

# 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 COSMO 18*

*Aug 27, 2018*

## ***Brief introduction to CTPU***

# Center for Theoretical Physics of the Universe

- *Study Particle Physics Theory and Cosmology*
- *Launched in 2014, settled down in a new IBS HQ building (2018 Feb)*
- *1 Director, 4 faculties, 17 postdocs, 3 admin staffs, 1 technician*
- *Official Language: English*
- *Organizing various workshops, seminars, and lecture series*
- *Strong support for individual researches and collaborations:*
  - *Weekly collaboration meetings for Cosmology/Collider divisions*
  - *TAU (CTPU-CAPP-CUP) th-ex collaboration meeting*

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Physics Beyond the Standard Model, Supersymmetry,  
Particle Cosmology, Axion



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Physics Beyond the Standard Model, Particle  
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Phenomenology, Supersymmetry, Cosmology



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Physics Beyond the  
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**Sushant Raut**

Neutrino, BSM



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BSM, Supersymmetry



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Physics Beyond the  
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Cosmology



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Standard Model



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Computer simulation



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Physics Beyond the  
Standard Model



**Chan Beom Park**

Collider Physics



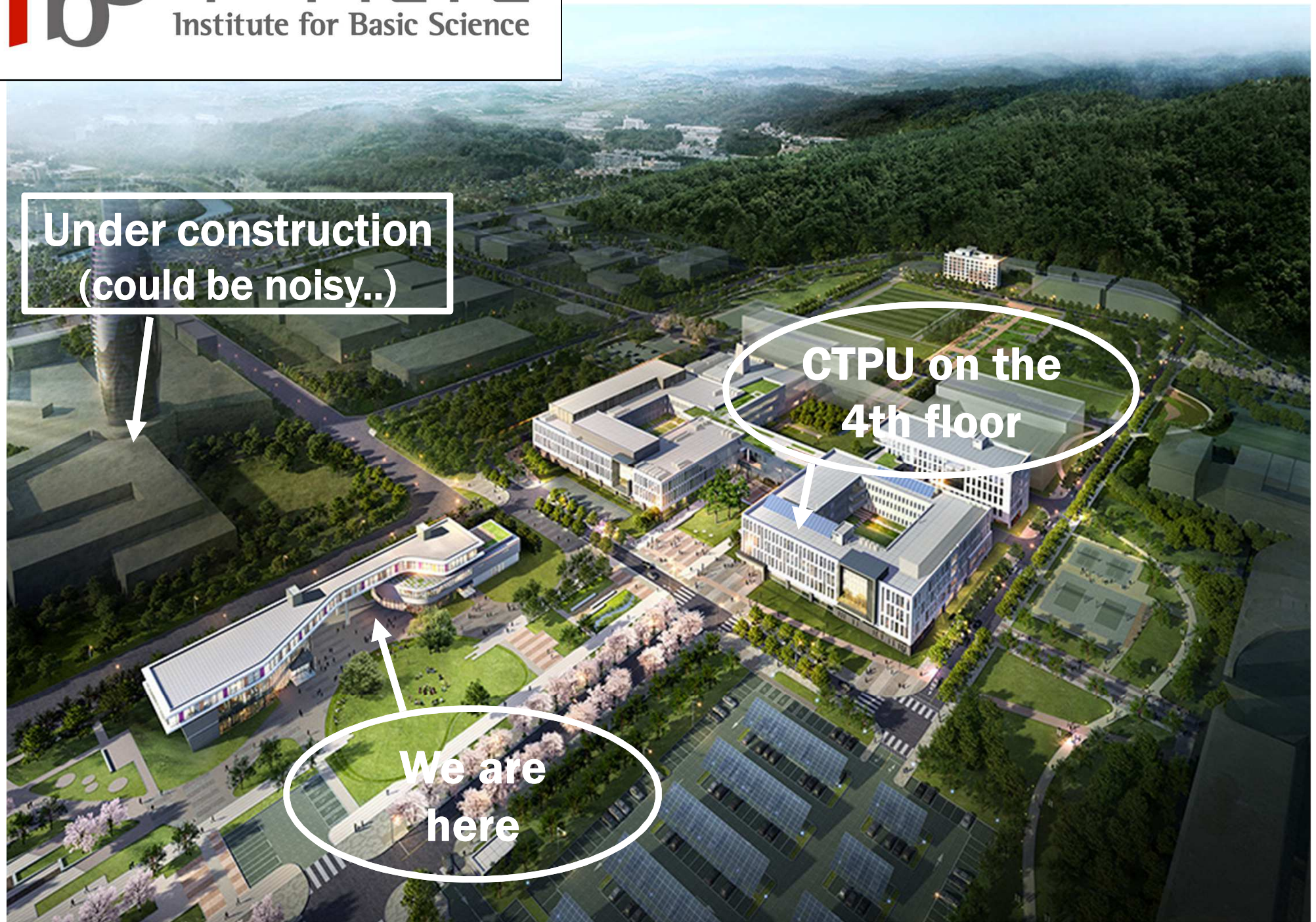
**Kohei Kamada**

Cosmology, Early  
universe









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**Landau  
Pole**

**Flavor**

**EDM**

**Light  
Colored  
Scalar**

**Higgs  
precision**

$$\frac{n_B}{s} = 0.8 \times 10^{-10}$$

**EWBG**

**Dark  
Matter**

**Higgs  
mass**

**hierarchy  
problems**

**GW**

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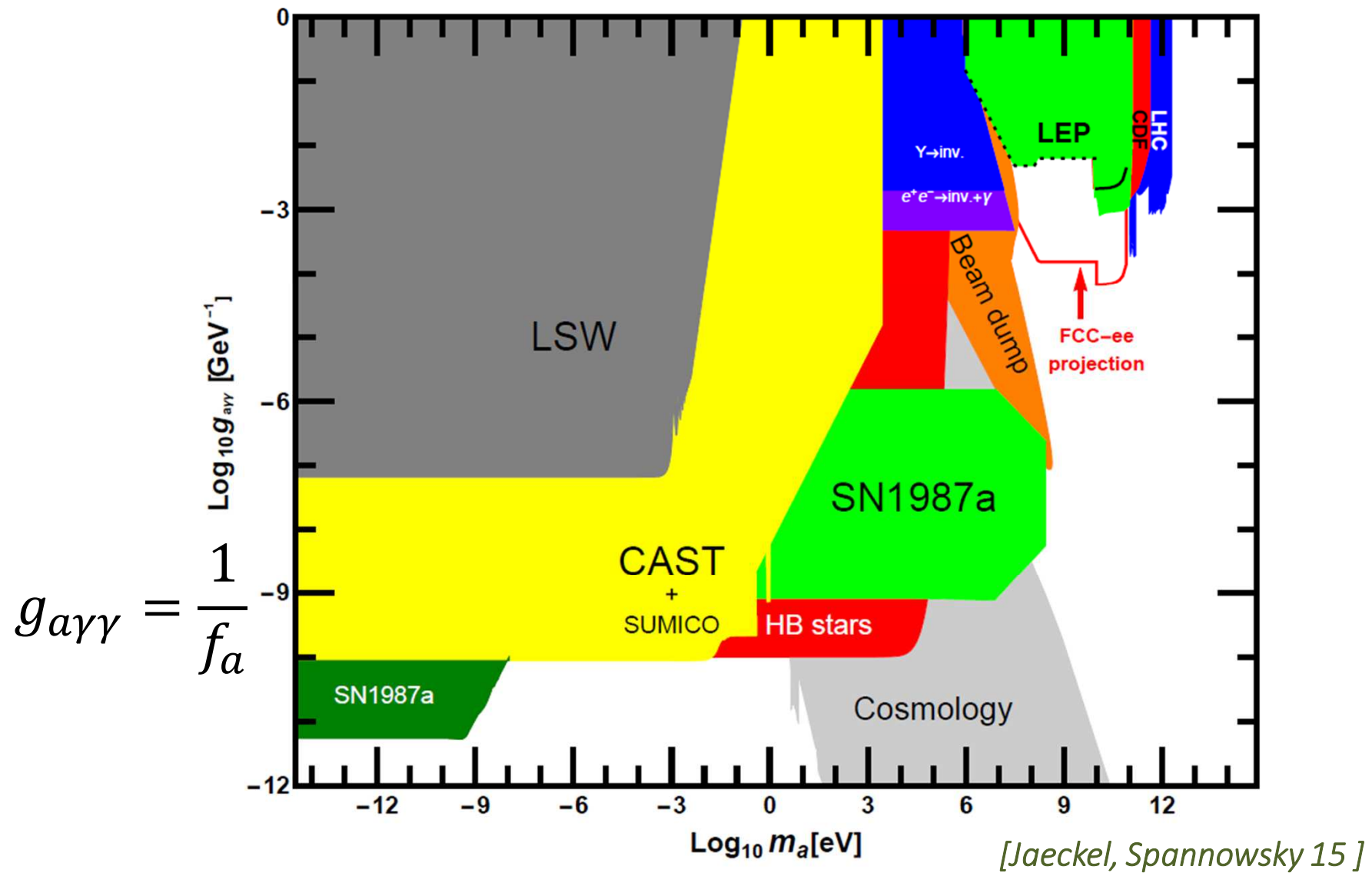
**EWBG**

