

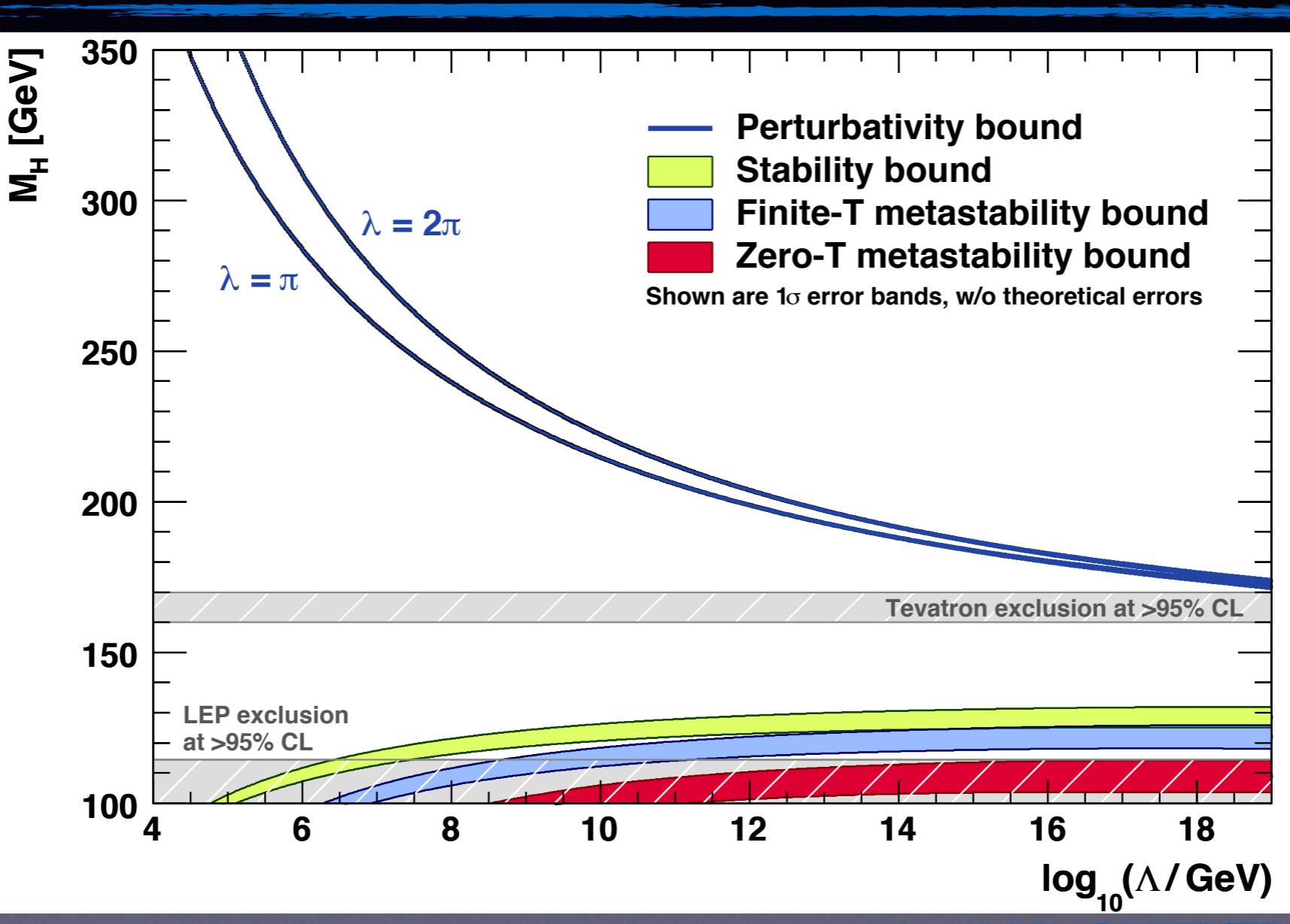
From the eV to the Planck scale: living on the edge of a precipice

Alfredo Urbano
CERN, Theory division

Based on:

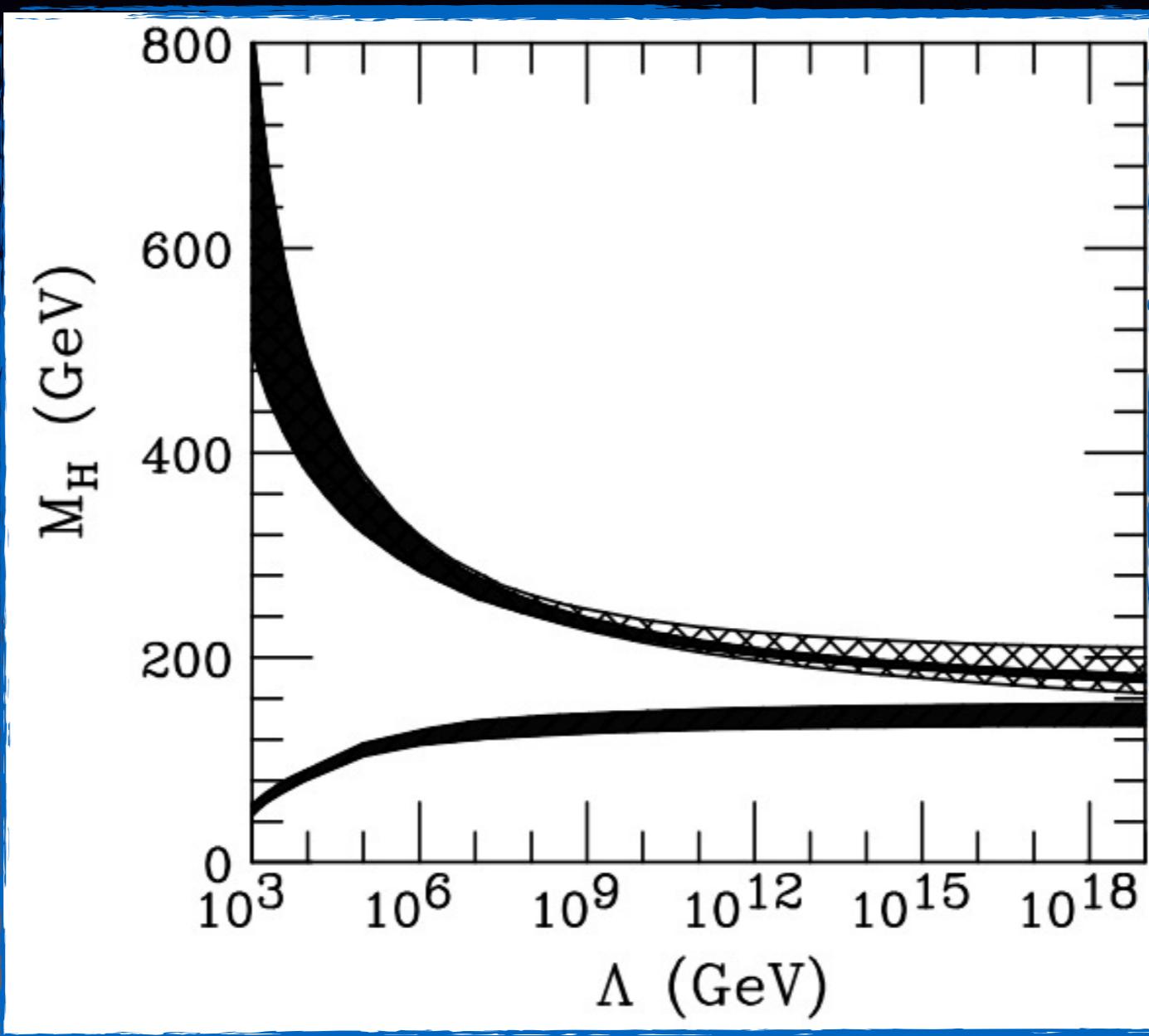
L. Delle Rose, C. Marzo, AU, arXiv:1506.03360
L. Delle Rose, C. Marzo, AU, arXiv:1507.06912

Motivation



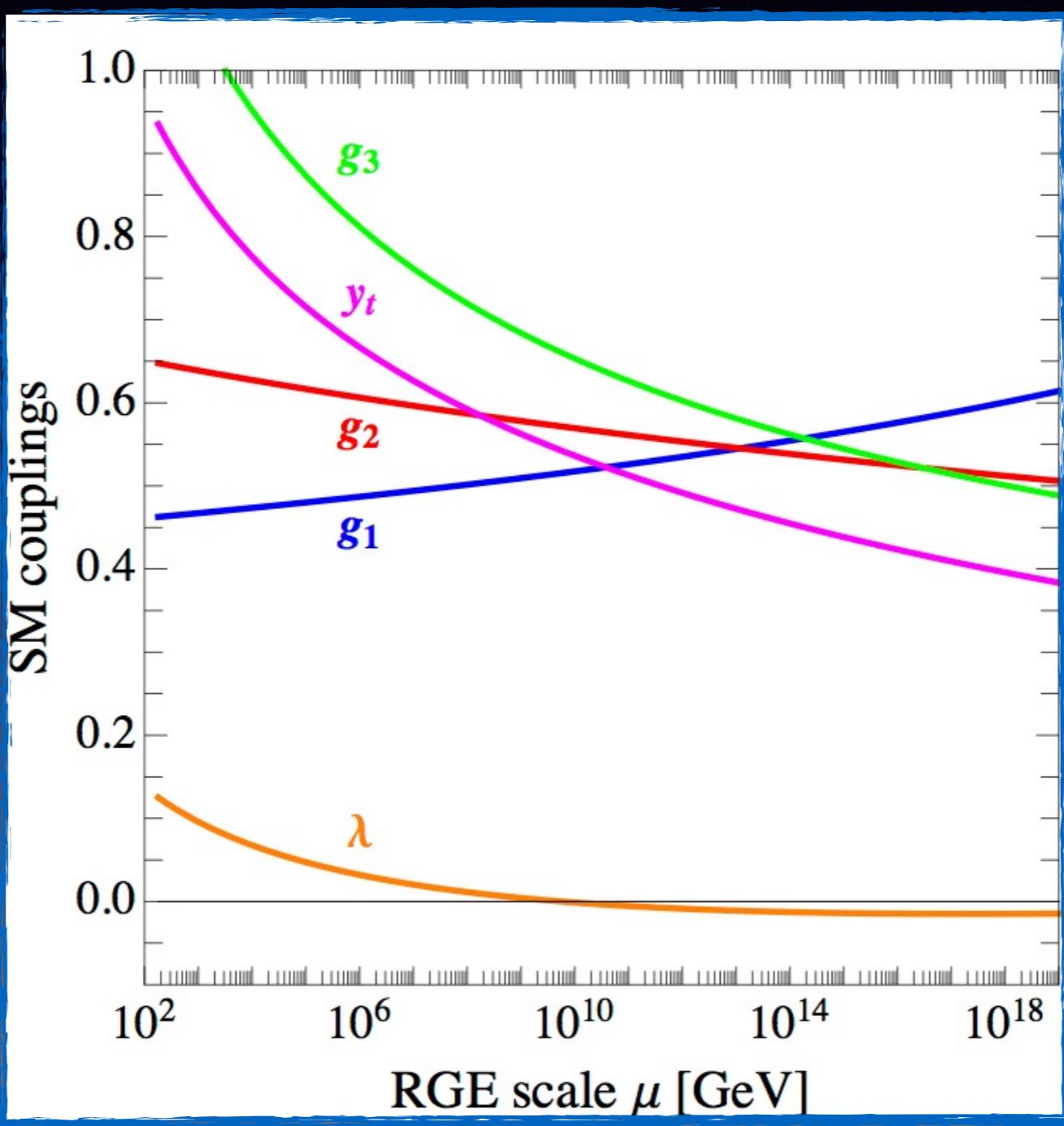
Ellis, Espinosa, Giudice, Hoecker, Riotto,
arXiv:0906.0954

Motivation



Hambye and Riesselmann,
hep-ph/9610272

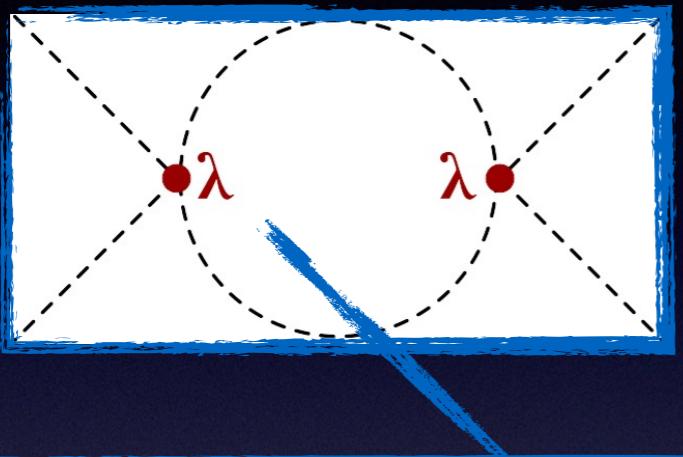
SM RGE



SM RGE

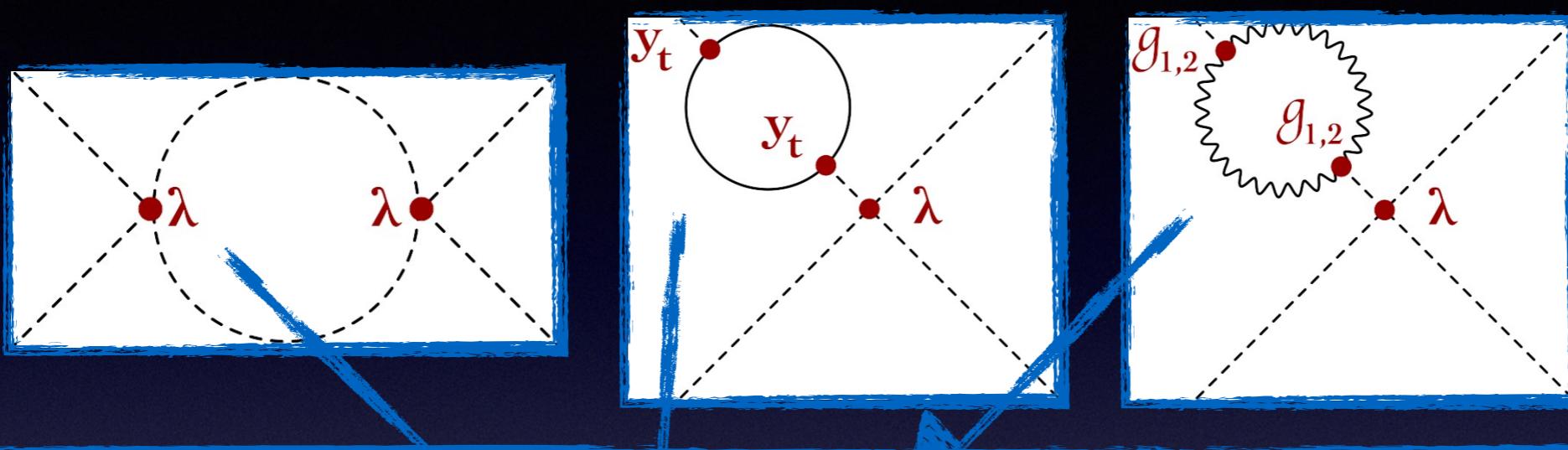
$$\frac{d\lambda}{d \ln \mu^2} = \frac{1}{16\pi^2} \left[\lambda \left(12\lambda + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10} \right) - 3y_t^4 + \frac{9g_2^4}{16} + \frac{27g_2^4}{400} + \frac{9g_1^2 g_2^2}{40} \right]$$

SM RGE



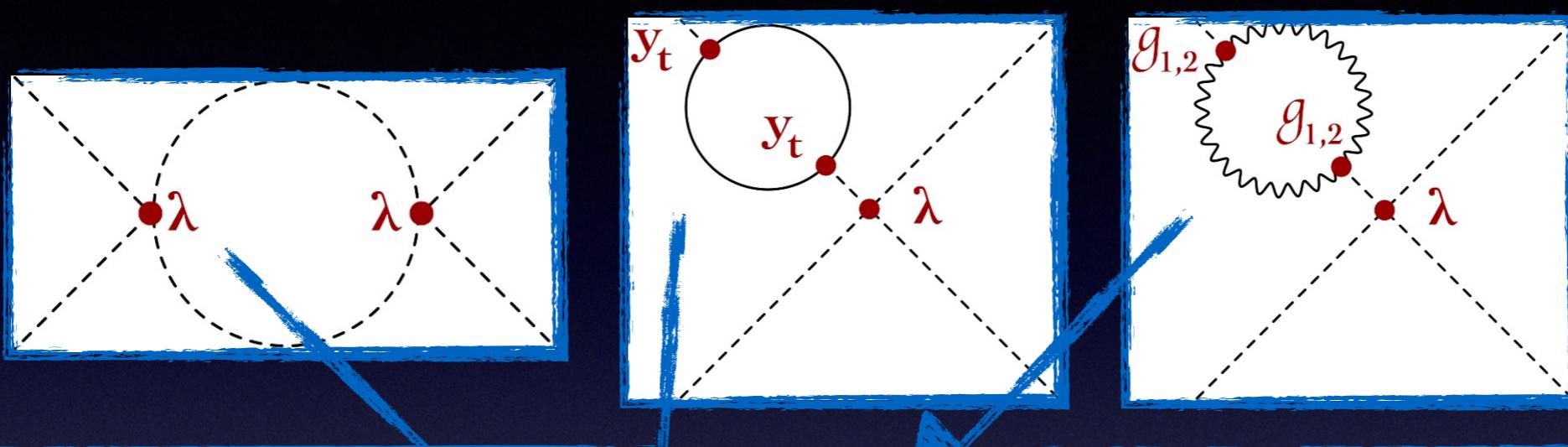
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SM RGE

