TON DUC THANG UNIVERSITY

ADVANCED INSTITUTE of MATERIALS SCIENCE

Magnetic mass effect on the sphaleron energy

Eibun Senaha (Ton Duc Thang U)
March 26, 2021 Online

Ref. Koichi Funakubo (Saga U, Japan) and E.S., PRD102, 041701(R) (2020) [2003.13929]

Outline

- Introduction
  - Electroweak baryogenesis (EWBG)
  - Sphaleron decoupling condition
- Magnetic mass effect on sphaleron in the SM
- Applications to 2 Higgs doublet model
- Summary

Baryon Asymmetry of the Universe (BAU)

Our Universe is baryon-asymmetric.

$$\eta^{\mathrm{BBN}} = \frac{n_B}{n_\gamma} = (5.8 - 6.5) \times 10^{-10},$$
$$\eta^{\mathrm{CMB}} = \frac{n_B}{n_\gamma} = (6.105 - 0.055) \times 10^{-10}.$$

PDG2020

Sakharov's conditions [Sakharov, JETP Lett. 5 (1967) 24]

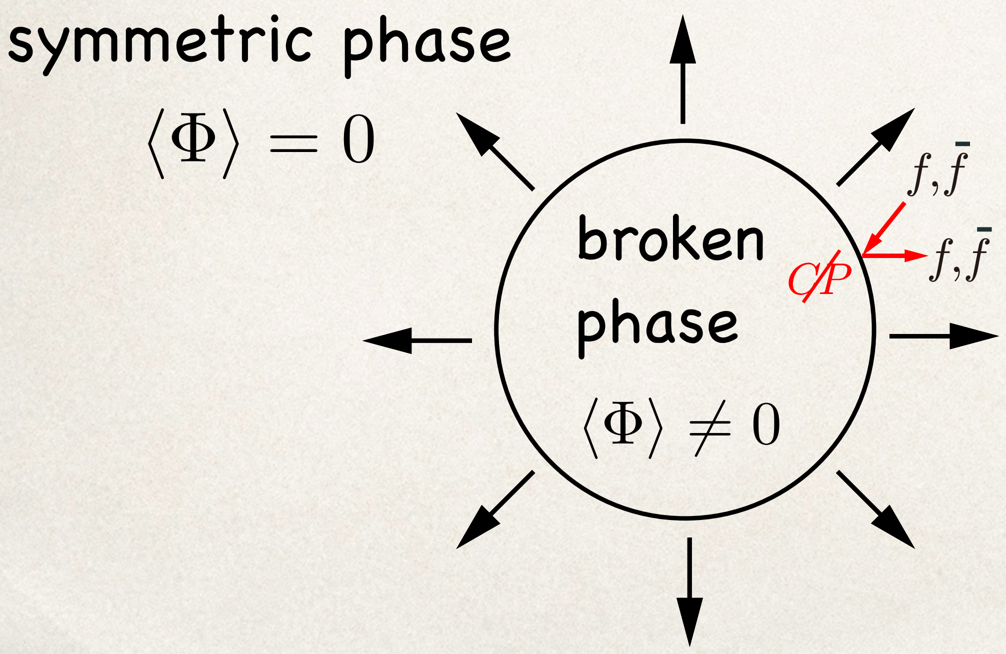
(1) Baryon number violation
(2) C and CP violation
(3) Out of equilibrium

❒ after inflation (scale is model dependent)
❒ before Big-Bang Nucleosynthesis (T≃O(1) MeV)

EW baryogenesis (EWBG)

Sakharov's conditions [Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

- B violation: anomalous (sphaleron) process
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st-order EW phase transition (EWPT) with expanding bubble walls



$$n_B = 0 \to n_B \neq 0 \text{ (sphaleron proecess)}$$

baryogengesis occurs outside bubbles!

sphaleron decoupling condition

$$\Gamma_B^{(\mathrm{br})}(T) < H(T)$$

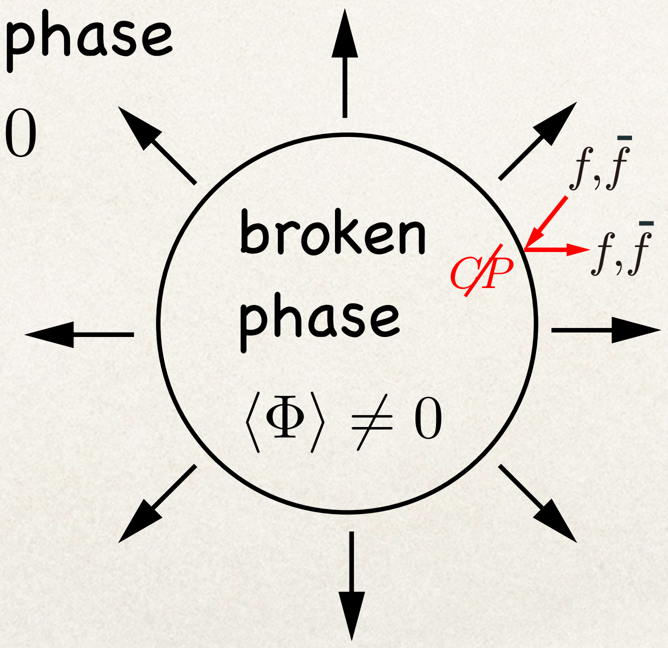
EW baryogenesis (EWBG)

Sakharov's conditions [Kuzmin, Rubakov, Shaposhnikov, PLB155,36 ('85)]

- B violation: anomalous (sphaleron) process
- C violation: chiral gauge interaction
- CP violation: KM phase and/or other sources in beyond the SM
- Out of equilibrium: 1st-order EW phase transition (EWPT) with expanding bubble walls

symmetric phase

$\langle \Phi \rangle = 0$



$n_B = 0 \rightarrow n_B \neq 0$ (sphaleron proecess)

baryogengesis occurs outside bubbles!

sphaleron decoupling condition

$$\Gamma_B^{(\mathrm{br})}(T) < H(T)$$

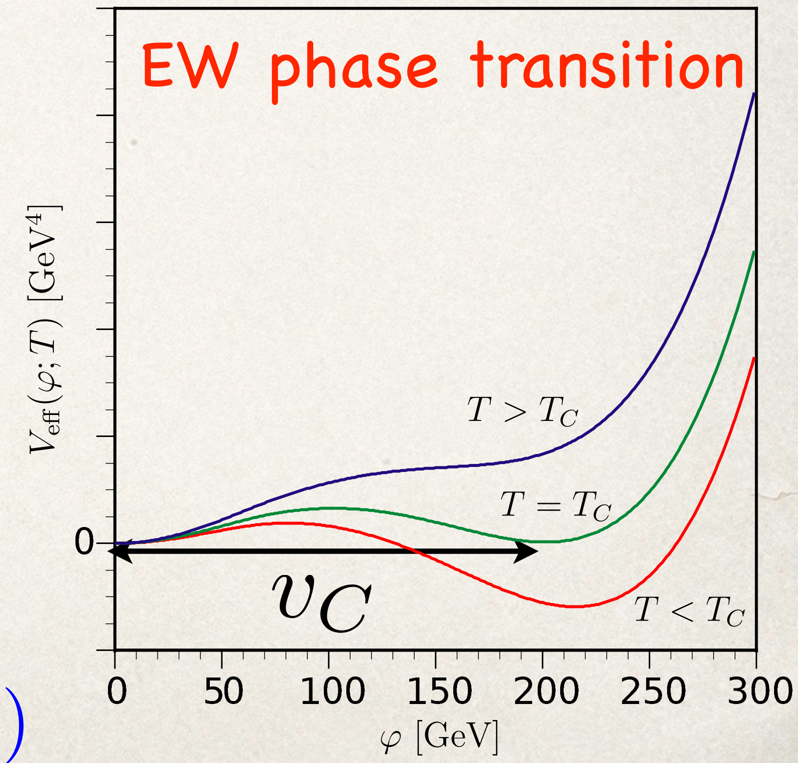
Sphaleron decoupling condition

To avoid washout of BAU, the sphaleron process must be suppressed after EWPT.

$$\Gamma_B^{(\mathrm{br})}(T) \simeq (\text{prefactor})e^{-E_{\rm sph}(T)/T} < \overset{\text{Hubble constant}}{\boxed{H(T)}} \simeq 1.66\sqrt{\underset{\substack{\shortparallel \\ \text{dof of relativistic particles}}}{g_*}}\,T^2/\overset{\substack{1.22\text{x}10^{19}\text{ GeV} \\ \shortparallel}}{m_{\rm P}}$$

Parametrizing $E_{\rm sph} = 4\pi v\mathcal{E}_{\rm sph}/g$,

$$\frac{v}{T} > \frac{g}{4\pi\mathcal{E}_{\rm sph}}\Big[44.35 + \text{log corrections}\Big] \equiv \zeta_{\rm sph}(T)$$



- It is important to calculate $\mathcal{E}_{\rm sph}$ precisely.
- We evaluate the condition at T_C. $\dfrac{v_C}{T_C} > \zeta_{\rm sph}(T_C)$

Sphaleron decoupling condition

To avoid washout of BAU, the sphaleron process must be suppressed after EWPT.

