Axionic Electroweak Baryogenesis

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arXiv: 1806.02591, 1811.03294

Brief introduction to electroweak baryogenesis

SM has a baryon number (B+L) changing process in a thermal plasma: **sphaleron**

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$\longrightarrow$ BAU?

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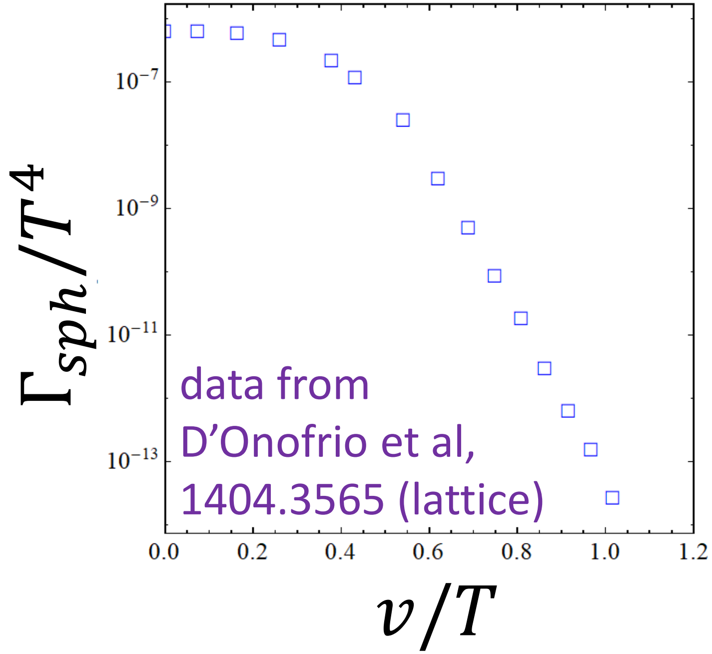
Basically, it is exponentially suppressed when $v \gtrsim T$



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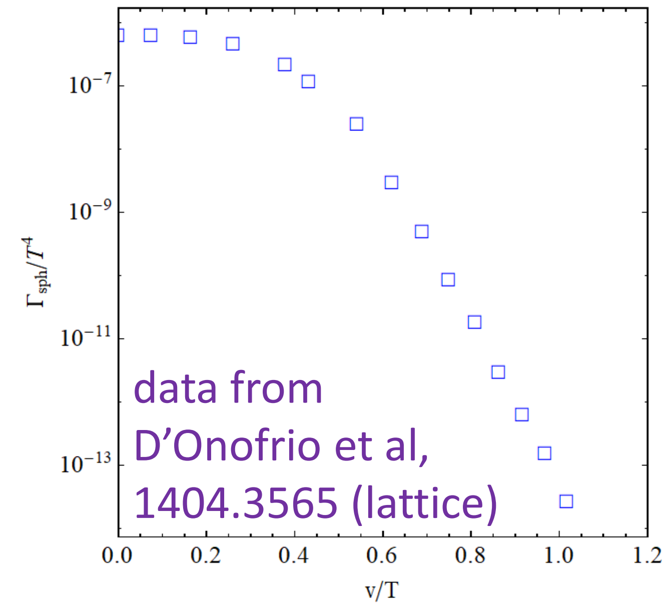

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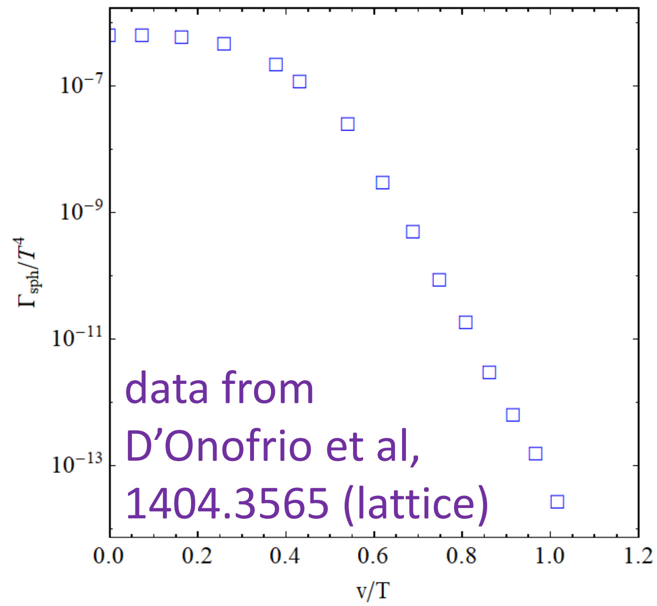

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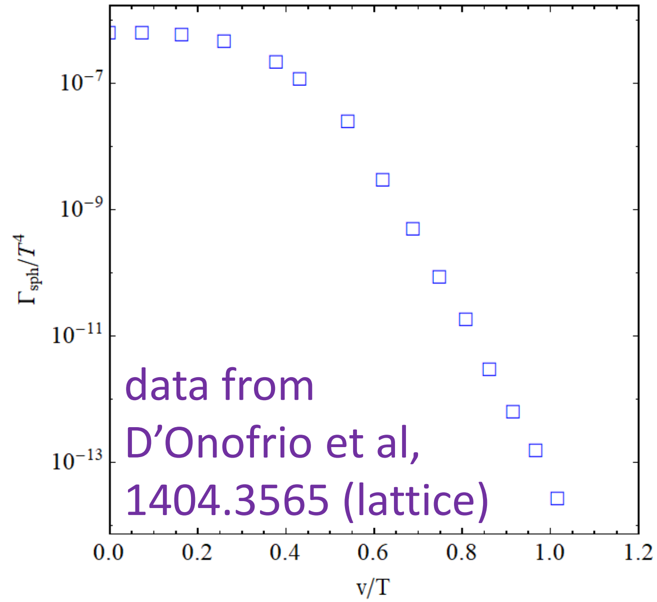

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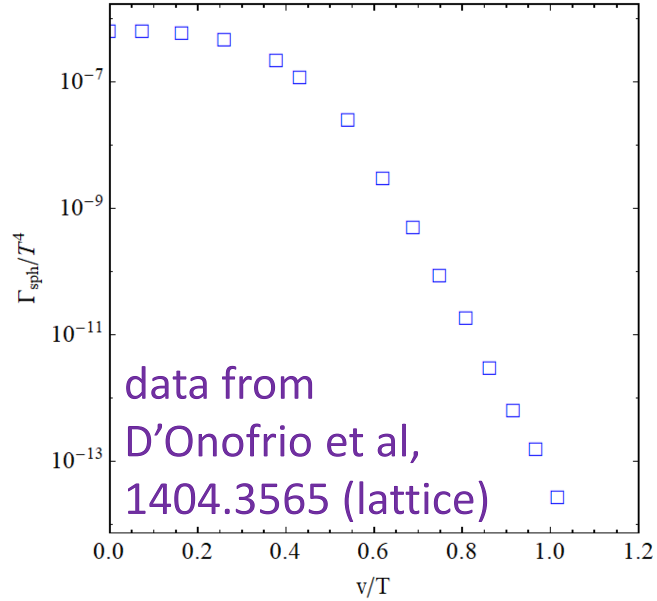

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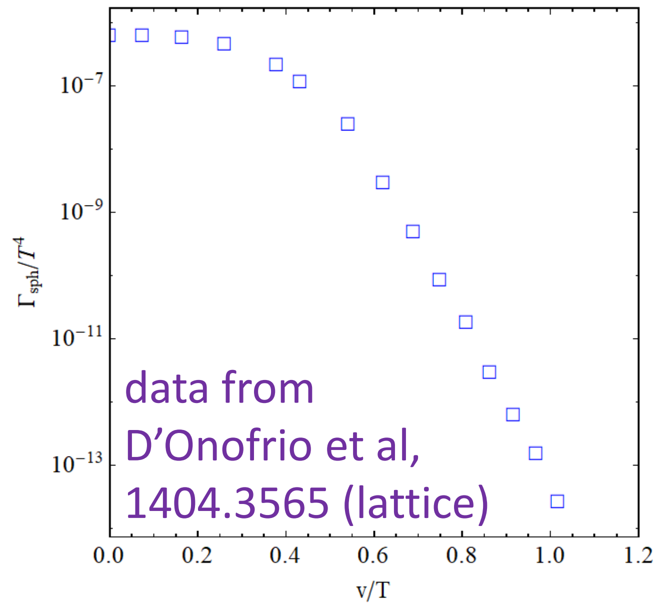

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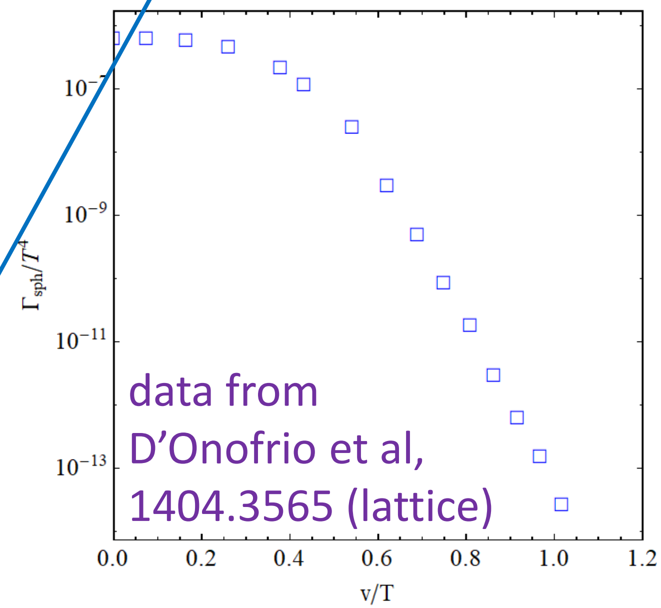

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Key words

Sphaleron (B violation)

First order EWPT (out of equilibrium)

CP violation

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Sphaleron (B violation): SM is enough!

First order EWPT (out of equilibrium): Higgs mass should be lighter.

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New physics $\Rightarrow$ LHC signal

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Only constraints are getting stronger and stronger…

Any EWBG model free from EDM or LHC?

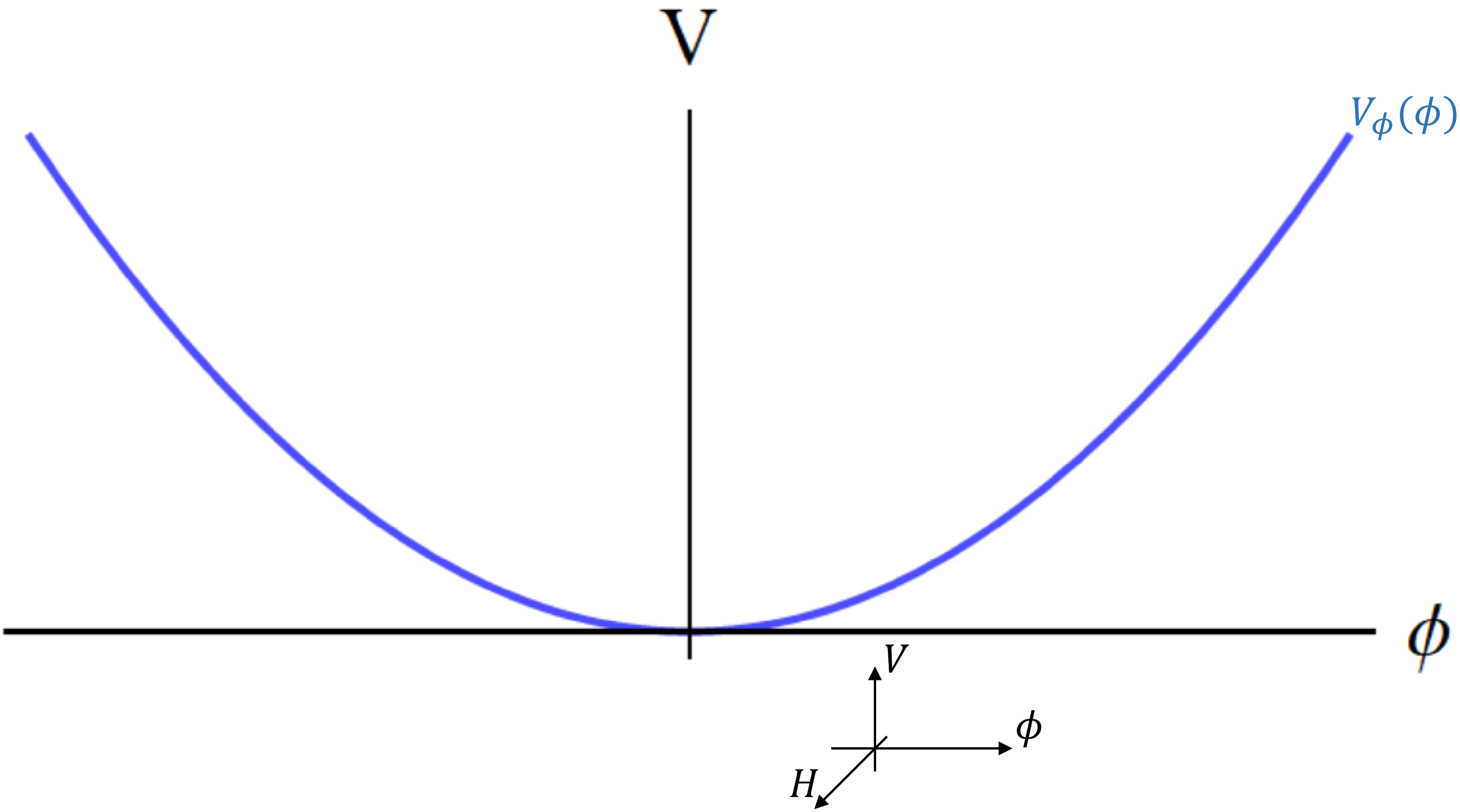
⇒ ***One example in this talk***

Contents

- Phase transition structure
- CP violation
- Phenomenology

First order EWPT with field-dependent Higgs mass

$$V(\phi, H) = \lambda |H|^4 + \mu_h^2(\phi)|H|^2 + V_\phi(\phi)$$



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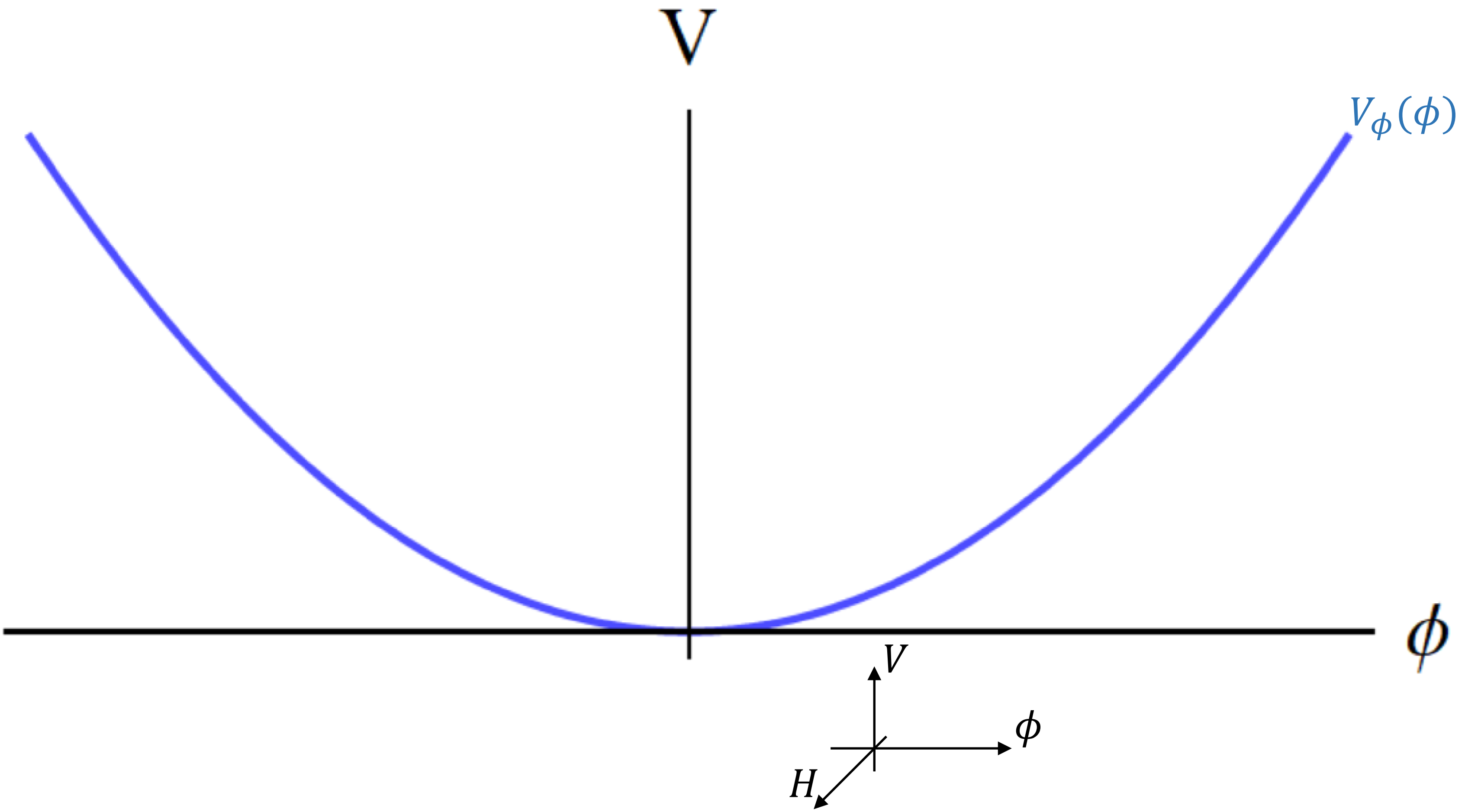

