Institute for Cosmic Ray Research
University of Tokyo

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False vacuum decay in gauge theory

~ the decay rate in the standard model and its gauge invariance ~

Yutaro Shoji
(ICRR)

work in progress; S. Chigusa, T. Moroi, YS
Phys. Rev. Lett. 119 (2017) no.21; S. Chigusa, T. Moroi, YS
JHEP 1711 (2017) 074; M. Endo, T. Moroi, M. M. Nojiri, YS
Phys. Lett. B771 (2017) 281; M. Endo, T. Moroi, M. M. Nojiri, YS

Vacuum decay in the Standard Model

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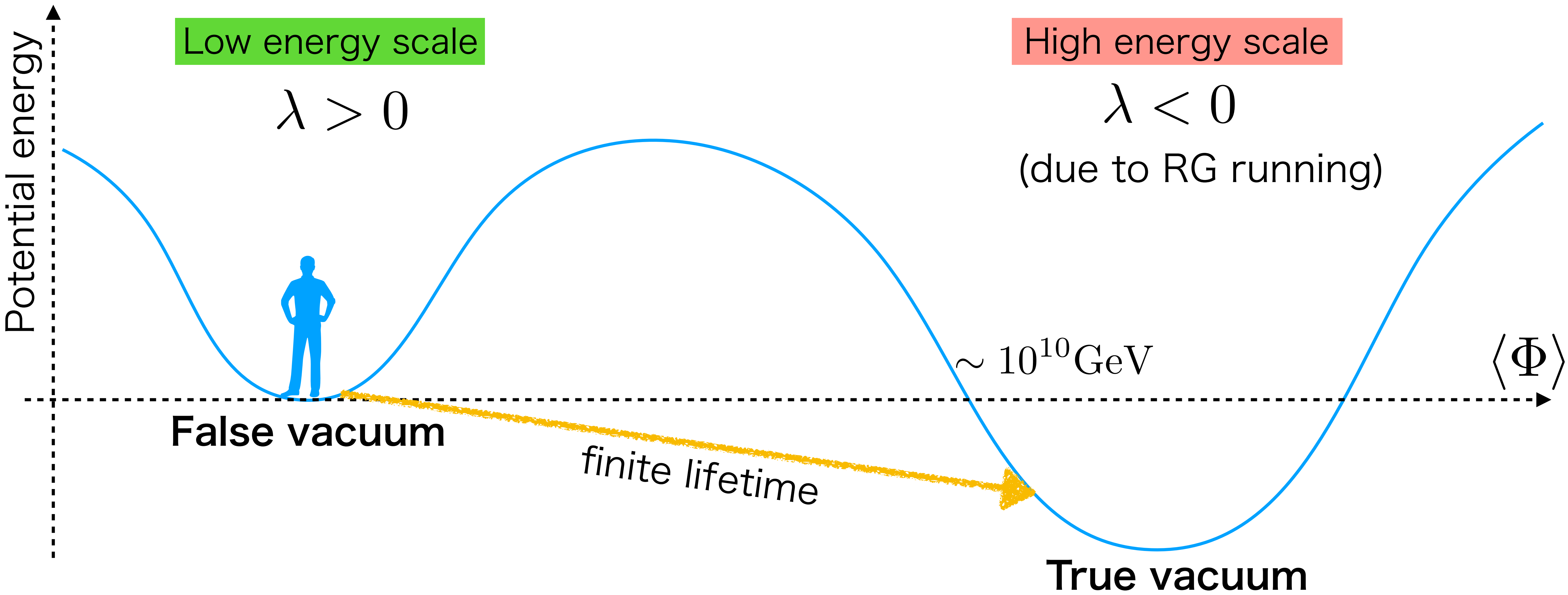