**hierarchy  
problems**

**GW**

**ALP**

# ALP searches



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



**Landau  
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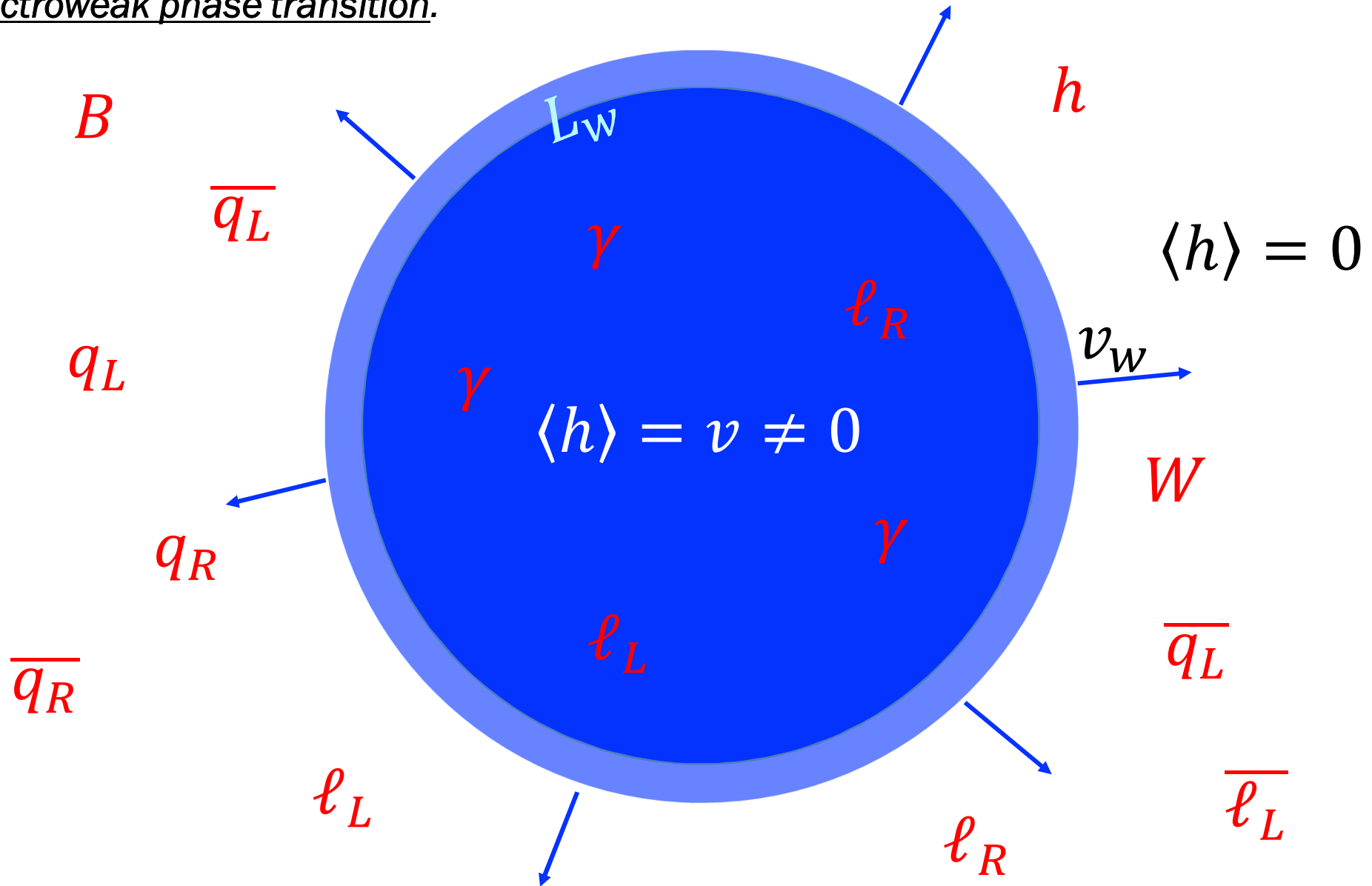
this study

**ALP**

***Idea of EWBG***

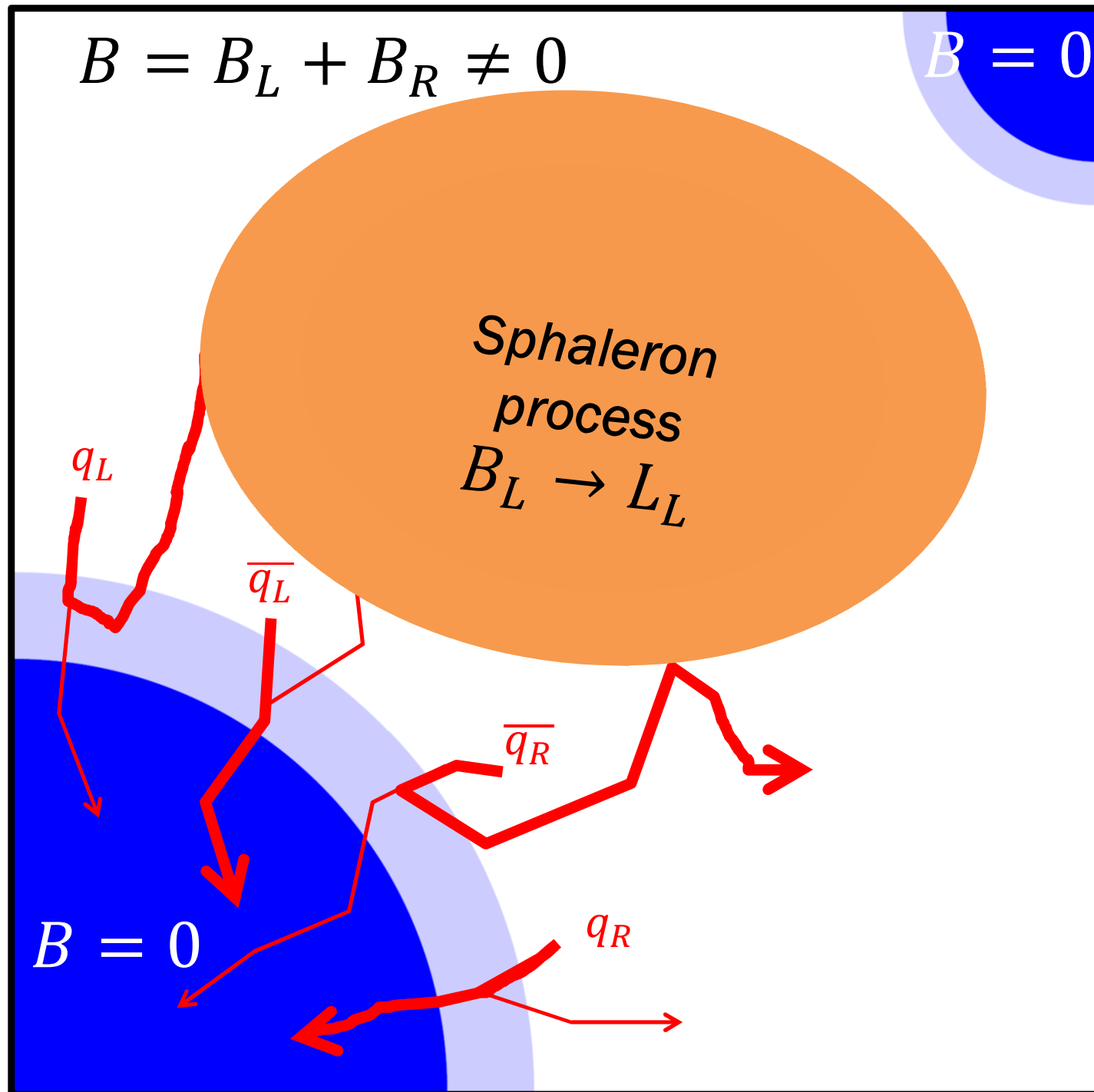
# Electroweak baryogenesis

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

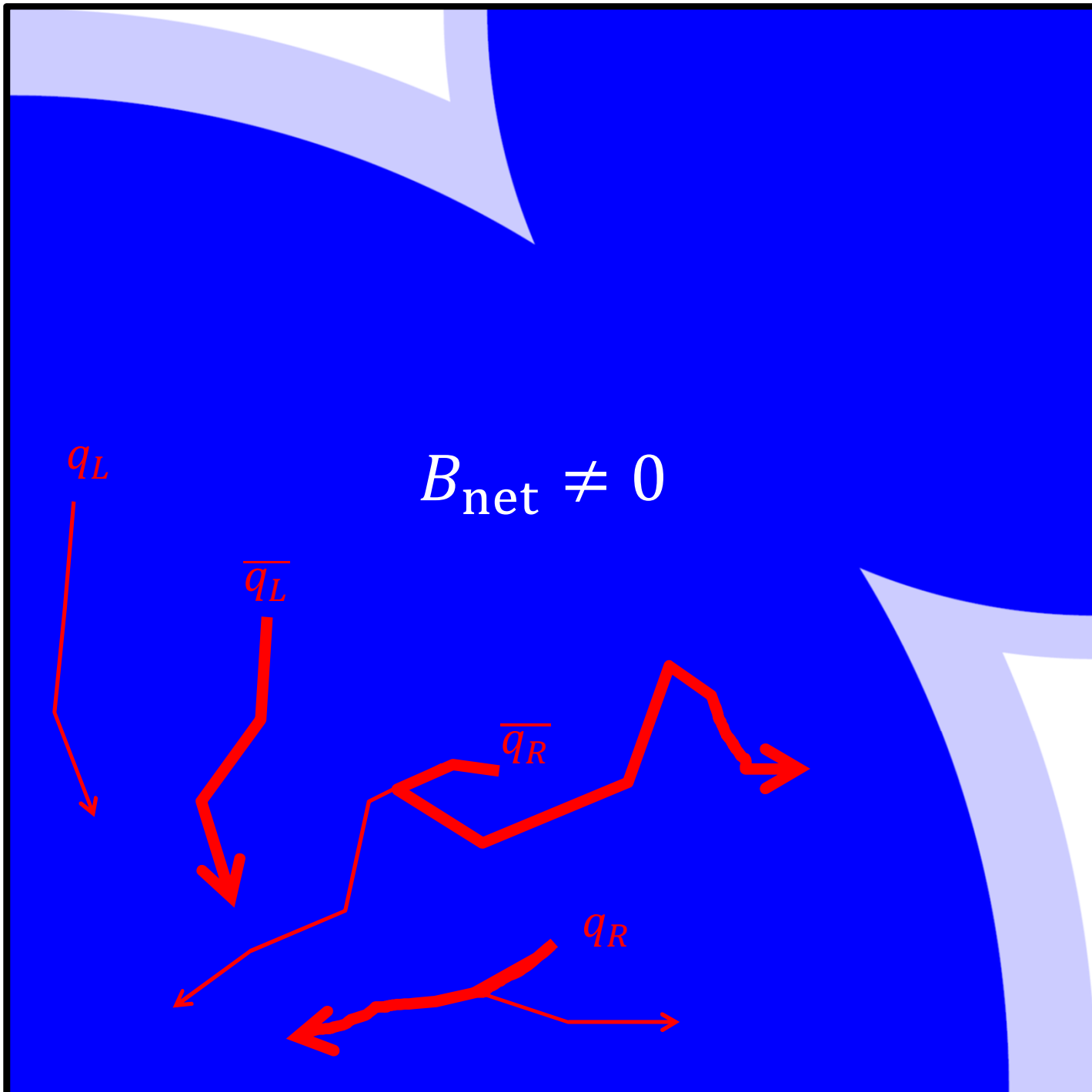




# EWBG 1 (2)



# EWBG 2 (2)

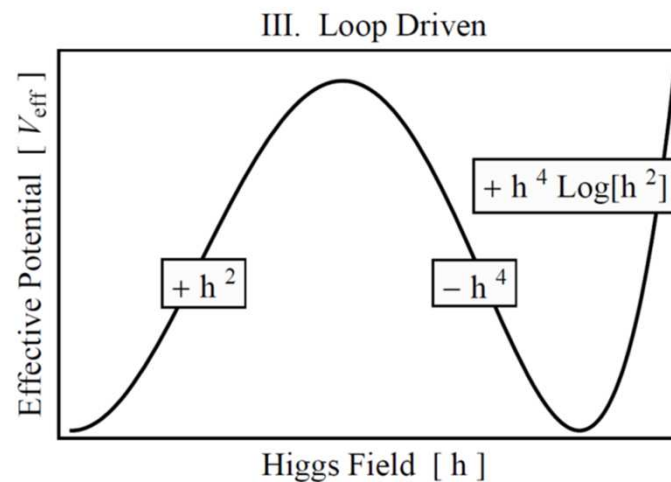
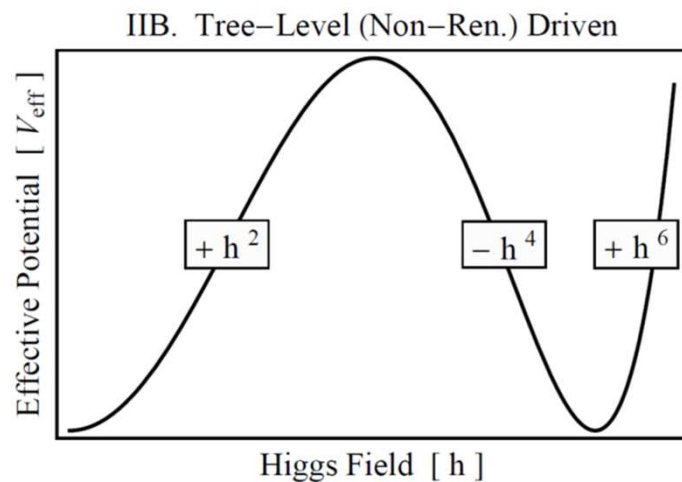
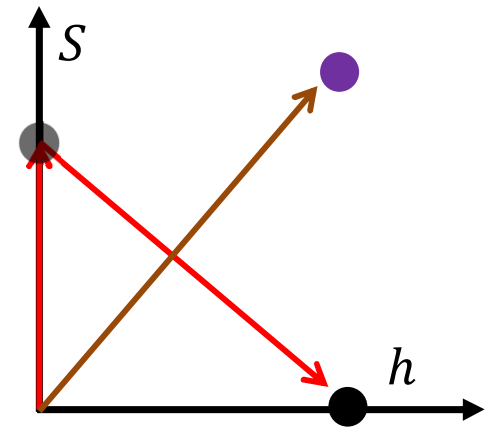
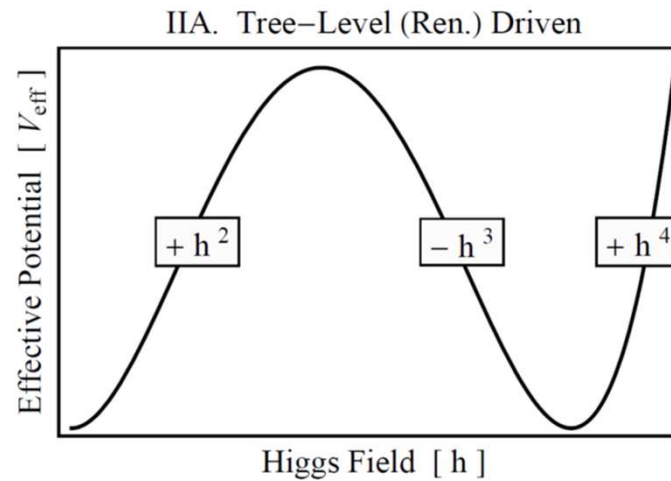
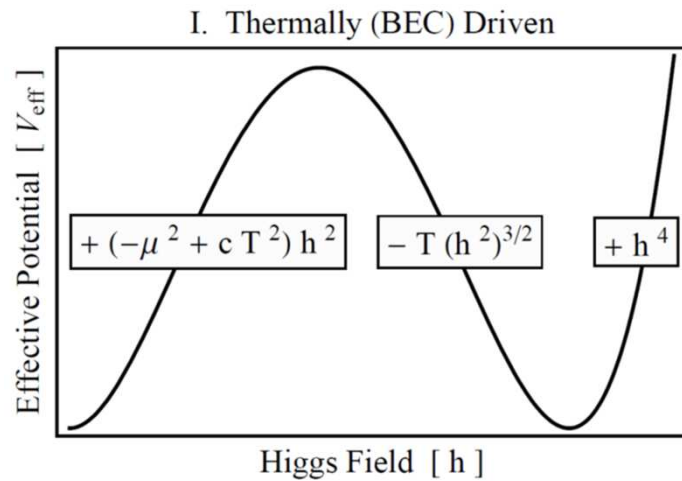


# First order phase transition

Most of extensions beyond the SM focuses on realizing strong 1<sup>st</sup> order EWPT

(single field description)

(multi field description)



[Chung, Long, Wang 12]



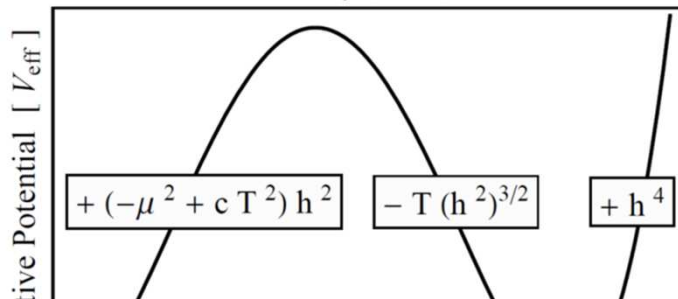
# First order phase transition

Most of extensions beyond the SM to realize strong 1<sup>st</sup> order EWPT *needs strong couplings*

(single field description)

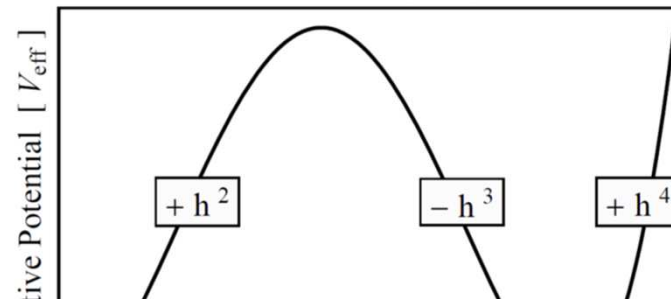
(multi field description)

I. Thermally (BEC) Driven



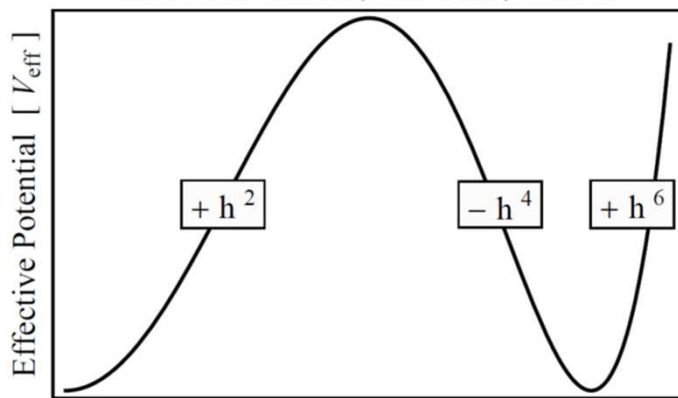
light scalars with large coupling to the Higgs without VEV

IIA. Tree-Level (Ren.) Driven



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

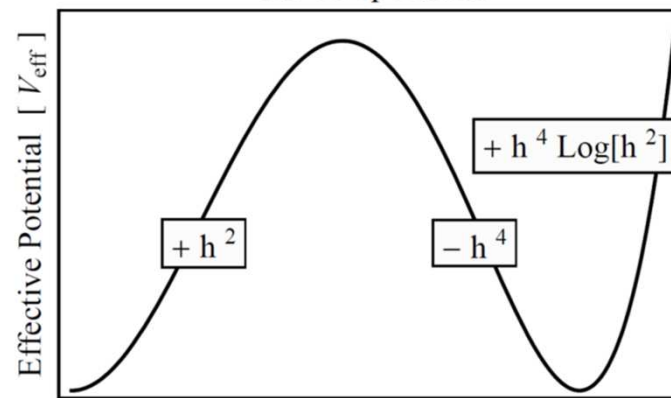
IIB. Tree-Level (Non-Ren.) Driven



Higgs Field [  $h$  ]