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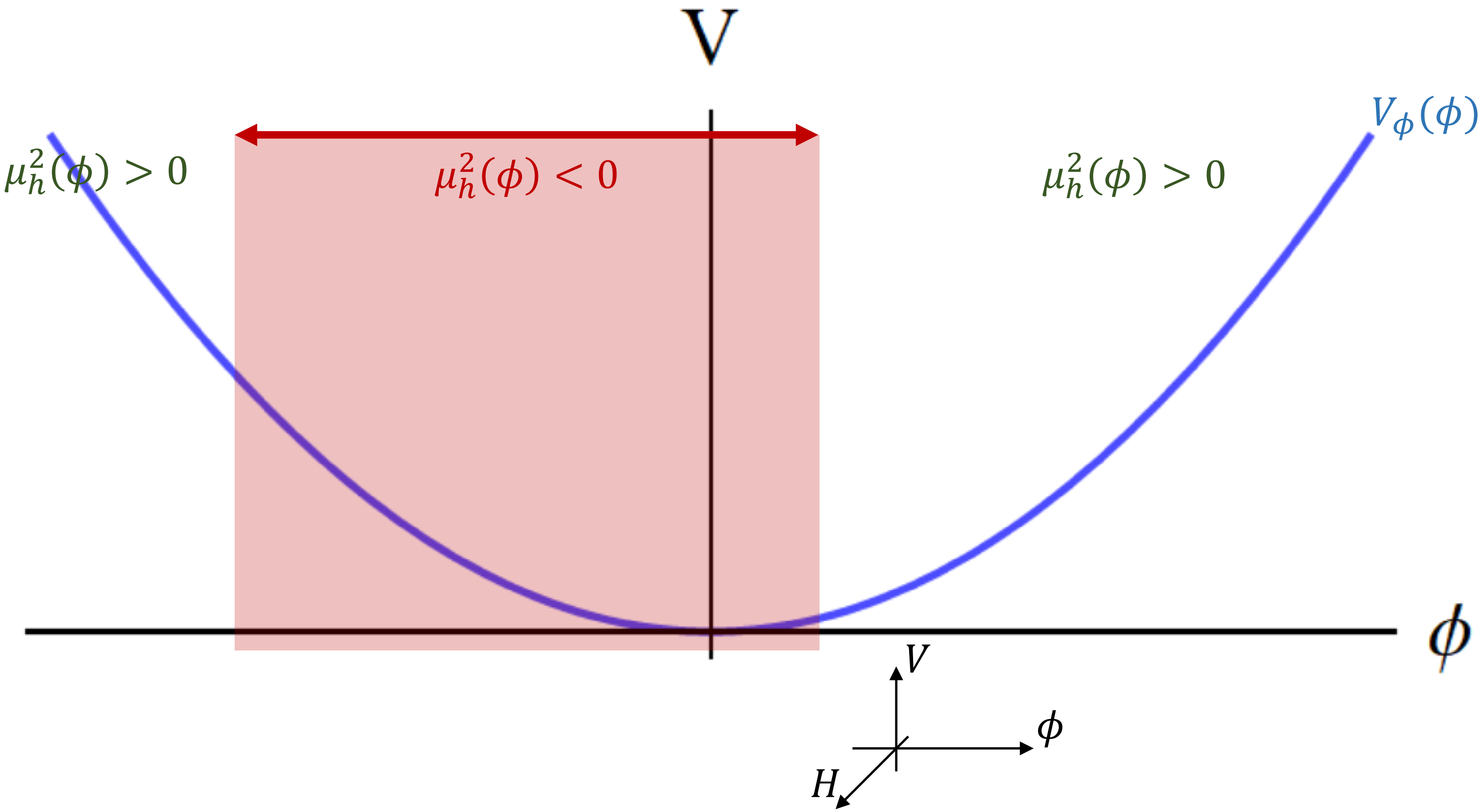

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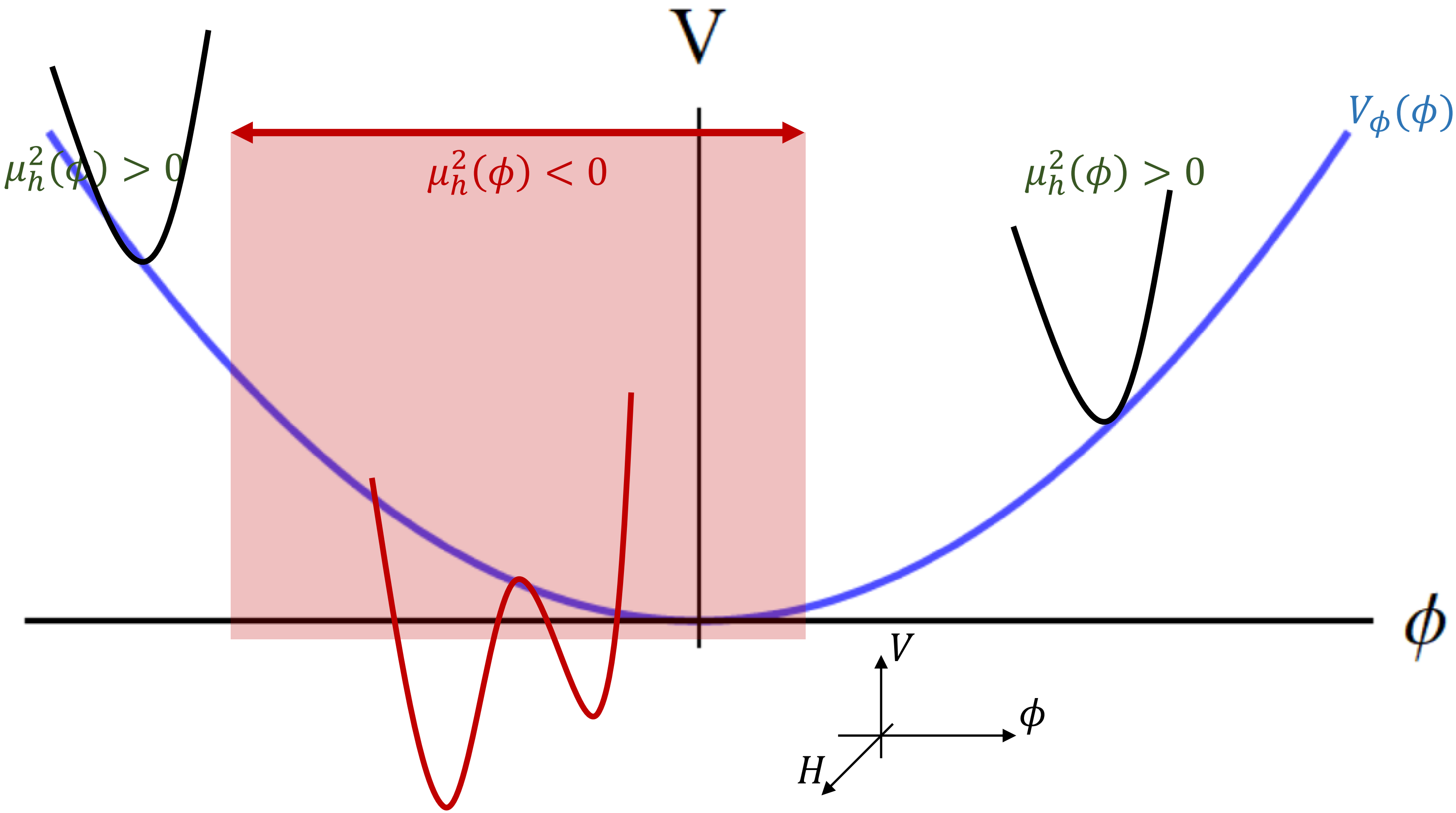

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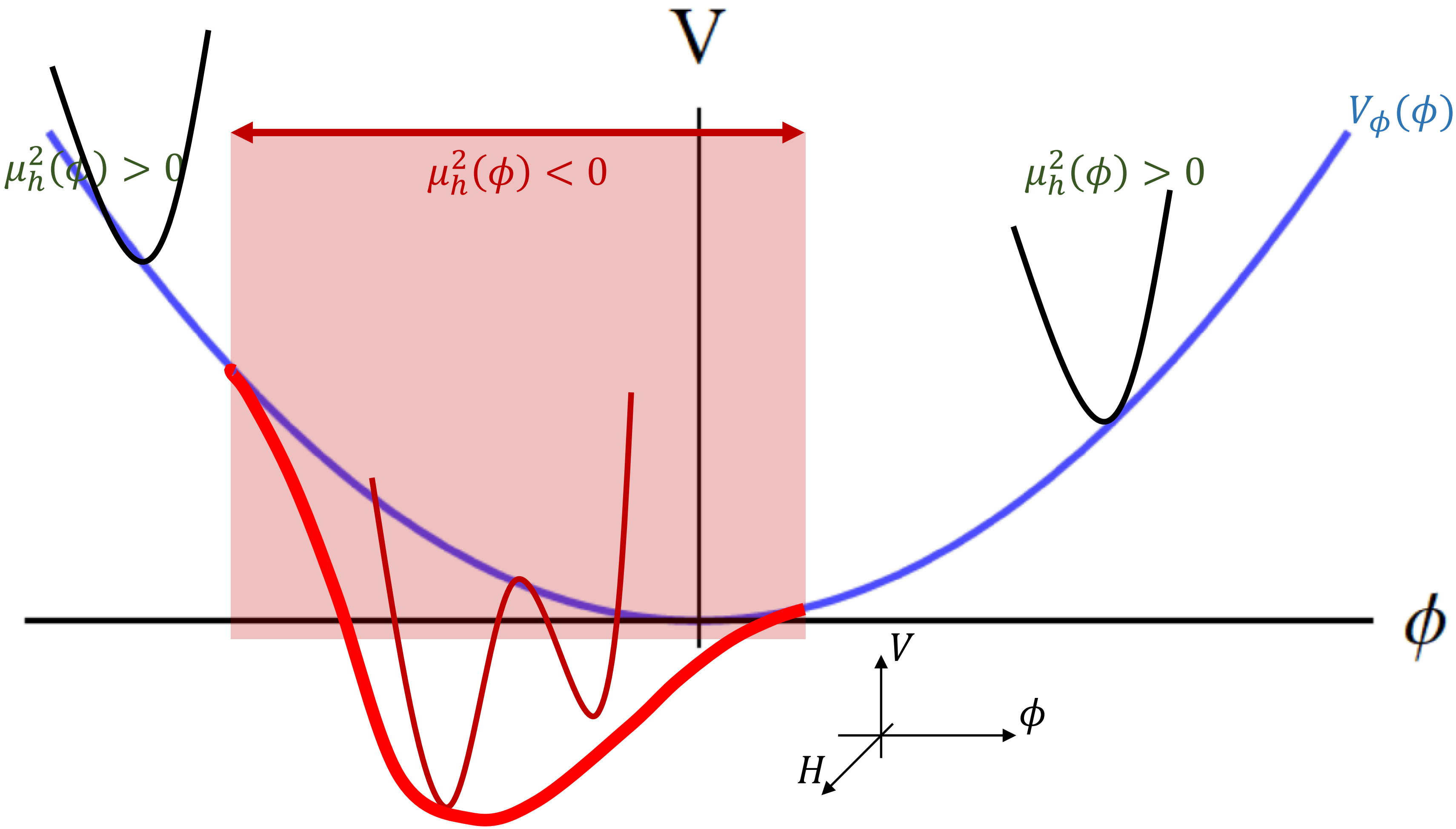

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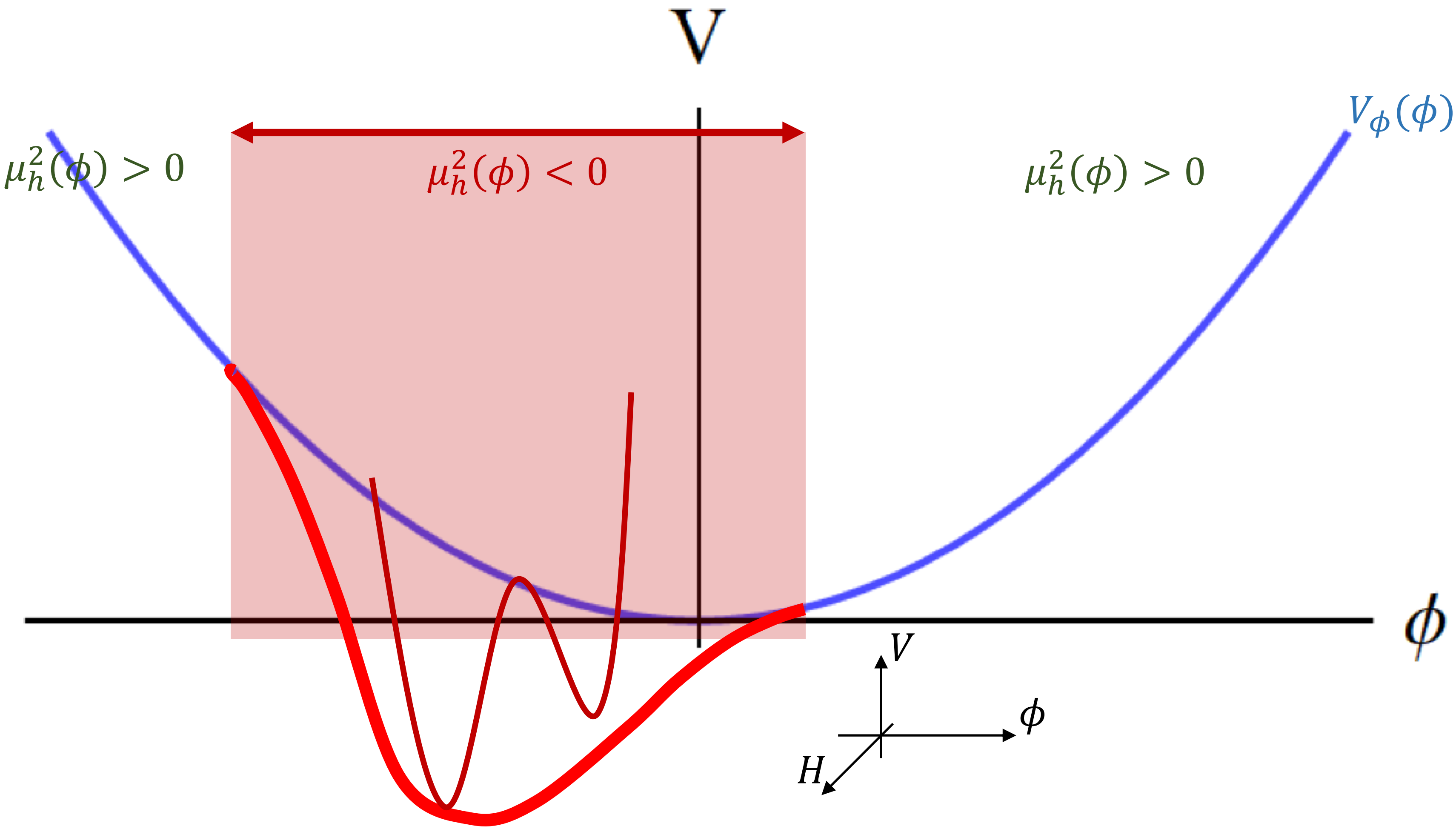

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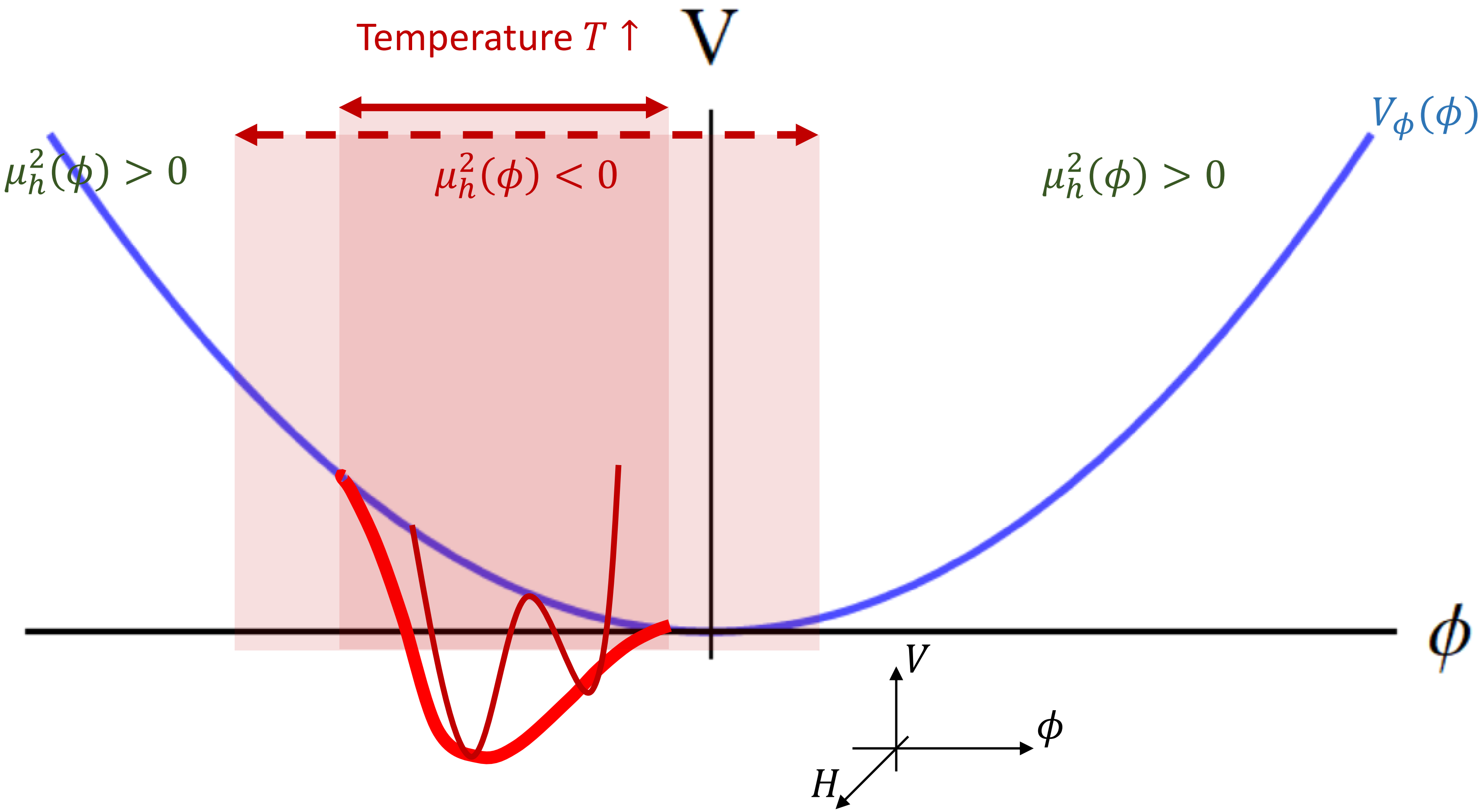

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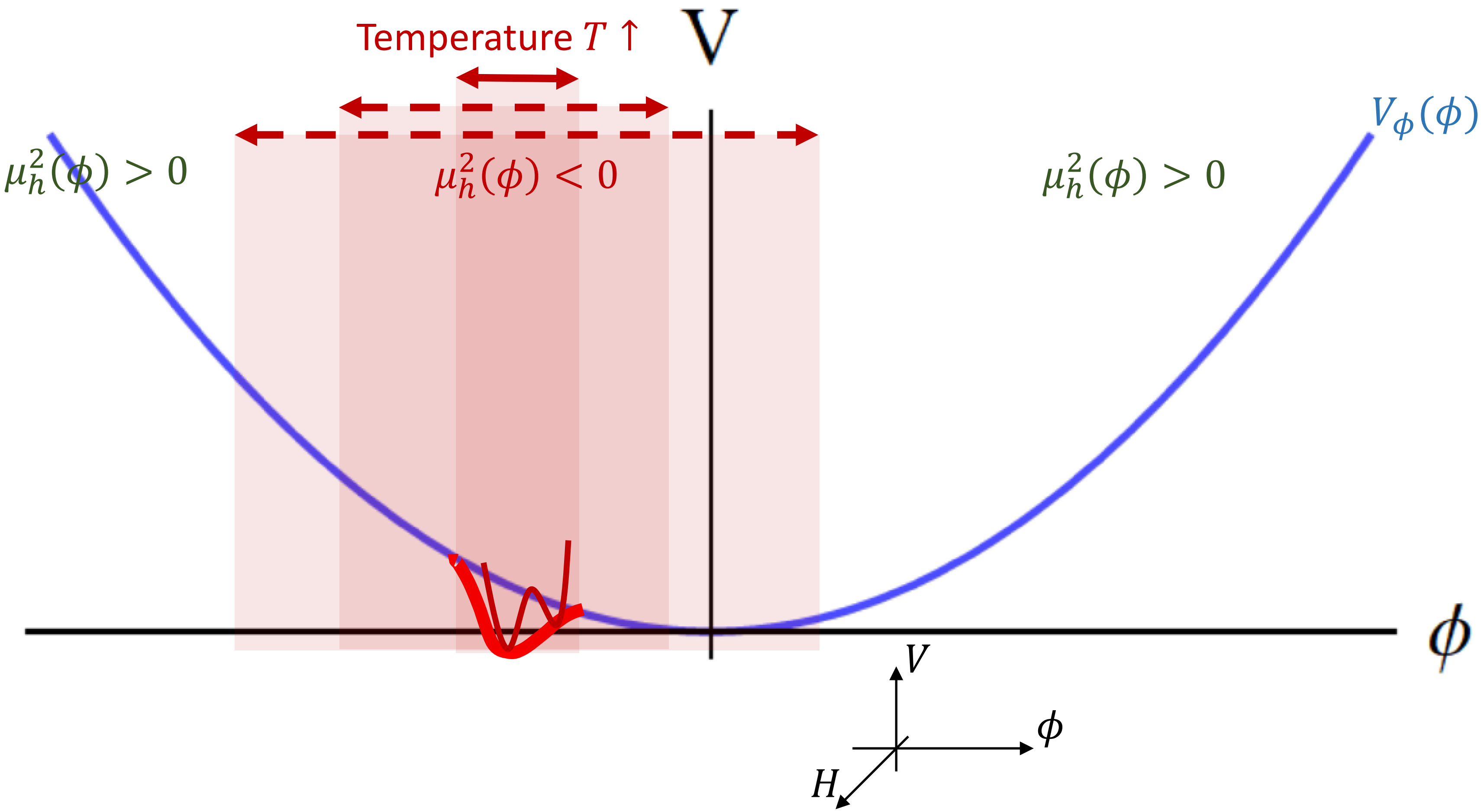