Hubble constant

1.22x10^{19} GeV

$$\Gamma_B^{(\mathrm{br})}(T) \simeq (\mathrm{prefactor})e^{-E_{\mathrm{sph}}(T)/T} < \boxed{H(T)} \simeq 1.66\underset{\shortparallel}{\sqrt{g_*}}T^2/\overset{\shortparallel}{m_{\mathrm{P}}}$$

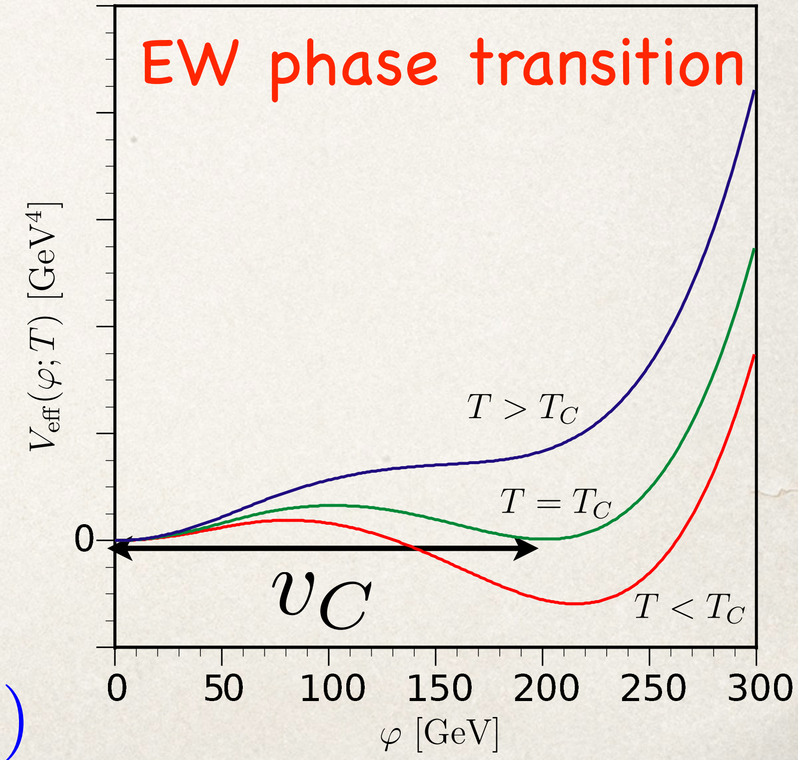
dof of relativistic particles

Parametrizing $E_{\mathrm{sph}} = 4\pi v\mathcal{E}_{\mathrm{sph}}/g$,

$$\frac{v}{T} > \frac{g}{4\pi\underset{\uparrow}{\mathcal{E}_{\mathrm{sph}}}}\left[44.35 + \text{log corrections}\right] \equiv \zeta_{\mathrm{sph}}(T)$$

leading

- It is important to calculate $\mathcal{E}_{\mathrm{sph}}$ precisely.
- We evaluate the condition at T_C. $\frac{v_C}{T_C} > \zeta_{\mathrm{sph}}(T_C)$



Sphaleron decoupling condition

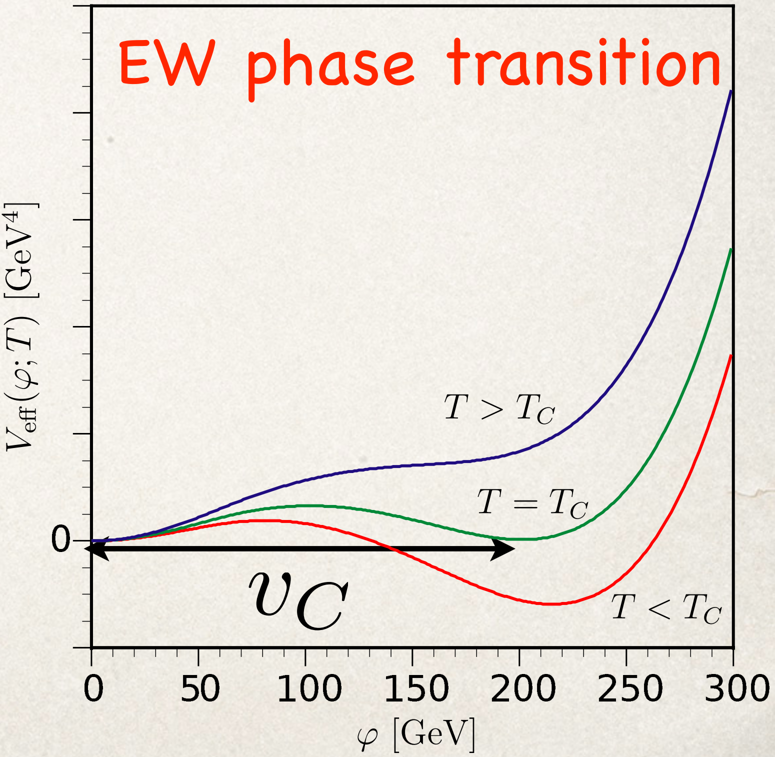
To avoid washout of BAU, the sphaleron process must be suppressed after EWPT.

$$\Gamma_B^{(\mathrm{br})}(T) \simeq (\mathrm{prefactor})e^{-E_{\mathrm{sph}}(T)/T} < \overset{\text{Hubble constant}}{\boxed{H(T)}} \simeq 1.66\sqrt{\underset{\substack{\parallel\\ \text{dof of relativistic particles}}}{g_*}}\,T^2/\overset{\substack{1.22\text{x}10^{19}\text{ GeV}\\ \parallel}}{m_{\mathrm{P}}}$$

Parametrizing $E_{\mathrm{sph}} = 4\pi v\mathcal{E}_{\mathrm{sph}}/g$,

$$\frac{v}{T} > \frac{g}{4\pi\underset{\substack{\uparrow\\ \text{leading}}}{\mathcal{E}_{\mathrm{sph}}}}\left[44.35 + \underset{\substack{\uparrow\\ \text{next-to-leading}}}{\text{log corrections}}\right] \equiv \zeta_{\mathrm{sph}}(T)$$

- It is important to calculate $\mathcal{E}_{\mathrm{sph}}$ precisely.
- We evaluate the condition at T_C. $\dfrac{v_C}{T_C} > \zeta_{\mathrm{sph}}(T_C)$



What is the problem?

- Effective potential with daisy resummation is often used to evaluate the sphaleron decoupling condition.

- In non-abelian gauge theories, transverse gauge bosons also have thermal corrections due to magnetic mass, $m_T=O(g^2T)$.

m_T effect on v_C/T_C: W. Buchmuller, Z. Fodor, T. Helbig, and D. Walliser, Ann.Phys.234,260 (1994).
J. R. Espinosa, M. Quiros, and F. Zwirner, PLB314, 206 (1993).

But no detailed study of m_T effect on ζ_{sph}!!

In this talk, we consider the m_T effect on both v_C/T_C and ζ_{sph}.

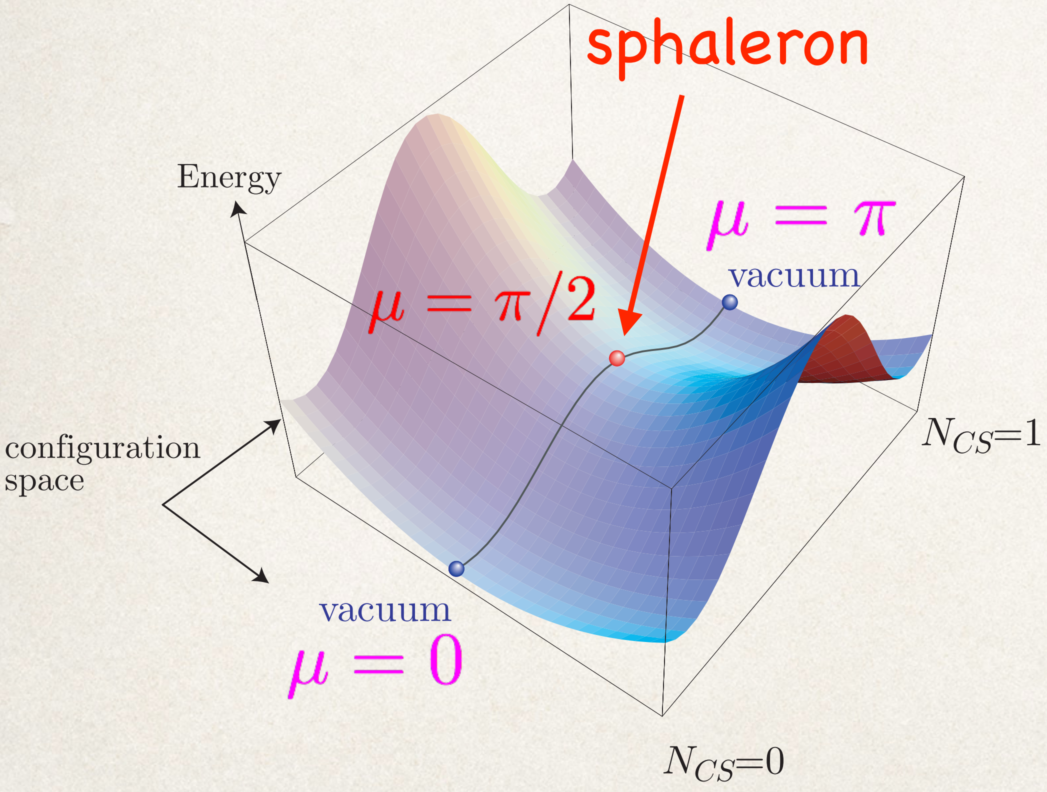
Sphaleron in the SM

~ w/o U(1)$_Y$ ~

$$\mathcal{L}_{\text{gauge+Higgs}} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + (D_\mu\Phi)^\dagger D^\mu\Phi - V(\Phi),$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc}A^b_\mu A^c_\nu,$$

$$D_\mu\Phi = \left(\partial_\mu + igA^a_\mu\frac{\tau^a}{2}\right), \qquad V(\Phi) = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2.$$



Manton's ansatz.