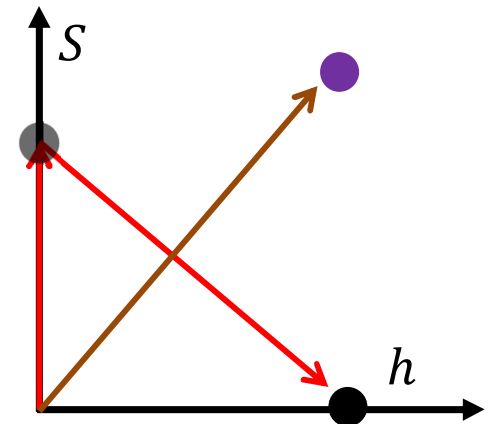
Strong dynamics to give a low cutoff

III. Loop Driven



Higgs Field [  $h$  ]

(charged) light fermions with large couplings to the Higgs



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

[Chung-Leng, Wang 12]

# 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  $V(H, s)$ ,

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

Suggestion:

*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:

$$V(H, a) = V(H^\dagger H, \sin \theta, \cos \theta).$$

As an simple example with  $\mu_1 \sim \mu_2 \sim \Lambda \sim m_W$  (a UV model will be 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  $a/f$ ,

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

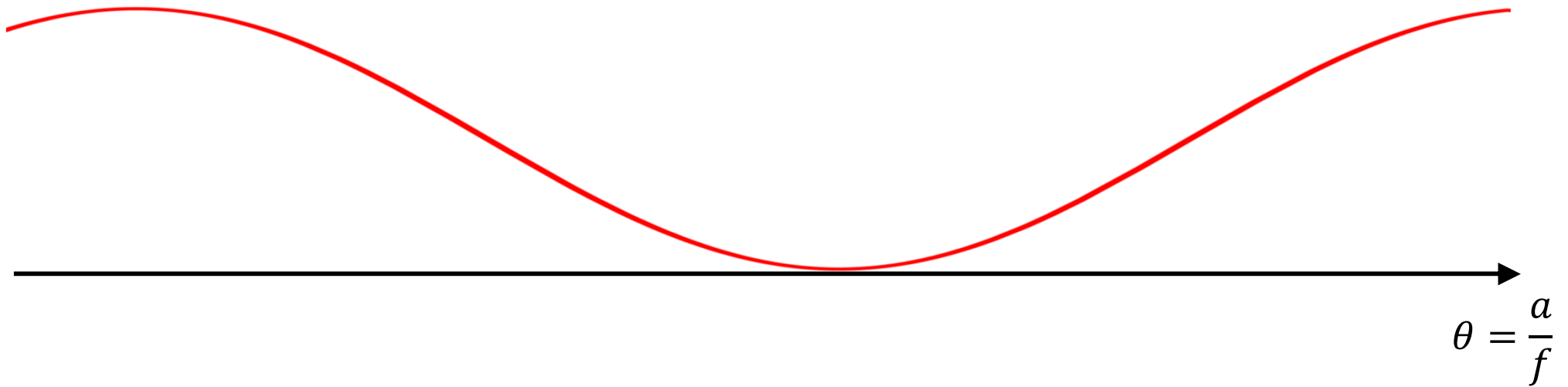
For  $\mu, \Lambda \sim O(m_W) \ll f$ , the couplings between ALP and the Higgs are suppressed.

Baryogenesis with  $\Delta a = O(f)$  during phase transitions cannot be described by renormalizable terms only.

Let us provide a description for such baryogenesis!

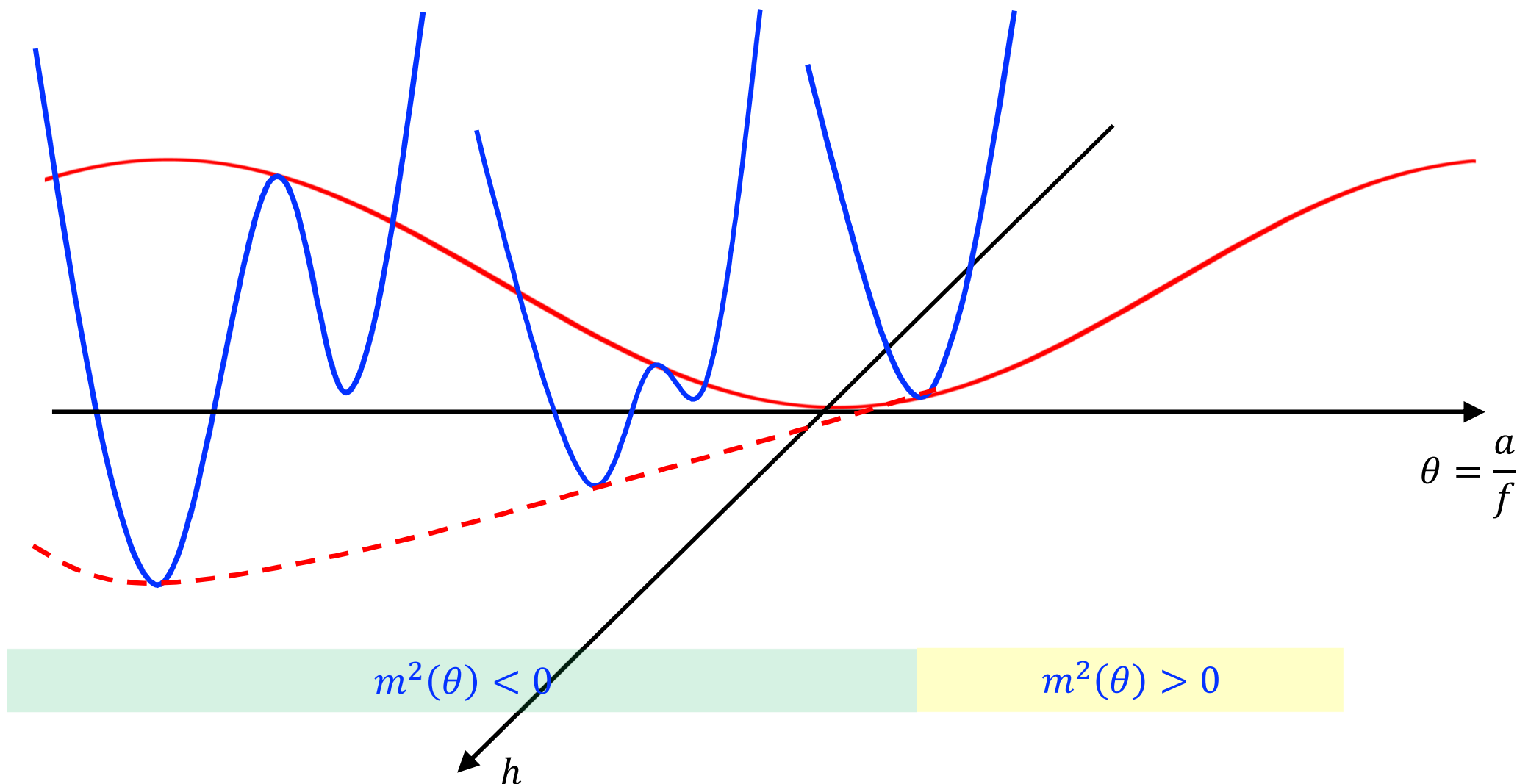
# Schematic description of the potential

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



# Schematic description of the potential

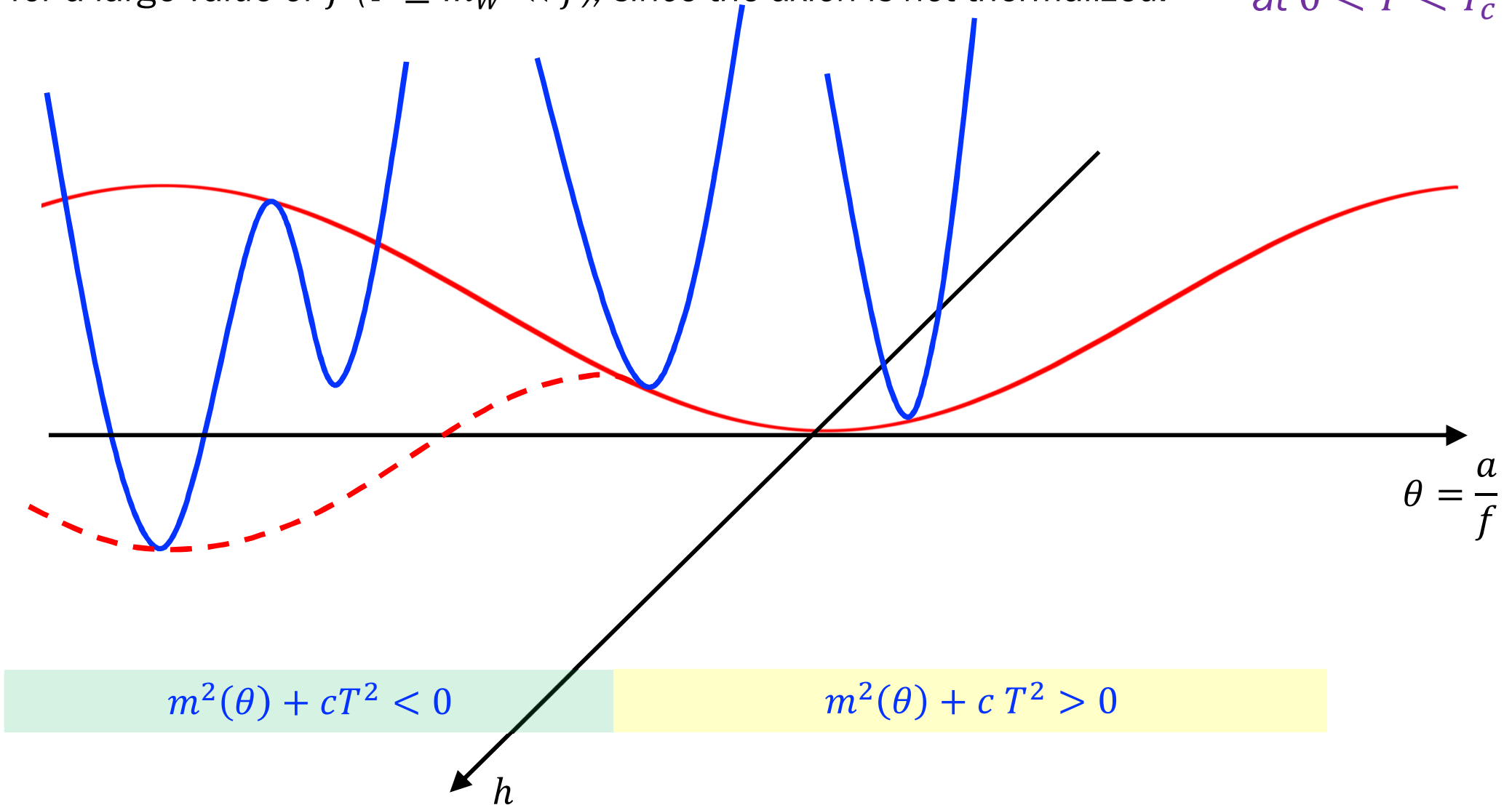
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The potential is bounded from below due to the periodicity of the axion dependence

# Schematic description of EWPT

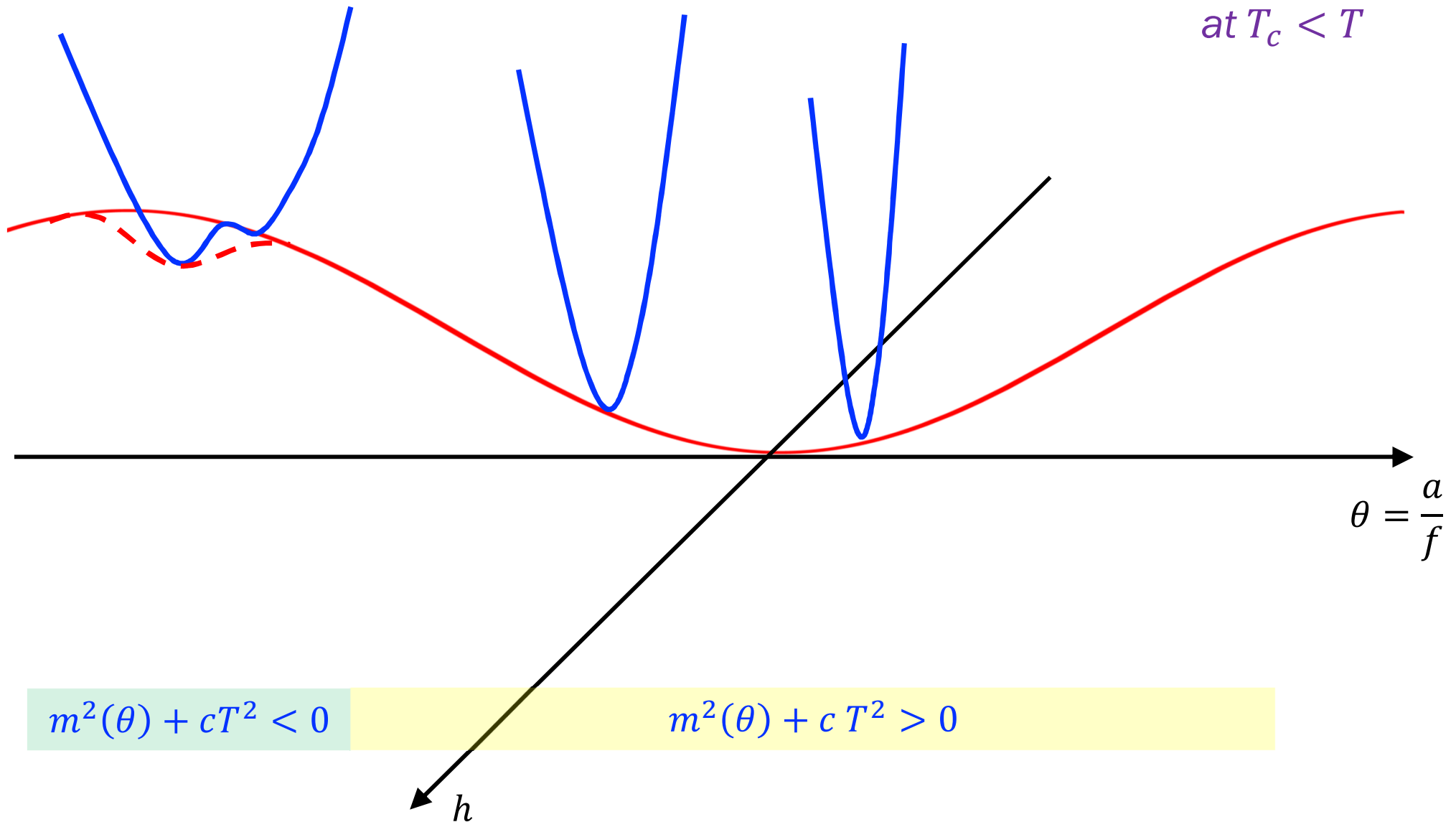
The scalar potential can be written as  $V_T(h, \theta) = \tilde{V}(\theta) + \frac{1}{2}(m^2(\theta) + cT^2)h^2 + \frac{\lambda}{4}h^4$  for a large value of  $f$  ( $T \leq m_W \ll f$ ), since the axion is not thermalized. at  $0 < T < T_c$



