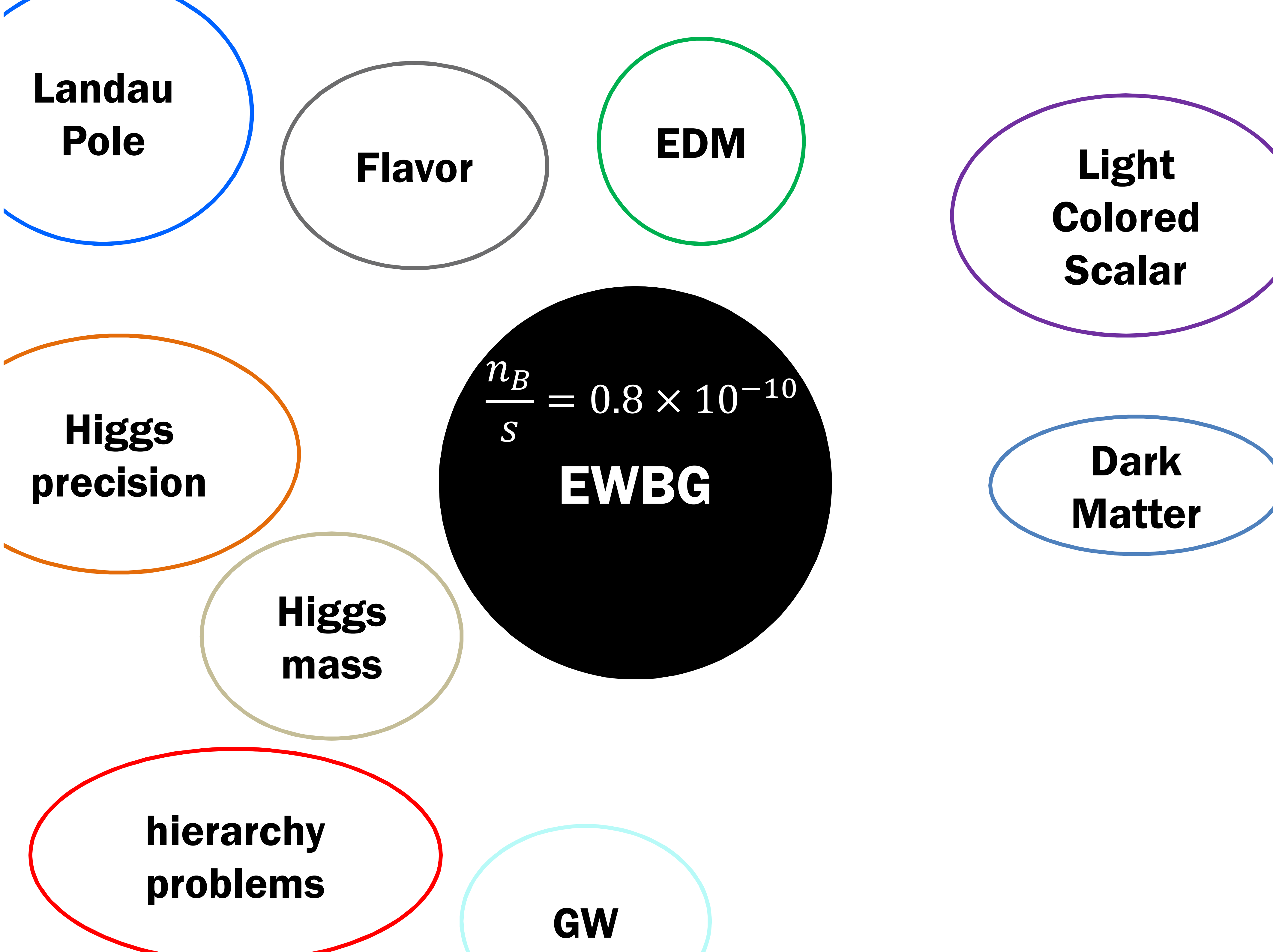
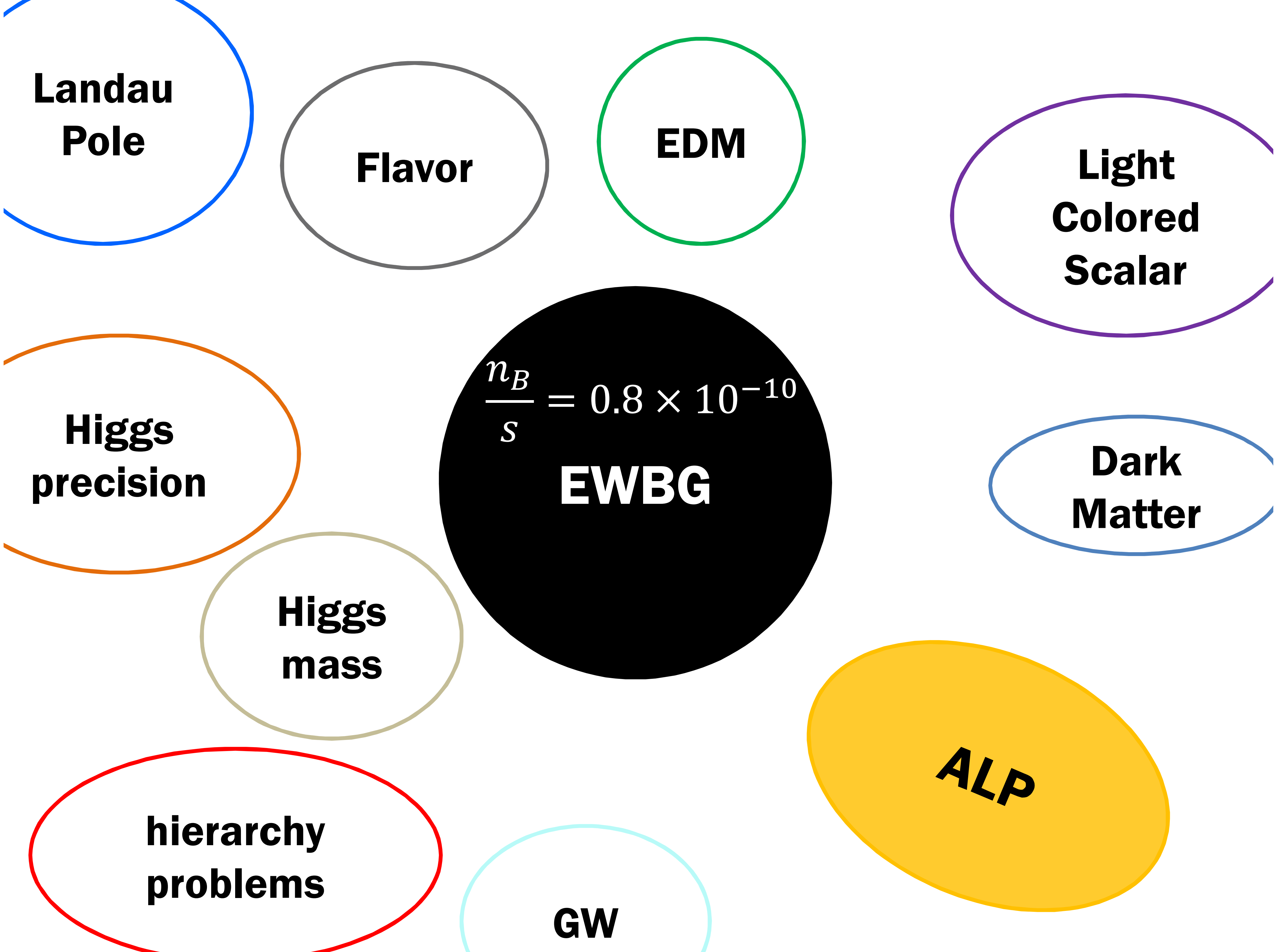
Axionic Electroweak Baryogenesis

Chang Sub Shin (IBS-CTPU)

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

At Corfu Summer Institute
Sep 6, 2018


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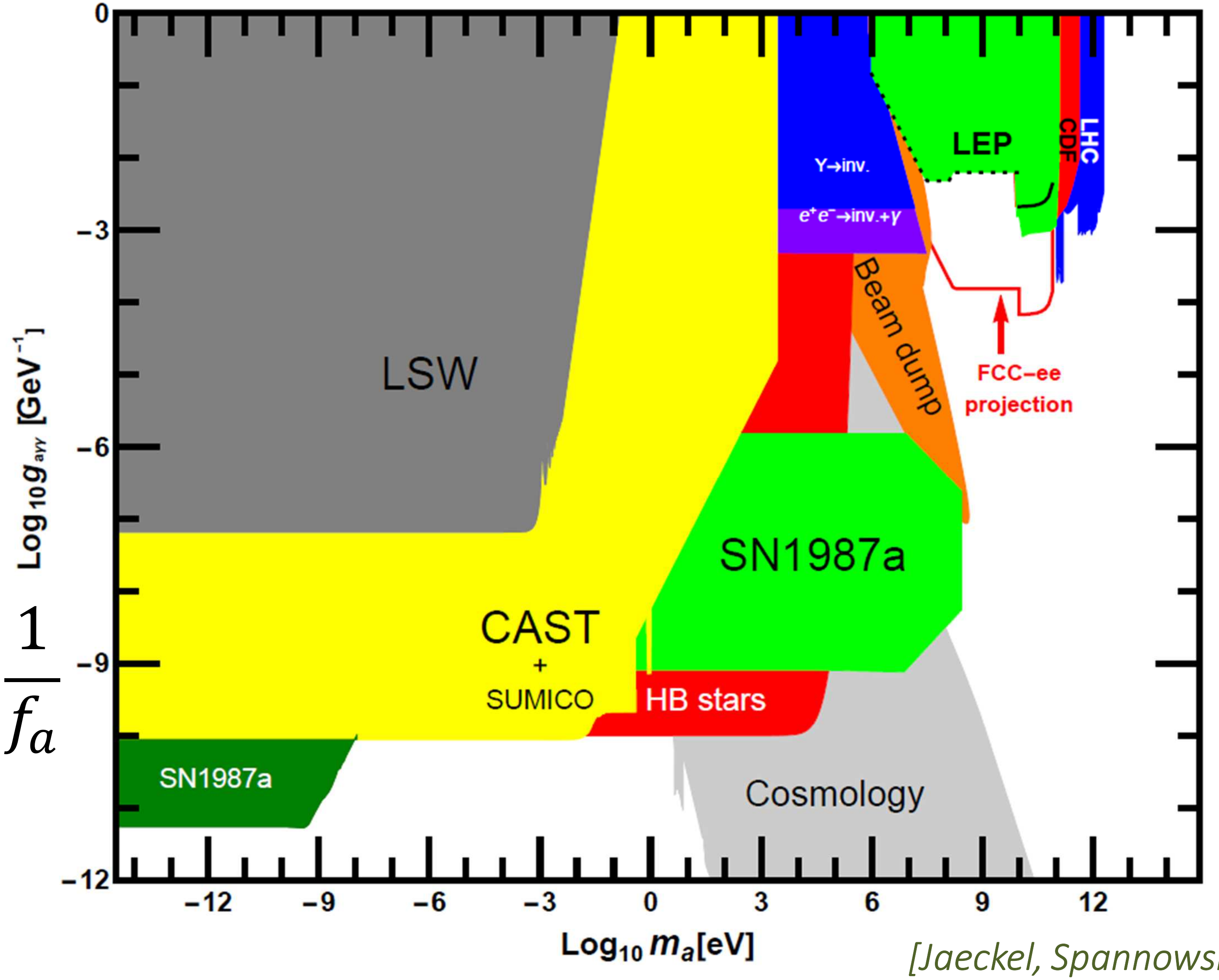
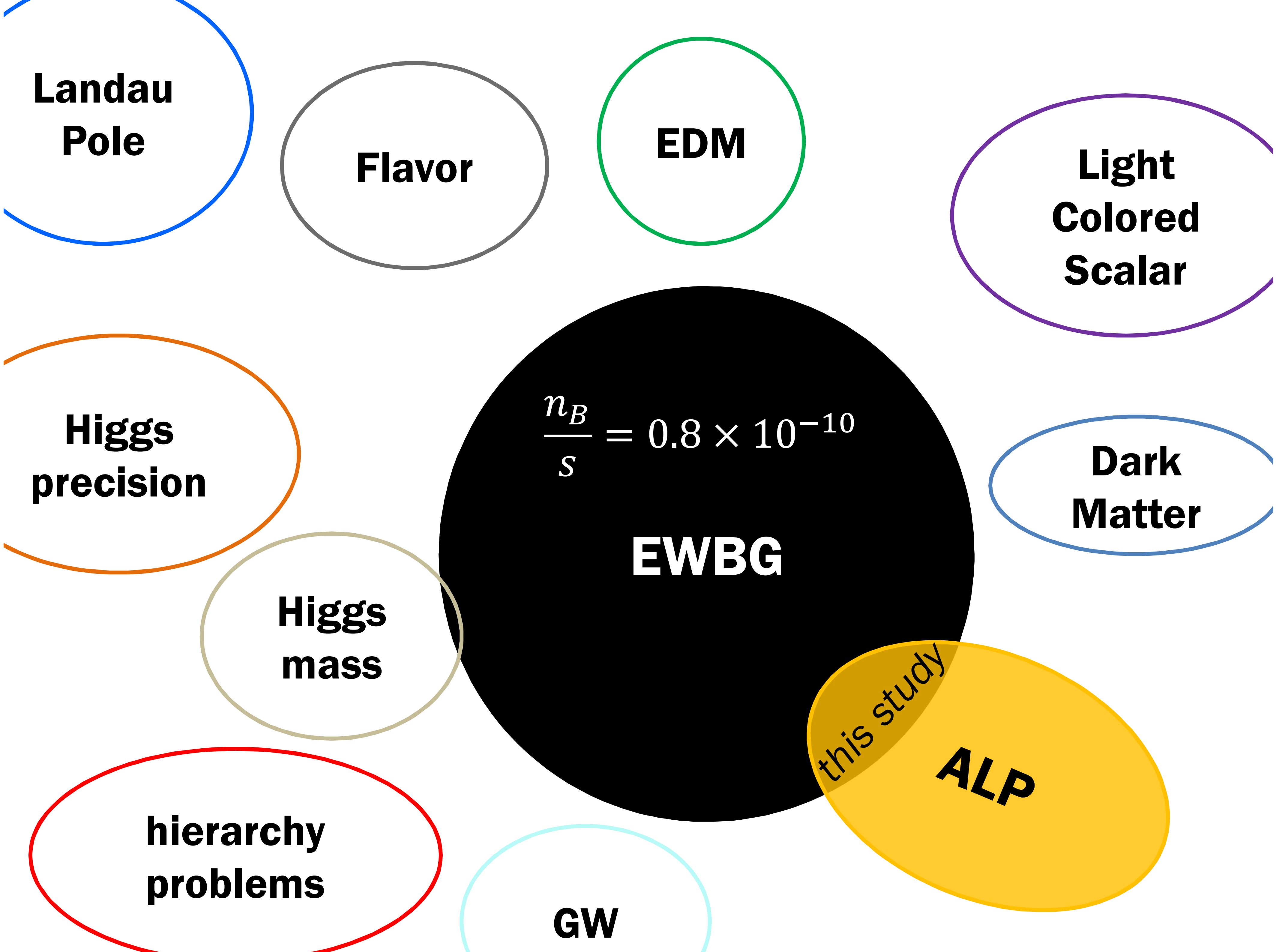


$$g_{a\gamma\gamma} = \frac{1}{f_a}$$

[Jaeckel, Spannowsky 15]