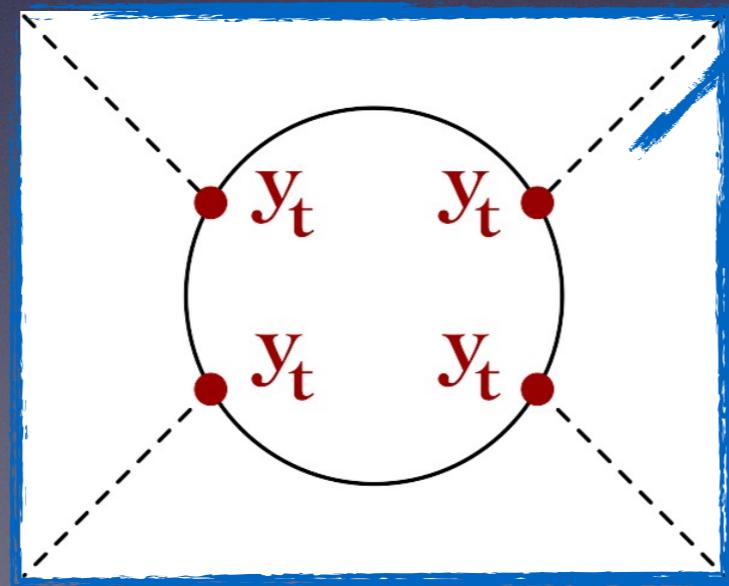


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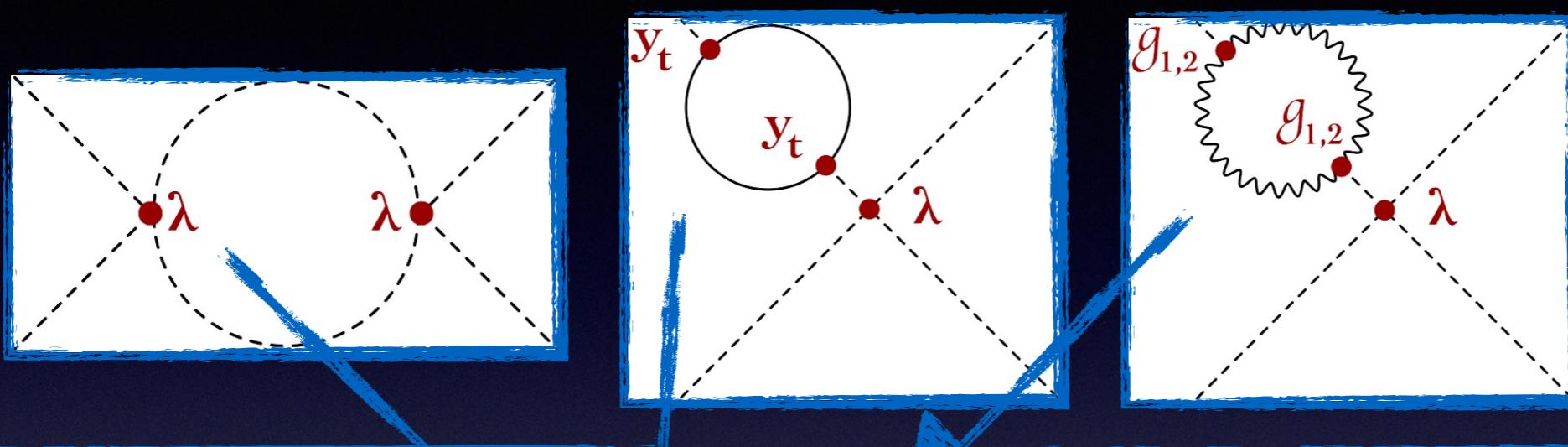
SM RGE



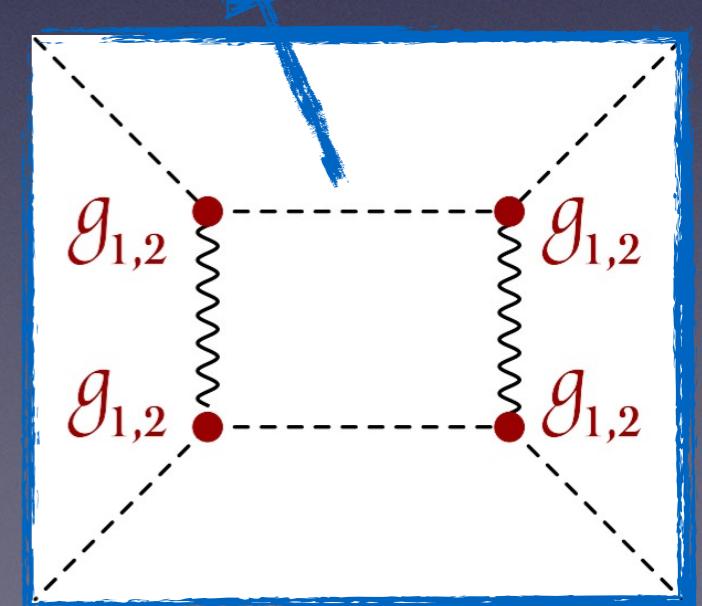
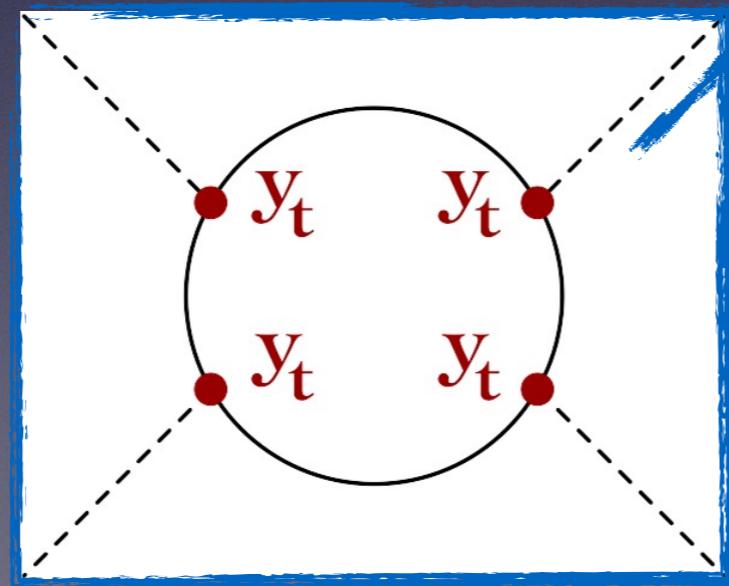
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SM RGE

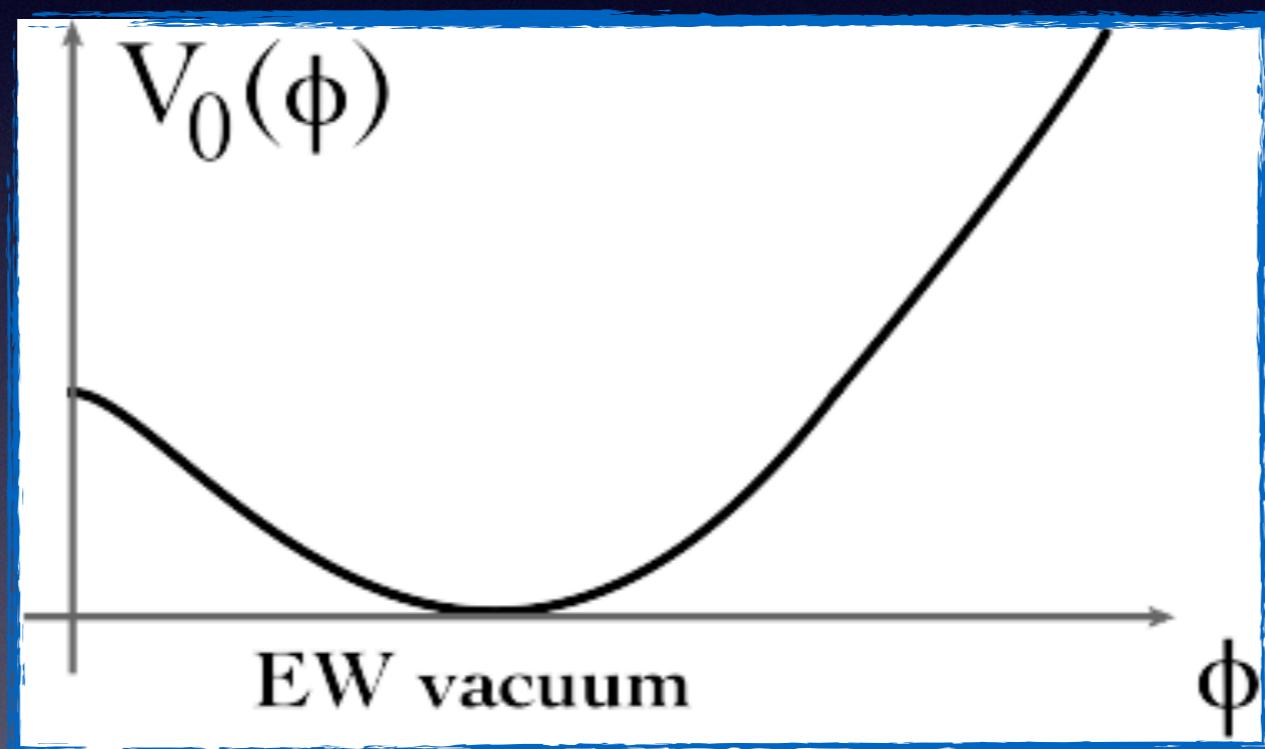


$$\frac{d\lambda}{d \ln \mu^2} = \frac{1}{16\pi^2} \left[\lambda \left(12\lambda + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10} \right) - 3y_t^4 + \frac{9g_2^4}{16} + \frac{27g_2^4}{400} + \frac{9g_1^2g_2^2}{40} \right]$$



Higgs effective potential

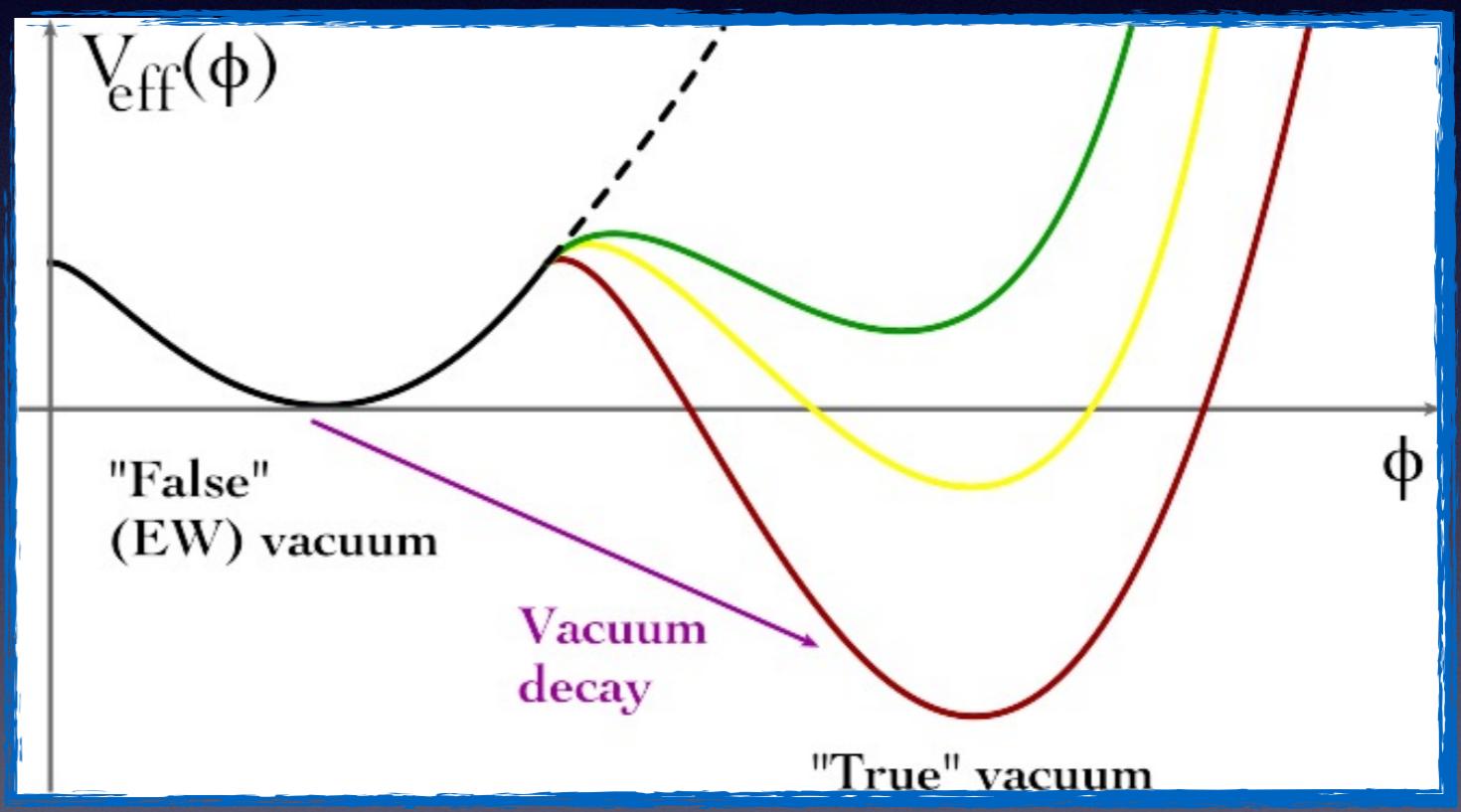
Classical (tree level) potential



$$V_0(\phi) = -\frac{m_0^2}{2}\phi^2 + \frac{\lambda_0}{4}\phi^4$$

Higgs effective potential

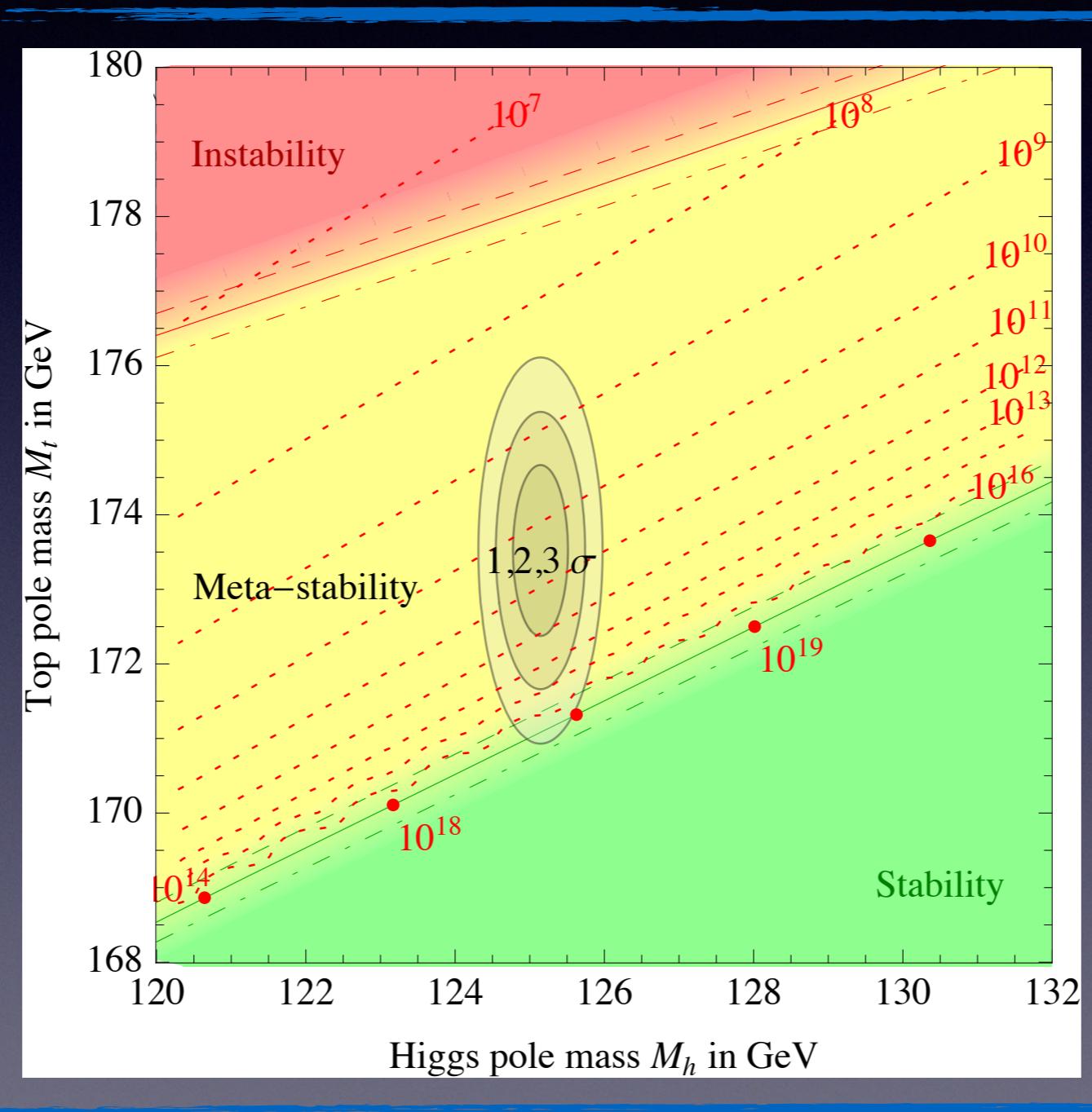
Quantum effective potential



$$V_{\text{eff}}(\phi, t) \approx \frac{\lambda_{\text{eff}}(\phi, t)}{4} \phi^4$$

$$\lambda_{\text{eff}}(\phi, t) \approx e^{4\Gamma(t)} \left[\lambda(t) + \frac{1}{(4\pi)^2} \sum_p N_p k_p^2(t) \left(\log \frac{k_p(t) e^{2\Gamma(t)} \phi^2}{\mu(t)^2} - C_p \right) \right]$$