# Schematic description of EWPT

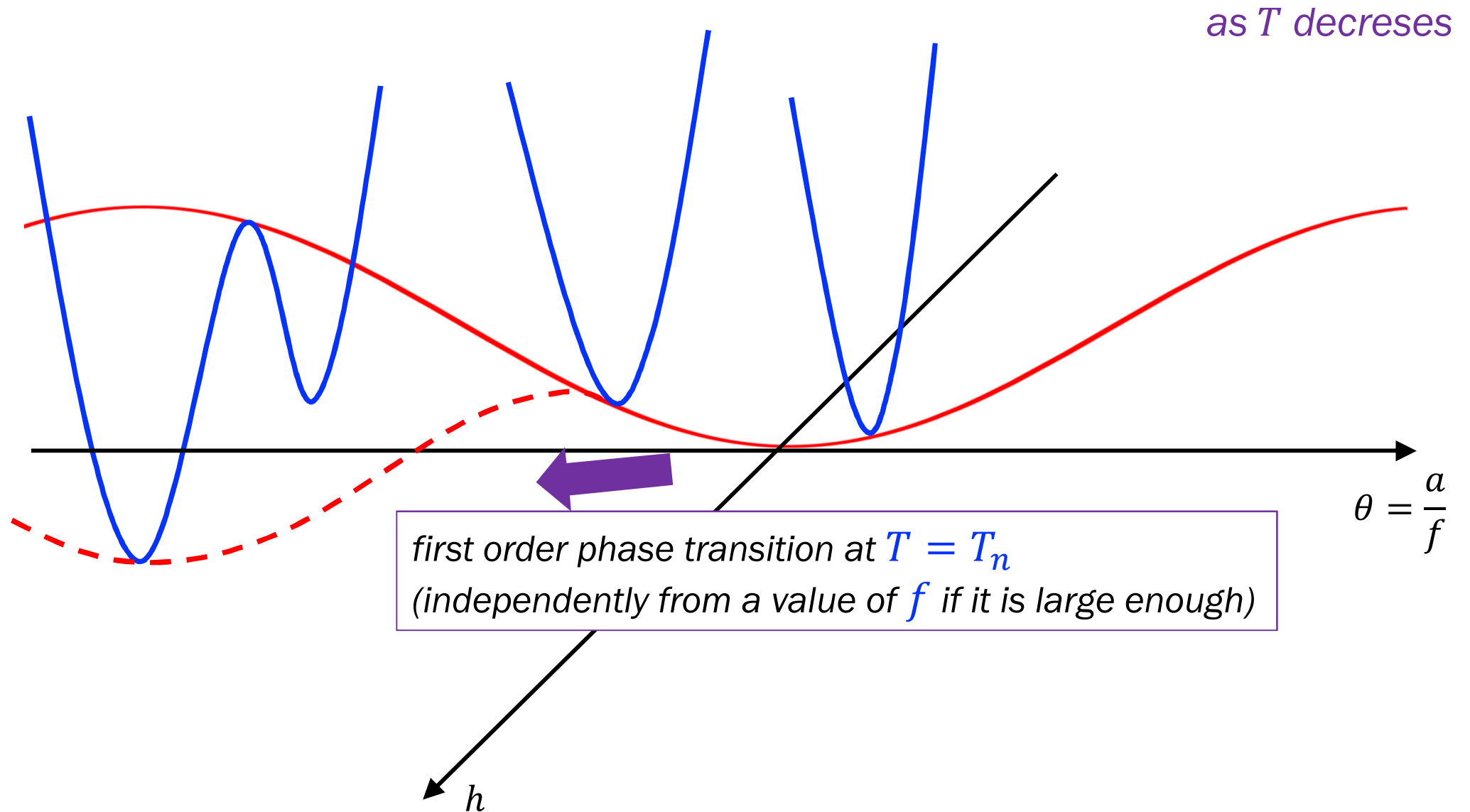
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at  $T_c < T$





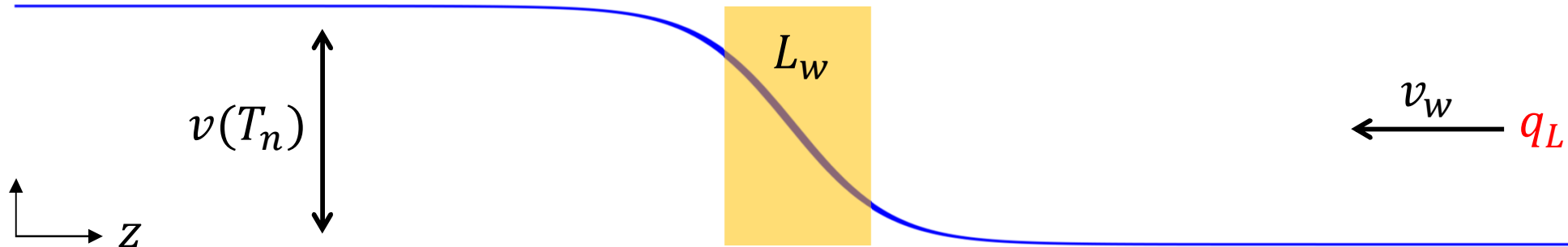
# Schematic description of EWPT



# Conditions for bubble profile

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

$v(T_n)/T_n$ ,  $L_w$ , 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*

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

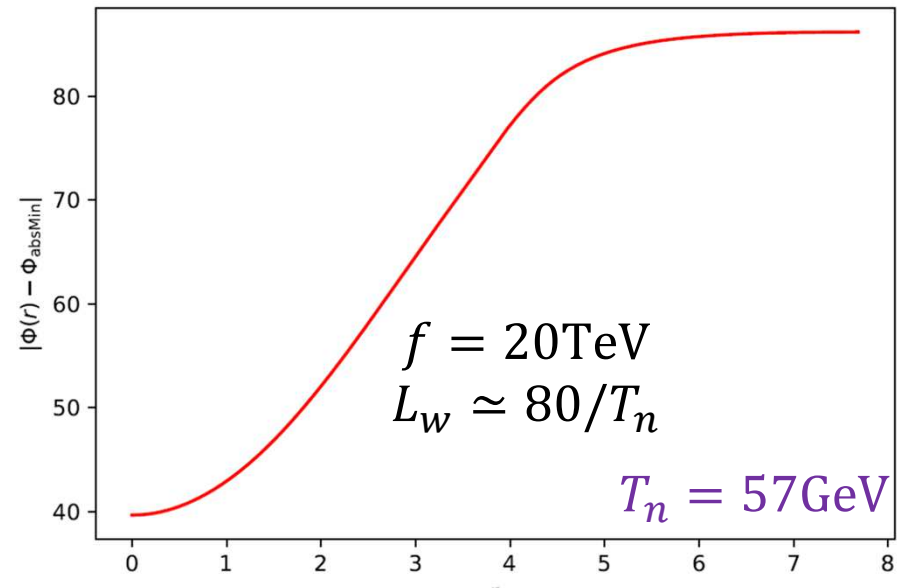
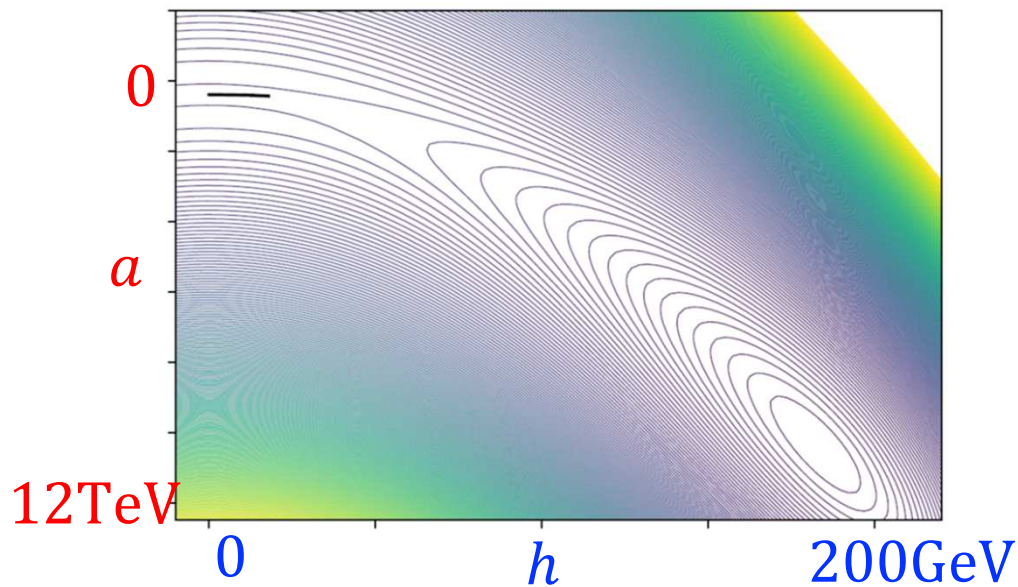
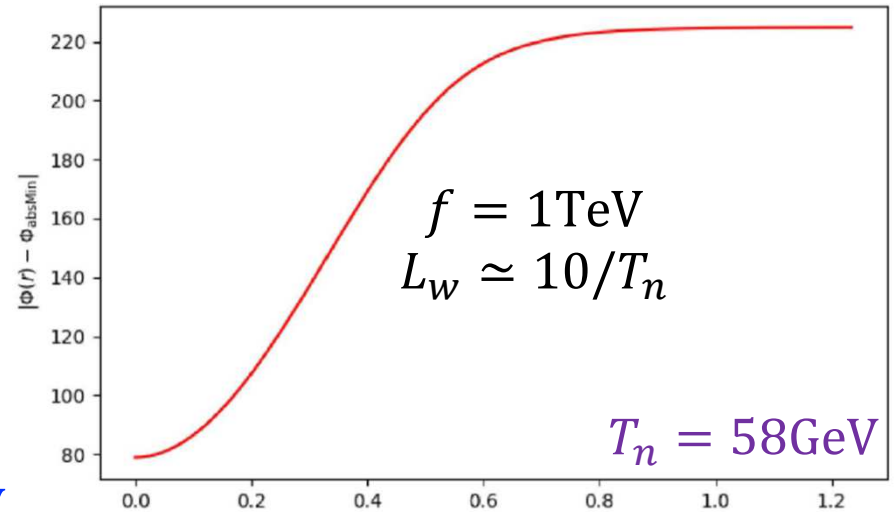
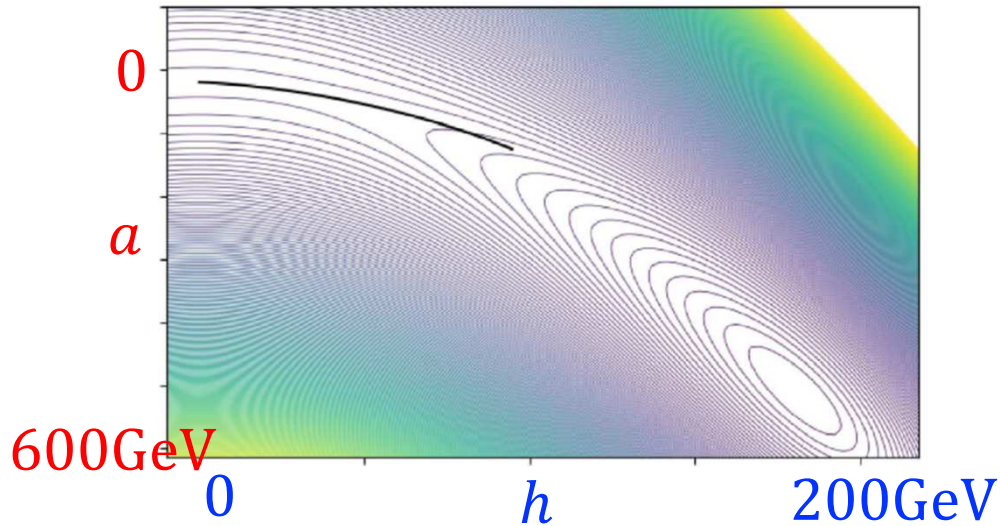
$L_w$  should not be too large *in order for sizable CP violating effects*. E.g. a fermion with CP violating mass,  $|m(z)|e^{i\phi(z)} q_L q_R + h.c$ , the semiclassical CP violating force is

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

[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  $f$ .

