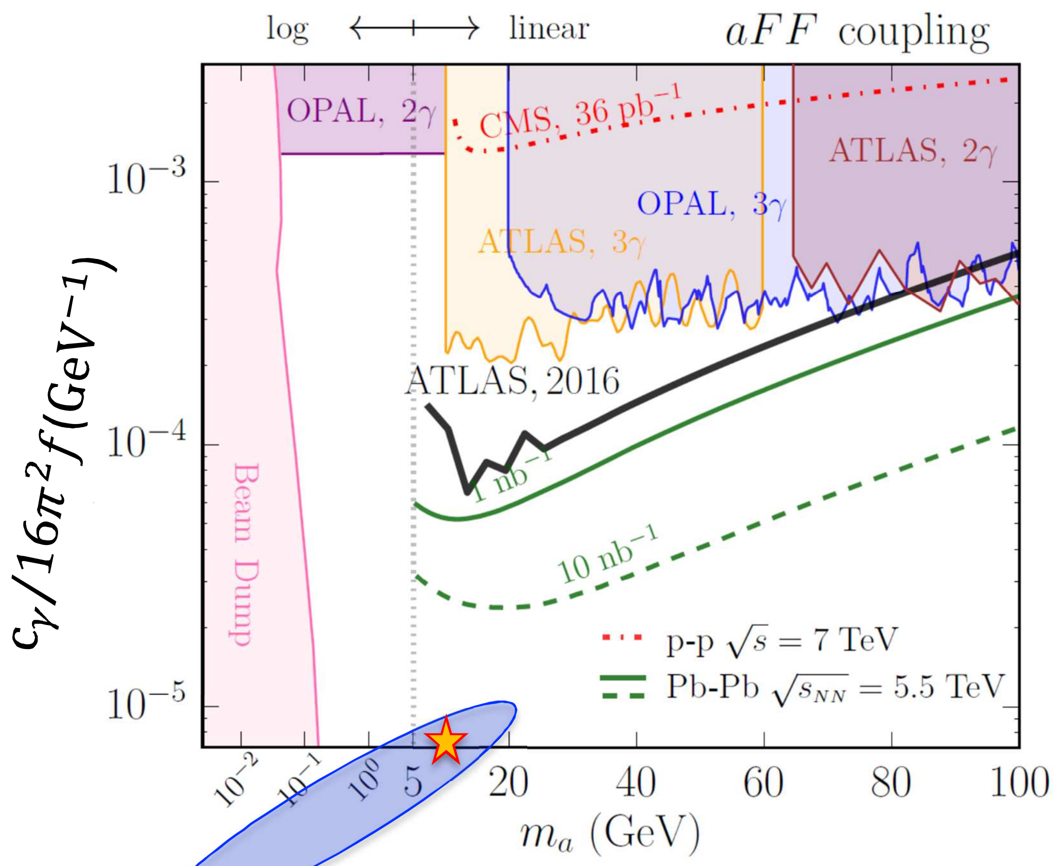
ALP searches

After integrating out top and Higgs, ALP couplings to <gluon, photon, light quark and lepton> are generated. Model dependent (axion decay channels) constraints are applied

$$\mathcal{L}_{eff} = \frac{1}{16\pi^2}\frac{(\delta a)}{f}\left(c_g G_{\mu\nu}\tilde{G}^{\mu\nu} + c_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots\right) + \frac{\delta a}{f}\delta_{\text{mix}} m_q \bar{q} q + \frac{\delta a}{f}\delta_{\text{mix}} m_\ell \bar{\ell}\ell$$

Axion with mass around $(5-10)\mathrm{GeV}$ *is model independently safe.*





[Knapen, Lin, Lou, Melia 17]