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

Idea of Electroweak Baryogenesis

- Basic ideas

- Extensions beyond the SM

Axionic Electroweak Baryogenesis

- First order phase transition with weak couplings

- Bubble wall profile

Results

- Benchmark points and features

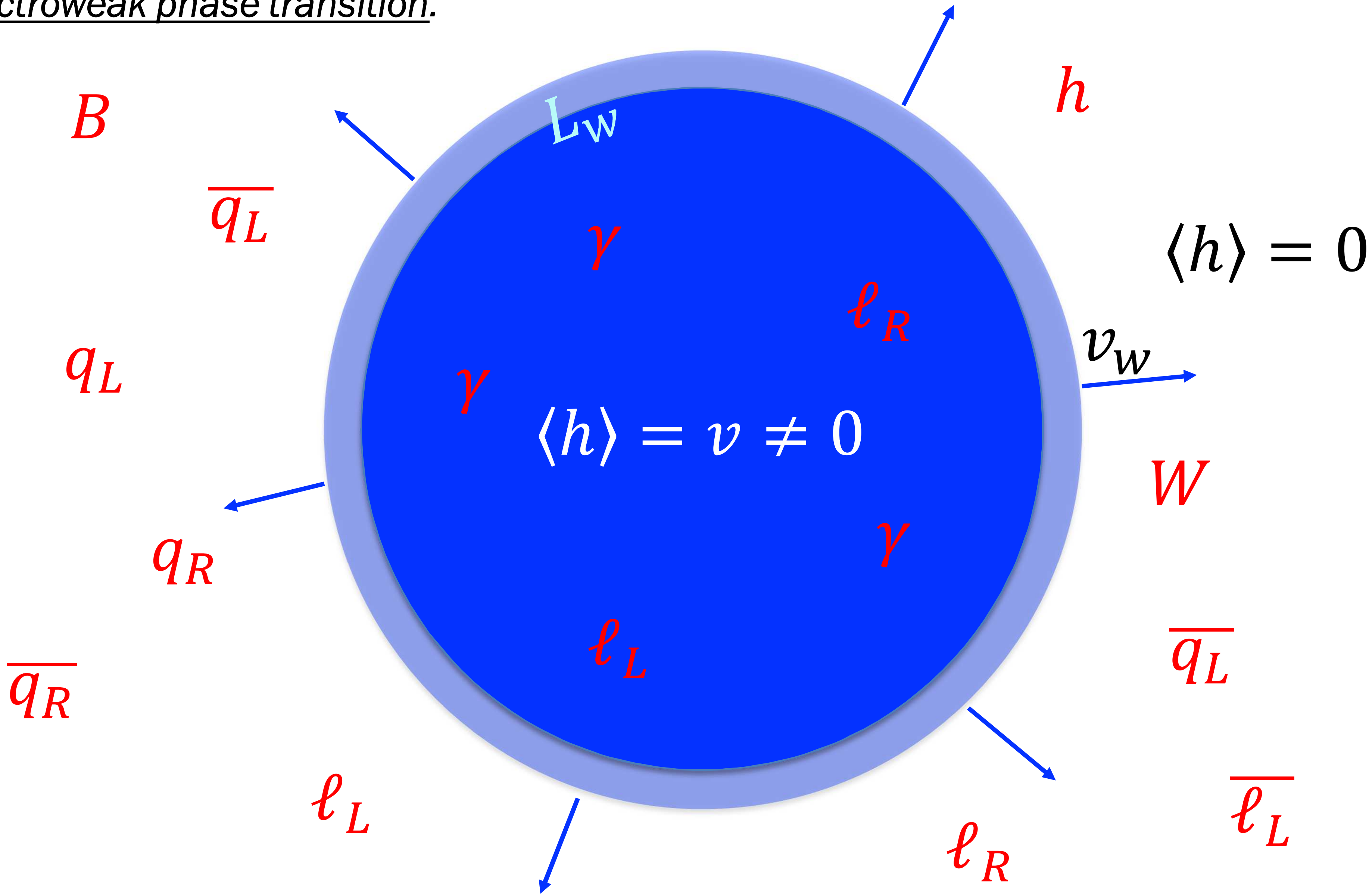
- Constraints and predictions

Conclusions

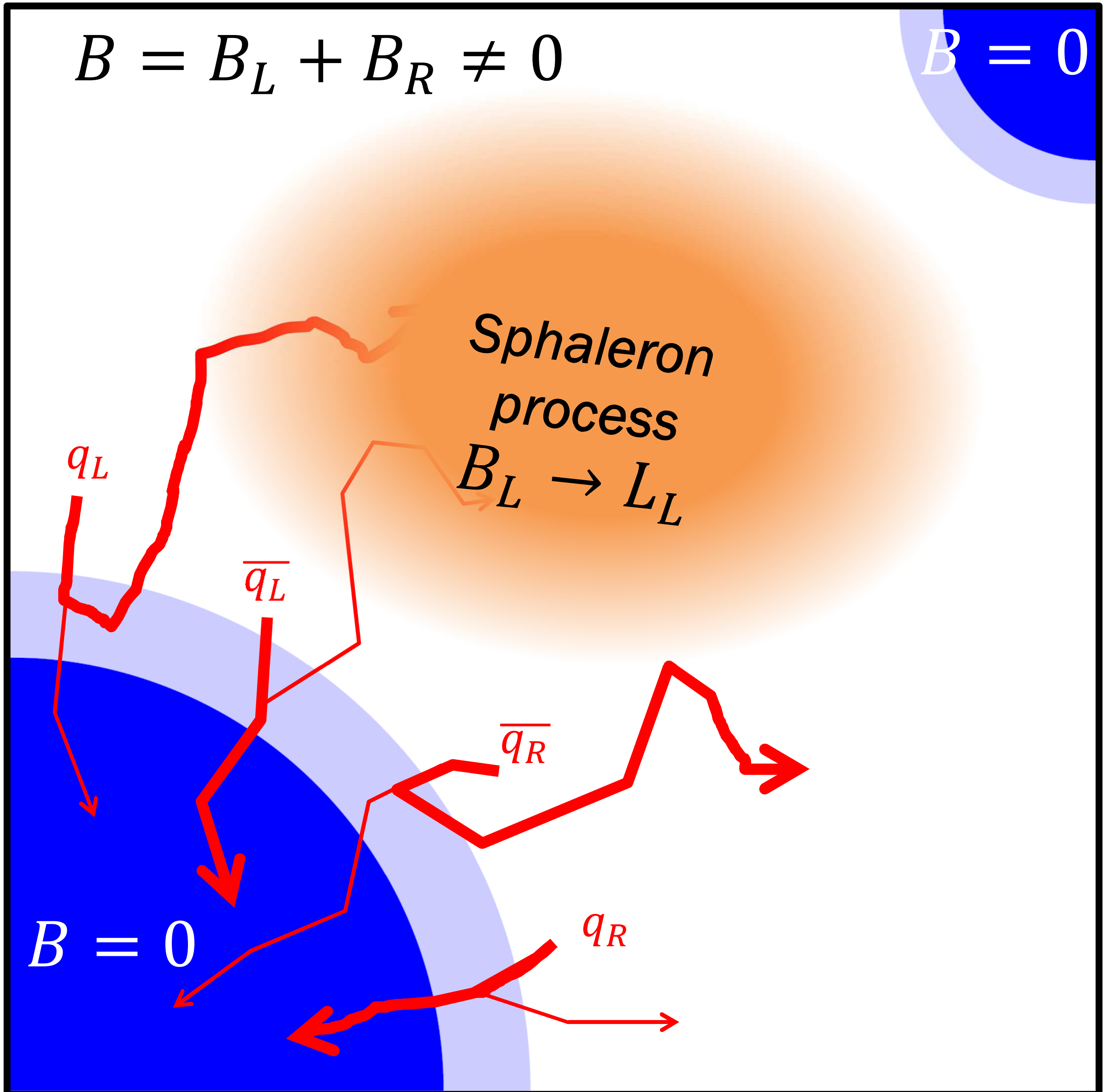
Idea of EWBG

Electroweak baryogenesis

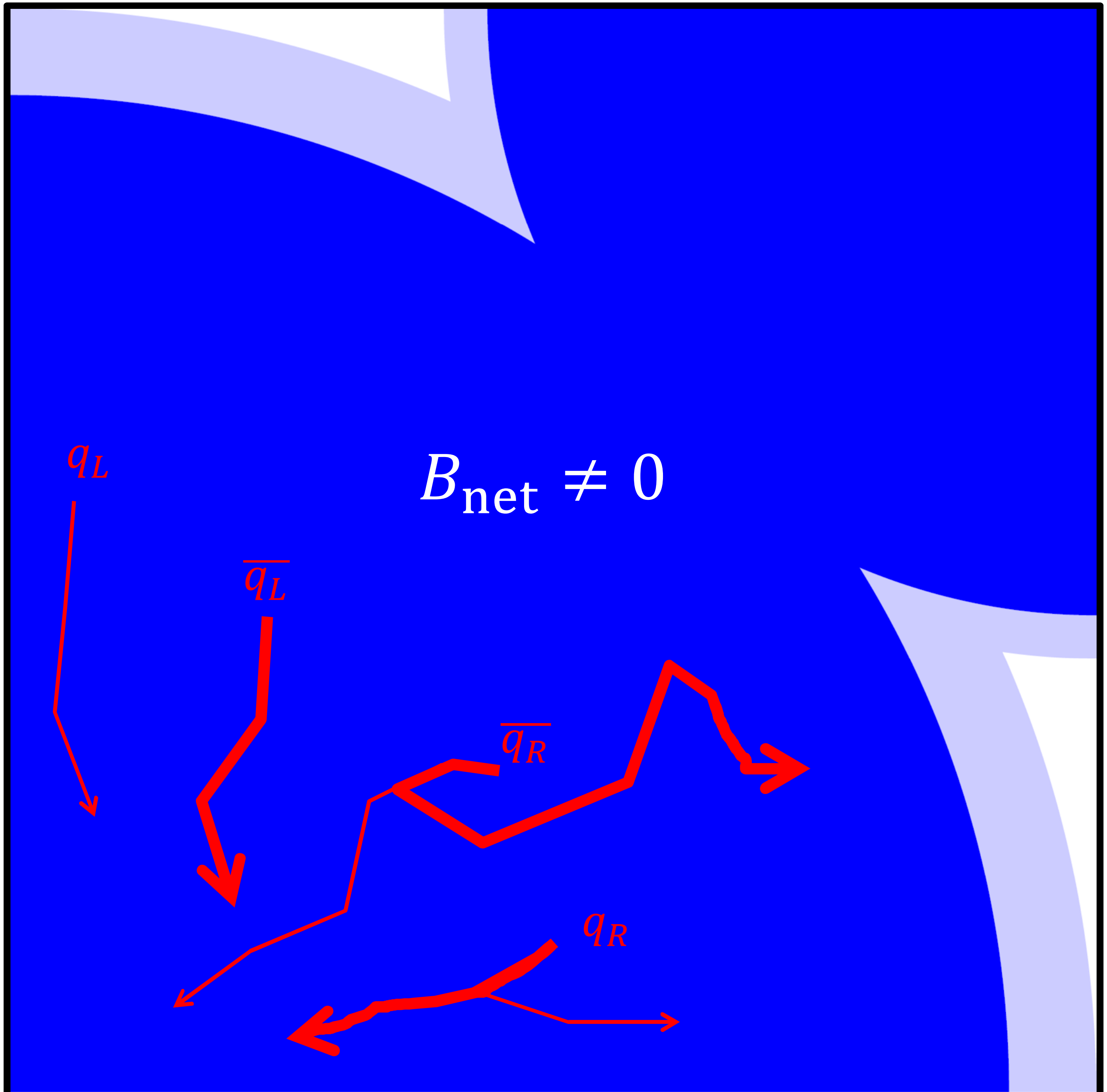
Baryon asymmetry of the Universe should be answered by physics beyond the SM. However, the Higgs still can play an important role to trigger <u>electroweak baryogenesis by first order electroweak phase transition</u>.



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
$B = 0$

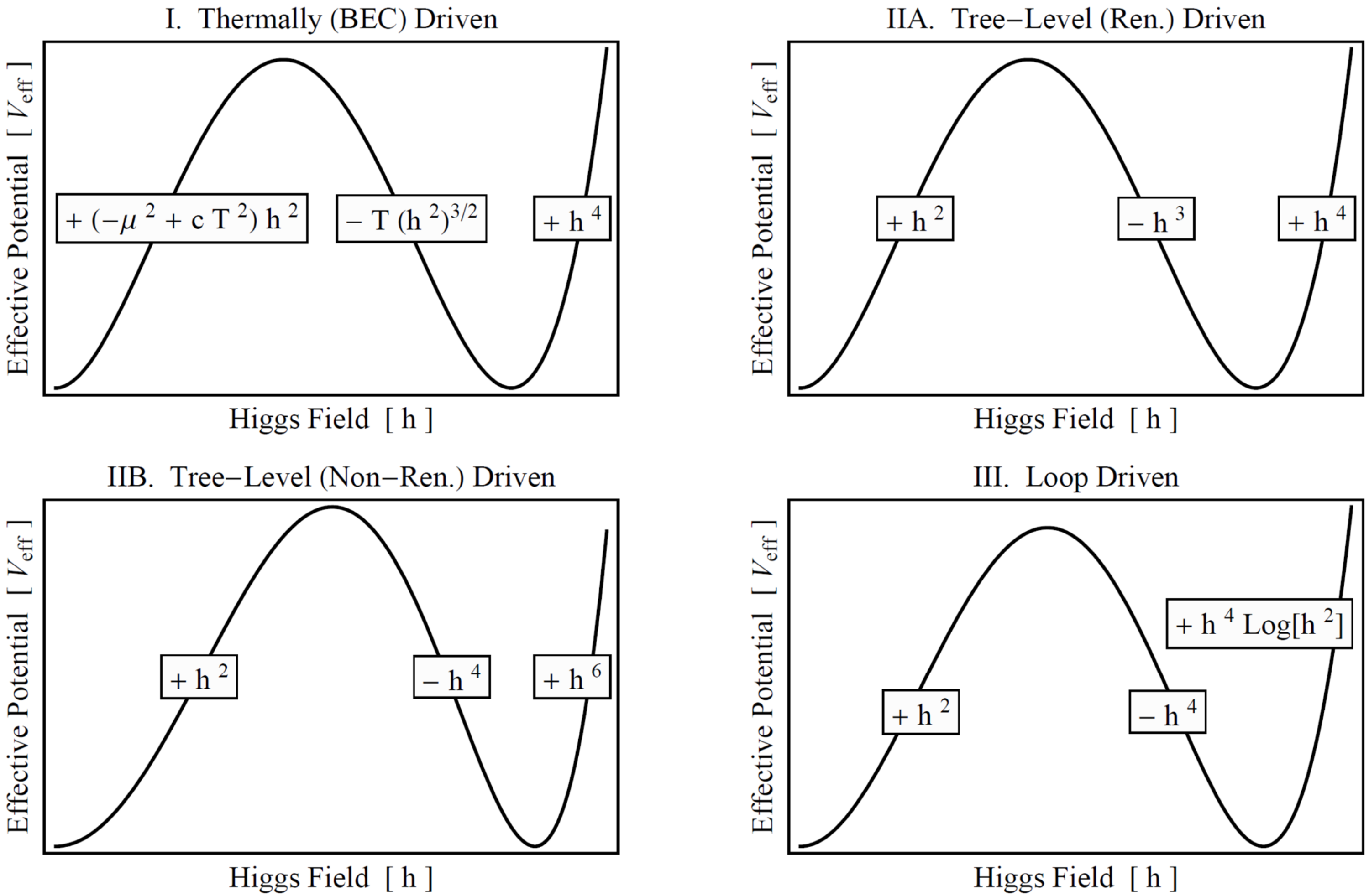
EWBG 2 (2)