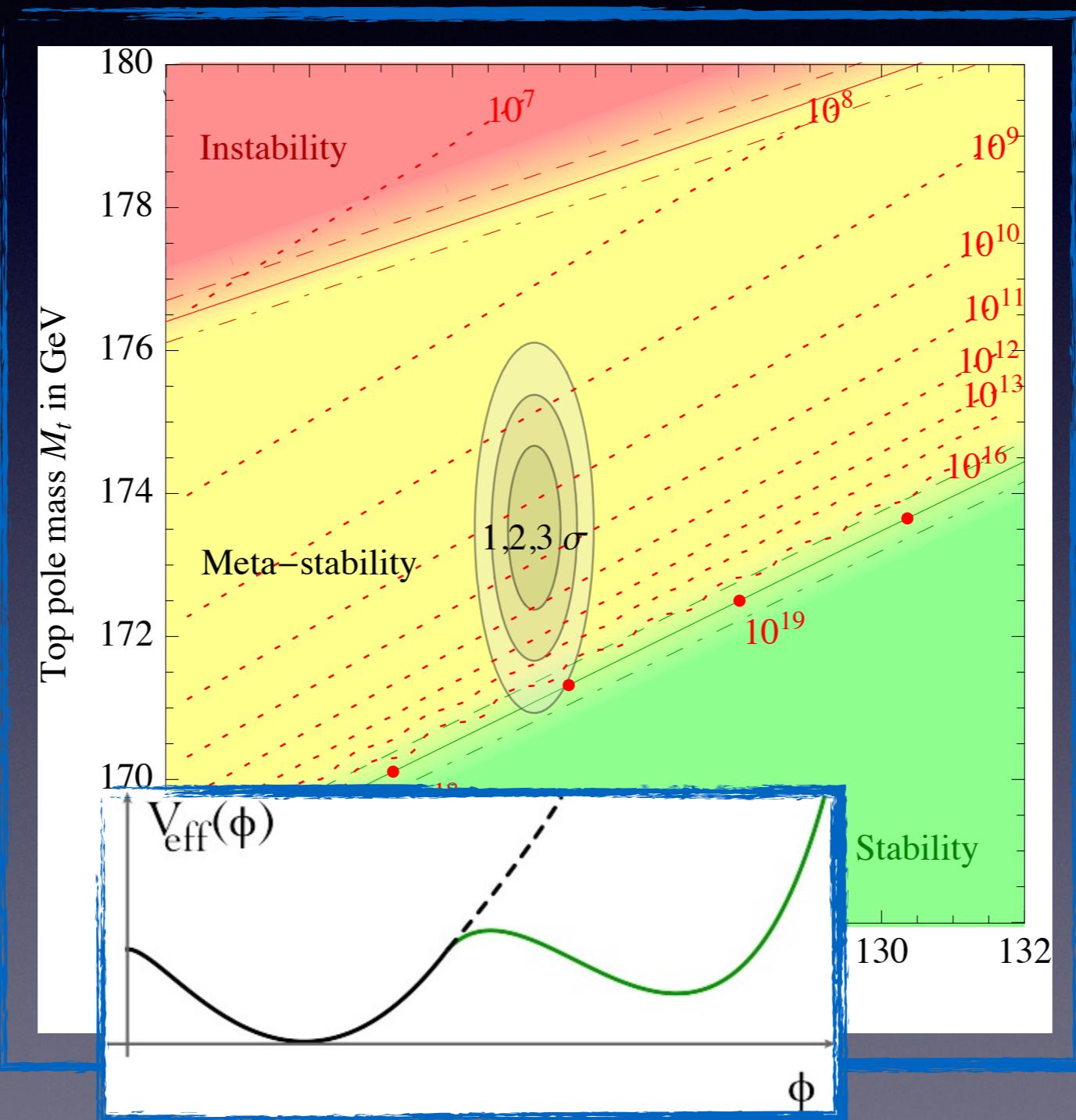
SM phase diagram



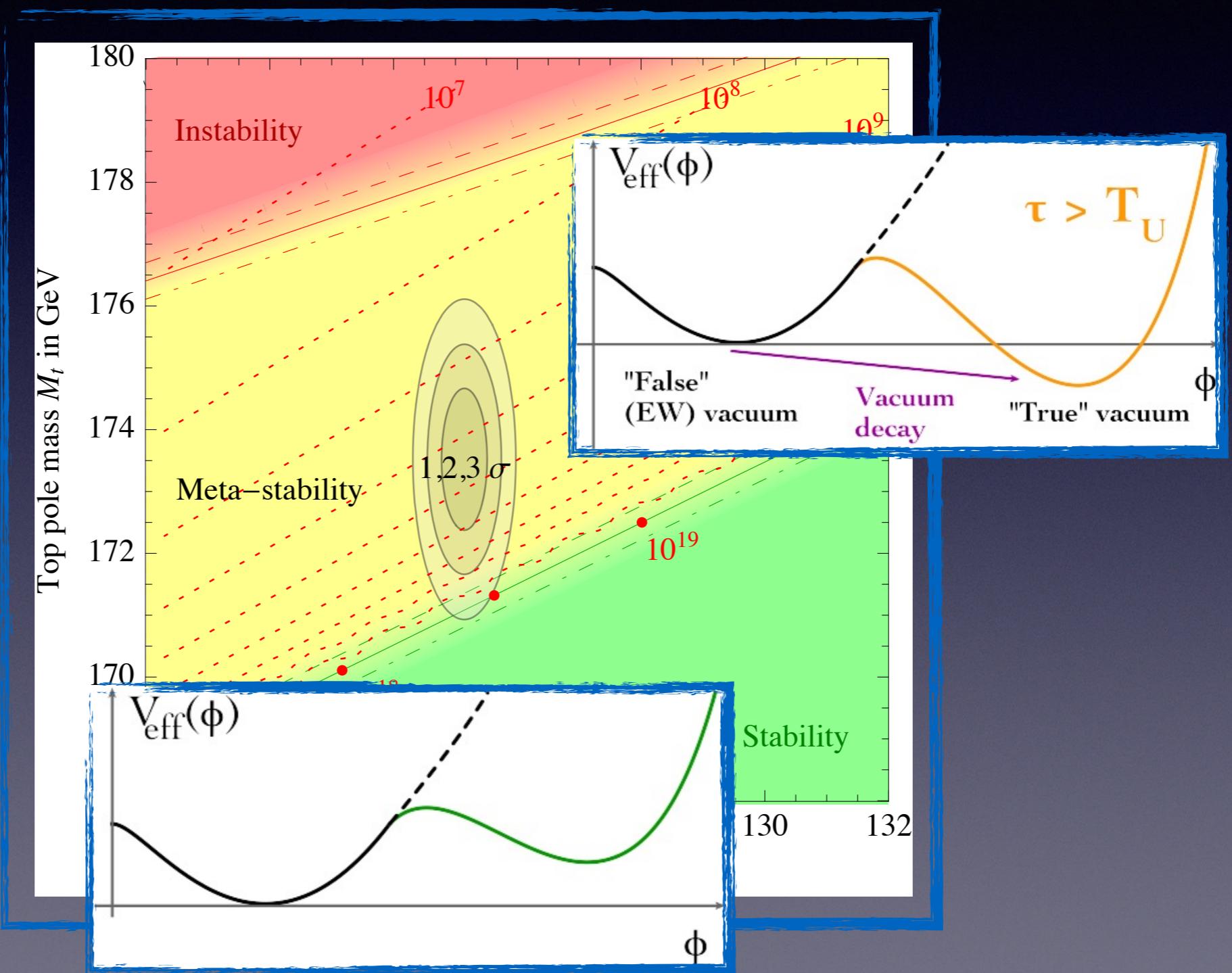
arXiv:1307.3536

Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia

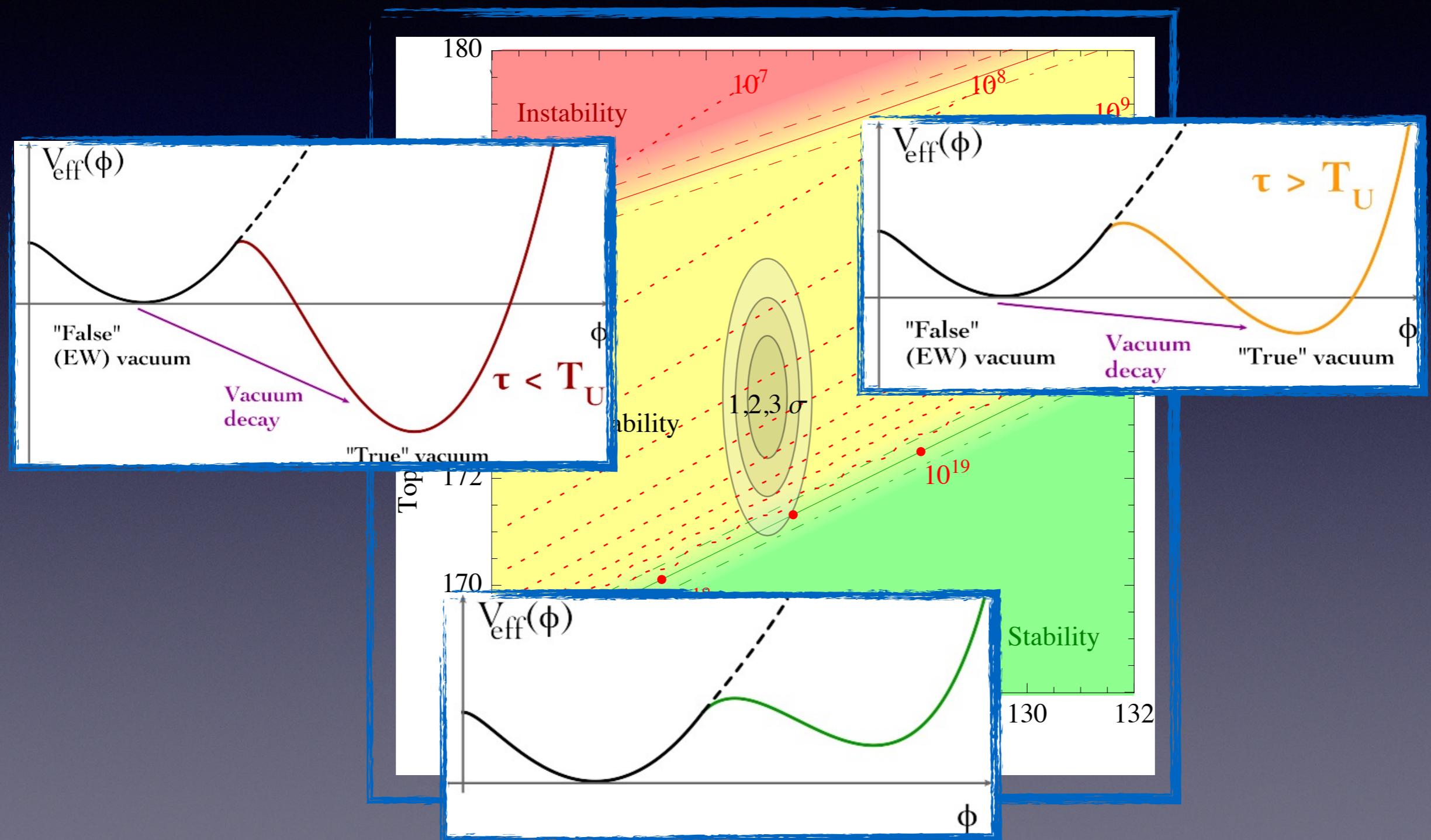
SM phase diagram



SM phase diagram



SM phase diagram



SM + Neutrinos...

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\gamma^\mu(\partial_\mu N_R) - \left[\overline{N_R}Y_\nu\tilde{H}^\dagger L + \frac{1}{2}\overline{N_R^C}M_RN_R + h.c. \right]$$

SM + Neutrinos...

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\gamma^\mu(\partial_\mu N_R) - \left[\overline{N_R}Y_\nu\tilde{H}^\dagger L + \frac{1}{2}\overline{N_R^C}M_RN_R + h.c. \right]$$

$$m_\nu = \frac{Y_\nu^2 v^2}{M_R}$$

$$N_L = \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix}$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & Y_\nu v/\sqrt{2} \\ Y_\nu v/\sqrt{2} & M_R \end{pmatrix}$$

SM + Neutrinos...

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\gamma^\mu(\partial_\mu N_R) - \left[\overline{N_R}Y_\nu\tilde{H}^\dagger L + \frac{1}{2}\overline{N_R^C}M_RN_R + h.c. \right]$$

$$m_\nu = \frac{Y_\nu^2 v^2}{M_R}$$

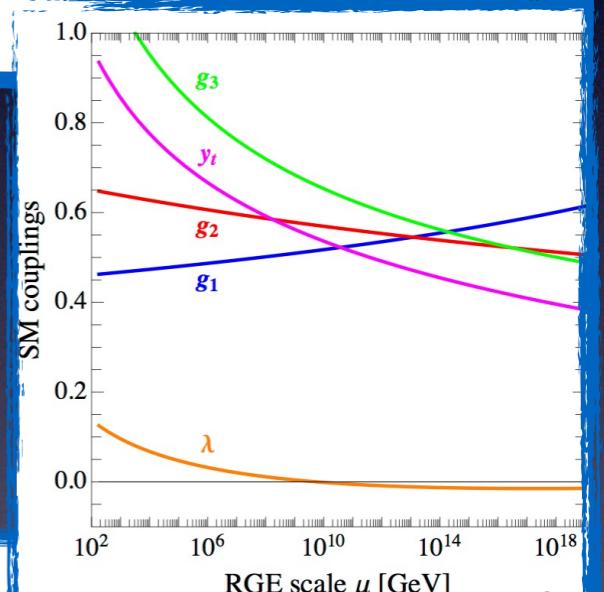
$$m_\nu \sim \mathcal{O}(0.1) \text{ eV} \implies \begin{cases} M_R \approx 10^{15} \text{ GeV} & \text{if } Y_\nu \approx 1 \\ M_R \approx 10^{11} \text{ GeV} & \text{if } Y_\nu \approx 10^{-3} \end{cases}$$

SM + Neutrinos...

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\gamma^\mu(\partial_\mu N_R) - \left[\overline{N_R}Y_\nu\tilde{H}^\dagger L + \frac{1}{2}\overline{N_R^C}M_RN_R + h.c. \right]$$

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E.g.: Casas, Di Clemente, Espinosa, Quiros,
hep-ph/9904295

SM + Neutrinos...

The case of the “Inverse seesaw”

R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D34 , 1642 (1986)

$$\mathcal{L}_{\text{ISS}} = \mathcal{L}_{\text{SM}} + i\overline{N_R}\gamma^\mu(\partial_\mu N_R) + i\overline{S}\gamma^\mu(\partial_\mu S) - \left[\overline{N_R}Y_\nu\tilde{H}^\dagger L + \frac{1}{2}\overline{N_R}M_RS + \frac{1}{2}\overline{S^C}\mu_SS + h.c. \right]$$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix}$$

$$N_L = \begin{pmatrix} \nu_L \\ N_R^C \\ S \end{pmatrix}$$

$$m_D \equiv Y_\nu v / \sqrt{2}$$

diagonalization...

$$m_\nu \approx m_D^T (M_R^T)^{-1} \mu_S M_R^{-1} m_D$$

SM + Neutrinos...