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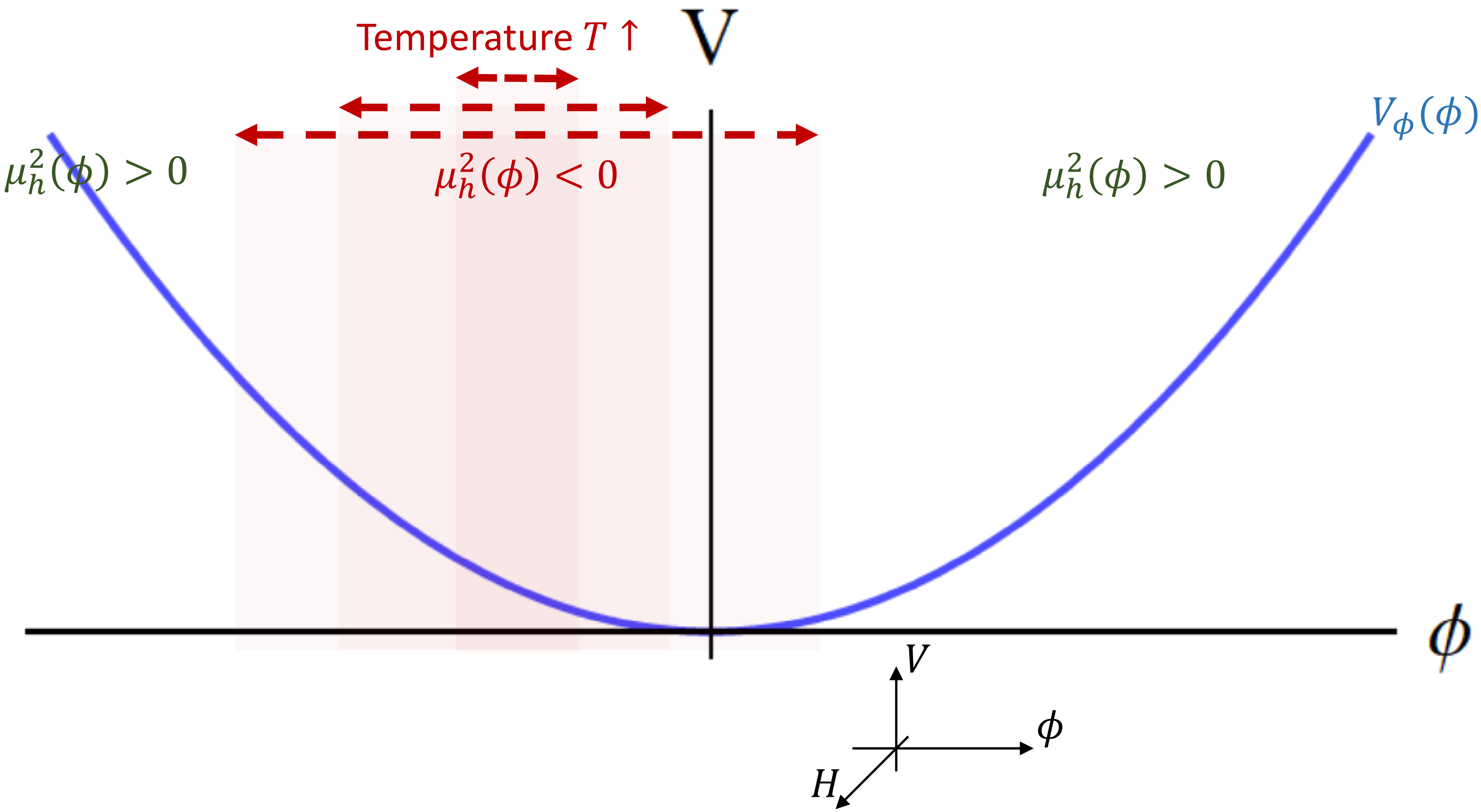

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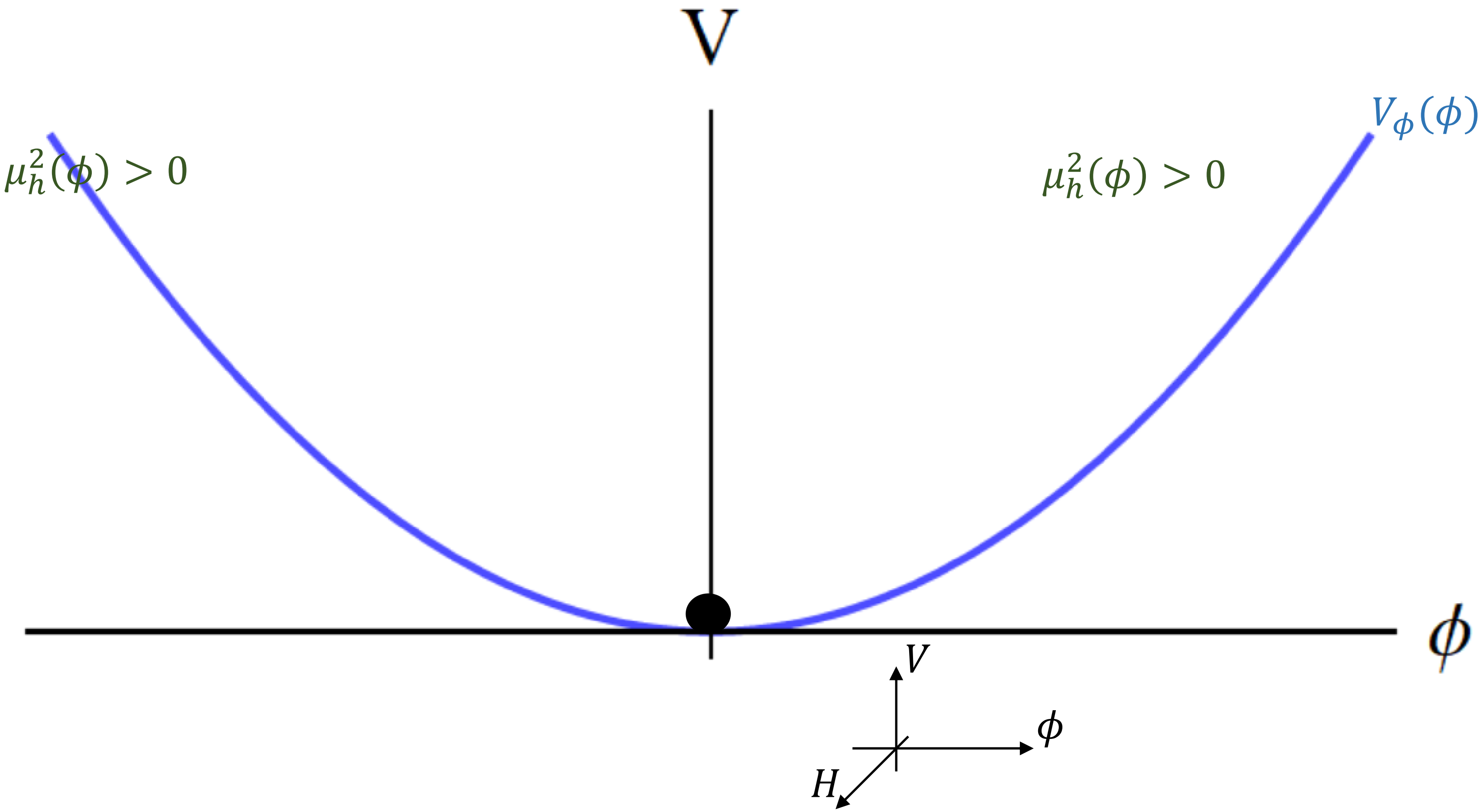

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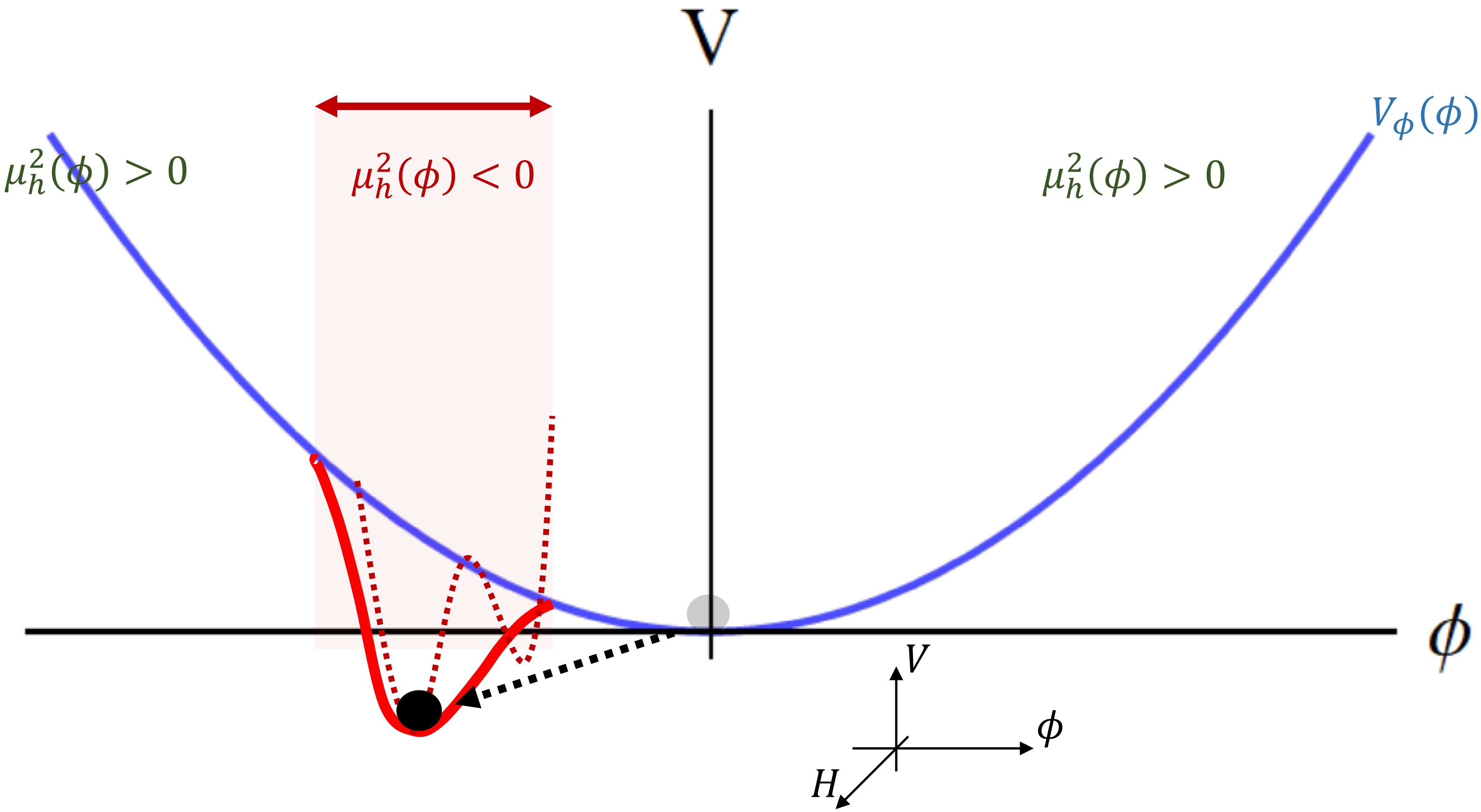

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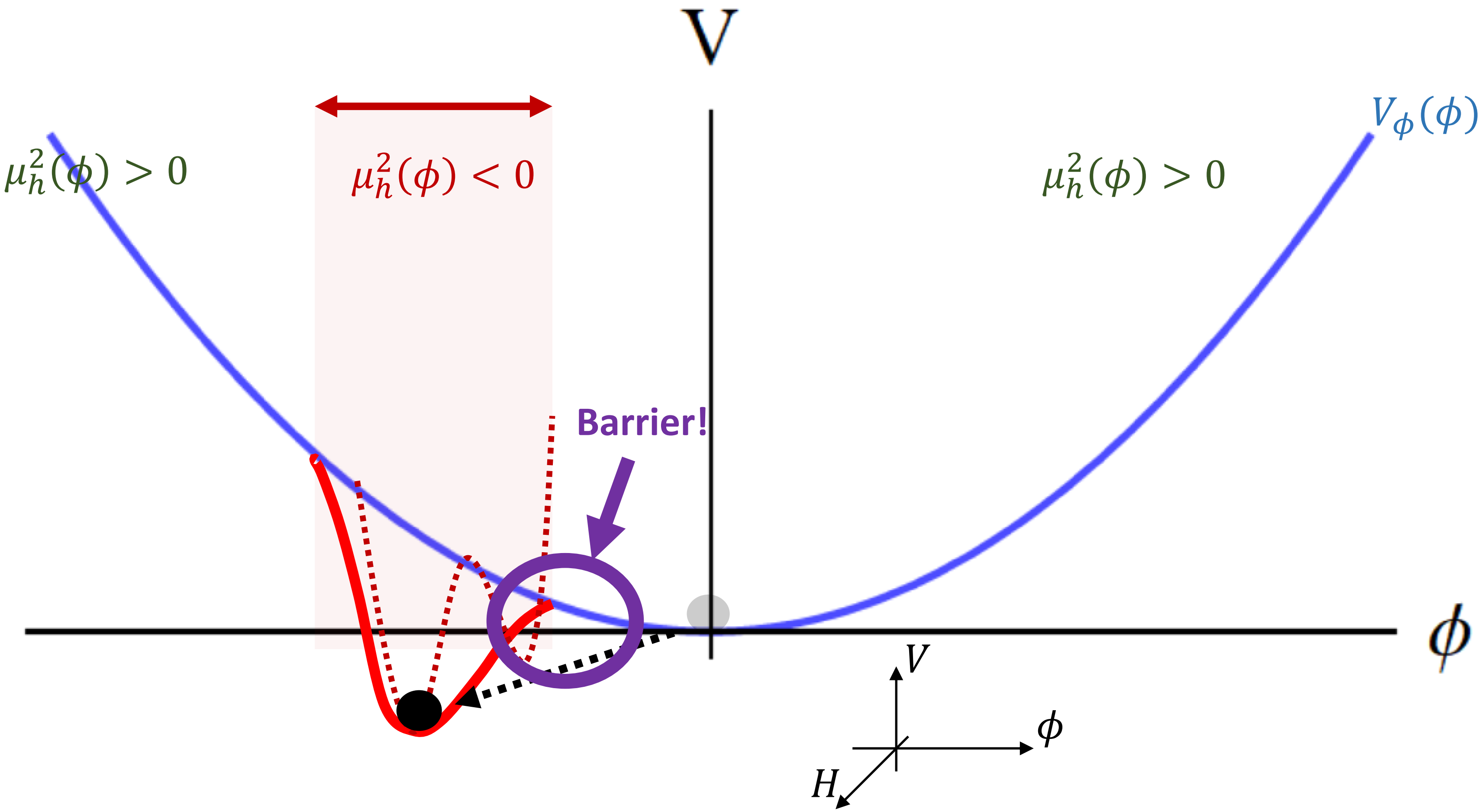

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Conditions for $\mu_h^2(\phi)$?