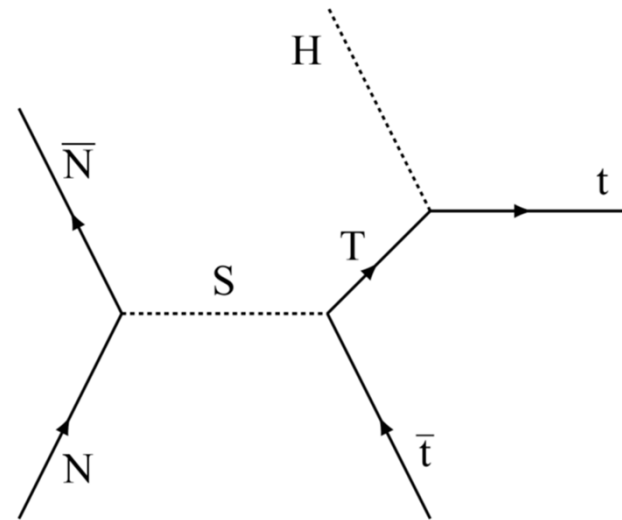
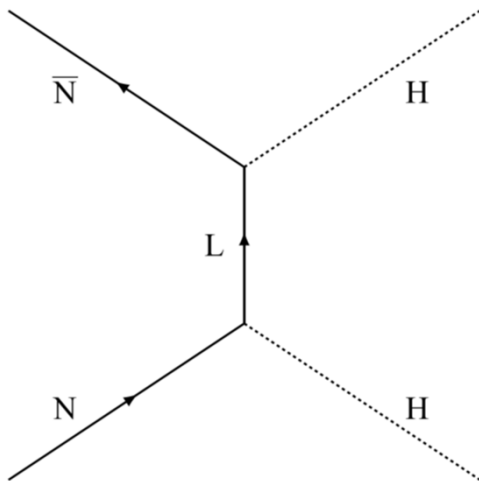


# CP violation and a UV model

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

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

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

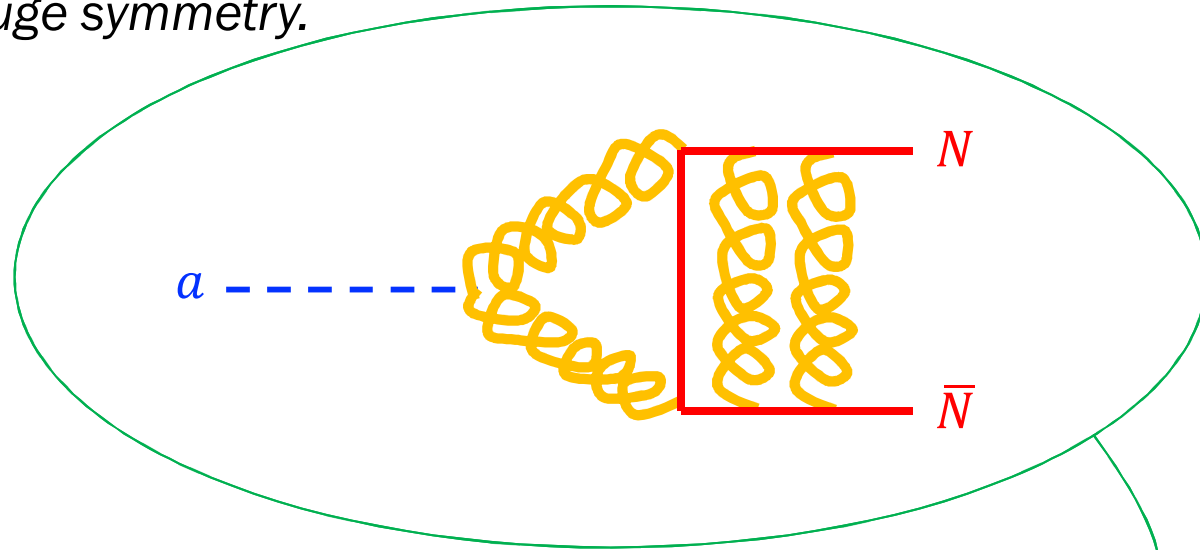
$$\mathcal{L}_{eff}^{(2)} = -m_N \Lambda_h^3 \cos \theta + \frac{yy' \Lambda_h^3}{m_L} \cos(\theta + \alpha) |H|^2 + \frac{\kappa \Lambda_h^3}{m_S^2 m_T} e^{i(\theta + \beta)} H Q_L t_R + h.c.$$

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# ***Results***

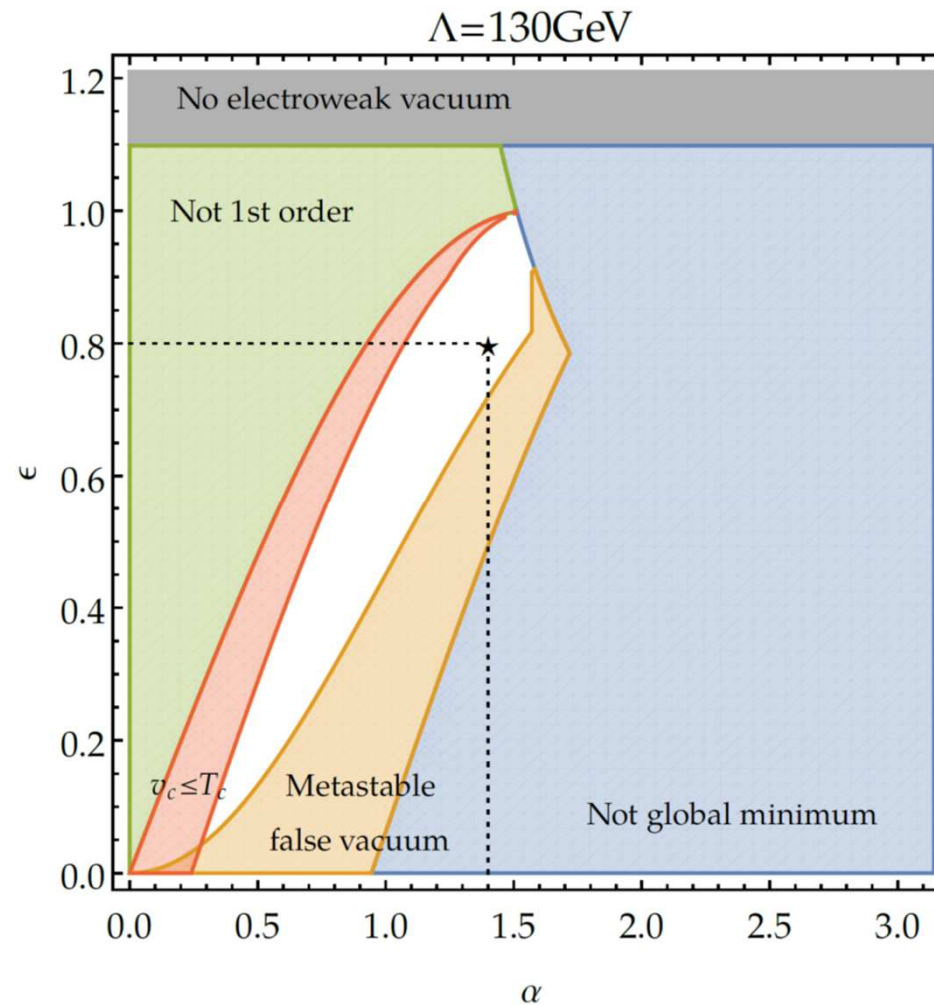
# Benchmark points

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

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

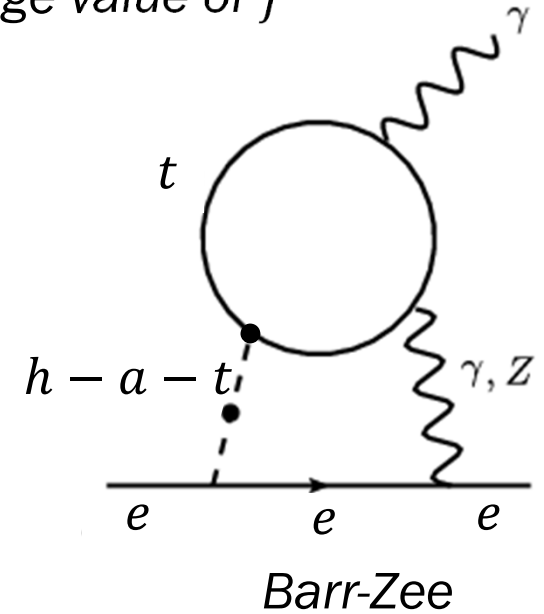
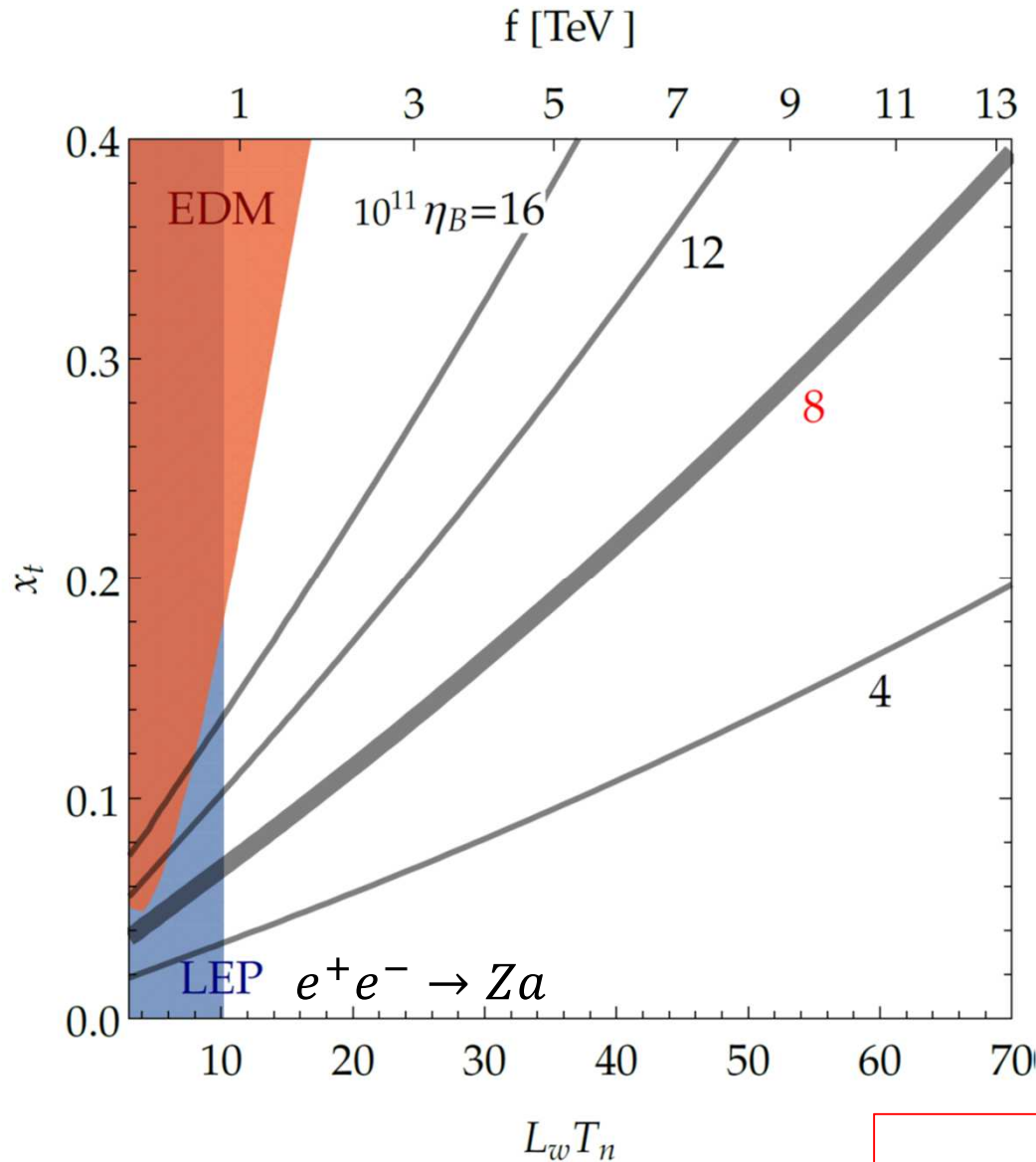
the free parameters are

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



# baryon asymmetry, EDM and collider

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



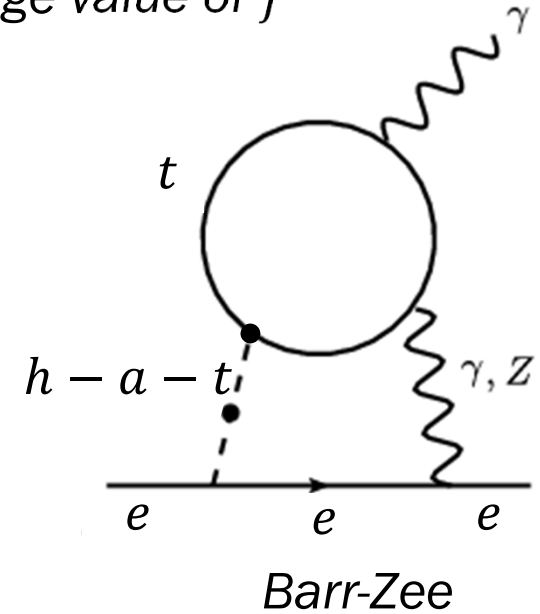
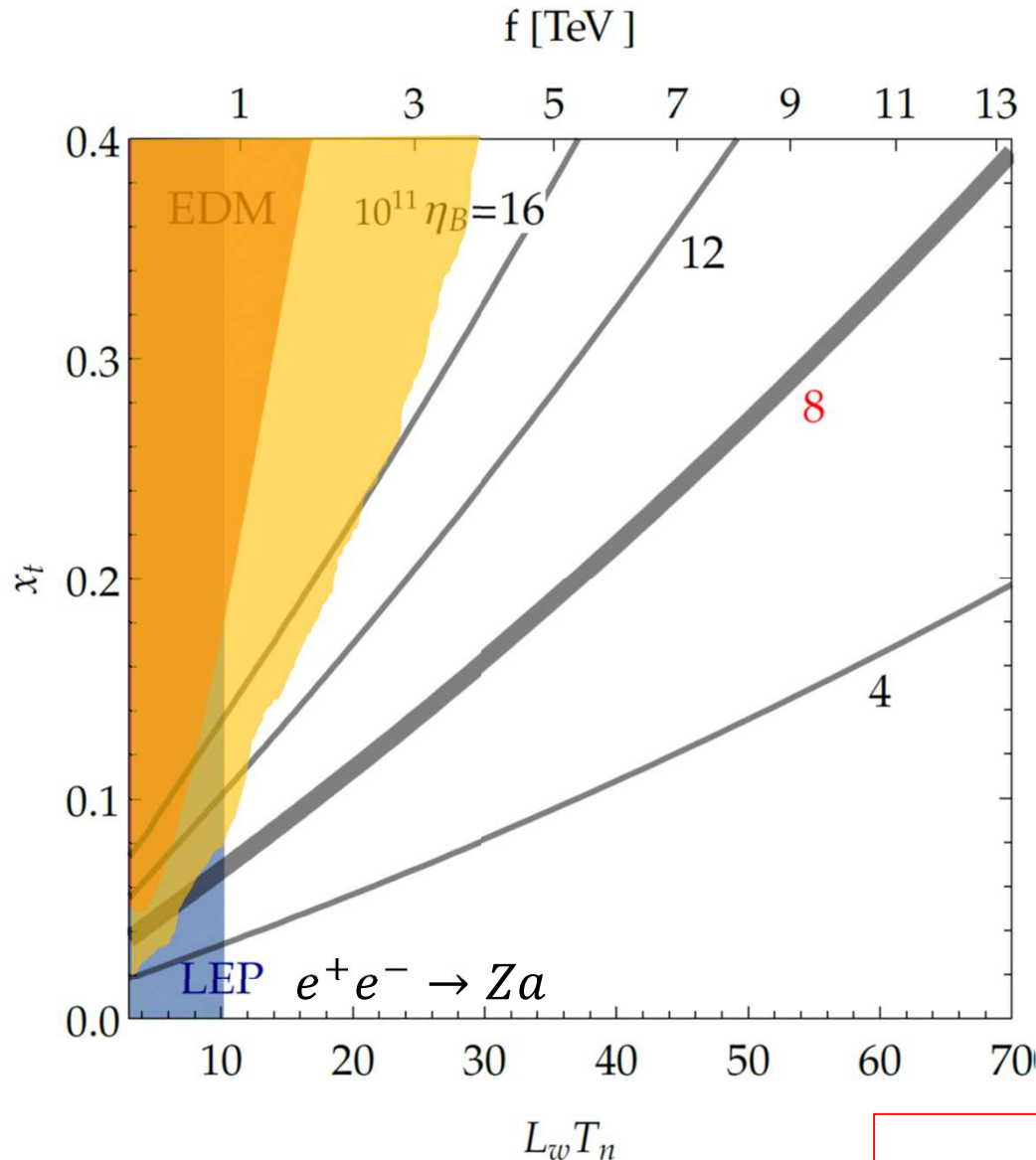
$$\mathcal{L}_{eff} = -\frac{\mu_0^4}{2} \frac{(\delta a)^2}{f^2} + \mu_1^3 \frac{\delta a}{f} \delta h + \mu_2^3 \frac{(\delta a)^2}{f^2} \delta h + i \frac{\delta a}{f} x_t m_t \bar{t} \gamma_5 t + h.c.$$