The case of the “Inverse seesaw”

▲ Mass spectrum

$N_R \quad \mathcal{O}(M_R) \sim \text{TeV}$

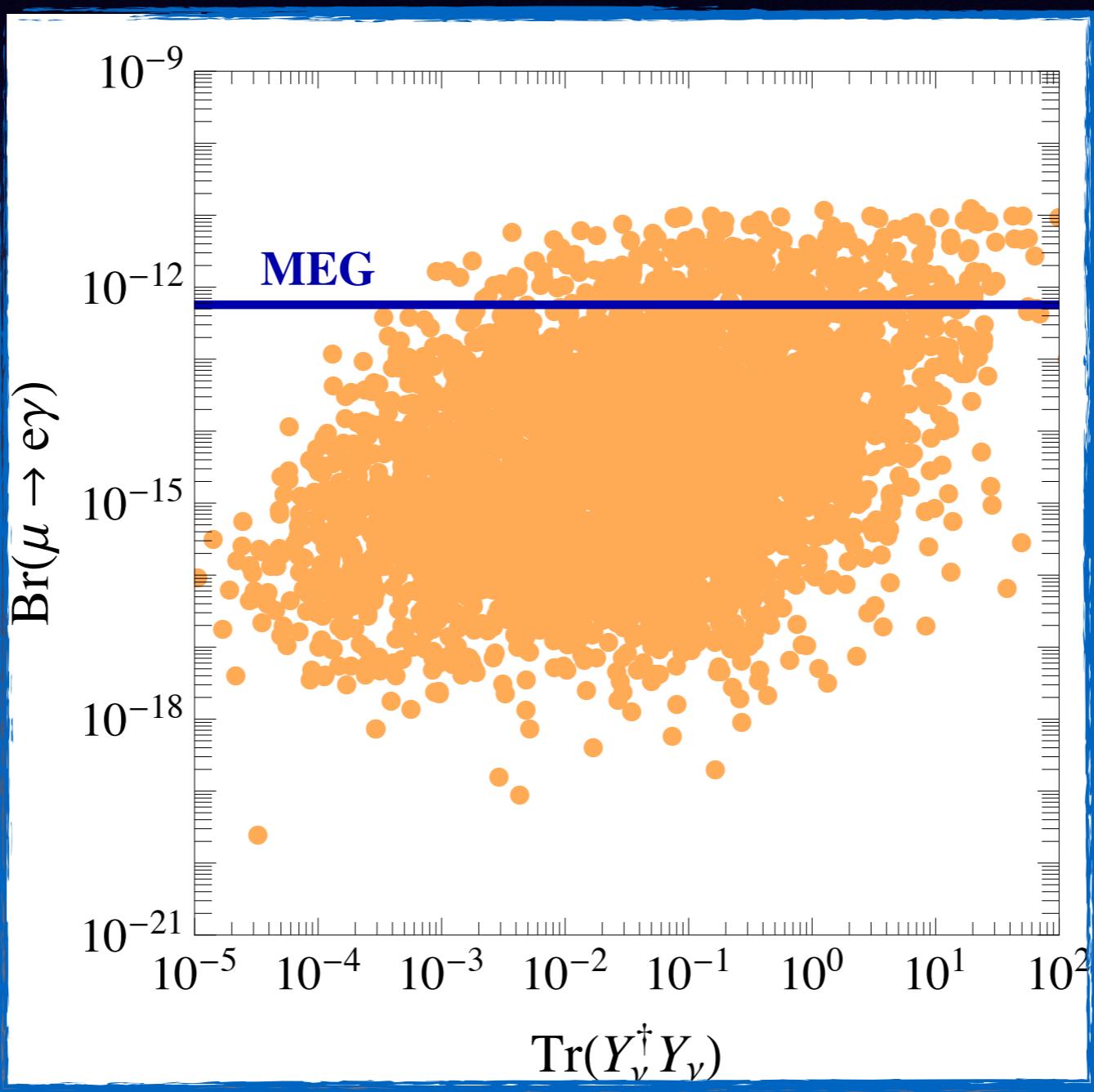
$S \quad \mathcal{O}(\mu_S) \sim \text{keV}$

$\nu_{\text{active}} \quad \mathcal{O}(\mu_S \times m_D^2/M_R^2) \sim \text{eV}$

keV dark matter?
e.g. Abada and Lucente,
arXiv:1401.1507

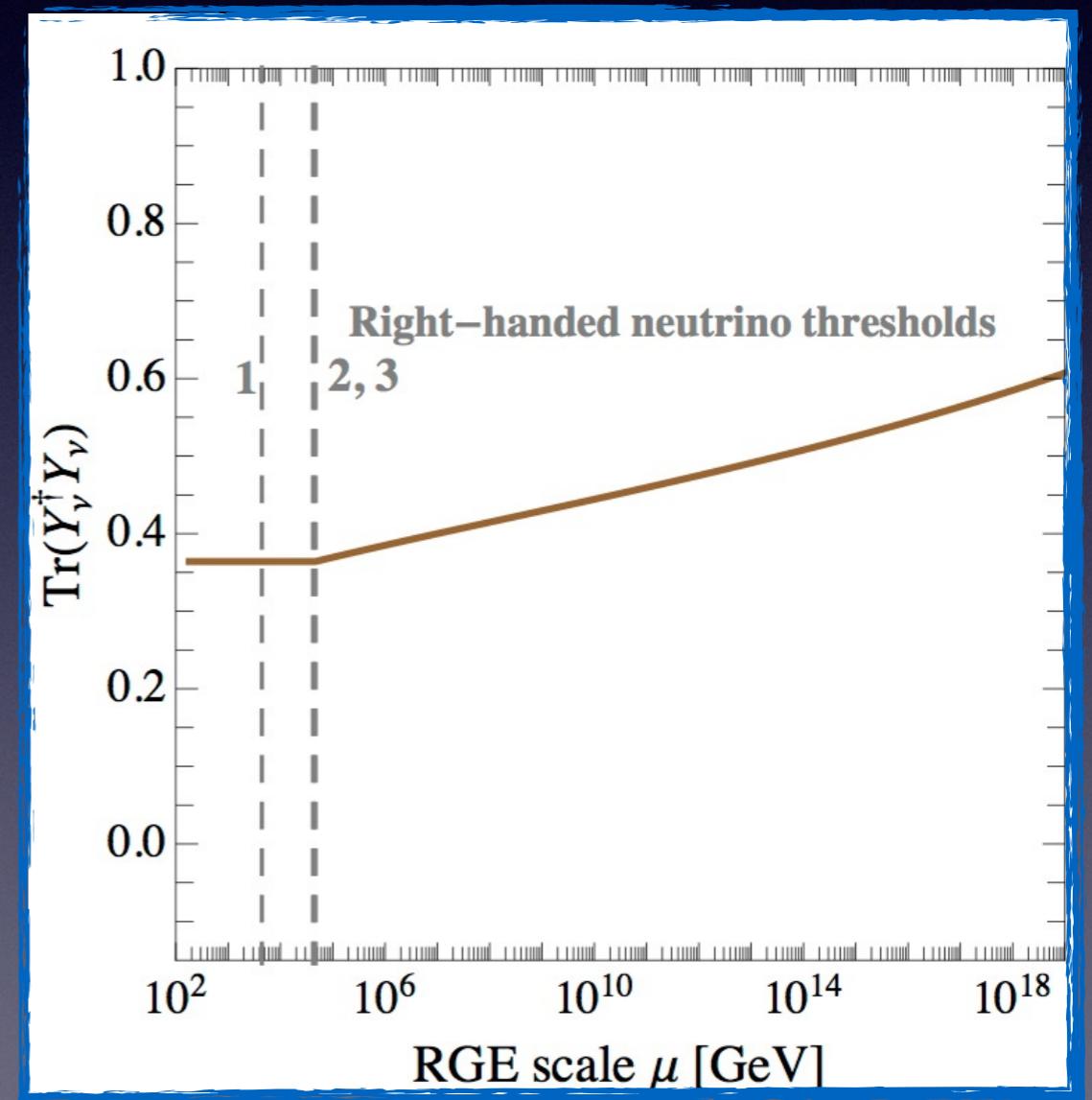
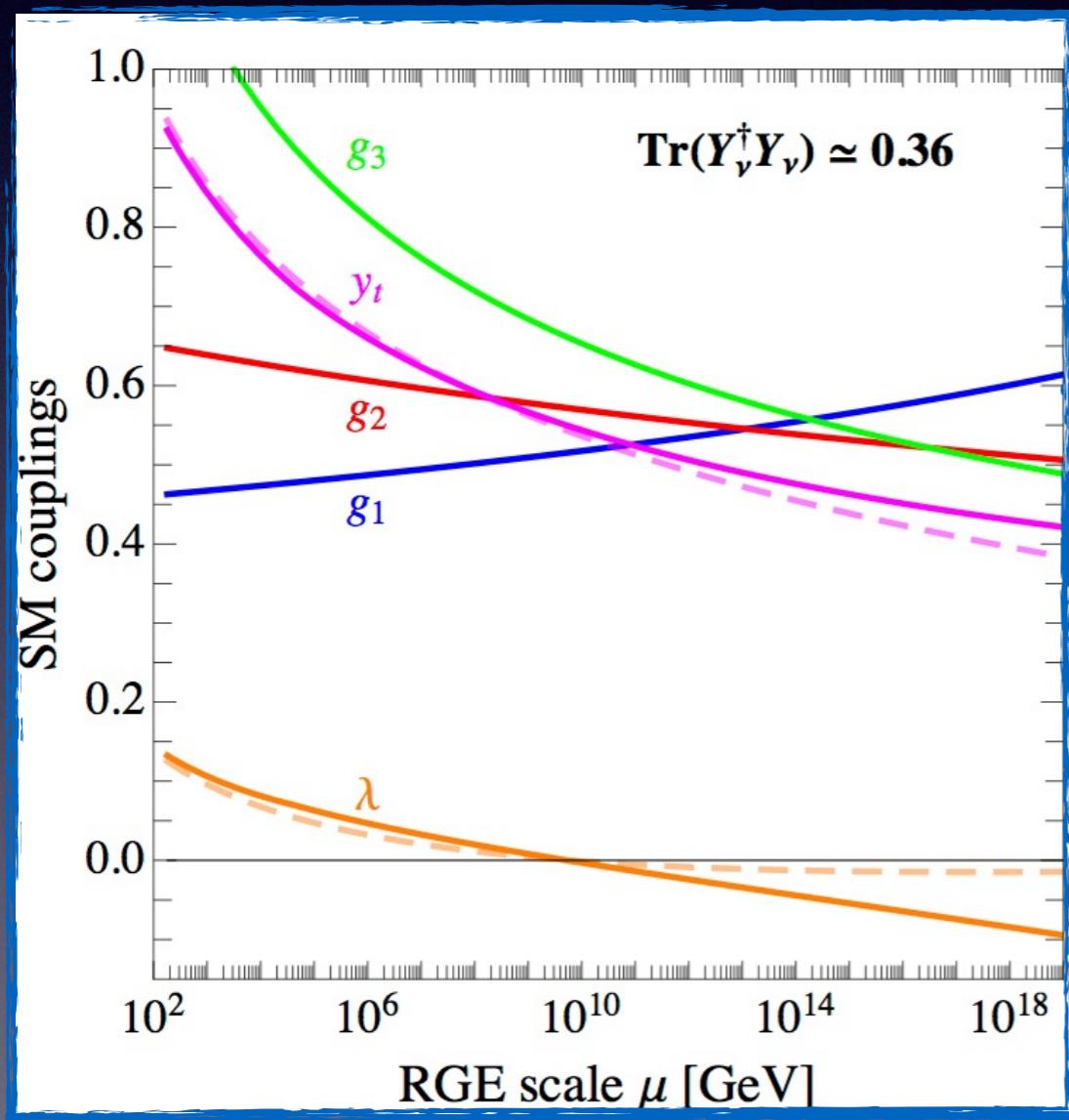
SM + Neutrinos...

The case of the “Inverse seesaw”



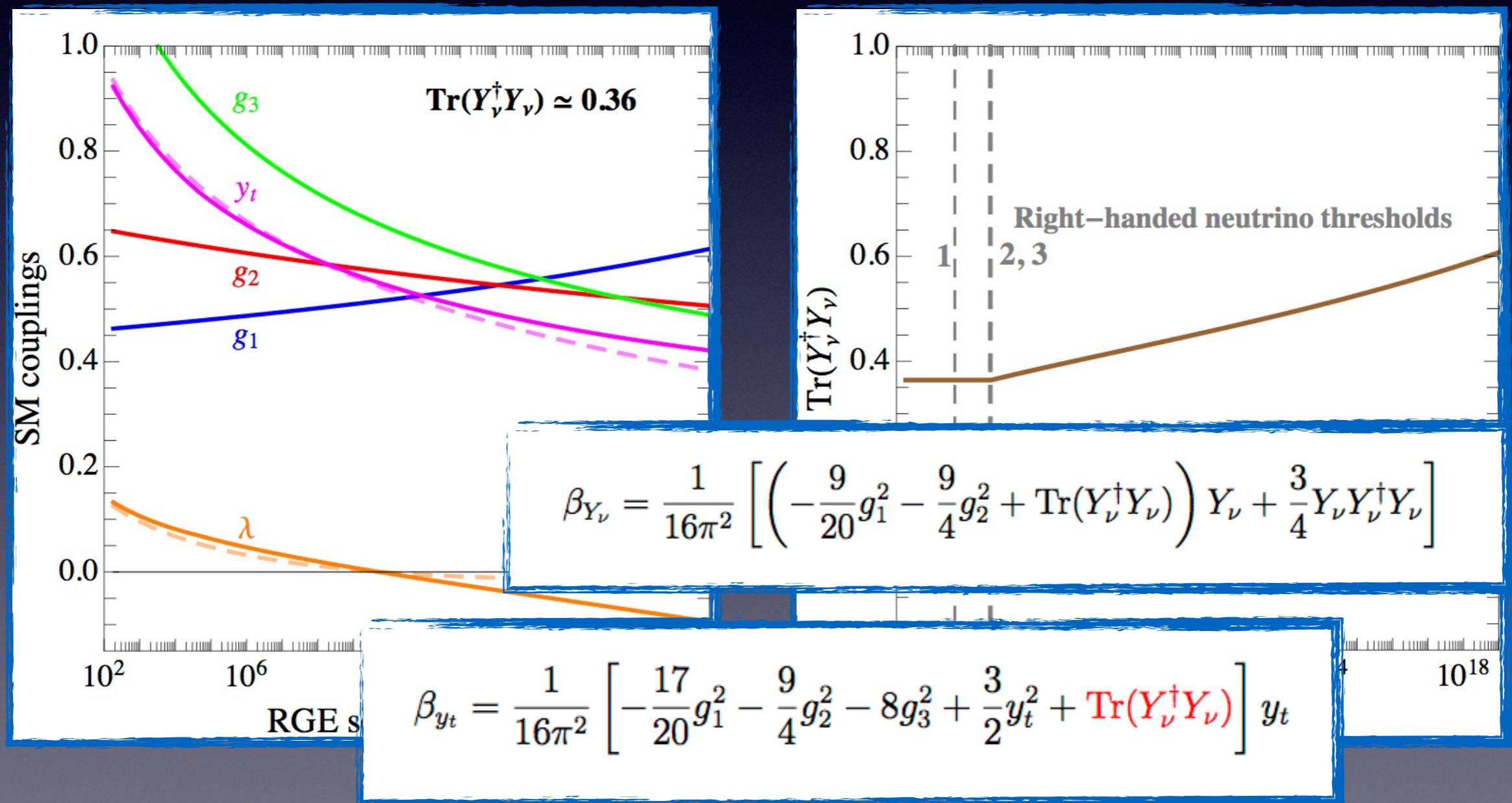
SM + Neutrinos...

