# Electroweak baryogenesis from a Naturally Light Singlet Scalar

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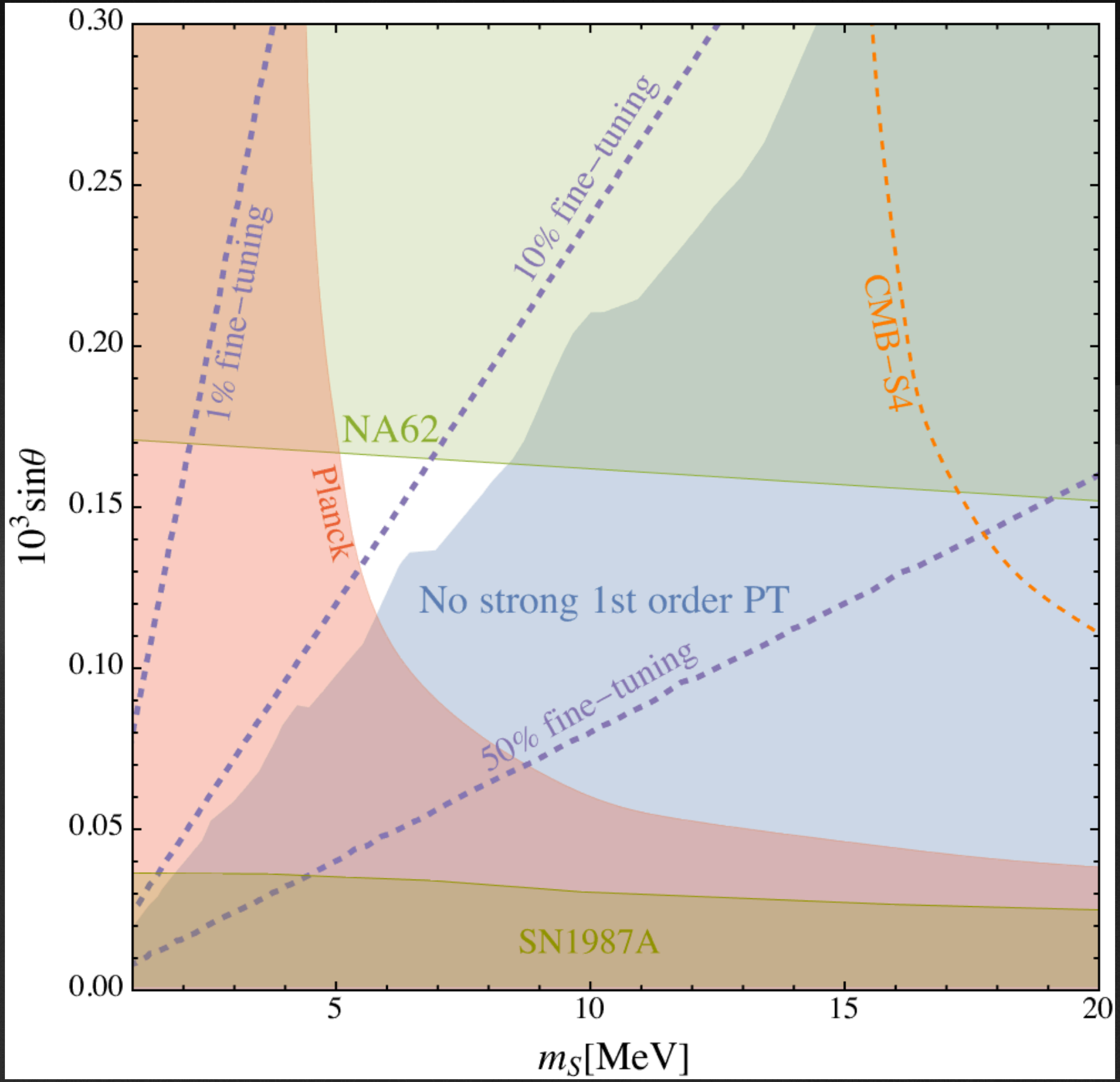
***Based on: 2207.02867 and future work***

# Outlook and summary

- Introduction: failure of SM electroweak baryogenesis
- Naturally light extra scalar model
- Thermal phase transition
- Electroweak baryogenesis
- Experimental probes
- Parity-symmetric generation



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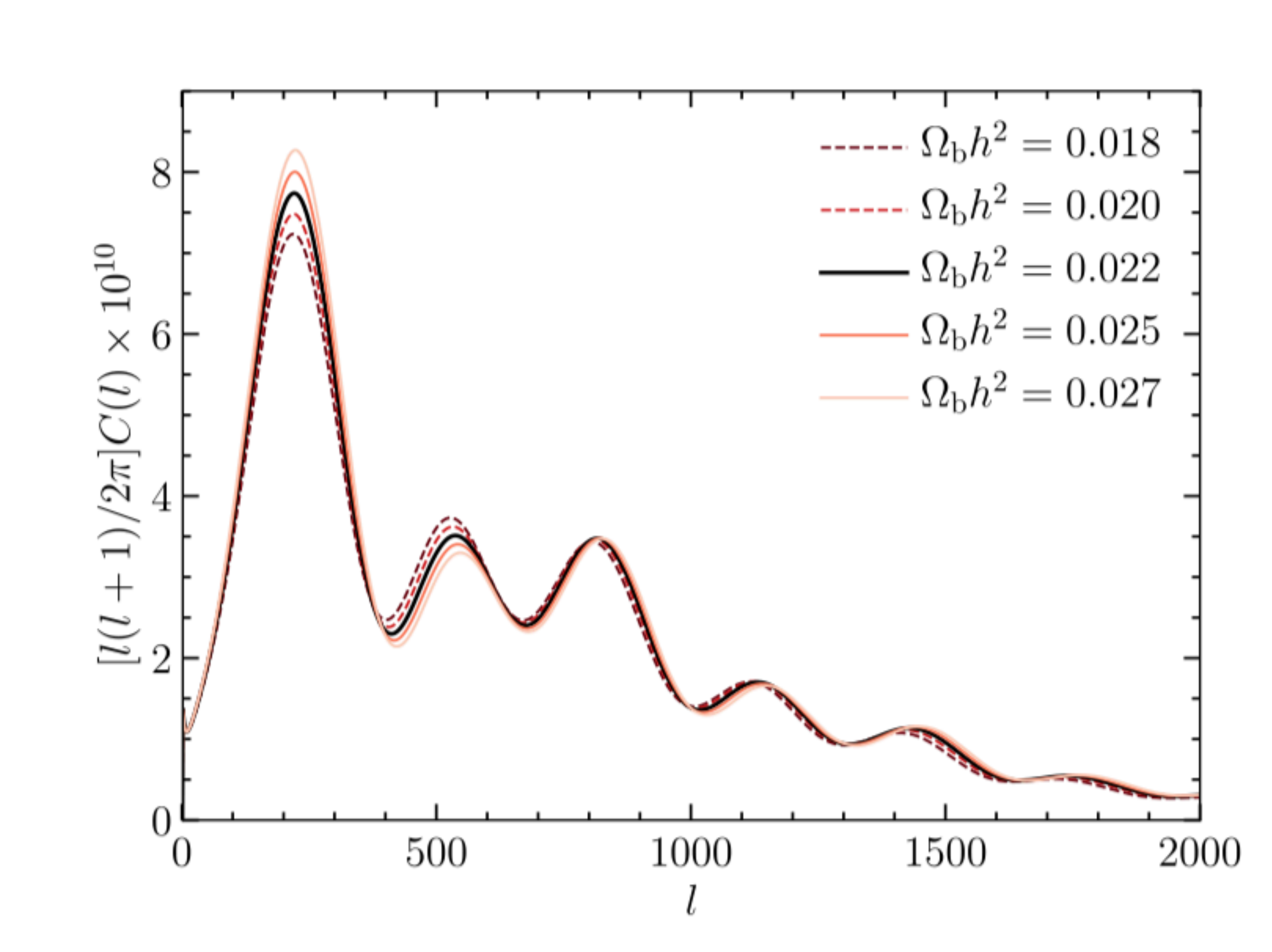
# Matter-Antimatter Asymmetry

## *The "baryogenesis" problem*

- matter > anti-matter
- Define $n_B = n_{\rm baryon} - n_{\rm anti-baryon}$
- $\Omega_b h^2 \simeq 0.022, \dfrac{n_B}{s} \simeq 9 \times 10^{-11}$
- What's the origin?




Planck 2018b

# Necessary conditions for baryogenesis

***The Sakharov condition***

- **Baryon number violation**: the one we want!

  SM: sphaleron process

- **C and CP violation**: anti-particle process won’t cancel what we get!

  SM: CKM (too small), or UV scale new physics, model dependent.

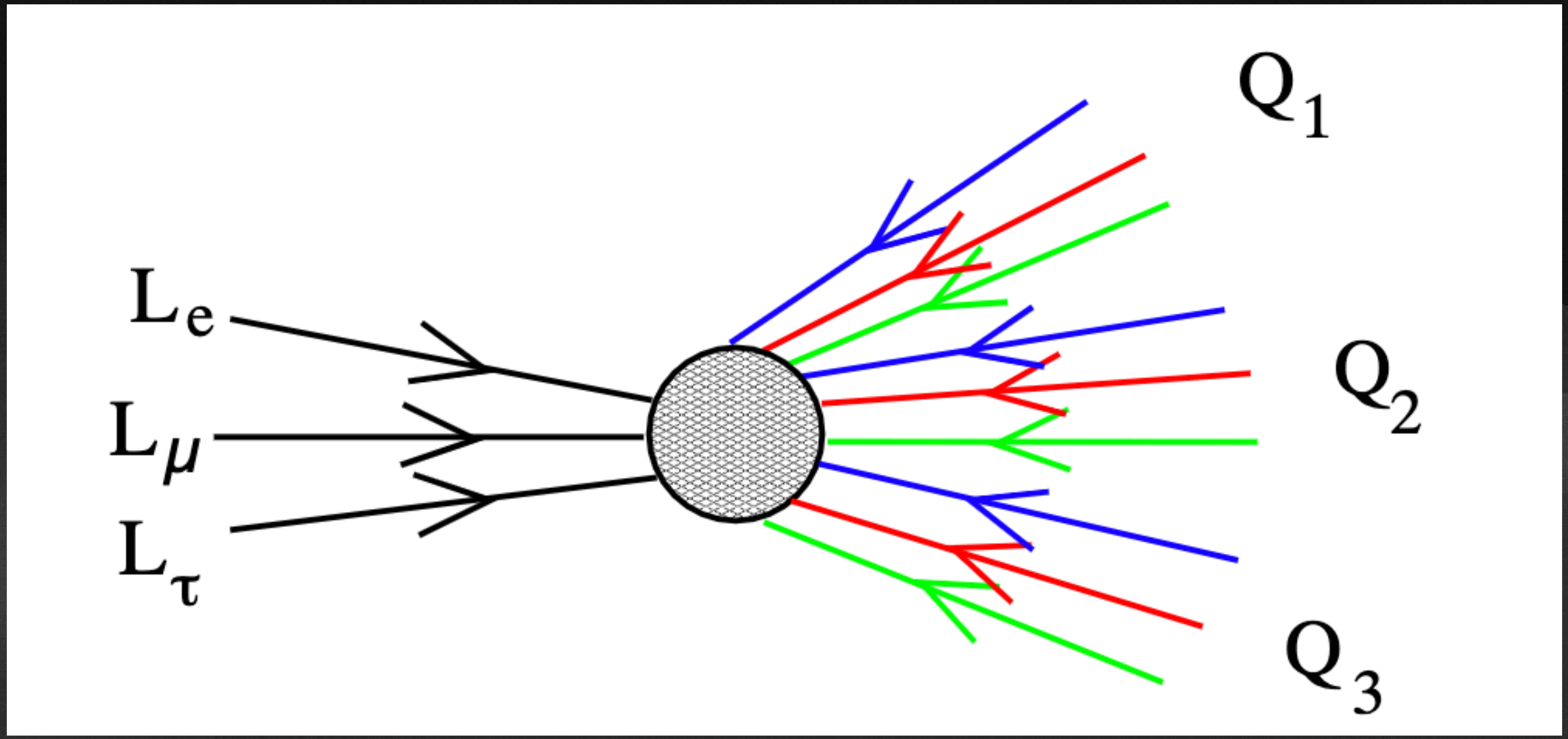
- **Out of thermal equilibrium**: produced number won’t go back!

  SM: ?

[Sakharov, 1967]

# B violation: sphaleron

- $B$ and $L$ symmetry is broken at the quantum level. This violation is via sphaleron process.
- $\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \dfrac{3g^2}{32\pi^2} W\tilde{W}$
- $B - L$ is conserved.




[G. ’t Hooft, Phys. Rev. Lett. 37, 8 (1976)]

# Electroweak phase transition (EWPT)

## Well-known option for out-of-equilibrium condition

Higgs potential

$$T = 0\text{: } V = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

$T > 0$: receive finite temperature correction.

Very high $T$: “symmetry restoration”

$T_c$: $h = 0$ and $h = v$ degenerate, “critical temperature”

