Implications of Topological Field Configurations for Baryon Asymmetry and Dark Matter

Yanda Wu

Tsung-Dao Lee Institute / Shanghai Jiao Tong University

In cooperation with Michael Ramsey-Musolf, Xu-Xiang Li, Lorenzo Sorbo, Tuomas Tenkanen, Wenxing Zhang

BPCS 2025 @ Beijing

2025/9/28

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Topological field configurations

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Perturbative QFT configurations

Topological field configurations

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Perturbative QFT configurations

Topological field configurations

$$S = \int dx \left[\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}} \right]$$

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Perturbative QFT configurations

Topological field configurations

$$S = \int dx \left[\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}} \right]$$

$$\frac{\delta \mathscr{L}_{\text{free}}}{\delta \phi, A_i} = 0$$

$$\phi, A_i \sim a_p e^{-ipx}$$

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Perturbative QFT configurations

Topological field configurations

$$S = \int dx \left[\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}} \right]$$

$$\frac{\delta \mathscr{L}_{\text{free}}}{\delta \phi, A_i} = 0$$

$$\frac{\delta (\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}})}{\delta \phi, A_i} = 0$$

$$\phi, A_i \sim a_p e^{-ipx}$$

$$\phi, A_i \sim \text{complicated}$$

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Perturbative QFT configurations

Topological field configurations

$$S = \int dx \left[\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}} \right]$$

$$\frac{\delta \mathscr{L}_{\text{free}}}{\delta \phi, A_i} = 0$$

$$\frac{\delta (\mathscr{L}_{\text{free}} + \mathscr{L}_{\text{interaction}})}{\delta \phi, A_i} = 0$$

$$\phi, A_i \sim a_p e^{-ipx}$$

$$\phi, A_i \sim \text{complicated}$$

$$\int dx \; F\tilde{F} = 0$$

$$\int dx \; F\tilde{F} = \int dx \; \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

sphaleron

$SU(2)_L + \text{Higgs}$

The nature of dark matter?

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

Topological field configurations

$\phi, A_i \sim \text{complicated}$

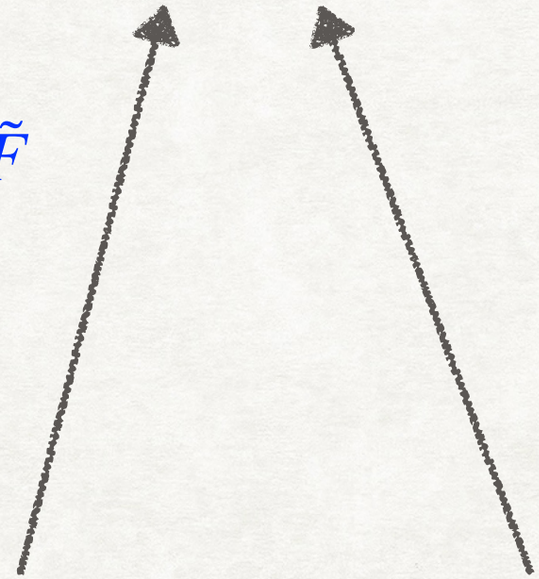
$$\int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

The nature of dark matter?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$



sphaleron

$SU(2)_L + \text{Higgs}$

monopole

$SU(2)_L + \text{Scalar(Y} = 0)$

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$

sphaleron

$SU(2)_L + \text{Higgs}$

The nature of dark matter?

WIMP

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$

The nature of dark matter?

sphaleron

$SU(2)_L + \text{Higgs}$

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

WIMP

local cosmic string

$U(1)_{\text{dark}} + \text{Scalar}$

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$

sphaleron

$SU(2)_L + \text{Higgs}$

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

The nature of dark matter?

WIMP

axion like particle

Novel ALP production channel

local cosmic string

$U(1)_{\text{dark}} + \text{Scalar}$

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

Open questions of our universe

The origin of baryon asymmetry?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$

sphaleron

$SU(2)_L + \text{Higgs}$

(A,B)

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

(B)

The nature of dark matter?

WIMP

axion like particle

Novel ALP production channel

local cosmic string

$U(1)_{\text{dark}} + \text{Scalar}$

(C)

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

(A) X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585
(B) YW, W. Zhang, M. J. Ramsey-Musolf, 2307.02187
(C) YW, L. Sorbo, 2510.XXXXX

Open questions of our universe

The origin of baryon asymmetry?

$$\partial_\mu j_B^\mu \sim \int dx\ F\tilde{F}$$

sphaleron

$SU(2)_L + \text{Higgs}$

(A,B)

Main Focus

The nature of dark matter?

WIMP

monopole

$SU(2)_L + \text{Scalar}(\text{Y} = 0)$

(B)

axion like particle

local cosmic string

$U(1)_{\text{dark}} + \text{Scalar}$

(C)

Novel ALP production channel

Topological field configurations

$$\phi, A_i \sim \text{complicated} \qquad \int dx\ F\tilde{F} = \int dx\ \partial_\mu K^\mu \neq 0$$

(A) X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585
(B) YW, W. Zhang, M. J. Ramsey-Musolf, 2307.02187
(C) YW, L. Sorbo, 2510.XXXXX

Roles of sphaleron in baryogengesis

Electroweak baryogengesis & Leptogenesis: sphaleron convert the lepton asymmetry into baryon asymmetry

Roles of sphaleron in baryogengesis

Electroweak baryogengesis & Leptogenesis: sphaleron convert the lepton asymmetry into baryon asymmetry

In the thermal equilibrium, final baryon asymmetry:

$$B = C(B_{\rm ini} - L_{\rm ini})$$

Roles of sphaleron in baryogengesis

Electroweak baryogengesis & Leptogenesis: sphaleron convert the lepton asymmetry into baryon asymmetry

In the thermal equilibrium, final baryon asymmetry:

$$B = C(B_{\rm ini} - L_{\rm ini})$$

Electroweak Baryogenesis (EWBG): $B_{\rm ini} - L_{\rm ini} = 0$

EWBG: out of equilibrium from first order phase transition!

Roles of sphaleron in baryogengesis

Electroweak baryogengesis & Leptogenesis: sphaleron convert the lepton asymmetry into baryon asymmetry

In the thermal equilibrium, final baryon asymmetry:

$$B = C(B_{\rm ini} - L_{\rm ini})$$

Electroweak Baryogenesis (EWBG): $B_{\rm ini} - L_{\rm ini} = 0$

EWBG: out of equilibrium from first order phase transition!

Be careful: The broken phase does NOT means out of equilibrium for baryon number violation (BNV).

BNV out of equilibrium criterion:

BNV rate (T) < Hubble constant (T)

Roles of sphaleron in baryogengesis

BNV out of equilibrium criterion:

$$\text{BNV rate } (T) < \text{Hubble constant } (T)$$

EWBG, in the broken phase, we might have BNV rate > Hubble constant, which will erase all the baryon asymmetry.

A rigorous computation of BNV rate (sphaleron rate) in the broken phase is crucial.

The tradition condition

BNV out of equilibrium criterion:

BNV rate (T) < Hubble constant (T)

Why we cannot trust the $\frac{v_c}{T_c} > 1$ condition?

It comes from the traditional sphaleron rate computations:

$$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c} \lesssim H, \quad \text{with } B \simeq 1.9$$

The tradition condition

BNV out of equilibrium criterion:

BNV rate (T) < Hubble constant (T)

Why we cannot trust the $\frac{v_c}{T_c} > 1$ condition?

It comes from the traditional sphaleron rate computations:

$$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c} \lesssim H, \quad \text{with } B \simeq 1.9$$

Drawbacks:

- v_c is the minimal of V_{eff}, which is gauge dependent under the general R_ξ gauge. Different gauges might lead into different lower bound.
- The B is chosen as the SM value; while BSM can modify this value, especially in 2HDM, Georgi-Machacek, etc.
- The effect of zero modes and positive modes (κ) are not been consistently considered for BSM.