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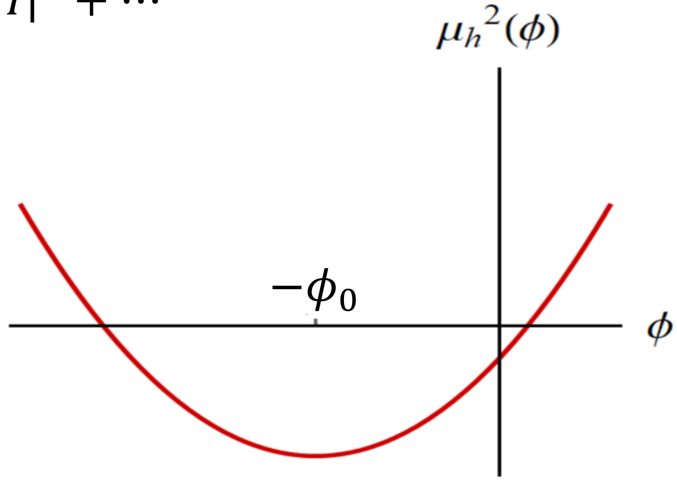

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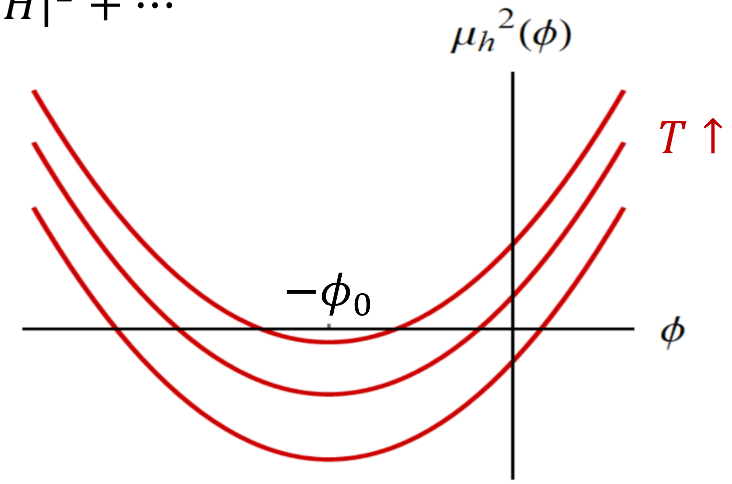

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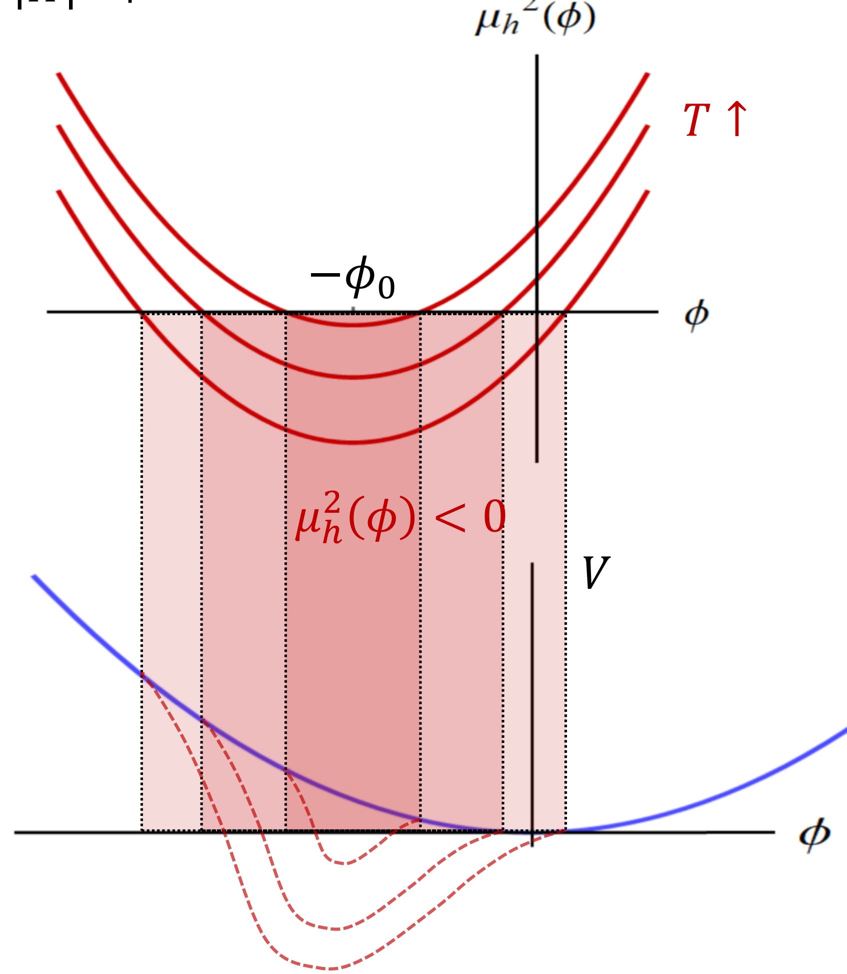

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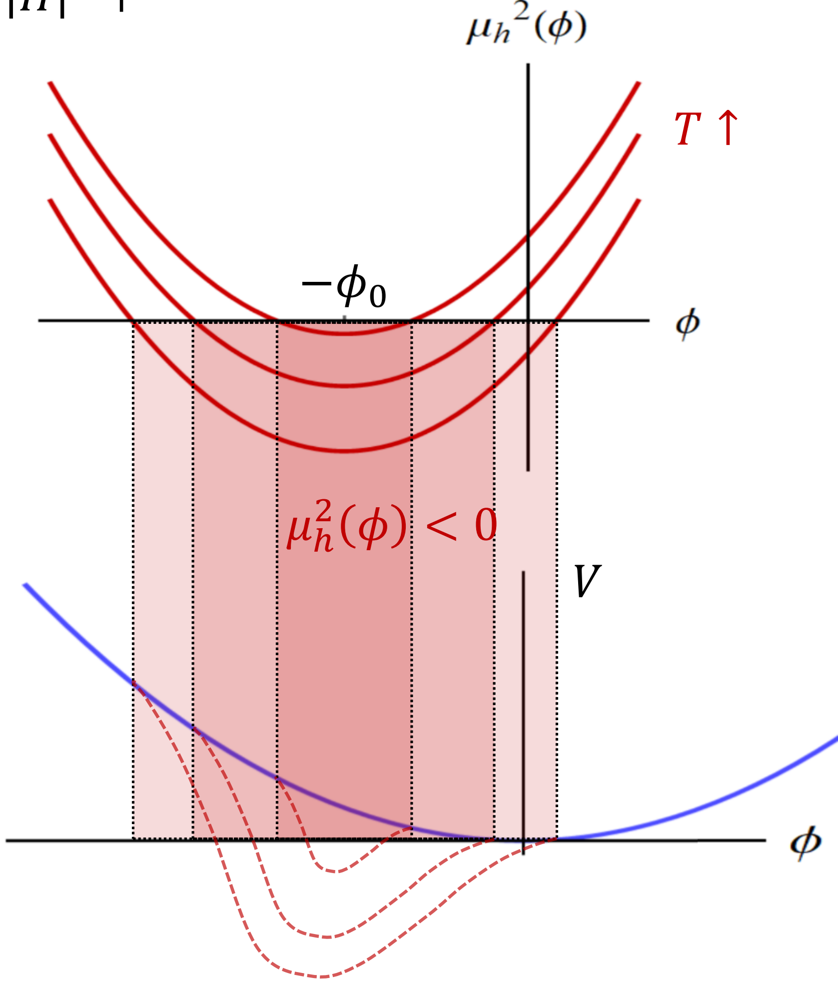

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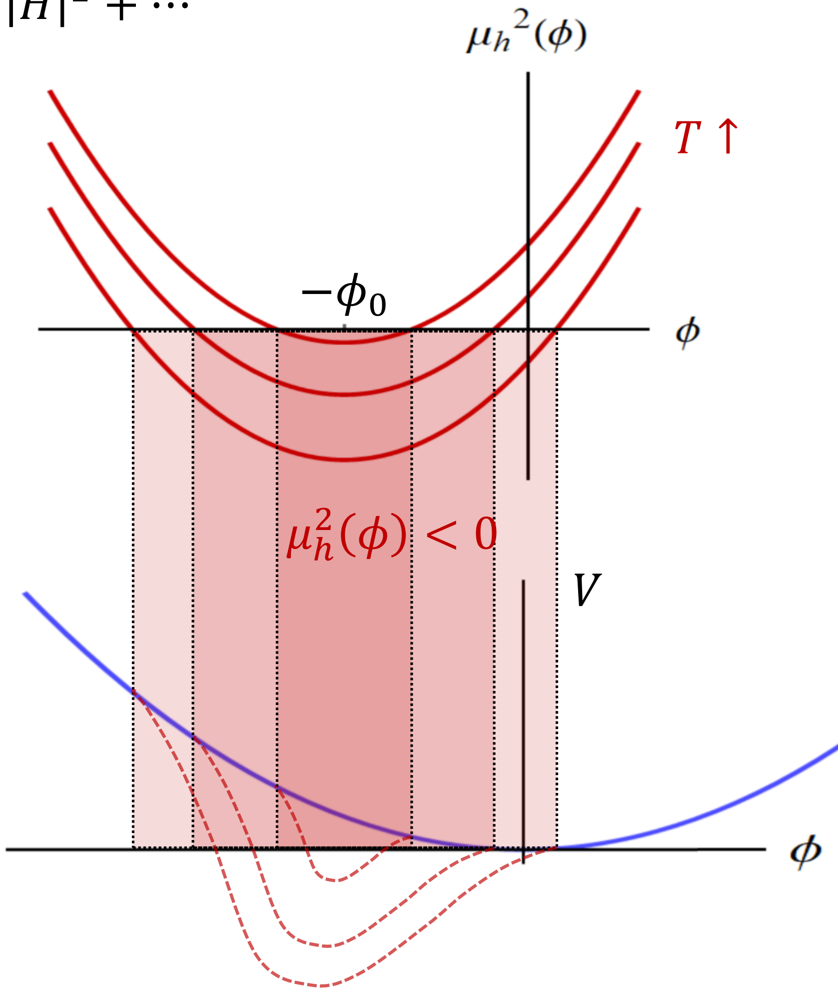

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For Higgs mass and vev,

$$\mu_0 \simeq \sqrt{\lambda} v_h = 88\ {\rm GeV} \sim {\rm O(m_w)}$$

For a strongly first-order EWPT,

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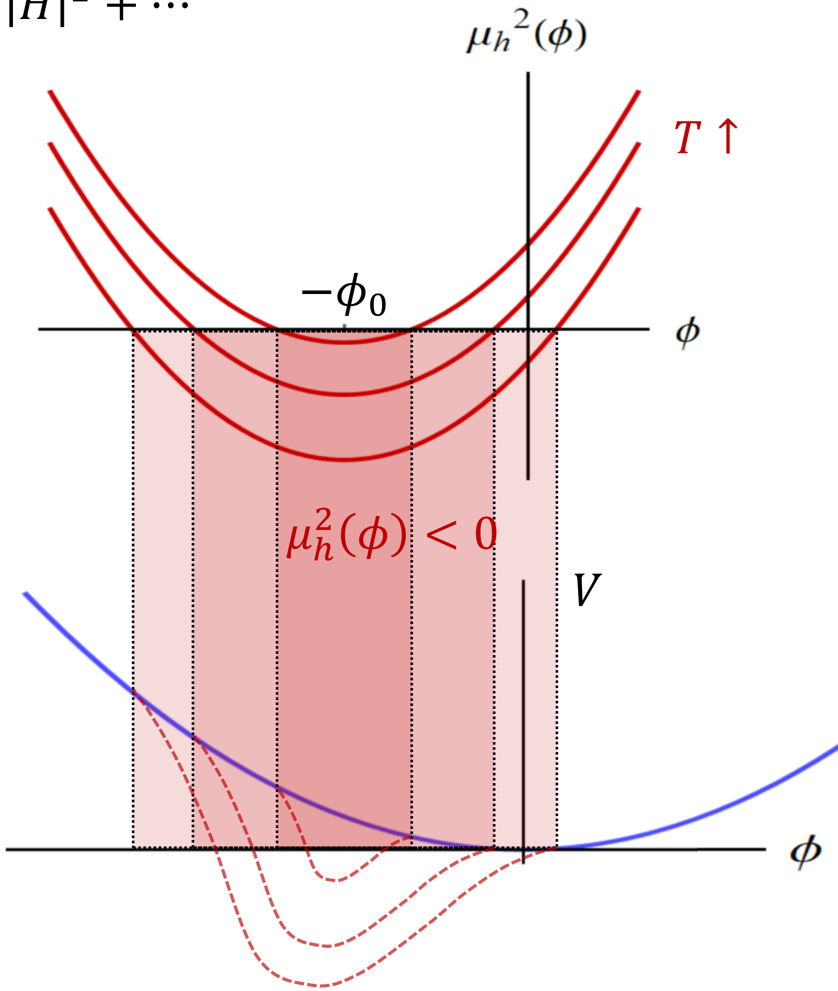

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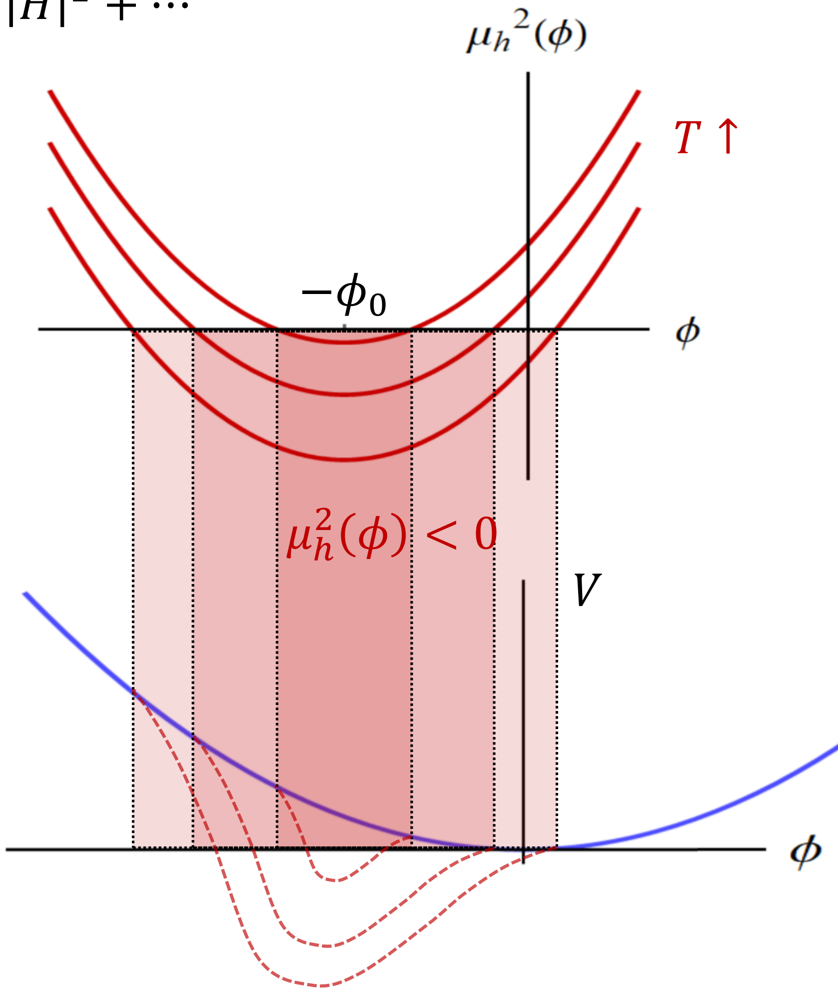
Weakly coupled limit: $\frac{\boldsymbol{m_w^2}}{\boldsymbol{\phi_0^2}} \lesssim \boldsymbol{\lambda_{\rm mix}} \ll \mathbf{1}$ **?**

Easily satisfied if ϕ = ALP



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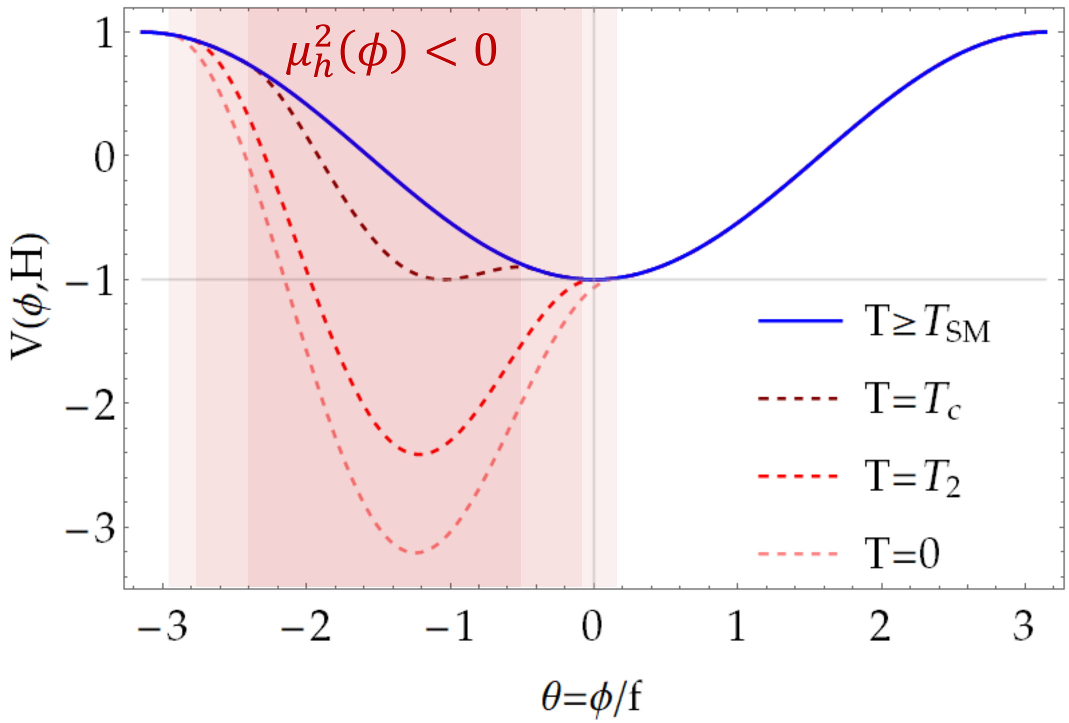

Advantage of ALP: The potential structure is (almost) independent of f.
(the potential is written in terms of $\theta = \phi/f$, not ϕ and f, individually)

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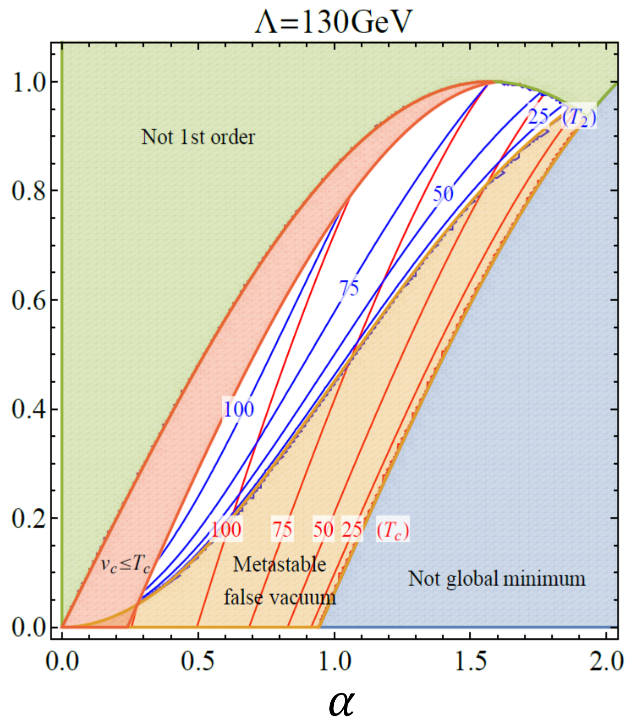

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T_2 : barrier disappearing temperature

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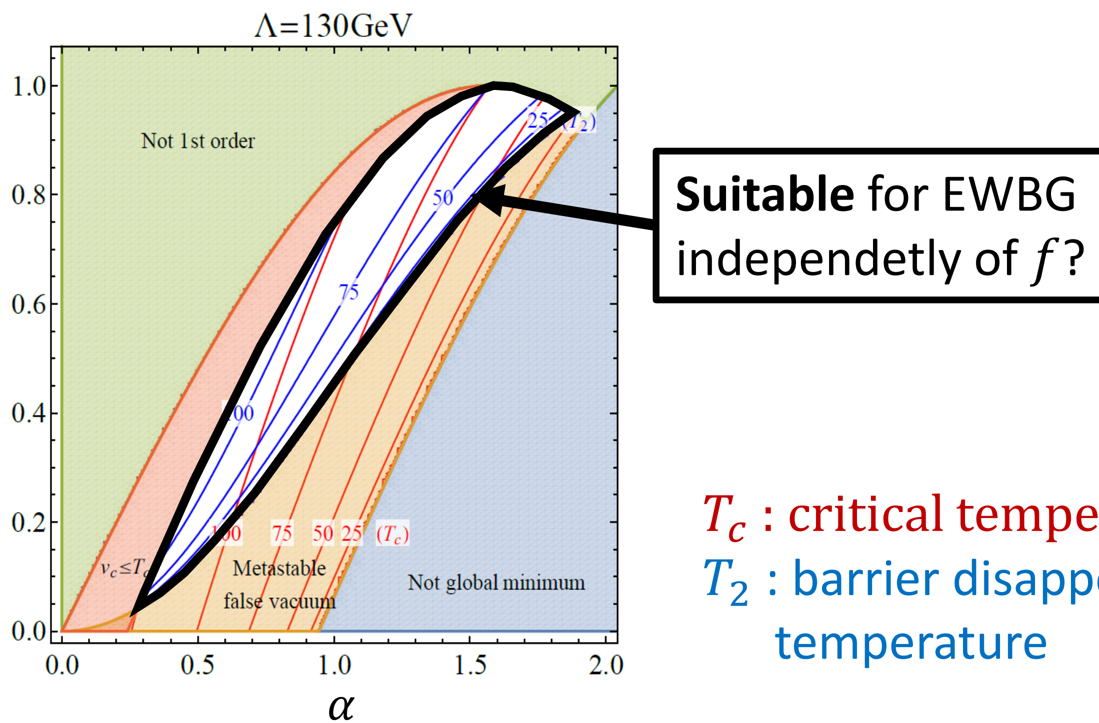

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Weakly coupled limit: simply large $f \gg m_w$
($\frac{m_w^2}{\phi_0^2} \lesssim \lambda_{\rm mix} \ll 1$)

Is f really irrelevant?