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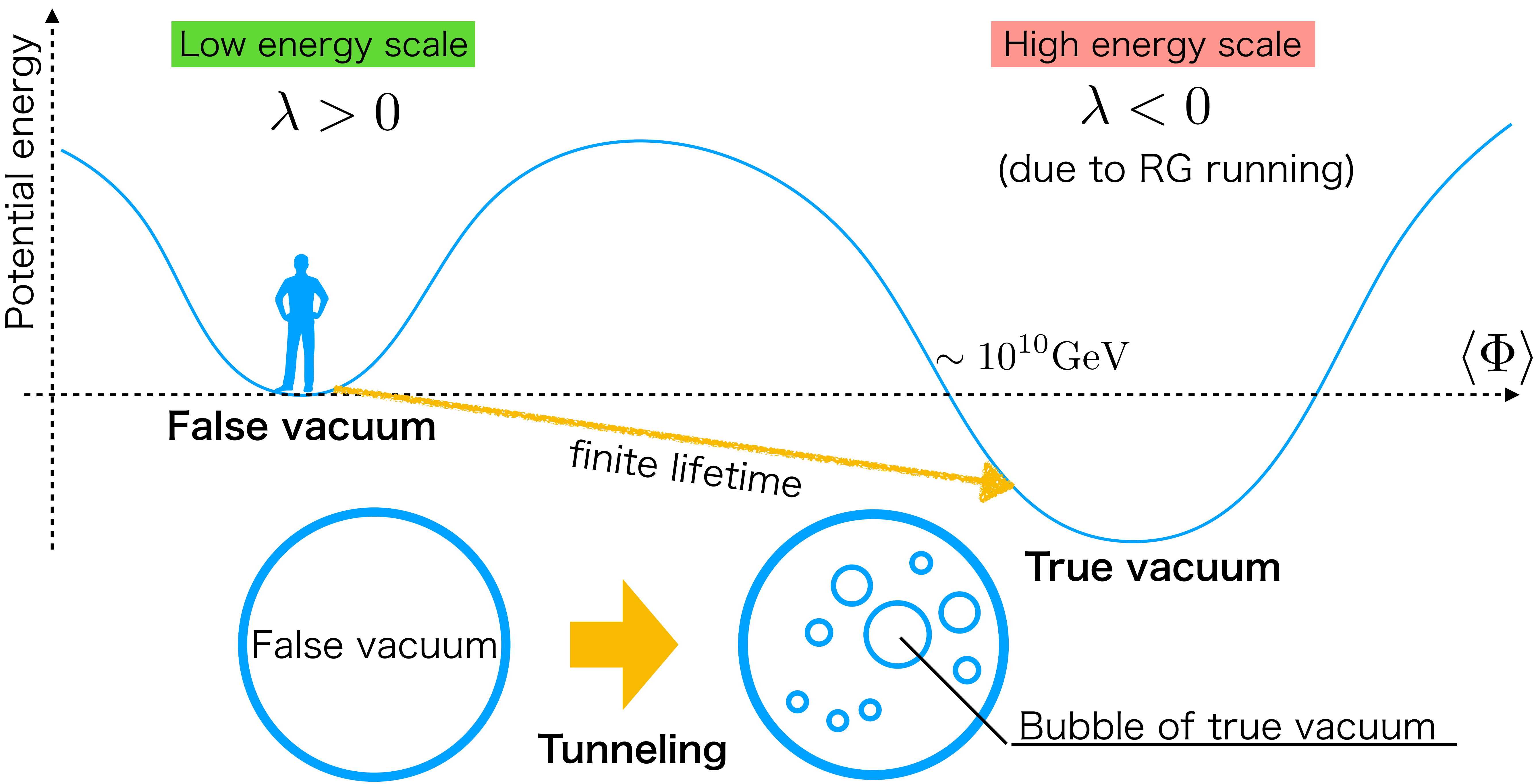


Bubble nucleation rate (zero temperature)

[C. G. Callan, S. R. Coleman, '77]

$$\gamma = Ae^{-B}$$

$B = S_E(\bar{\phi})$ ← **Bounce solution**

O(4) symmetric solution to Euclidean EoM

In the Standard Model

$$V(\Phi) = \lambda(\Phi^\dagger\Phi)^2, \; \lambda < 0$$

Fubini-Lipatov instanton

$$\bar{\phi}(r) = \frac{\bar{\phi}_C}{1 + \frac{|\lambda|}{8}\bar{\phi}_C^2 r^2}.$$