Gauge invariant rigorous sphaleron rate

BNV out of equilibrium criterion: BNV rate (T) < Hubble constant (T)

Our approach: sphaleron rate under 3D EFT for SM EFT (BSM are heavy to be integrated out).

Gauge invariant rigorous sphaleron rate

BNV out of equilibrium criterion: BNV rate (T) < Hubble constant (T)

Our approach: sphaleron rate under 3D EFT for SM EFT (BSM are heavy to be integrated out).

Traditional case

$$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c}$$

$$\frac{v_c}{T_c} > 1$$

Our case

$$\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4 \, (\text{zero modes}(x,y)) \, e^{-f(x,y)}$$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Gauge invariant rigorous sphaleron rate

BNV out of equilibrium criterion: BNV rate (T) < Hubble constant (T)

Our approach: sphaleron rate under 3D EFT for SM EFT (BSM are heavy to be integrated out).

Traditional case

$$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c}$$

$$\frac{v_c}{T_c} > 1$$

- v_c gauge dependent and fixed B

Our case

$$\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4 \, (\text{zero modes}(x,y)) \, e^{-f(x,y)}$$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

- x, y are gauge invariant quantities under power countering (to g^4);

Gauge invariant rigorous sphaleron rate

BNV out of equilibrium criterion: BNV rate (T) < Hubble constant (T)

Our approach: sphaleron rate under 3D EFT for SM EFT (BSM are heavy to be integrated out).

Traditional case	Our case
$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c}$	$\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4 \, (\text{zero modes}(x,y)) \, e^{-f(x,y)}$
$\dfrac{v_c}{T_c} > 1$	$x = \dfrac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \dfrac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$
• v_c gauge dependent and fixed B	• x, y are gauge invariant quantities under power countering (to g^4);
• No consistent zero and positive modes	• Two-loop matching under 3D EFT Zero modes are consistently considered.

Gauge invariant rigorous sphaleron rate

BNV out of equilibrium criterion: BNV rate (T) < Hubble constant (T)

Our approach: sphaleron rate under 3D EFT for SM EFT (BSM are heavy to be integrated out).

Traditional case

$$\Gamma_{\mathrm{BNV,sph}} \sim T^4 \, \kappa \, e^{-B \, v_c/T_c}$$

$$\frac{v_c}{T_c} > 1$$

- v_c gauge dependent and fixed B
- No consistent zero and positive modes
- Condition immediately in the broken phase

Our case

$$\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4 \, (\text{zero modes}(x,y)) \, e^{-f(x,y)}$$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

- x, y are gauge invariant quantities under power countering (to g^4);
- Two-loop matching under 3D EFT Zero modes are consistently considered.
- Quantitively control of baryon washout in the broken phase.

New baryon number preservation condition

Our sphaleron rate:

$$\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4 \ (\text{zero modes}(x,y)) \ e^{-f(x,y)}$$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.

X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

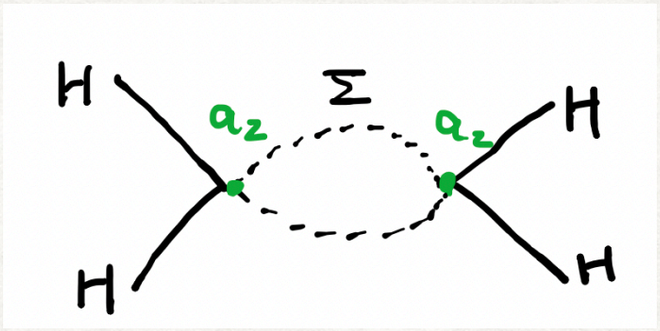
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ

X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

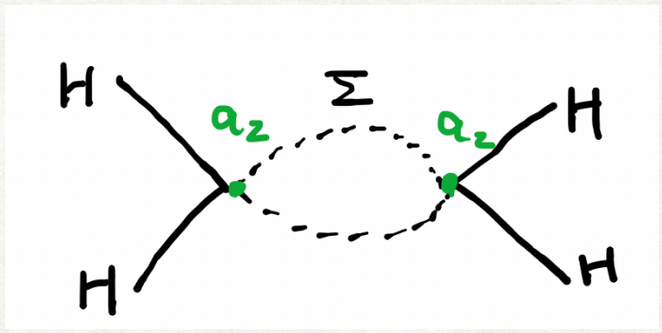
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

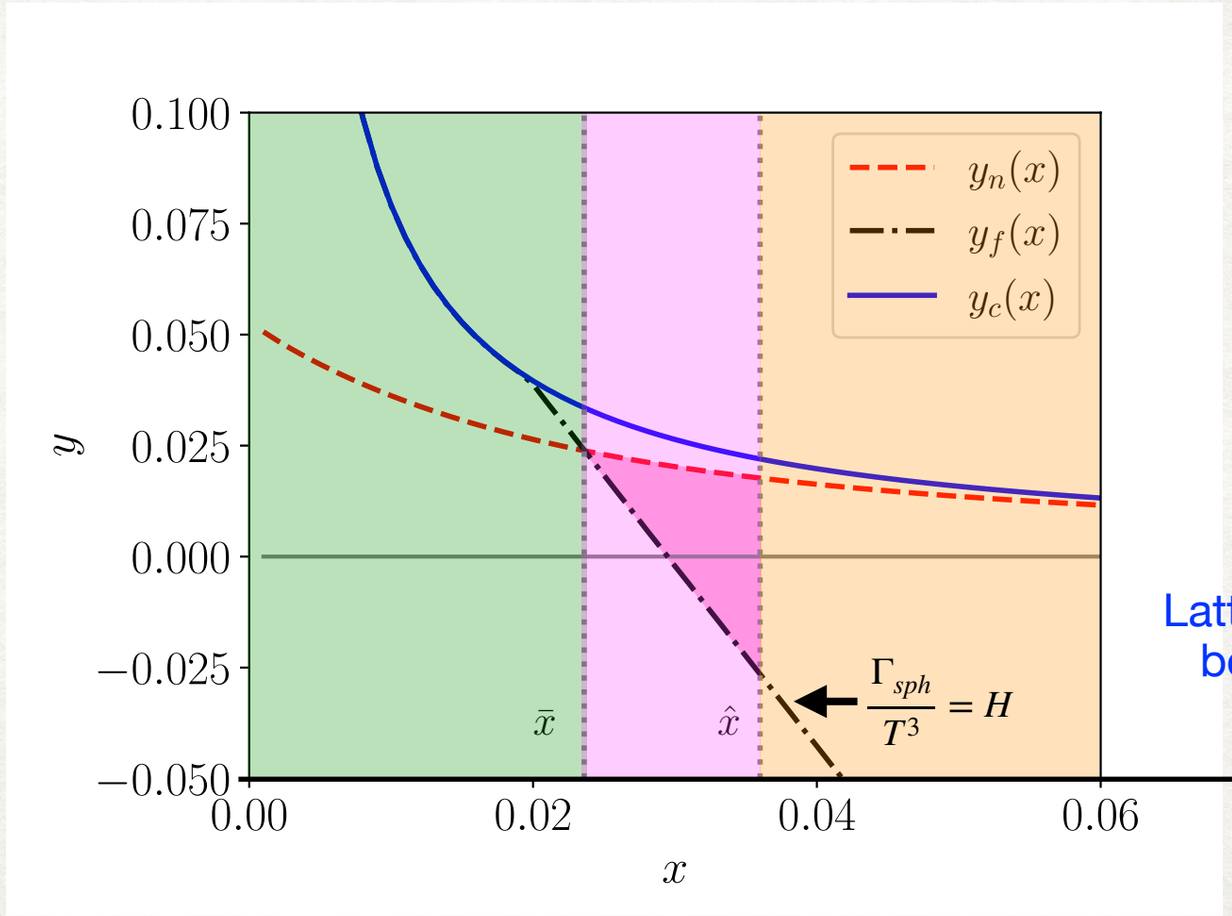
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