Extension for first order phase transition

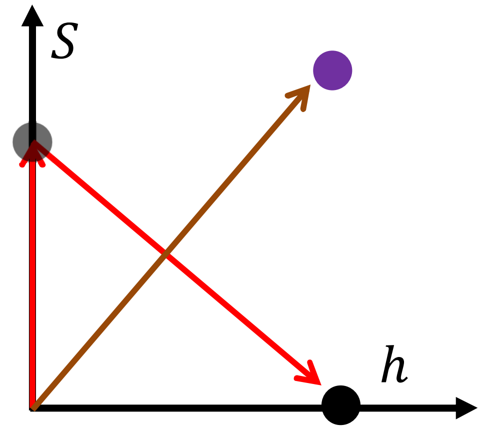
Most of extensions beyond the SM focuses on realizing strong 1st order EWPT

(single field description)



[Chung, Long, Wang 12]

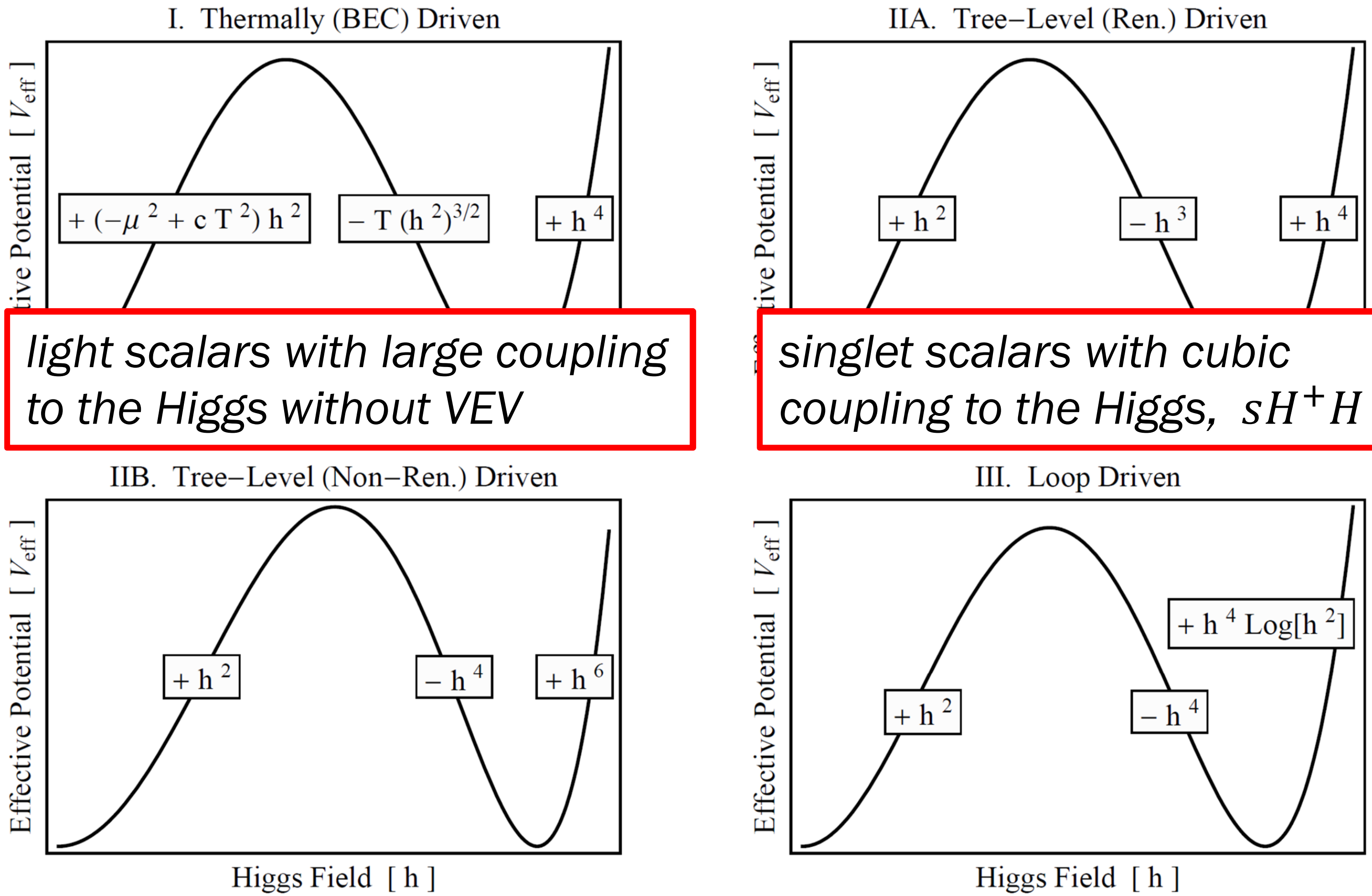
(multi field description)



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)*



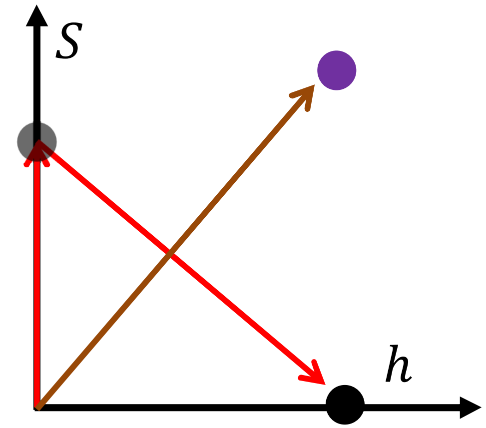
light scalars with large coupling to the Higgs without VEV

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

[Chung, Long, Wang 12]

Strong dynamics to give a low cutoff

(charged) light fermions with large couplings to the Higgs



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

A singlet extension to satisfy…

$$V(H,s) = a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4$$
$$+\mu^2 |H|^2 + \lambda |H|^4 + b_1 s\, |H|^2 + b_2 s^2 |H|^2$$

Realization of weakly coupled singlet extension to prevent a large Higgs-singlet mixing.

Scalar potential is naturally bounded from below : well organizing principle to introduce higher dimensional operators for the singlet along the runaway direction of $V(H,s)$,

$$\Delta V(H,s) = c_1 s^3 |H|^2 + c_2 s^5 + \cdots$$

Suggestion:

$$\boxed{\textit{Axionic (ALP) extension}}$$

1) *Axion is the compact field: for a positive Higgs quartic, it is bounded from below*
2) *Axion interaction is suppressed by its decay constant, $f \gg m_W$, so a small Higgs-axion mixing can be realized*
3) *How about its effect on baryogenesis?*

Axionic EWBG

[Jeong, Jung, CSS 18]

Axionic extension of the Higgs potential

A scalar potential is constructed by the Higgs and the axion field $a(x) = f\theta(x)$ *with a* $2\pi f$ *periodicity:*

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

As an simple example with $\mu_1 \sim \mu_2 \sim \Lambda \sim m_W$ *(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*,*

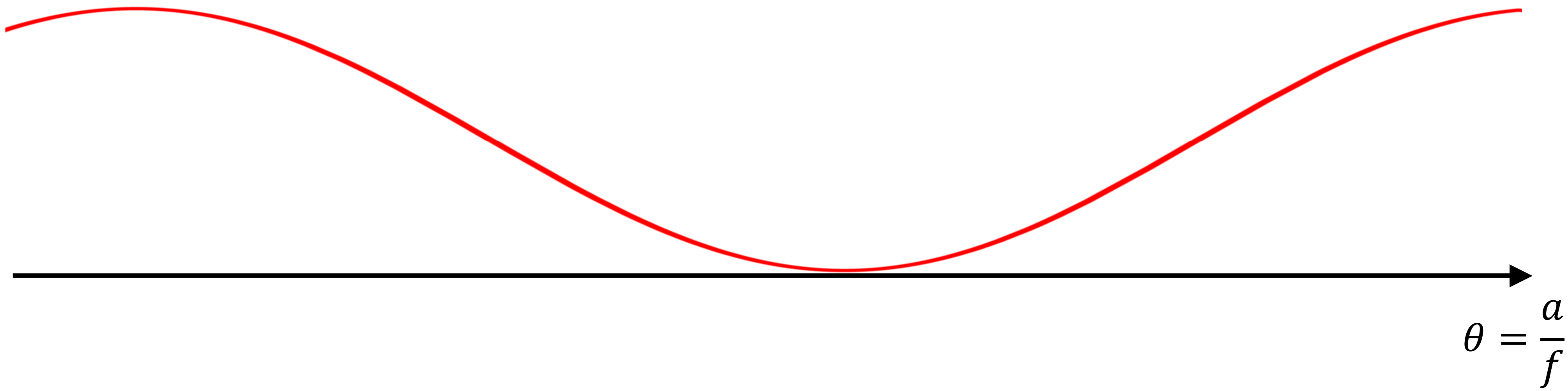
$$V(h,a) = \frac{1}{2}\left(\mu^2 + c_1\frac{\mu^2}{f}a + c_2\frac{\mu^2}{f^2}a^2 + c_3\frac{\mu^2}{f^3}a^3 + \cdots\right)h^2 + \frac{\lambda}{4}h^4$$
$$+\frac{\Lambda^4}{2f^2}a^2 - \frac{\Lambda^4}{24f^4}a^4 + \frac{\Lambda^4}{720f^6}a^6 + \cdots.$$

For $\mu, \Lambda \sim O(m_w) \ll f$*, the couplings between ALP and the Higgs are suppressed.*
Baryogenesis with $\Delta a = O(f)$ *during phase transitions cannot be described by renormalizable terms only.*

Let us provide a description for such baryogenesis!

Schematic description of the potential

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



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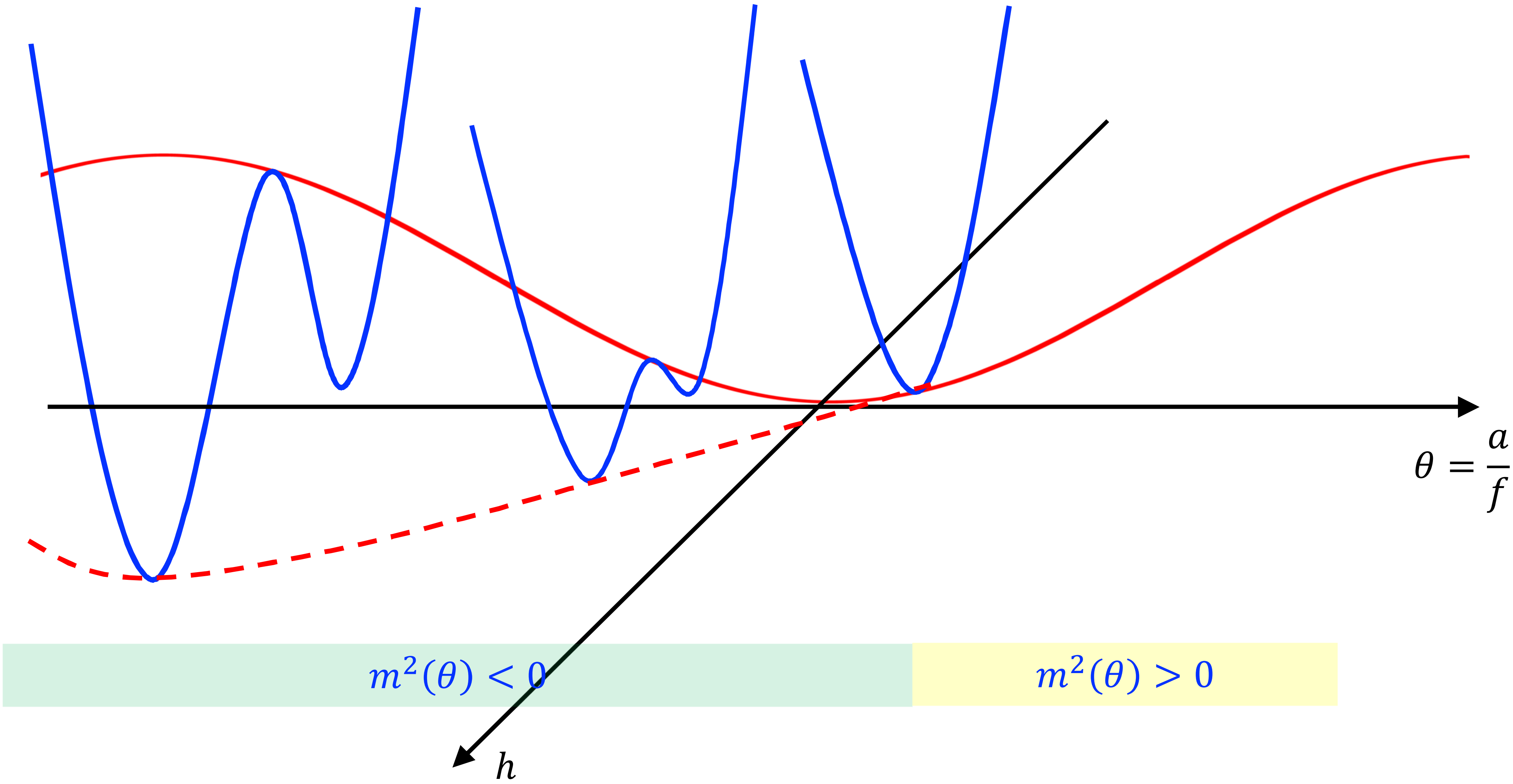