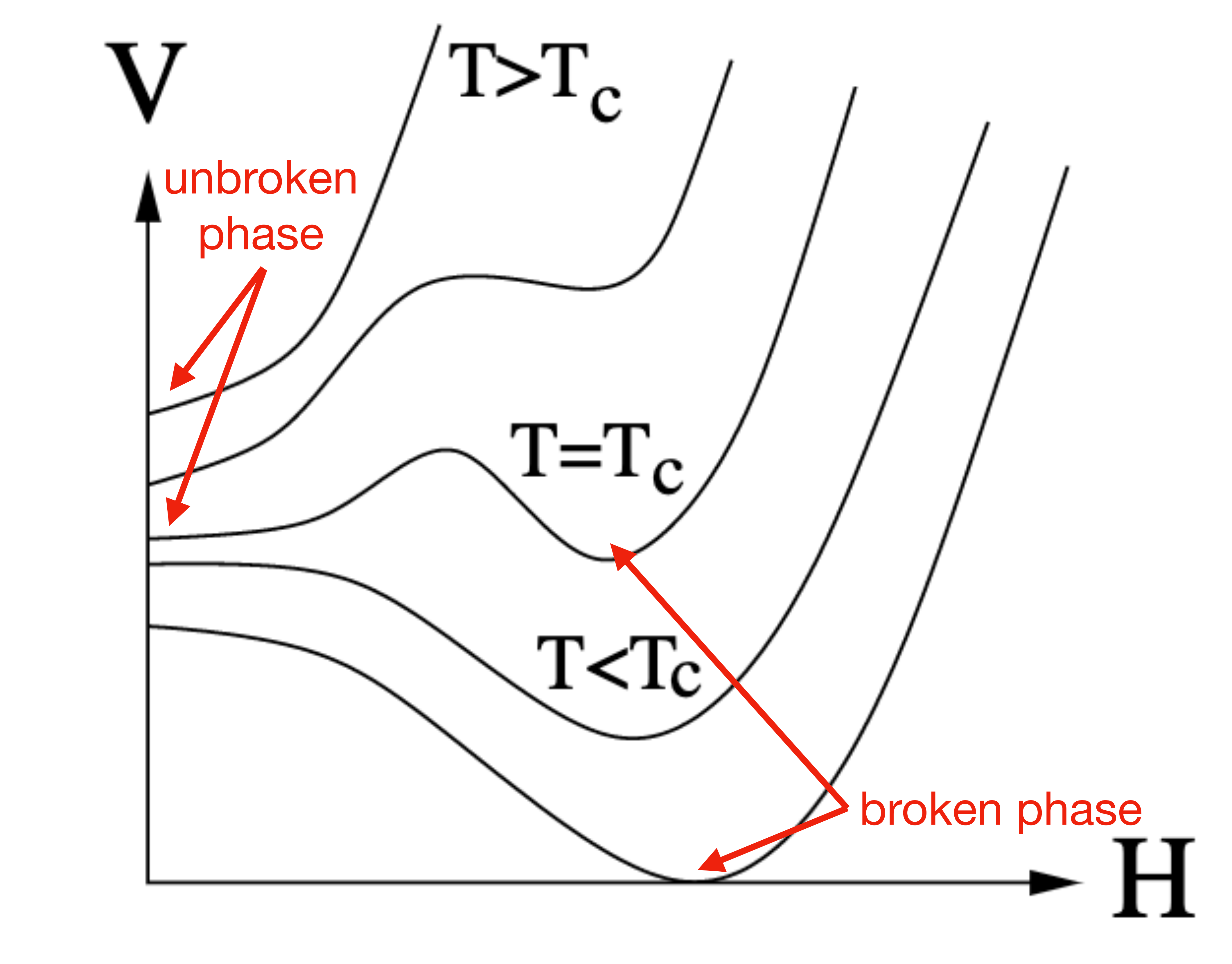
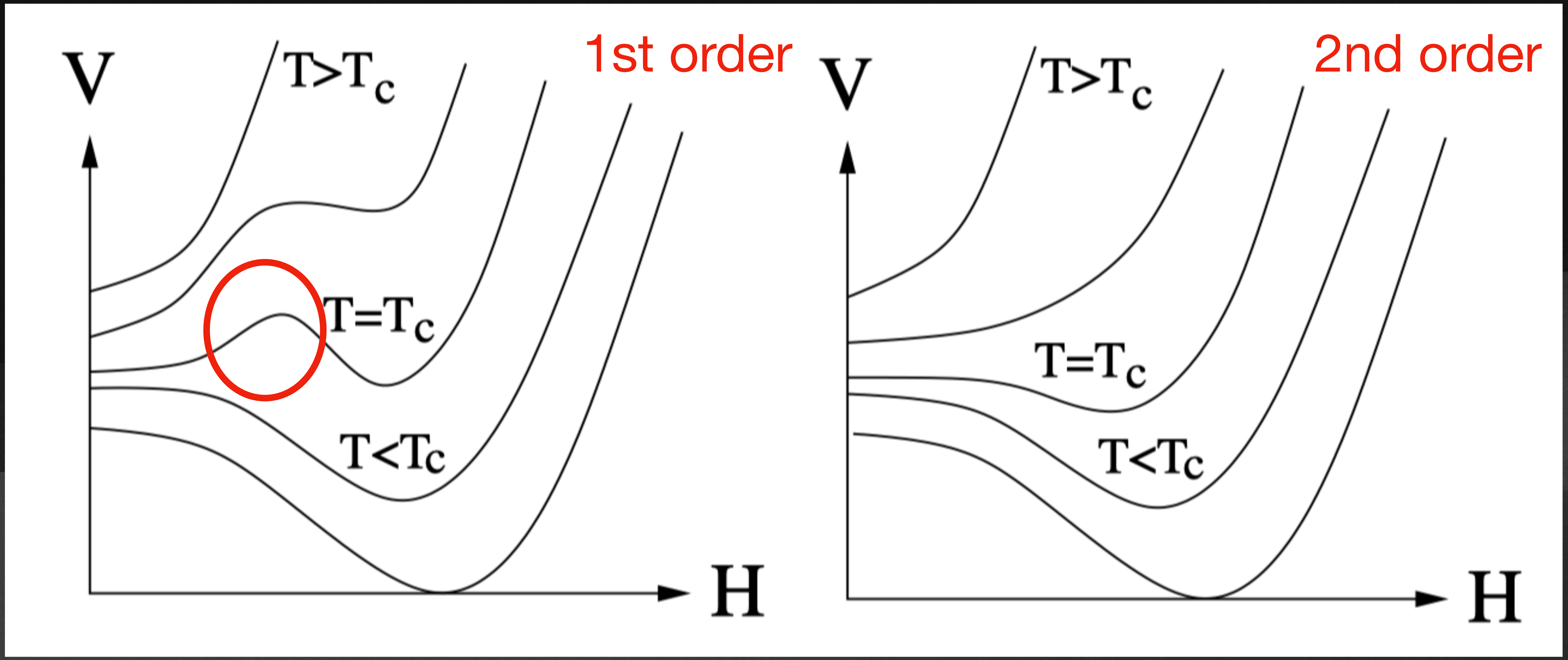
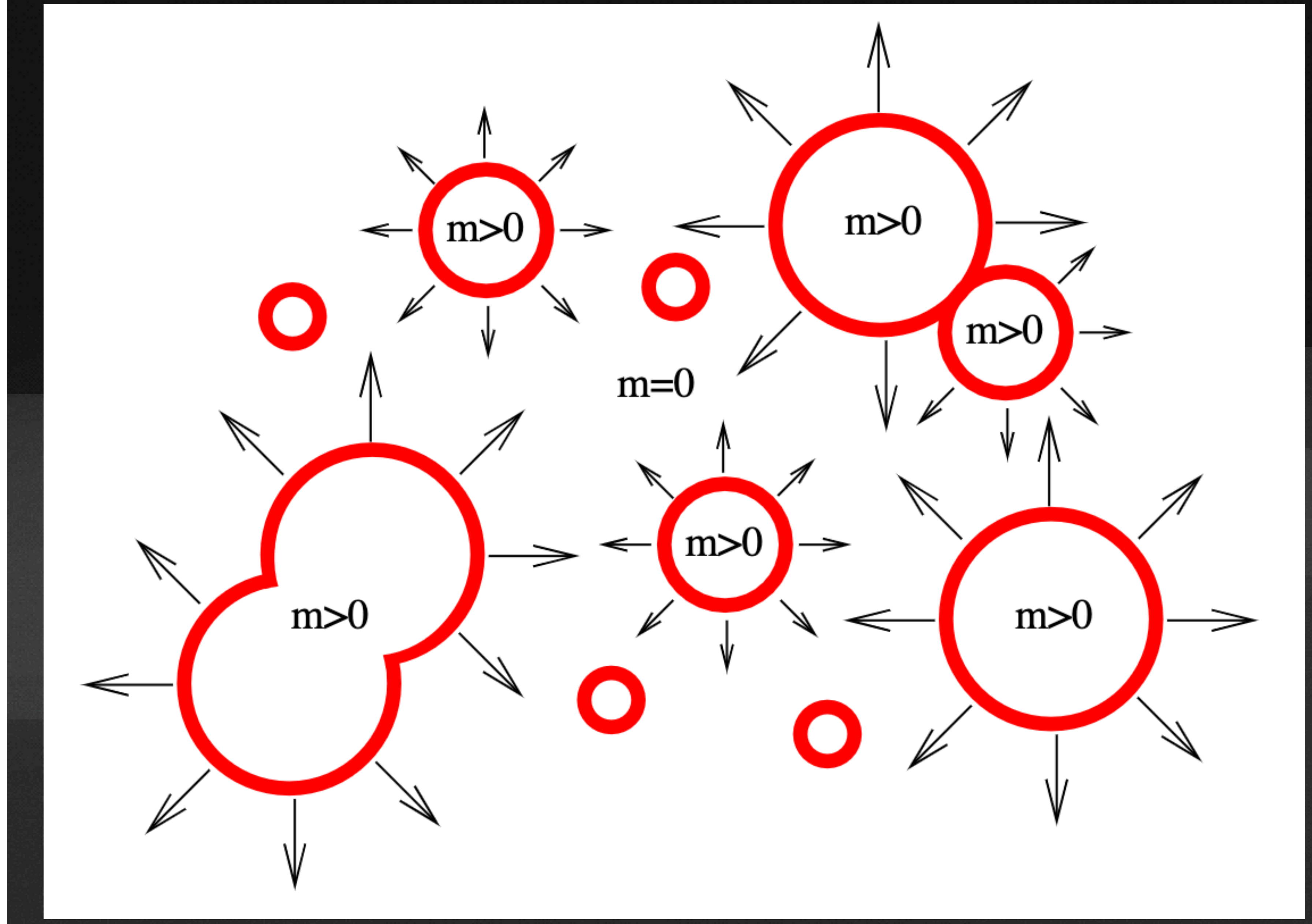



Figure from:
[J Cline: hep-ph/0609145]

# EWPT: 1st order vs 2nd order



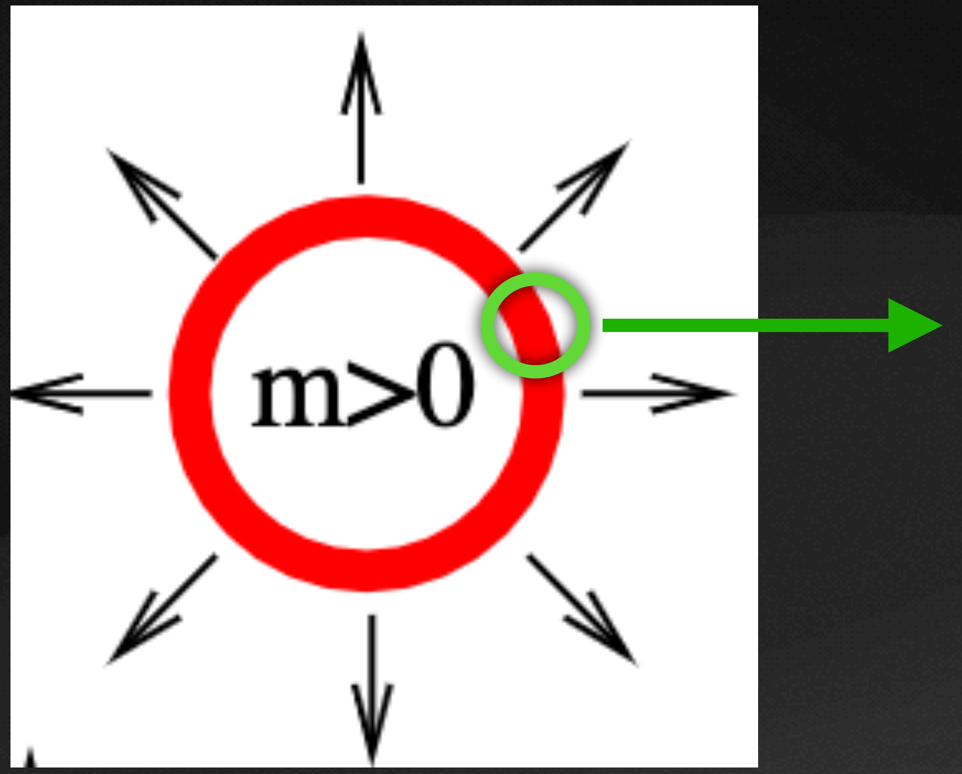

1st order: clear, well-defined barrier
2nd order: smooth crossover.

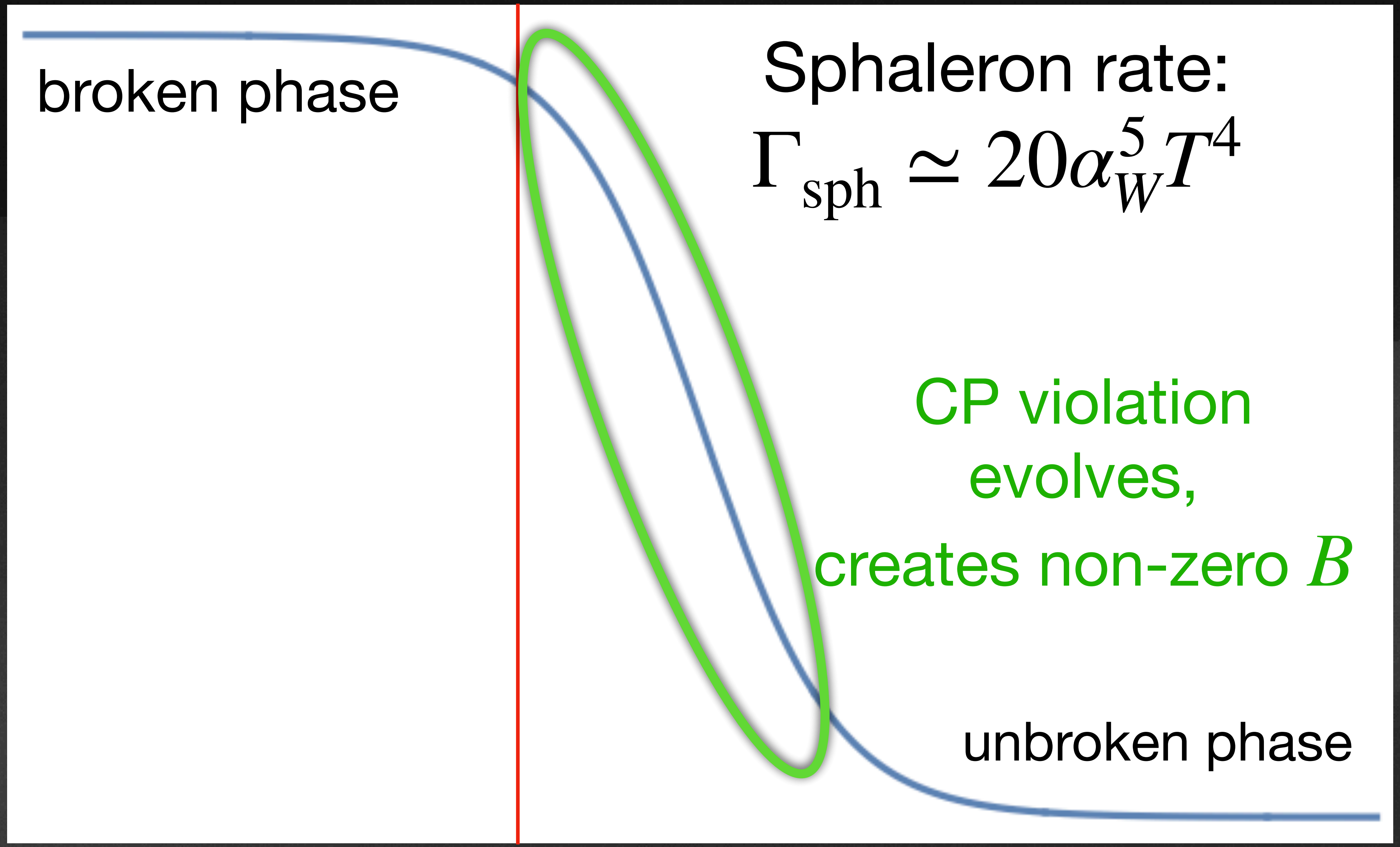



1st-order PT processes via
bubble nucleation

Figure from:
[J Cline: hep-ph/0609145]

# Electroweak baryogenesis from 1st order EWPT




Wall profile

Sphaleron rate in the bubble:

$$\Gamma_{\rm sph} \sim \exp(-E_{\rm sph}/T),\ E_{\rm sph} \propto \frac{4\pi v}{g},$$

suppressed by $v$

Need to be turned off inside the bubble!

[F. R. Klinkhamer and N. S. Manton, Phys. Rev. D 30, 2212]
[V. A. Kuzmin, V. A. Rubakov and M. E. Shaposhnikov, Phys. Lett. B 155, 36 (1985)]
[M. E. Shaposhnikov, JETP Lett. 44, 465 (1986),Nucl. Phys. B 287, 757 (1987)]
[A. G. Cohen, D. B. Kaplan and A. E. Nelson,hep-ph/9302210]
[D'Onofrio et al: 1404.3565]

# Sphaleron suppression: Strong 1st-order EWPT (SFOPT)

## (1) Sphaleron decoupling inside bubble

$$\Gamma_{\rm sph} \sim \exp(-E_{\rm sph}/T),\ E_{\rm sph} \propto \frac{4\pi v}{g},$$

Need to turn this off inside the bubble: decoupling

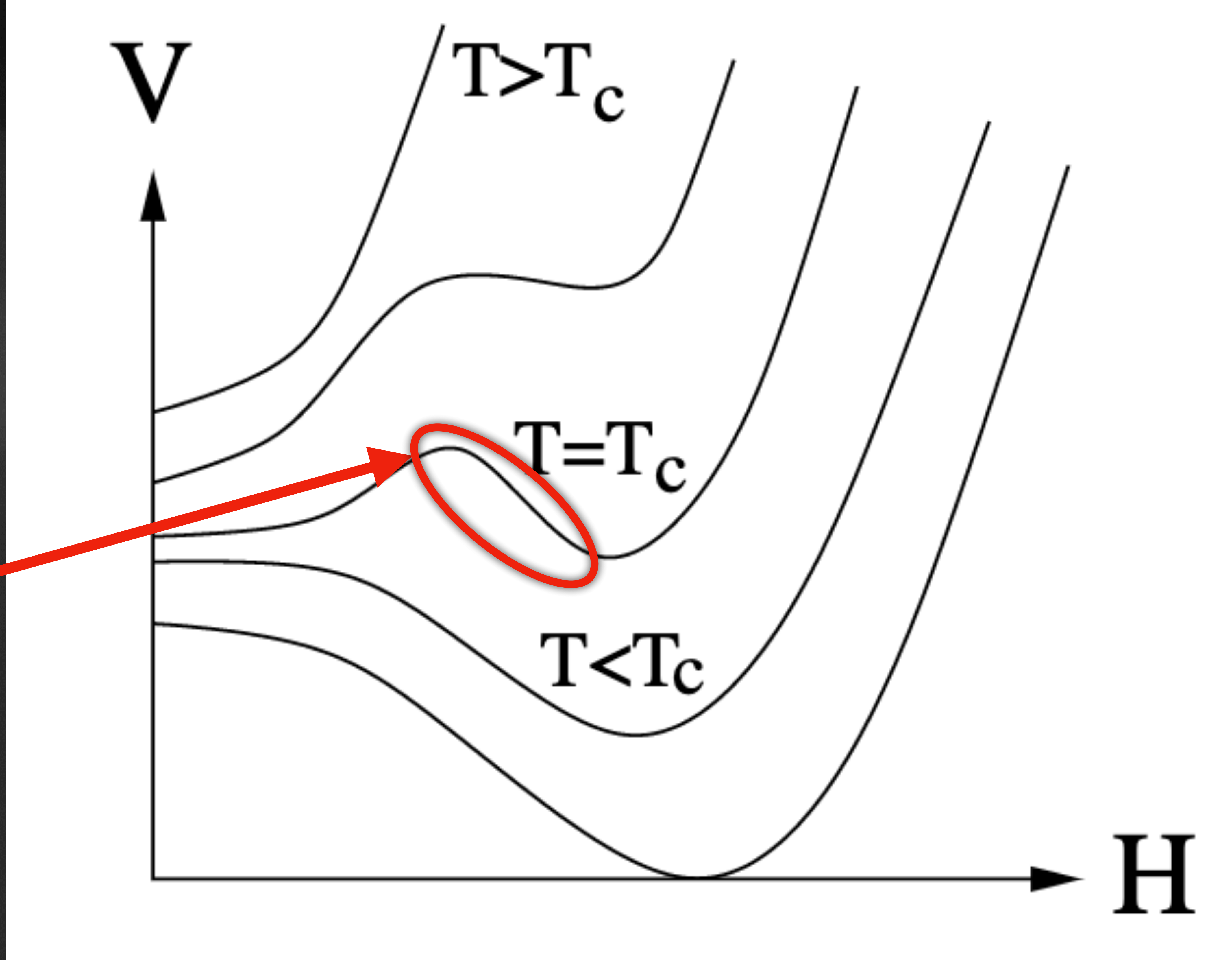
Require: large $\frac{v(T)}{T}$ at the phase transition

Typical condition: $\frac{v(T)}{T} \geq 1$

Intuition: $v(T)$ should be far away.

equivalent: we need a higher barrier.