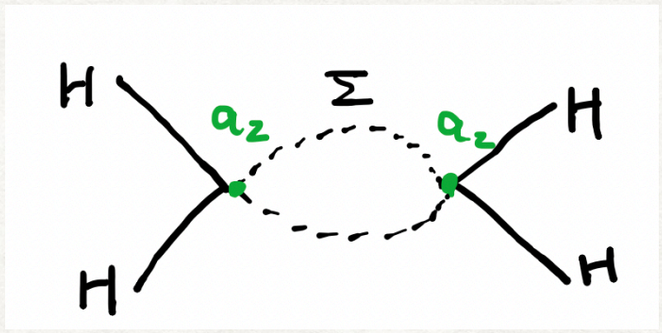
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

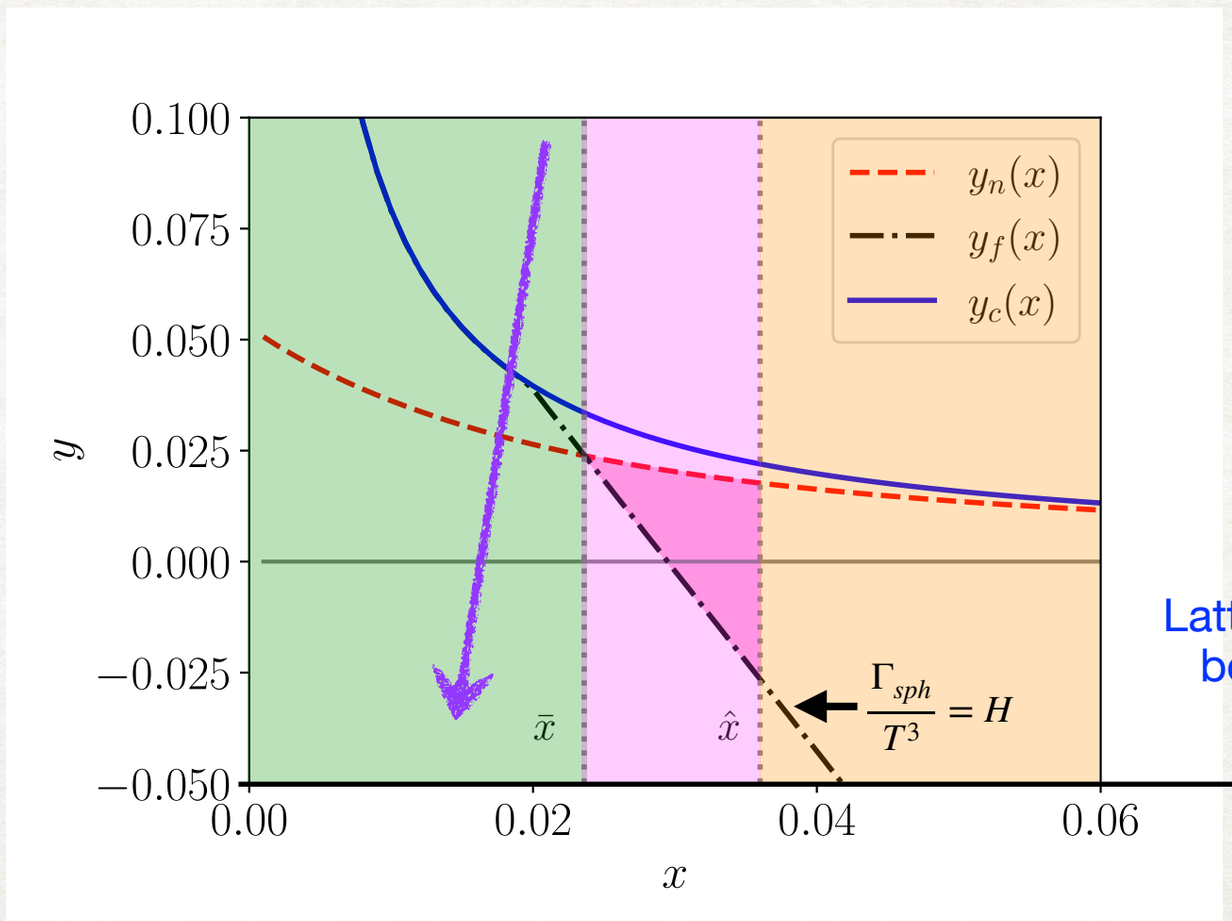
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

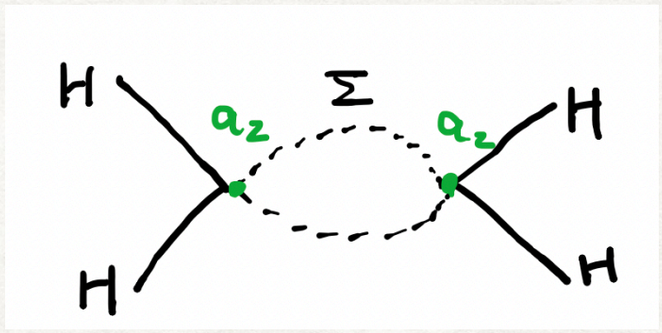
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

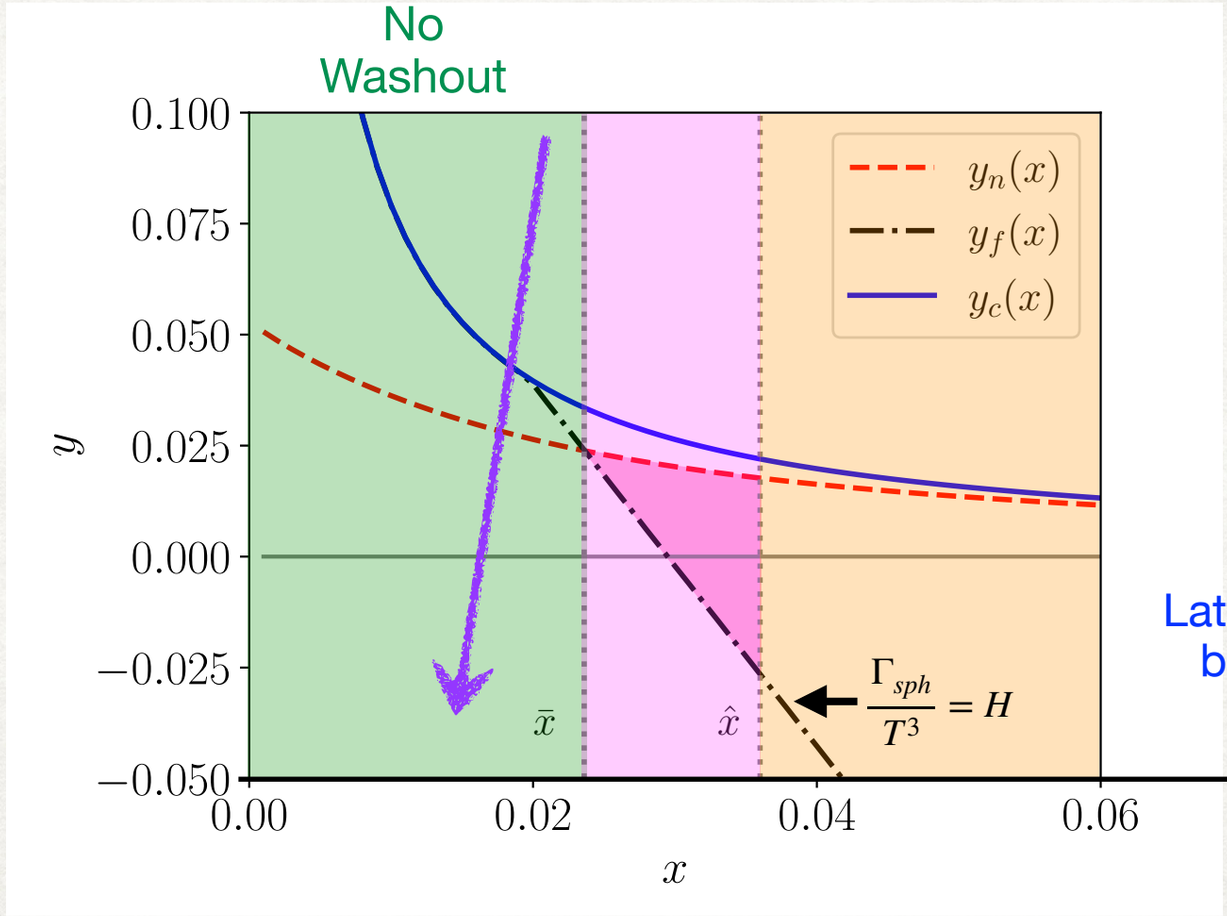
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