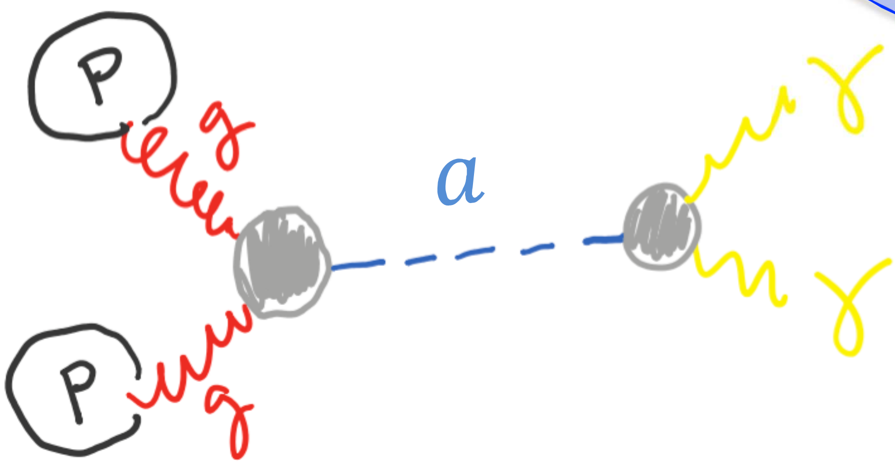
ALP searches

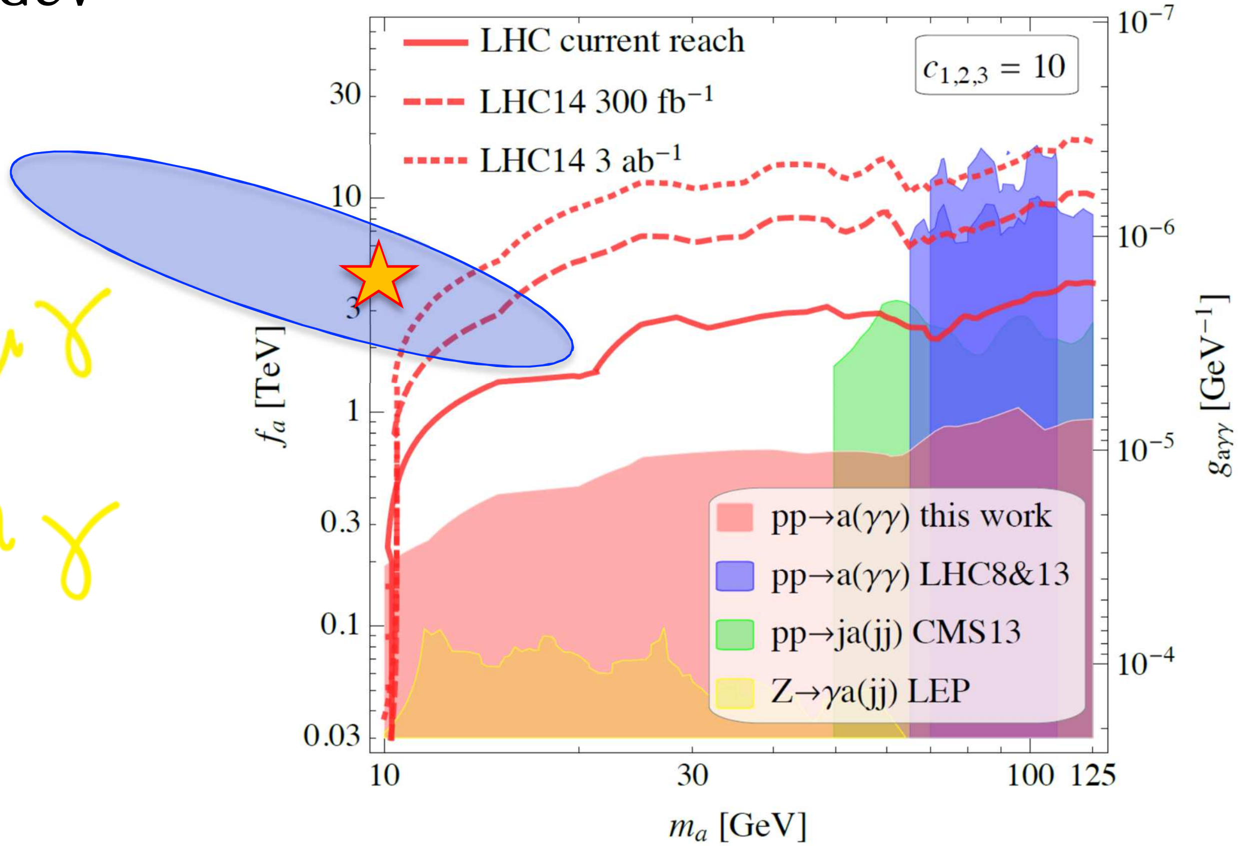
After integrating out top and Higgs, ALP couplings to <gluon, photon, light quark and lepton> are generated. Model dependent (axion decay channels) constraints are applied