To find a saddle point configuration, we use noncontractible loop.

$$\mu \in [0, \pi]$$

[N.S. Manton, PRD28 ('83) 2019]

Sphaleron in the SM

~ w/o U(1)$_Y$ ~

Energy functional

$A_0 = 0$

$$E_{\rm sph} = \frac{4\pi v}{g}\int_0^\infty d\xi \left[4\left(\frac{df}{d\xi}\right)^2 + \frac{8}{\xi^2}(f-f^2)^2 + \frac{\xi^2}{2}\left(\frac{dh}{d\xi}\right)^2 + h^2(1-f)^2 + \underset{\uparrow}{\frac{\lambda}{4g^2}}\xi^2(h^2-1)^2\right]$$

$$= \frac{4\pi v}{g}\mathcal{E}_{\rm sph},$$

input: $\dfrac{\lambda}{g^2} \simeq 0.3$ (SM)

Equations of motion for the sphaleron

$$\frac{d^2}{d\xi^2}f(\xi) = \frac{2}{\xi^2}f(\xi)(1-f(\xi))(1-2f(\xi)) - \frac{1}{4}h^2(\xi)(1-f(\xi)),$$

$$\frac{d}{d\xi}\left(\xi^2\frac{dh(\xi)}{d\xi}\right) = 2h(\xi)(1-f(\xi))^2 + \frac{\lambda}{g^2}(h^2(\xi)-1)h(\xi)$$

with the boundary conditions:

$$\lim_{\xi\to 0} f(\xi) = 0, \quad \lim_{\xi\to 0} h(\xi) = 0,$$

$$\lim_{\xi\to \infty} f(\xi) = 1, \quad \lim_{\xi\to \infty} h(\xi) = 1.$$

$$\mathcal{E}_{\rm sph} = 1.92,$$

$$(E_{\rm sph} = 9.08\ {\rm TeV}),$$

$$\zeta_{\rm sph} = 1.17.$$

[NOTE]

$$\mathcal{E}_{\rm sph}(T=0) > \mathcal{E}_{\rm sph}(T\neq 0); \quad \zeta_{\rm sph}(T=0) < \zeta_{\rm sph}(T\neq 0)$$

Higher order corrections are important!!

Higher-order corrections

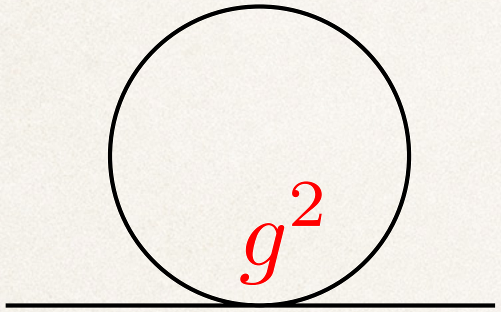
T=0: $$V_1^{T=0} = \sum_i \frac{\bar{m}_i^4}{64\pi^2}\left(\ln\frac{\bar{m}_i^2}{\bar{\mu}^2} - c_i\right)$$

T>0: $$V_1^{T\neq 0} = \sum_i \frac{T^4}{2\pi^2} I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right), \quad I_{B,F}(a^2) = \int_0^\infty dx\ x^2 \ln\left[1 \mp e^{-\sqrt{x^2+a^2}}\right].$$

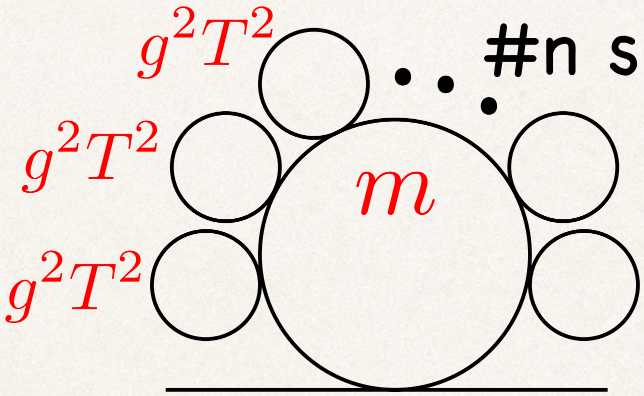
Daisy resummation

Perturbative expansion breaks down at high T.

e.g.



$\sim g^2T^2$



#n sub-bubbles

$$\sim \frac{g^4T^3}{m}\left(\frac{g^2T^2}{m^2}\right)^{n-1}$$

$$m^2 \to m^2 + \mathcal{O}(g^2T^2)$$

Resummed Lagrangian

[Parwani (92), Buchmüller et al (93) etc.]

$$\mathcal{L} = \boxed{(\mathcal{L}_R - \Delta m^2(T)\Psi^2)} + \boxed{(\mathcal{L}_{\rm CT} + \Delta m^2(T)\Psi^2)}$$

new 0th-order part　　new counterterm

Ψ: scalar & gauge fields

Δm²(T): thermal masses

We evaluate sphaleron energy using the resummed Lagrangian.

Magnetic mass corrections to E$_{\text{sph}}$

$$\mathcal{L}_{\text{eff}}^{(2)} = \mathrm{Tr}\left[A^\mu \Pi_{\mu\nu} A^\nu\right] = \frac{1}{2} A^{a\mu} \Pi_{\mu\nu} A^{a\nu},$$

Static limit $p^0 = 0,\ \boldsymbol{p} \to 0 \text{ with } \partial_i A_i = 0$ (sphaleron ansatz)

$$\mathcal{L}_{\text{eff}}^{(2)} = \underbrace{\frac{1}{2} m_L^2(T)(A_0^a)^2}_{\text{electric mass}} - \underbrace{\frac{1}{2} m_T^2(T)(A_i^a)^2}_{\text{magnetic mass}}, \qquad m_{L,T}^2 = \lim_{p^0=0,\boldsymbol{p}\to 0} \Pi_{L,T}(p^0, \boldsymbol{p})$$

E$_{\text{sph}}$ is modified by $\Delta E_{\text{sph}} = \frac{m_T^2}{2} \int d^3\boldsymbol{x}\ A_i^a A_i^a.$

Magnetic mass: $m_T = cg^2T$

c = 0.11 [Espinosa, Quiros, Zwirner, PLB314,206(93);
Buchmuller, Fodor, Helbig, Walliser, AP234,260(94)] **gauge-dep. 1-loop gap eq.**

c = 0.28 [Buchmuller, Philipsen, hep-ph/9411334]

c = 0.38 [Alexanian, Nair, hep-ph/9504256]

c = 0.35 [Patkos, Petreczky, Szep, hep-ph/9711263]

} **gauge-inv. 1-loop gap eq.**

c = 0.46 [Heller, Karsch, Rank, hep-lat/9710033] **Lattice**

Since there is no robust result, we regard c as the varying parameter.

Sphaleron energy with m$_T$.

Energy functional

$$E_{\rm sph} = \frac{4\pi v}{g}\int_0^\infty d\xi\left[4f'^2 + \frac{8}{\xi^2}(f-f^2)^2 + \frac{\xi^2}{2}h'^2 + (h^2 + r_m^2)(1-f)^2 + \frac{\xi^2 V_0(h)}{g^2 v^4}\right] \equiv \frac{4\pi v}{g}\mathcal{E}_{\rm sph}$$

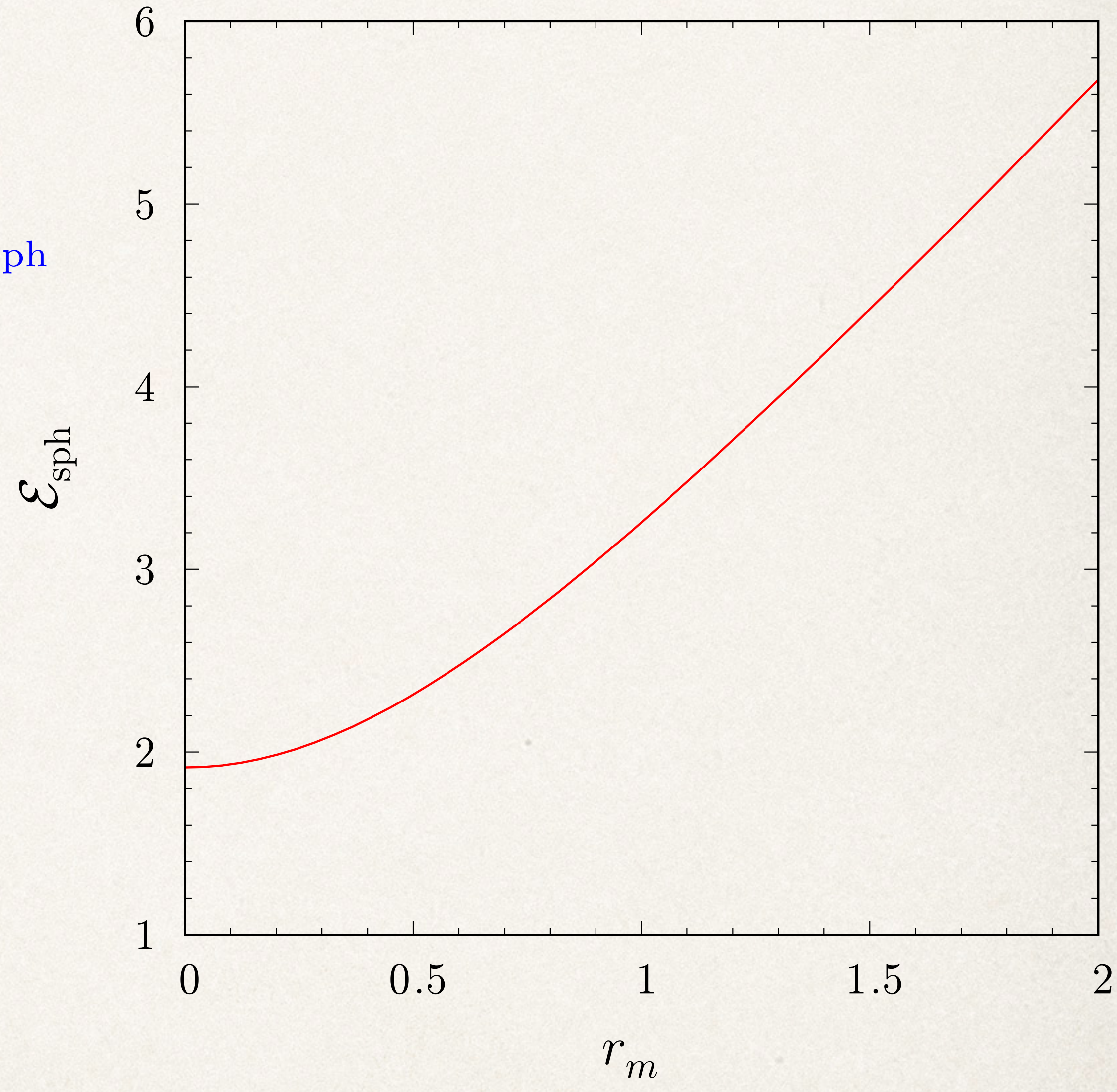
where $\xi = gvr,\ r_m = \dfrac{m_T}{m_W}\qquad V_0(h) = \lambda v^4(h^2-1)^2/4$