⇒

$$B = \frac{8\pi^2}{3|\lambda|}$$

independently of $\bar{\phi}_C$

Bubble nucleation rate (zero temperature)

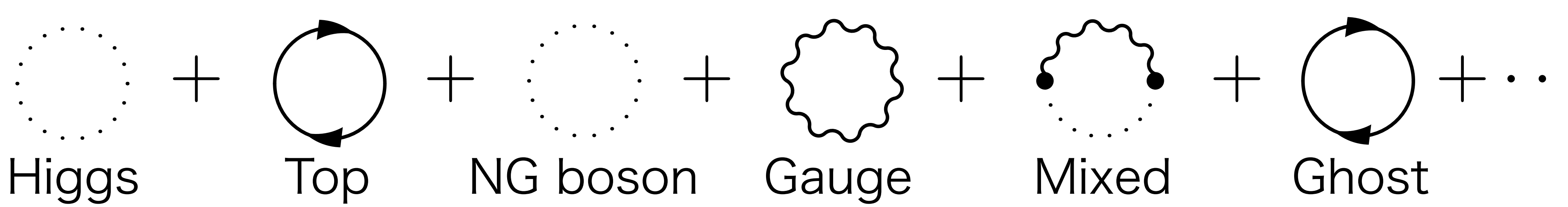
[C. G. Callan, S. R. Coleman, '77]

$$\gamma = A e^{-B}$$

Subtraction of zero modes

$$A = \frac{B^2}{4\pi^2} \left(\frac{\det' S''|_{\bar{\phi}}}{\det S''|_v} \right)^{-1/2}$$