$$\mathcal{L}_{eff} = \frac{1}{16\pi^2}\frac{(\delta a)}{f}\left(c_1 G_{\mu\nu}\tilde{G}^{\mu\nu} + c_2 F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots\right) + \frac{\delta a}{f}\delta_{\rm mix} m_q \bar{q} q + \frac{\delta a}{f}\delta_{\rm mix} m_\ell \bar{\ell}\ell$$

Axion with mass around $(5-10)\mathrm{GeV}$ *is model independently safe.*

Interesting hints for $m_a \sim 10 - 20\ \mathrm{GeV}$

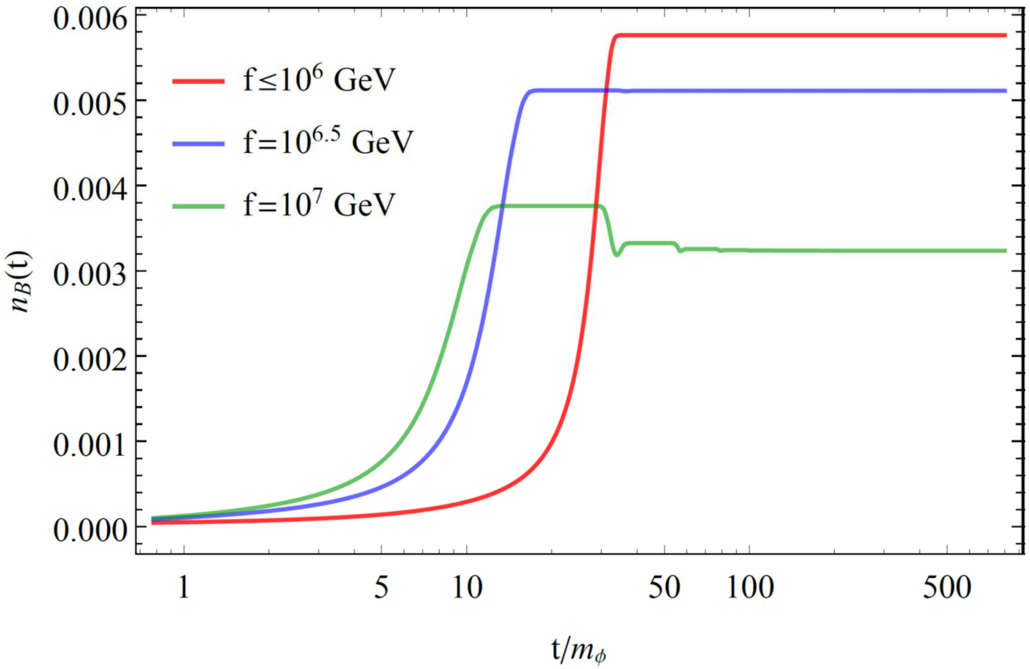


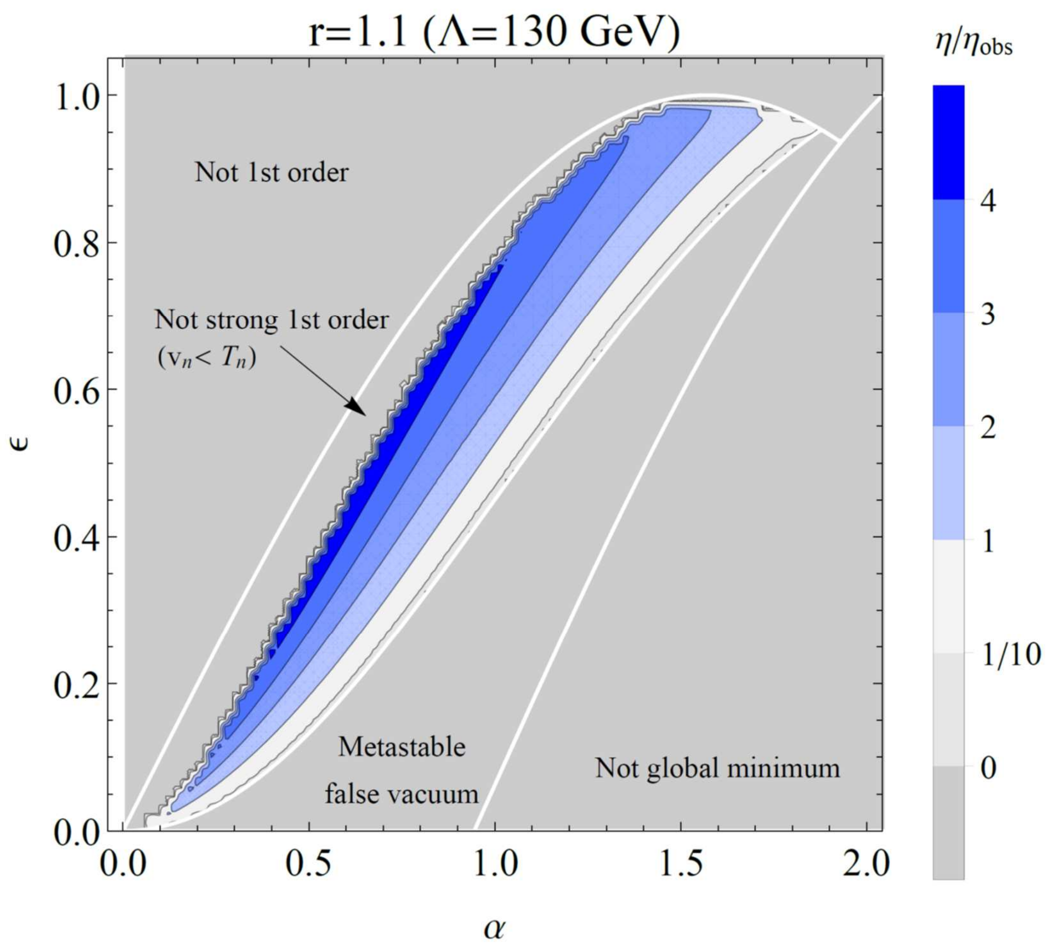


[Mariotti, Redigolo, Sala, Tobioka 17]

For $f > O(10 - 100)$ TeV $\frac{g_2^2\,\theta}{16\pi^2}\,\mathrm{Tr}[W_{\mu\nu}\,\widetilde{W}^{\mu\nu}]$