One obvious change: **the physical field distance between two local minima** $\propto f$.

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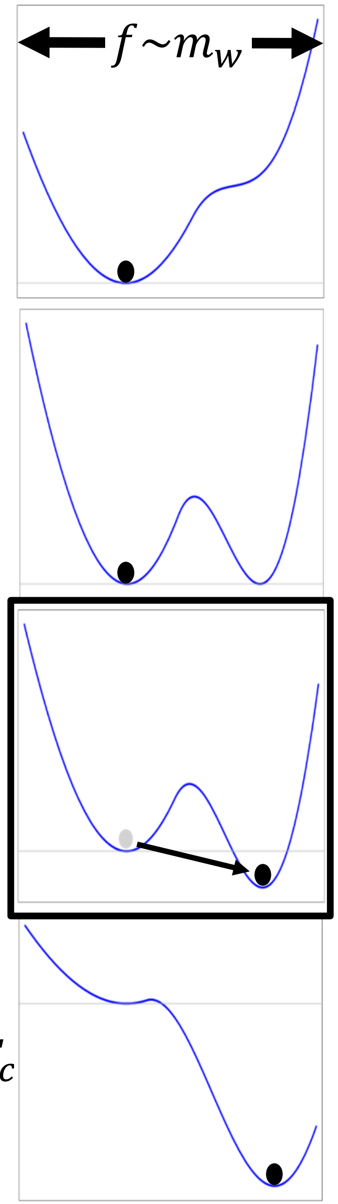
It changes many things!!

How?

What changes at large $\boldsymbol{f}$?



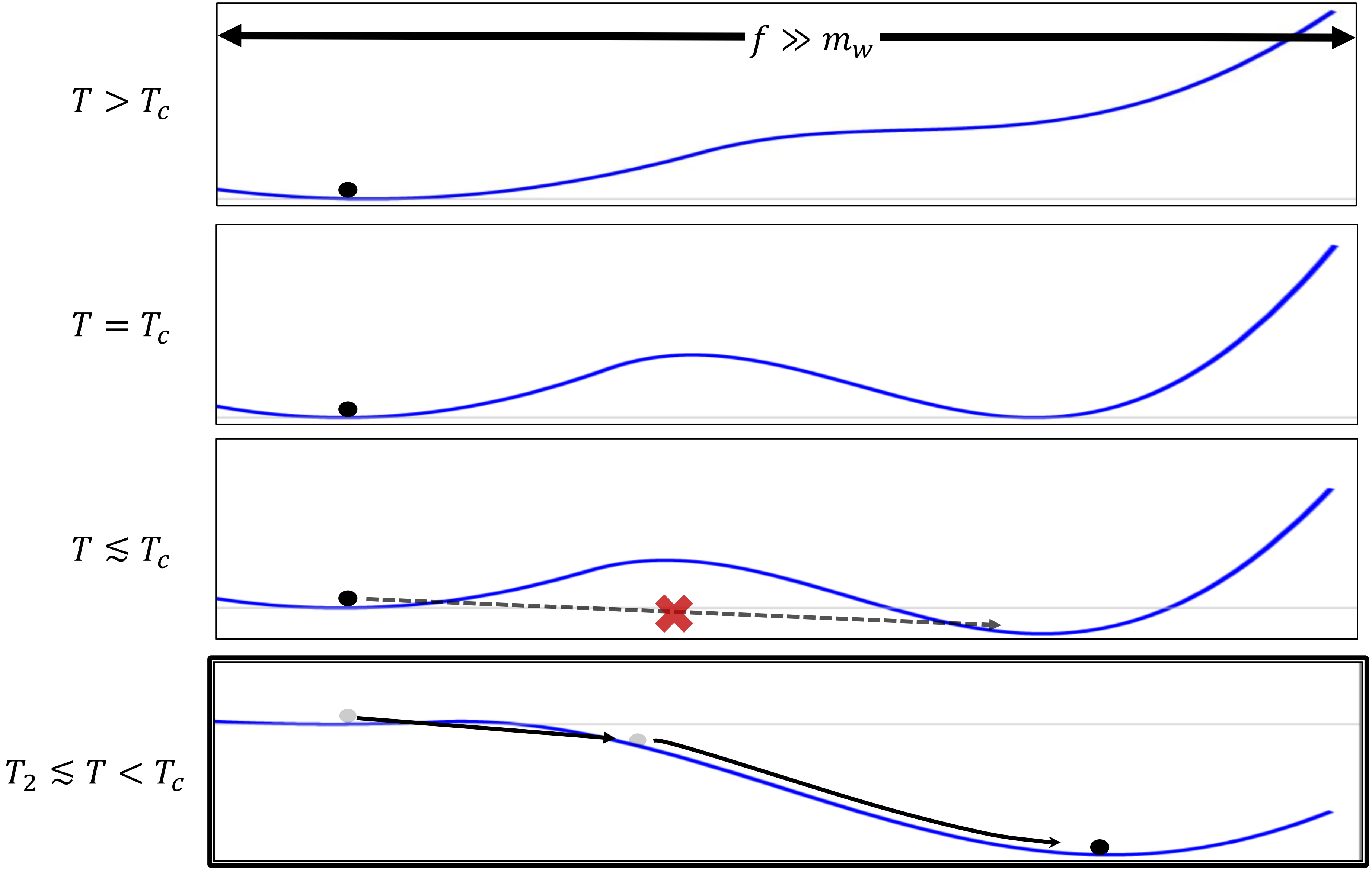
$T > T_c$

$T = T_c$

$T \lesssim T_c$

$T_2 \lesssim T < T_c$

What changes at large f ?



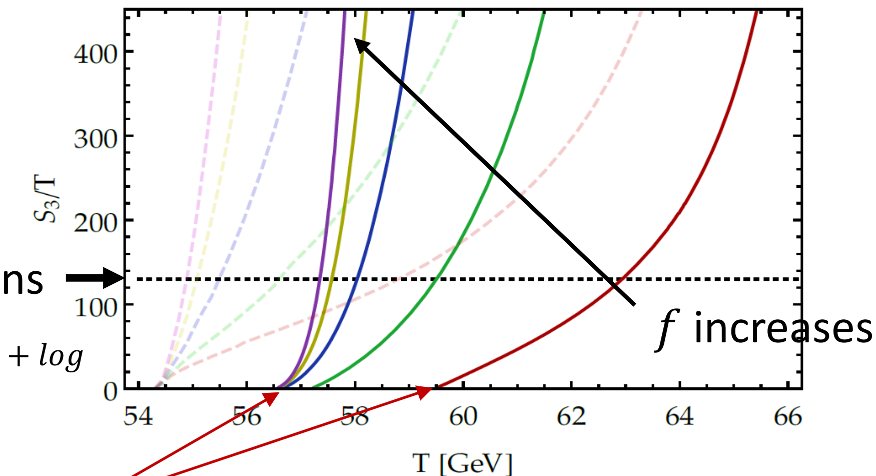
What changes at large f ?

Critical action: $S_3 = 4\pi \int r^2 dr \left(\left(\frac{dh}{dr}\right)^2 + \left(\frac{d\phi}{dr}\right)^2 + V(h,\theta) \right)$

$$= 4\pi f^3 \int x^2 dx \left(\frac{h'^2}{2f^2} + \frac{\theta'^2}{2} + V(h,\theta) \right) \propto f^3, \qquad x \equiv \frac{r}{f}, \qquad ' \equiv \frac{d}{dx}$$

T_n: nucleation begins

$\Gamma_{nuc}(T_n) \simeq H(T_n) \Rightarrow \frac{S_3}{T} \simeq 130 + log$



T_2: barrier disappearing temperature

$$S_3/T \propto (T - T_2)^n f^3$$

$\Rightarrow T_n \simeq T_2, \qquad \Delta t_{PT} \simeq \frac{6}{\beta} \propto f^{3/n}$ where $\beta = d(S_3/T)/dt \,|_{T=T_n}$

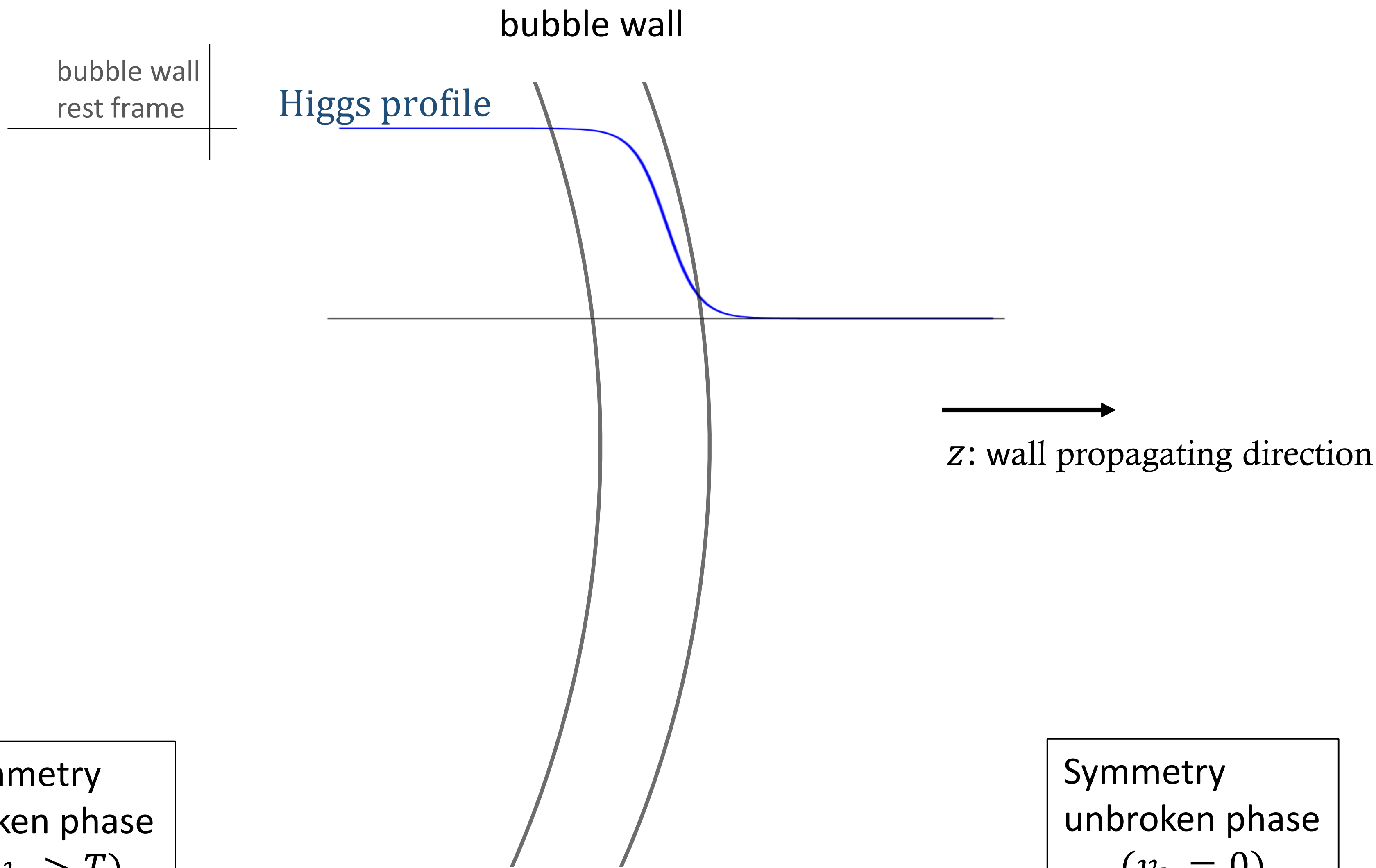
Is f really irrelevant?
ans: NO

One obvious change: **the physical field distance between two local minima $\propto f$**.

⇒ Phase transition is delayed (i.e. supercooling occurs): $T_n \simeq T_2 < T_c$

How does it affect baryogenesis?
e.g. diffusion effect

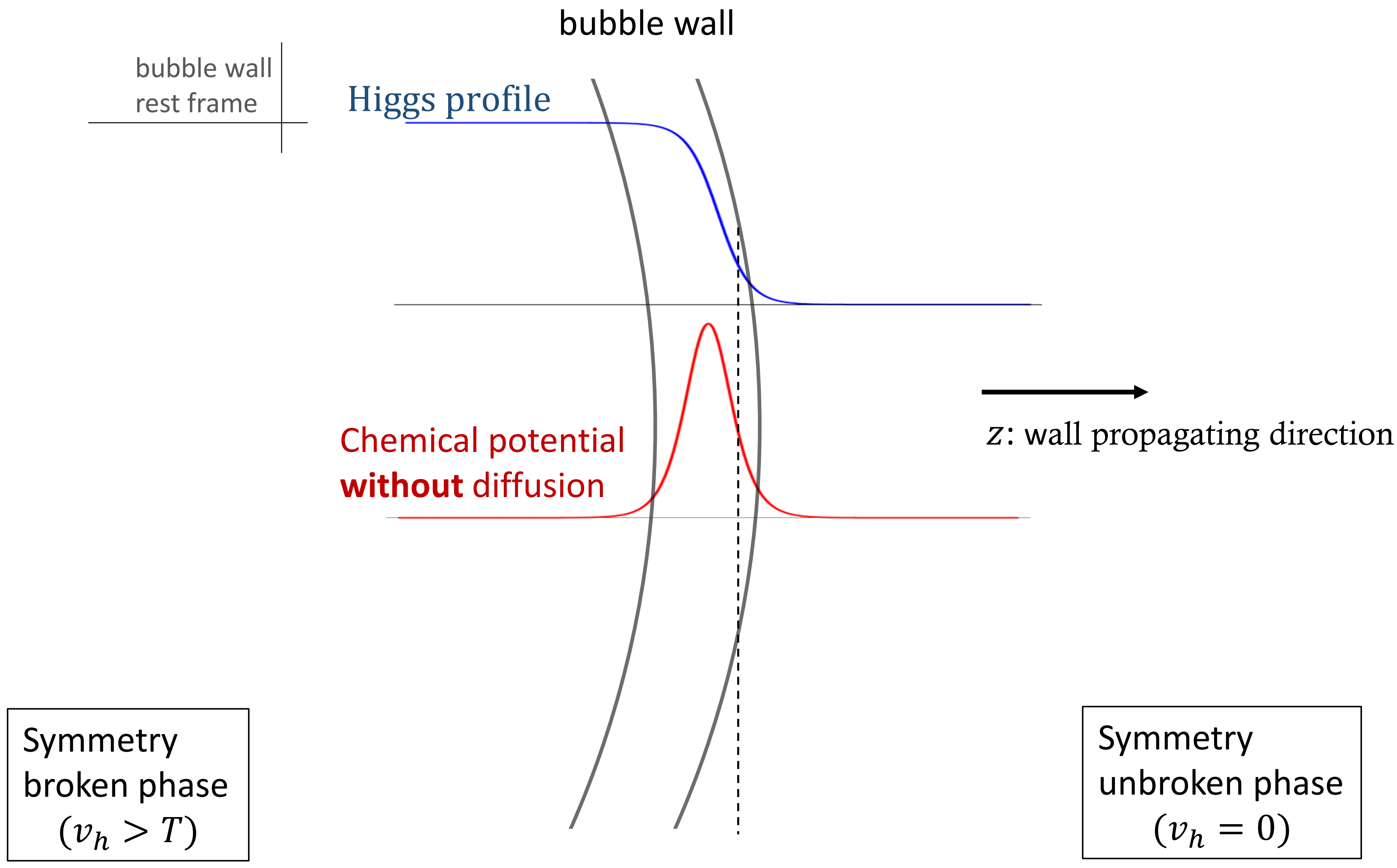
Diffusion effect around bubble wall



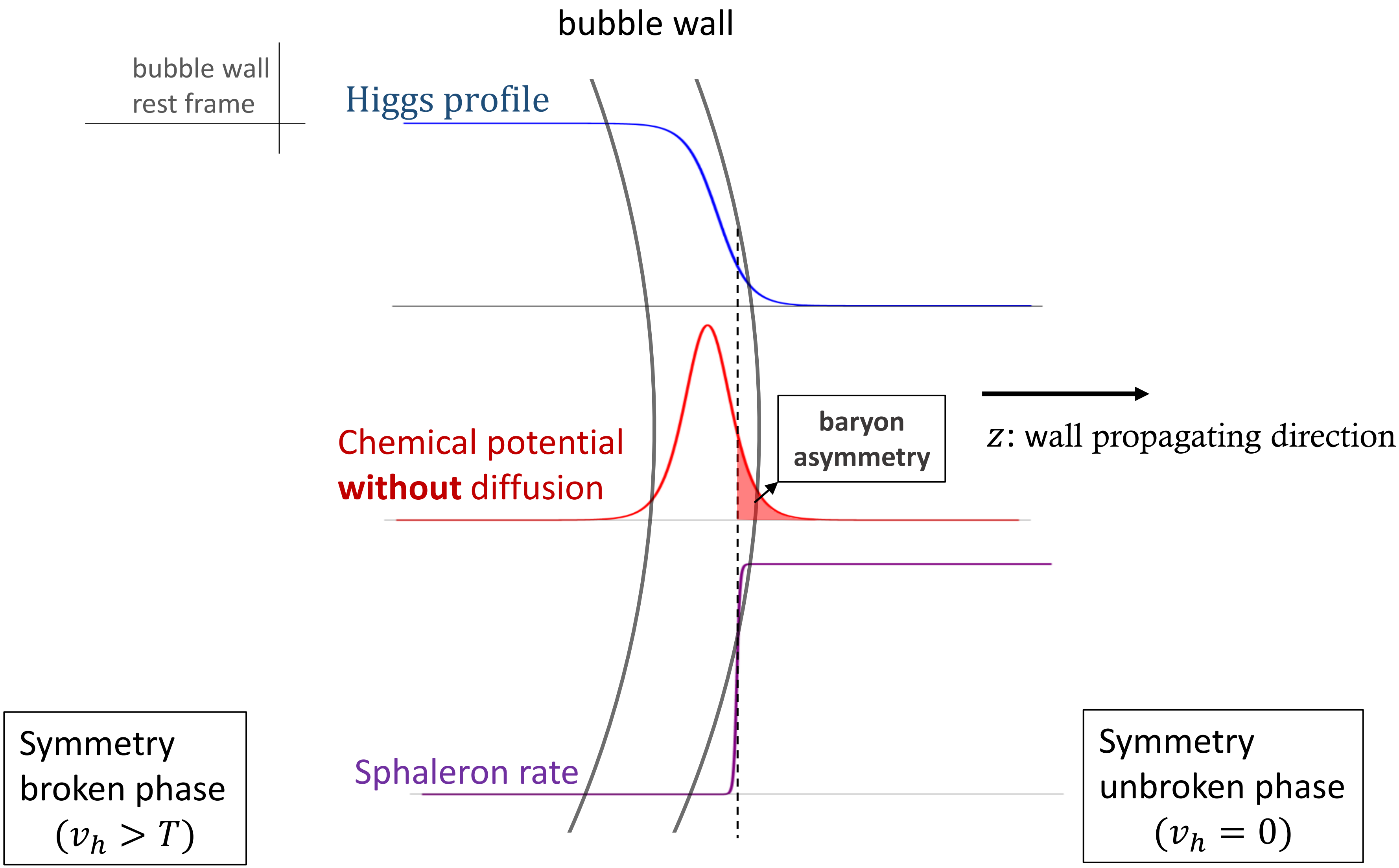
Symmetry broken phase ($v_h > T$)