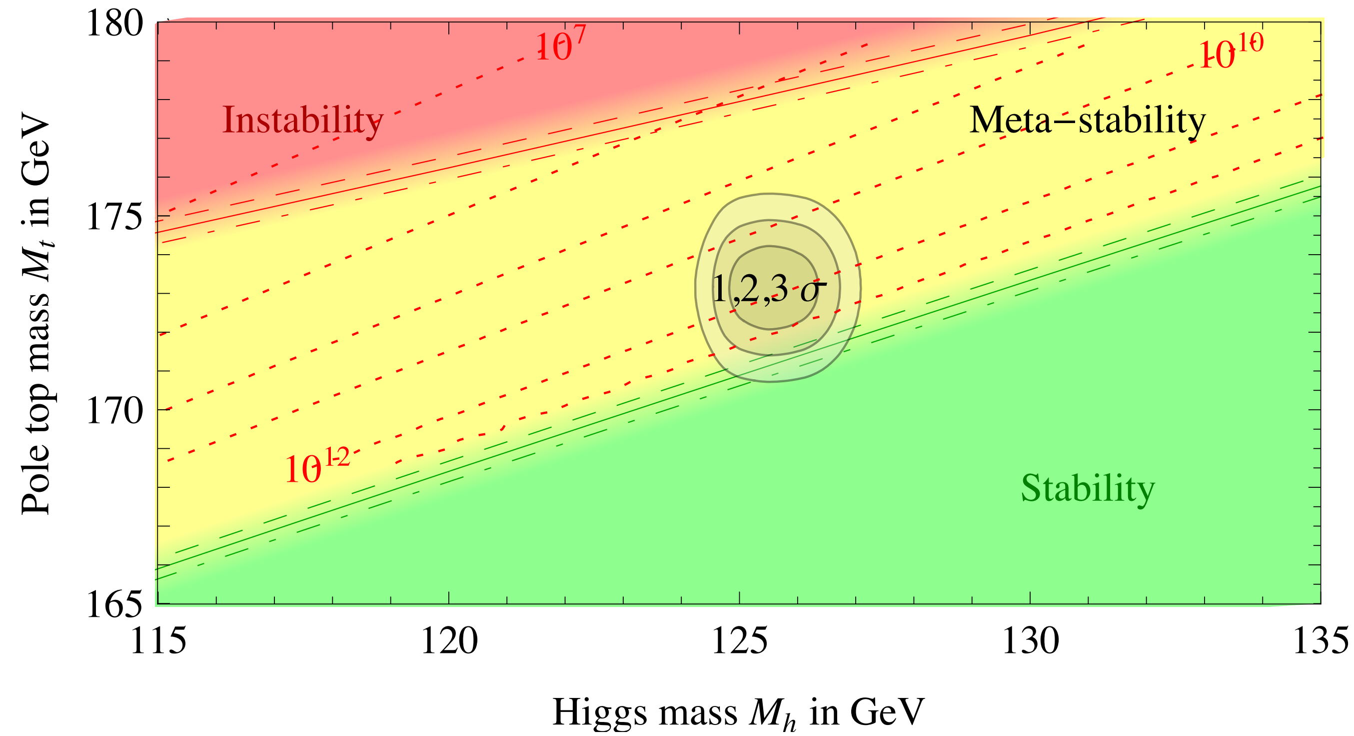
one loop correction to B



some of them are comparable with exp(-B)

Standard Model @one-loop

G. Ishidori, G. Ridolfi, A. Strumia; '01



Gauge fixing

$$\mathcal{L}_{\rm GF} = \frac{1}{\xi}(\partial_\mu A_\mu - \xi g \bar{\phi} \varphi)^2$$

φ : NG boson

with $\xi = 1$

$A = Z, W^+, W^-$

No prescription for gauge zero mode

gauge dependent mode function, ⋯

Gauge invariance is not clear

zero mode, regulators,⋯

Zero mode

Gauge fixing

$$\mathcal{L}_{\mathrm{GF}} = \frac{1}{\xi}(\partial_\mu A_\mu - \xi g \bar{\phi} \varphi)^2$$

Zero mode

$$\delta A_\mu = \partial_\mu f(r)$$
$$\delta \varphi = g\bar{\phi} f(r)$$

$\Rightarrow$ $\delta S = 0$

with $\left(-\frac{1}{r^3}\partial_r r^3 \partial_r + \xi g^2 \bar{\phi}^2\right) f = 0$

Gauge dependent zero mode

Global symmetry

?

Fluctuation matrix changes after a finite rotation

Zero mode

Gauge fixing

$$\mathcal{L}_{\mathrm{GF}} = \frac{1}{\xi}(\partial_\mu A_\mu - \xi g \bar{\phi} \varphi)^2$$

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Gauge dependent zero mode