Equations of motion

$$\frac{d^2 f}{d\xi^2} = \frac{2}{\xi^2}(f-f^2)(1-2f) - \frac{1}{4}(h^2 + r_m^2)(1-f),$$
$$\frac{d^2 h}{d\xi^2} = -\frac{2}{\xi}\frac{dh}{d\xi} + \frac{2}{\xi^2}h(1-f)^2 + \frac{1}{g^2v^4}\frac{\partial V_0}{\partial h},$$

w/ b.c.

$$\lim_{\xi\to 0} f(\xi) = 0,\quad \lim_{\xi\to 0} h(\xi) = 0,$$
$$\lim_{\xi\to\infty} f(\xi) = 1,\quad \lim_{\xi\to\infty} h(\xi) = 1.$$



Sphaleron energy gets larger as m$_T$ increases.

w/o any symmetry, e.g. Z2
↓

General 2 Higgs doublet model (g2HDM)

Particle content: SM + Φ_2 ⟵ 2nd Higgs doublet

Yukawa int.

$$\mathcal{L}_Y = \bar{q}_L(Y_1^{(d)}\Phi_1 + Y_2^{(d)}\Phi_2)d_R + \bar{q}_L(Y_1^{(u)}\tilde{\Phi}_1 + Y_2^{(u)}\tilde{\Phi}_2)u_R + \bar{l}_L(Y_1^{(e)}\Phi_1 + Y_2^{(e)}\Phi_2)e_R + \text{h.c.} \qquad \tilde{\Phi}_{1,2} = i\tau^2\Phi_{1,2}^*$$

Higgs potential:

$$\begin{aligned} V_0(\Phi_1, \Phi_2) = {} & m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left[\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \left\{\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)\right\}(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right], \end{aligned}$$

Assumption: CP is **NOT** violated by the Higgs potential and VEVs.

inputs: $\sin(\beta-\alpha)$, $\tan\beta$, m_H, m_A, $m_{H^\pm}$, $M^2 = \frac{m_3^2}{\sin\beta\cos\beta}$, $\lambda_{6,7}$

$v = 246$ GeV, $m_h = 125$ GeV.

Effective potential

EWPT is studied in the SM-like limit. $\sin(\beta-\alpha)=\tan\beta=1$

$$V_{\rm eff}(\varphi;T)=V_0(\varphi)+V_1(\varphi;T),$$

where

$$V_0(\varphi)=-\frac{\mu^2}{2}\varphi^2+\frac{\lambda_{\rm eff}}{4}\varphi^4,$$

$$V_1(\varphi;T)=\sum_{\substack{i=h,H,A,H^\pm,G^0,G^\pm\\ W^\pm_{L,T},Z_{L,T},\gamma_{L,T},t,b}} n_i\left[\frac{\bar{m}_i^4}{64\pi^2}\left(\ln\frac{\bar{m}_i^2}{\bar{\mu}^2}-c_i\right)+\frac{T^4}{2\pi^2}I_{B,F}\left(\frac{\bar{m}_i^2}{T^2}\right)\right]$$

with $I_{B,F}(a^2)=\int_0^\infty dx\ x^2\log\left(1\mp e^{-\sqrt{x^2+a^2}}\right),\quad a^2=m^2/T^2$

$\bar{m}_i^2$ are the thermally-corrected field dependent masses. (Parwani's method)

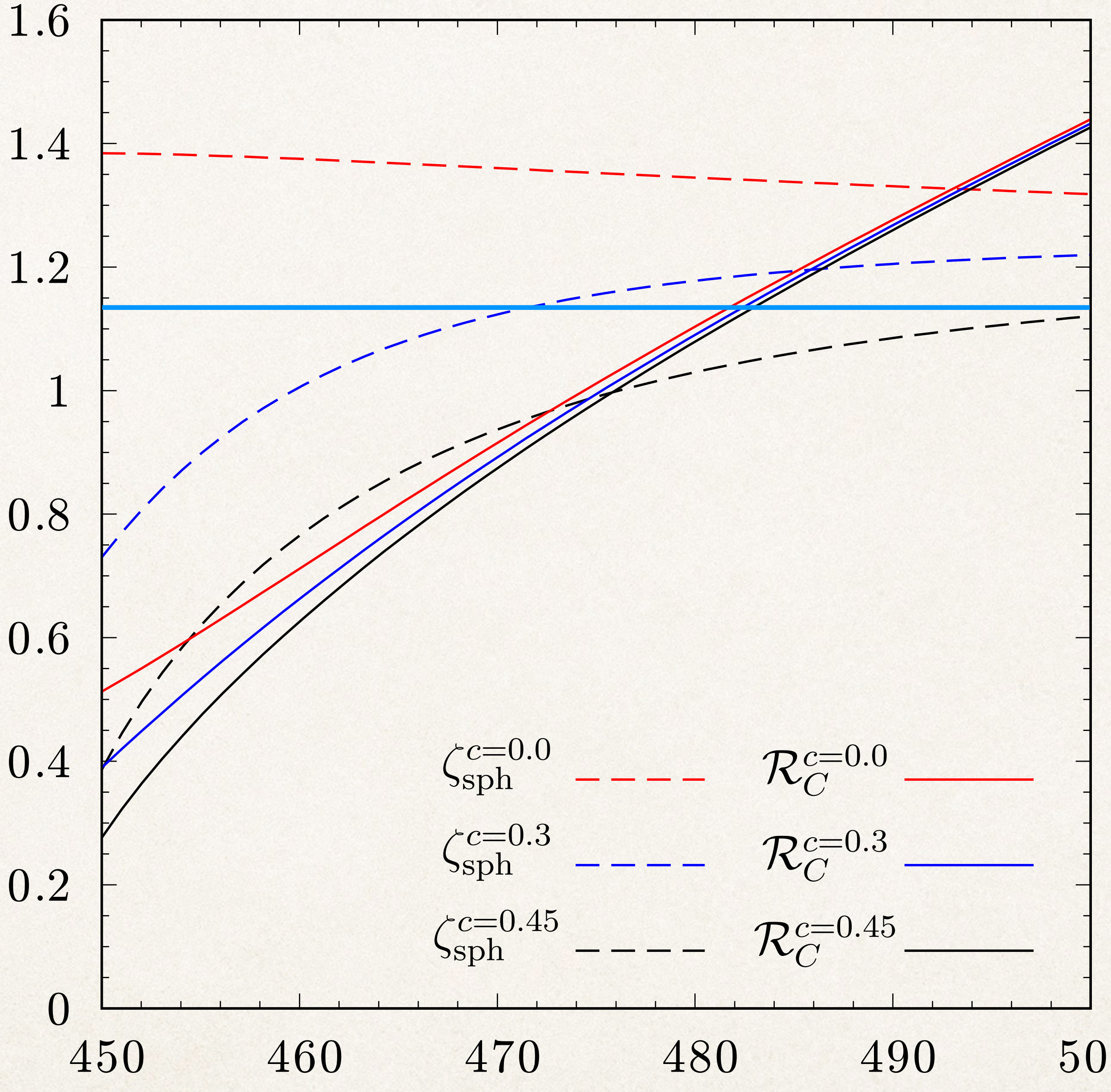
Using this potential, we evaluate $v_C/T_C(\equiv R_C)$ and $\zeta_{sph}(T_C)$.

$v_C/T_C > \zeta_{\rm sph}(T_C)$ region

$$s_{\beta-\alpha} = t_\beta = 1,\ M = \sqrt{m_3^2/s_\beta c_\beta} = 300\ \text{GeV},\ \lambda_{6,7} = 0.$$

$v_C/T_C > \zeta_C$ -> $\Gamma_{\rm sph} < H$

$m_T = cg^2T$



$\zeta_{\rm sph}$=1.17 (@tree level)

m_Φ [GeV] $\quad m_\Phi \equiv m_H = m_A = m_{H^\pm}$

sphaleron decoupling region can be expanded due to the magnetic mass effect.