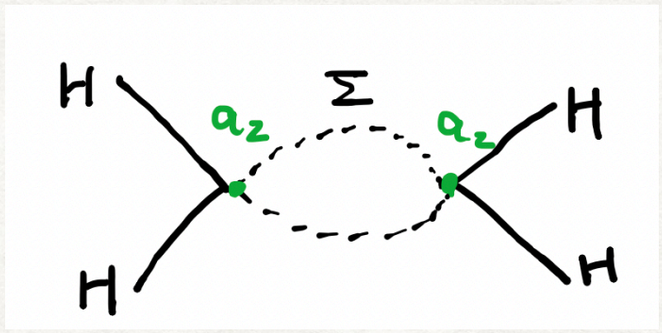
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

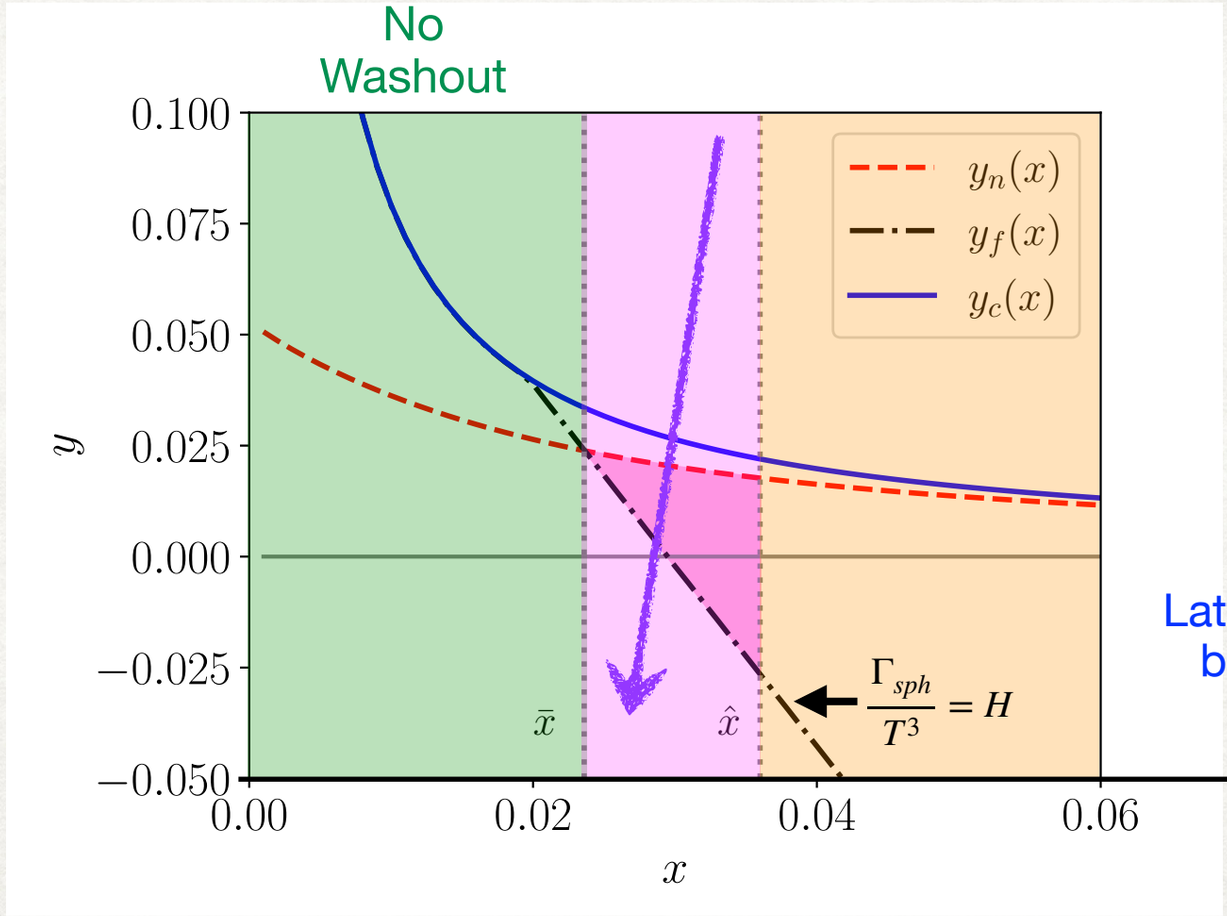
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

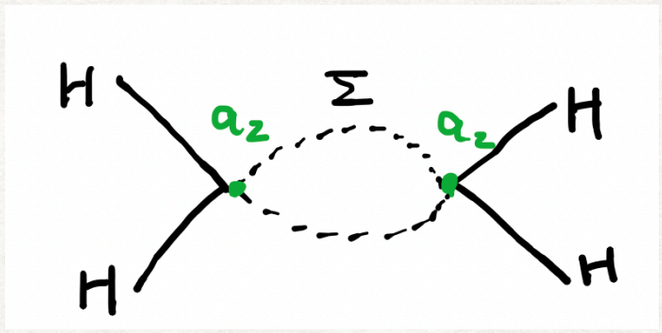
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