Baryon asymmetry is nearly independent of f for $f < O(10^7\ \mathrm{GeV})$



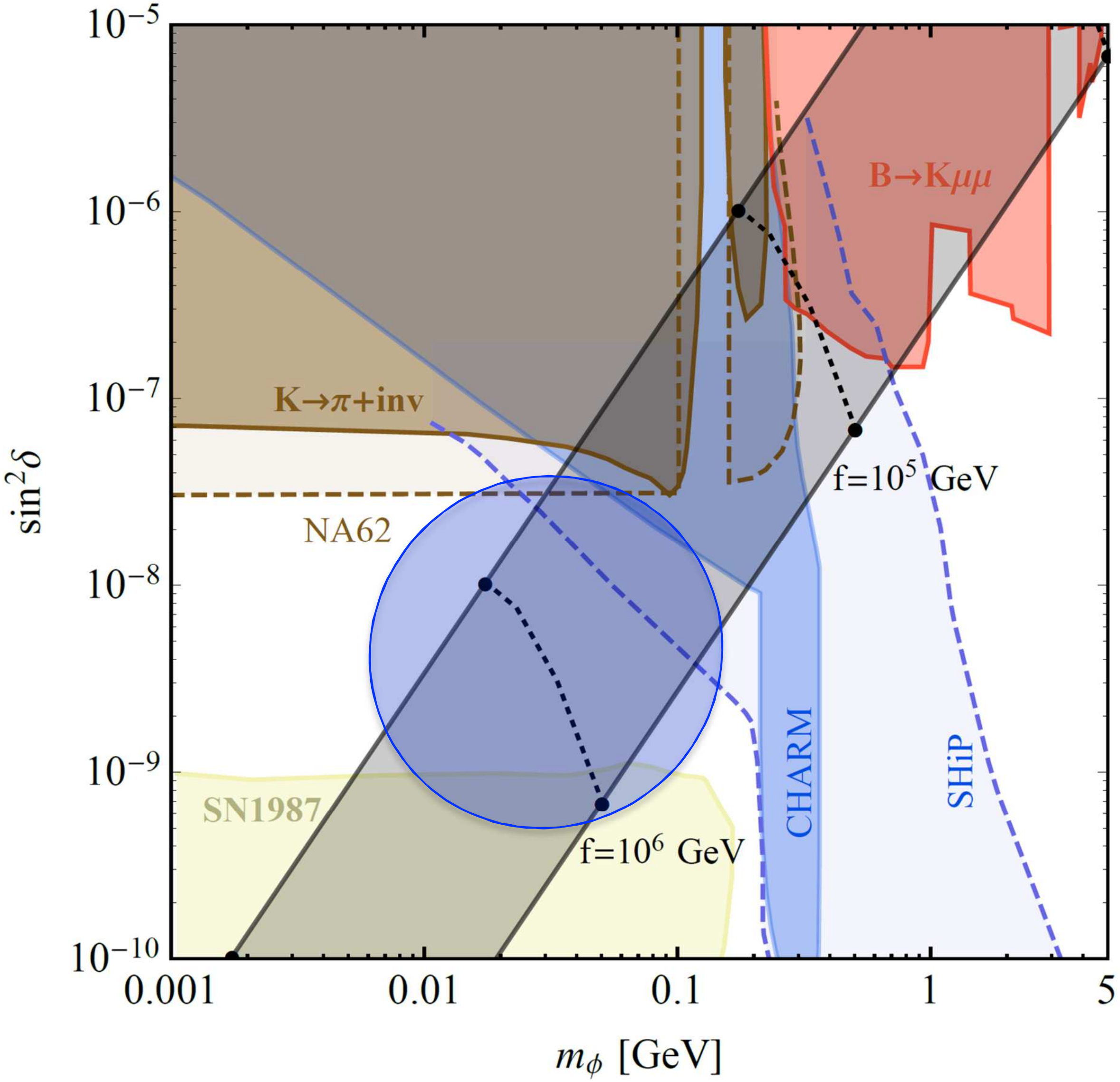


Totally safe from EDM and LHC constraints!

ALP searches

There is the interesting allowed window for $f \sim 10^6 - 10^7$ GeV *(*$m_a \sim 5 - 100$ MeV*)*

$\delta =$ *axion-Higgs mixing* $\propto 1/f$



Conclusions

- *Axionic extension of the Higgs potential gives new parameter spaces for singlet extensions of EWBG: weakly coupled, controllable higher dimensional operators.*

- *EWPT and its cosmological evolution show different features compared to usual EWBS models: We can get stronger first order phase transition to compensate large bubble wall effects.*

- *Non-local and local baryogenesis can be realized depending on the axion decay constant.*

- *Interesting mass ranges of the ALP mass between 5-20 GeV and 5-100MeV are motivated by EWBG for the target of future ALP searches.*