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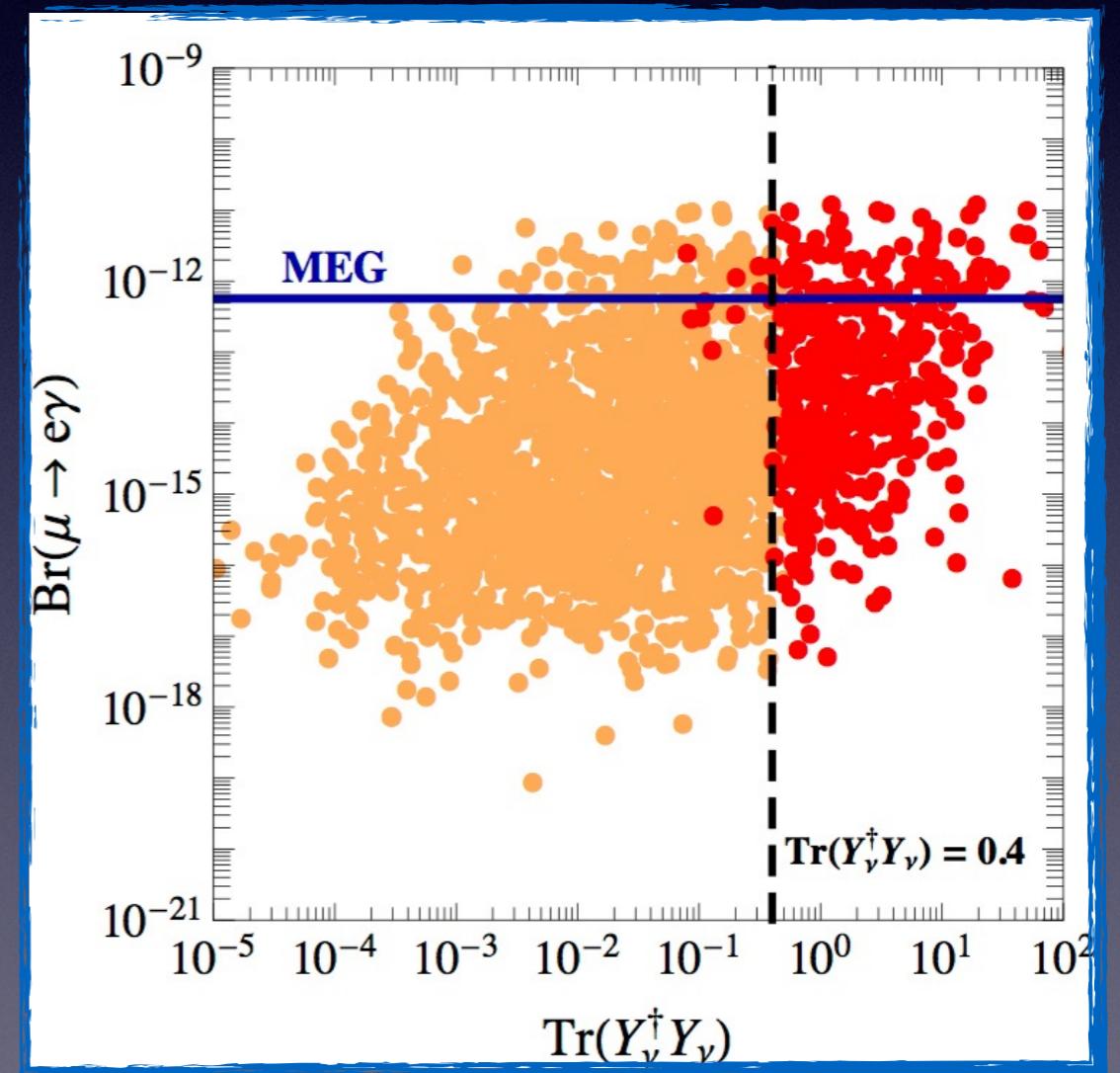
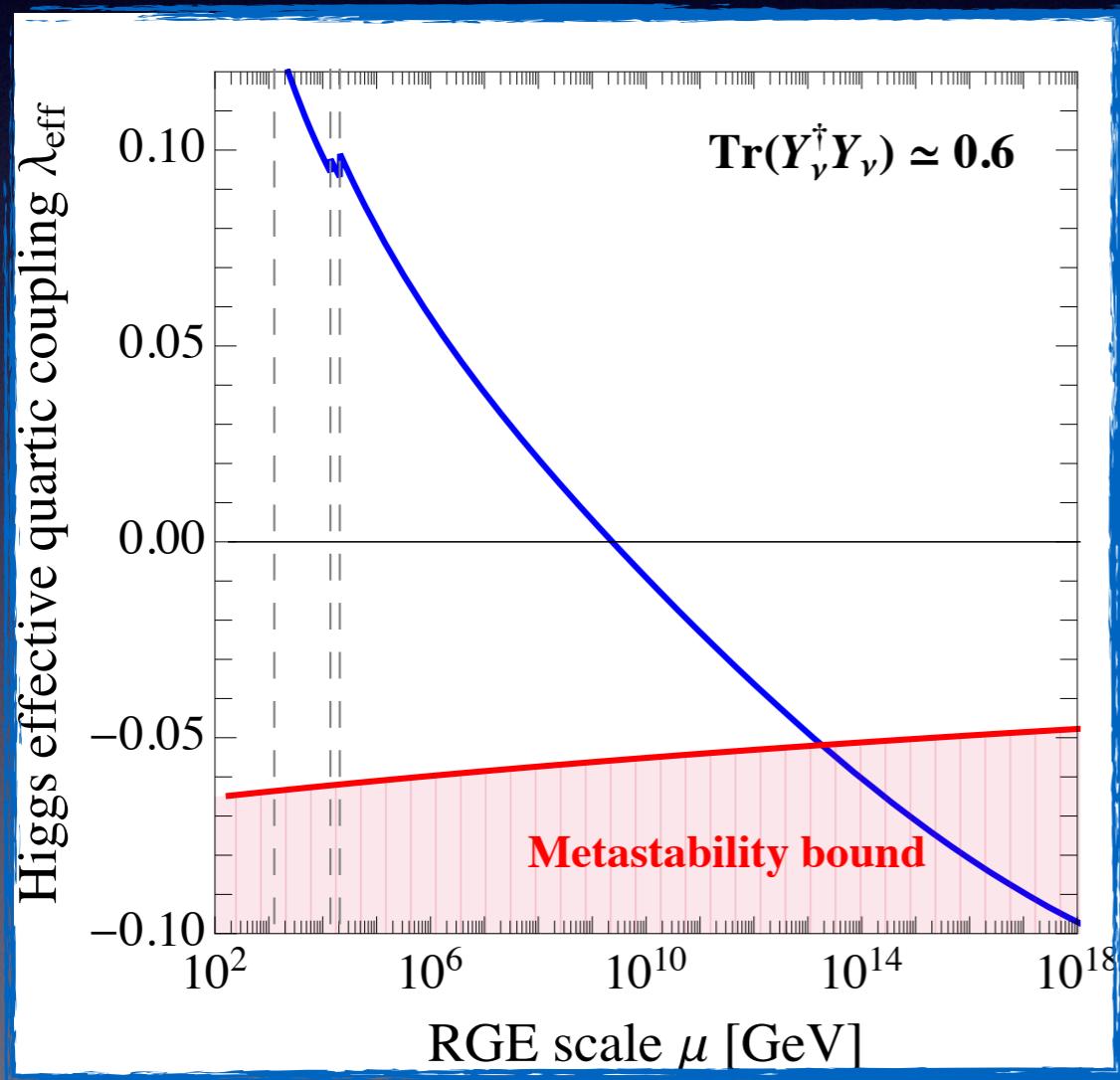
SM + Neutrinos...

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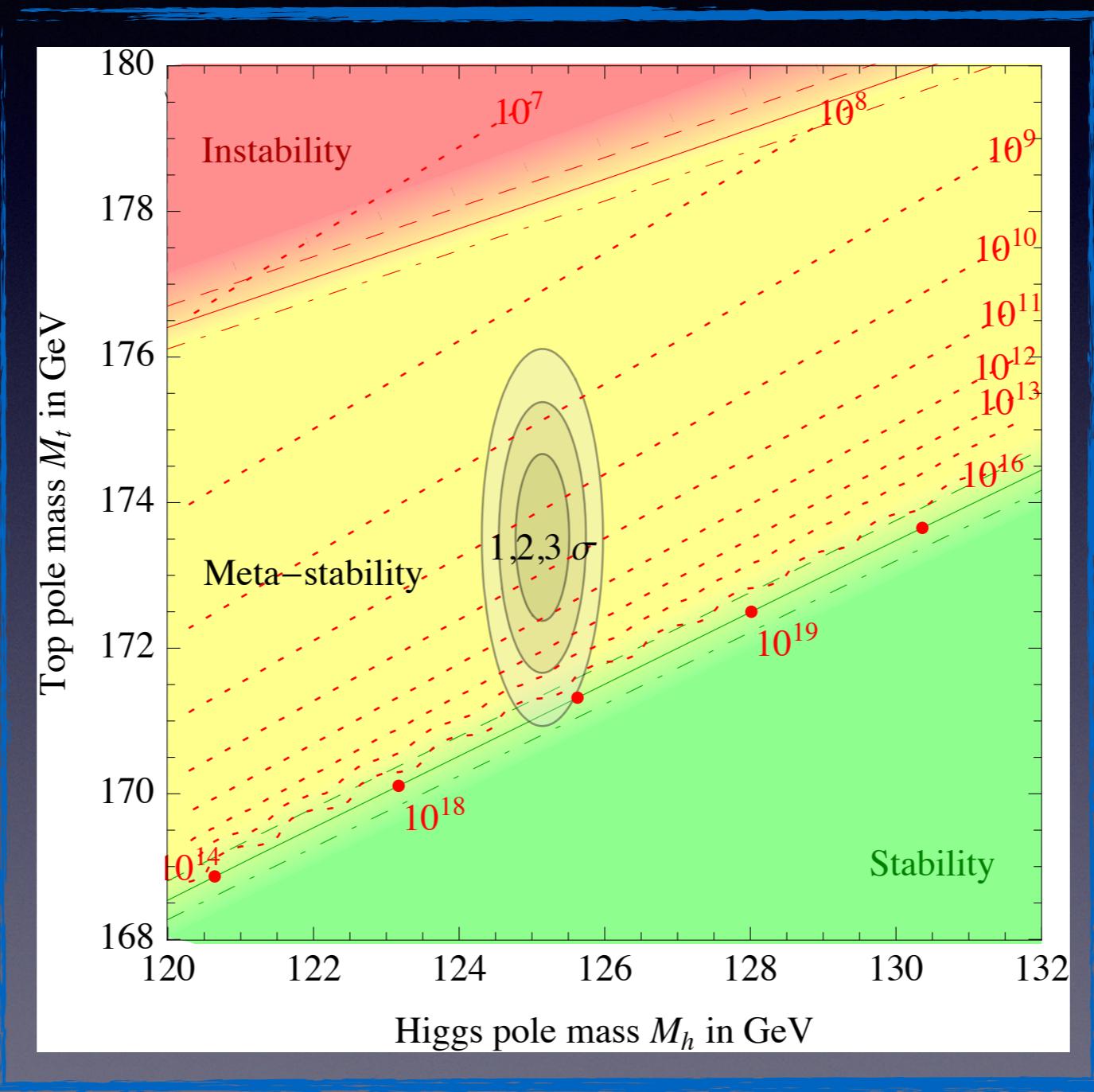


SM + Neutrinos...

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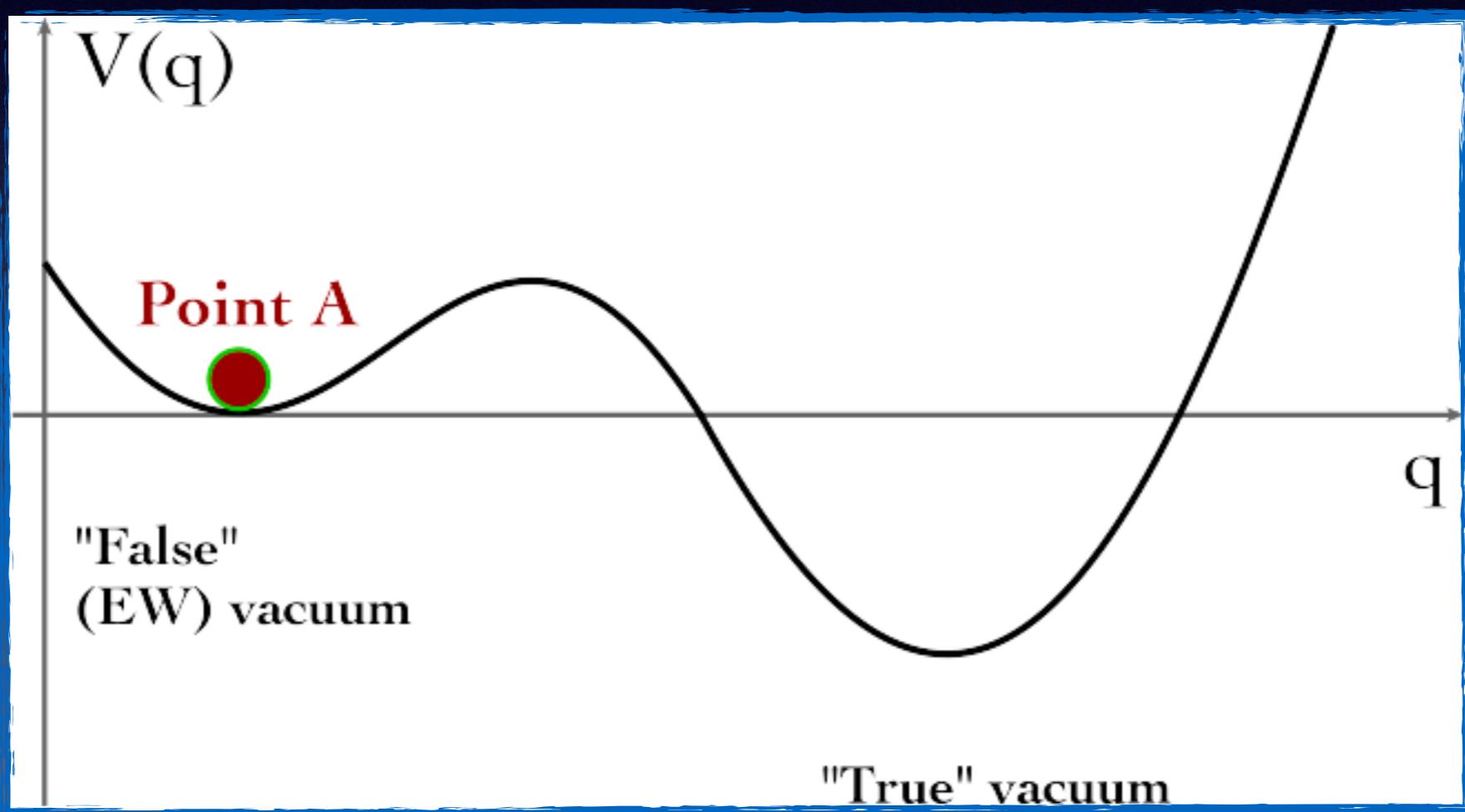
SM phase diagram...



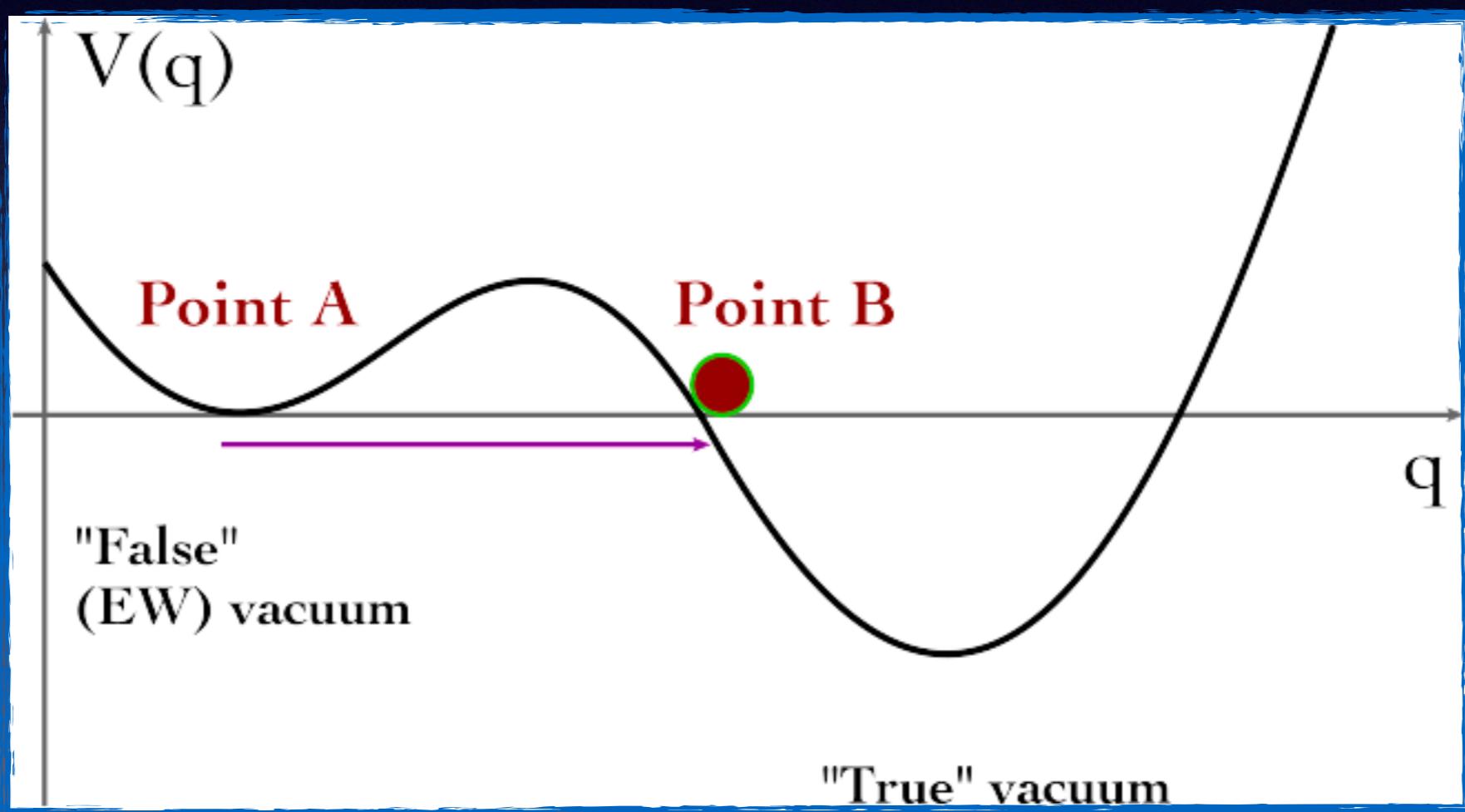
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Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia,