Need effective potential to compute this

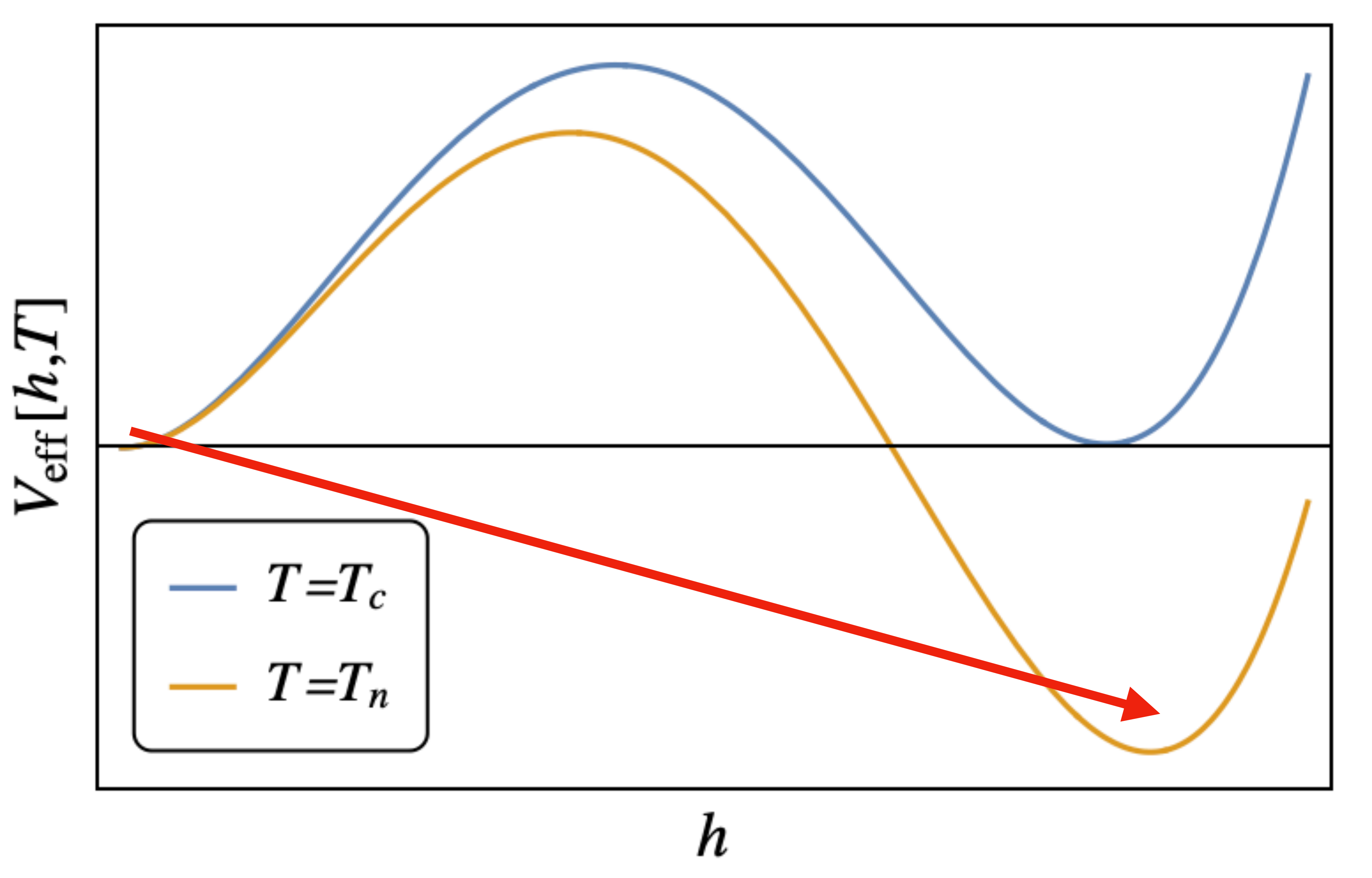


# Sphaleron suppression: Strong 1st-order EWPT (SFOPT)

## (2) thermal phase transition

- At $T = T_c$, two minima degenerate.
- Thermal transition becomes allowed by energy.
- Transition rate: $\Gamma \simeq T^4 \exp(-S_3/T)$, 3d action.
- $S_3 \equiv \int r^2 (\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi))dr$, decrease as universe cools down. $r$: radius of the 3d space along the solution.
- Transition happens when $\Gamma/H^3 \simeq H$, the Hubble rate.

  Condition: $\frac{S_3}{T} \simeq 140$. Then bubble nucleates.
- Transition happens at nucleation temperature $T_n$




Thermal potential at $T_c$ and $T_n$.

Typically (not supercooling):

$$\frac{v(T_c)}{T_c} \simeq \frac{v(T_n)}{T_n}$$

Require this to be $> 1$ for SFOPT

# Sphaleron suppression: Strong 1st-order EWPT (SFOPT)

## (3) Thermal potential at 1-loop

- Finite-T: thermal correction to the effective potential $V$.
- Boson contribution: $\frac{T^4}{2\pi^2} n_B (\frac{\pi^2}{12}(\frac{m}{T})^2 - \frac{\pi}{6}(\frac{m}{T})^3 + \ldots)$, $n_B$: degree of freedom
- Fermion contribution: $\frac{T^4}{2\pi^2} n_F (\frac{\pi^2}{24}(\frac{m}{T})^2 + \ldots)$, $n_F$: degree of freedom.
- Total: $V = DT^2h^2 - \frac{1}{2}\mu^2h^2 - ETh^3 + \frac{1}{4}\lambda h^4$, cubic from bosons
- $\frac{v(T_c)}{T_c} = \frac{2E}{\lambda}$

# The Standard Model Result

## Lattice simulation: the most trustable result

$$\frac{v}{T} \simeq \frac{2E}{\lambda}$$

$$m_H \simeq \sqrt{2\lambda} v$$

- For $m_H \leq 46\ \mathrm{GeV}$, we can have SFOPT
- For $46 < m_H < 73\ \mathrm{GeV}$, we can have a weak 1st-order PT
- For $m_H > 73\ \mathrm{GeV}$, smooth crossover.
- Experiments found $m_H \simeq 125\ \mathrm{GeV}$

Conclusion: SM EWBG fails. No out-of-equilibrium condition.

[K. Jansen, hep-lat/9509018], [K. Kajantie et al, hep-lat/9510020]
[K. Rummukainen, hep-lat/9608079], [K. Kajantie et al, hep-ph/9605288.]
[M. Gurtler et al, hep-lat/9704013], [F. Csikor et al, hep-ph/9809291]
[M. Laine and K. Rummukainen, hep-ph/9804255, hep-lat/9804019]
[K. Rummukainen et al, hep-lat/9805013], [Z.Fodor, hep-lat/9909162]

# Take home notes

- Baryogenesis requirement: B violation, C and CP violation, out-of-equilibrium condition.
- The electroweak sphaleron offers B violation
- C and CP violation: model-dependent, not discussed here.
- Electroweak phase transition, if strong 1st order, i.e. $\frac{v(T_c)}{T_c} \simeq \frac{v(T_n)}{T_n} > 1$, provides out-of-equilibrium condition.
- $\frac{v(T_c)}{T_c} \simeq \frac{2E}{\lambda}$ where $E$ comes from bosons contribution.
- SM EWPT is a smooth crossover, not enough for successful EWBG.

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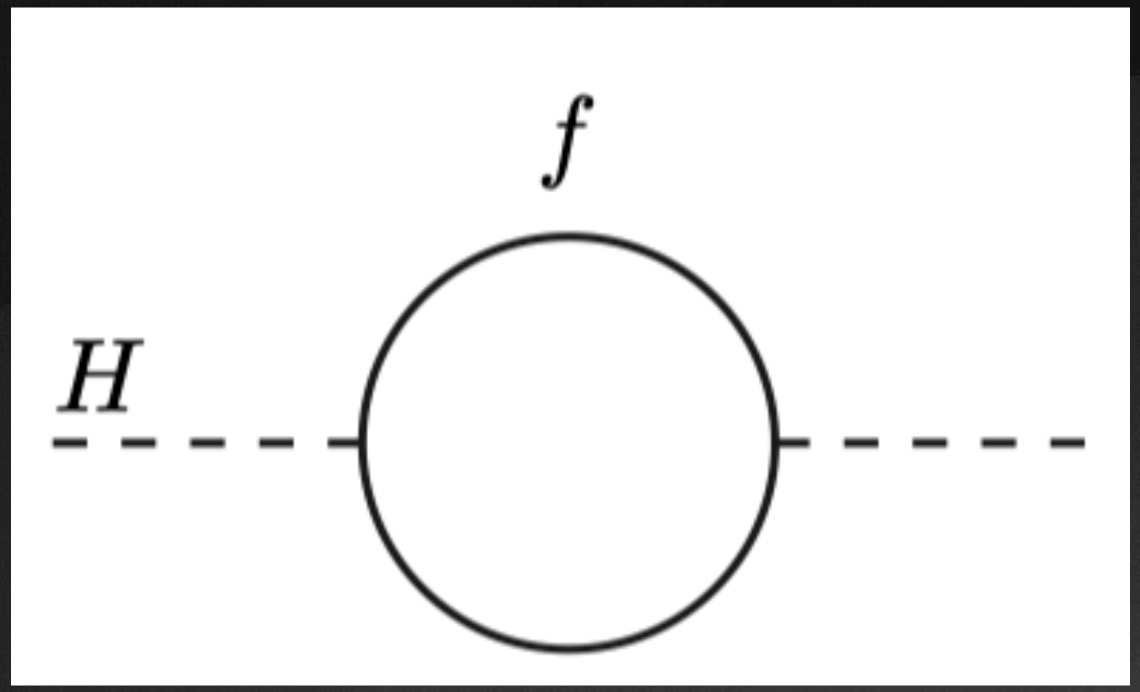
# A simple solution: extra singlet scalar

$$\frac{v(T_c)}{T_c} = \frac{2E}{\lambda}$$

- Introduce $S$ : $(1,1,0)$ singlet
- General: $\mathscr{L} = \mathrm{SM} + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{4}\lambda_S S^4$ + other interactions
- Only interact with Higgs: $SSHH$, $S^4$, $S^3$, $SHH$…., depending on the symmetry
- Z2-even $S$: $SHH$, $S^3$, $S^4$, $SSHH$, etc. Enhanced $E$ term at zero temperature.
- Z2-odd $S$: $S^4$, $SSHH$. Enhanced $E$ at finite temperature.

# Extra hierarchy problem

The SM electroweak hierarchy problem

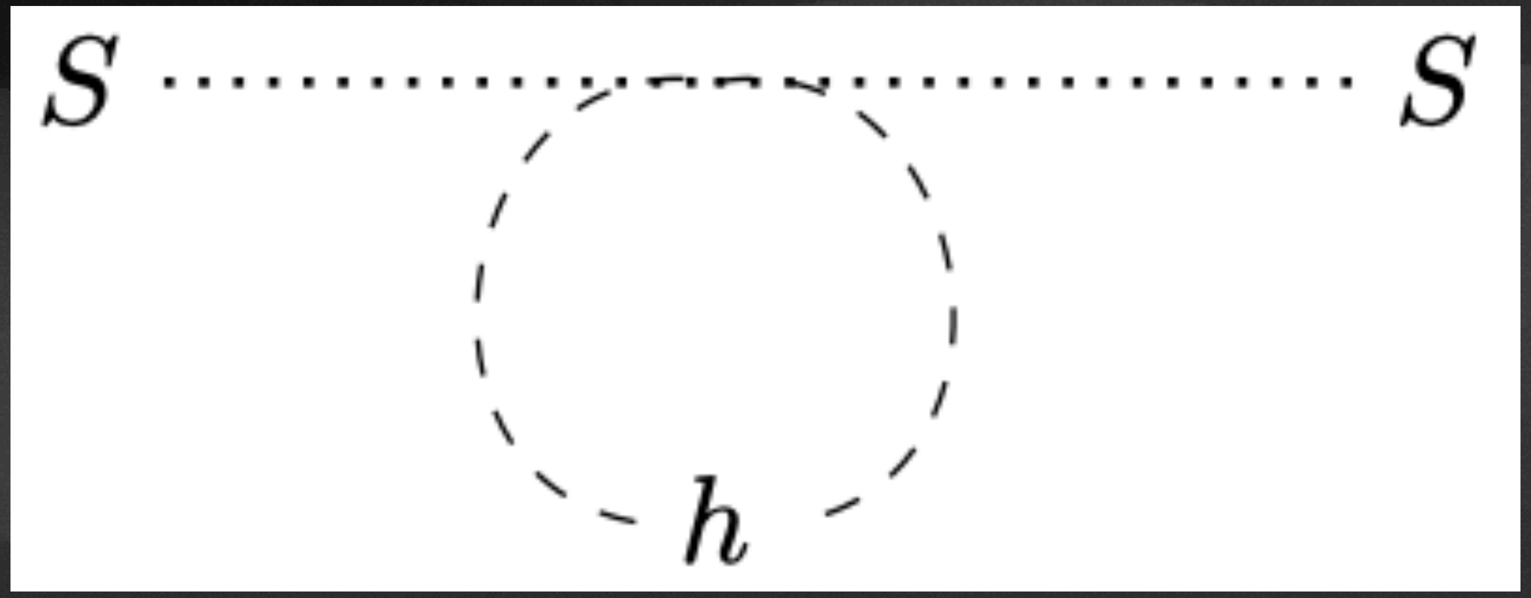



$$\delta m_H^2 = -\frac{y_f^2}{8\pi^2}\Lambda_{\rm UV}^2$$

Quadratic sensitive to $\Lambda_{\rm UV}$:
Huge quantum corrections!

The extra hierarchy problem from extra singlet

Typical models have $\frac{1}{4}\lambda_{hS}S^2h^2$




$$\delta m_S^2 = \frac{\lambda_{hs}}{16\pi^2}\Lambda_{\rm UV}^2$$

Typical singlet scalar model introduced
extra hierarchy problem!

Some traditional solutions: SUSY, compositeness….

# A “Naturally Light” Model

## Solve the extra hierarchy problem

Things could be easier if we can remove the $S^2h^2$ term

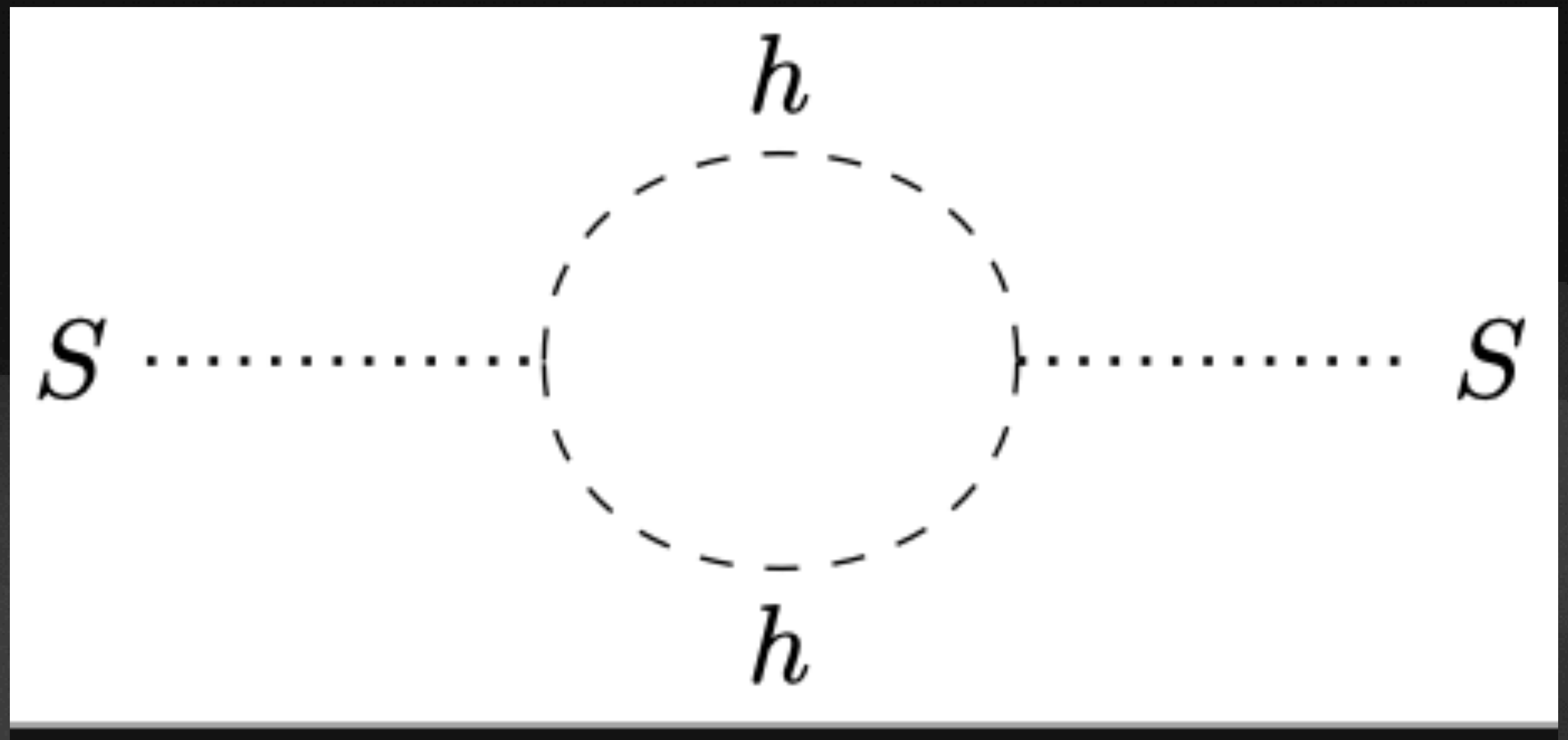
$$V = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}AS(h^2 - v^2)$$

First introduce:
P. Fox et al, 0910.1262
for minimality

How to kill all those interaction terms?