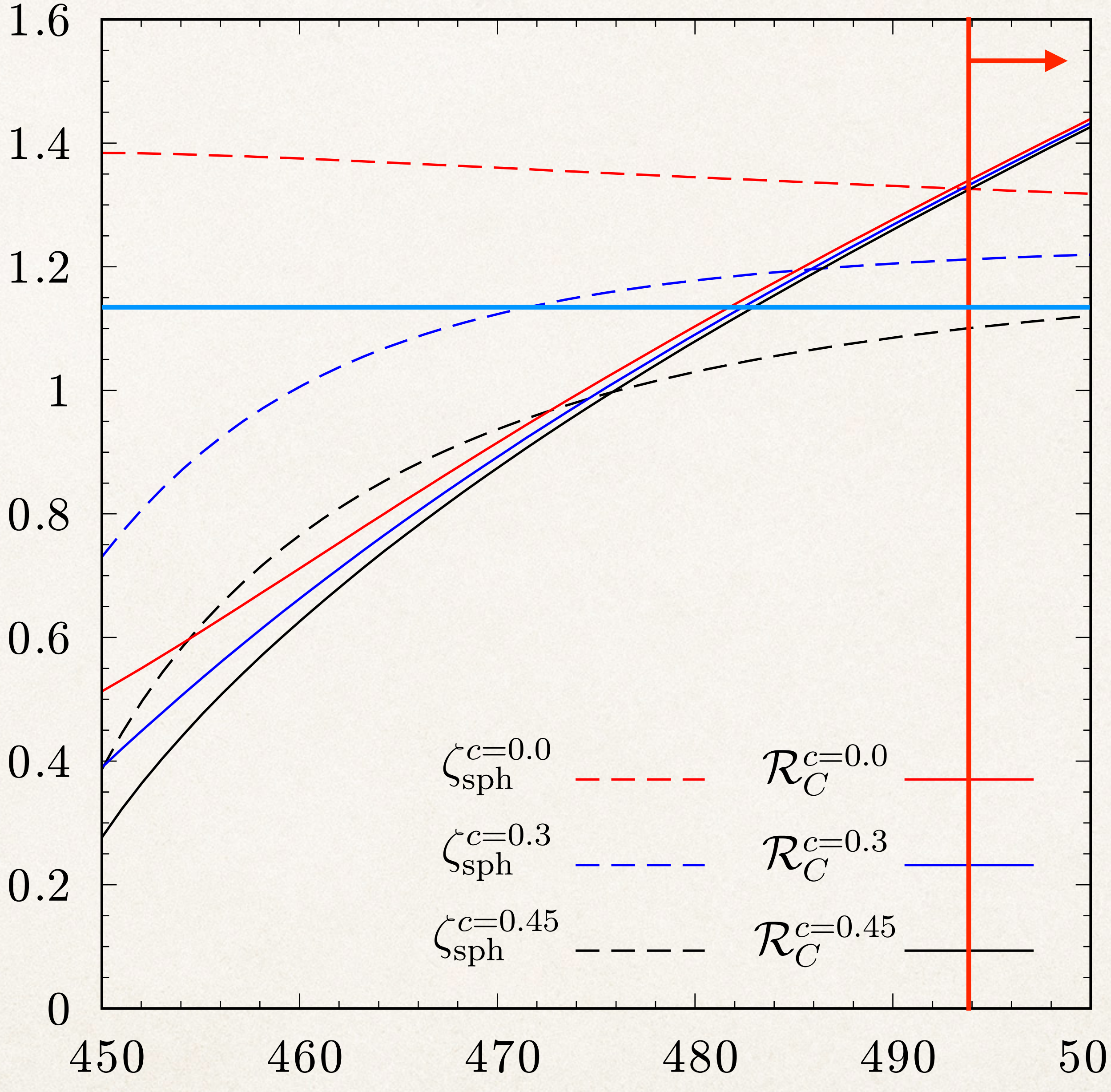
$v_C/T_C>\zeta_{sph}(T_C)$ region

$s_{\beta-\alpha}=t_\beta=1,\ M=\sqrt{m_3^2/s_\beta c_\beta}=300$ GeV, $\lambda_{6,7}=0.$

$v_C/T_C>\zeta_C$ -> $\Gamma_{sph}<H$

c=0.0

m_T = cg^2T



ζ_{sph}=1.17 (@tree level)

$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

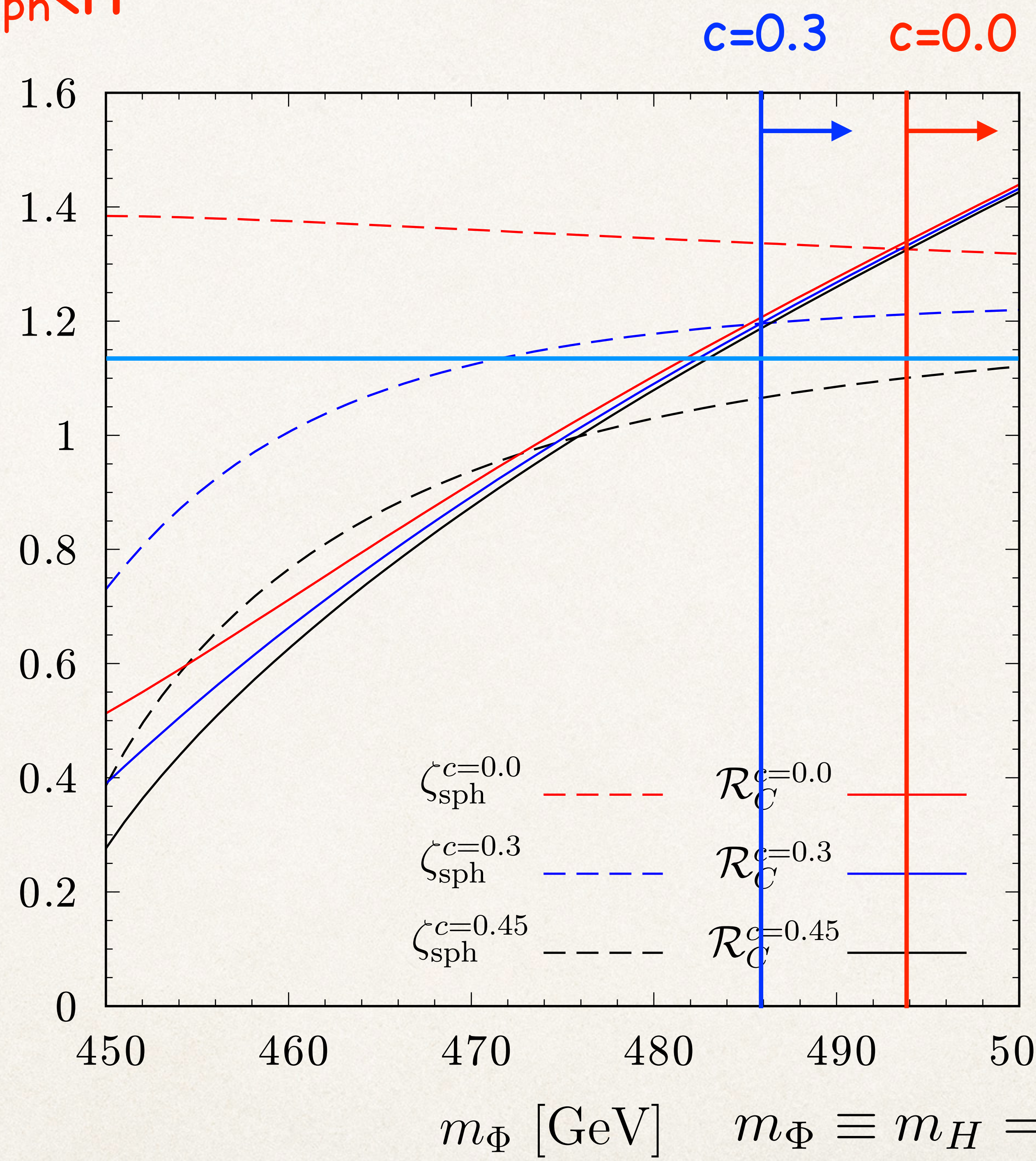
sphaleron decoupling region can be expanded due to the magnetic mass effect.

$v_C/T_C > \zeta_{sph}(T_C)$ region

$$s_{\beta-\alpha} = t_\beta = 1,\ M = \sqrt{m_3^2/s_\beta c_\beta} = 300\ \text{GeV},\ \lambda_{6,7} = 0.$$

$v_C/T_C > \zeta_C \rightarrow \Gamma_{sph} < H$

$m_T = cg^2T$



$\zeta_{sph}=1.17$ (@tree level)

$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

sphaleron decoupling region can be expanded due to the magnetic mass effect.