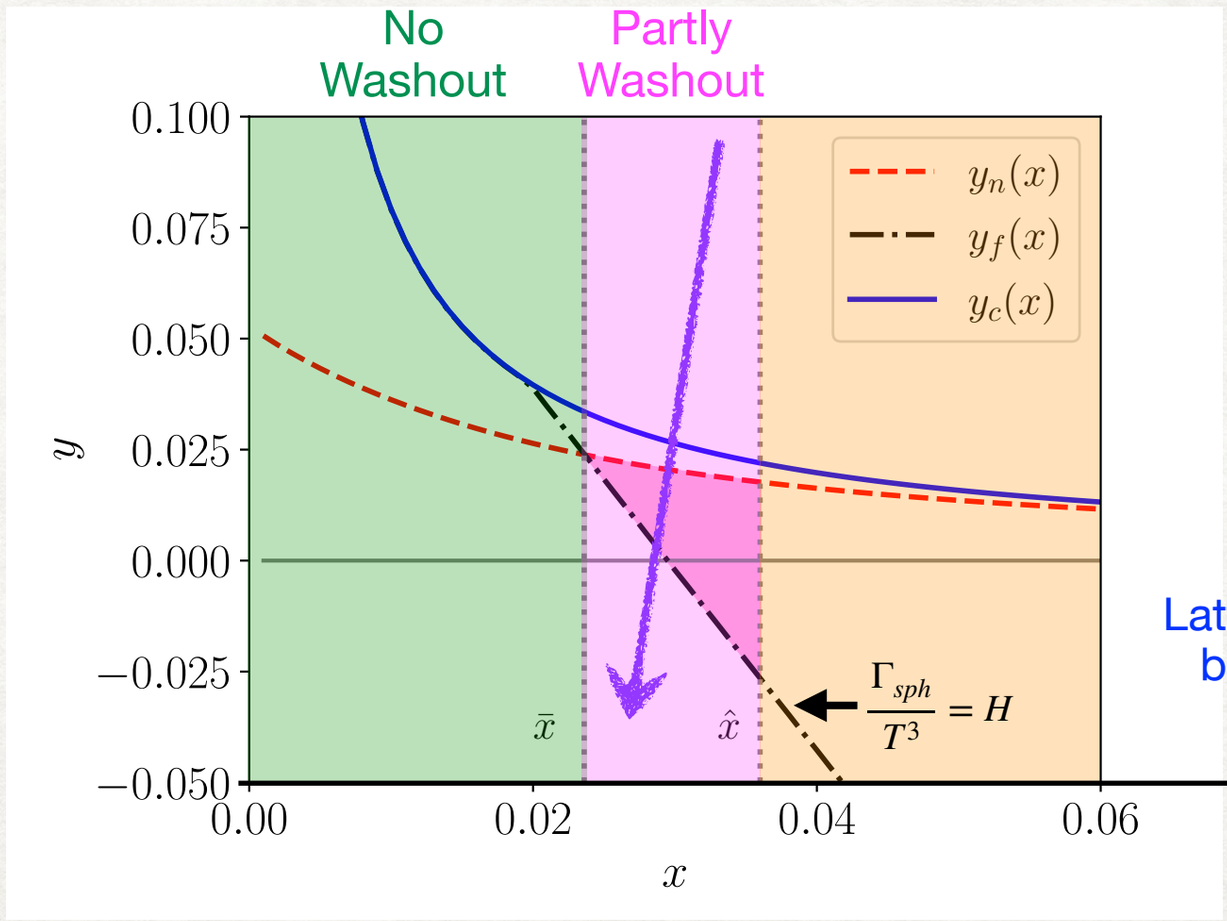
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

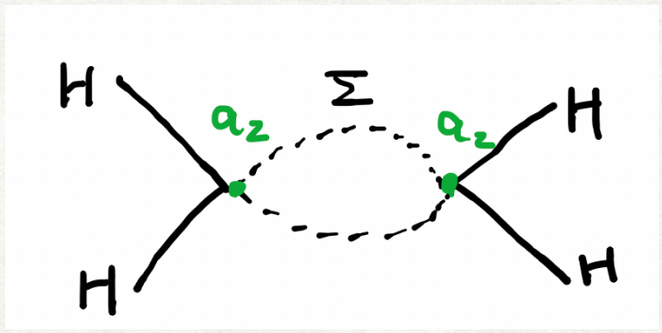
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

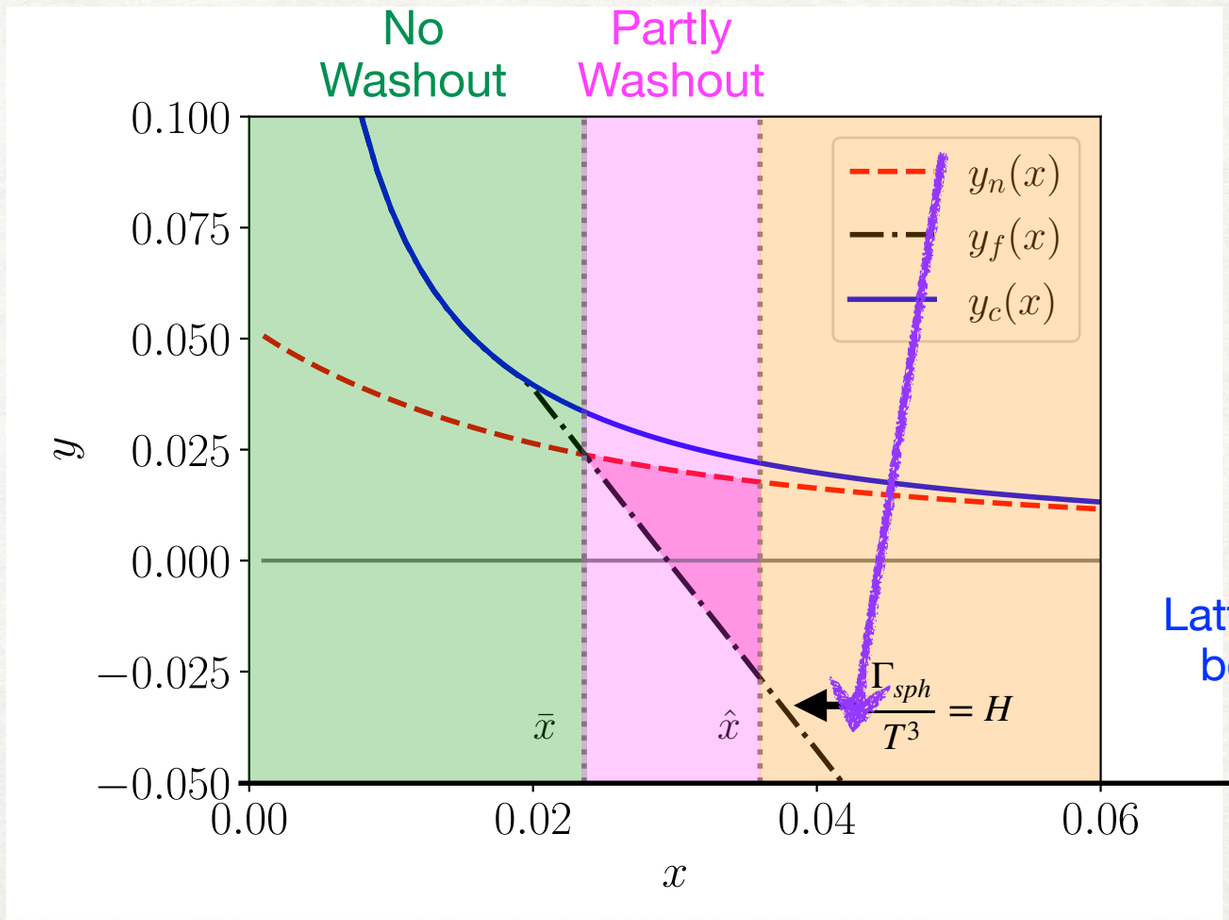
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

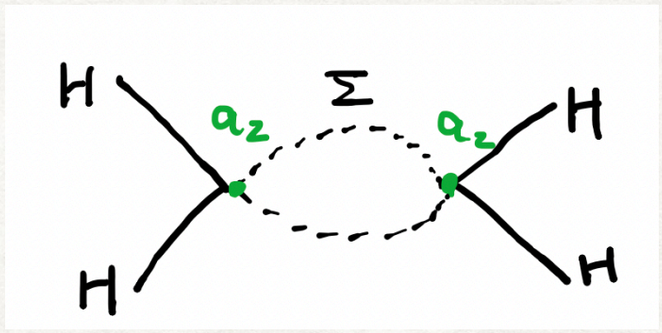
New baryon number preservation condition

Our sphaleron rate: $\Gamma_{\mathrm{BNV,sph}}(x,y) \sim T^4\ (\text{zero modes}(x,y))\ e^{-f(x,y)}$