$$\delta \varphi = \bar{\phi} \quad \Rightarrow \quad \delta S = 0$$

Global symmetry

?

Fluctuation matrix changes after a finite rotation

$$(\bar{\phi} + h + i\varphi) \to e^{i\theta}(\bar{\phi} + h + i\varphi)$$

For each θ, we have the same fluctuation matrix

Gauge boson loops

Gauge contribution

with $\mathcal{L}_{\mathrm{GF}} = \frac{1}{\xi}(\partial_\mu A_\mu)^2$

$$\ln A^{(\mathrm{Gauge})} = -\frac{1}{2} \ln \frac{\det \mathcal{M}}{\det \widehat{\mathcal{M}}}$$

$$\mathcal{M} = \begin{pmatrix} -\partial^2 \delta_{\mu\nu} + \left(1 - \frac{1}{\xi}\right) \partial_\mu \partial_\nu + g^2 \bar{\phi}^2 & g(\partial_\nu \bar{\phi}) - g\bar{\phi}\partial_\nu \\ 2g(\partial_\mu \bar{\phi}) + \bar{\phi}\partial_\mu & -\partial^2 + \frac{\partial^2 \bar{\phi}}{\bar{\phi}} \end{pmatrix}$$

$$\widehat{\mathcal{M}} = \begin{pmatrix} -\partial^2 \delta_{\mu\nu} + \left(1 - \frac{1}{\xi}\right) \partial_\mu \partial_\nu & 0 \\ 0 & -\partial^2 \end{pmatrix}$$

It is difficult to calculate it numerically, but we succeeded in calculating it semi-analytically.