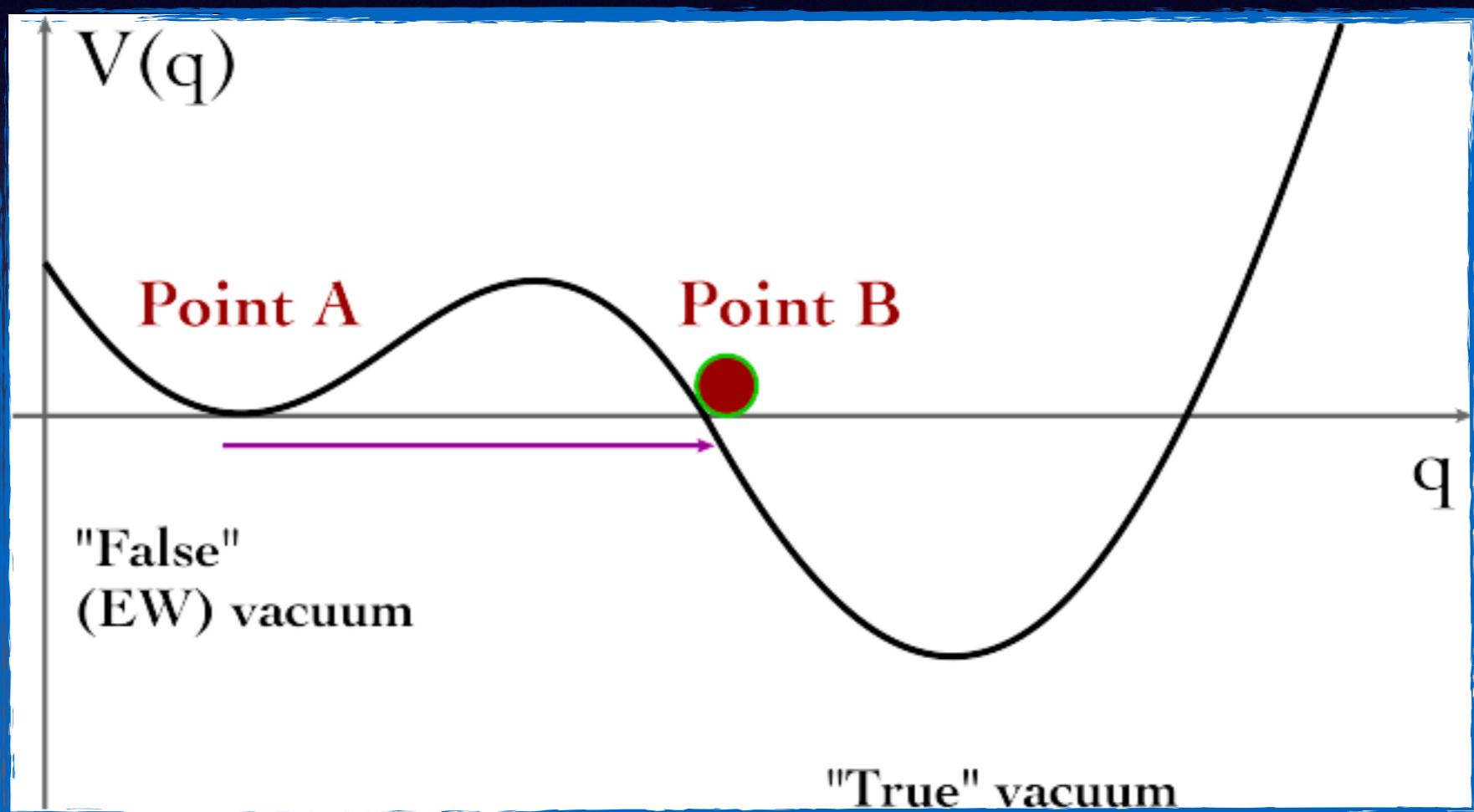
More on stability...



More on stability...

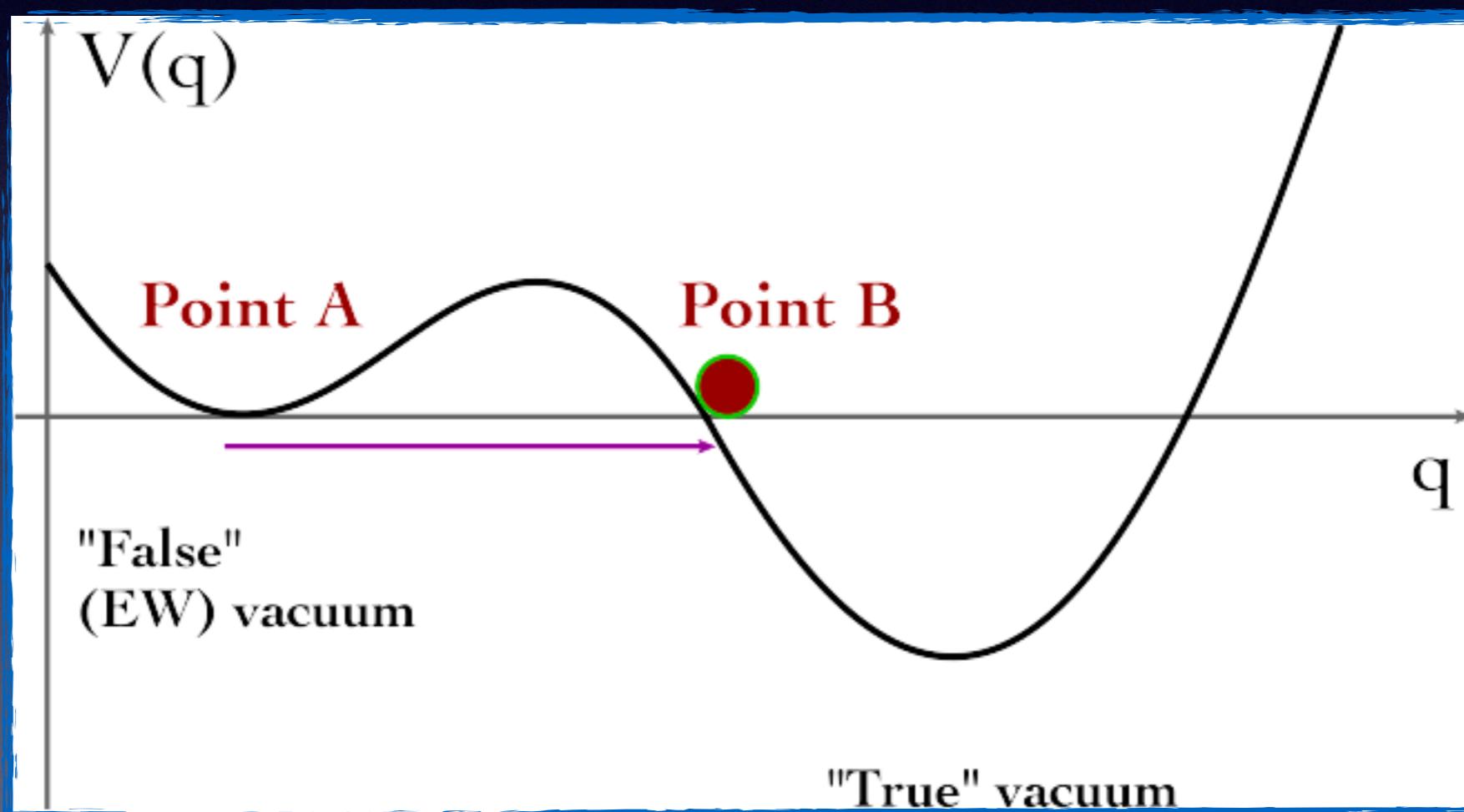


More on stability...



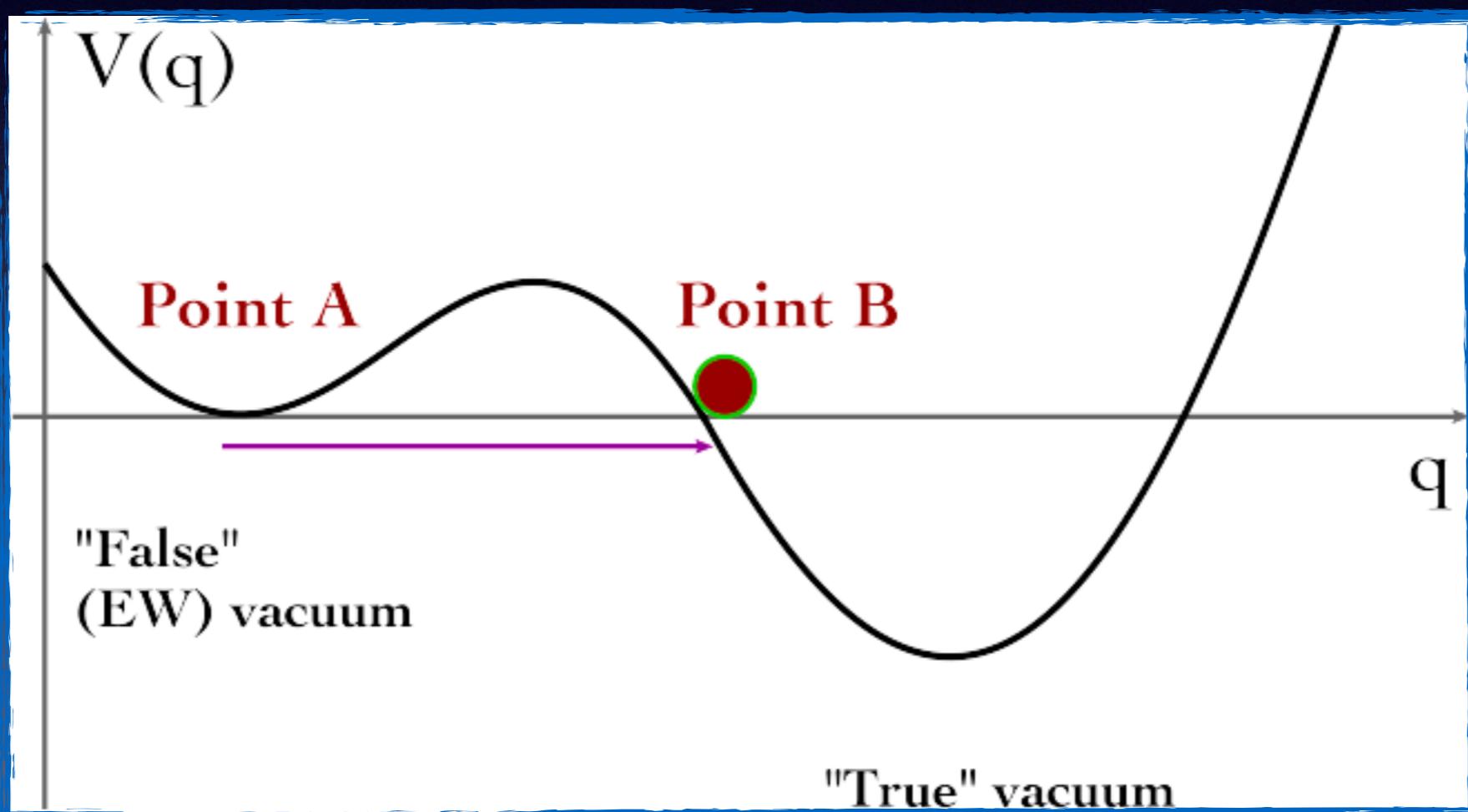
$$\Gamma \sim \exp \left[-2 \int_{q_A}^{q_B} dq \sqrt{2mV(q)} \right]$$

More on stability...



$$\Gamma \sim \exp \left[-2 \min \int_{\vec{q}_A}^{\vec{q}_B} d\vec{q} \sqrt{2mV(\vec{q})} \right]$$

More on stability...



$$\Gamma \sim e^{-S_E}, \quad S_E = \int_{t_i}^{t_f} \left\{ \frac{1}{2} m \dot{\vec{q}}(\tau)^2 + V[\vec{q}(\tau)] \right\}$$

More on stability...

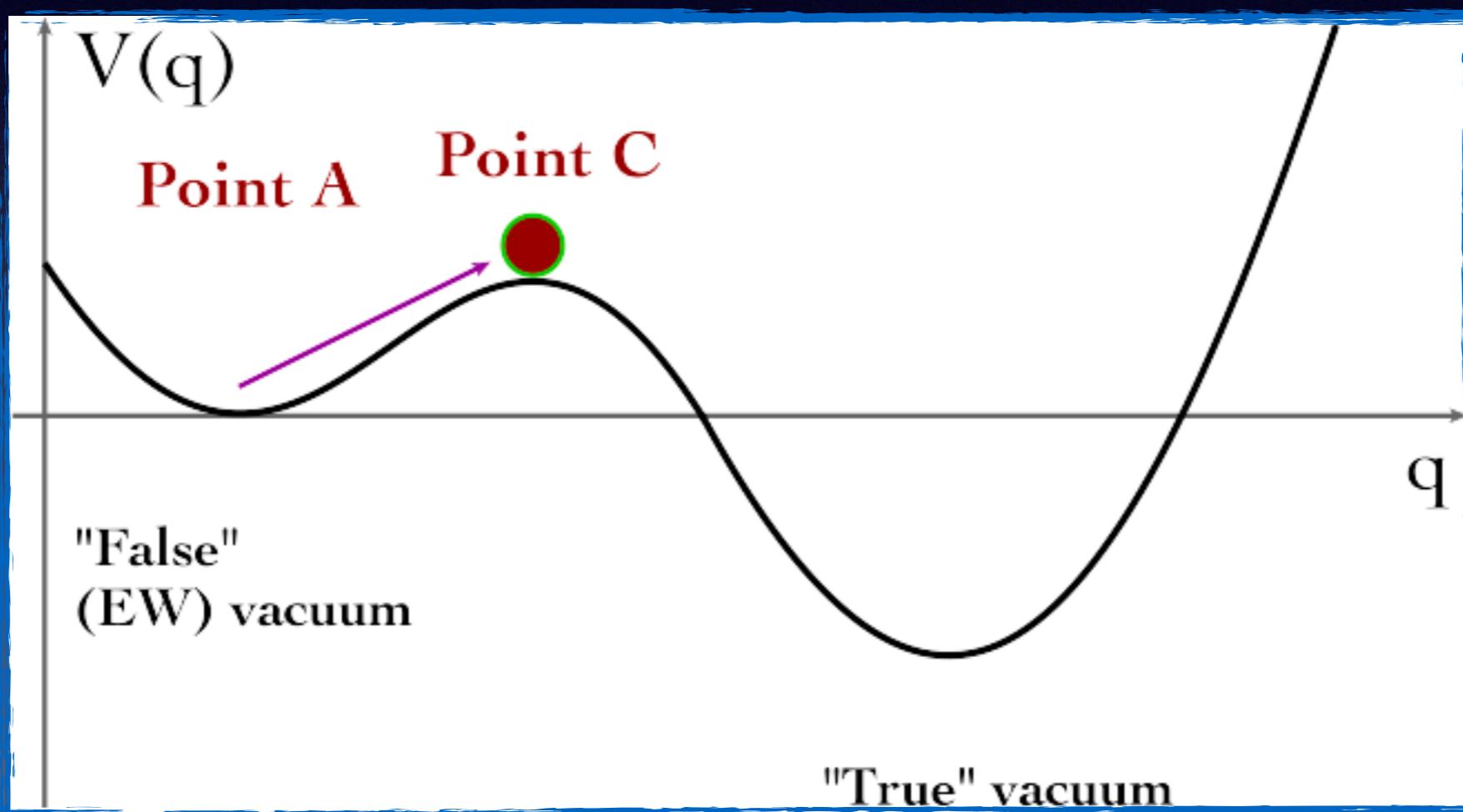
$$\Gamma \sim e^{-S_4[\phi_B(r)]}$$
$$S_4[\phi(r)] = 2\pi^2 \int_0^\infty dr r^3 \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\text{eff}}(\phi) \right]$$
$$\frac{d^2\phi}{dr^2} + \frac{3}{r} \frac{d\phi}{dr} = \frac{dV_{\text{eff}}}{d\phi} ; \quad \lim_{r \rightarrow \infty} \phi(r) = 0 , \quad \left. \frac{d\phi}{dr} \right|_{r=0} = 0$$