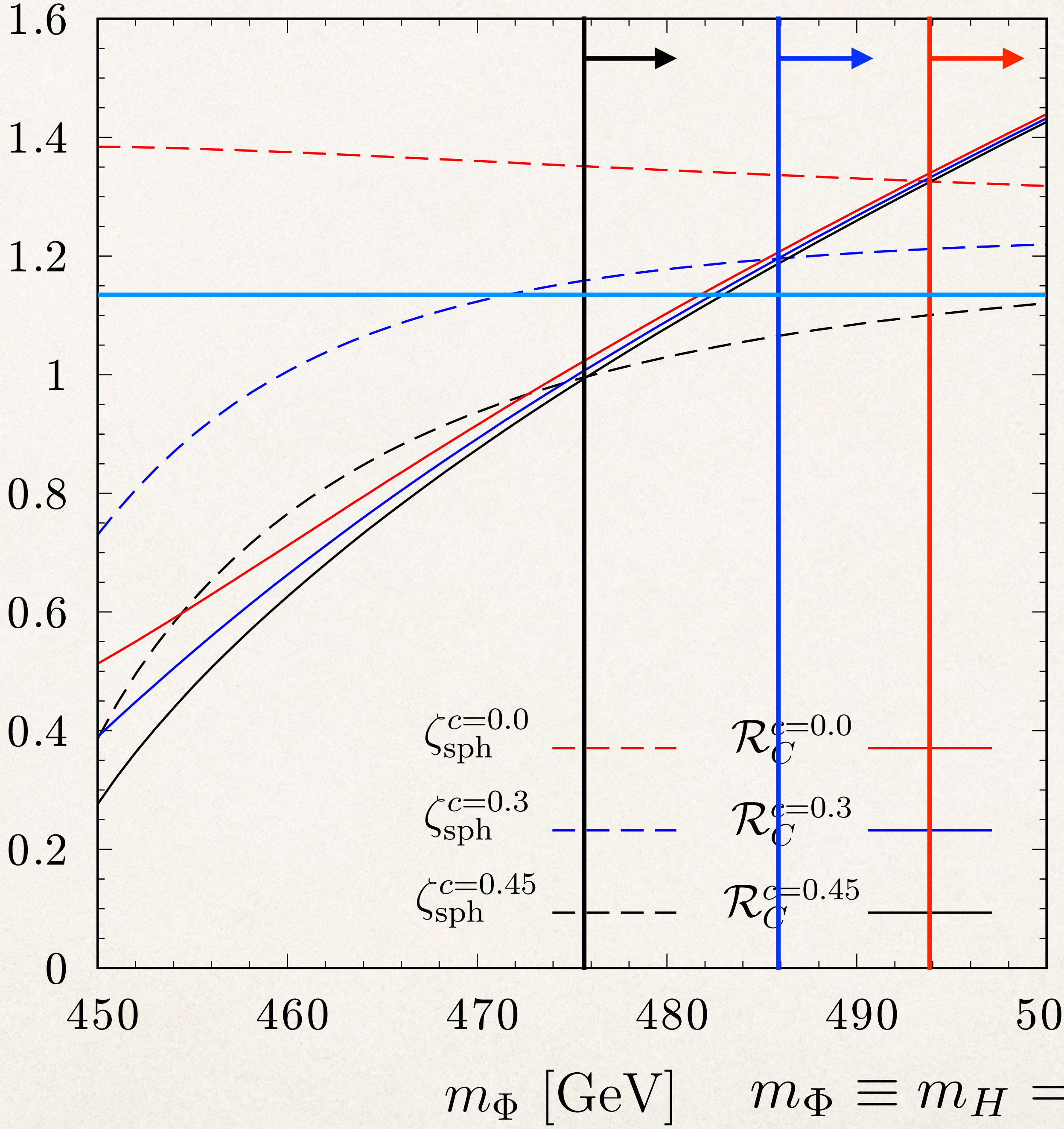
$v_C/T_C>\zeta_{sph}(T_C)$ region

$v_C/T_C> \zeta_C$ -> $\Gamma_{sph}<H$

$$s_{\beta-\alpha}=t_\beta=1,\ M=\sqrt{m_3^2/s_\beta c_\beta}=300\ \text{GeV},\ \lambda_{6,7}=0.$$

c=0.45 c=0.3 c=0.0

$m_T = cg^2T$



ζ_{sph}=1.17 (@tree level)

$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

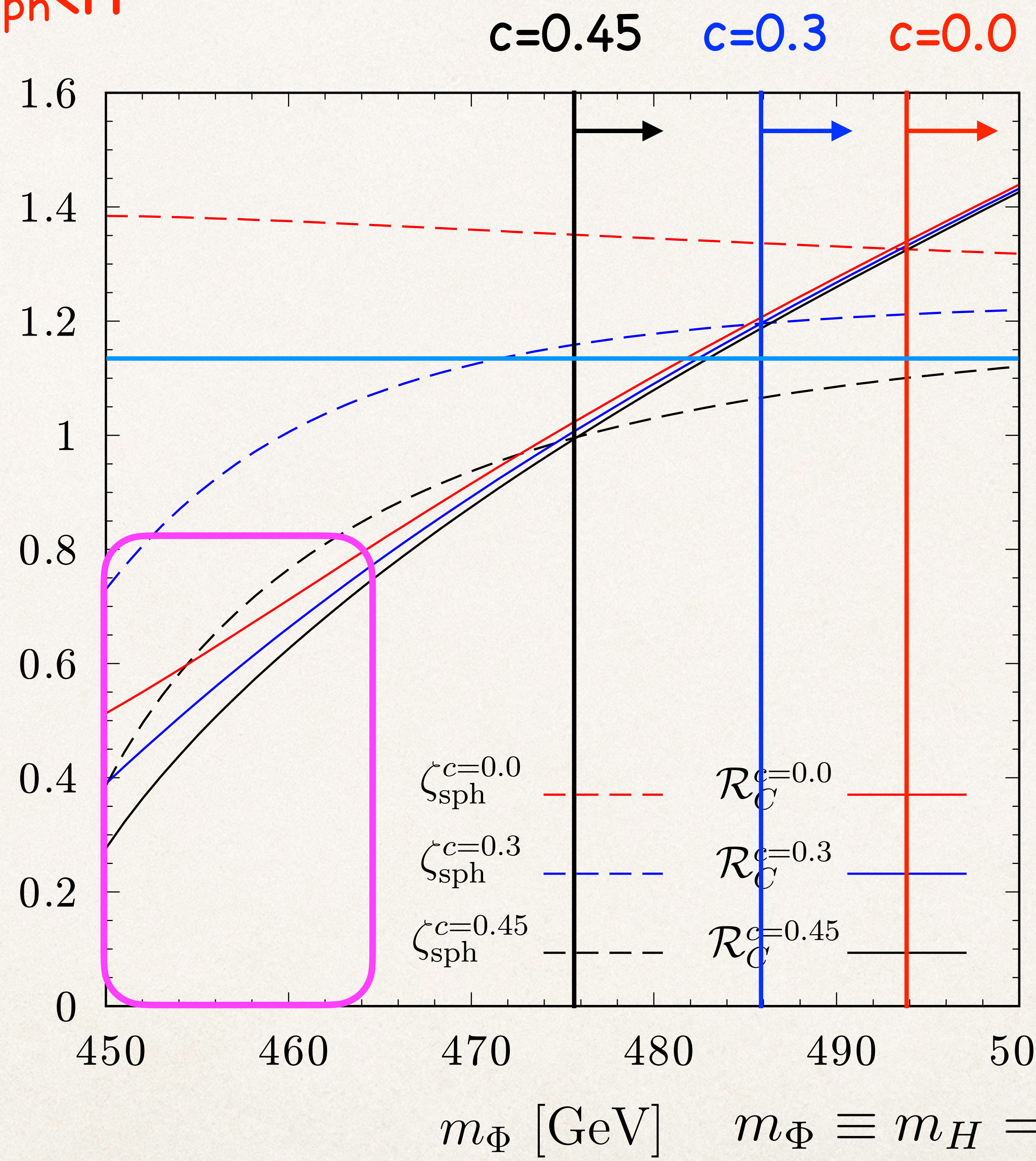
sphaleron decoupling region can be expanded due to the magnetic mass effect.

$v_C/T_C>\zeta_{sph}(T_C)$ region

$v_C/T_C>\zeta_C$ -> $\Gamma_{sph}<H$

$$s_{\beta-\alpha}=t_\beta=1,\ M=\sqrt{m_3^2/s_\beta c_\beta}=300\ \text{GeV},\ \lambda_{6,7}=0.$$

m_T = cg^2T



ζ_{sph}=1.17 (@tree level)

$m_\Phi\equiv m_H=m_A=m_{H^\pm}$

sphaleron decoupling region can be expanded due to the magnetic mass effect.