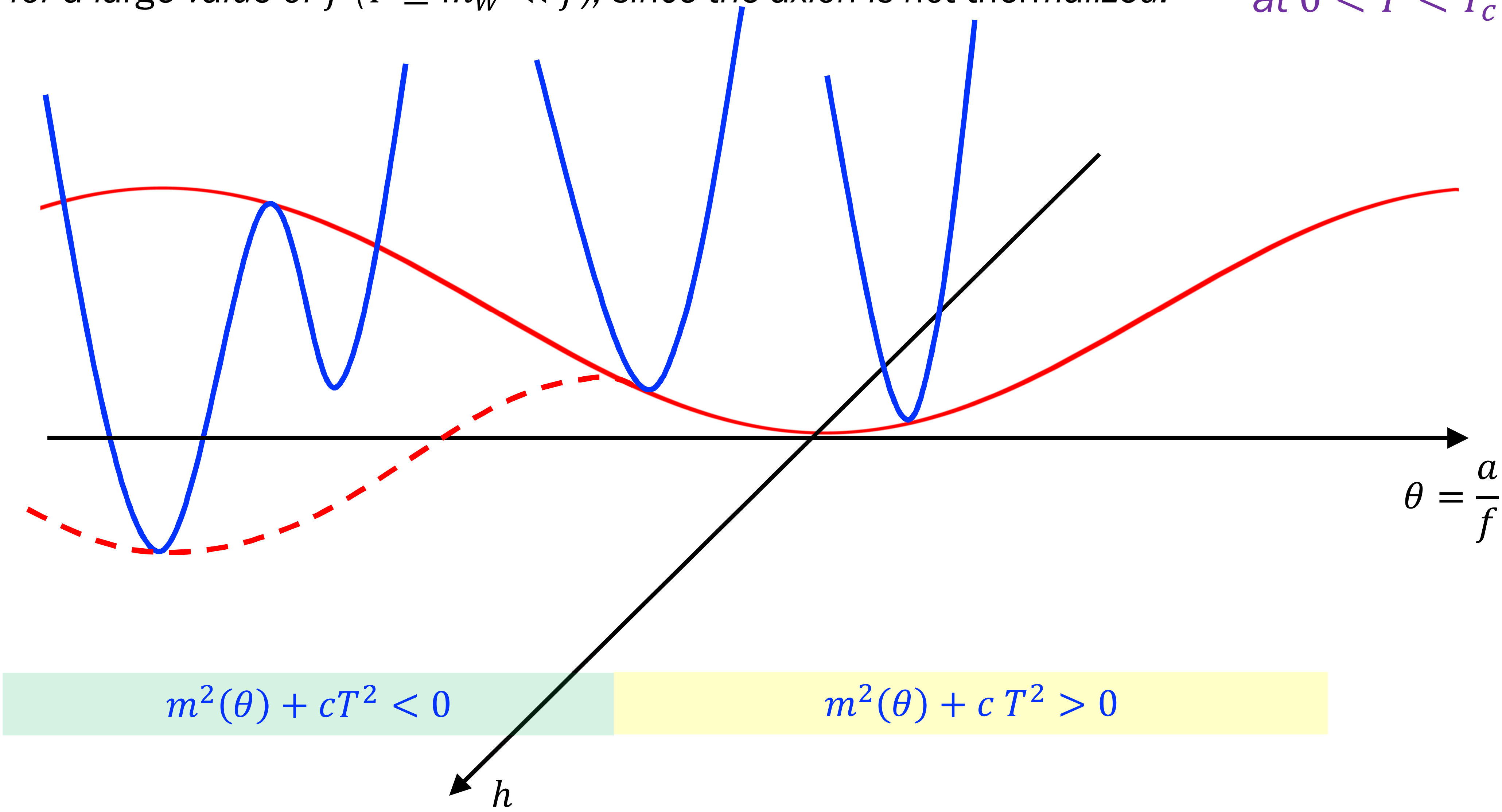
The potential is bounded from below due to the periodicity of the axion dependence

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 $0 < T < T_c$



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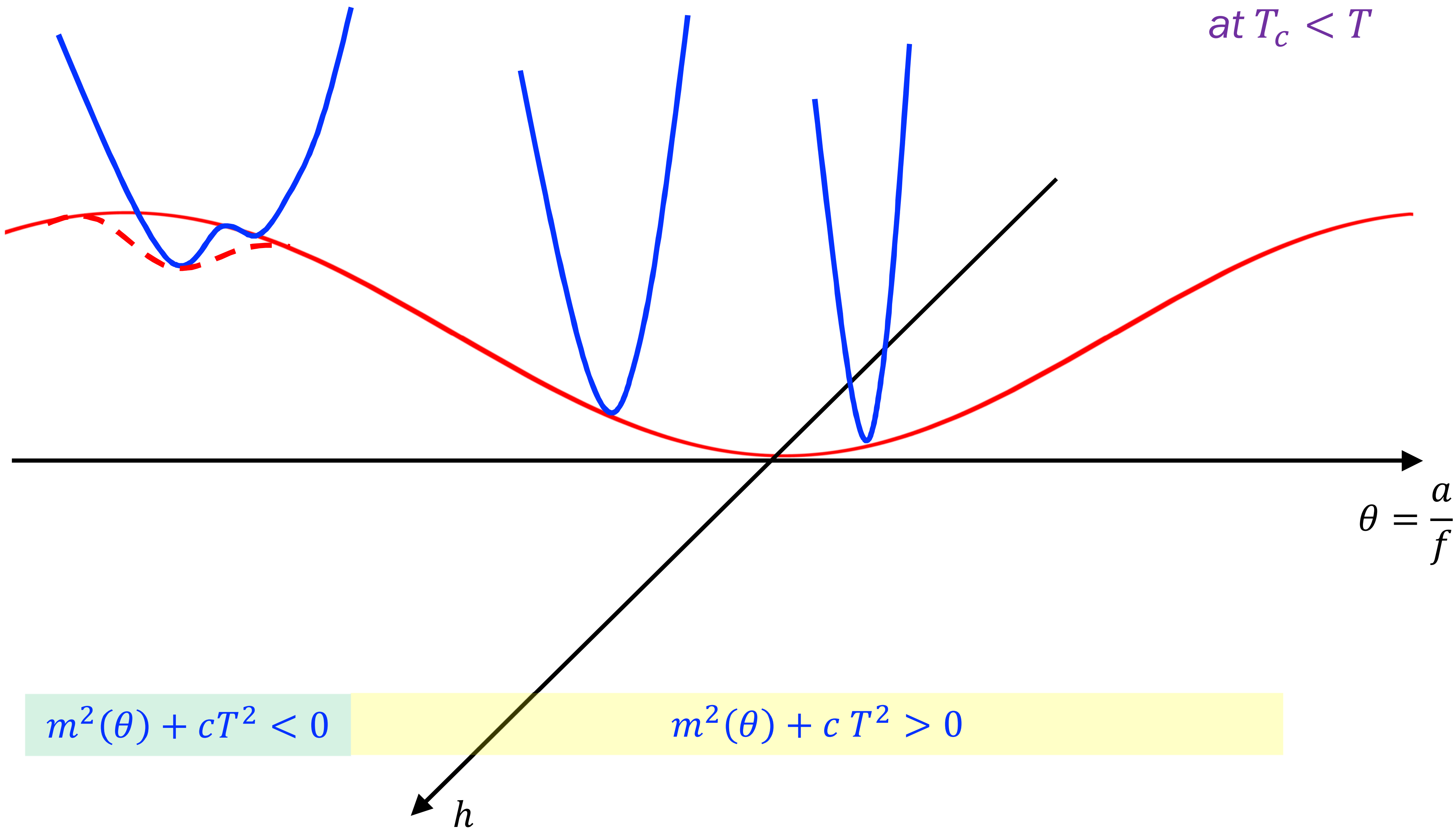

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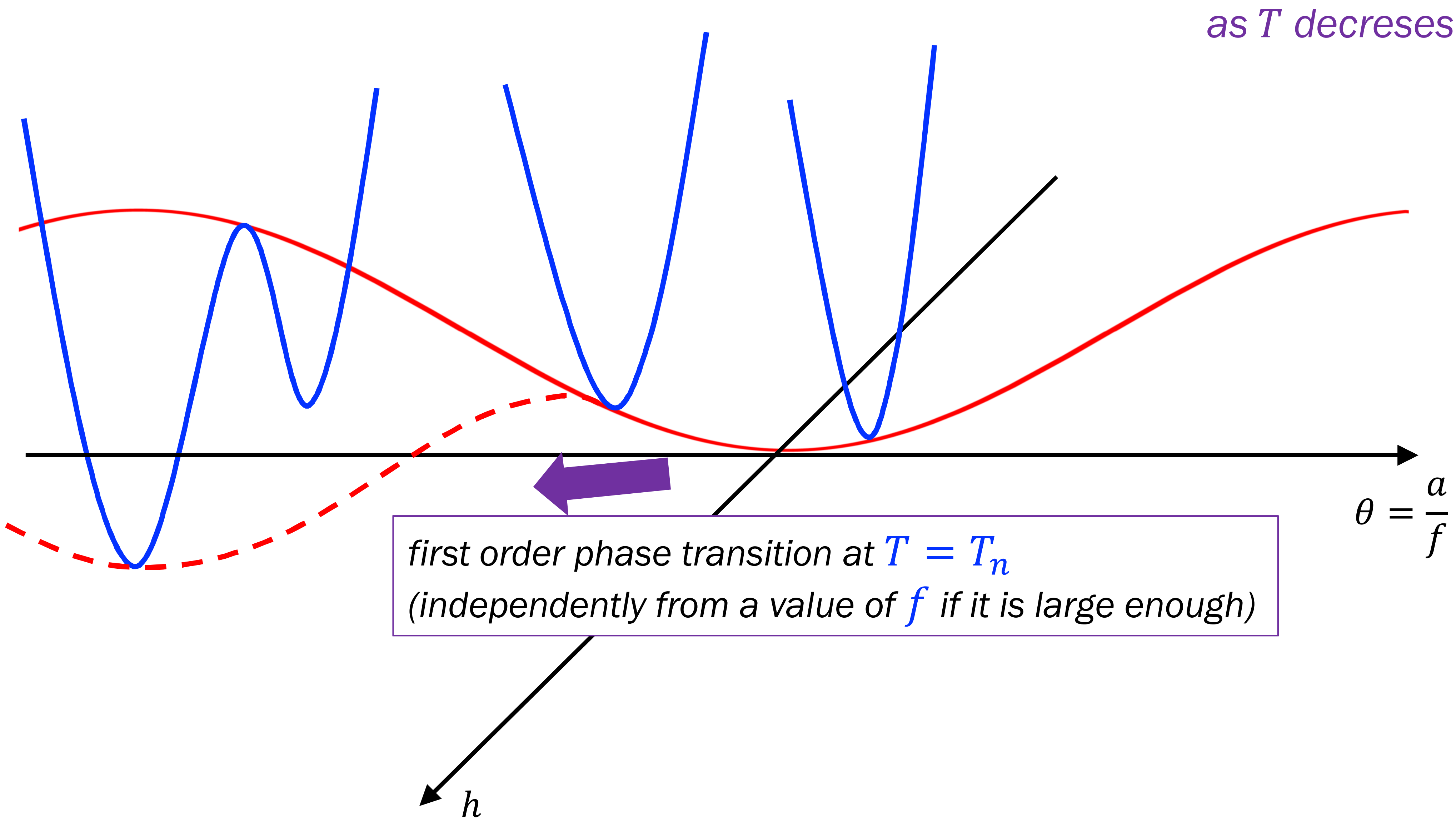
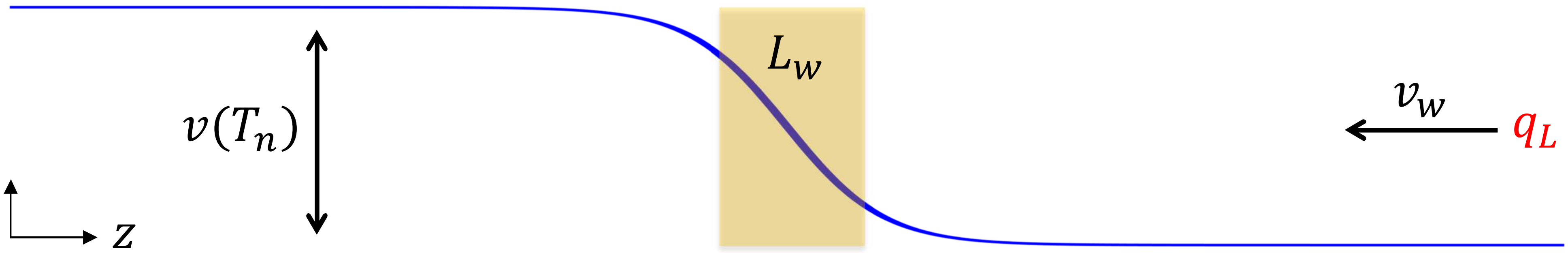


Conditions for bubble profile

For successful EWBG (after 1st order EWPT), three dynamical parameters are crucial:

$$v(T_n)/T_n,\ \ L_w,\ \text{and}\ \ v_w.$$



Large $v(T_n)/T_n > 1$ is needed for sufficient suppression of sphaleron process inside the bubble : out-of-equilibrium condition of Sakharov

$$\Gamma_{sph} \propto e^{-O(1)\frac{4\pi\, v}{g_2 T}}$$

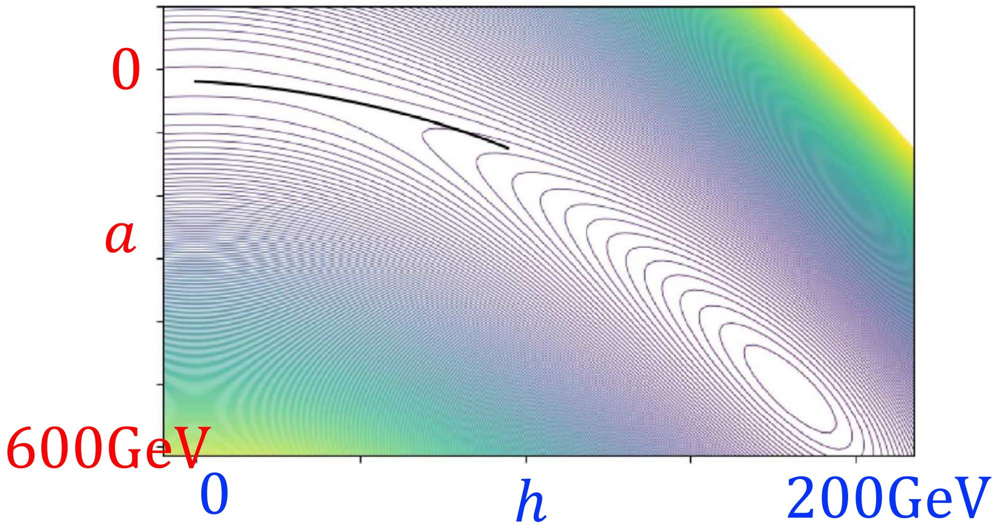
L_w should not be too large in order for sizable CP violating effects. E.g. a fermion with CP violating mass, $|m(z)|e^{i\phi(z)}\, q_L q_R + h.c$, the semiclassical CP violating force is

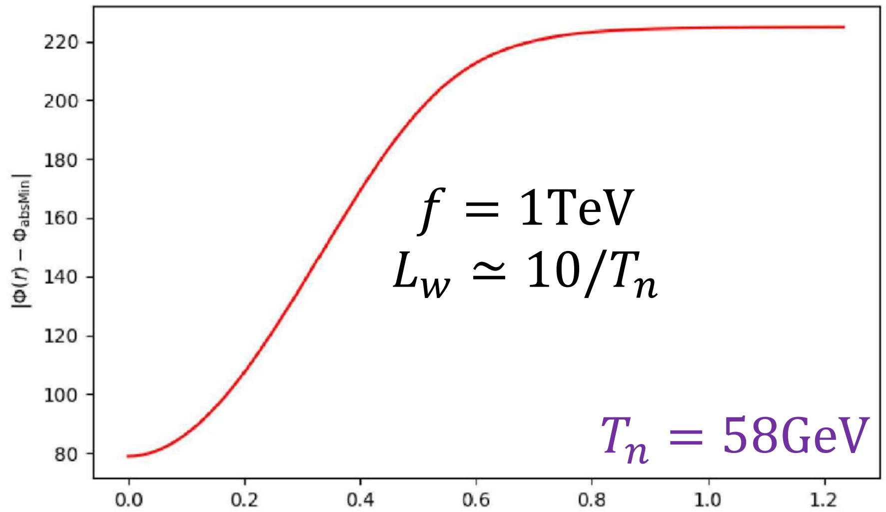
$$F_q - F_{\bar{q}} = \frac{\left(|m|^2\phi'\right)'}{2E_0 E_{0z}} - \frac{\phi'|m|^2\left(|m|^2\right)'}{4E_0^3 E_{0z}} \propto \frac{1}{L_w^2}$$