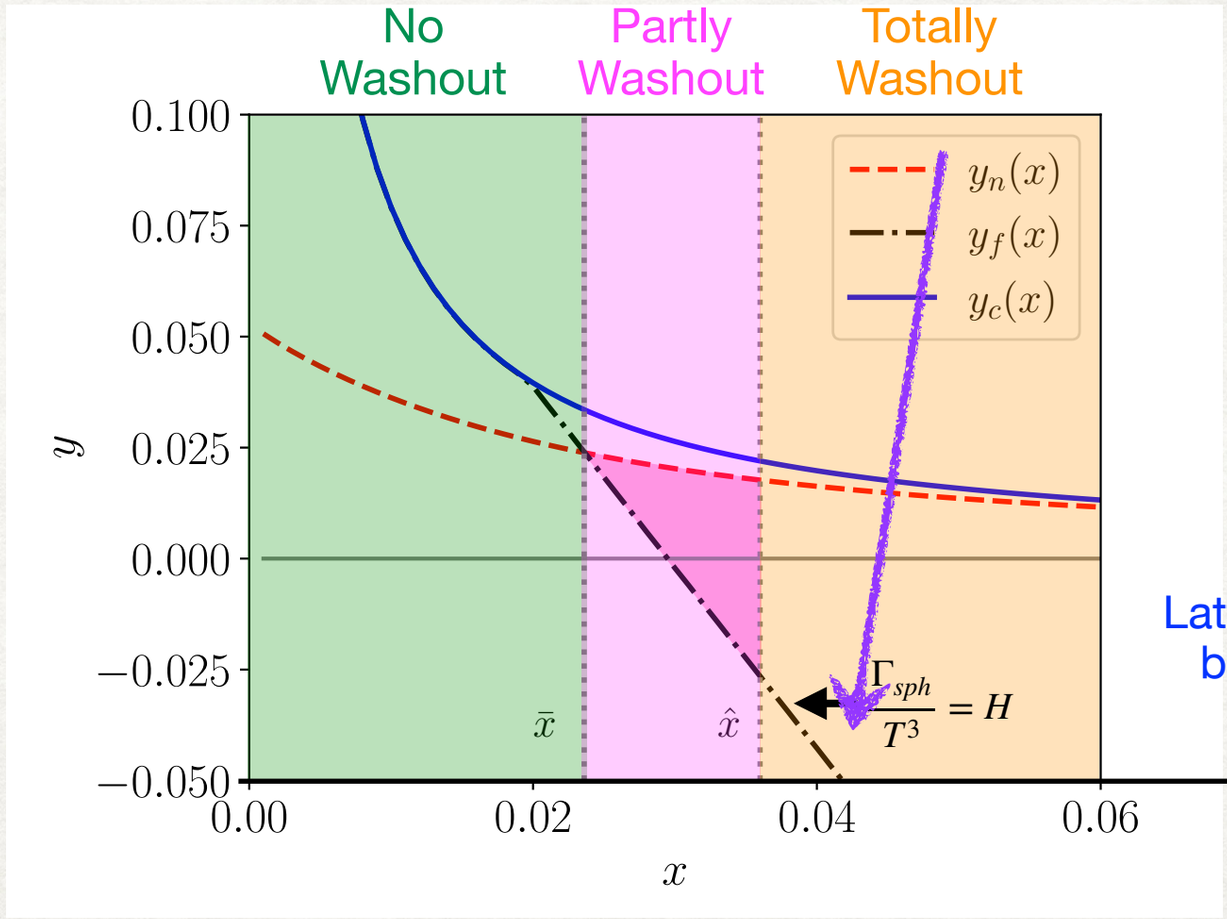
$$x = \frac{\text{Higgs selfcoupling}_3}{\text{gauge coupling}_3^2} \quad y = \frac{\text{Higgs mass}_3^2}{\text{gauge coupling}_3^4}$$

Assume BSM fields are heavy, which can be integrated out.

BSM fields (different BSM parameters) will modify the values of x, y.



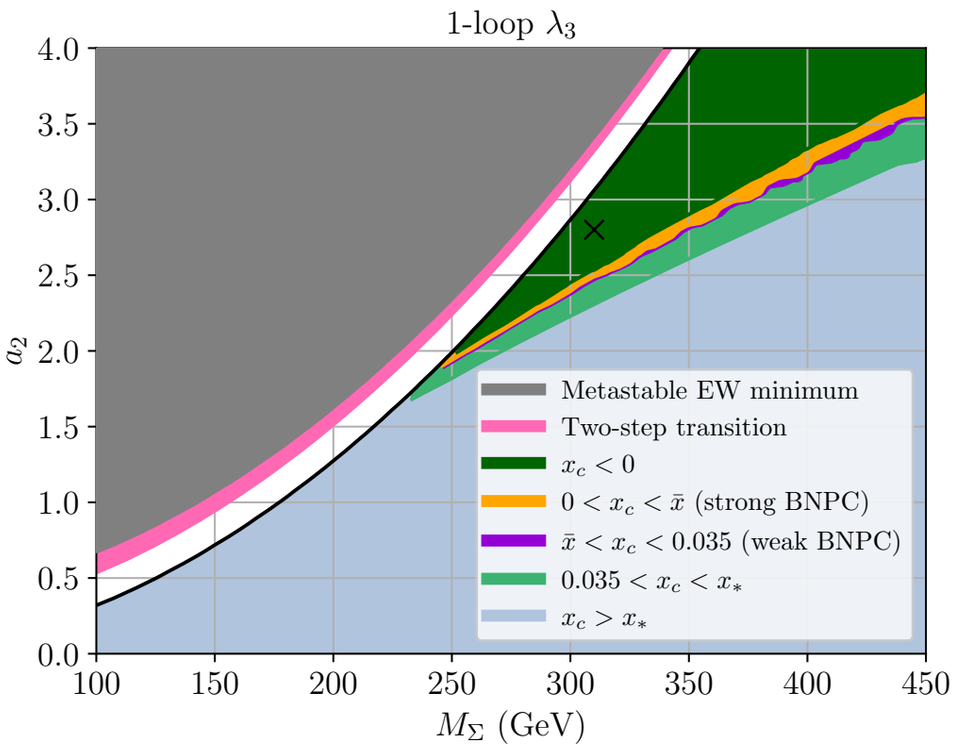
BSM field affects λ



X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

BSM applications: real triplet extension

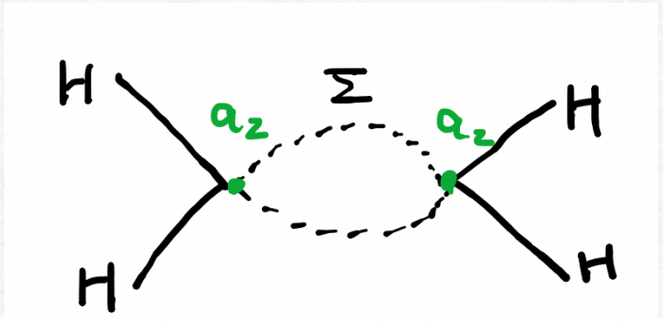
a_2: portal coupling between triplet (Σ) and Higgs (H)