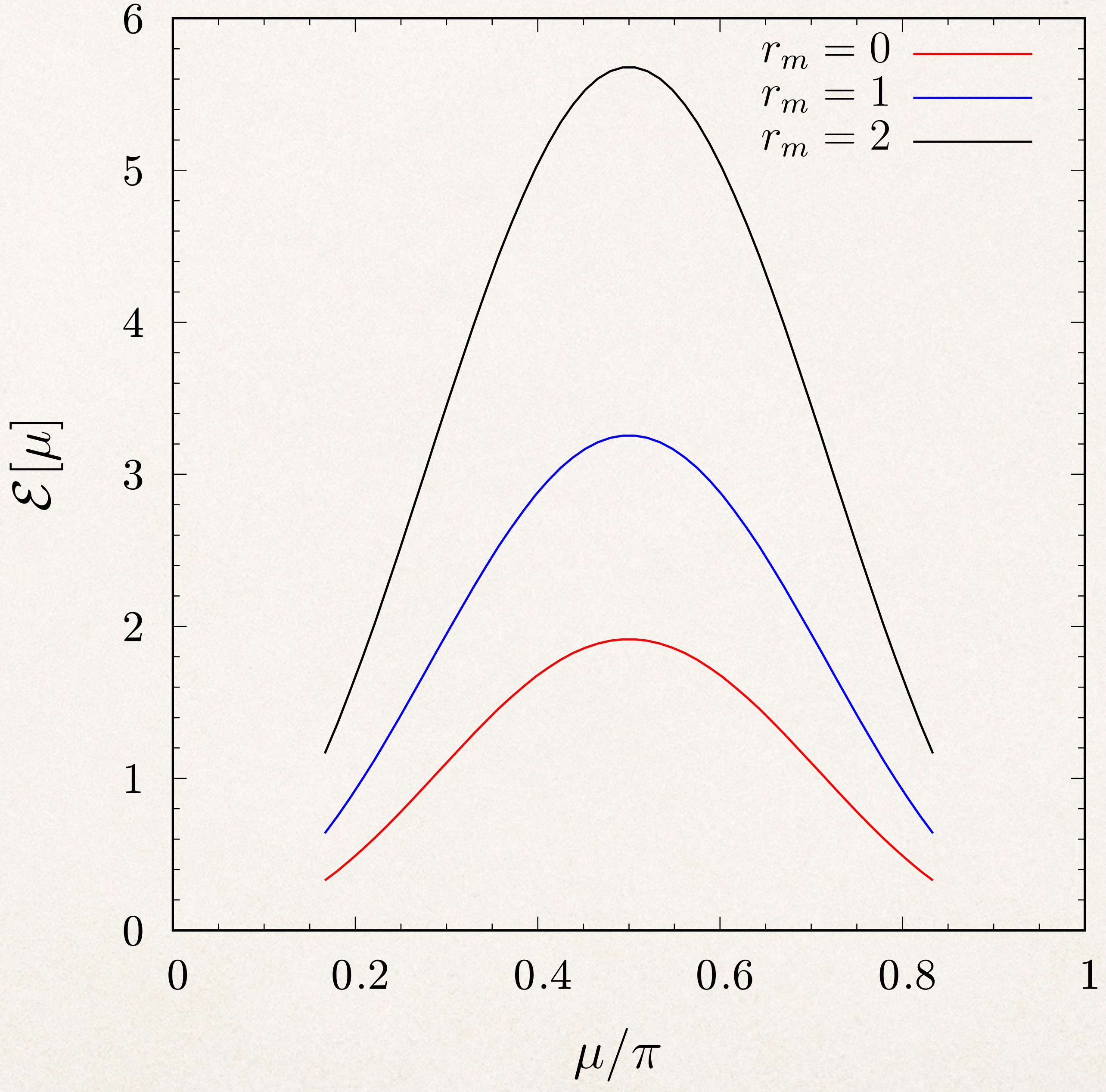
Summary

- We have studied the sphaleron decoupling condition taking the magnetic mass into account.
- Nonzero magnetic mass can increase the sphaleron energy.
- We applied this to 2HDM and found that the sphaleron decoupling condition gets more relaxed, enlarging the domain of the successful EWBG regions.
- Our findings would hold in other BSM models as long as the gauge sector is common to the SM.

Backup

Sphaleron energy in the SM

Cross-check of the results.



Obtained sphaleron energies become maximum at μ=π/2.

Magnetic mass corrections to E$_{\rm sph}$

$$\mathcal{L}_{\rm eff}^{(2)} = {\rm Tr}\left[A^\mu \Pi_{\mu\nu} A^\nu\right] = \frac{1}{2} A^{a\mu} \Pi_{\mu\nu} A^{a\nu},$$

At T>0, Lorentz sym. is broken by thermal bath specified by u^μ.

$u^\mu = (1, \mathbf{0})$ in the rest frame of thermal bath

Polarization tensor: $\{g_{\mu\nu}, p_\mu p_\nu, u_\mu u_\nu, p_\mu u_\nu + p_\nu u_\nu\}$

$$\Pi_{\mu\nu}(p^0, \boldsymbol{p}) = \Pi_L(p^0, \boldsymbol{p}) L_{\mu\nu}(p) + \Pi_T(p^0, \boldsymbol{p}) T_{\mu\nu}(p) + \Pi_G(p^0, \boldsymbol{p}) G_{\mu\nu}(p) + \Pi_S(p^0, \boldsymbol{p}) S_{\mu\nu}(p),$$

$$L_{\mu\nu}(p) = \frac{u_\mu^T u_\nu^T}{(u^T)^2}, \quad T_{\mu\nu}(p) = g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} - L_{\mu\nu}(p),$$

$$G_{\mu\nu}(p) = \frac{p_\mu p_\nu}{p^2}, \quad S_{\mu\nu}(p) = \frac{p_\mu u_\nu^T + p_\nu u_\mu^T}{\sqrt{(p \cdot u)^2 - p^2}}.$$

$$u_\mu^T = u_\mu - (p \cdot u) p_\mu / p^2$$

$$u_\mu^T p^\mu = 0$$

Static limit $p^0 = 0,\ \boldsymbol{p} \to 0$ with $\partial_i A_i = 0$ (sphaleron ansatz)

$$\mathcal{L}_{\rm eff}^{(2)} = \frac{1}{2} m_L^2(T) (A_0^a)^2 - \frac{1}{2} m_T^2(T) (A_i^a)^2, \qquad m_{L,T}^2 = \lim_{p^0=0, \boldsymbol{p}\to 0} \Pi_{L,T}(p^0, \boldsymbol{p})$$

electric mass magnetic mass

$$A_0 = 0 \quad \Rightarrow \quad \Delta E_{\rm sph} = \frac{m_T^2}{2} \int d^3\boldsymbol{x}\ A_i^a A_i^a.$$

Magnetic mass corrections to E$_{\rm sph}$

Gauge-inv. dim.2 operator [D. Zwanziger, Nucl. Phys. B 345, 461 (1990)]

$$\int d^4x\ A^2_{\rm min} = \min_{\{U\}} \int d^4x\ \mathrm{Tr}[(A^U_\mu)^2] \simeq \int d^4x \left[F_{\mu\nu}\frac{1}{D^2}F^{\mu\nu} + \cdots\right]$$

$$A^U_\mu = UA_\mu U^{-1} + \tfrac{i}{g}(\partial_\mu U)U^{-1}$$

expressed by infinite series of non-local gauge-inv. terms.

It is known that $\int d^4x\ A^2_{\rm min} = \int d^4x\ \mathrm{Tr}[A_\mu A^\mu]$ if $\partial_\mu A^\mu = 0$

Since the sphaleron ansatz satisfies this condition, one has the same mass form as the previous case.

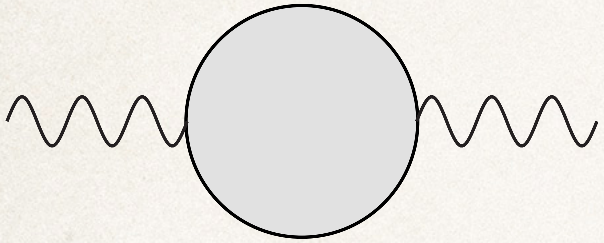
$$\boxed{\Delta E_{\rm sph} = \frac{m_T^2}{2}\int d^3\boldsymbol{x}\ A_i^a A_i^a.}$$

We regard this as the magnetic mass correction to E$_{\rm sph}$.

Magnetic mass

In SU(2) gauge Higgs model,

Espinosa, et al, PLB314, 206 (1993);
Buchmuller, et al, AP234, 260 (1994).



$$\Rightarrow \quad m_T^2 = \frac{g^2 T}{3\pi} m_T + \mathcal{O}(v)$$

1-loop gap eq. at high T.

$$m_T = c g^2 T, \quad c = \frac{1}{3\pi} \simeq 0.11$$

but, this is gauge dependent.

Other studies show that

methods	Refs.	c
gauge-inv. 1-loop gap eq.	Buchmuller, Philipsen, hep-ph/9411334	0.28
"	Alexanian, Nair, hep-ph/9504256	0.38
"	Patkos, Petreczky, Szep, hep-ph/9711263	0.35
Lattice	Heller, Karsch, Rank, hep-lat/9710033	0.46

Since there is no robust result, we regard c as the varying parameter.

1st-order EWPT

$$s_{\beta-\alpha} = t_\beta = 1, m_{H^\pm} = m_A,\ \ M = \sqrt{m_3^2/s_\beta c_\beta} = 300\ \text{GeV}$$

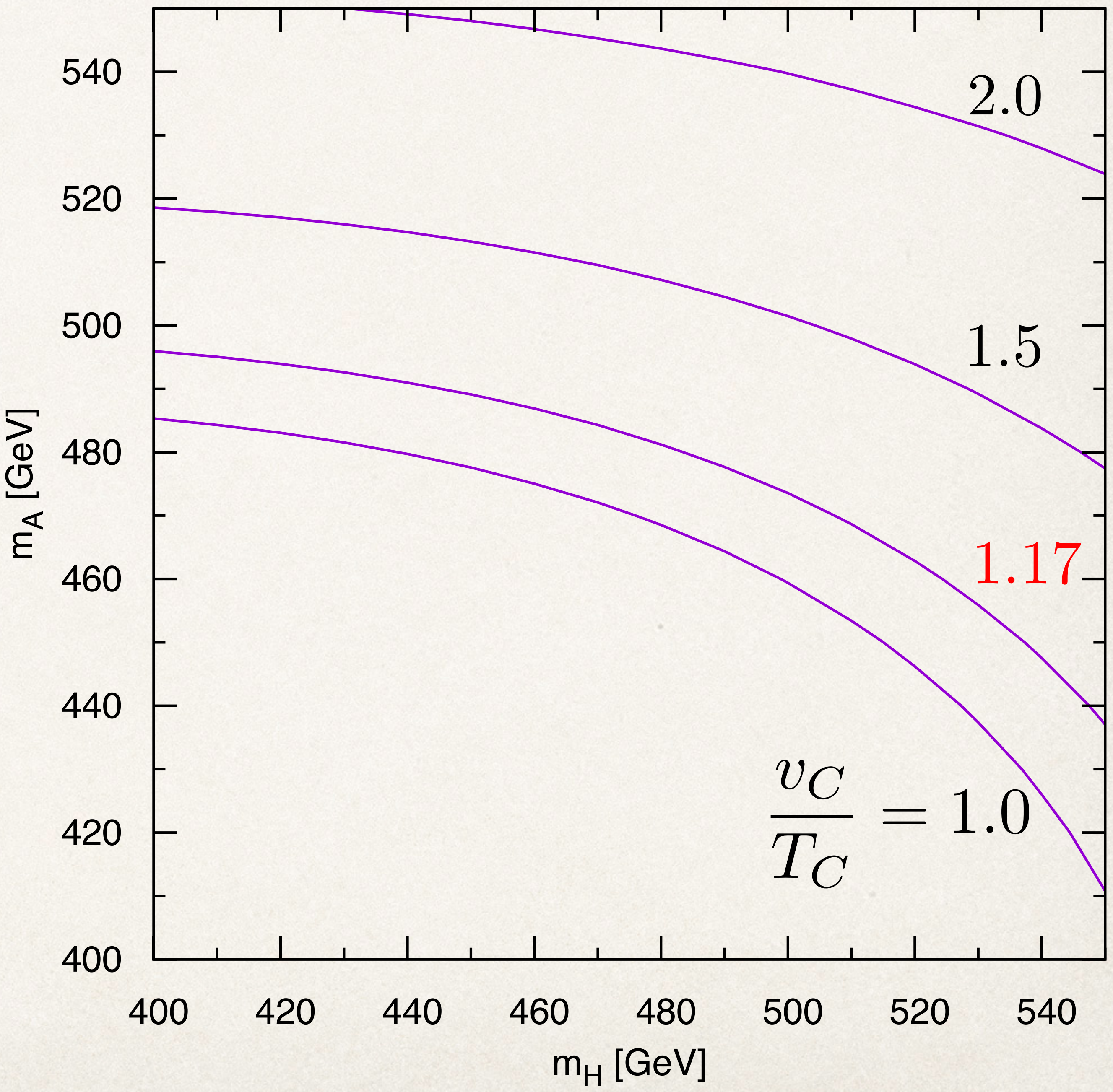
$$\lambda_6 = \lambda_7 = 0$$

- Heavy Higgs w/ non-decoupling plays a role.