Symmetry unbroken phase ($v_h = 0$)

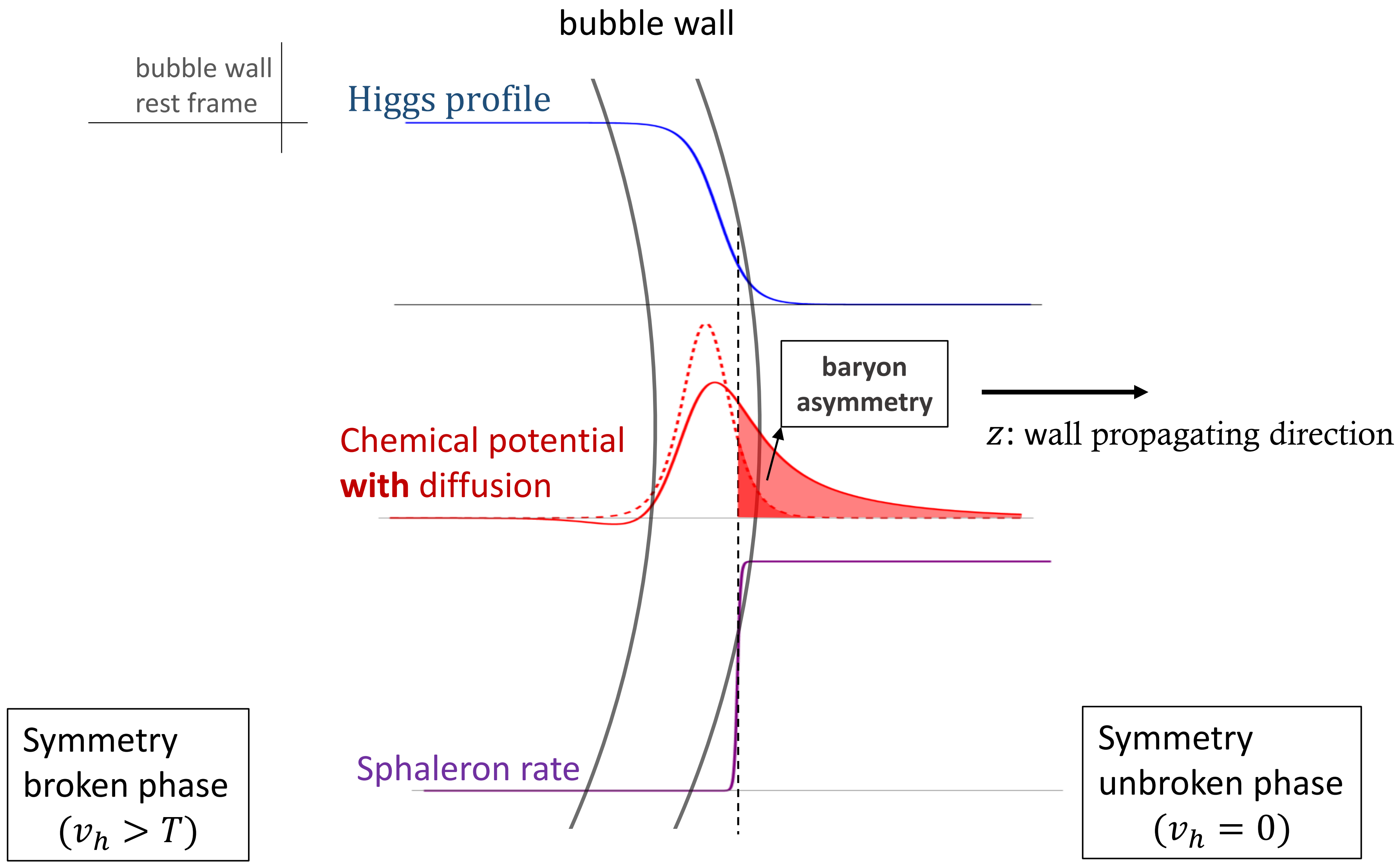
Diffusion effect around bubble wall



Diffusion effect around bubble wall



Diffusion effect around bubble wall



Whether the diffusion effect can give a significant enhancement is determined by

$L_w v_w$ vs Diffusion length scale ($\simeq O(100)/T_n$)

Whether the diffusion effect can give a significant enhancement is determined by

$$L_w v_w \text{ vs Diffusion length scale } (\simeq O(100)/T_n)$$

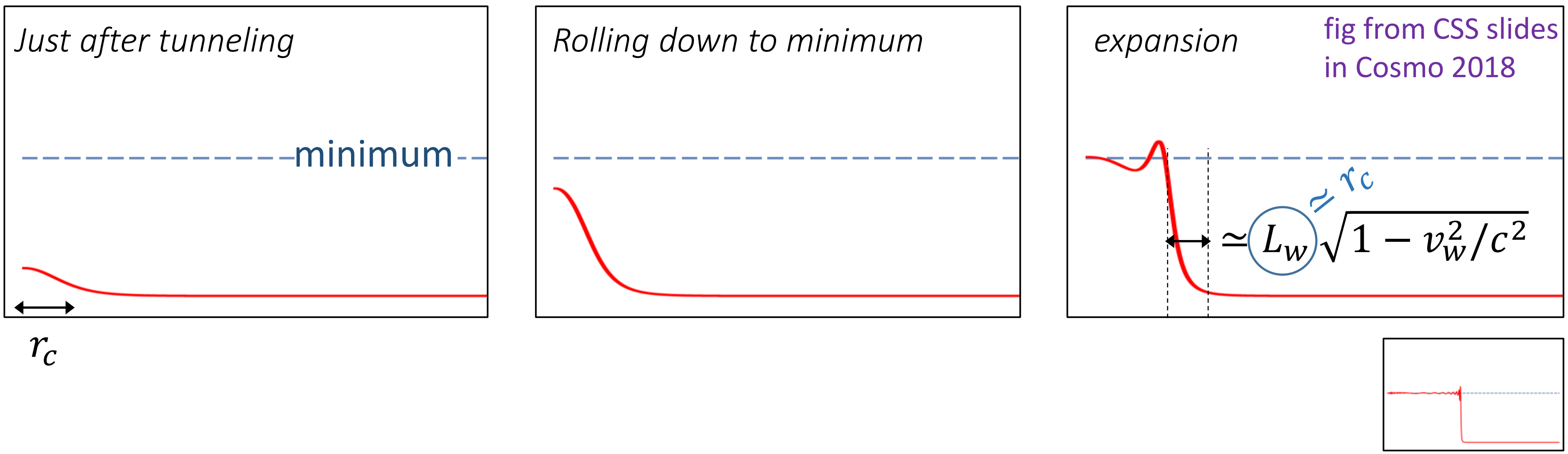
L_w: $\propto \boldsymbol{f}$

v_w: $\sim$ **independent of** $\boldsymbol{f}$

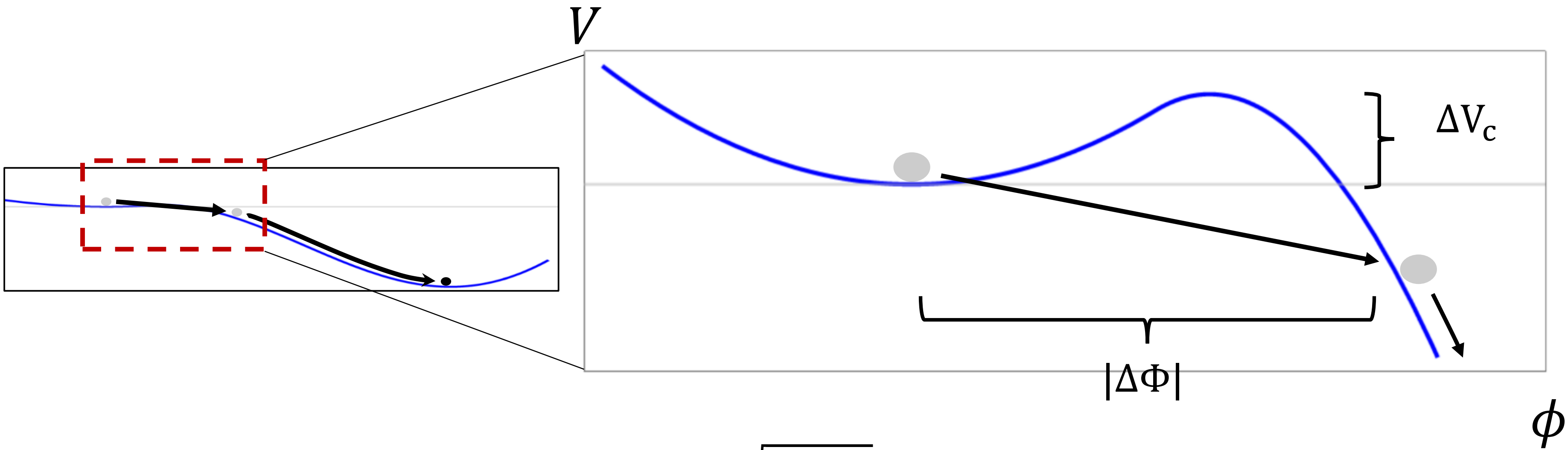
Bubble wall width

Whether diffusion can be a significant effect is determined by two quantities:

$\mathbf{L_w}$: approximated by a critical bubble size $\boldsymbol{r_c}$



Bubble wall width

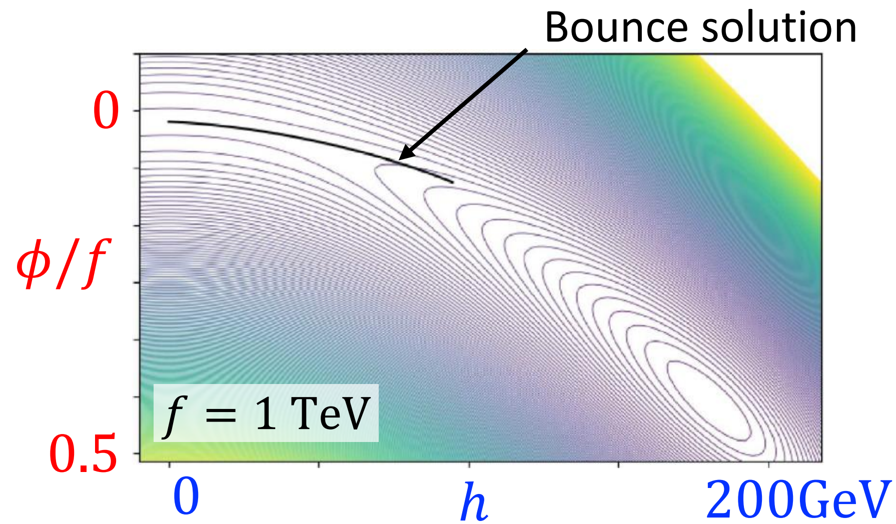


$$\Rightarrow L_w \sim r_c \sim \sqrt{\frac{|\Delta\Phi|^2}{8\Delta V}} \sim \frac{f}{m_w^2}$$

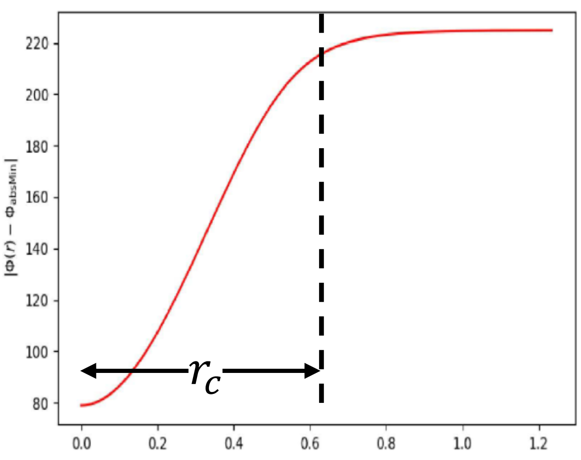
(rough estimation)

Bubble wall width

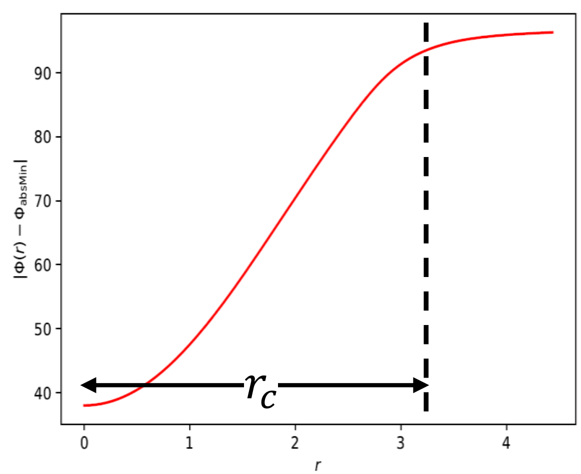
We also checked r_c, numerically.
CosmoTransitions (Wainwright, 1109.4189):
bounce solution, bubble profile, critical action



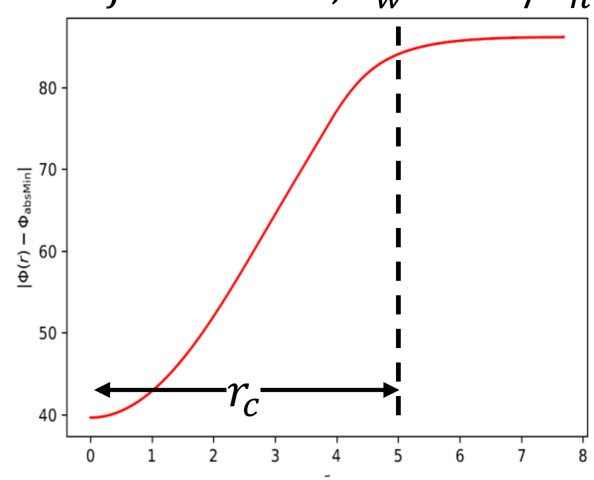
$f = 1\text{TeV}, L_w \simeq 10/T_n$



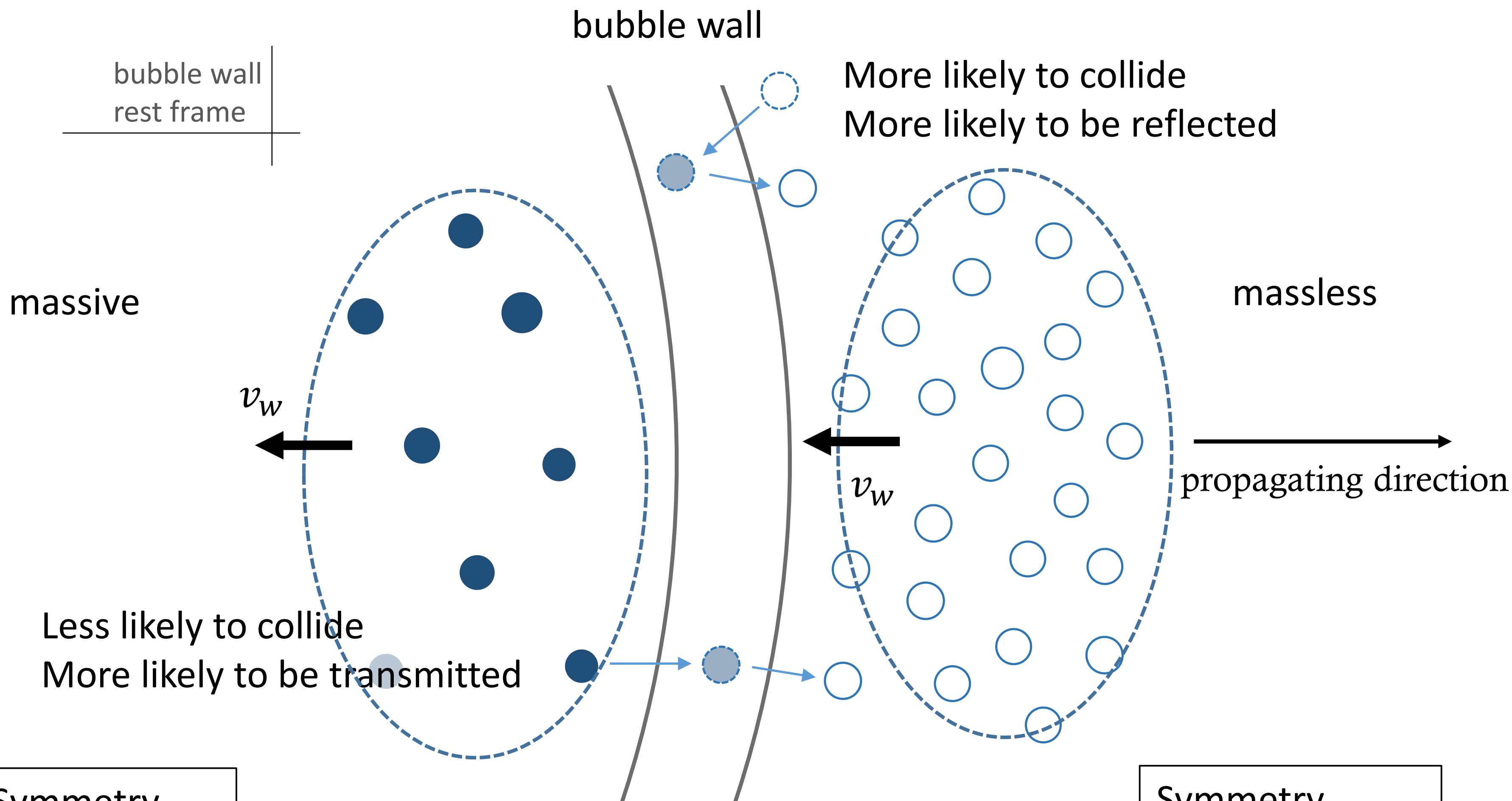
$f = 10\text{TeV}, L_w \simeq 50/T_n$



$f = 20\text{TeV}, L_w \simeq 80/T_n$



Bubble wall velocity



Symmetry broken phase ($v_h > T$)

Symmetry unbroken phase ($v_h = 0$)

$\boldsymbol{v_w}$: by solving $\Delta(\text{Pressure}) = \Delta V$

where $P_{1(2)}$ =pressure from inside (outside) bubble wall

Bubble wall velocity

$$\Delta P = \text{Pressure from outside } - \text{Pressure from inside} = \Delta V$$

$$\Rightarrow v_w \simeq O(0.1), \text{numerically}$$

Here, f does not seem to play anything.