"True" vacuum

Coleman, Phys.Rev.D15,2929

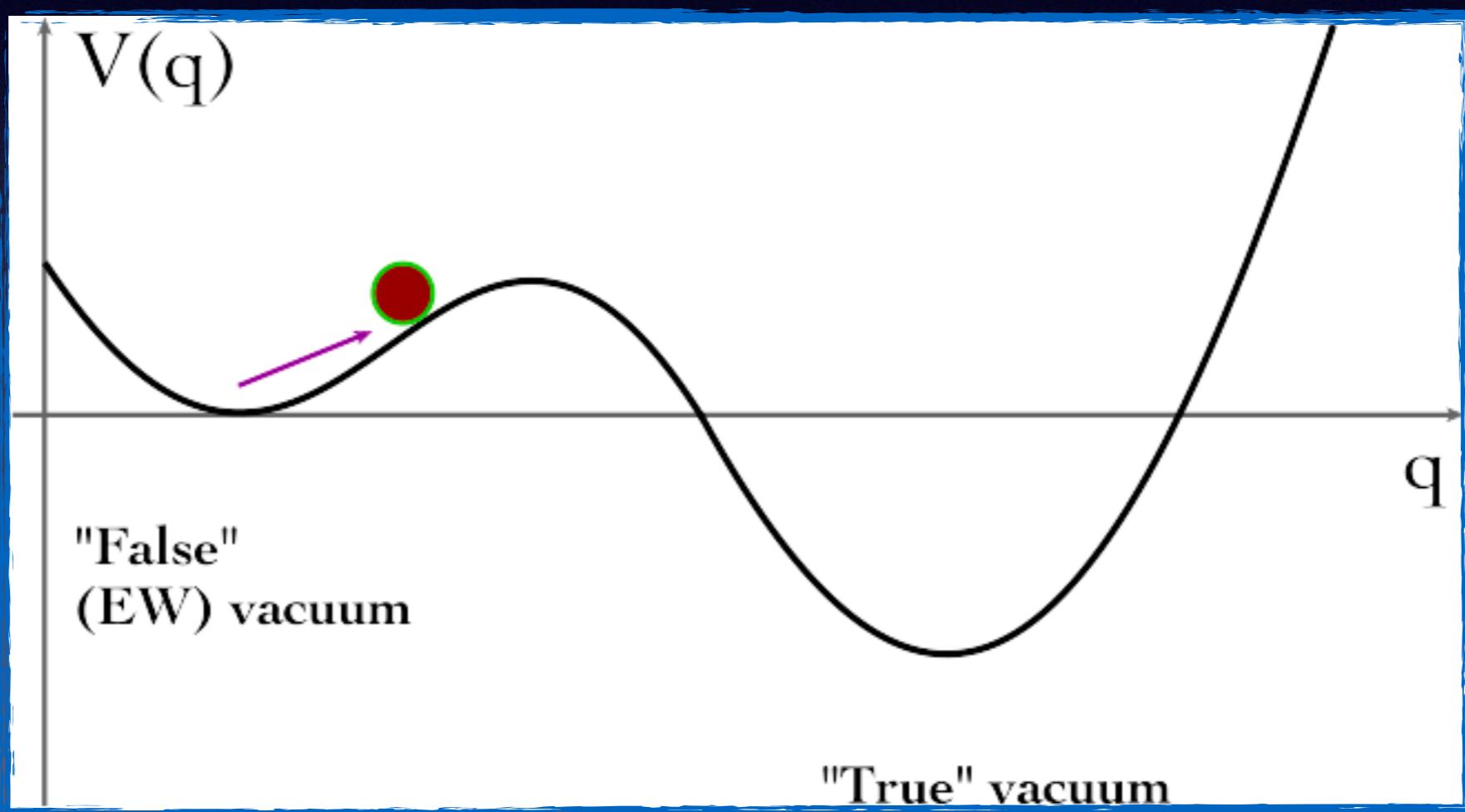
Callan and Coleman, Phys.Rev.D16,1762

More on stability...

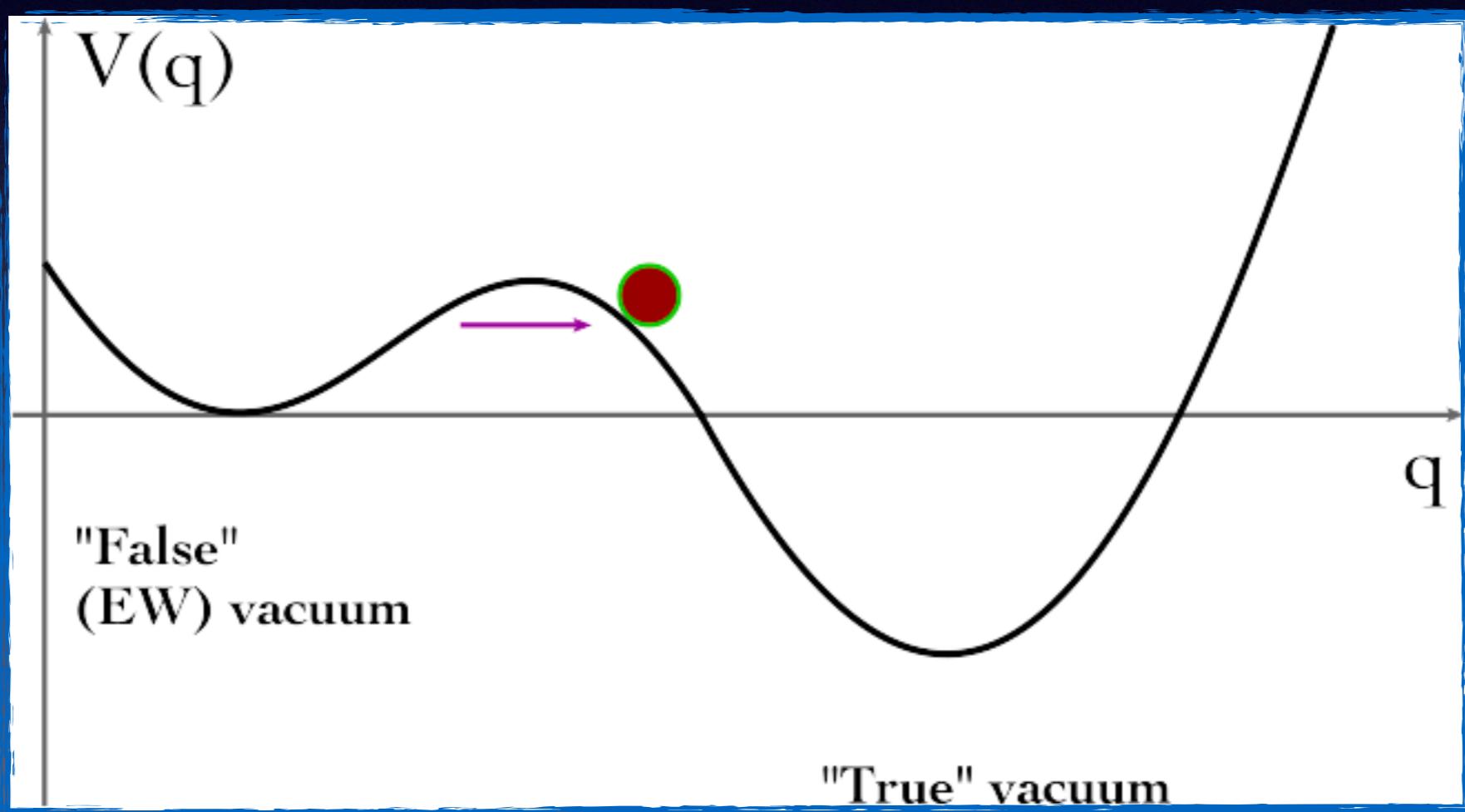


$$P_{A \rightarrow C} \sim \exp \left[-\frac{V_C(T) - V_A(T)}{k_B T} \right]$$

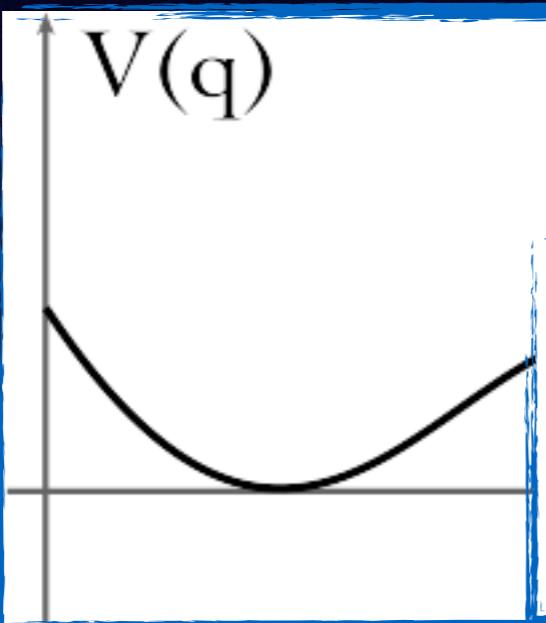
More on stability...



More on stability...



More on stability...



$$\Gamma(T) \sim e^{-S_3[\phi_B(r)]/T}$$

$$S_3[\phi(r)] = 4\pi \int_0^\infty dr r^2 \left[\frac{1}{2} \left(\frac{d\phi}{dr} \right)^2 + V_{\text{eff}}(\phi, T) \right]$$

More on stability...

$$V_{\text{eff}}(\phi, T) = V_0(\phi) + V_{1-\text{loop}}(\phi) + V_{2-\text{loop}}(\phi) + V_{1-\text{loop}}(\phi, T) + V_{\text{ring}}(\phi, T) ,$$

G. W. Anderson,

Phys. Lett. B 243 (1990) 265

P. B. Arnold and S. Vokos,

Phys. Rev. D 44, 3620 (1991)

J. R. Espinosa and M. Quiros,

Phys. Lett. B 353, 257

$$V_{1-\text{loop}}(\phi, T) = \sum_{i=W, Z, \chi, h} \frac{n_i T^4}{2\pi^2} J_B\left(\frac{m_i^2(t)}{T^2}\right) + \frac{n_t T^4}{2\pi^2} J_F\left(\frac{m_t^2(t)}{T^2}\right) ,$$

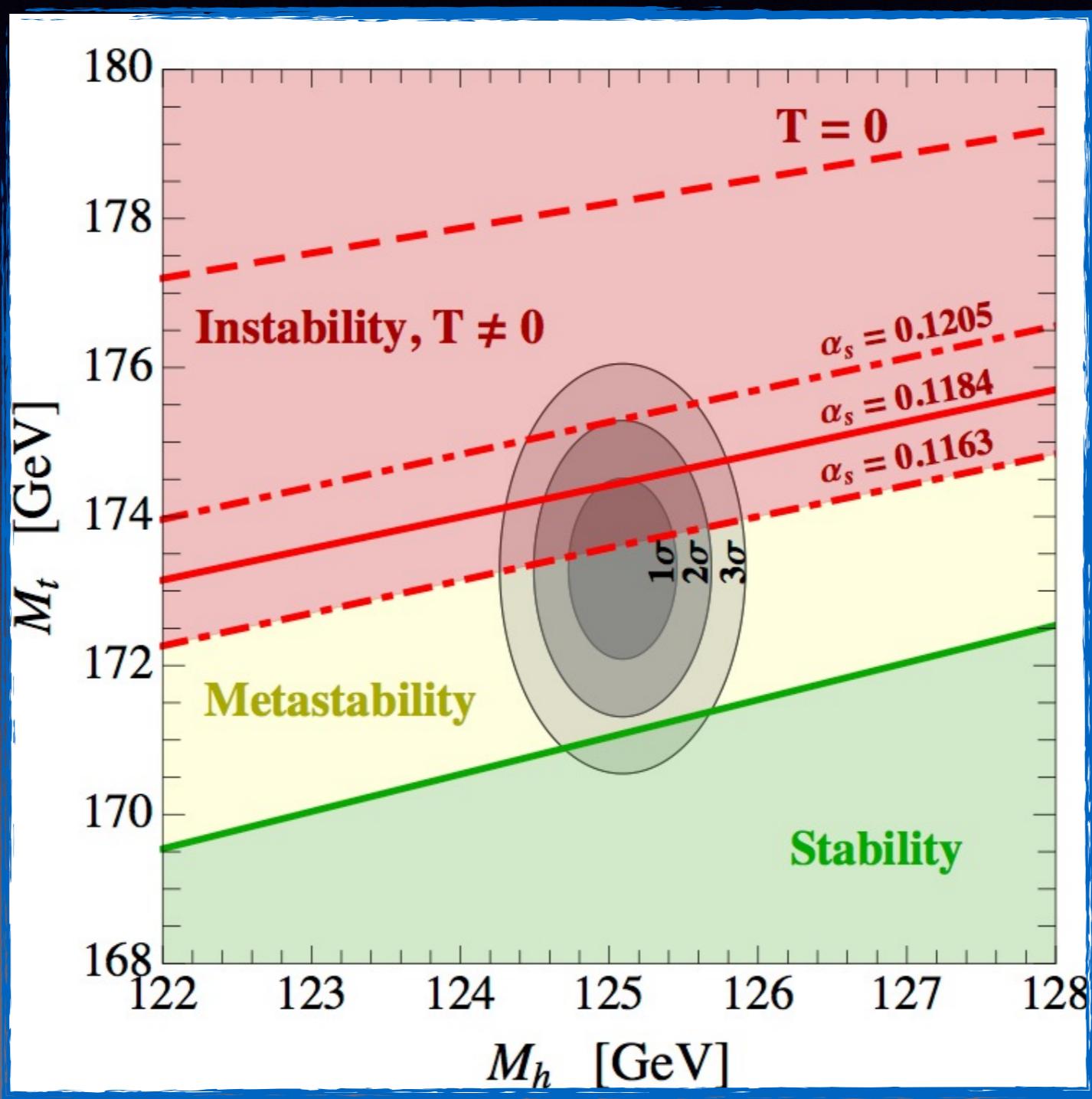
$$V_{\text{ring}}(\phi, T) = \sum_{i=W_L, Z_L, \chi_L, h} \frac{n_i T^4}{12\pi} \left\{ \left[\frac{m_i^2(t)}{T^2} \right]^{3/2} - \left[\frac{\mathcal{M}_i^2(\phi)}{T^2} \right]^{3/2} \right\}$$

$$P(T_{\text{cut-off}}) = \int_0^{T_{\text{cut-off}}} \frac{dP(T')}{dT'} dT'$$

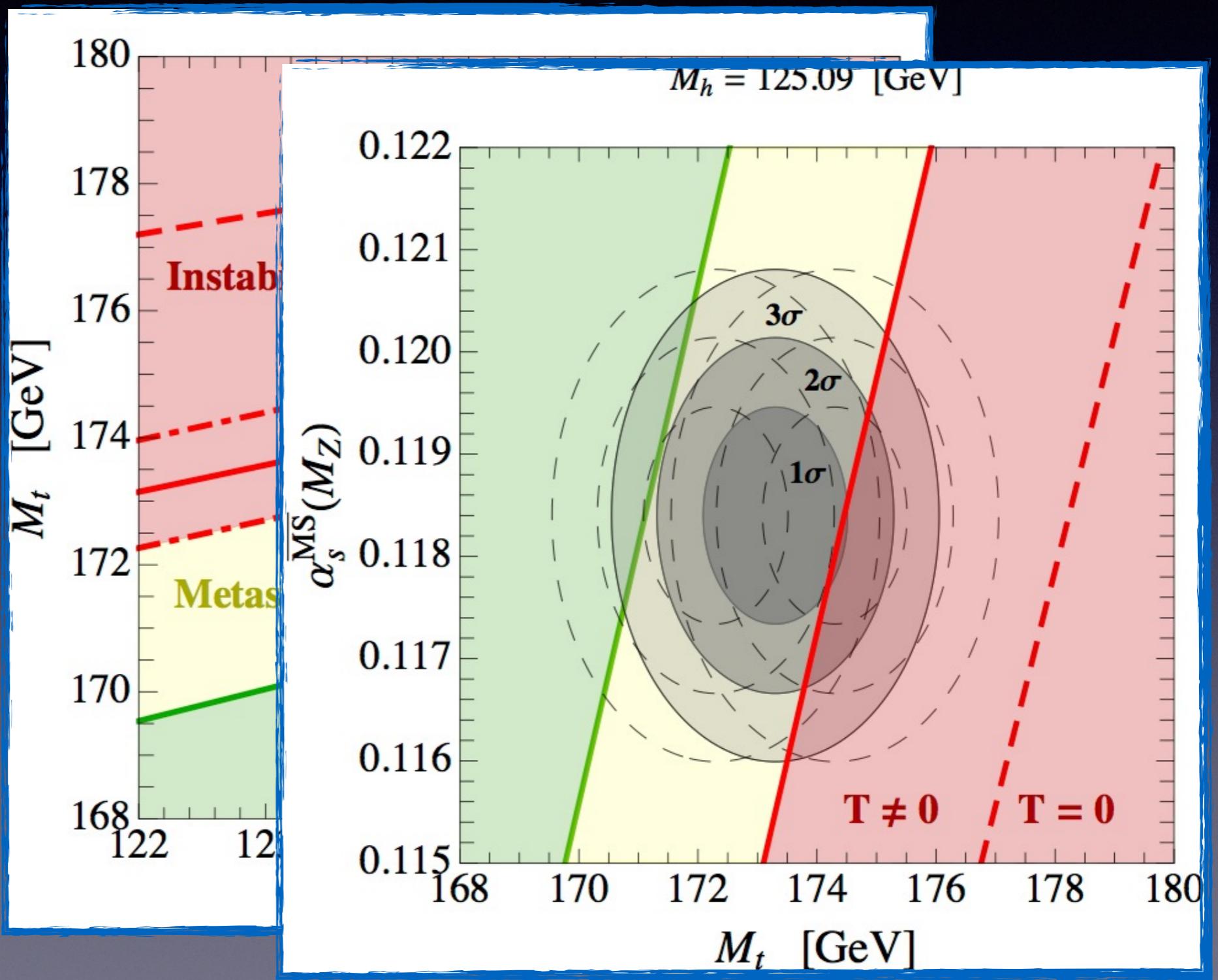
$$J_F(y) = \int_0^\infty dx x^2 \ln \left[1 + e^{-\sqrt{x^2+y}} \right]$$