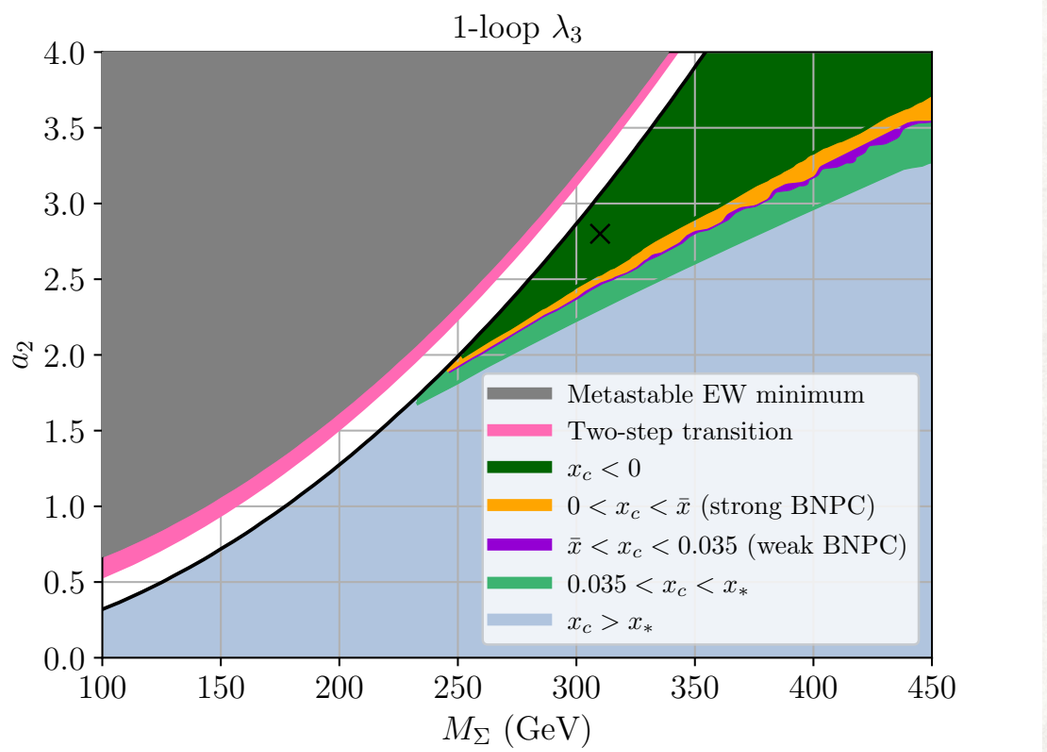


X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

BSM applications: real triplet extension

a_2: portal coupling between triplet (Σ) and Higgs (H)

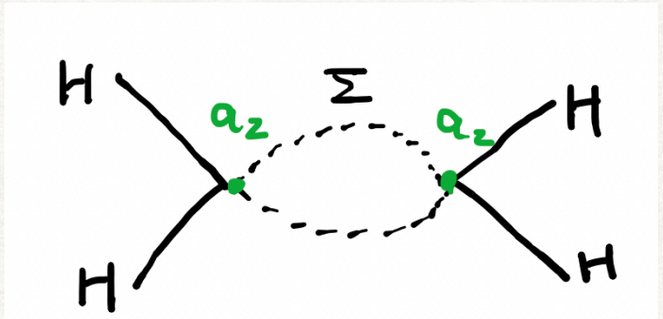


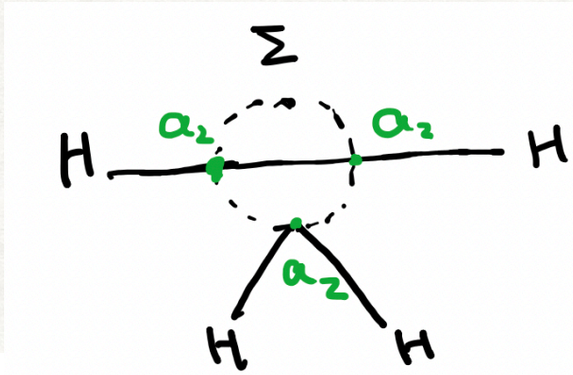


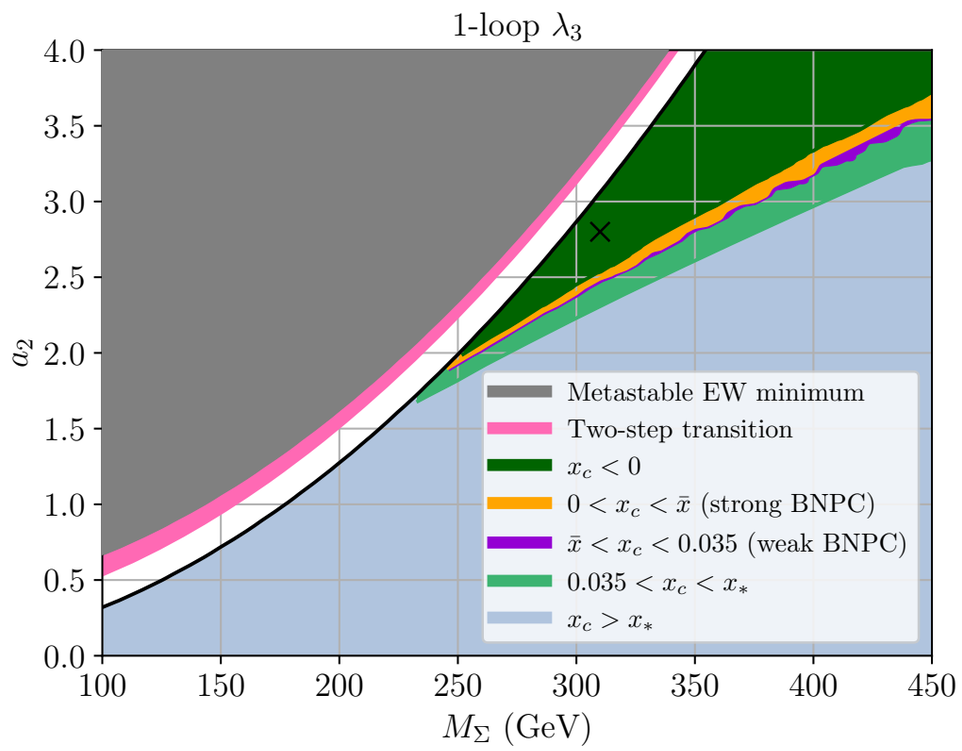
X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

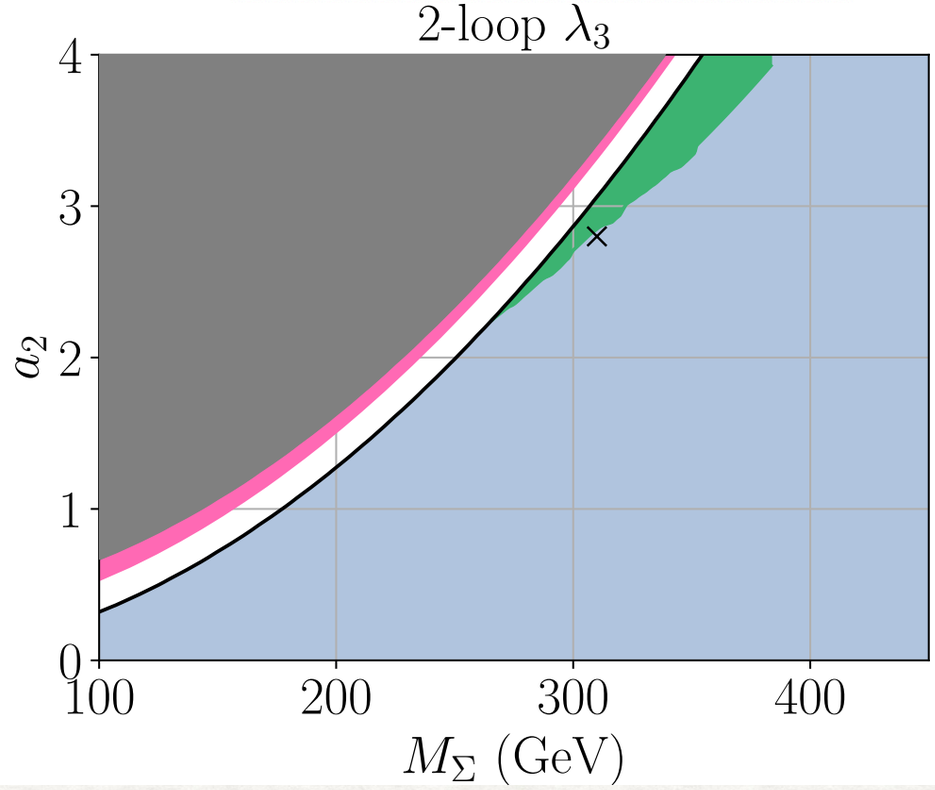
BSM applications: real triplet extension

a_2: portal coupling between triplet (Σ) and Higgs (H)