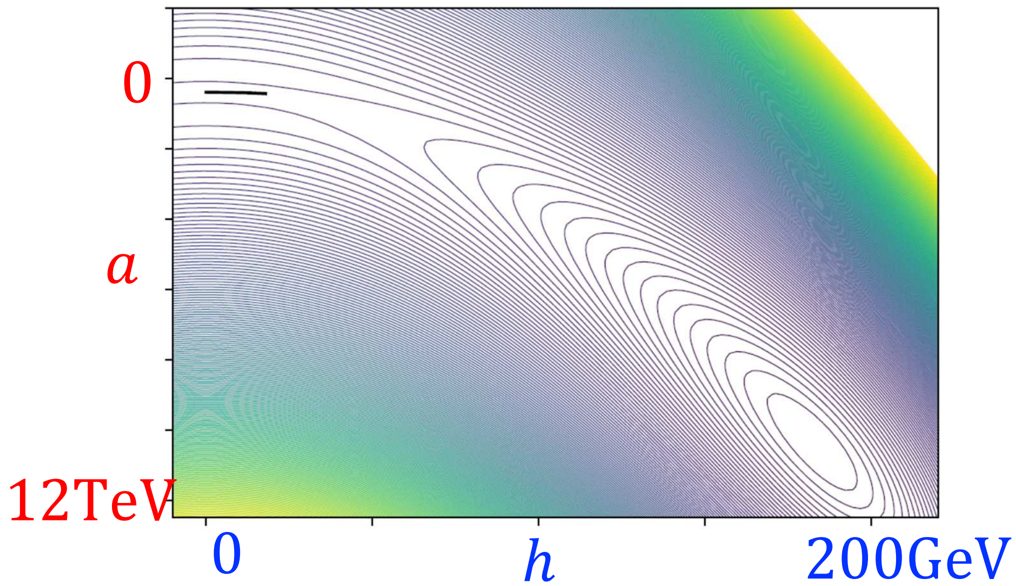
[Joyce, Prokopec, Turok 95]
[Cline, Kainulainen 00]

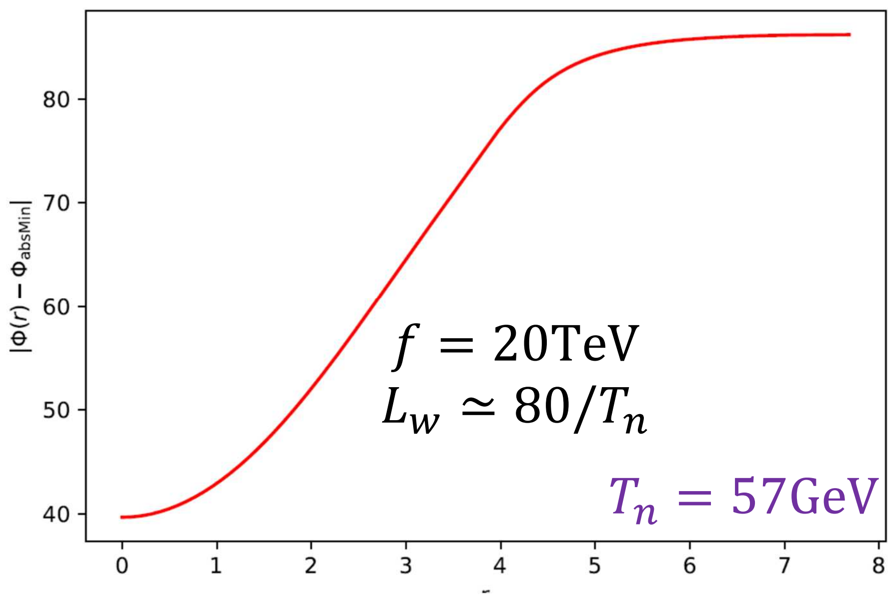
Bubble profile for a large f

Typical EWBGs: $L_w = (3-10)/T_n$. *In our case,* L_w *increases as the axion decay constant,* f, *increases. A negative effect of large wall width could be compensated by a large* $v(T_n)/T_n$. *Numerically,* L_w *is not very sensitive* f.







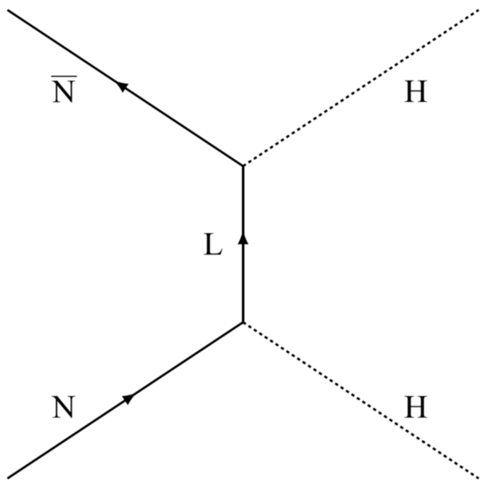


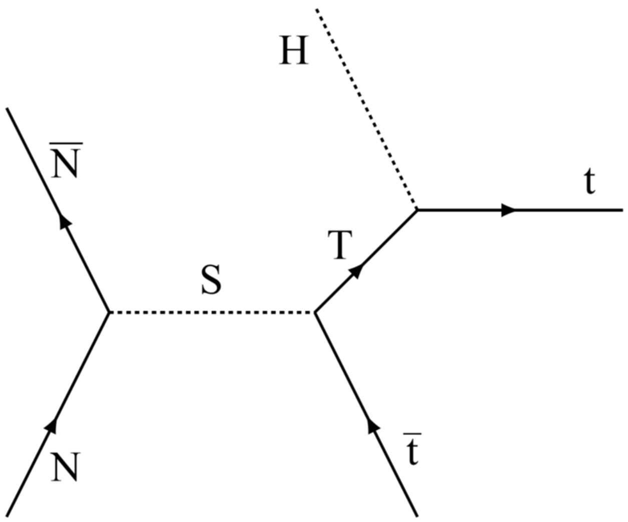
CP violation and a UV model

For CP violating sources, Top transport is used with axion dependent mass terms:

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

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





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

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

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

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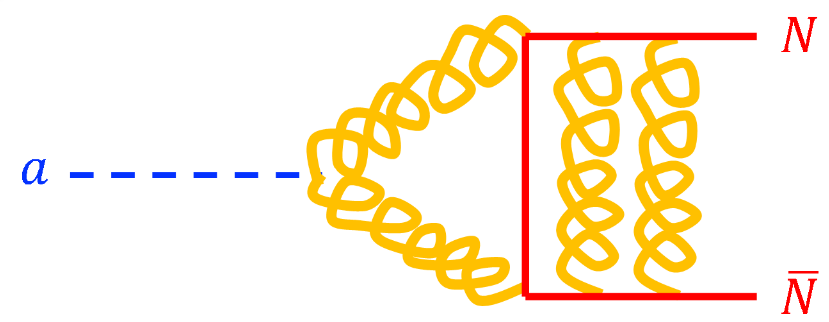

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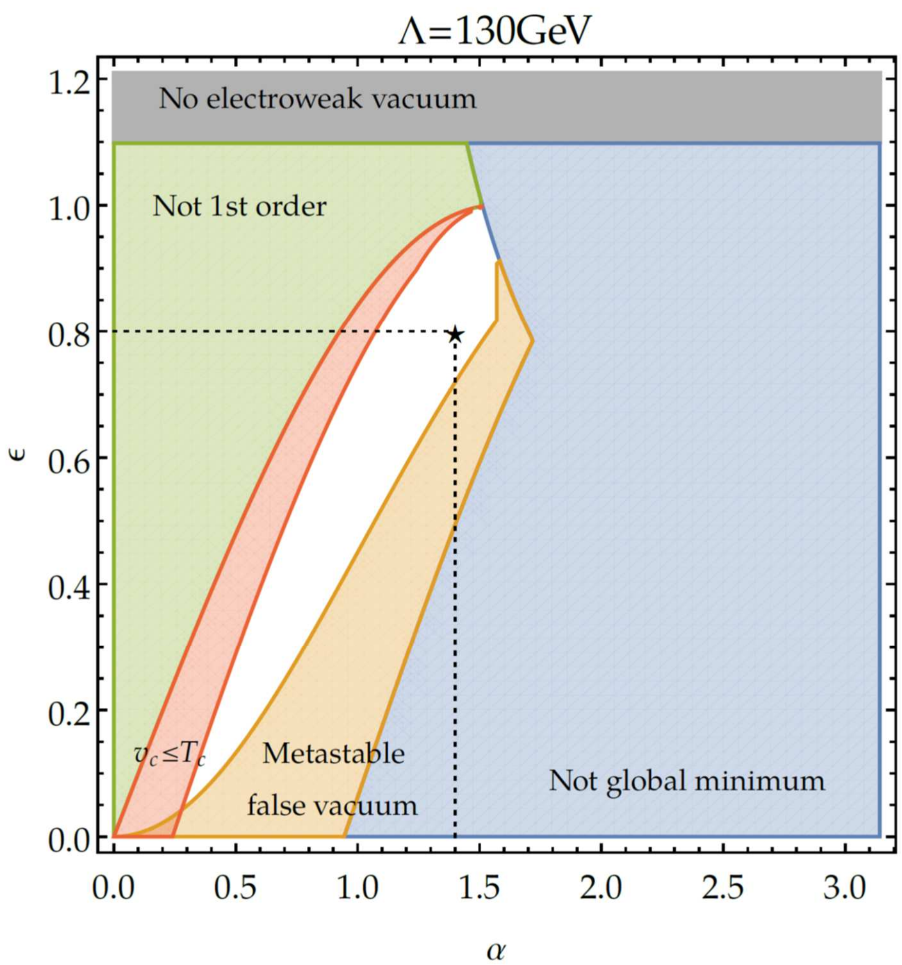
Results

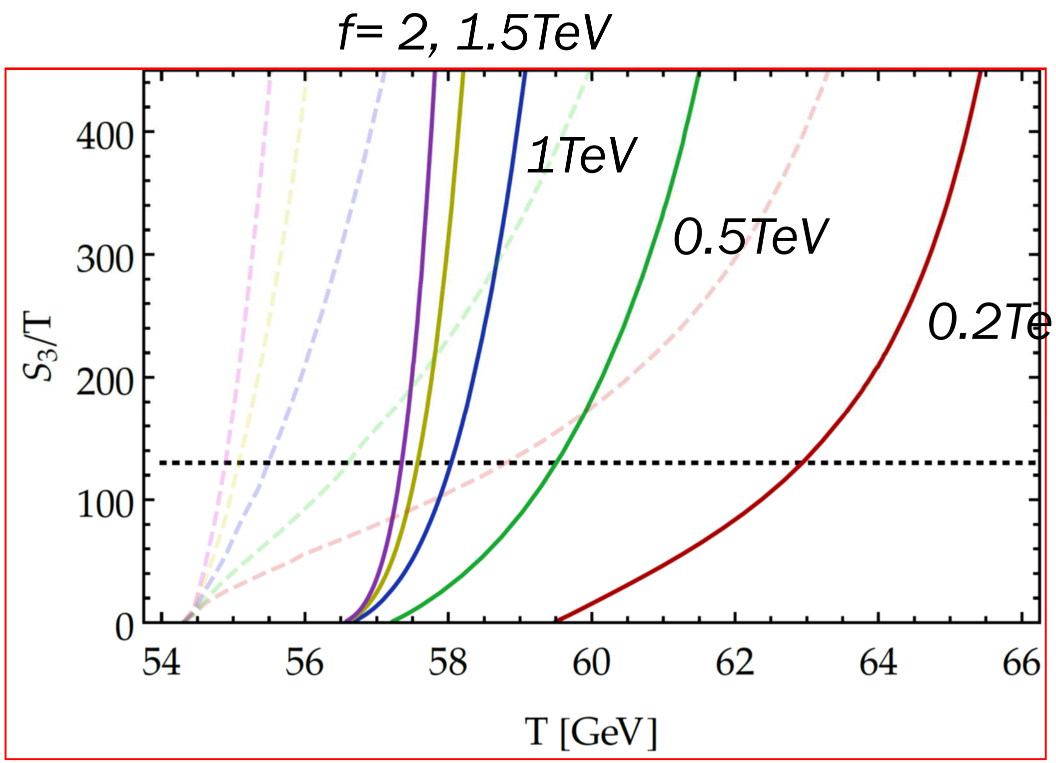
Benchmark points

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 $\boxed{\Lambda, \alpha, \epsilon = \sqrt{2\lambda}\Lambda^2/(-\mu_2^2)}$



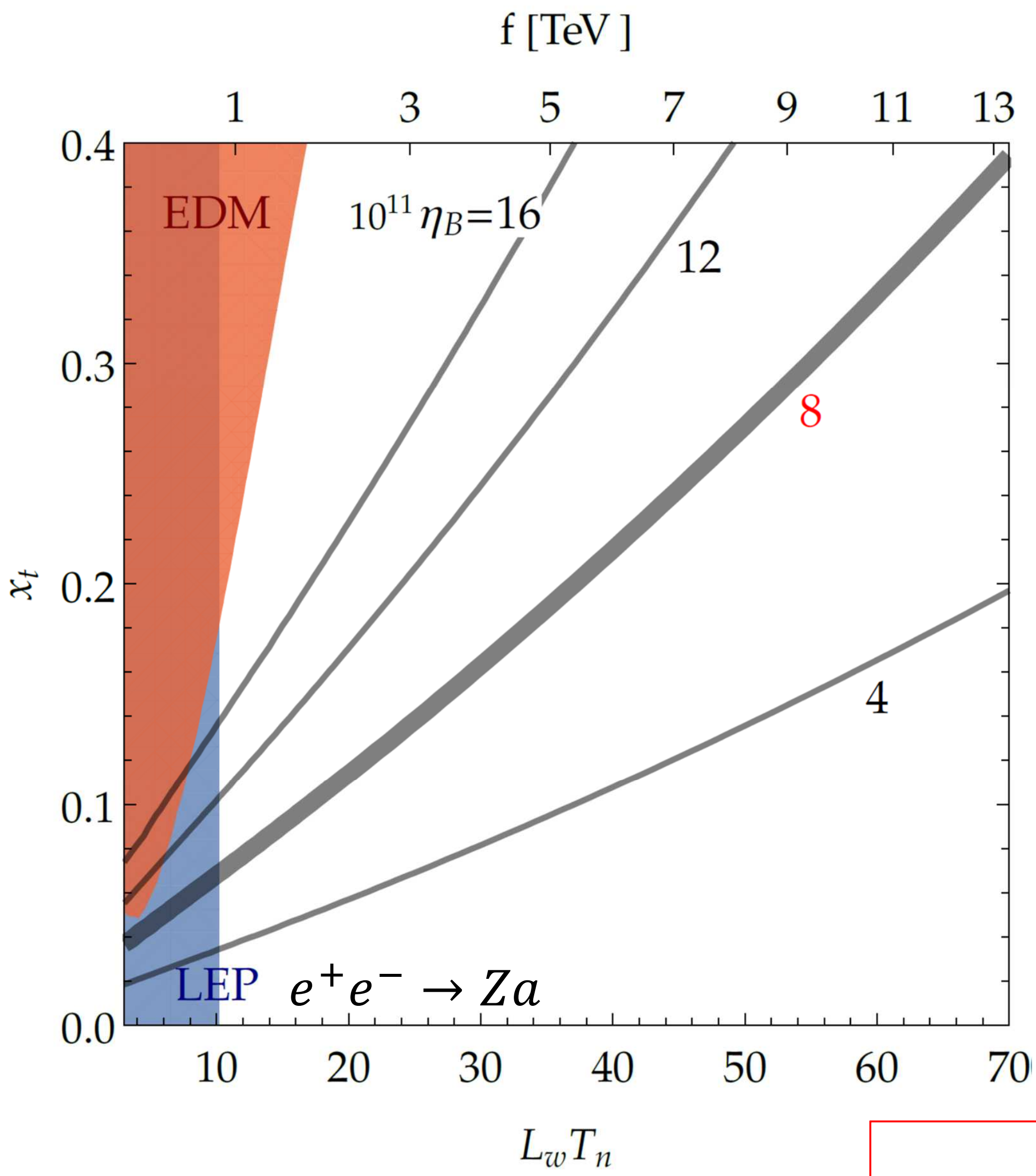


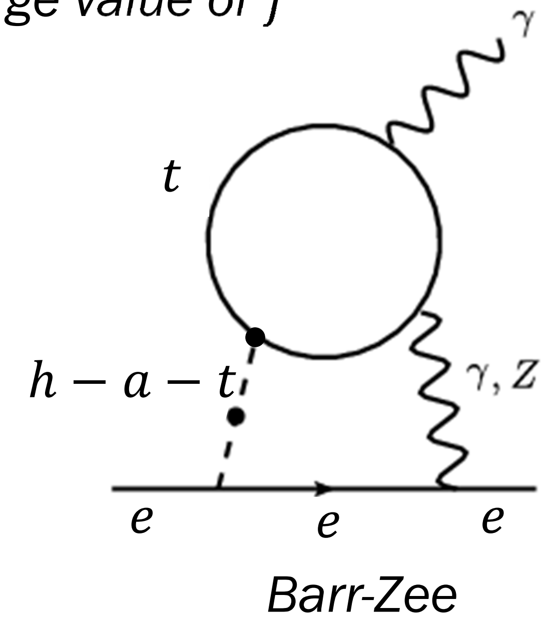
$\frac{S_3}{T} = 130$: T_n (*nucleation starts*)