Shift symmetry: $S \to S + \delta S$

Only softly broken: $ASh^2$, and mass term.




$$\delta m_S^2 \simeq \frac{A^2}{16\pi^2}\ln(\frac{\Lambda_{UV}}{v}),$$ $A$ is soft, thus protected

“Naturally Light”!

[K. Harigaya and IW, 2207.02867]

# $T = 0$ Structure

$$\mu_H^2 = \frac{1}{2}\left(m_h^2 \cos^2\theta + m_S^2 \sin^2\theta\right), \quad \mu_S^2 = m_S^2 \cos^2\theta + m_h^2 \sin^2\theta,$$
$$A = \frac{\left(m_h^2 - m_S^2\right)\sin 2\theta}{2v}, \quad \lambda = \frac{m_h^2 \cos^2\theta + m_S^2 \sin^2\theta}{2v^2}.$$

$$V = -\frac{1}{2}\mu_h^2 h^2 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}AS(h^2 - v^2)$$ vev: $h = v, S = 0$

$\langle S \rangle = \dfrac{A}{2\mu_S^2}(h^2 - v^2)$ for arbitrary $h$, $\quad V(h, \langle S \rangle) = -\dfrac{1}{2}\mu_h^2 h^2 + \dfrac{1}{4}(\lambda - \dfrac{A^2}{2\mu_S^2})h^4$

Now we can define $\lambda_{\rm eff} = \lambda - \dfrac{A^2}{2\mu_S^2}$. Small $\lambda_{\rm eff}$ will enhance the EWPT. Requires $\mu_S < v$!

Fine-tuning: $\dfrac{\lambda_{\rm eff}}{\lambda} \simeq \dfrac{m_S^2}{\mu_S^2}$, $m_S$: measured physical $S$ mass

[P. Fox et al, 0910.1262]
[K. Harigaya and IW, 2207.02867]

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# Thermal phase transition

## (1) Thermal potential and 1-d analysis

$$V = DT^2h^2 - \frac{1}{2}\mu_h^2 h^2 - ETh^3 + \frac{1}{4}\lambda h^4 + \frac{1}{2}\mu_S^2 S^2 - \frac{1}{2}AS(h^2 + \frac{1}{3}T^2 - v^2)$$

$D = D_{SM}, E = E_{SM} +$ $\underbrace{\text{scalar terms}}_{\text{small, neglect}}$

At high-$T$: $\langle h \rangle = 0$, restored symmetry!
At low-$T$: $\langle h \rangle = v(T)$

$$\langle S \rangle(h,T) = \frac{A}{2\mu_S^2}(h^2 + \frac{1}{3}T^2 - v^2) \text{ for all } T$$

1-step PT: $(0, \langle S \rangle(0,T)) \rightarrow (v(T), \langle S \rangle(v(T),T))$

Fix $S$ at $\langle S \rangle$: $V = D'(T^2 - T_0'^2)h^2 - ETh^3 + \frac{1}{4}\lambda' h^4$, $D' = D - \frac{1}{3}\frac{A^2}{4\mu_S^2}$, $\lambda' = \lambda_{\text{eff}} = \lambda - \frac{A^2}{2\mu_S^2}$, $T_0'^2 = \frac{\mu_h^2\mu_S^2 - A^2v^2}{2D'\mu_S^2}$

Transition strength estimate: $\frac{v_c}{T_c} = \frac{2E}{\lambda'}$

[P. Fox et al, 0910.1262]
[K. Harigaya and IW, 2207.02867]

# Thermal phase transition

## (2) 2-d analysis: kinetic energy

$$S_3 = 4\pi \int r^2 (K + V) dr$$

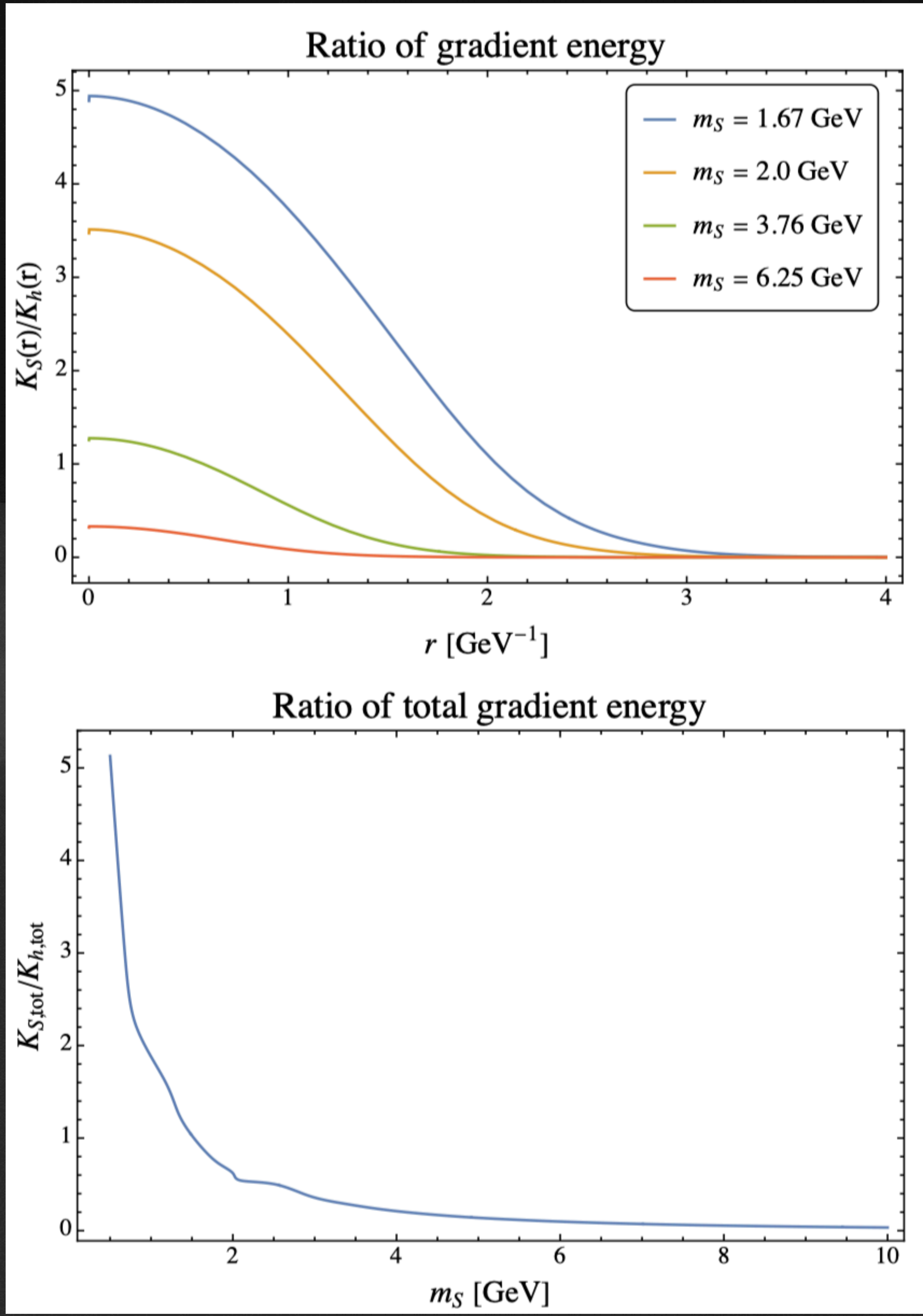
2-d field space: $S$ contributes large kinetic (gradient) energy.

$$K_{1d} = K_h = \frac{1}{2}\left(\frac{dh(r)}{dr}\right)^2 \longrightarrow K_{2d} = K_h + K_S = K_h + \underline{\frac{1}{2}\left(\frac{dS(r)}{dr}\right)^2}$$

$$\langle S \rangle (h, T) = \frac{A}{2\mu_S^2}\left(h^2 + \frac{1}{3}T^2 - v^2\right)$$

$$\Downarrow$$

$$K_S(r) = K_h(r)\frac{A^2}{\mu_S^4}h(r)^2$$ Diverge for $\mu_S \to 0$

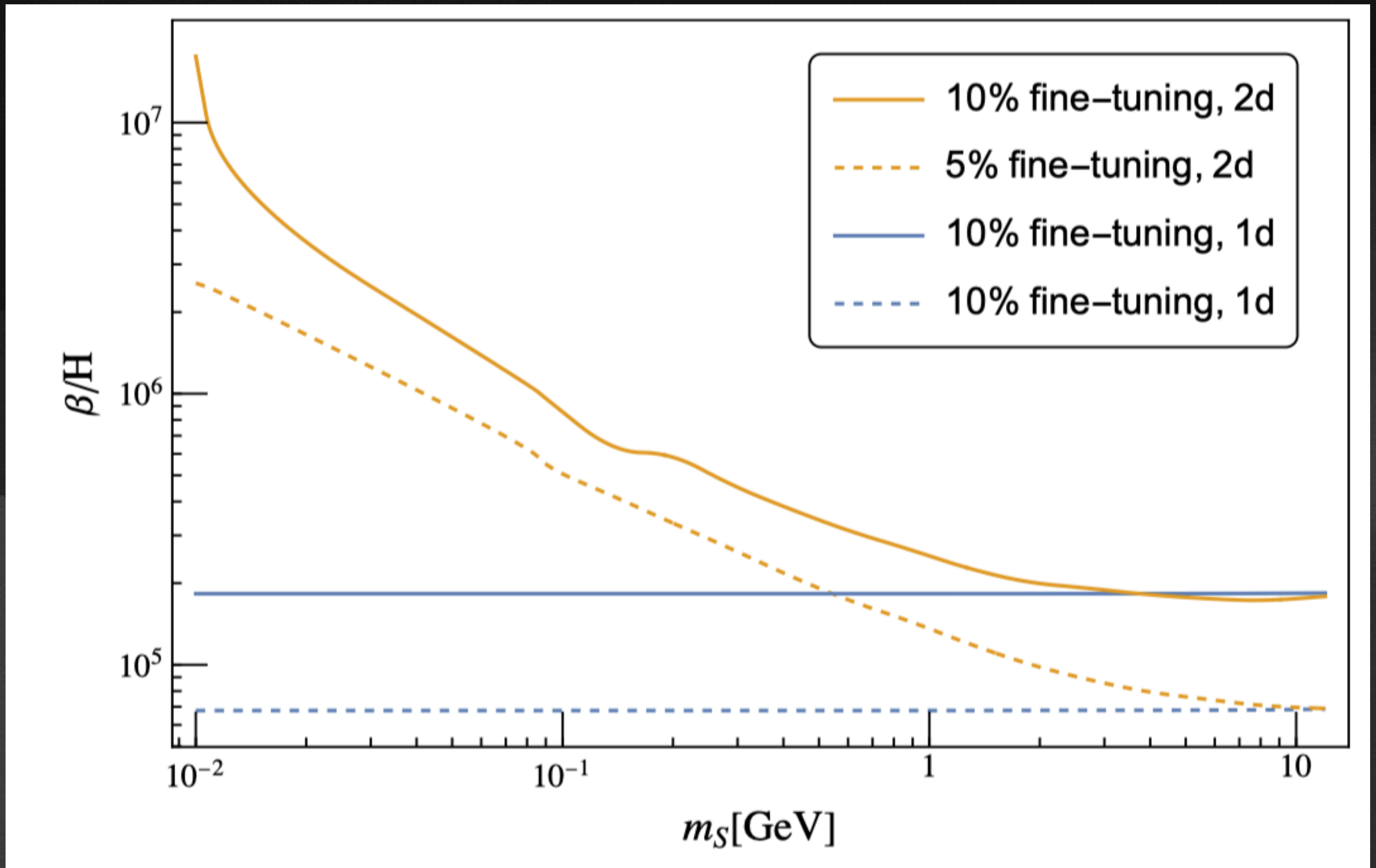



[K. Harigaya and IW, 2207.02867]