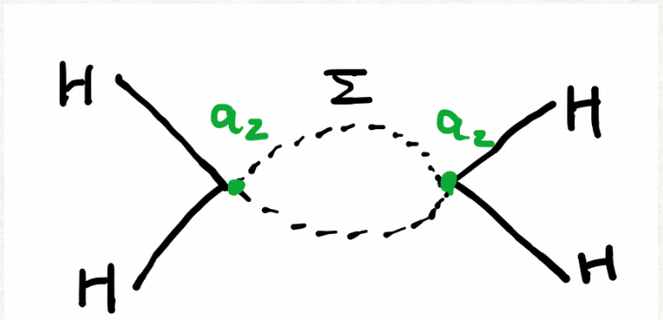


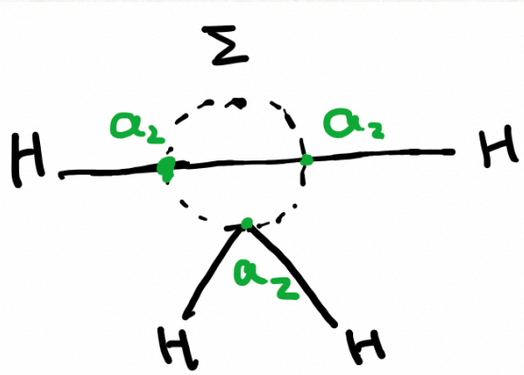


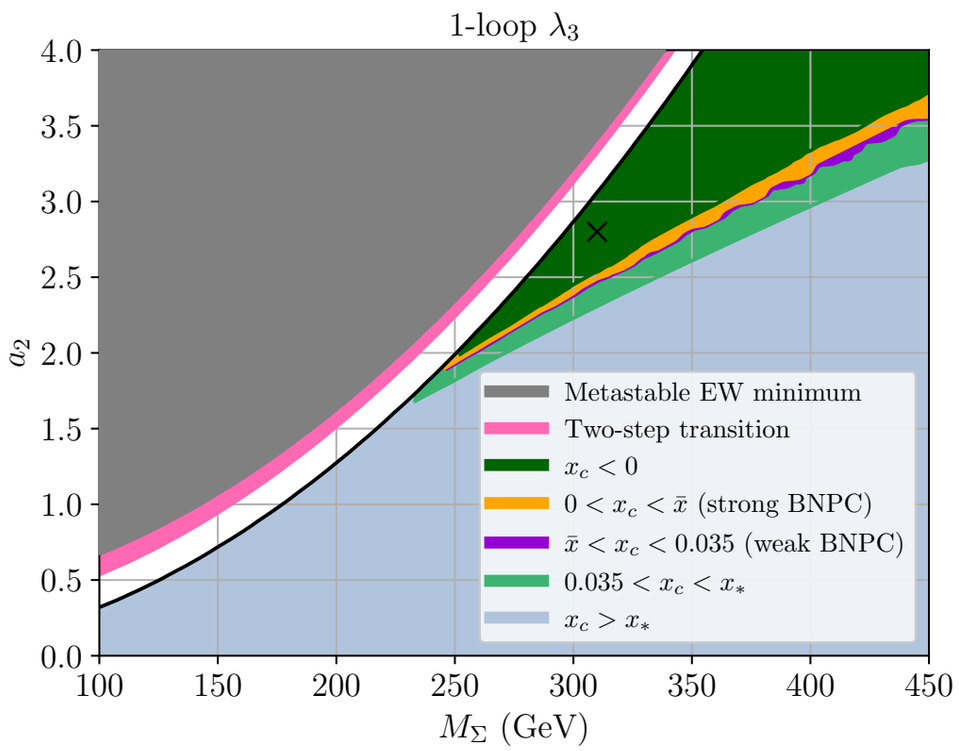
X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

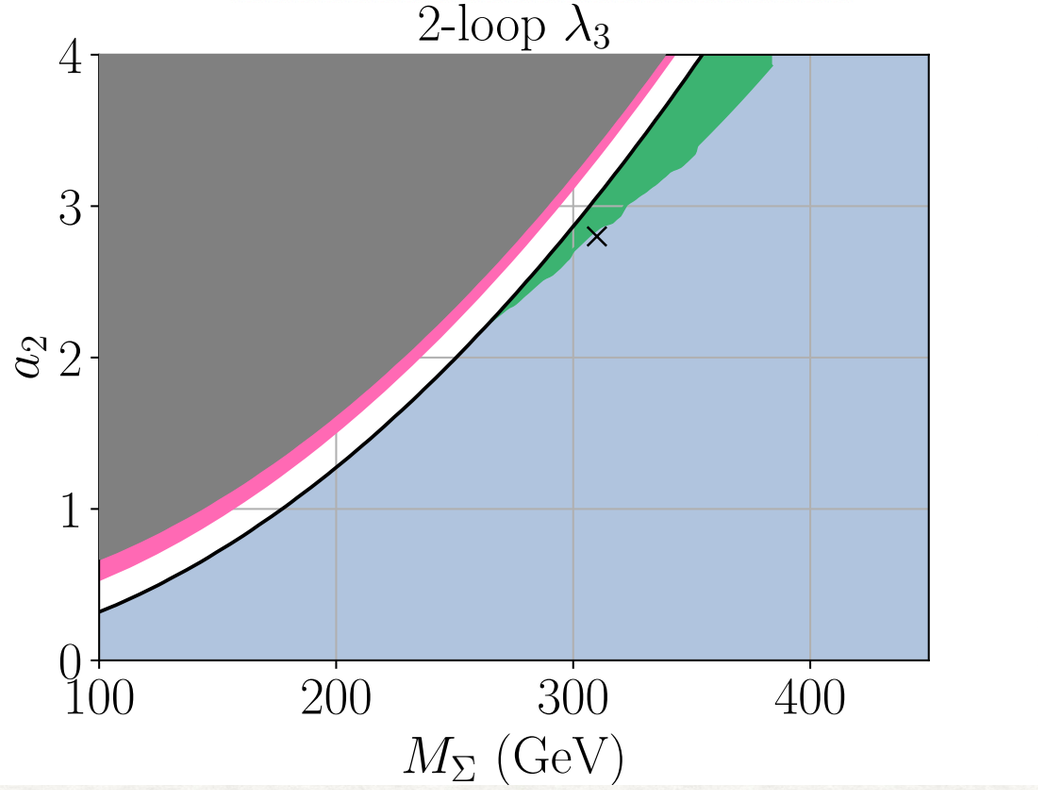
BSM applications: real triplet extension

a_2: portal coupling between triplet (Σ) and Higgs (H)









At 1-loop level, there are (No, Partly, Totally) Washout regions.

At 2-loop level, region only with Totally Washout! (All parameters fails for EWBG).

X.X. Li, M. J. Ramsey-Musolf, T. V. I. Tenkanen, YW, 2506.01585

Summary

- The topological field configurations play an important role to understand the baryon asymmetry and dark matter of our universe.
- A rigorous computation of sphaleron rate in the EW vacuum is crucial for electroweak baryogengesis.
- The traditional baryon number preservation (out of equilibrium) condition $v_c/T_c > 1$ is inaccurate and gauge-dependent. We propose new condition in the 3D $x-y$ panel, which is accurate and gauge independent.
- Two loop thermal corrections from the BSM fields are important to determine the properties of baryon washout and phase transition.