- Too heavy Higgs could violate perturbativity.

- EWBG-viable region

$v_C/T_C > \zeta_{sph}$



cf. ζ_{sph}=1.17 using V_0 w/o m_T.

1st-order EWPT

- Heavy Higgs w/ non-decoupling plays a role.

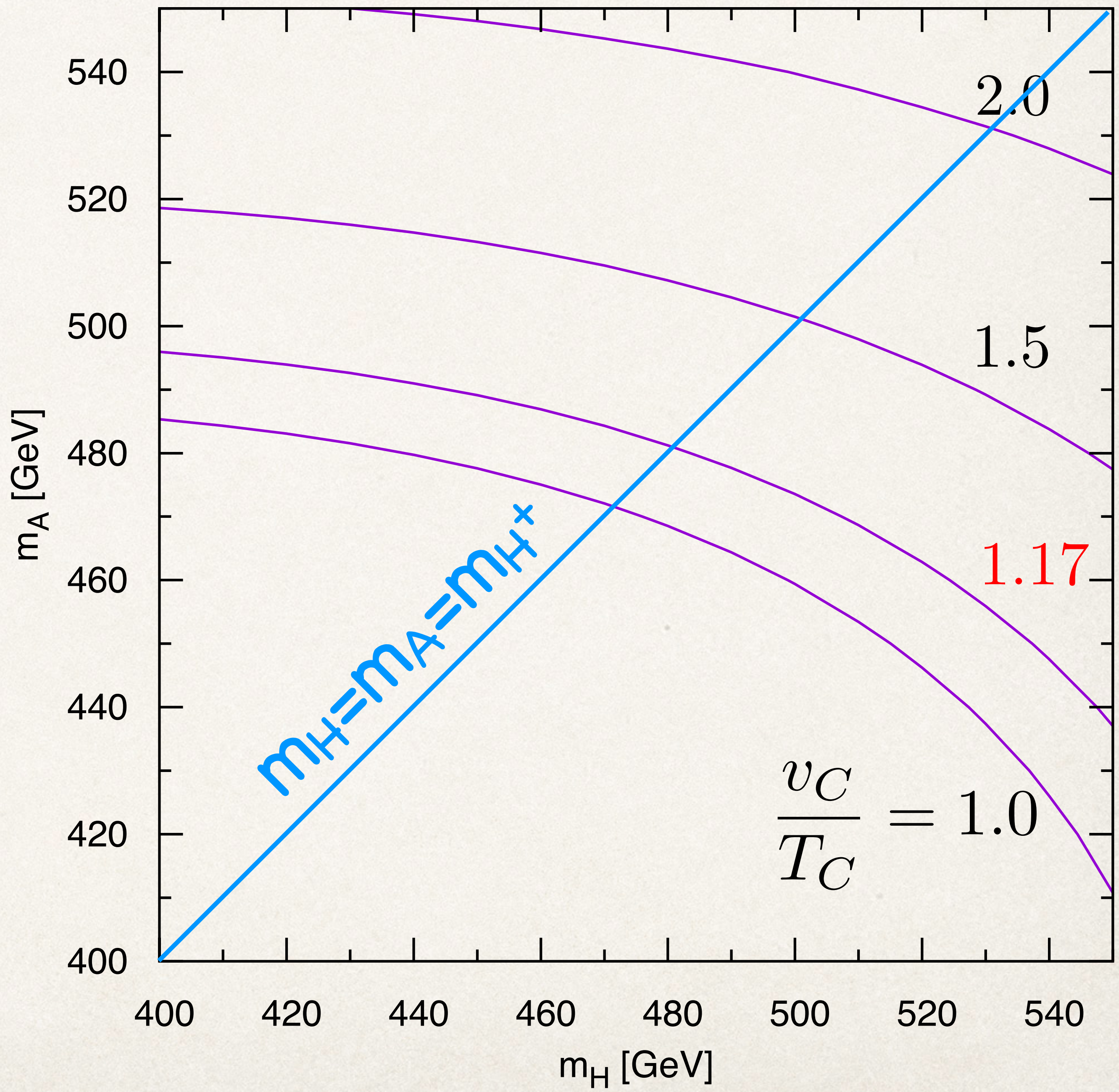
- Too heavy Higgs could violate perturbativity.

- EWBG-viable region

$v_C/T_C > \zeta_{sph}$

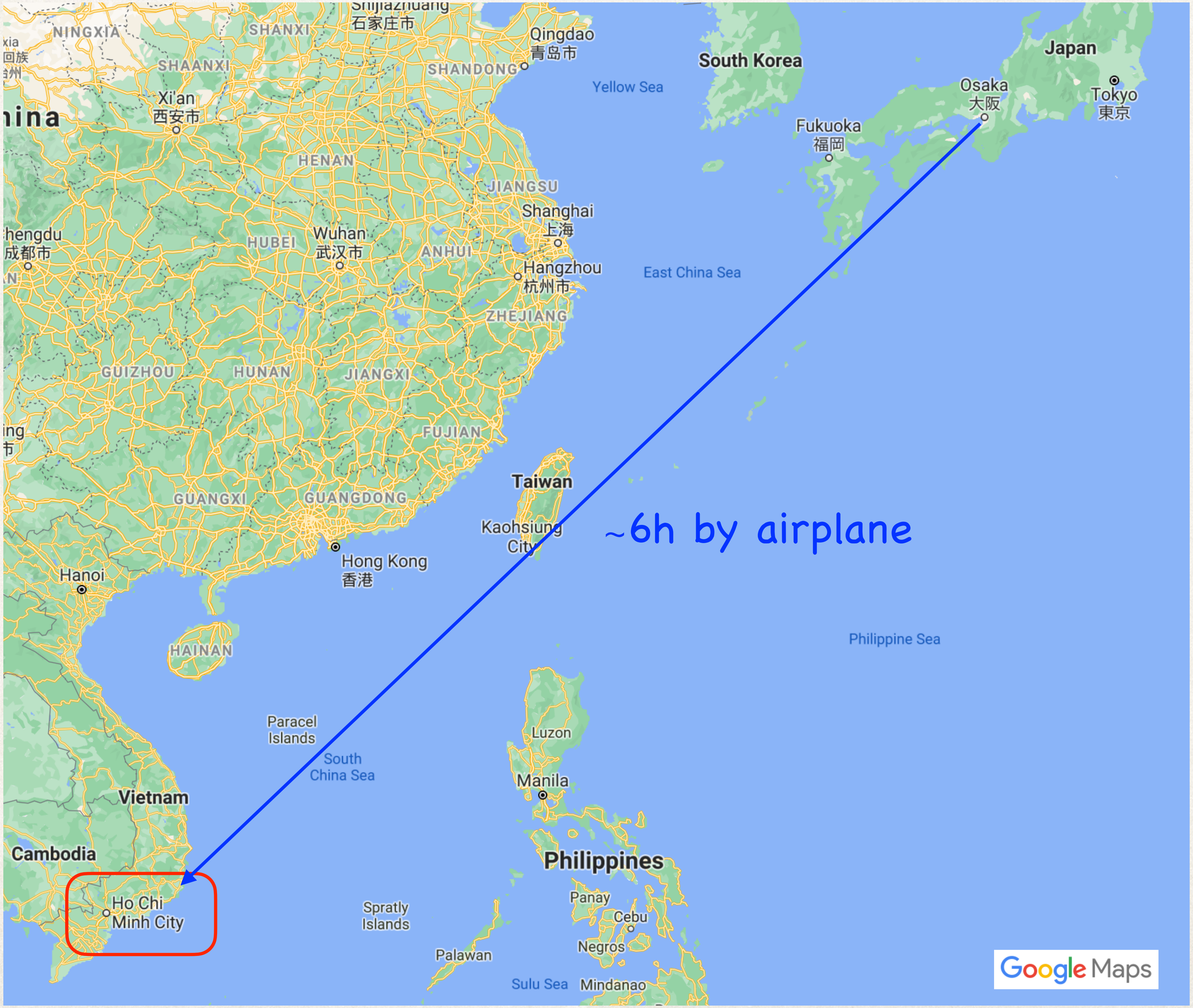
$$s_{\beta-\alpha} = t_\beta = 1, m_{H^\pm} = m_A, \;\; M = \sqrt{m_3^2/s_\beta c_\beta} = 300 \text{ GeV}$$

$$\lambda_6 = \lambda_7 = 0$$



cf. ζ_{sph}=1.17 using V_0 w/o m_T.

Where is Ton Duc Thang Univ.?



~6h by airplane

Where is Ton Duc Thang Univ.?

I belong to Theoretical Particle Physics and Cosmology Research Group (TPPC) in Advanced Institute of Materials Science (AIMaS).