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

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

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

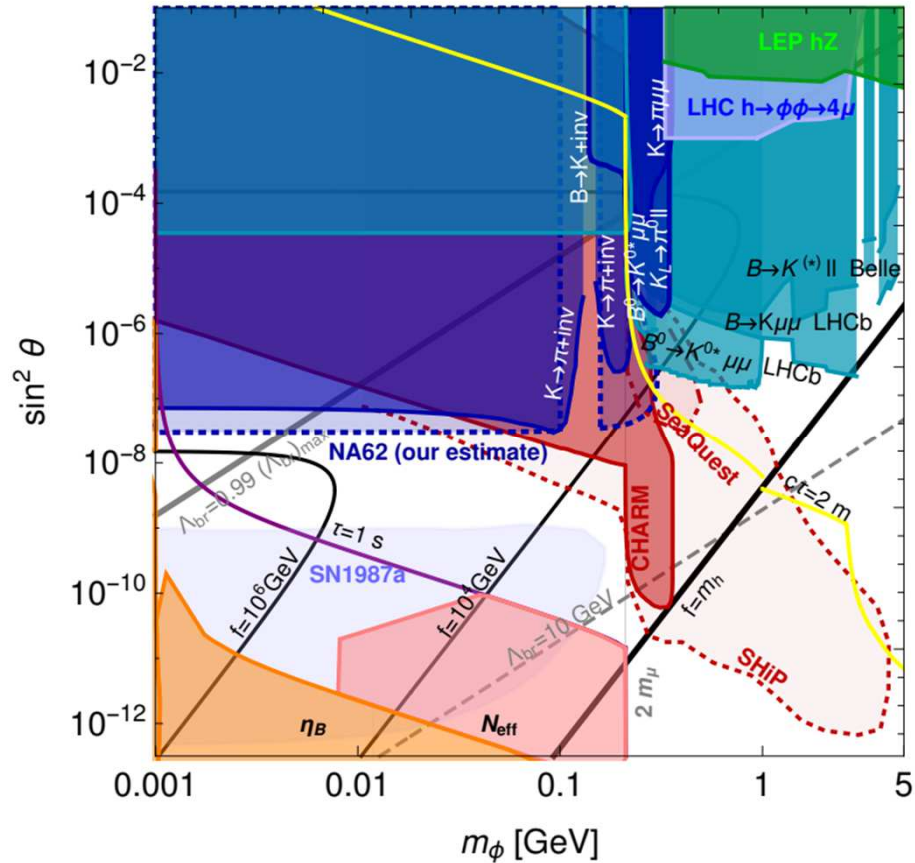
$$m_a \sim m_w \left( \frac{m_w}{f} \right) \rightarrow m_a \sim O(0.1 - 10) \text{ GeV}$$

# ALP searches

After integrating out top and Higgs, ALP couplings to  $\langle \text{gluon, photon, light quark and lepton} \rangle$  are generated. *Model dependent (axion decay channels)* constraints are applied

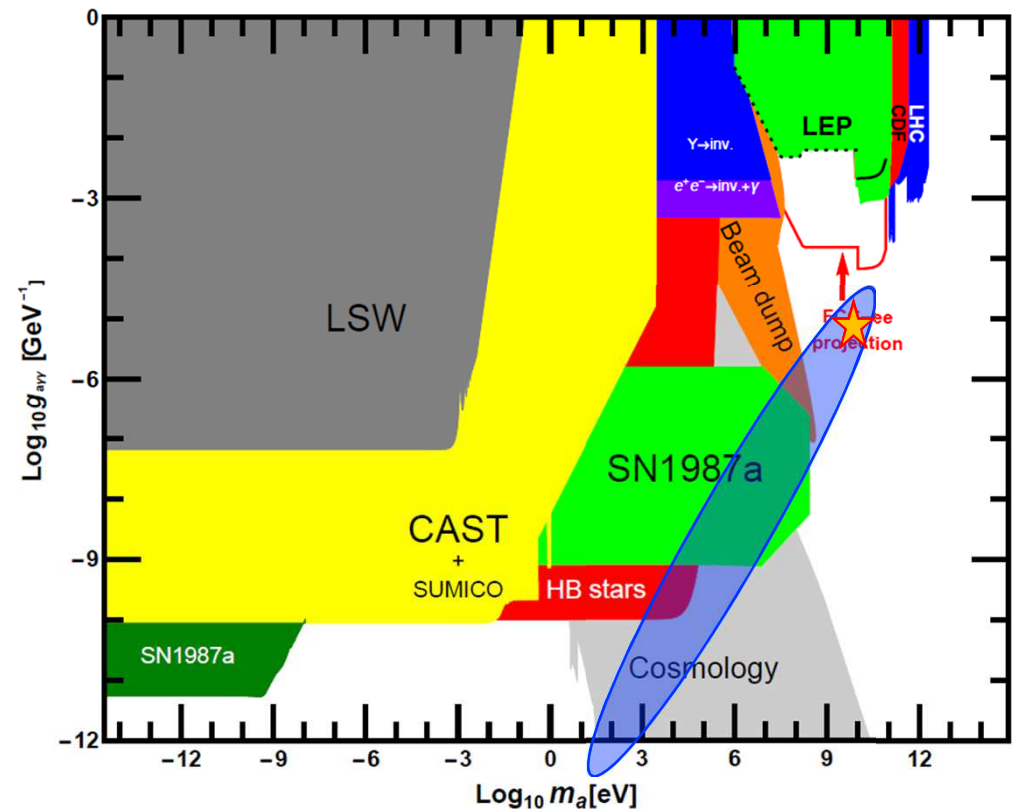
$$\mathcal{L}_{eff} = \frac{1}{16\pi^2} \frac{(\delta a)}{f} \left( c_1 G_{\mu\nu} \tilde{G}^{\mu\nu} + c_2 F_{\mu\nu} \tilde{F}^{\mu\nu} + \dots \right) + \frac{\delta a}{f} \delta_{\text{mix}} m_q \bar{q}q + \frac{\delta a}{f} \delta_{\text{mix}} m_\ell \bar{\ell}\ell$$

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



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

[Choi, Im 16]



[Jaeckel, Spannowsky 15]

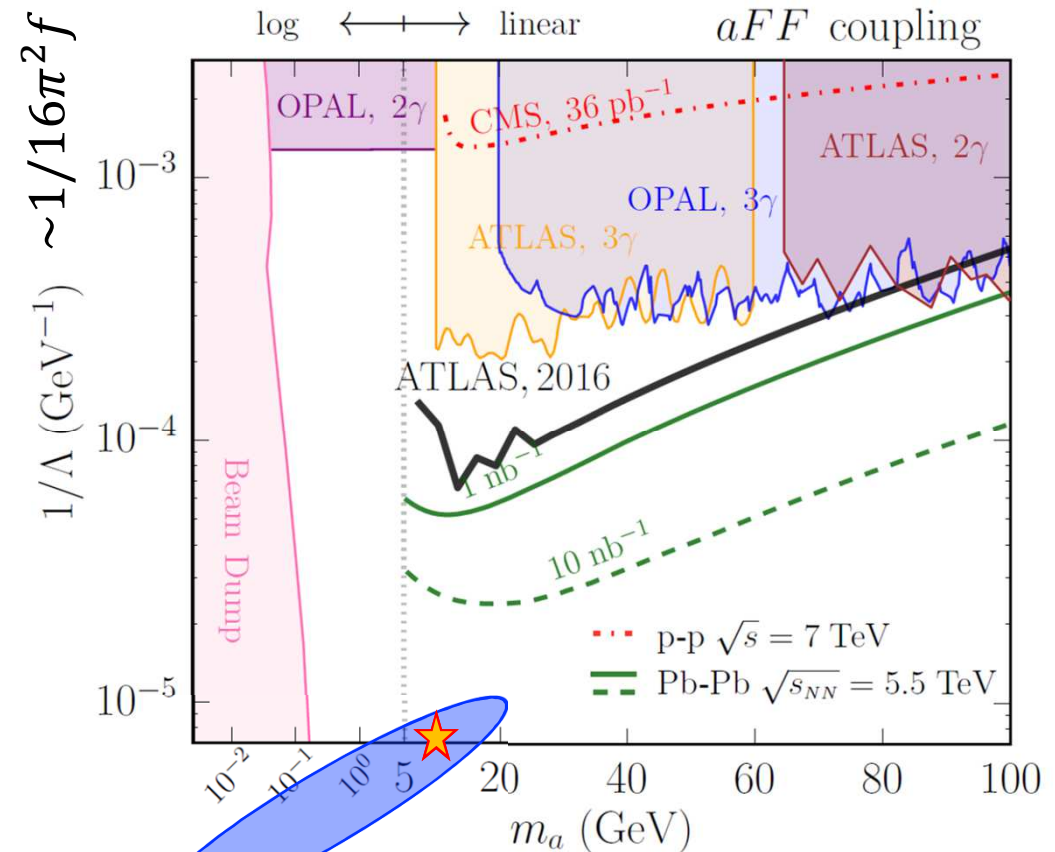
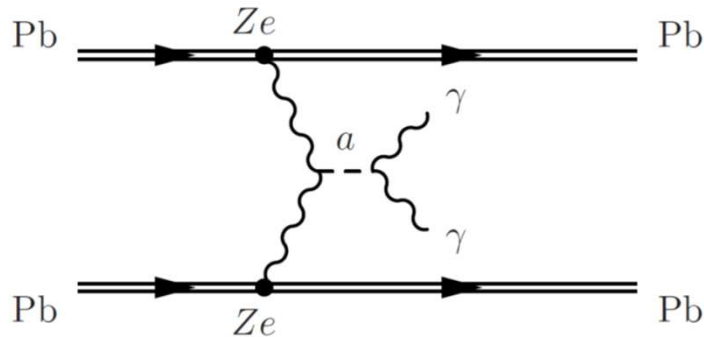


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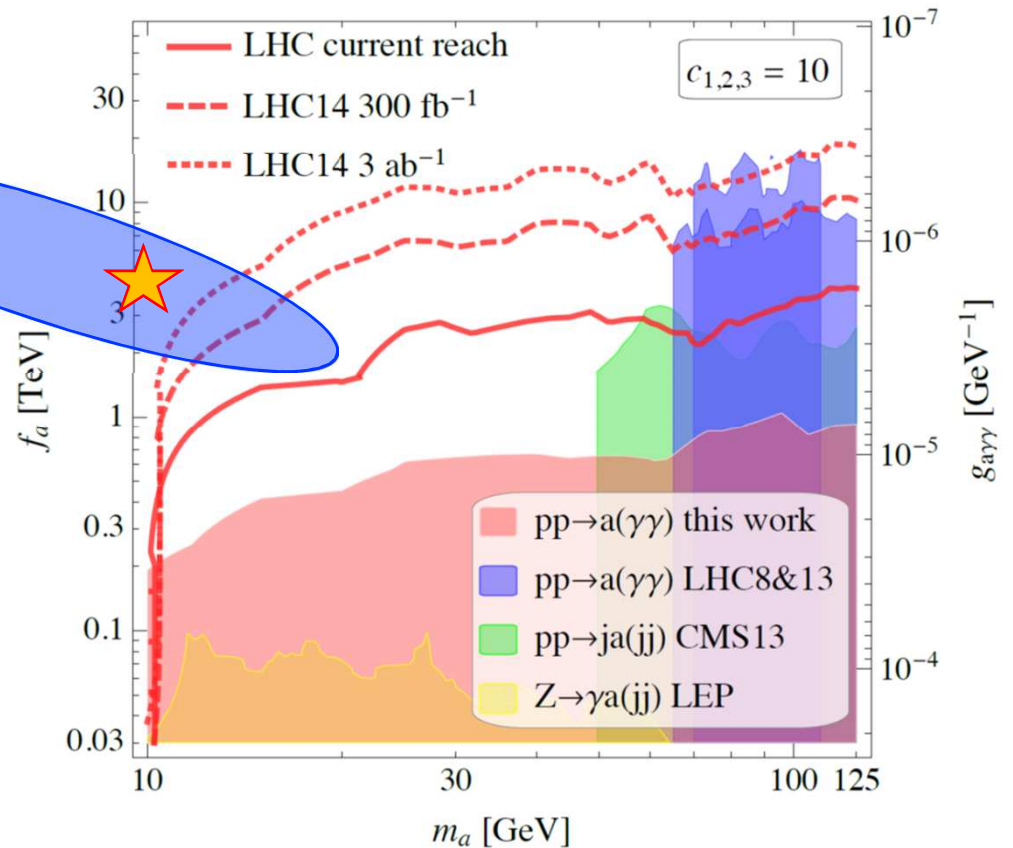
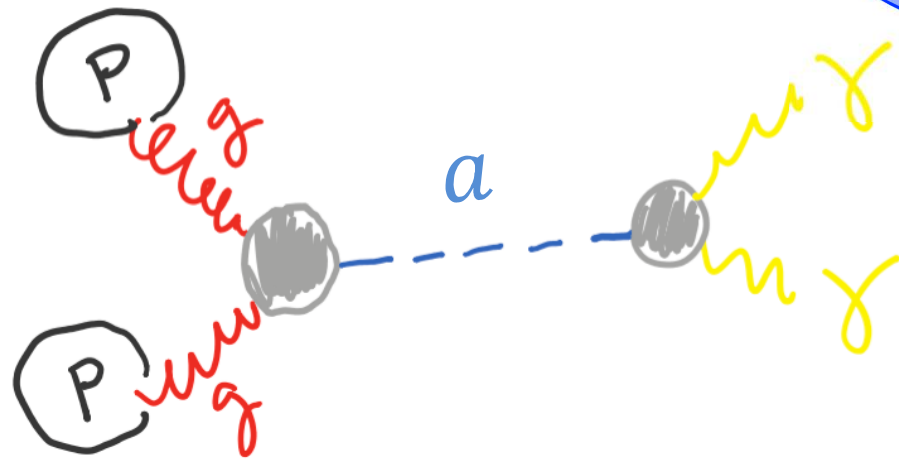
[Knapen, Lin, Lou, Melia 17]

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Axion with mass around (5 – 10) GeV is model independently safe.