Gauge contribution

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$$\ln A^{(\mathrm{Gauge})} = -\frac{1}{2}\ln\frac{\det\mathcal{M}}{\det\widehat{\mathcal{M}}}$$

After the zero mode subtraction

$$\to -\frac{1}{2}\left[\ln\frac{|\lambda|}{16\pi} + \sum_{J\geq 1/2}(2J+1)^2 \lim_{r\to\infty}\ln\frac{|\lambda| J\bar{\phi}_C^2 f_J^{(\eta)}(r)\left[f_J^{(T)}(r)\right]^2}{8(J+1)r^{6J-2}}\right]$$

$$\left(-\frac{1}{r^3}\partial_r r^3\partial_r + 4\frac{J(J+1)}{r^2} + g^2\bar{\phi}^2 + 2\frac{\bar{\phi}'}{\bar{\phi}}\frac{1}{r^2}\partial_r r^2\right) f_J^{(\eta)} = 0$$

$$\left(-\frac{1}{r^3}\partial_r r^3\partial_r + 4\frac{J(J+1)}{r^2} + g^2\bar{\phi}^2\right) f_J^{(T)} = 0$$

$$\lim_{r\to 0}\frac{f_J^{(T)}}{r^{2J}} = \lim_{r\to 0}\frac{f_J^{(\eta)}}{r^{2J}} = 1$$

No gauge dependence!

A little more detail of SM calculation

Dilatational invariance in the Standard model

Tree level action is invariant under a change of $\bar{\phi}_C$

$$\bar{\phi}(r) = \frac{\bar{\phi}_C}{1 + \frac{|\lambda|}{8}\bar{\phi}_C^2 r^2}.$$

Thus, we need to integrate over $\bar{\phi}_C$

$$\gamma = \int d(\ln \bar{\phi}_C) \frac{d\gamma}{d \ln \bar{\phi}_C}$$

However, the integrand suffers from large logarithmic corrections

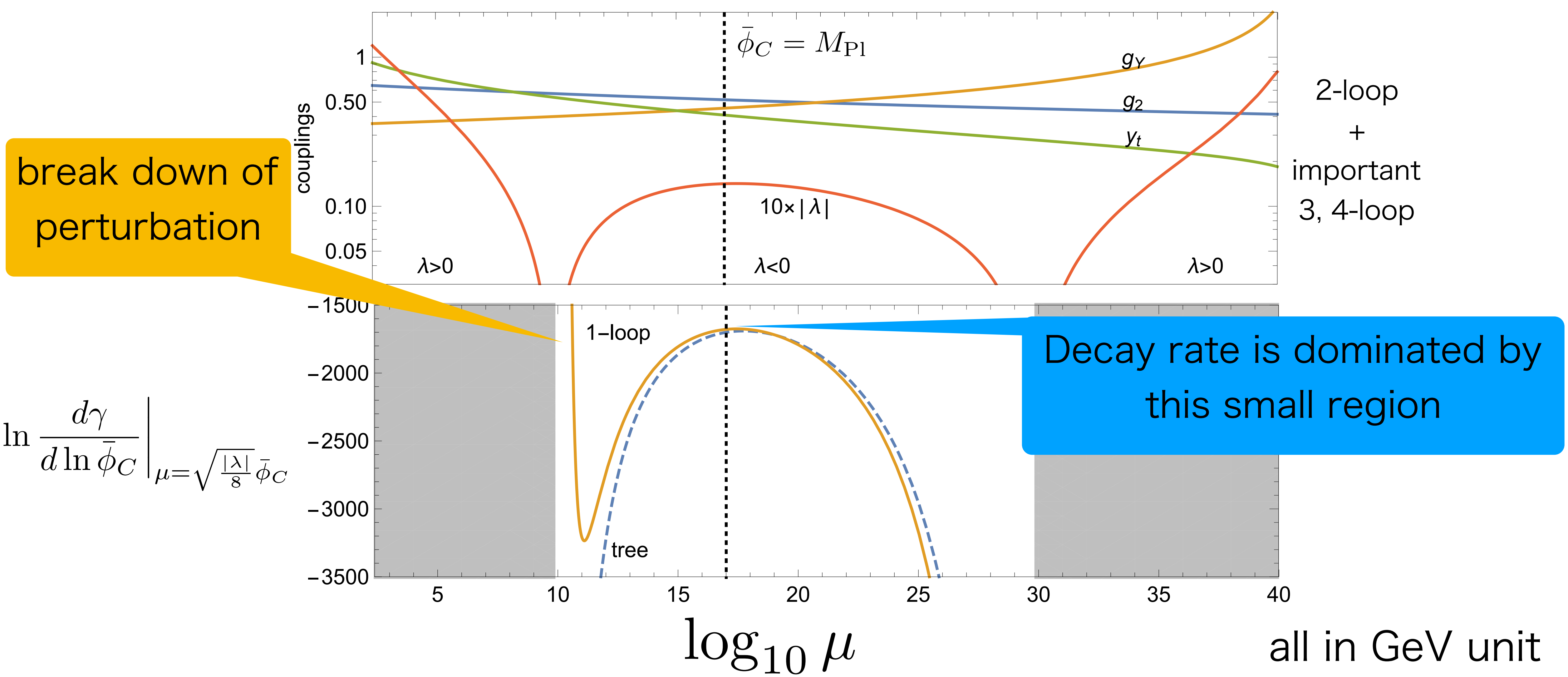
$$\ln \sqrt{\frac{|\lambda|}{8}} \frac{\bar{\phi}_C}{\mu}$$