$\frac{S_3}{T} = 0$: T_2 (*barrier disappears*)

baryon asymmetry, EDM and collider

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





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

$|d_e| < 8.7 \times 10^{-29}$ cm · *e at 90% C.L*

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

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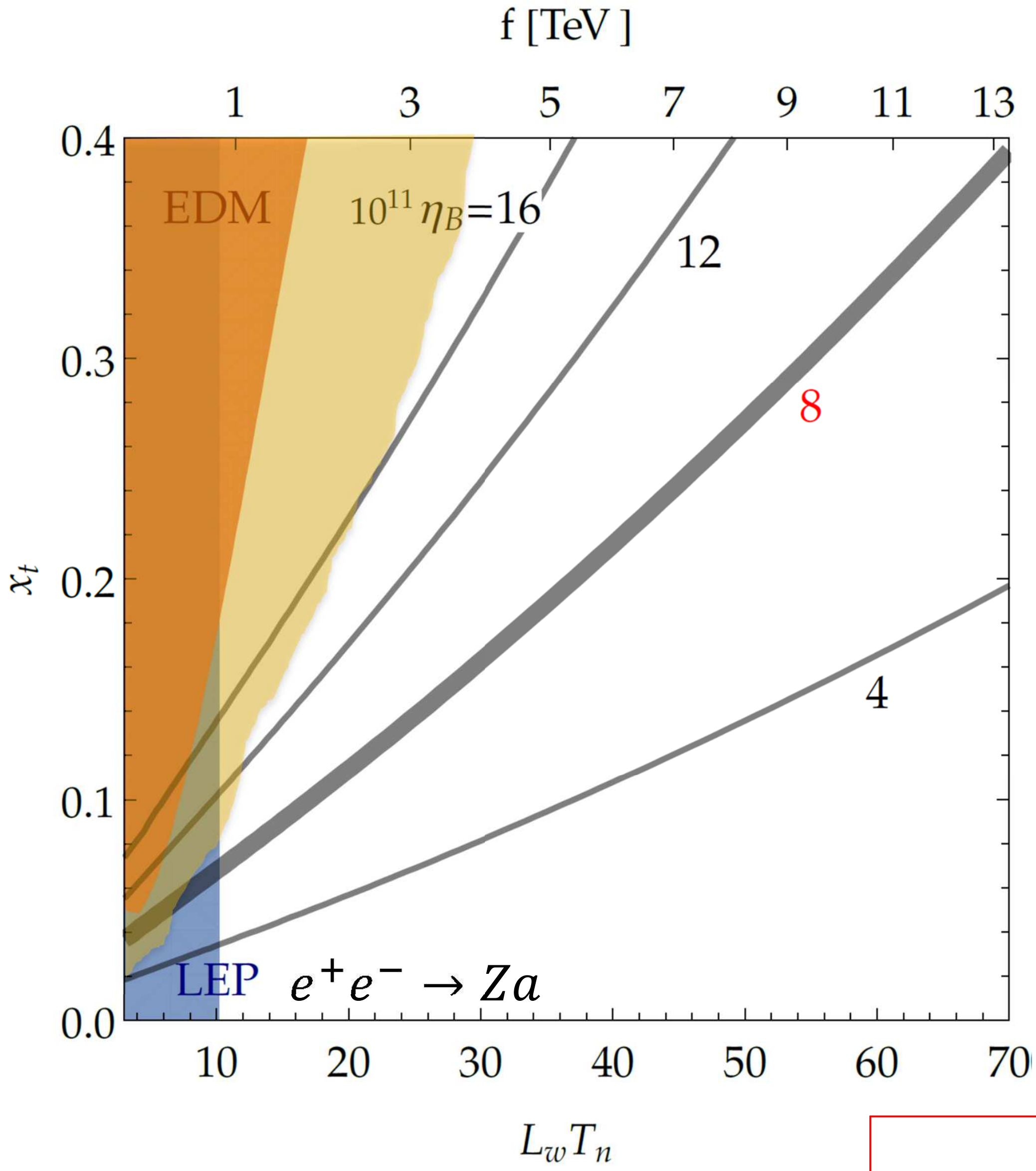
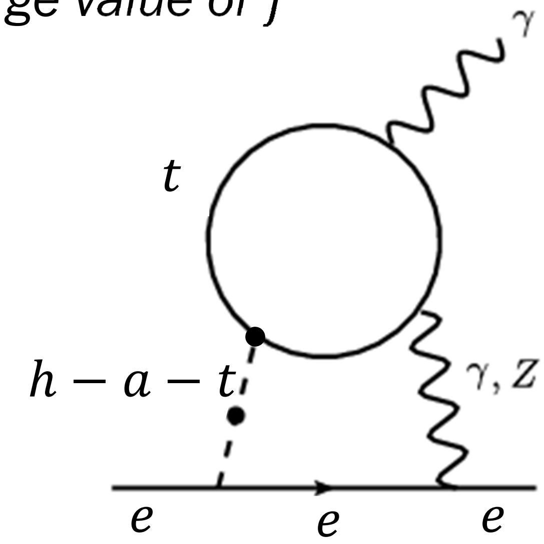




Barr-Zee

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

If $|d_e| < 4\times\ 10^{-29}$ cm $\cdot$ *e at 90% C.L*

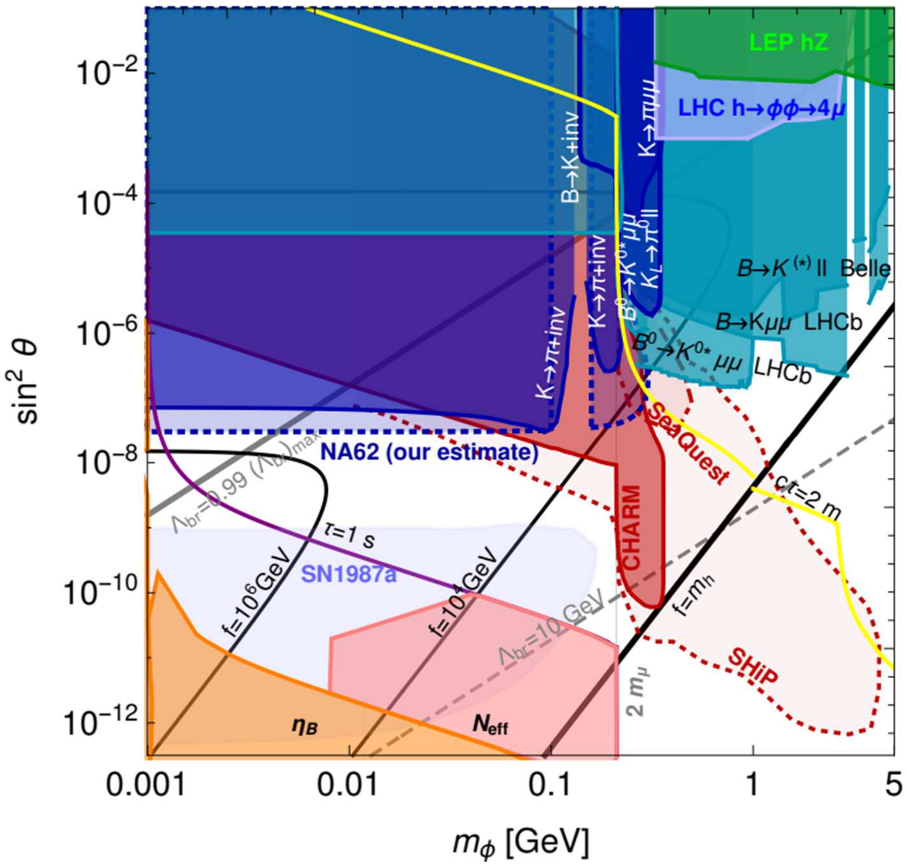
$$\boxed{m_a \sim m_w\left(\frac{m_w}{f}\right) \rightarrow\ \ m_a \sim O(0.1-10)\ \mathrm{GeV}}$$

ALP searches

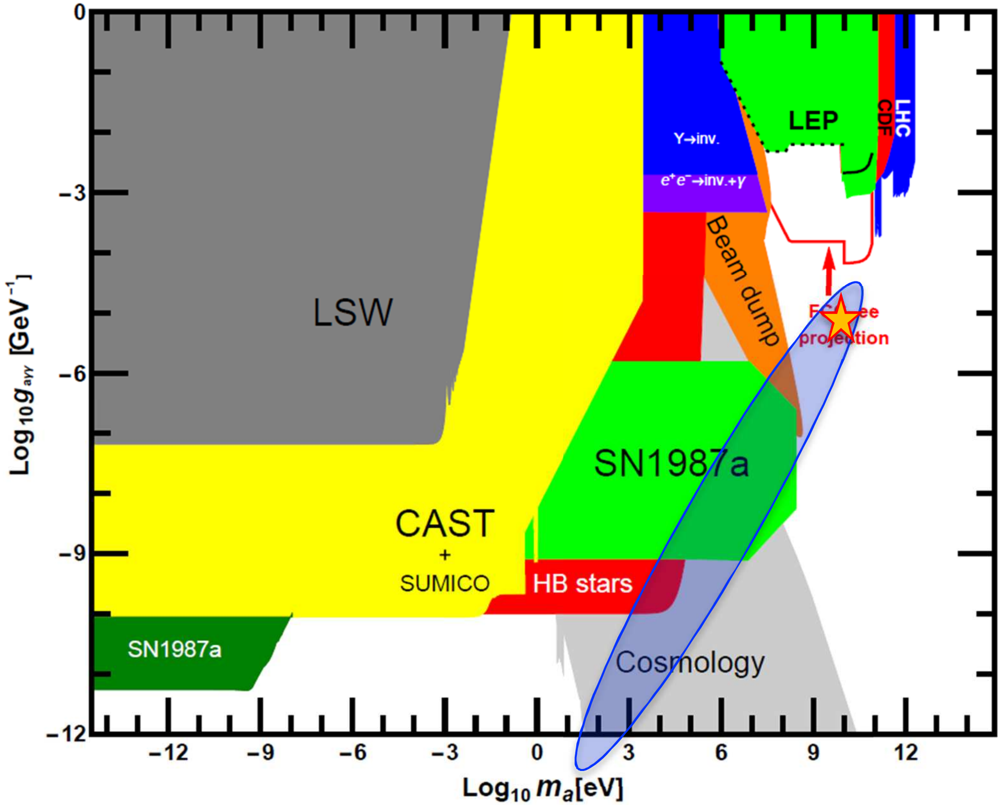
After integrating out top and Higgs, ALP couplings to <gluon, photon, light quark and lepton> are generated. Model dependent (axion decay channels) constraints are applied

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

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



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



[Jaeckel, Spannowsky 15]

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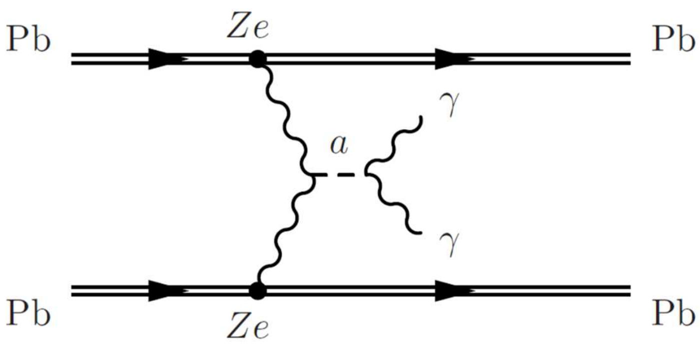
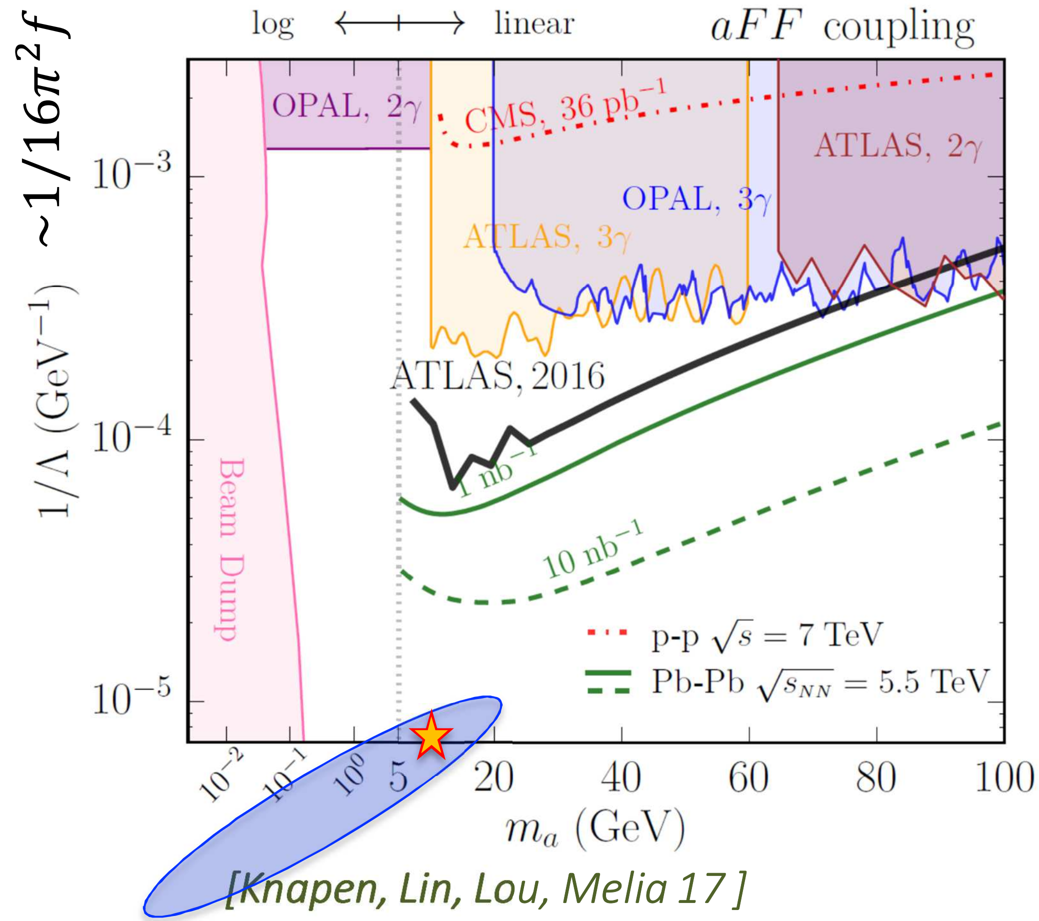
Axion with mass around $(5-10)\mathrm{GeV}$ *is model independently safe.*