Whether diffusion gives a significant effect

$$v_w L_w T_n \sim \frac{f}{m_w} \; vs \; \text{Diffusion length scale} \times T_n \left(\simeq O(100)\right)$$

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$$\Rightarrow \begin{array}{l} f \lesssim O(10-100\ \text{TeV}):\ \text{diffusion is important} \\ f \gtrsim O(10-100\ \text{TeV}): \text{diffusion is unimportant} \end{array}$$

Whether diffusion gives a significant effect

$$v_w L_w T_n \sim \frac{f}{m_w} \; vs \; \text{Diffusion length scale} \times T_n \left(\simeq O(100)\right)$$

varying top Yukawa model where diffusion formalism is well-established 1806.02591

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weak anomalous coupling ($\theta W \widetilde{W}$ coupling)

1811.03294

1806.02591

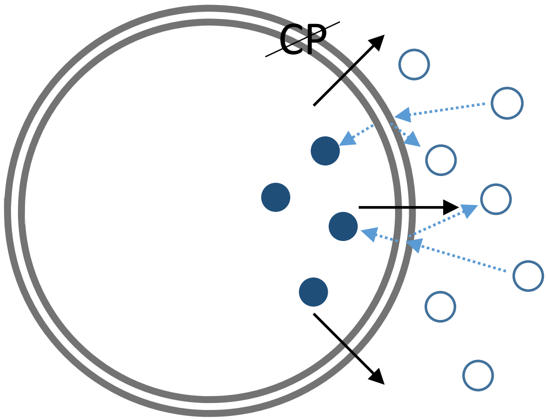
Charge transport mechanism

$$L_{CPV} = (y_t + x_t e^{i\theta})\bar{q}_{L3} t_R H$$

$f \lesssim O(10-100\ \text{TeV})$: diffusion is important

Transport mechanism is well-studied in a complex top quark mass scenario: $m_t(z)\bar{q}_{L3}t_R H$

$$m_t(z) = \left(y_t + x_t e^{i\theta(z)}\right) \equiv m(z)e^{i\Theta(z)}$$



$$\Rightarrow\ F_z = -\frac{(m^2)'}{2E_0} \pm \frac{(m^2\Theta')'}{2E_0E_{0z}} \mp s\frac{\Theta' m^2 (m^2)'}{4E_0^3 E_{0z}}$$

$\Rightarrow$ Boltzmann equations in the wall rest frame (with $f = f_0 + \delta f$)

$$v_w K_1 \mu_2' + v_w K_2 (m^2)'\mu_2 + u_2' - < C[f] > = S_\mu$$
$$-K_4\mu_2' + v_2\widetilde{K}_5 u_2' + v_w \widetilde{K}_6 (m^2)' u_2 - < \frac{p_z}{E_0} C[f] > = S_\theta + S_u$$

where

$$S_\mu = K_7 \Theta' m^2 \mu_1'$$
$$S_\theta = -v_w K_8 (m^2\Theta')' + v_w K_9 \Theta' m^2 (m^2)'$$
$$S_u = -\widetilde{K}_{10} m^2 \Theta' u_1'$$

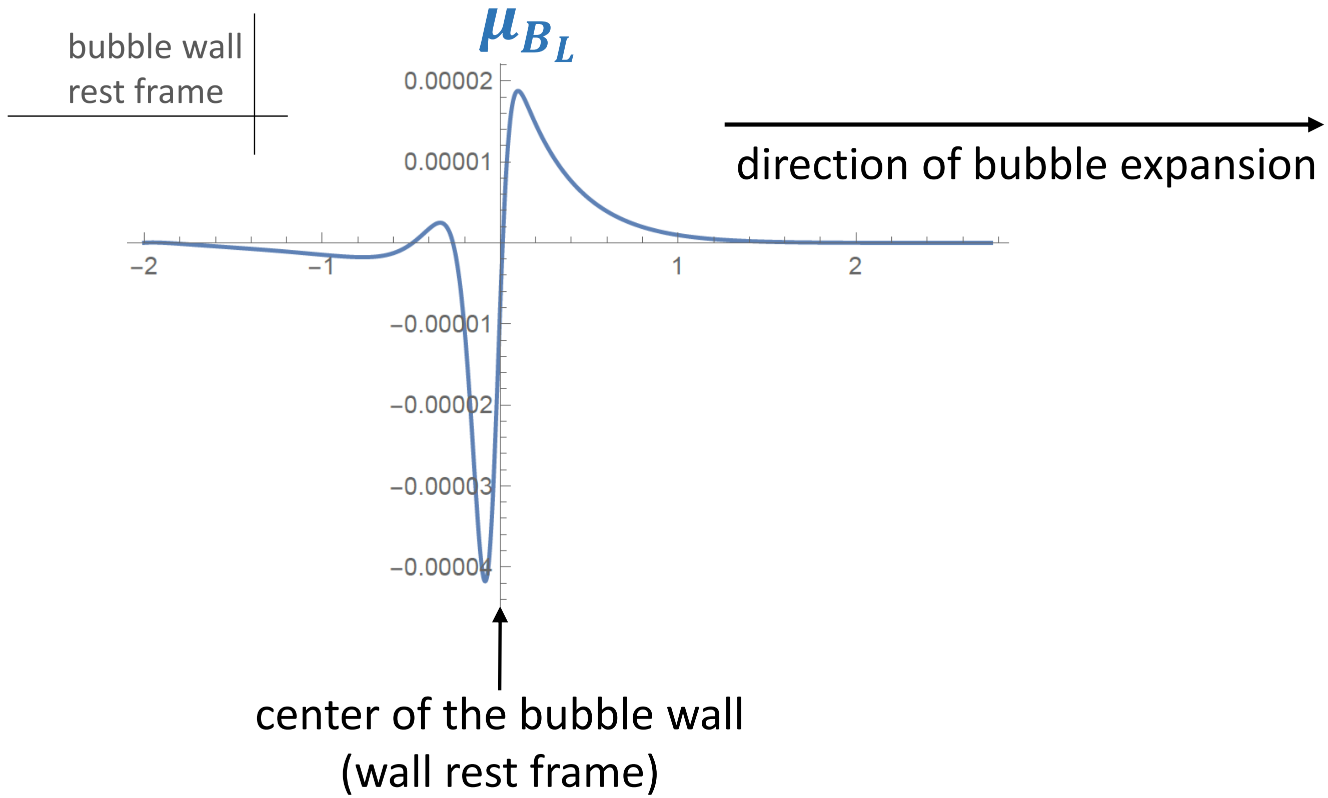
Formalisms are well-established in
- Joyce et. al., 9408339
- Fromme, Huber, 0604159
- Konstandin et. al., 1706.08534

1806.02591

Charge transport mechanism

$$L_{CPV} = (y_t + x_t e^{i\theta})\bar{q}_{L3} t_R H$$

After solving Boltzmann equations,
the chemical potential of left-handed baryon is obtained



1806.02591

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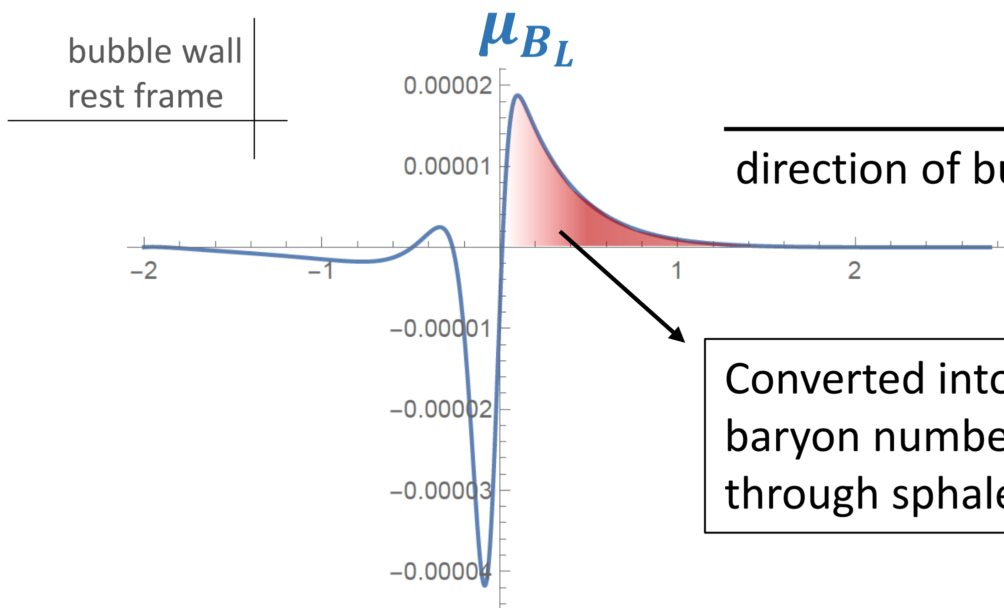


direction of bubble expansion

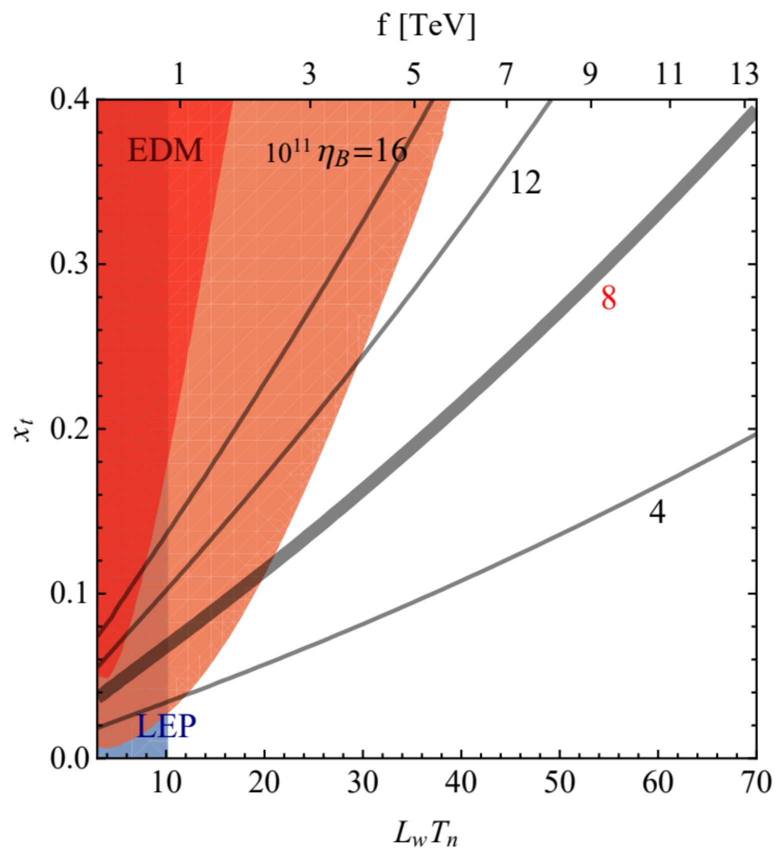
Converted into
baryon number density
through sphaleron

center of the bubble wall
(wall rest frame)

1806.02591

Charge transport mechanism

$$L_{CPV} = (y_t + x_t e^{i\theta})\bar{q}_{L3} t_R H$$



Benchmark parameters

$\Lambda = 130$ GeV,
$\alpha = 1.4$,
$M = 103$ GeV

$T_c \simeq 68$ GeV
$T_n \simeq T_2 \simeq 54$ GeV
$v_w \simeq 0.07$

✓ For an UV completion, $x_t \lesssim 0.3$.

✓ large f ⇒ large L_w ⇒ small η_B ⇒ requires larger x_t
⇒ smaller couplings (this is what I want)

1811.03294

Adiabatic electroweak baryogenesis

If $\boldsymbol{f} > \boldsymbol{O}(\mathbf{10}-\mathbf{100\ TeV})$, diffusion effect is negligible.
(Particles in the plasma do not have enough time to transport from the wall to the outside.)
(They feel like that the Higgs vev changes in time, homogeneously.)

$$L_{CPV} = \frac{g_2^2}{32\pi^2}\theta W_{\mu\nu}\widetilde{W}^{\mu\nu} = \theta\,\partial_\mu J_{CS}^\mu \to -\partial_\mu\theta\, J_{CS}^\mu \sim -\partial_t\,\theta\, N_{CS} \to \mu_{CS} = \partial_t\theta$$

$$\Gamma_{sph} \equiv 2\lim_{\mu\to 0}\frac{\dot{N}_{CS}T}{\mu_{CS}V} \;\Rightarrow\; \dot{n}_{CS} = \frac{1}{2}\frac{\Gamma_{sph}}{T}\mu_{CS}\left(1-\frac{n_{CS}}{n_{CS}^{(eq)}}\right) \;\Rightarrow\; \dot{n}_B = \frac{3}{2}\frac{\Gamma_{sph}}{T}\dot{\theta}\left(1-\frac{n_B}{n_B^{(eq)}}\right)$$

$$n_B^{(eq)} = \frac{13}{2}\dot{\theta}$$

$$\Gamma_{sph} \simeq 18\,\alpha_w^5 T^4 \;\Rightarrow\; n_B \simeq 27\,\alpha_w^5 T_n^3(\Delta\theta)e^{-K_\phi}$$

K_ϕ becomes order one when $f > 10^{6-7}GeV$

1811.03294

Adiabatic electroweak baryogenesis

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$$n_B^{(eq)} = \frac{13}{2}\dot{\theta}$$

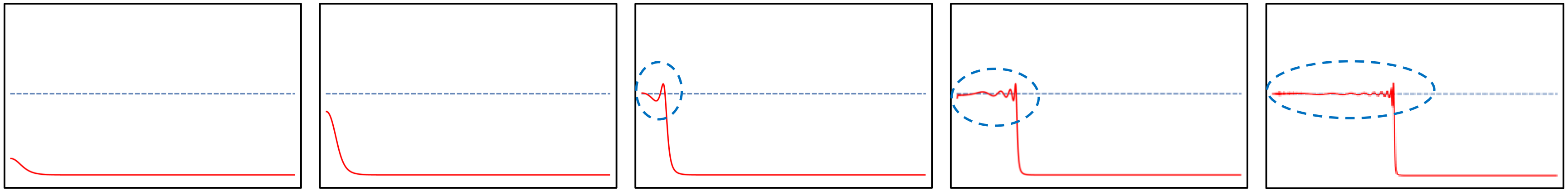
Large suppression if $f > 10^{6-7} GeV$

Two contributions to K_ϕ

1. When $f \uparrow$, $\delta t_{PT} \simeq 1/m_\phi \uparrow$ (i.e. time scale increases)

$$\Rightarrow \dot{\theta} \downarrow \Rightarrow \quad n_B^{(eq)} \downarrow$$

2. Oscillation after tunneling does not stop (small dissipation rate).



Adiabatic electroweak baryogenesis

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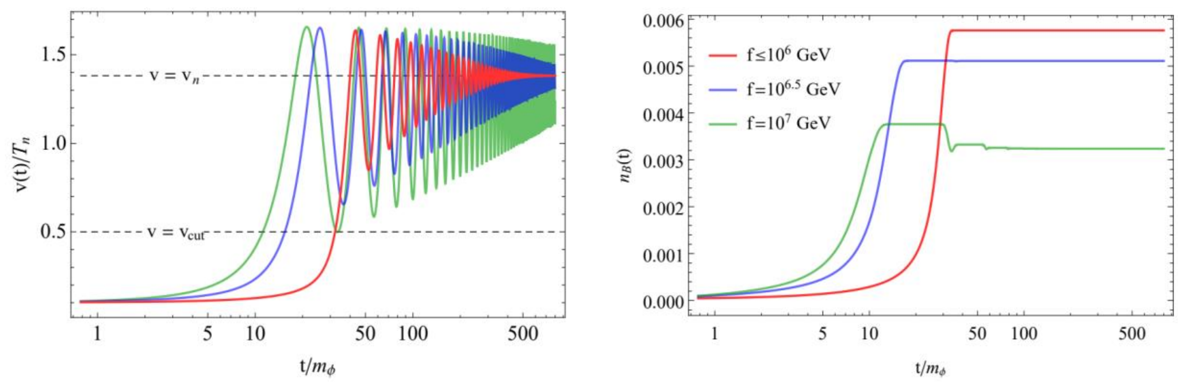
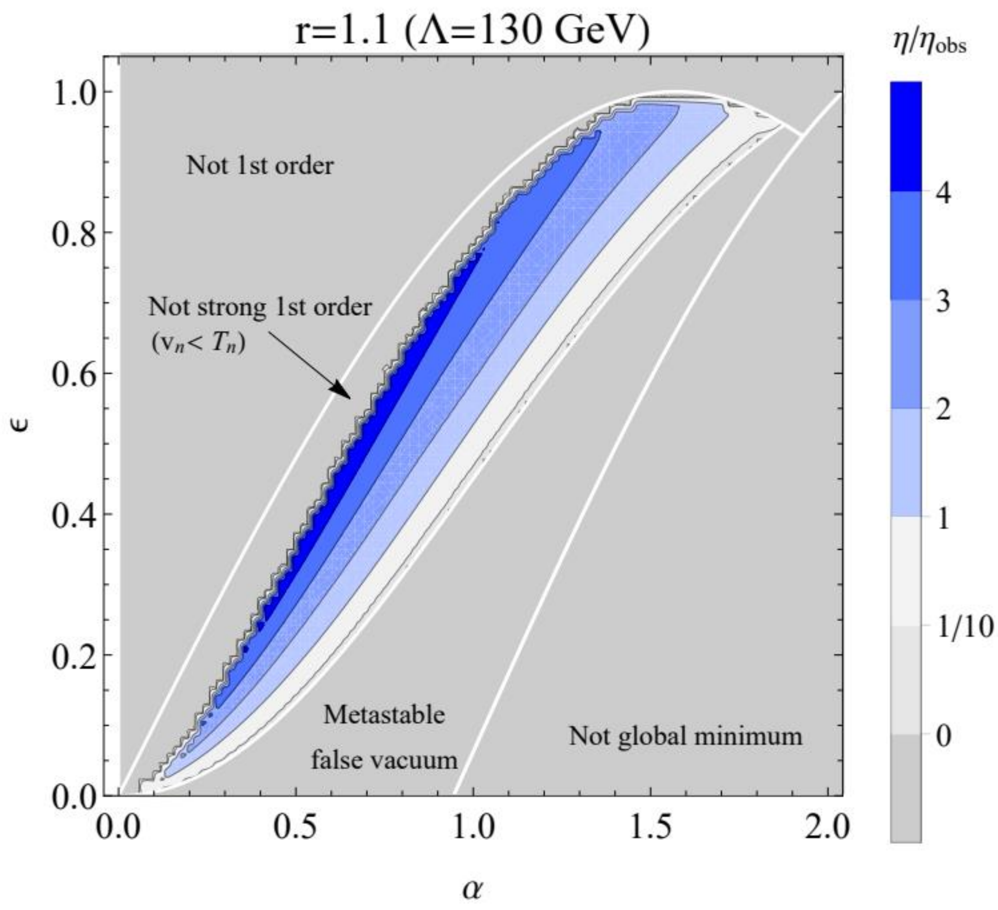


Adiabatic electroweak baryogenesis

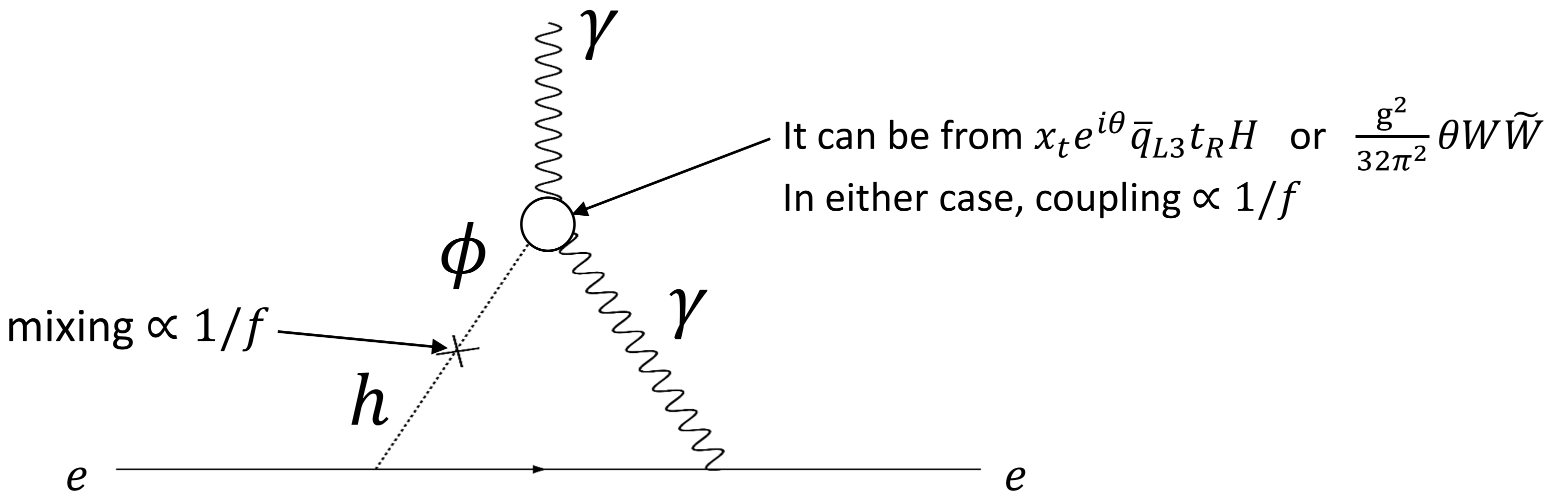
$f < 10^{6-7} GeV$ can naturally explain the observed baryon asymmetry.