μ : renormalization scale

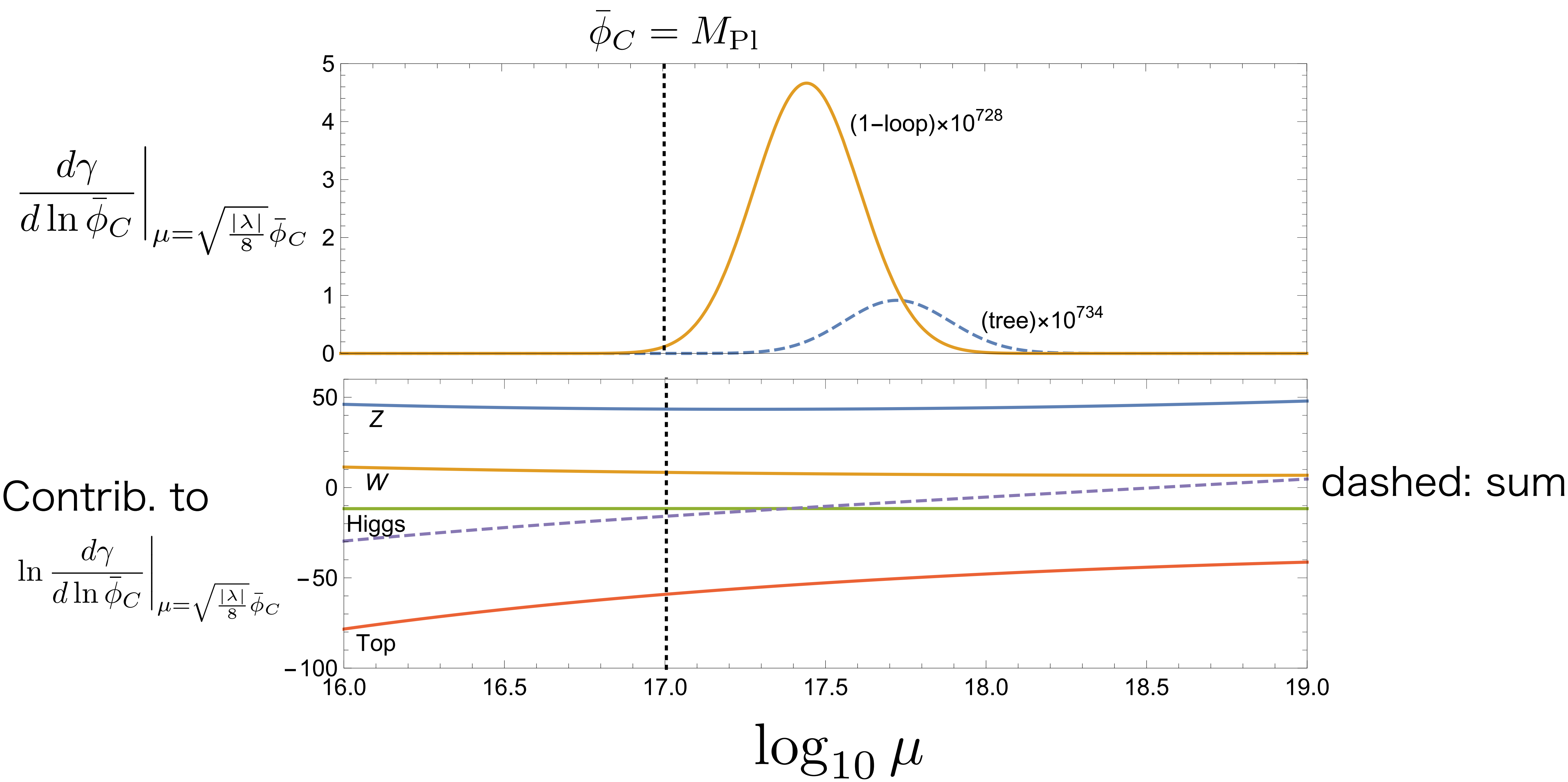
One-loop
+ log re-summation

To avoid large logs in higher order corrections, we improve our result by RG

$$\gamma = \int d(\ln \bar{\phi}_C) \frac{d\gamma}{d\ln \bar{\phi}_C}\bigg|_{\mu=\sqrt{\frac{|\lambda|}{8}}\bar{\phi}_C}$$