[Mariotti, Redigolo, Sala, Tobioka 17]

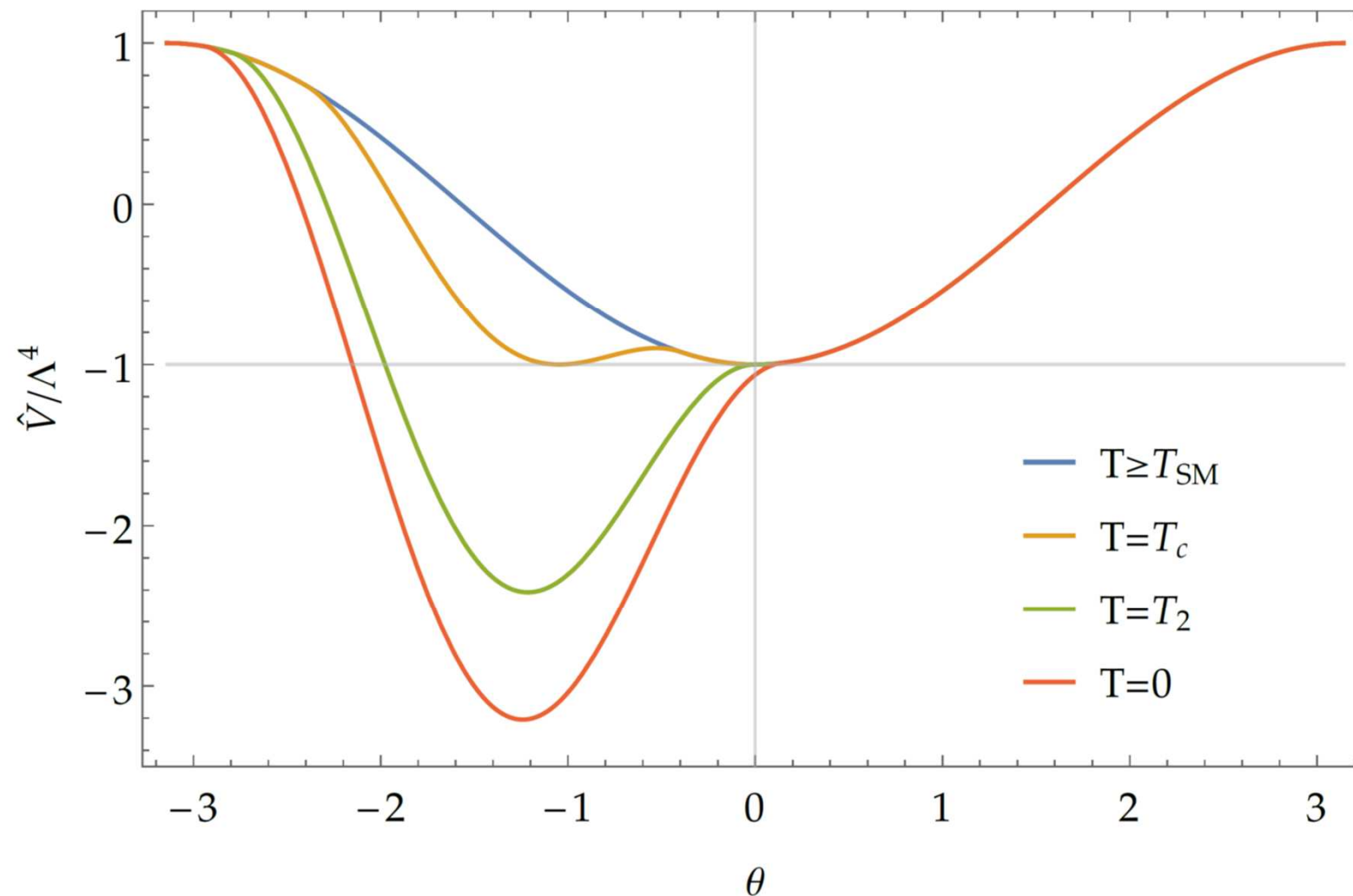
# Conclusions

- *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 $\theta$

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  $\partial_h V(h, \theta)|_{h=h_{ex}} = 0$

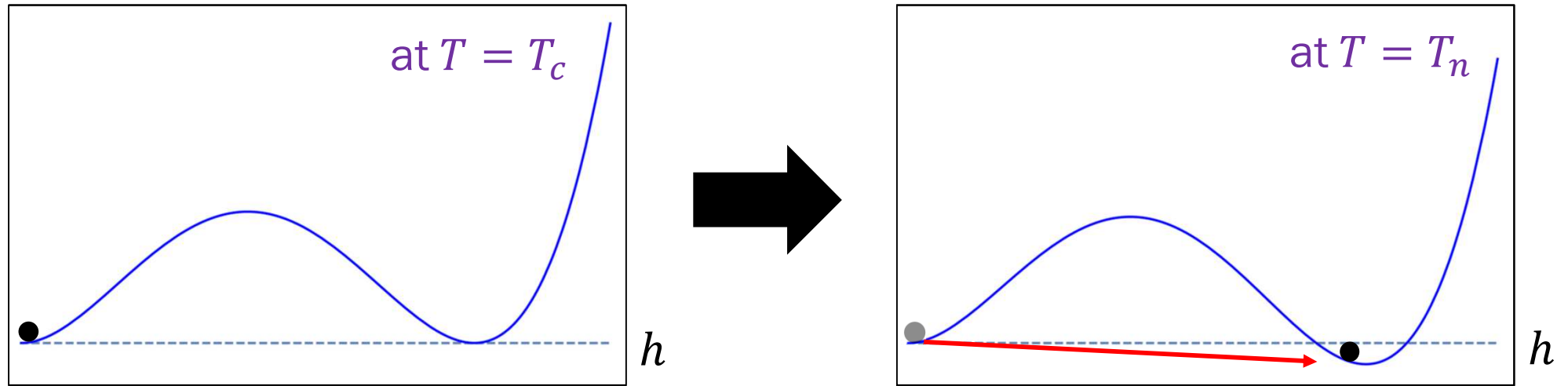


What would be the **constraints (predictions)** of the axionic extension for EWBG?



# Tunneling

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

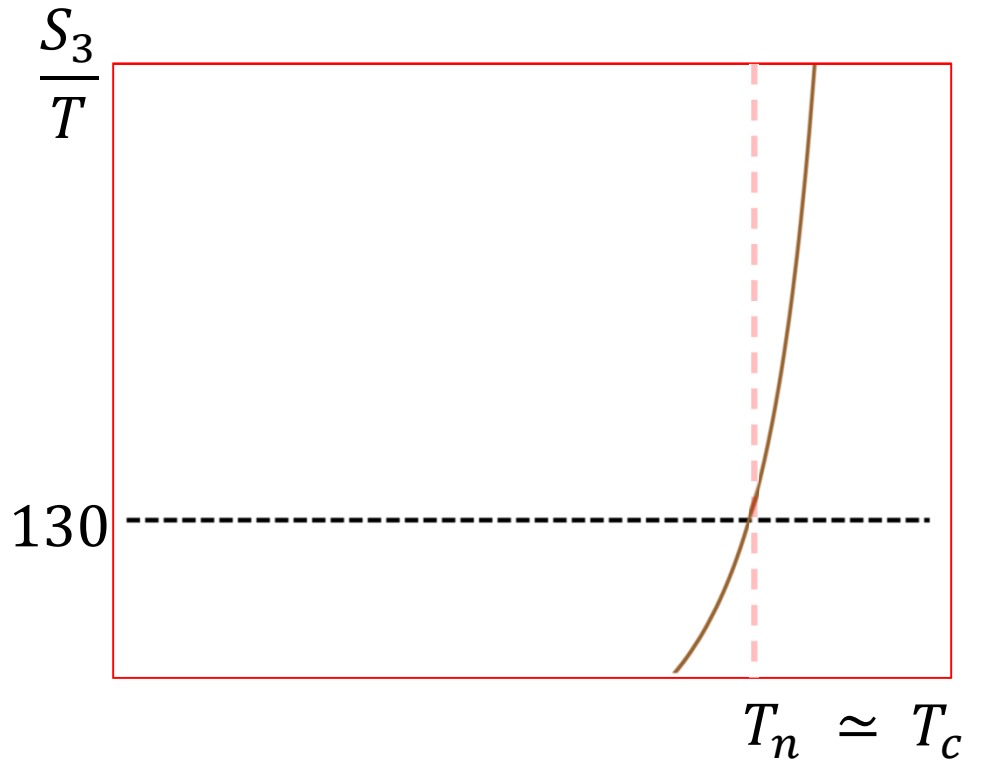


Bubble nucleation rate with the Euclidean action  $S_3$  for an  $O(3)$ -symmetric critical bubble

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

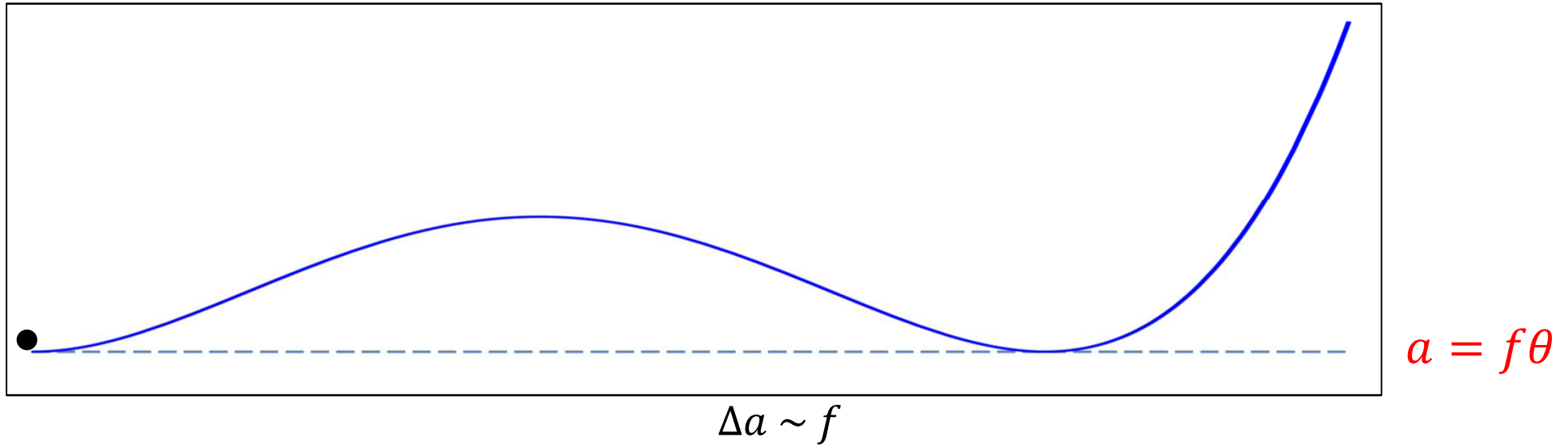
Typically,

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



# Tunneling

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



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

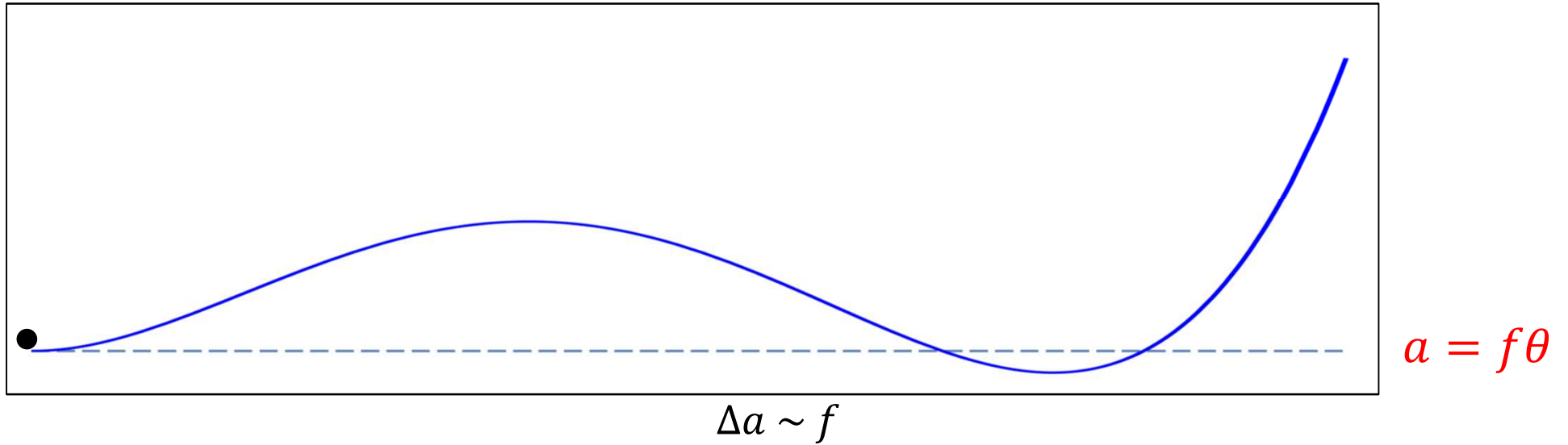
$$= 4\pi f^3 \int du u^2 \left( \frac{h'^2}{2f^2} + \frac{1}{2} \theta'^2 + V_T(h, \theta) \right) \text{ where } u = r/f \text{ with e.o.m.}$$