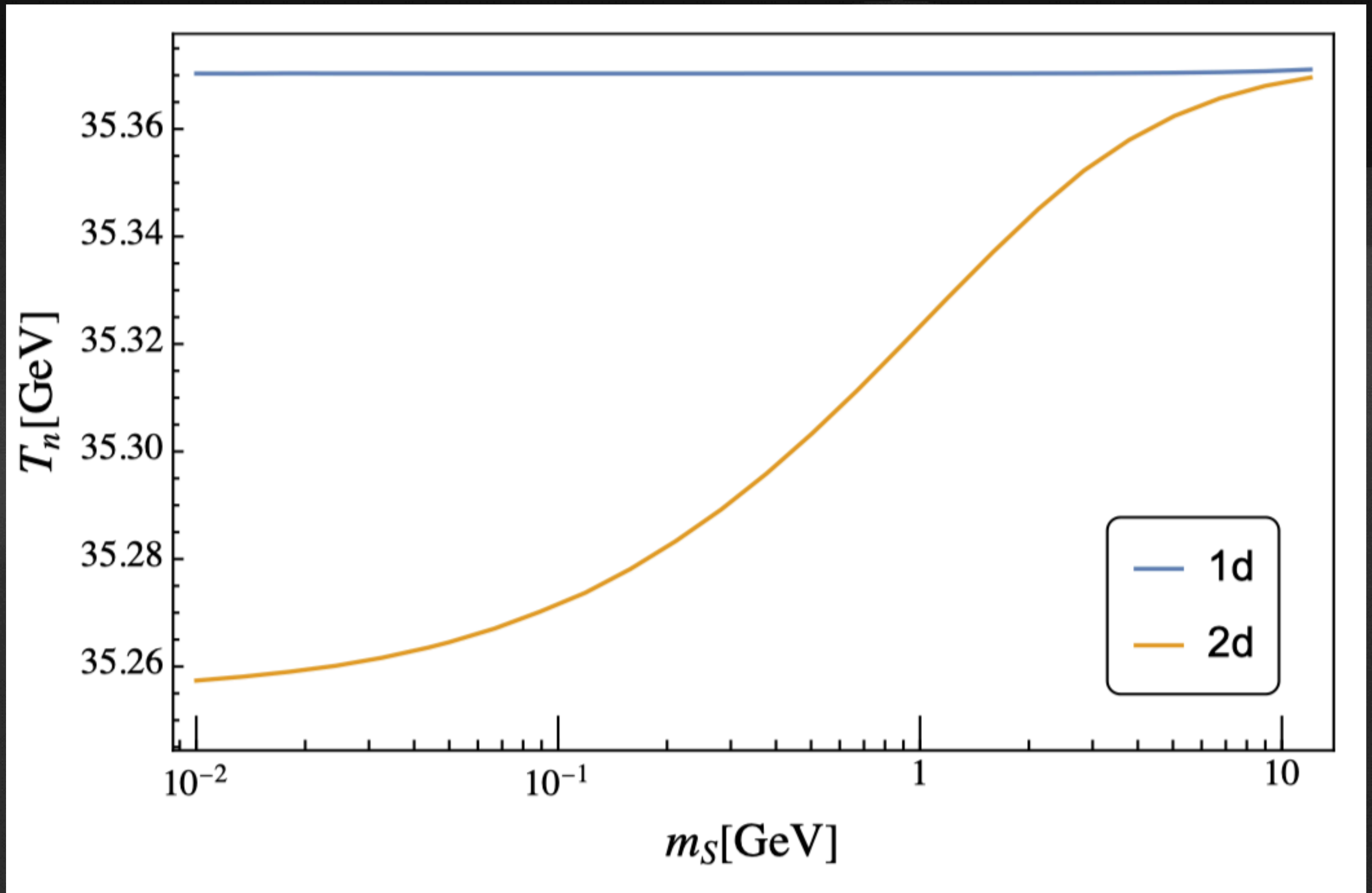
# Thermal phase transition

## (3) 2-d analysis: nucleation

Plots made along fixed fine-tuning




Plots made along fixed $T_c$



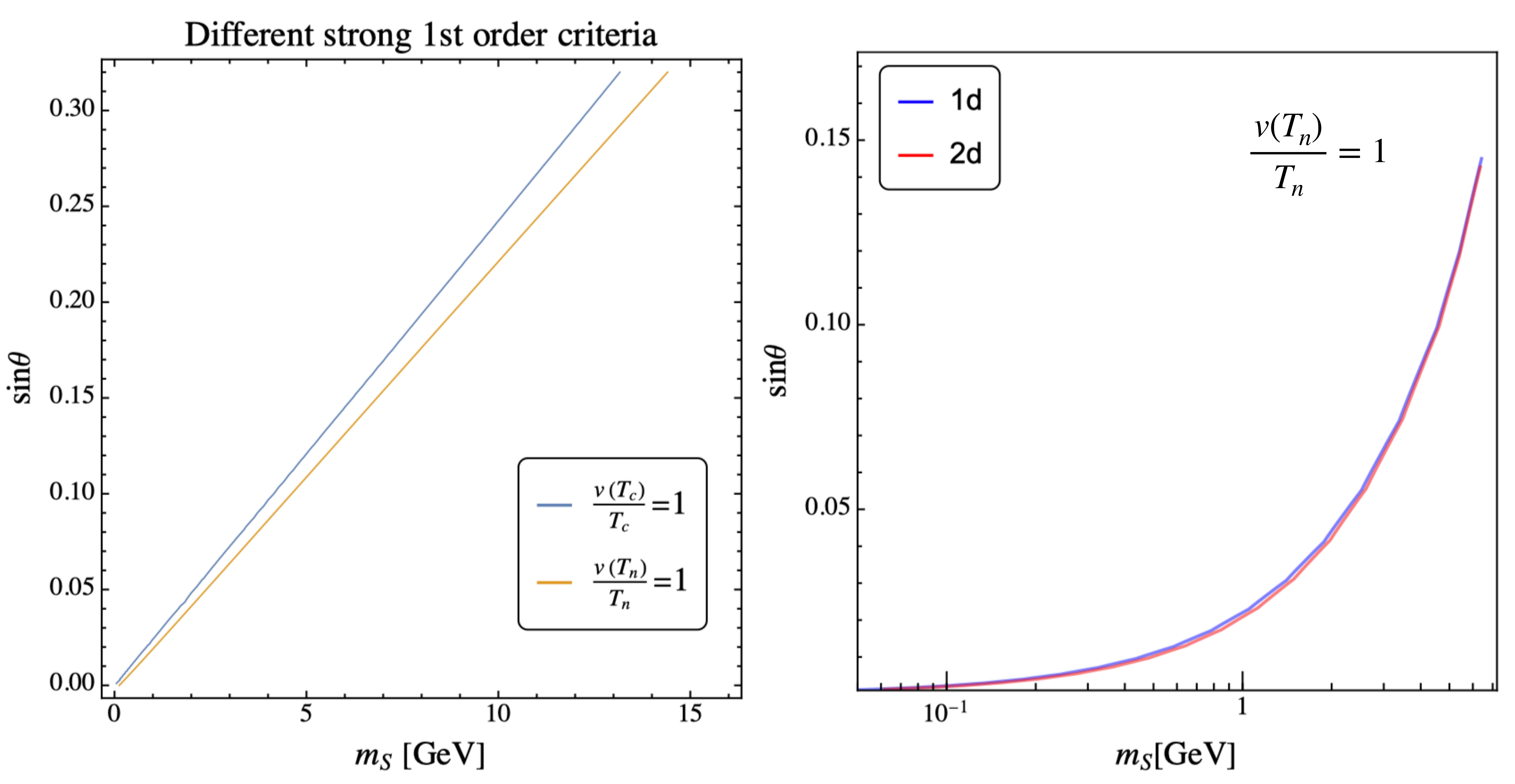

$$\frac{\beta}{H} \equiv T_n \frac{d(S_3/T)}{dT}\bigg|_{T=T_n}$$ inverse time duration

becomes huge for small $m_S$

Large $\beta/H$ compensates large $S_3$, nucleation is not delayed too much.

[K. Harigaya and IW, 2207.02867]

# Nucleation is more than critical




Criteria based on $T_n$ can sometimes favor very different parameter space.

Here, the difference is not large. But still slightly increase it.

Nucleation is more physical:
Bubble nucleates at $T_n$
The definition for SFOPT aims at sphaleron process decoupling inside the bubble.

[Baum et al, 2009.10743]
[K. Harigaya and IW, 2207.02867]

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# Local EWBG

$$\boxed{\partial_\mu J^B_\mu = \partial_\mu J^L_\mu = \frac{3g^2}{32\pi^2} W\tilde{W}}$$

A general effective CP-violating operator: $\mathscr{L}_{CP} \propto \frac{\alpha_2}{8\pi}\frac{S}{M}W\tilde{W}$, $M$: UV scale.

CP-violation come from $W\tilde{W}$!

$S$: need $SHH^\dagger$ to be CP-even (no CP-violation at non-UV scale!). $S$ is CP-even.

Rewrite: $\mathscr{L}_{CP} \propto \frac{1}{M}(\partial_0 S)n_B$ in thick-wall regime!

From minimizing free energy, $n_B$ gets a minimum $n_B^0 \propto \frac{1}{M}(\partial_0 S)$

$$\langle S \rangle \simeq \frac{A}{2\mu_S^2}h^2$$

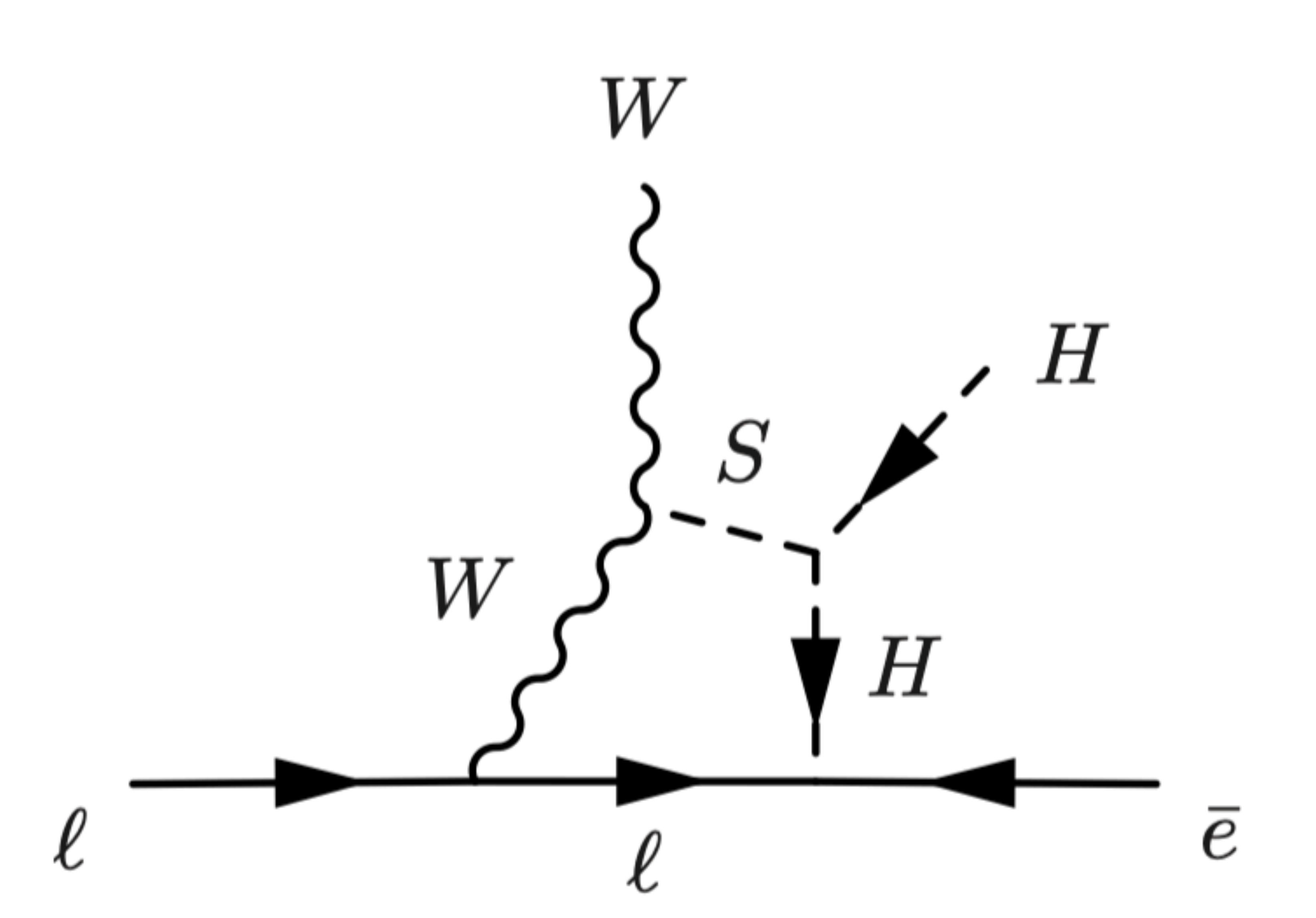
Thus $\dot{n}_B \propto \frac{\Gamma_{\rm sph}}{T^3}(n_B - n_B^0) \simeq \frac{\Gamma_{\rm sph}}{T^3}n_B^0 = \frac{\Gamma_{\rm sph}}{T^3}\boxed{\dot{S}}$ Large field-value shift!

$$\frac{n_B}{s} \simeq 10^{-10}\frac{10^8\mathrm{GeV}}{M}\left(\frac{v(T_n)}{60\ \mathrm{GeV}}\right)^2\frac{10\ \mathrm{MeV}}{\mu_S}$$

For old literature using $\mathscr{L}_{CP} \propto \frac{\sin(\delta)}{M^2}h^2 W\tilde{W}$:


[A. Cohen and B. Kaplan, Phys.Lett.B 199 (1987) 251-258,
Nucl.Phys.B 308 (1988) 913-928]
[M. Dine et al, Phys.Lett.B 257 (1991) 351-356]
[M. Dine, hep-ph/9206220]
[K. Harigaya and IW, 2207.02867]

# The electric dipole moment




EDM: $\frac{d_e}{e} \simeq 10^{-36}\text{cm}\frac{10^8\text{ GeV}}{M}\frac{\mu_S}{10\text{ MeV}}$, avoided!

CP-violation and baryogenesis:

high $M$ (weakly interacting)

large field value shift

[K. Harigaya and IW, 2207.02867]

# Take home notes

- Introduce a singlet scalar with shift-symmetry to achieve SFOEWPT without introducing extra hierarchy problem.
- Extra singlet modifies the tree-level quartic coupling and thus enhances EWPT.
- 2-dimensional analysis shows huge $S_3$ and $\beta/H$ in the model, slightly delay the bubble nucleation.
- EWBG can be achieved without violating EDM constraints. e.g. local EWBG. CP-violation happens from a high-scale theory.

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# Collider Signals

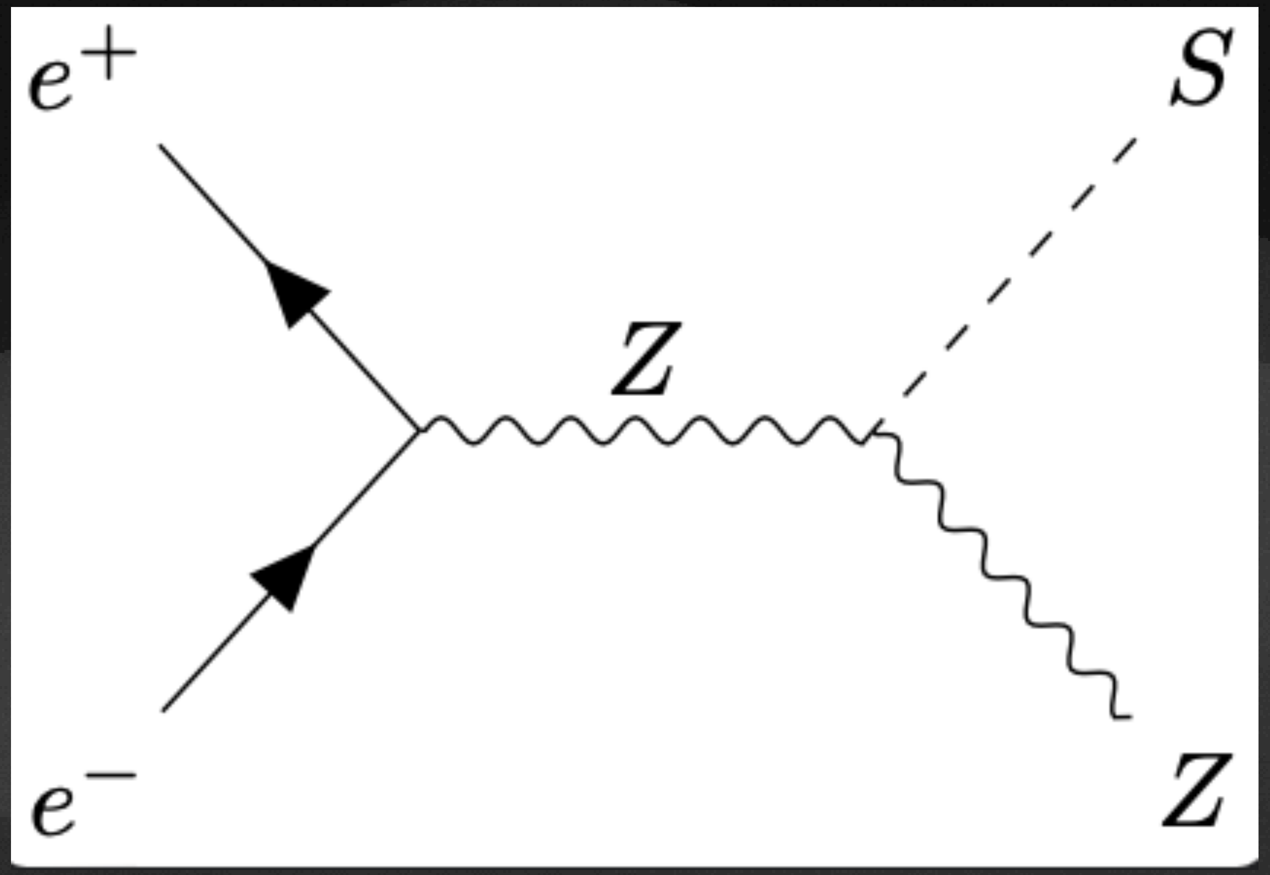
$S$ can mix with $h$, mixing angle $\sin\theta$. Generating vertex:

$$hZZ \rightarrow \sin\theta\ SZZ$$

$$h^3 \rightarrow \sin\theta\ hhS, \sin^2\theta\ hSS$$

General probe: scalar production, Higgs exotic decay

Collider search can probe the extra singlet scalar at GeV scale




Current best collider bound comes from LEP on scalar production


[L3 collaboration, Phys. Lett. B 385 (1996) 454–470.]
[K. Harigaya and IW, 2207.02867]

# Rare Meson Decay and $\Delta N_{\rm eff}$

- Extra decay channel for $B$ meson:

  $B^0 \to K^0 S, B^+ \to K^+ S$, searched by LHCb at $200\ \mathrm{MeV} < m_S < 4\ \mathrm{GeV}$

- Extra decay channel for Kaon:

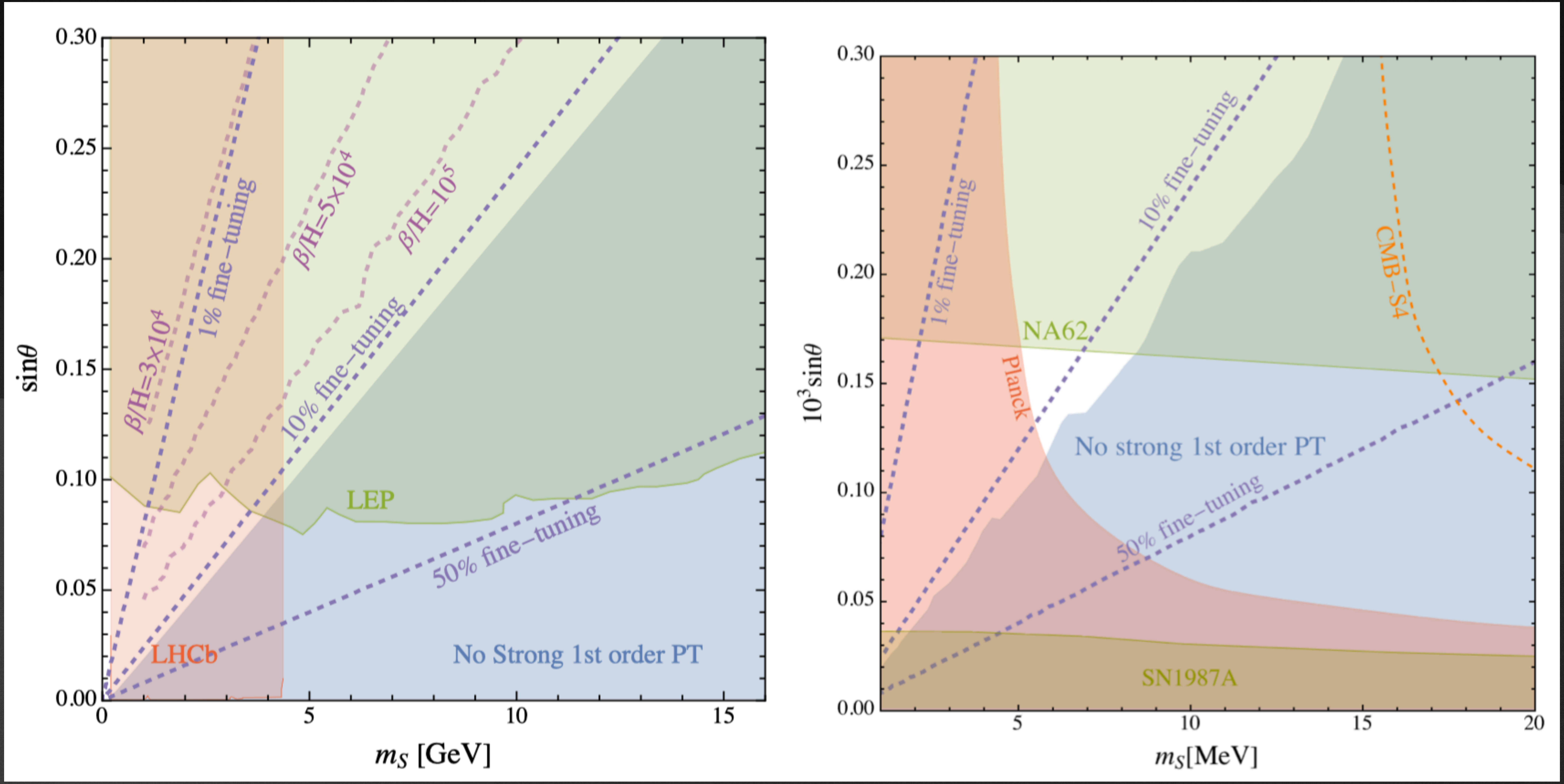
  $K^+ \to \pi^+ S, K^0 \to \pi^0 S$, searched by NA62, KLEVER…. for MeV scale.