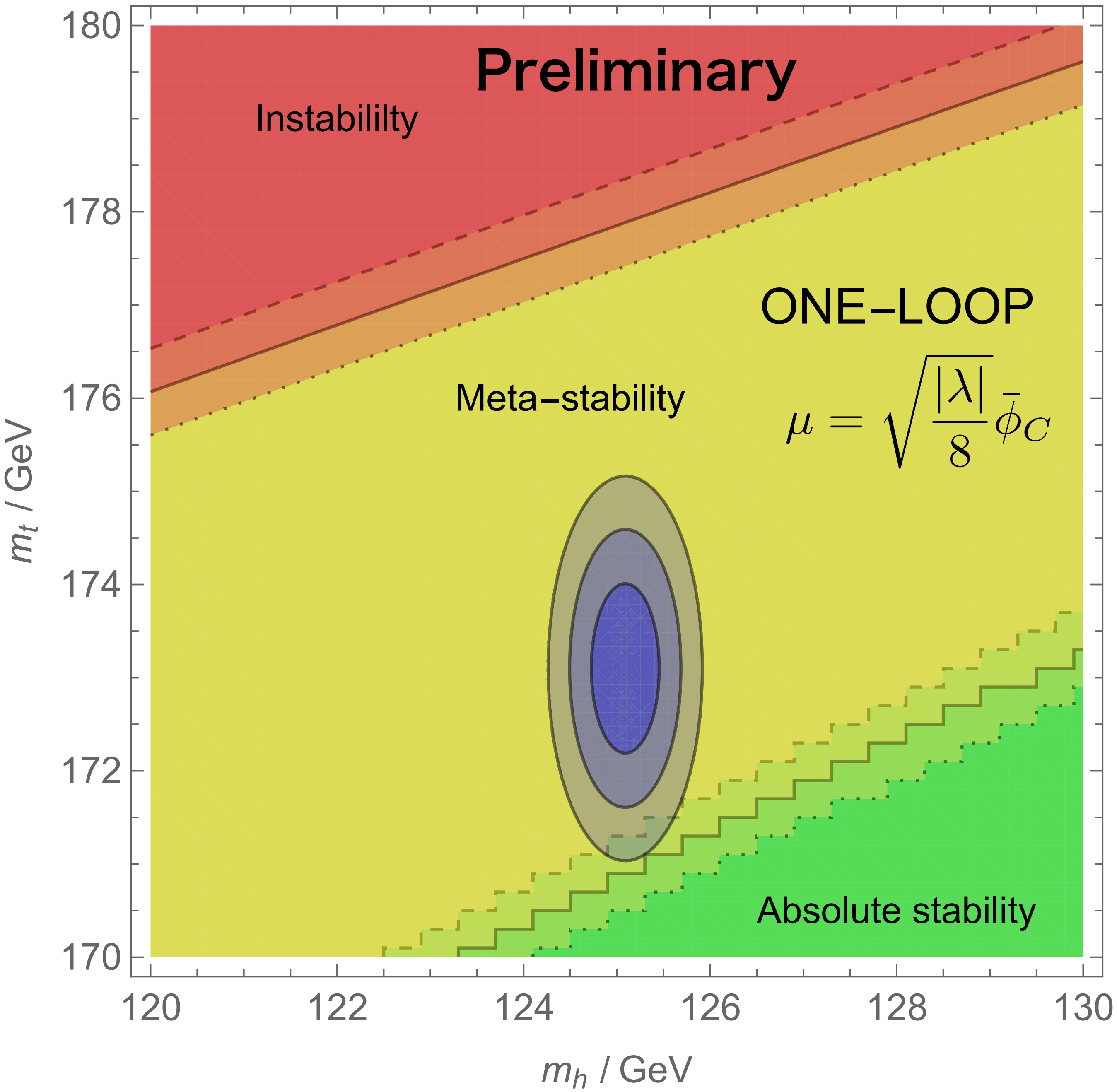
The size of each contribution



all in GeV unit

Standard Model @one-loop

$\mu = \bar{\phi}_C$ is used → A. Andreassen, W. Frost, M. D. Schwartz; '17
S. Chigusa, T. Moroi, YS; '17
+ we are preparing a follow-up paper



$$m_h = 125.09 \pm 0.24,$$
$$m_t^{(\text{pole})} = 173.1 \pm 0.6,$$
$$\alpha_s(m_Z) = 0.1181 \pm 0.0011.$$

cut-off@Mpl

$$\log_{10}\left[\gamma_{\text{pl}} \times \text{Gyr Gpc}^3\right] = -564^{+38}_{-43}{}^{+177}_{-312}{}^{+139}_{-208}{}^{+2}_{-2},$$
$$\log_{10}\left[\gamma_{\infty} \times \text{Gyr Gpc}^3\right] = -563^{+38}_{-43}{}^{+177}_{-313}{}^{+139}_{-209}{}^{+1}_{-3},$$

(hig.) (top) (str.) (ren.)

cf.) $\log_{10}\left[H_0^4 \times \text{Gyr Gpc}^3\right] \simeq -3$

Gauge contributions ~Beyond the SM~

Radiatively generated true vacuum

Standard Model + extra fields

work in progress; S. Chigusa, T. Moroi, YS

Tree level true vacuum (ONE bounce field)

Gauge symmetry is BROKEN in the false vacuum

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Gauge symmetry is UNBROKEN in the false vacuum

JHEP 1711 (2017) 074; M. Endo, T. Moroi, M. M. Nojiri, YS

Tree level true vacuum (MORE THAN ONE bounce fields)

CCB in the MSSM

work in progress; M. Endo, T. Moroi, M. M. Nojiri, YS

Summary

- The gauge invariance of a vacuum decay rate had been unclear and there had been no prescription for gauge zero modes.

- We subtracted the gauge zero modes analytically, and get a gauge independent result, showing that the gauge invariance of the decay rate at one-loop level.

- We calculated the decay rate of the EW vacuum at the one-loop level in the standard model, and confirmed that the decay rate is much longer than the age of the universe.