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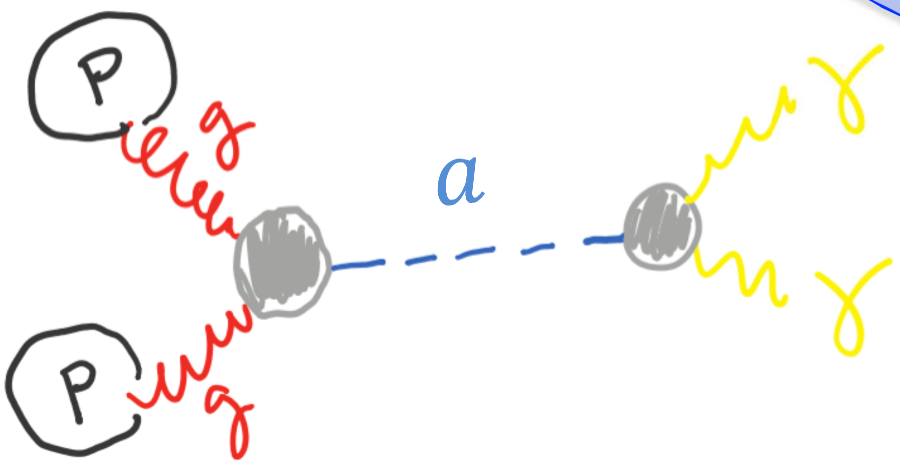
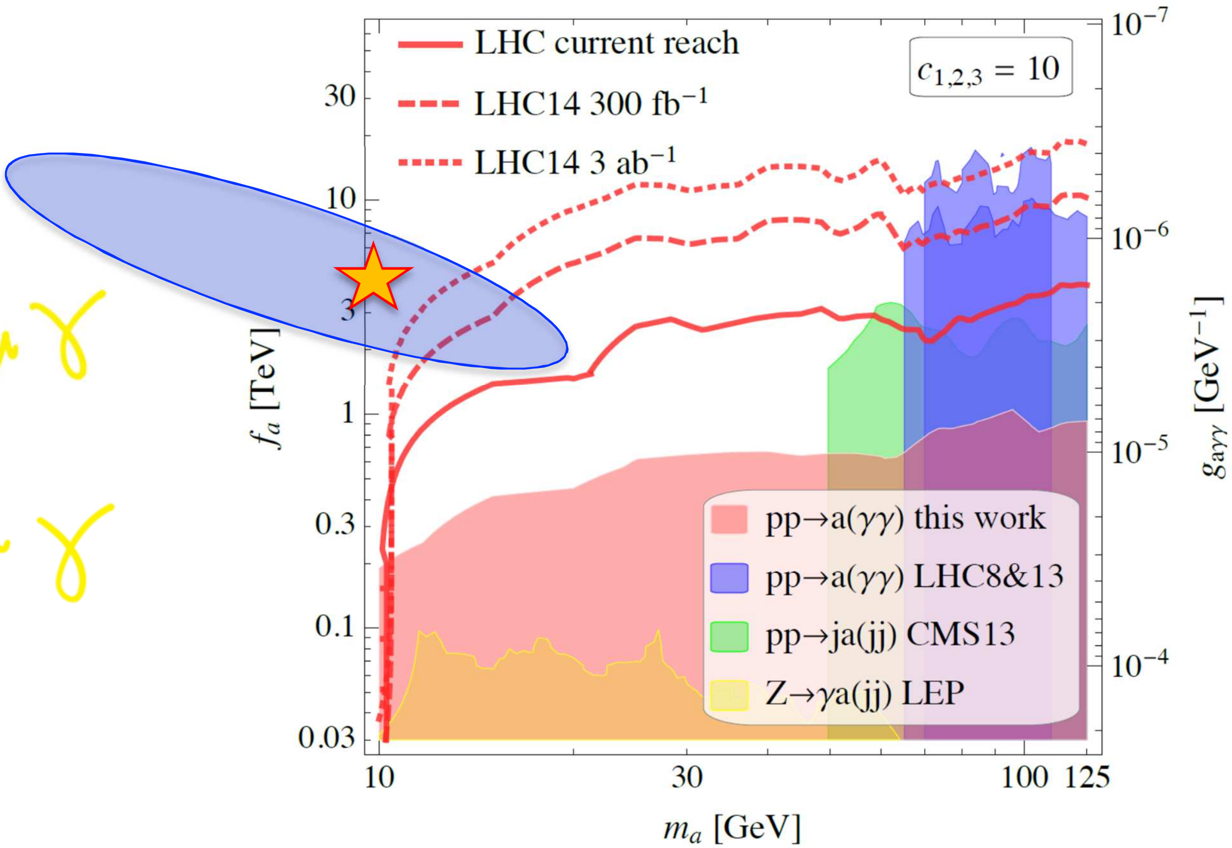




[Mariotti, Redigolo, Sala, Tobioka 17]

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.*

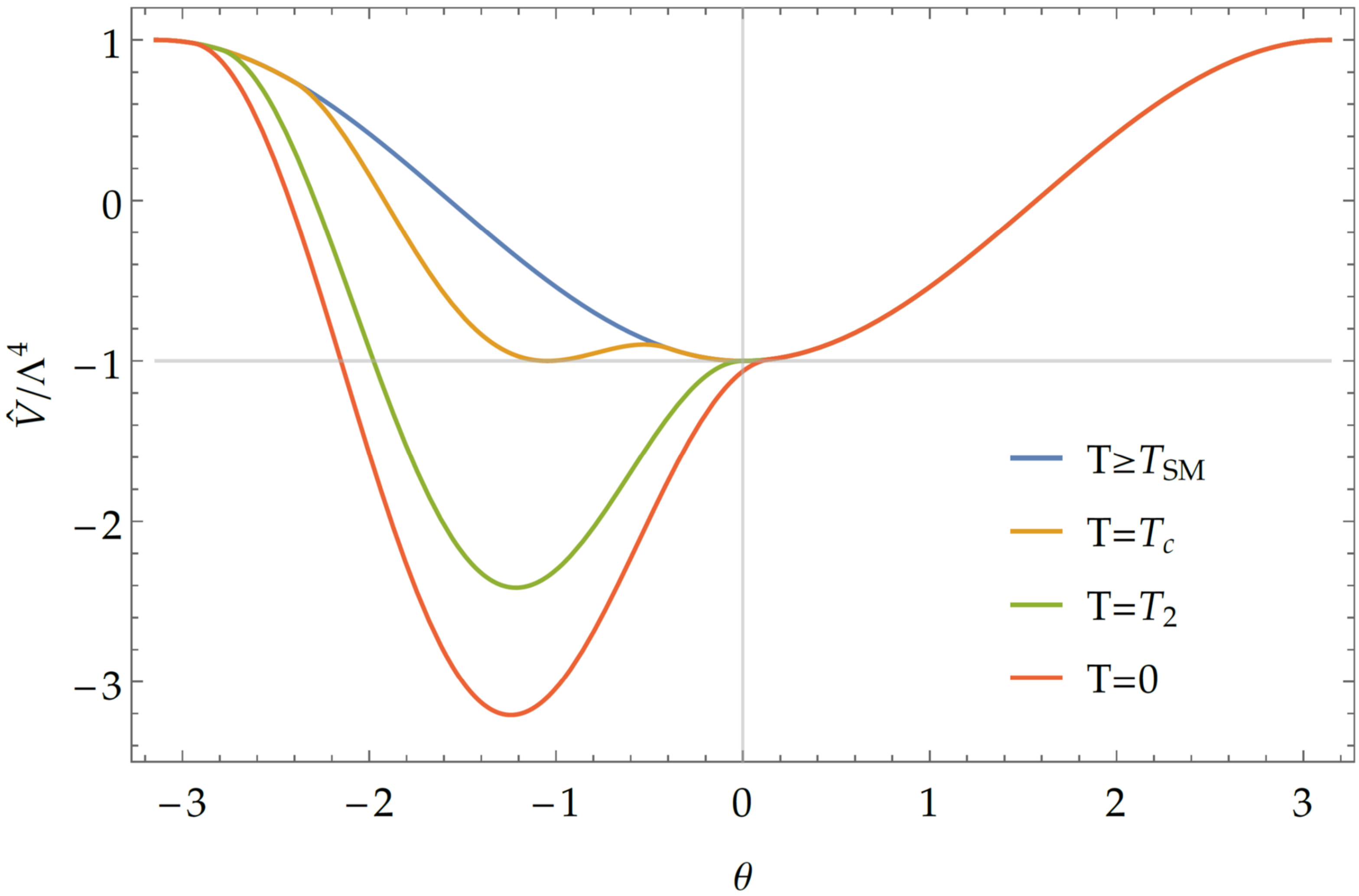
- *Axion mass and its decay constant are constrained by baryon asymmetry and ALP searches with Higgs-axion mixing.*

- *Most safe range of the ALP mass is between 5-10 GeV*

Backup

Evolution of the effective potential of θ

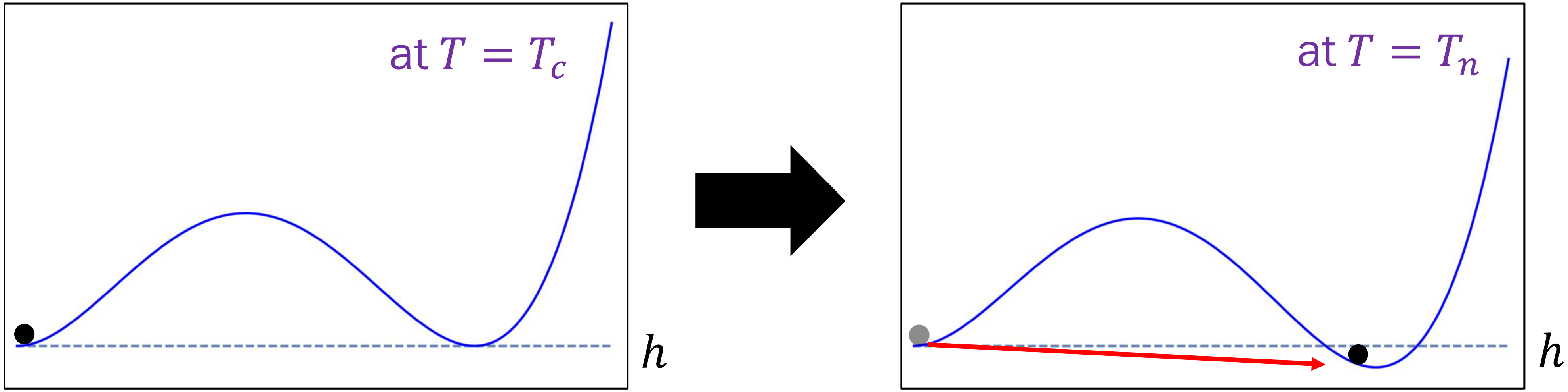
For a large value of f, the phase transition can be described by the effective potential of the axion: $\hat{V}_{eff}(\theta) = V(h_{ex}(\theta), \theta)$*, where* $\partial_h V(h,\theta)|_{h=h_{ex}} = 0$



What would be the constraints (predictions) of the axionic extension for EWBG?

Tunneling

For usual EWBGs ($\Delta h \sim m_W$), the phase transition happens just after T_c, *i.e.* $T_n \simeq T_c$.

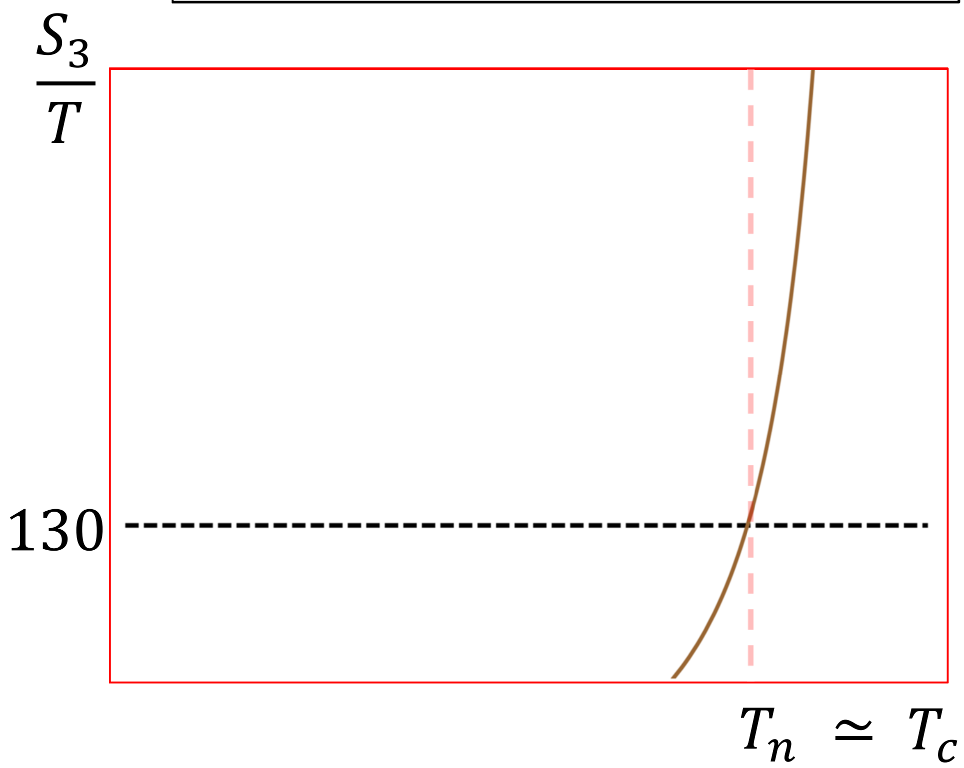


Bubble nucleation rate with the Euclidean action S_3 *for an O(3)-symmetric critical bubble*

$$\Gamma_{\mathrm{tunnel}}(T) = c\, T^4\, e^{-S_3/T} \simeq H^4$$

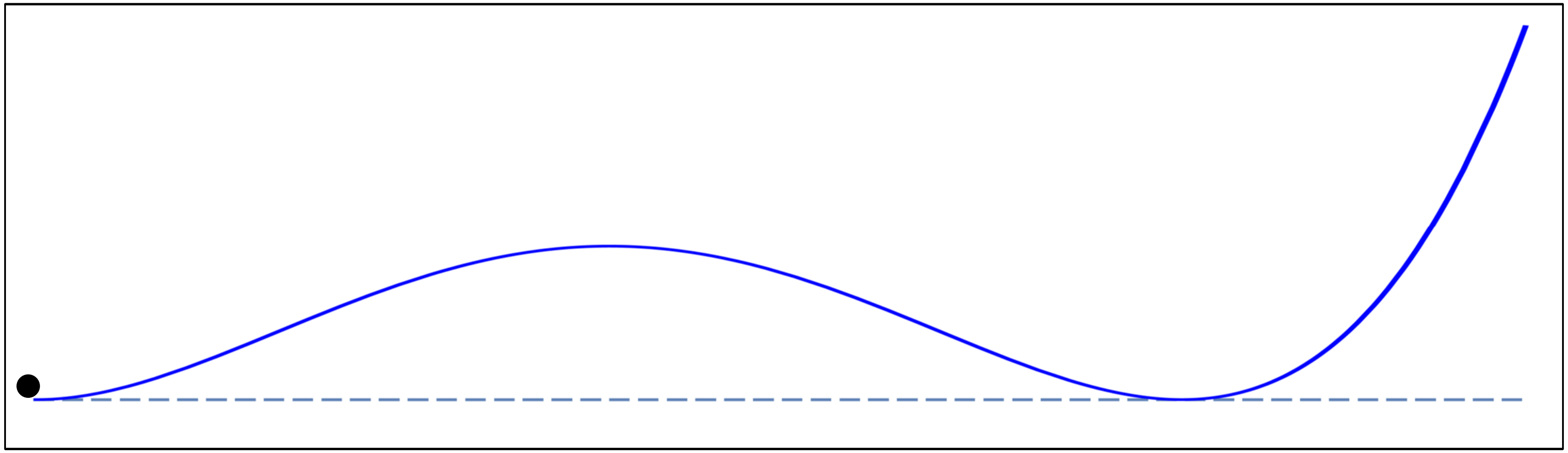
Typically,

$$\frac{T_c - T_n}{T_c} \leq O(0.01 - 0.1)$$



Tunneling

As increasing $f \gg m_W$, S_3 *increases as* f^3 *, so phase transition is delayed.*