- MeV scale $m_S$: large energy density when neutrino decouples.

  $S$ decays into $\gamma$: negative $\Delta N_{\rm eff}$

Review: [PBC Group, 1901.09966], [E. Goudzovski et al, 2201.07805]
[LHCb Collaboration, 1508.04094, 1612.07818, 1703.08501]
[NA62 Collaboration, 2010.07644, 2103.15389]
[KLEVER Project Collaboration, 1901.03099]
[M. Ibe et al, 2112.11096], [Planck Collaboration, 1807.06209]
[CMB-S4 Collaboration, 1610.02743],[K. Harigaya and IW, 2207.02867]

# Results




[K. Harigaya and IW, 2207.02867]

# Take home notes

- Collider experiment can probe extra scalar at GeV scale via scalar production and Higgs exotic decay.
- Rare B-meson and Kaon decay can be used to probe the scalar at MeV scale.
- CMB detection can exclude scalar with very light mass, i.e. a few MeV.

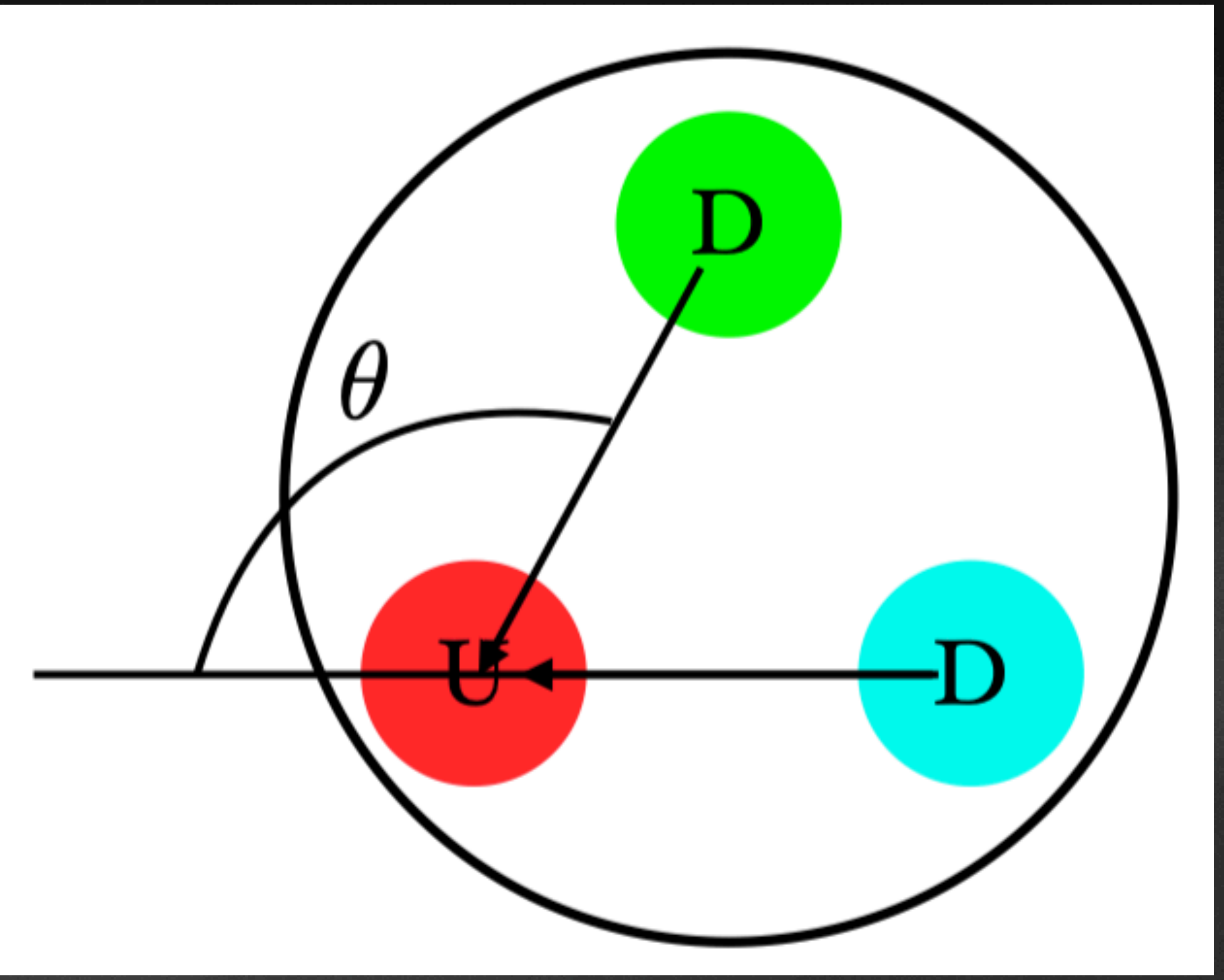
# Summary

- Electroweak baryogenesis faces the problem of lack of SFOPT. A singlet scalar extension with imposed approximate shift symmetry can enhance the phase transition without bringing in an extra hierarchy problem.
- Extra singlet can be very light, at MeV scale, and can be detected by CMB-S4, rare meson decay, and so forth.
- EWBG can be achieved. As an example, local EWBG can be achieved assuming a CP-violation source from $10^8$ GeV scale.
- EDM constraints are avoided by the high UV scale.

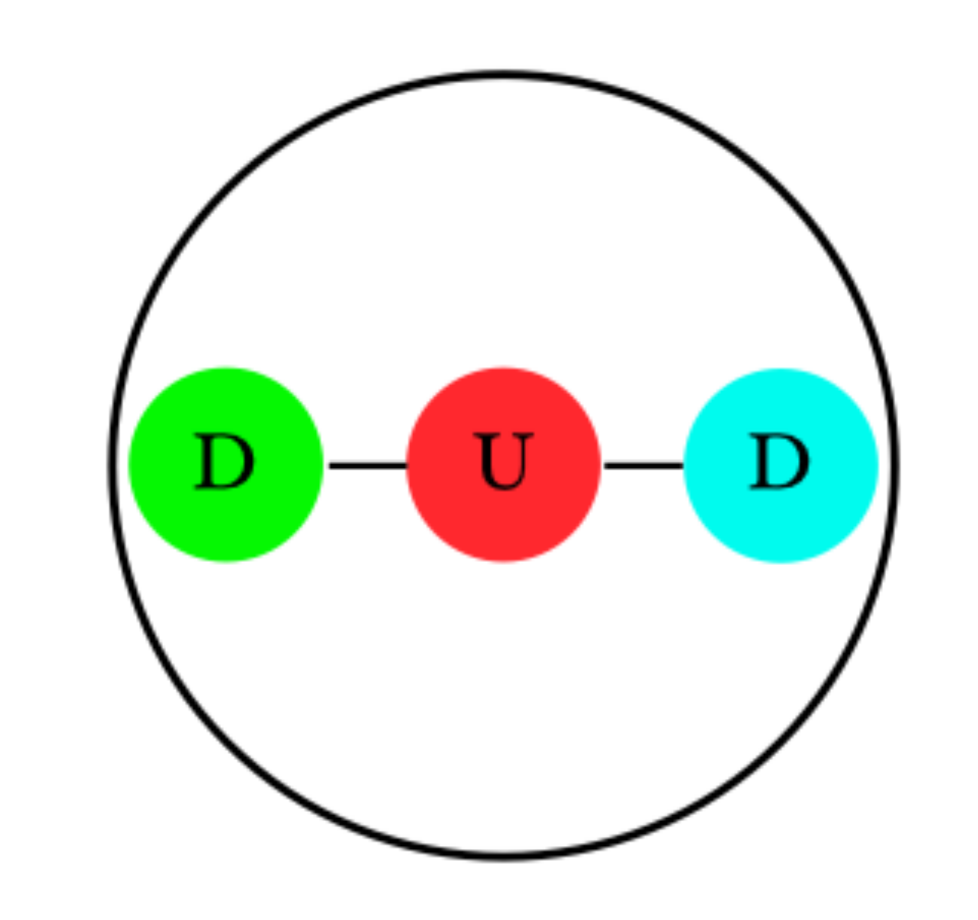
# Encore: Parity-symmetric generation

# Strong CP problem
## (1) Classical level: an intuition

Neutron EDM




$d_n \simeq 10^{-13}\sqrt{1-\cos\theta}\, e\mathrm{cm}$




$d_n = 0$

Experimental limit: $d_n < 10^{-26} e\mathrm{cm}$
Right one is preferred.
Why $\theta \to 0$?

This description is from:
[A. Hook, 1812.02669]

# Strong CP problem

## (2) Quantum level: the strong CP phase

$$\frac{\theta_s g_s^2}{32\pi^2} G\tilde{G} \quad \xleftrightarrow{\psi \to e^{i\gamma_5 \delta\theta},\ \theta_F \to \theta_F - \delta\theta} \quad \theta_F = \arg(\det Y_u Y_d)$$

$$\int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}G \exp\left(\frac{\theta_s g_s^2}{32\pi^2} G\tilde{G}\right)$$

$$\to \int \mathcal{D}\bar{\psi}\mathcal{D}\psi\mathcal{D}G \exp\left(\frac{(\theta_s + \delta\theta) g_s^2}{32\pi^2} G\tilde{G}\right)$$

$$\bar{\theta} = \theta_s + \theta_F$$

$\theta_F$ and $\theta_s$ rotate into each other.

$\bar{\theta}$ physical.

Experiments: $\bar{\theta} < 10^{-10}$ !

Why?

# Parity solution to the strong CP
## (1) Gauge group, fermion sector, Higgs, and Yukawa

- Gauge group: $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$.

| | $H_L$ | $H_R$ | $q_i$ | $\bar{u}_i$ | $\bar{d}_i$ | $\ell_i$ | $\bar{e}_i$ | $\bar{Q}_i$ | $U_i$ | $D_i$ | $\bar{\ell}_i$ | $E_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SU(3)_c$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{3}$ | $\bar{\mathbf{3}}$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\bar{\mathbf{3}}$ | $\mathbf{3}$ | $\mathbf{3}$ | $\mathbf{1}$ | $\mathbf{1}$ |
| $SU(2)_L$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ |
| $SU(2)_R$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{1}$ |
| $U(1)_X$ | $-\frac{1}{2}$ | $\frac{1}{2}$ | $\frac{1}{6}$ | $-\frac{2}{3}$ | $\frac{1}{3}$ | $-\frac{1}{2}$ | $1$ | $-\frac{1}{6}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ | $\frac{1}{2}$ | $-1$ |

- 

- Symmetric Higgs potential: $-\frac{1}{2}\mu_L^2 h_L^2 - \frac{1}{2}\mu_R^2 h_R^2 + \frac{1}{4}\lambda(h_L^4 + h_R^4) + \frac{\lambda_{LR}}{4} h_L^2 h_R^2$
- Yukawa: $y_u \bar{Q} U H_R^\dagger + y_d \bar{Q} D H_R + \bar{y}_u q \bar{u} H_L^\dagger + \bar{y}_d q \bar{d} H_L + y_e \bar{\ell} E H_R + \bar{y}_e \ell \bar{e} H_L$
- Extra Dirac mass term: $m_{ij}^u \bar{u}^i U^j + m_{ij}^d \bar{d}^i D^j + m_{ij}^e E_i \bar{e}_j$

[M. A. B. Beg and H. S. Tsao, Phys. Rev. Lett. 41 (1978) 278],
[R. N. Mohapatra and G. Senjanovic, Phys. Lett. 79B (1978) 283], [K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. 62 (1989) 1079], [K. S. Babu and R. N. Mohapatra, Phys. Rev. D41 (1990) 1286], [L. J. Hall and K. Harigaya, 1803.08119], [N. Craig et al, 2012.13416]

# Parity solution to the strong CP

## (2) Fermion masses and vanishing strong CP phase

Masses generated from: $y_u \bar{Q} U H_R^\dagger + \bar{y}_u q \bar{u} H_L^\dagger + m_{ij}^u U \bar{u}$

- $y v_R \gg m^u$: SM quark $q, \bar{u}$ has $y v_L$, mirror quark $\bar{Q}, U$ has $y v_R$.
- $y v_R \ll m^u$: integrate out heavy fermion $\bar{u}, U$. SM fermion $q, \bar{Q}$ have $\dfrac{y_u \bar{y}_u}{M} q \bar{Q} H_L^\dagger H_R^\dagger$

Parity: $q \leftrightarrow \bar{Q}^\dagger, \bar{u} \leftrightarrow U^\dagger, H_L \leftrightarrow H_R^\dagger$

Forces $y_u = \bar{y}_u^\dagger, y_d = \bar{y}_d^\dagger$

From each theory $\theta_F = \arg(y_u y_d) + \arg(\bar{y}_u \bar{y}_d) = 0$

$\theta_s$ directly forbidden by parity ($G\tilde{G}$ violates parity)

[M. A. B. Beg and H. S. Tsao, Phys. Rev. Lett. 41 (1978) 278], [R. N. Mohapatra and G. Senjanovic, Phys. Lett. 79B (1978) 283], [K. S. Babu and R. N. Mohapatra, Phys. Rev. Lett. 62 (1989) 1079], [K. S. Babu and R. N. Mohapatra, Phys. Rev. D41 (1990) 1286], [L. J. Hall and K. Harigaya, 1803.08119], [N. Craig et al, 2012.13416]

# Phase Transition Stages

## Left-Right symmetry breaking

$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_X$$

$$\downarrow$$

$$SU(3) \times SU(2)_L \times U(1)_Y$$

$$\downarrow$$

$$SU(3) \times U(1)_{\mathrm{em}}$$

CP-violation, B violation…etc

$T_{n,R}$

create $B - L \neq 0$ Need $B - L$ anomaly !