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

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

# Tunneling

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

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

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

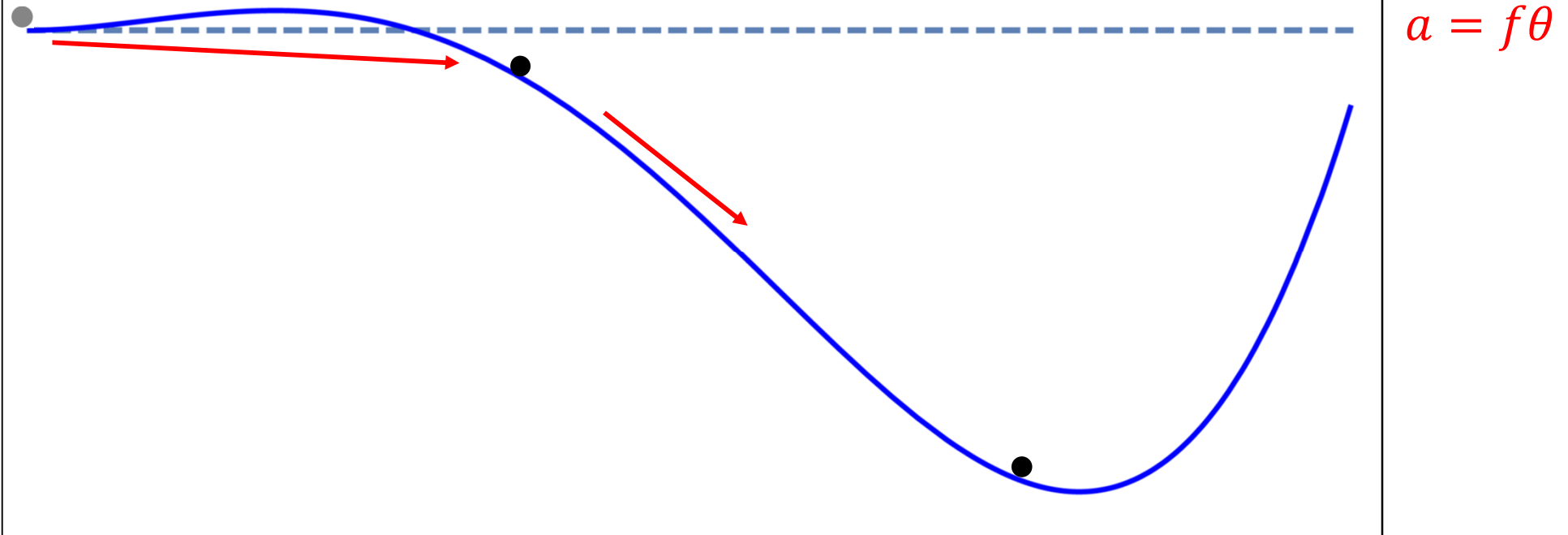
For a large  $f$ , the Higgs trajectory is nearly following  $\partial_h V \approx 0$  and its effect on  $S_3$  negligible.

# 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)



Still this is very different from second order phase transitions

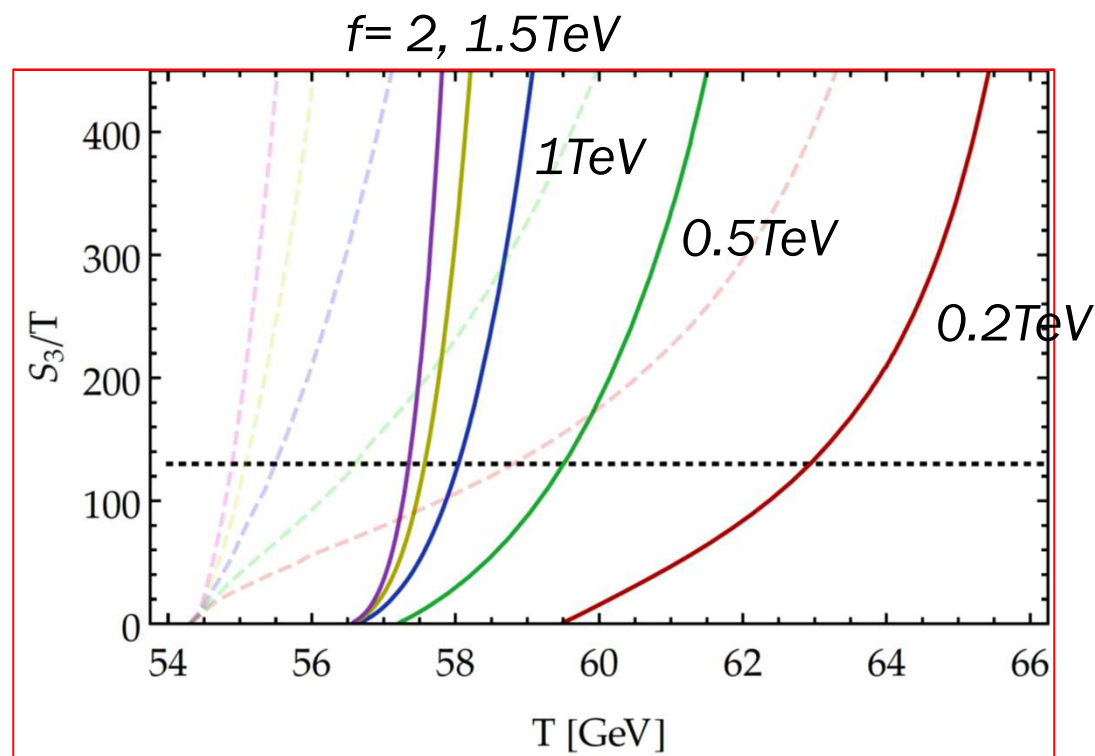
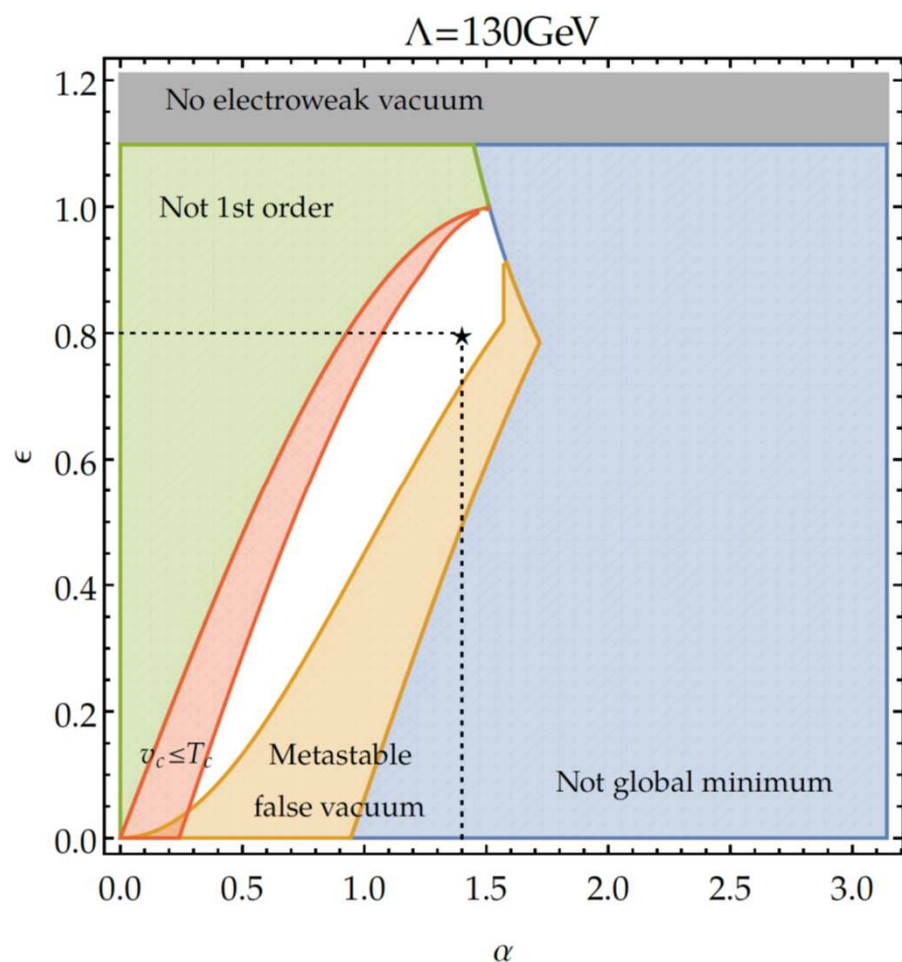
# Benchmark points

After fixing parameters by the Higgs mass 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

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

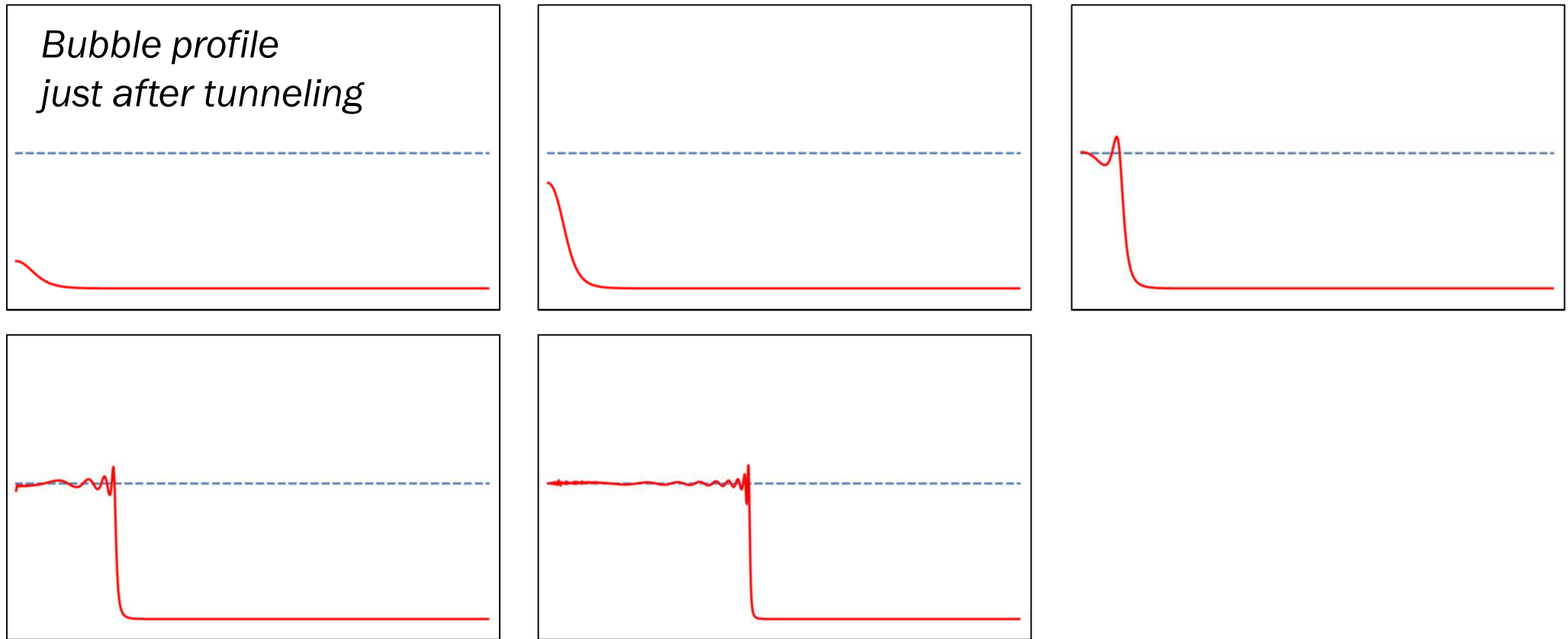


$$\frac{S_3}{T} = 130: T_n \text{ (nucleation starts)}$$

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

# 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  $\Delta t \sim 1/m_a \sim f/m_W^2$ .

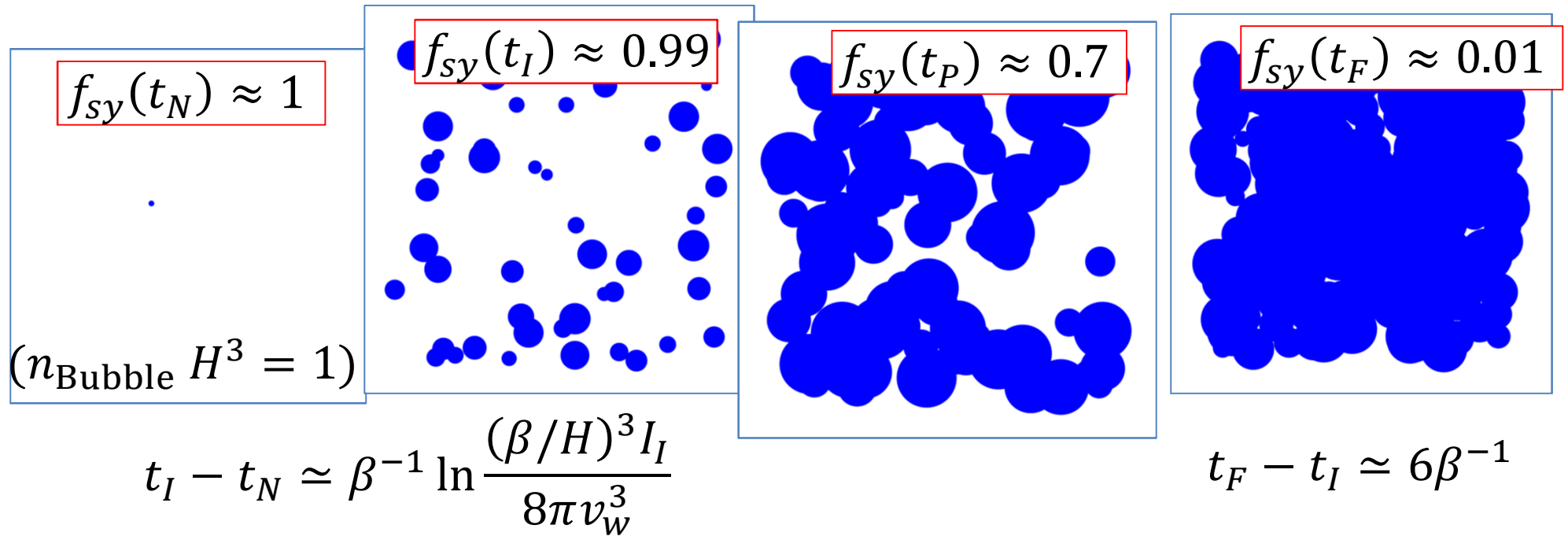


- 1) *The axion (so the Higgs) should quickly arrive at its vacuum value.* Otherwise strong first order phase transition cannot be obtained before bubbles collide and fill the Universe.
- 2) *The bubble wall width  $L_W$  should not be too large compared to  $1/T_n$ .* Otherwise, the effects of CP violation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



[Megevand, Ramirez 16]

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

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