$a = f\theta$

$\Delta a \sim f$

$$S_3 = \int d^3\vec{x}\left(\frac{1}{2}(\vec{\nabla}h)^2 + \frac{1}{2}\left(\vec{\nabla}a\right)^2 + V_T(h,a)\right)$$
$$= 4\pi f^3 \int du\, u^2\left(\frac{h'^2}{2f^2} + \frac{1}{2}\theta'^2 + V_T(h,\theta)\right)$$

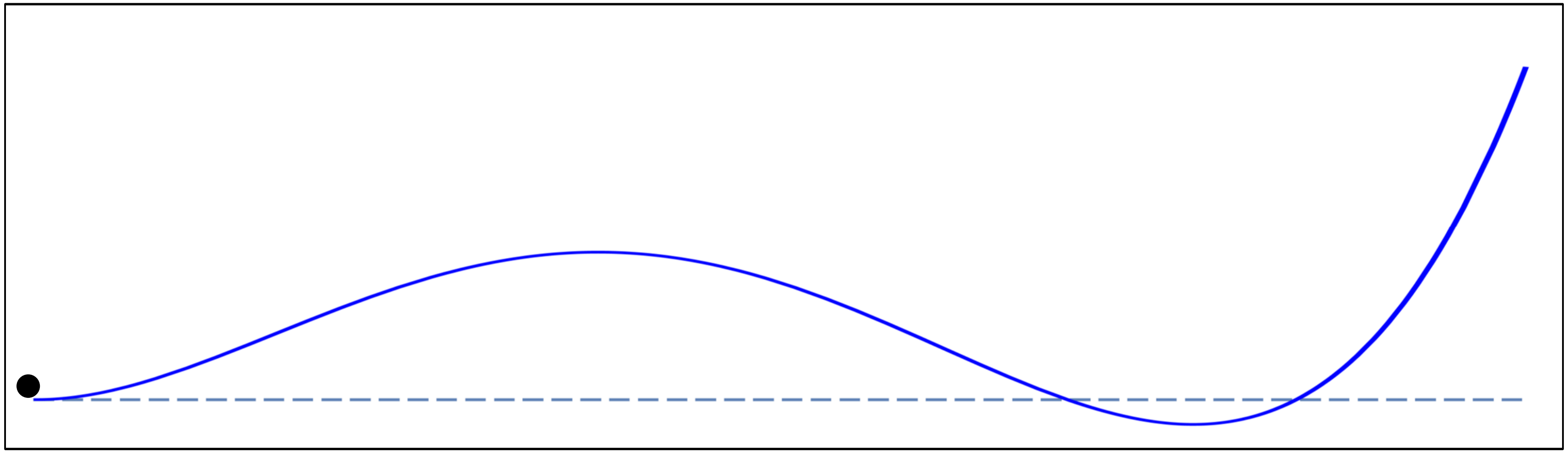
where $u = r/f$ *with e.o.m.*

$$\boxed{\frac{d^2\theta}{du^2} + \frac{2}{u}\frac{d\theta}{dt} = \frac{\partial V_T}{\partial\theta}, \qquad \frac{1}{f}\left(\frac{d^2h}{du^2} + \frac{2}{u}\frac{dh}{dt}\right) = \frac{\partial V_T}{\partial h}}$$

For a large f, the Higgs trajectory is nearly following $\partial_h V \approx 0$ *and its effect on* S_3 *negligible.*

Tunneling

As increasing $f \gg m_W$, S_3 increases as f^3, so phase transition is delayed.



$\Delta a \sim f$

$a = f\theta$

$$S_3 = \int d^3\vec{x}\left(\frac{1}{2}(\vec{\nabla}h)^2 + \frac{1}{2}\left(\vec{\nabla}a\right)^2 + V_T(h,a)\right)$$

$$= 4\pi f^3 \int du\, u^2 \left(\frac{h'^2}{2f^2} + \frac{1}{2}\theta'^2 + V_T(h,\theta)\right)$$ *where $u = r/f$ with e.o.m.*

$$\boxed{\frac{d^2\theta}{du^2} + \frac{2}{u}\frac{d\theta}{dt} = \frac{\partial V_T}{\partial\theta}, \qquad \frac{1}{f}\left(\frac{d^2h}{du^2} + \frac{2}{u}\frac{dh}{dt}\right) = \frac{\partial V_T}{\partial h}}$$

For a large f, the Higgs trajectory is nearly following $\partial_h V \approx 0$ and its effect on S_3 negligible.

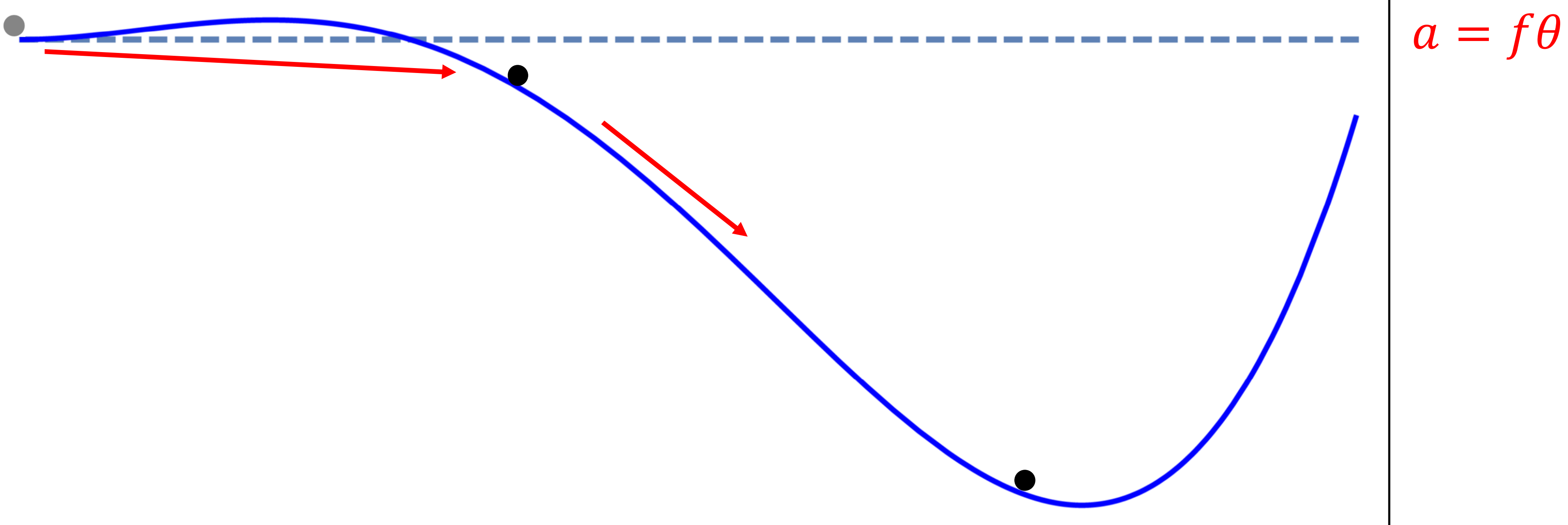
Tunneling

As increasing $f \gg m_W$, S_3 *increases as* f^3 *, so phase transition is delayed,*

until the barrier is quite lowered

(T_n *is lower than* T_c *—could be stronger first order phase transition—*

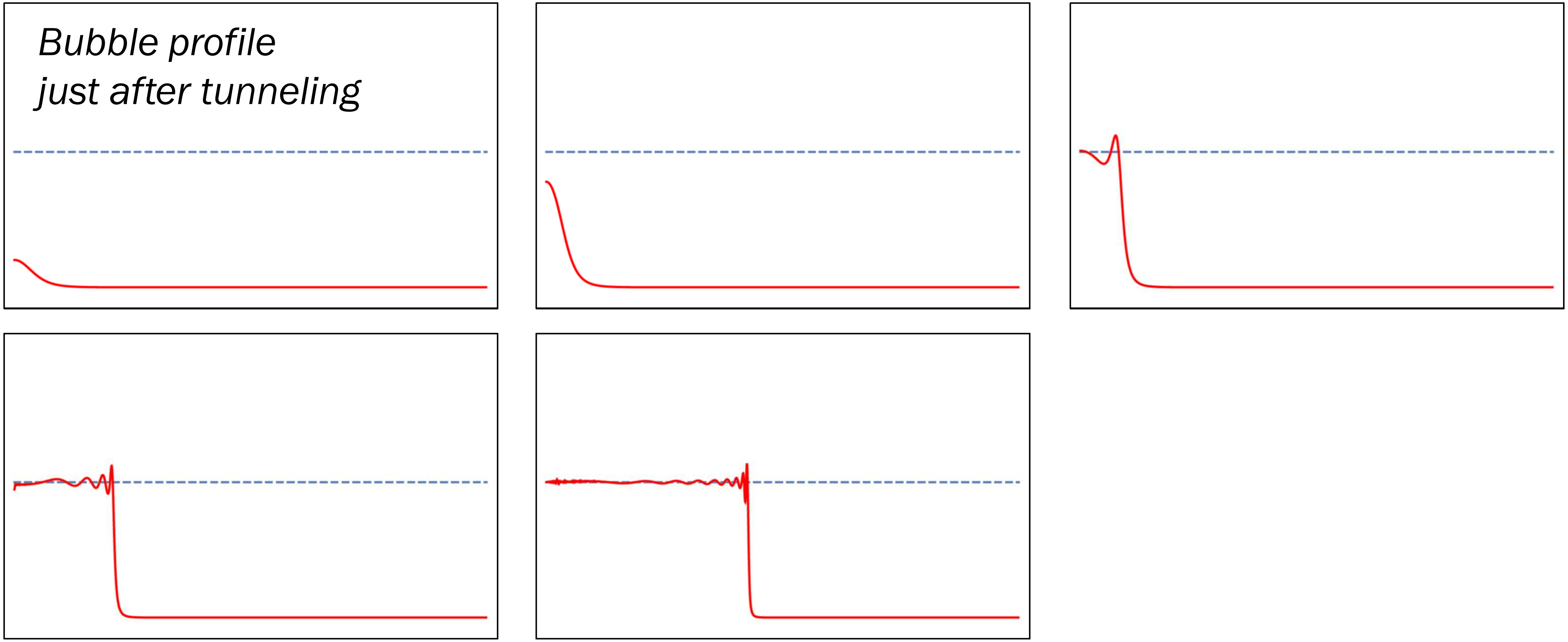
but it approaches T_2 *at which the barrier disappears)*



<u>Still this is very different from second order phase transitions</u>

Conditions for baryogenesis

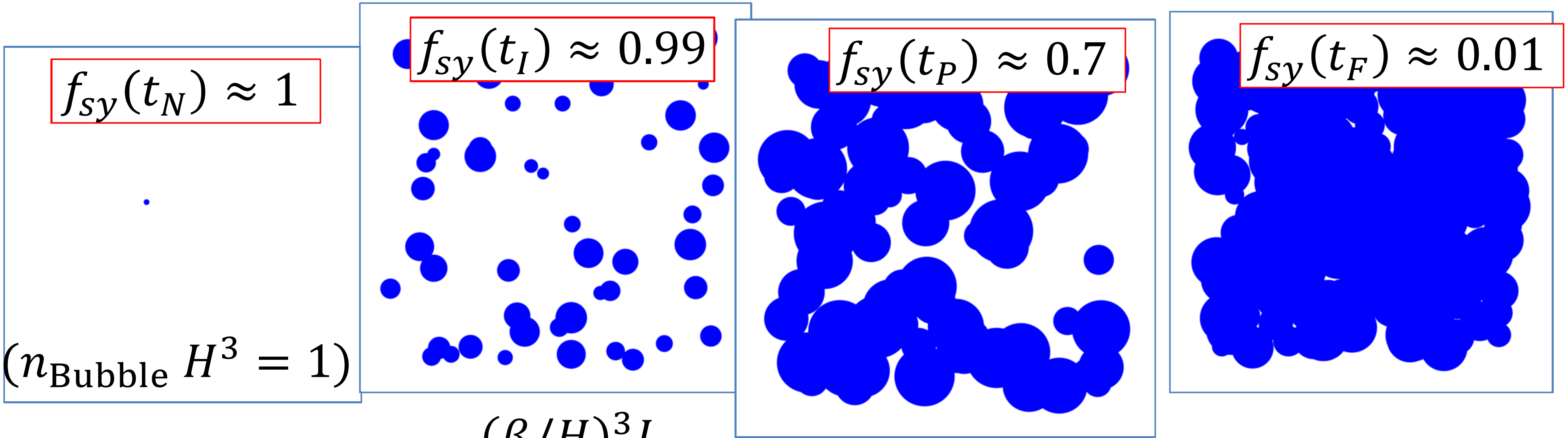
As the bubble expands, the scalar fields (a, h) will settle down at the potential minimum values : $(a(T), v(T))$ within time scales $\Delta t \sim 1/m_a \sim f/m_W^2$.



1) *The axion (so the Higgs) should quickly arrive at its vacuum value. Otherwise strong first order phase transition cannot be obtained before bubbles collide and fill the Universe.*
2) *The bubble wall width L_W should not be too large compared to $1/T_n$. Otherwise, the effects of CP violation is too suppressed.*

Time scales for bubble expansion

After a first bubble is formed, bubbles are continuously produced and expand. They percolate and fill the Universe. Using the fraction of symmetric phase, $f_{sy}(t)$



$$t_I - t_N \simeq \beta^{-1} \ln \frac{(\beta/H)^3 I_I}{8\pi v_w^3}$$

$$t_F - t_I \simeq 6\beta^{-1}$$

[Megevand, Ramirez 16]

for a Euclidean action expanded as $S_3/T = S_3(t_N)/T - \beta(t - t_N) + O\left((t - t_N)^2\right)$
where $\beta/H = d(S_3/T)/d\ln T \simeq 130/(1 - T_2/T_n)$.

$$\boxed{\beta \ll m_a \rightarrow \frac{10^{-3}\text{eV}}{1 - T_2/T_n} \simeq 10^{-3}\text{eV}\left(\frac{f}{m_W}\right)^{\gamma} \ll m_a \sim \frac{m_W^2}{f}}$$