$B \propto (B - L) \neq 0$

$T_{n,L}$

Remember: $B - L$ is non-anomalous in SM

Any $B$ will be washed out if there is no primordial non-zero $B - L$

# Avoiding wash-out

Effective Chiral Matter

$$\partial_\mu j^\mu_{B-L} = 0$$

$T_{n,R}$

$$(B-L)_{\rm SM} \neq 0, L_{\rm exotic} \neq 0$$
$$(B-L)_{\rm SM} - L_{\rm exotic} = 0$$

$$B \propto (B-L)_{\rm SM} \neq 0$$

$T_{n,L}$

$n_B$

Extra particles
decay after EWPT

[K. Harigaya and IW, 2107.09679]
[K. Harigaya and IW, 2207.02867]

# Effective chiral matter: an example

"Quarantine" one generation of mirror lepton

$$\mathscr{L} = x^e_{ij}\ell_i\bar{e}_jH_L + \bar{x}^e_{ij}\bar{\ell}_iE_jH_R + M^e_{ij}E_i\bar{e}_j \quad (i, j = 1,2)$$

$$+x^e_3\ell_3\bar{e}_3H_L + \bar{x}^e_3\bar{\ell}_3E_3H_R$$

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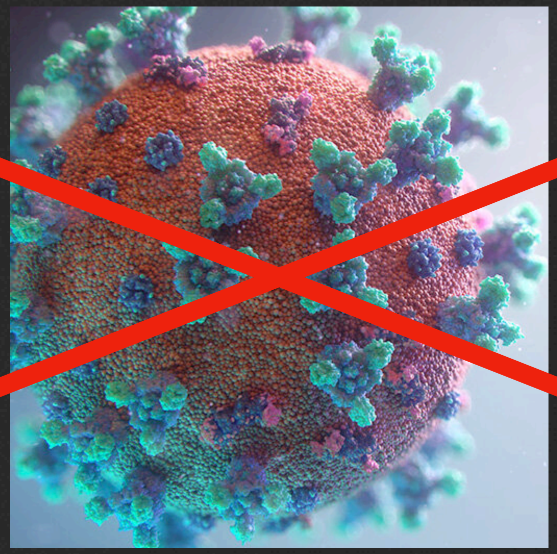
$$\cancel{\mathrm{SM} \leftrightarrow \bar{\ell}_3, E_3}$$

Until EWPT, or decay into right-handed neutrino

$$n_B = \frac{28}{79} n_{B-L} = \frac{28}{79} n_{\bar{\ell}_3, E_3}$$

$n_{\bar{\ell}_3}$ produced during $SU(2)_R$ PT



? Days

Freedom

[K. Harigaya and IW, 2107.09679]
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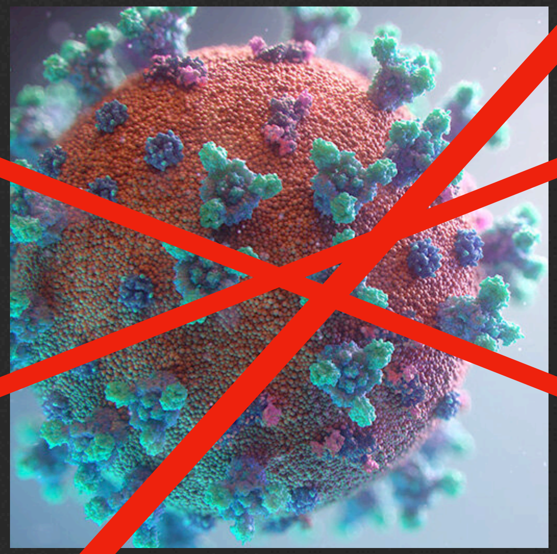

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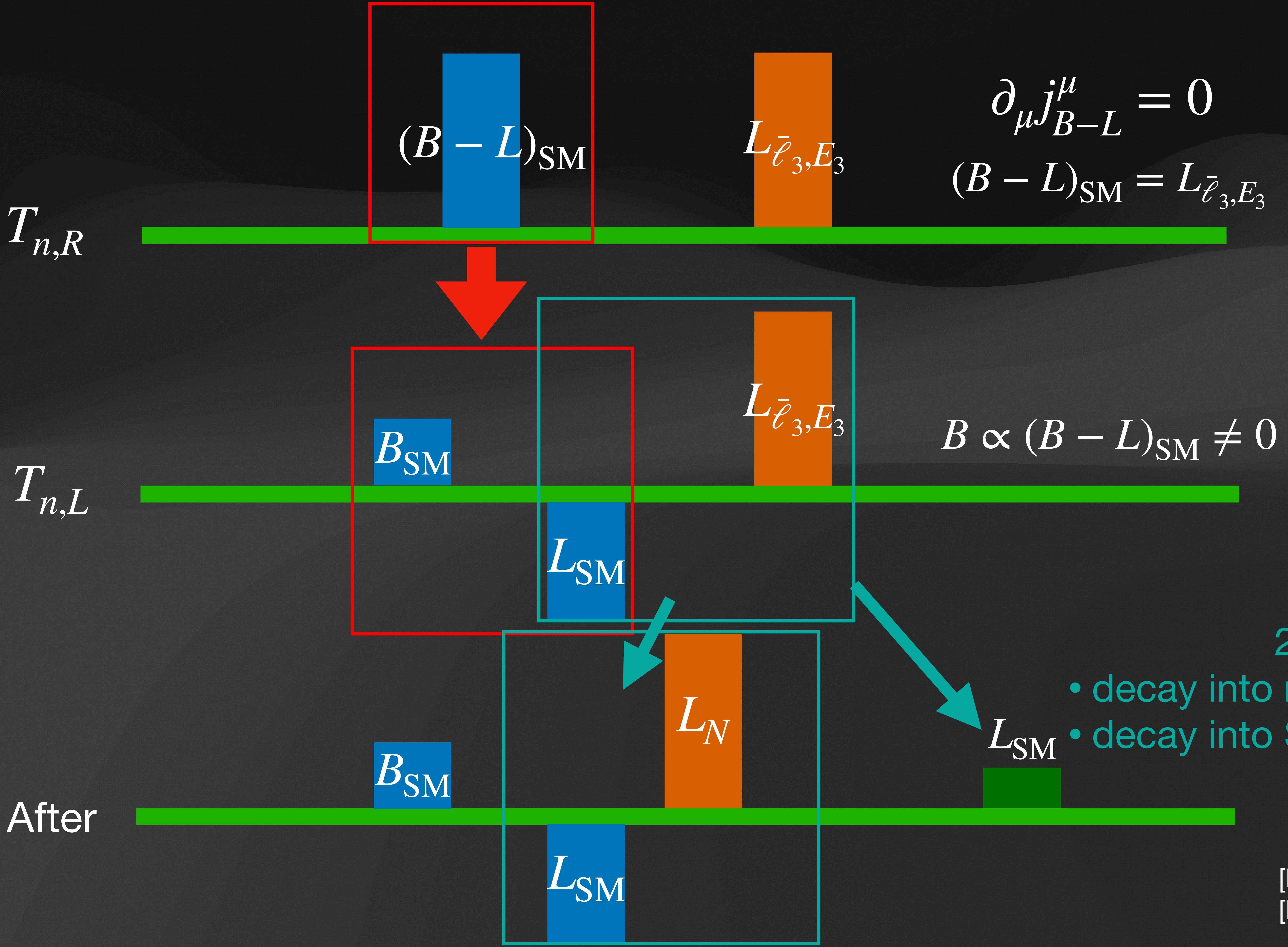



2 Options:

- decay into right-handed neutrino
- decay into SM

[K. Harigaya and IW, 2107.09679]
[K. Harigaya and IW, 2207.02867]

# Scalar Extension: PT and BAU

$$V_0 = -\frac{1}{2}\mu_{H_L}^2 h_L^2 - \frac{1}{2}\mu_{H_R}^2 h_R^2 + \frac{1}{4}\lambda(h_L^4 + h_R^4)$$
$$+ \frac{1}{2}\mu_S^2(S_L^2 + S_R^2) + \frac{1}{2}AS_L(h_L^2 - v_L^2) + \frac{1}{2}AS_R(h_R^2 - v_R^2)$$
$$+ \frac{1}{4}\lambda_{\rm LR} h_L^2 h_R^2,$$

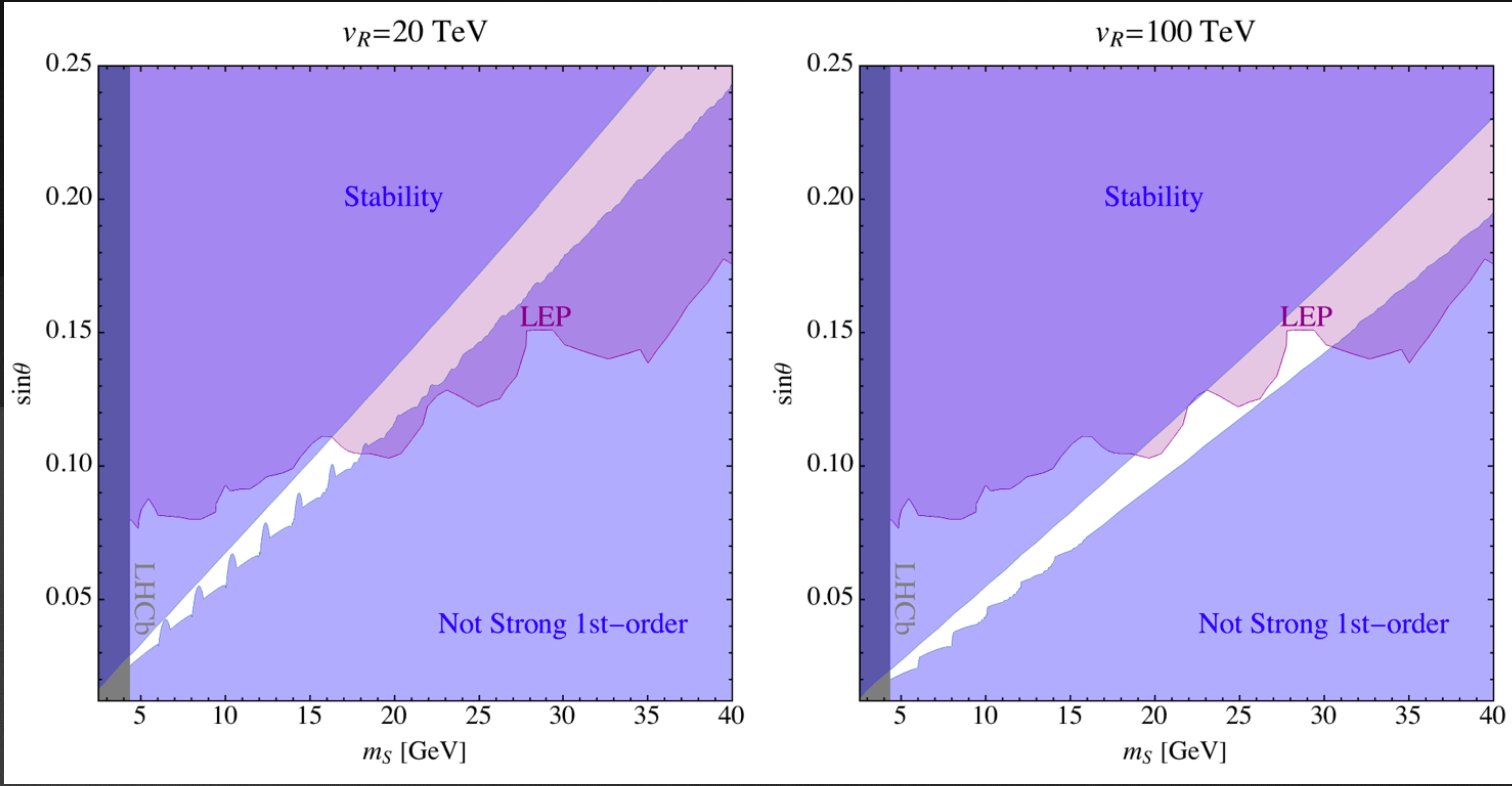
$S_L$: to be probe. $S_R$: enhances $h_R$ PT, $\lambda(v_R) < \lambda(v_L)$ by running: different parameter space

$$\mathscr{L}_{CP} \propto \frac{\alpha_R}{8\pi}\frac{S_R}{M} W_R \tilde{W}_R, \quad n_{\bar{\ell}_3} \propto \frac{\Gamma_{\rm sph}}{T^3}\frac{\partial_0 S}{M}$$

$$Y_B \simeq 8.7 \times 10^{-11} \left(\frac{v_R}{20\ \mathrm{TeV}}\right)\left(\frac{10T_n}{v_R}\right)^2 \left(\frac{10v_R}{M}\right)\left(\frac{10\ \mathrm{GeV}}{\mu_S}\right)$$

[K. Harigaya and IW, future work]

# Result

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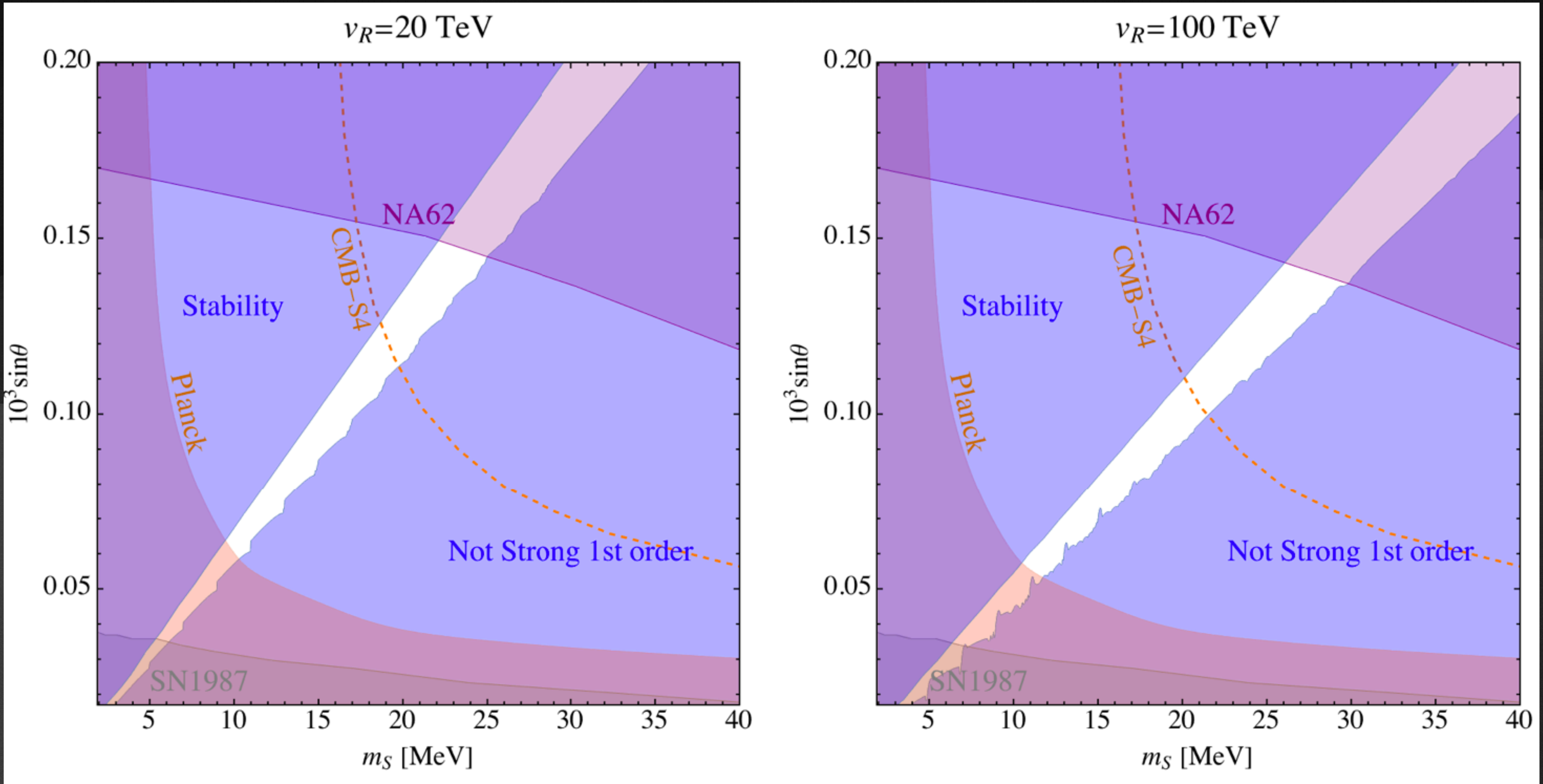



[K. Harigaya and IW, future work]

# Summary

- Applying the singlet extension into a parity symmetric model can solve the strong CP and baryogenesis problem together. New parameter space is opened.

- Baryon asymmetry can still be achieved from large UV scale CP-violating source.

- Effective $B - L$ is required to pass a non-zero $B - L$ number.