Phenomenological constraints

EDM constraints

- Generally, electron EDM constraint (ACME II) provides the most stringent obstacle.
- Our axion coupling is suppressed by $1/f$, so it is not so severe.
- there are other ways bypassing the constraint: e.g. dynamical CP violation (F. Huang, M. Zhang, Z. Qian)
  cancelation mechanism (E. Senaha)



EDM $\propto 1/f^2$

for the top transport case: $f \gtrsim 3\ TeV$
for the weak anomaly case: $f \gtrsim 5\ TeV$

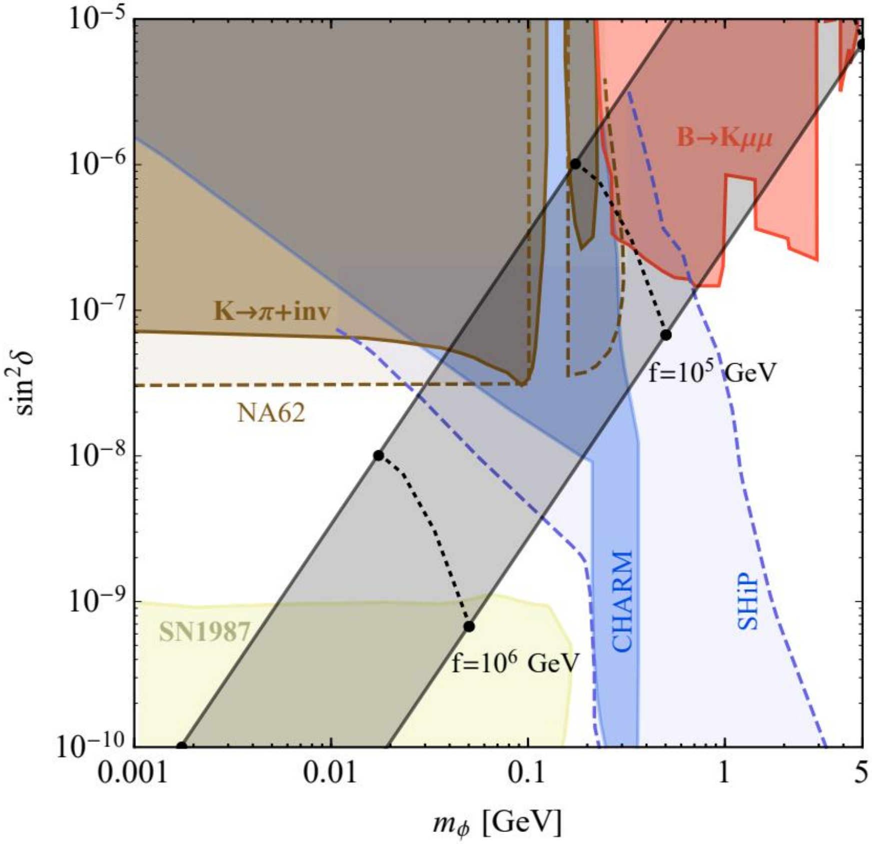
$cf.$ condition for baryon asymmetry: $f \lesssim 10^{6-7}\ GeV$

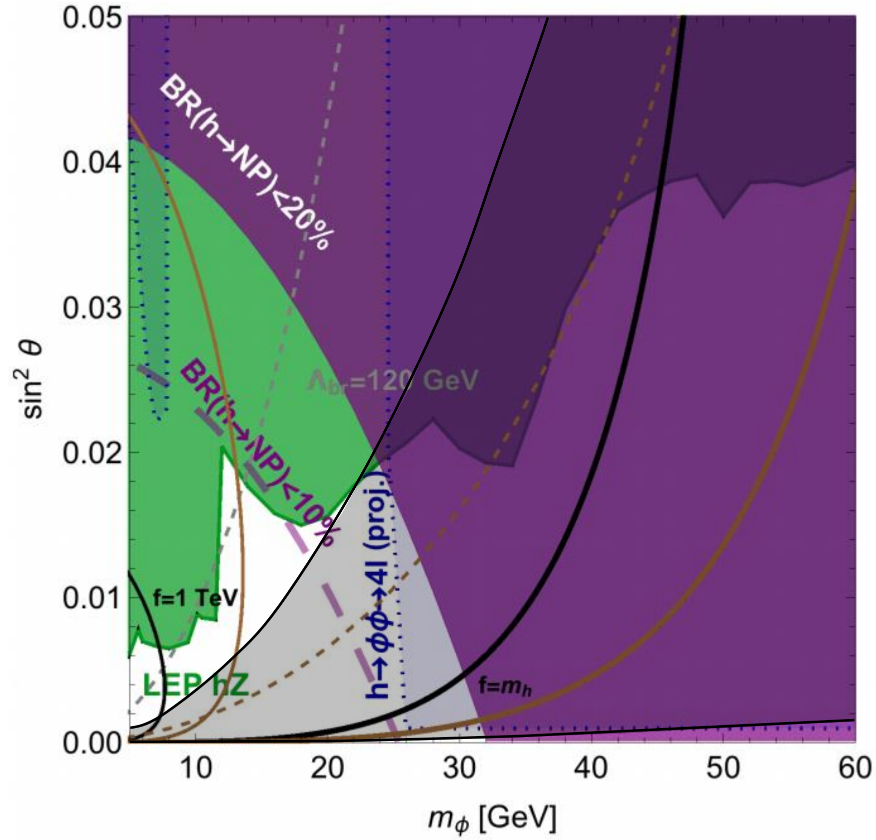
How can we test the model?

→ALP Searches

ALP-Higgs mixing

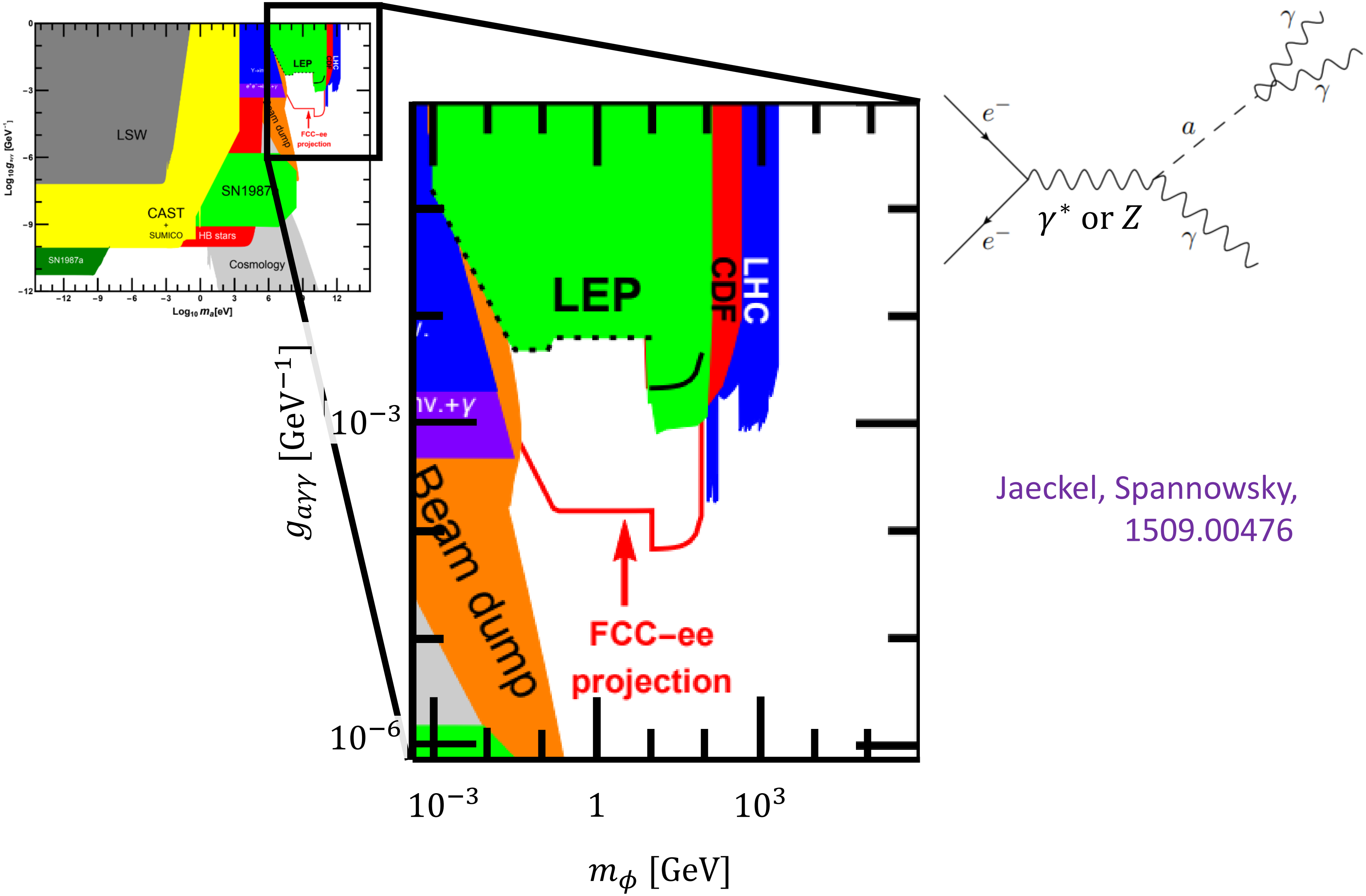
Flacke et. al., 1610.02025
Choi, Im, 1610.00680





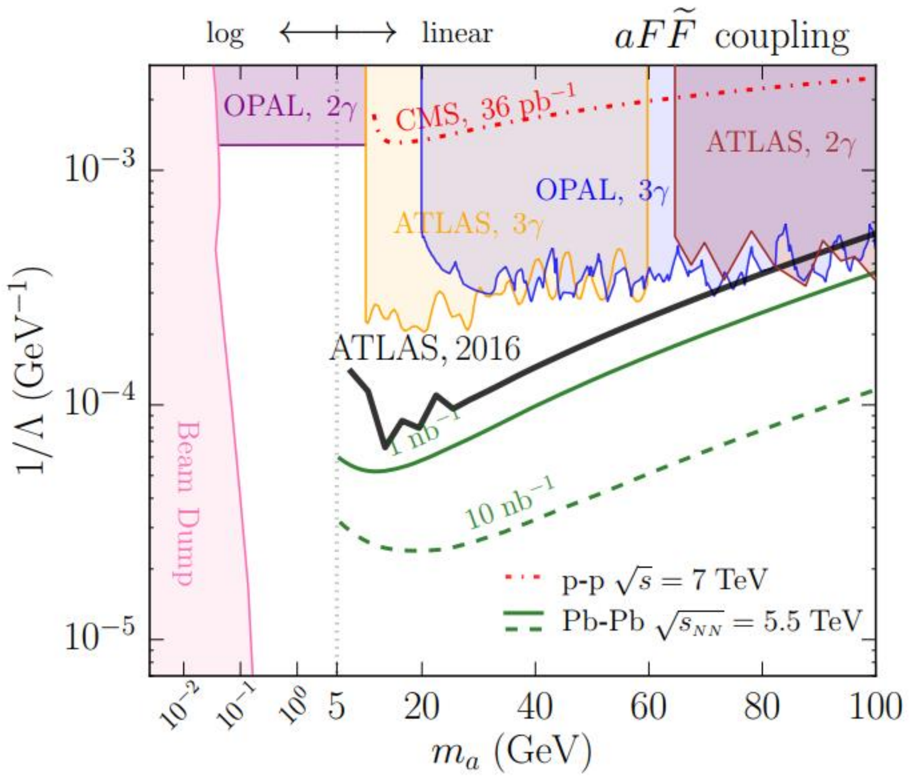
$$\rightarrow 5\ \mathrm{MeV} \lesssim m_\phi \lesssim 100\ \mathrm{MeV}\ or\ 5\ \mathrm{GeV} \lesssim m_\phi \lesssim 25\ \mathrm{GeV}$$

ALP Searches at future lepton colliders

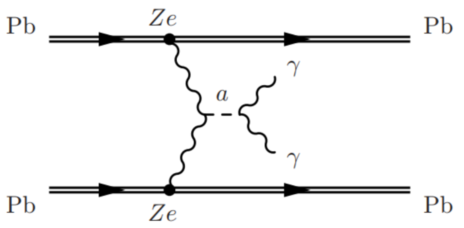


Jaeckel, Spannowsky,
1509.00476

ALP Searches at heavy ion collision



Diphoton resonance search at heavy ion collision



Knapen, Lin, Lou, Melia, 1607.06083

Summary

We considered an ALP extended Higgs sector where EWBG is realized.

- Strong first order phase transition is possible
  - ✓ ALP dependent Higgs mass drives a first order phase transition, independently of f.
  - ✓ large f $\rightarrow$ weakly coupled limit.

- How large can f be?
  - ✓ **It depends on CPV operator.**
  - ✓ **If diffusion is required (top transport)**: $\mathrm{L_W} \propto f \Rightarrow n_B \propto 1/f^{\#} \Rightarrow f < 10\ \mathrm{TeV}$.
  - ✓ **Weak anomalous coupling** : wash-out term $\rightarrow f < 10^{6-7}\ \mathrm{GeV}$

- Phenomenology
  - ✓ EDM $\propto 1/f^2 \Rightarrow \begin{cases} \text{top transport: } f > 3\ TeV \\ \text{weak anomalous coupling: } f > 5\ TeV \end{cases}$
  - ✓ ALP searches from ALP-Higgs mixing $\Rightarrow \begin{cases} 5\ \mathrm{GeV} \lesssim m_\phi \lesssim 25\ \mathrm{GeV} \Leftarrow \text{lepton collider? heavy ion collision?} \\ 5\ \mathrm{MeV} \lesssim m_\phi \lesssim 100\ \mathrm{MeV} \Leftarrow ??\ \text{not clear at current stage} \end{cases}$

Thank you for your attention!

Back up slides

Diffusion effect around bubble wall

It is well-known that a diffusion effect (so-called charge transport mechanism) around bubble wall helps the electroweak baryogenesis. (Joyce et. al. 9401351, Cohen et. al. 9406345)

In a wall rest frame, CP violation occurs proportionally to $\partial_z h$ (with $z =$coordinate along the bubble wall), and it drives a nonzero baryon number chemical potential.

If there is no diffusion effect, chemical potential is nonzero **only at the wall ($\boldsymbol{\partial_z h \neq 0}$)**, while sphaleron rate is exponentially suppressed $\left(\exp\left(-\frac{h}{T}\right)\right)$.

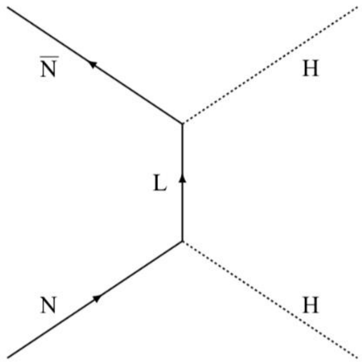
If there is a diffusion effect, chemical potential is **spread away** and becomes **nonzero outside bubble wall** where sphaleron rate is not suppressed.

UV Completion

Similar to relaxion models
(Graham, Kaplan, Rajendran, 1504.07551)

Vector-like lepton pair L, L^c and singlet pair N, N^c charged under hidden non-Abelian gauge group,

$$-L = y\, H\, L\, N^c + y' H^\dagger L^c N + m_N N\, N^c + m_L L\, L^c + \text{h.c.}$$



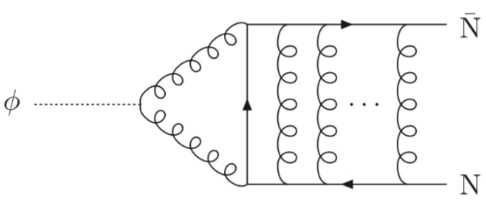
$$m_N \ll \Lambda_{con} \ll m_L,$$

$$-L_{eff} \to \left(m_N + \frac{y\, y'}{m_L} |H|^2 \right) N\, N^c$$

Confinement → axion−η' mixing → $< N\, N^c > \sim \Lambda_{con}^3 e^{i\phi/f}$,

$$-L_{eff} \to m_N \Lambda_{con}^3 \cos\frac{\phi}{f} + \frac{y\, y'}{m_L} \Lambda_{con}^3 |H|^2 \cos\left(\frac{\phi}{f} + \alpha\right)$$

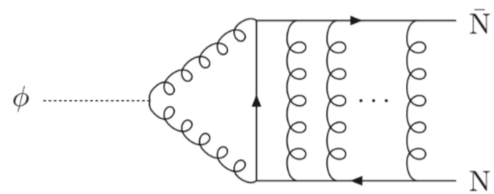
$$\alpha = Arg\left(\frac{y\, y' m_N}{m_L}\right)$$



1806.02591

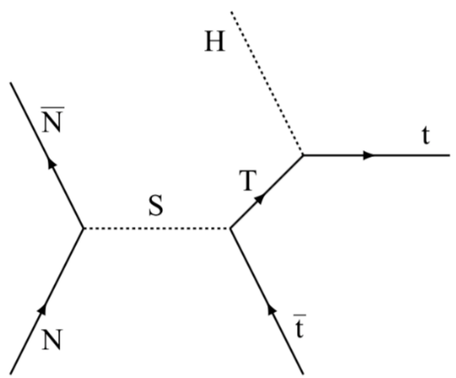
UV Completion for $(y_t + x_t e^{i\theta})\bar{q}_{L3} t_R H$

Hidden sector confinement → axion−η' mixing → $< N\, N^c > \sim \Lambda_{con}^3 e^{i\theta}$.



We need a contact interaction between $N\, N^c\, \bar{q}_{L3} t_R H$.

One example :



$$x_t \simeq \frac{\Lambda_{con}^3}{m_S^2 m_T}$$