# 100%

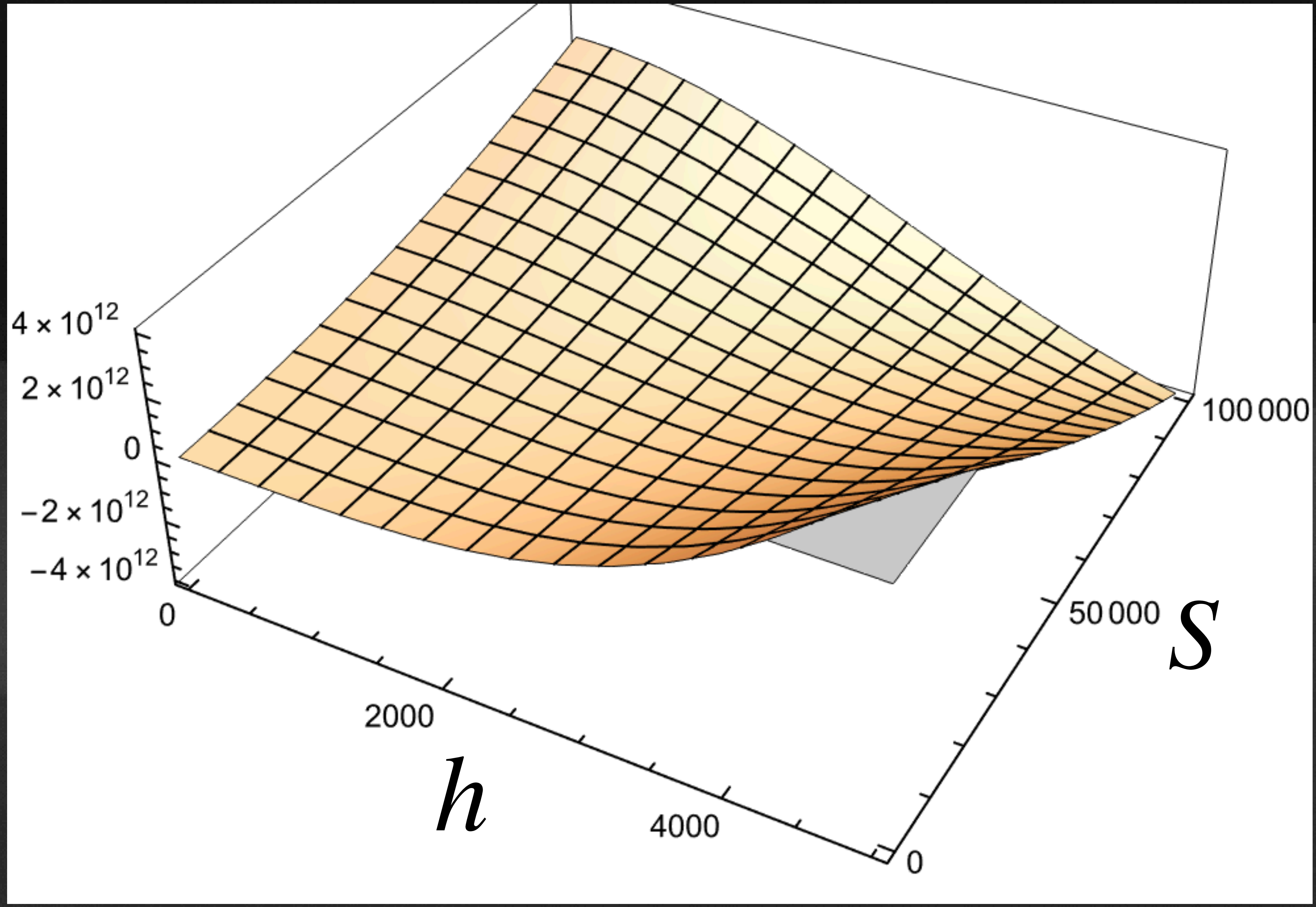
# Backup

# $T = 0$ Structure
## Metastability at 1-loop

- 1-loop correction:

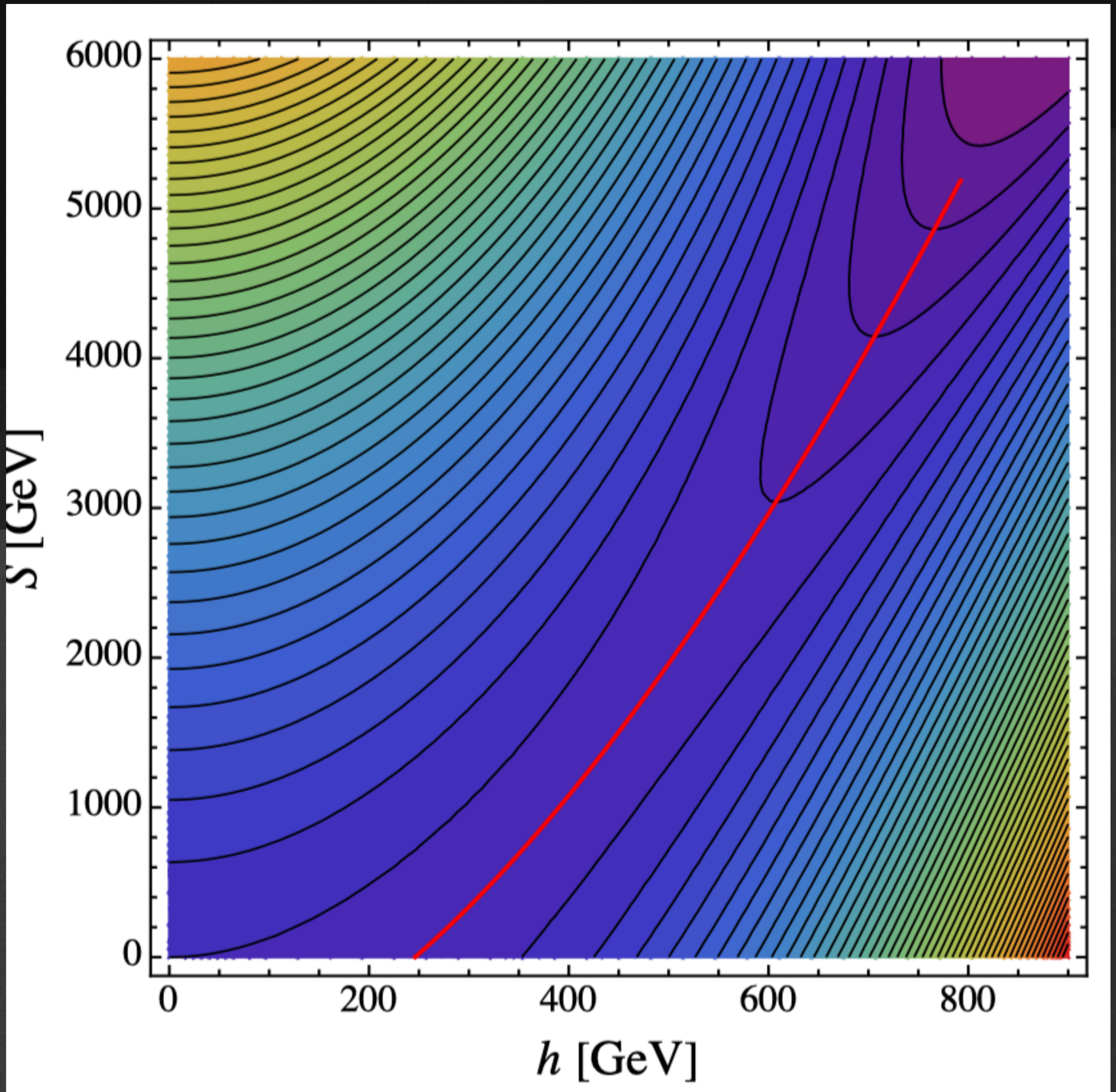
$$V_{\rm CW} \sim \sum_B n_B m_b^4 \log(\frac{m_B^2}{\mu^2}) - \sum_F n_F m_F^4 \log(\frac{m_F^2}{\mu^2}))$$

- Heavy top makes the $V_{\rm CW}$ negative at large $h$!
- Will the world tunnel from the EW vev to infinity?
- Tunneling action: $S_4 \equiv 2\pi^2 \int (\frac{1}{2}\left(\frac{dh}{dr}\right)^2 + \left(\frac{dS}{dr}\right)^2 + V) r^3 dr$
- Tunneling within the age of universe: $S_4 \lesssim 400$

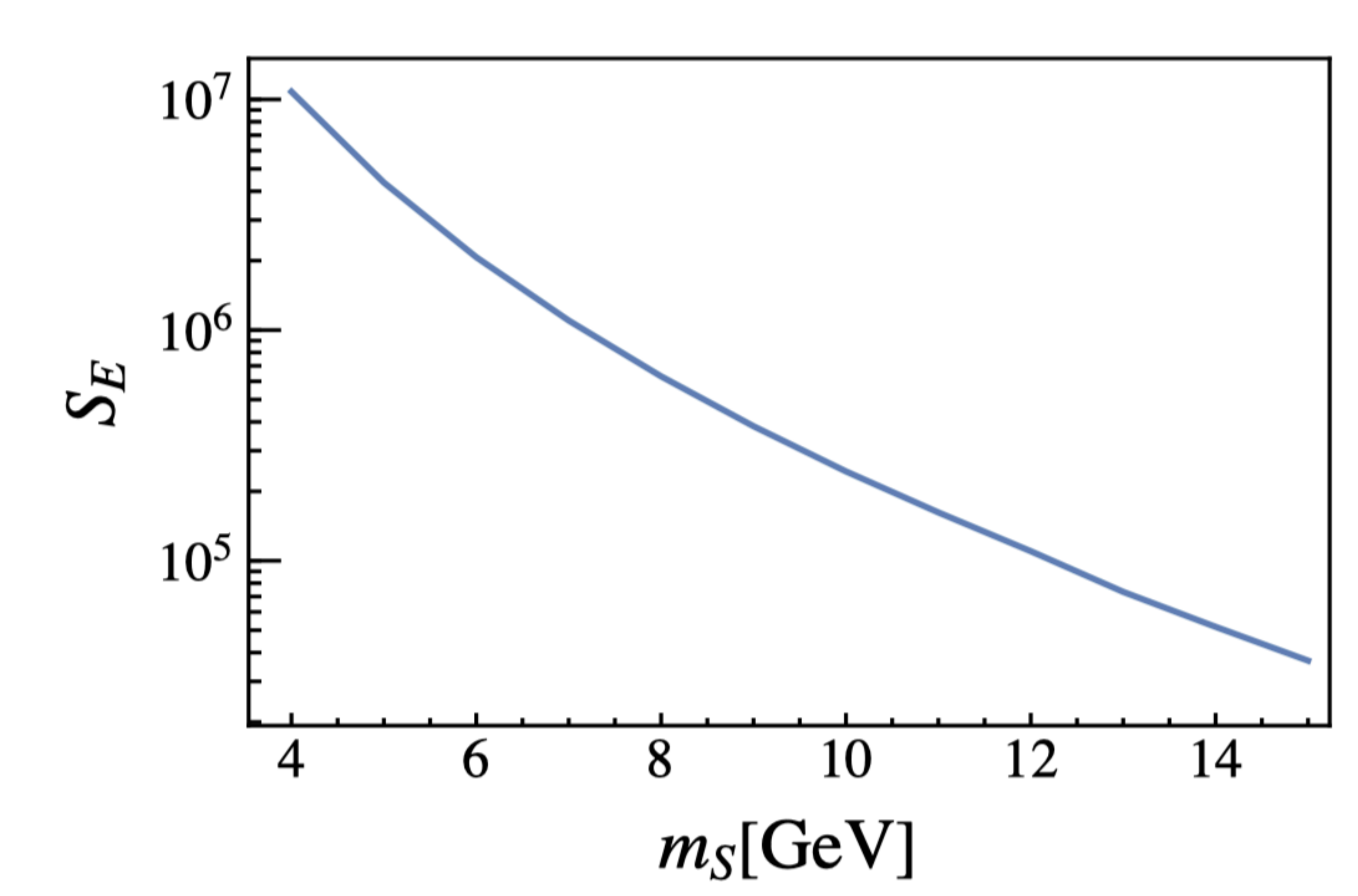



Potential not bounded at infinity.
Will it tunnel from $(v,0)$ to infinity?

# $T = 0$ Structure
## Metastability at 1-loop: continue




Bounce solution shows tunneling path is along the "valley".




Bounce action increases as we decrease $m_S$

- Bounce solution gives huge bounce action, path along the "valley".
- $\langle S \rangle \simeq \dfrac{A^2}{2\mu_S^2}(h^2 - v^2)$, light $m_S$ has huge kinetic energy.
- However, bounce action does not guarantee a global minimum! (Or, the bounce solution does not exist for some case)
- e.g. If we move along $S = 0$, same as SM. Action is much smaller. But bounce does not exist in this case.
- There are many ways to solve the action without bounce. See [J. Espinosa, 1908.01730]

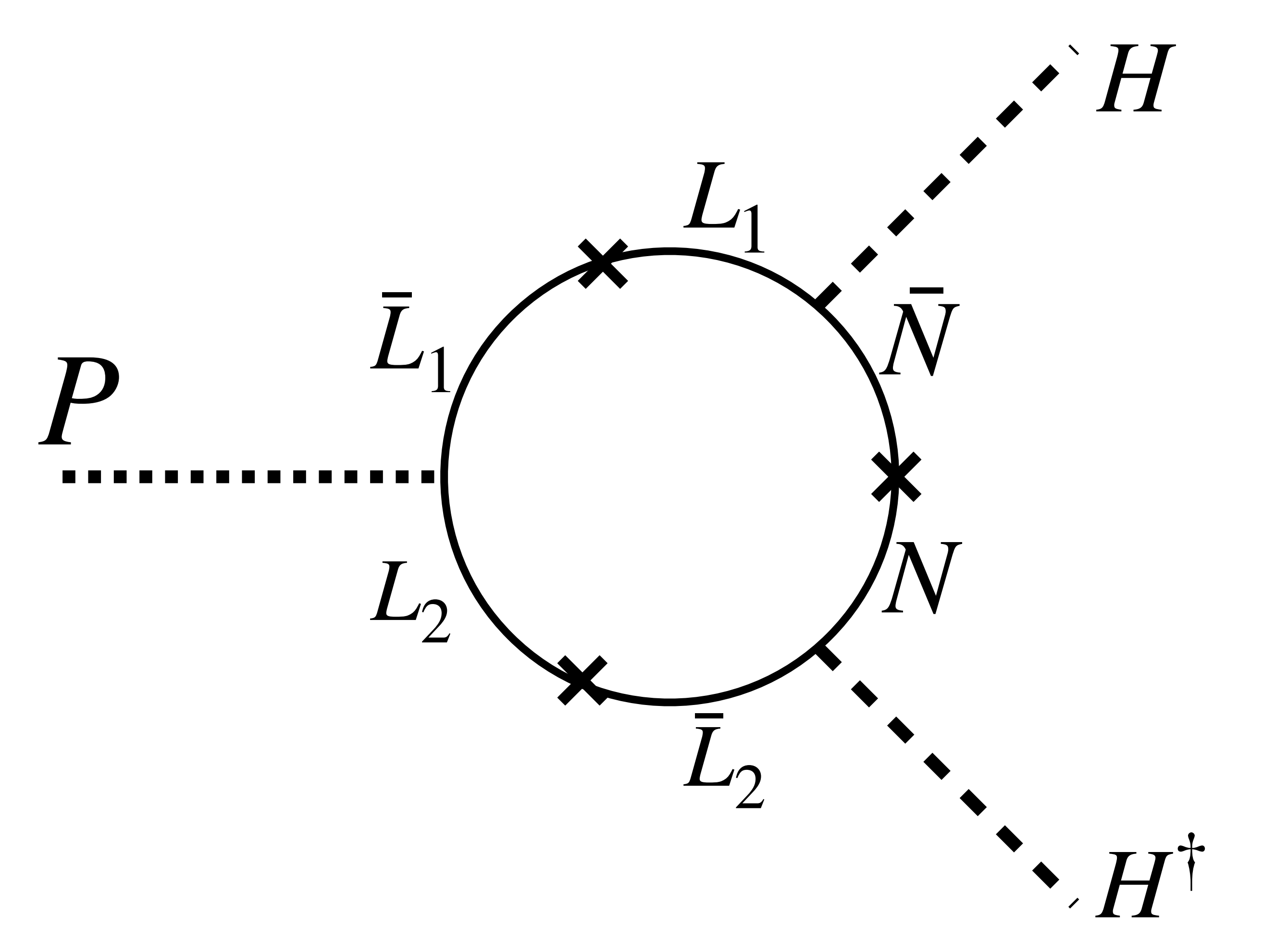
[J.Espinosa, 1908.01730], [S. Chigusa et al, 1803.03902]
[K. Harigaya and IW, 2207.02867], [R. Sato, 1908.10868 (bounce code)]

# A toy model of UV-completion for $ASh^2$ term

$$yP\bar{L}_1L_2 + \lambda_1 H\bar{N}L_1 + \lambda_2 H^\dagger N\bar{L}_2 + m_1\bar{L}_1L_1 + m_2\bar{L}_2L_2 + m_N\bar{N}N$$

$$A \sim \frac{y\lambda_1\lambda_2}{16\pi^2}\frac{m_1m_2m_N}{\Lambda^2}, \quad \Lambda = \max(y\langle P\rangle, m_1, m_2, m_N)$$

$P$: scalar with phase direction $S$




[K. Harigaya and IW, 2207.02867]

# Options for neutrino masses

## (1) Majorana mass from dim-5 operator

$$c_{ij}^{M} \ell_i \ell_j H_L^{\dagger} H_L^{\dagger} + c_{ij}^{M*} \bar{\ell}_i \bar{\ell}_j H_R^{\dagger} H_R^{\dagger}$$

Right-handed neutrino mass: $\sum_i m_{\nu_i} (\frac{v_R}{v_L})^2 = 12 \text{ keV} \frac{\sum_i m_{\nu_i}}{100 \text{ meV}} \left(\frac{v_R}{60 \text{ TeV}}\right)^2$

DM overproduction solved by dilution from entropy production

Dilution factor $D = 150 \frac{\sum_i m_{\nu_i}}{100 \text{ meV}} \left(\frac{v_R}{60 \text{ TeV}}\right)^2 \frac{80}{g_s(T_D)}$

# Options for neutrino masses

## (2) Dirac mass from dim-5 operator

$$c_{ij}^D \ell_i \bar{\ell}_j H_L^\dagger H_R^\dagger$$

UV completion

$$\mathcal{L} = x^\nu \ell H_L^\dagger \bar{S} + \bar{x}^\nu \bar{\ell} H_R^\dagger S + M^\nu S \bar{S}.$$

Same mass as SM neutrino.

Behave as Dark Radiation. Estimation: $N$ decouple before QCD PT, $\Delta N_{\text{eff}} < 0.3$.

# Options for neutrino masses

## (3) Radiative inverse seesaw

$$yS\left(\ell H_L^\dagger + \bar{\ell} H_R^\dagger\right)$$

$S$: singlet fermion

Right-handed neutrino mass: $SH_R^\dagger \bar{\ell}$

Left-handed neutrino mass: genrated radiatively

$$m_\nu \sim \frac{y^2}{16\pi^2}\frac{m_S v_L^2}{(yv_R)^2} = \frac{1}{16\pi^2}\frac{m_S v_L^2}{v_R^2} \sim 0.1\ \mathrm{eV}\frac{m_S}{10\ \mathrm{MeV}}\left(\frac{100\ \mathrm{TeV}}{v_R}\right)^2$$

Assign a charge to avoid baryon number wash-out:

$\ell_3(-1), \bar{\ell}_3(-1), E_3(+1), \bar{e}_3(+1), S(+1)$