$$J_B(y) = \int_0^\infty dx x^2 \ln \left[1 - e^{-\sqrt{x^2+y}} \right]$$

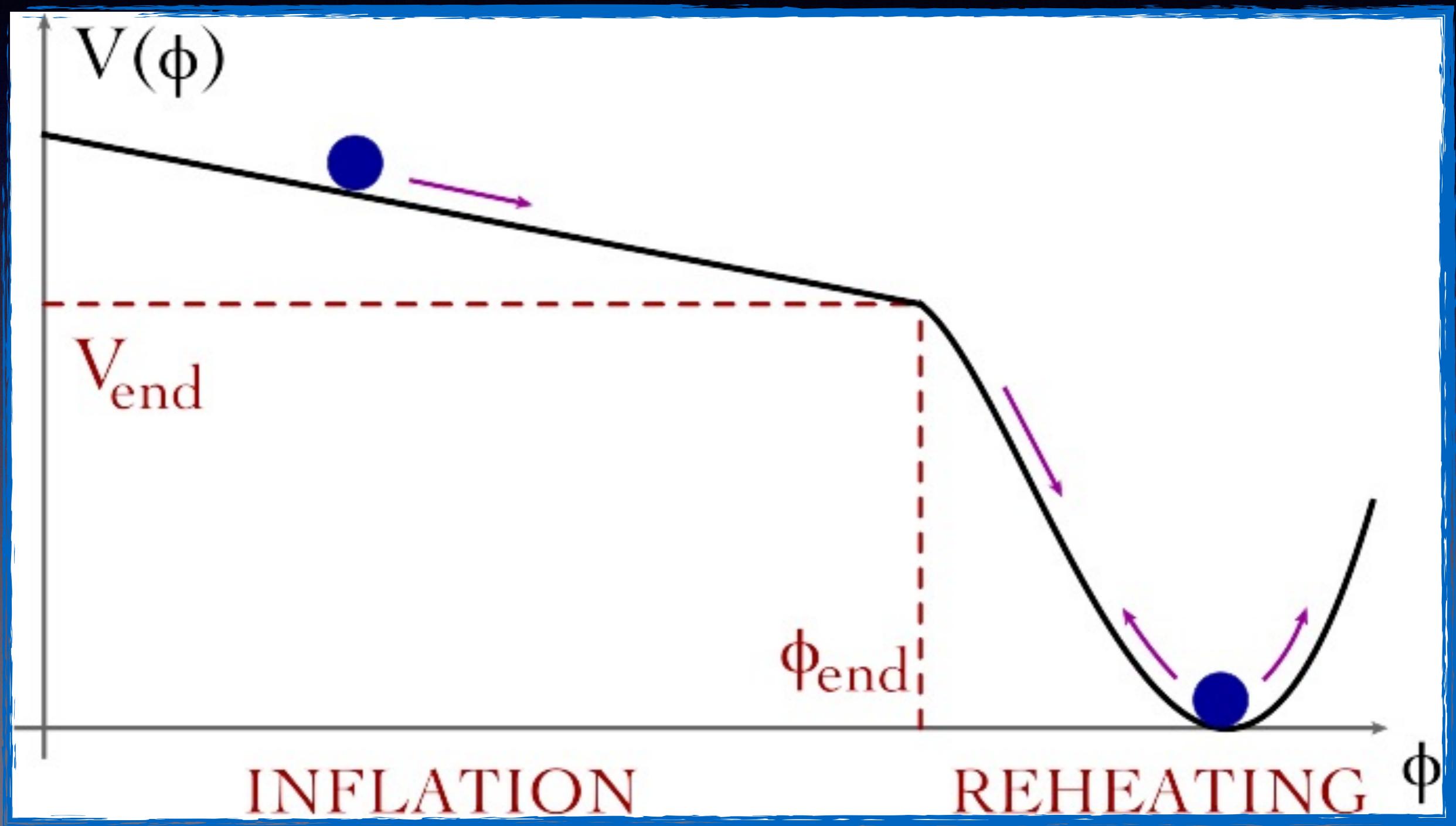
Thermal phase diagram



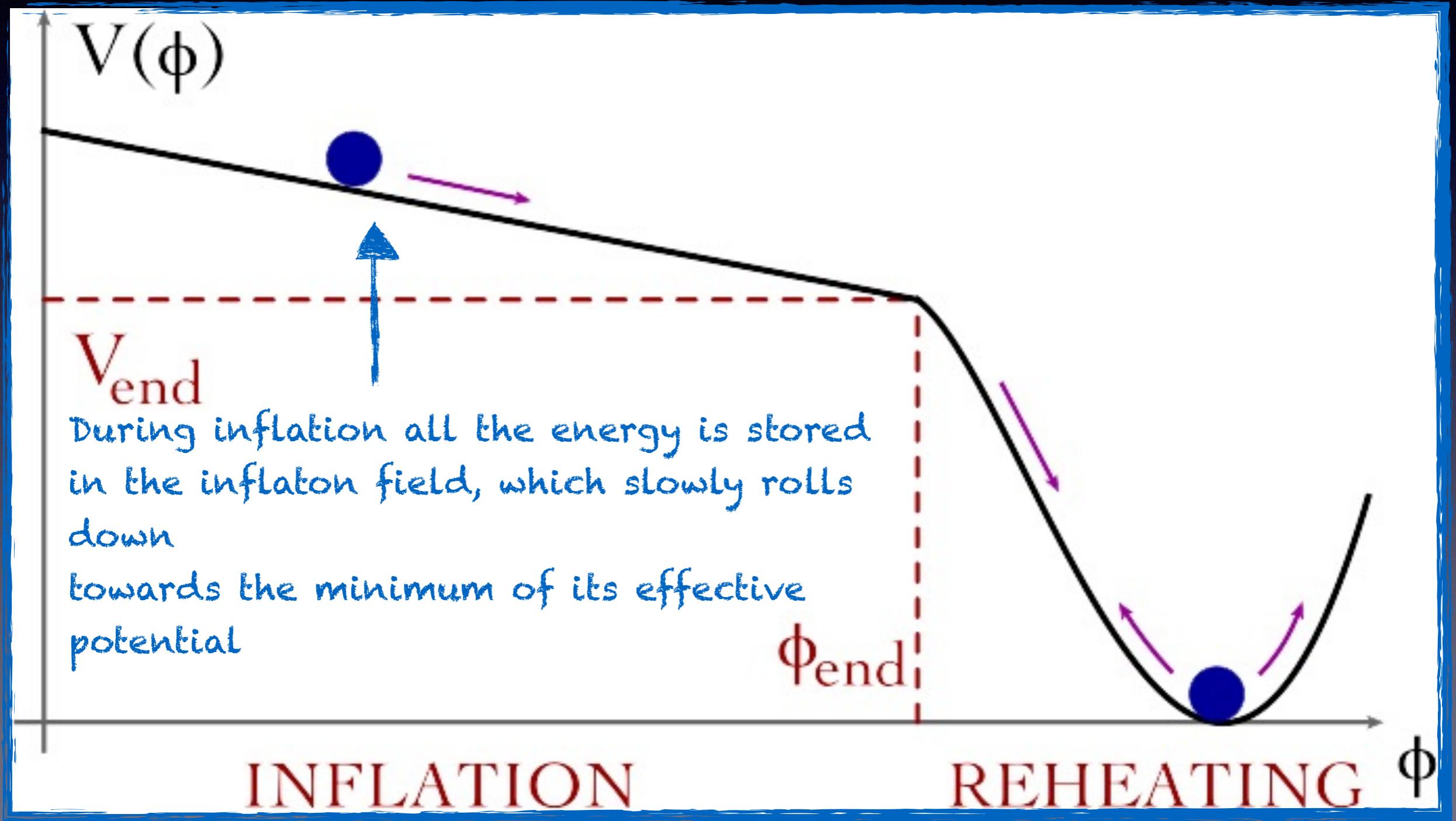
Thermal phase diagram



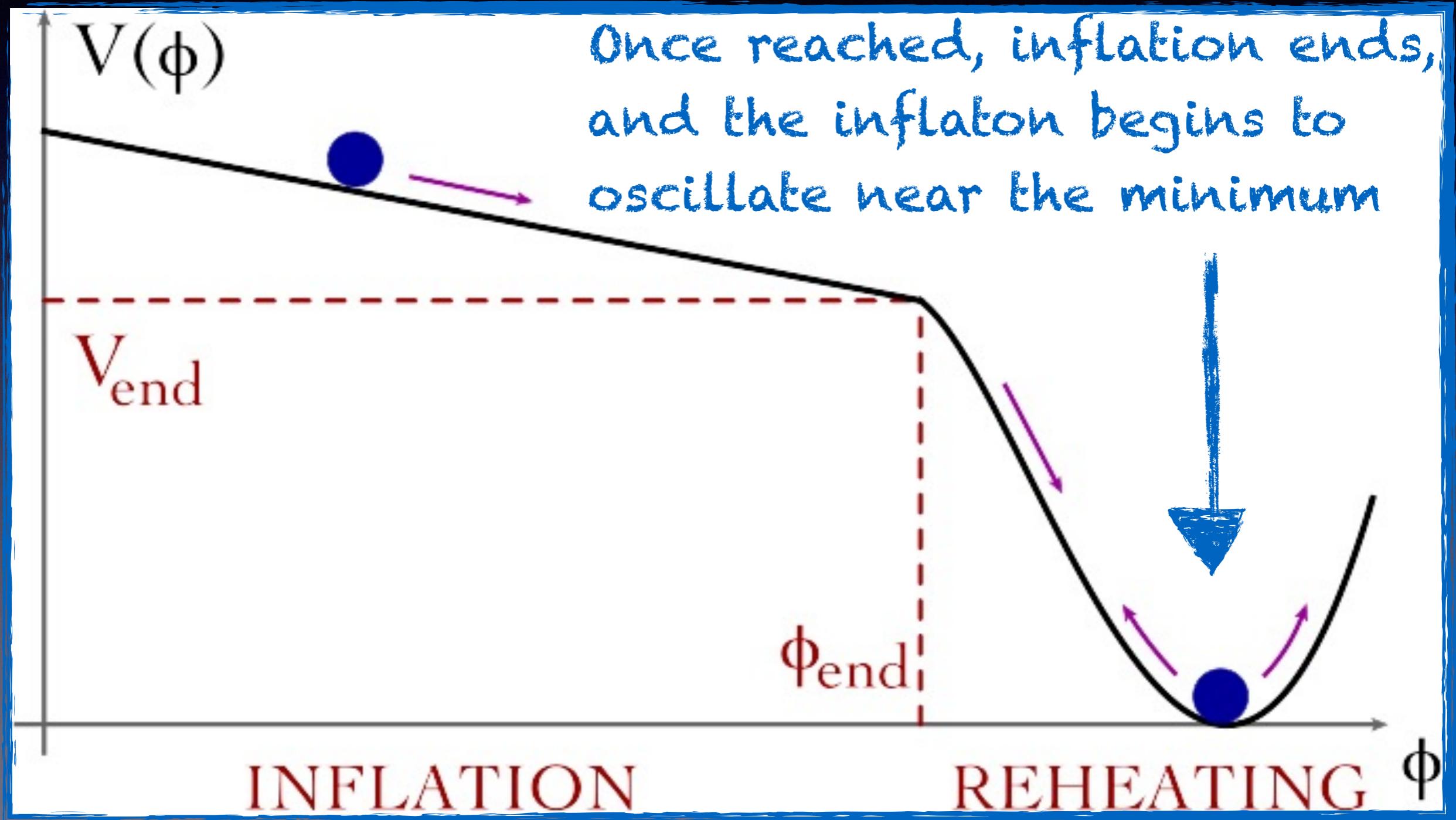
Inflation and the reheating temperature



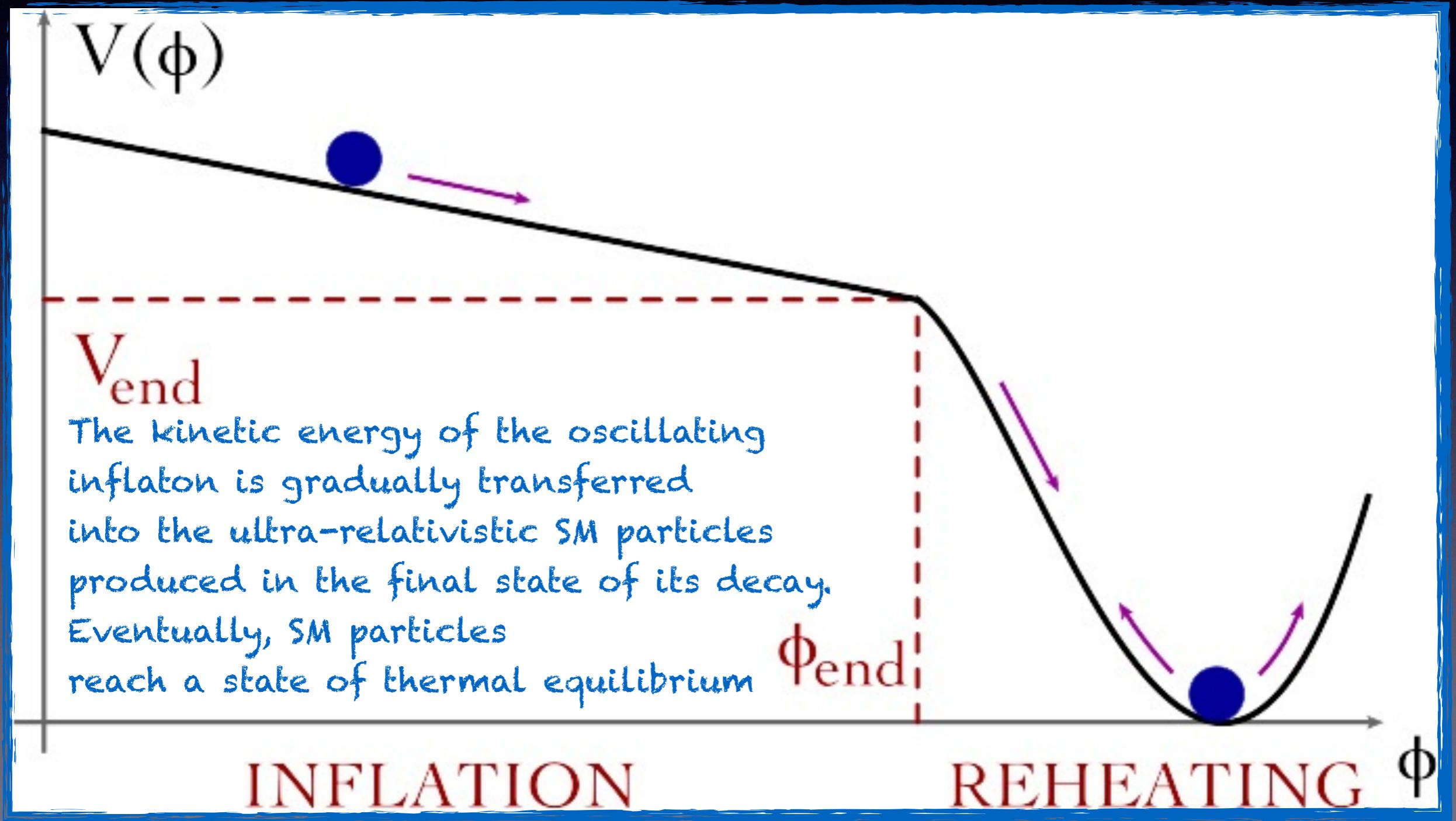
Inflation and the reheating temperature



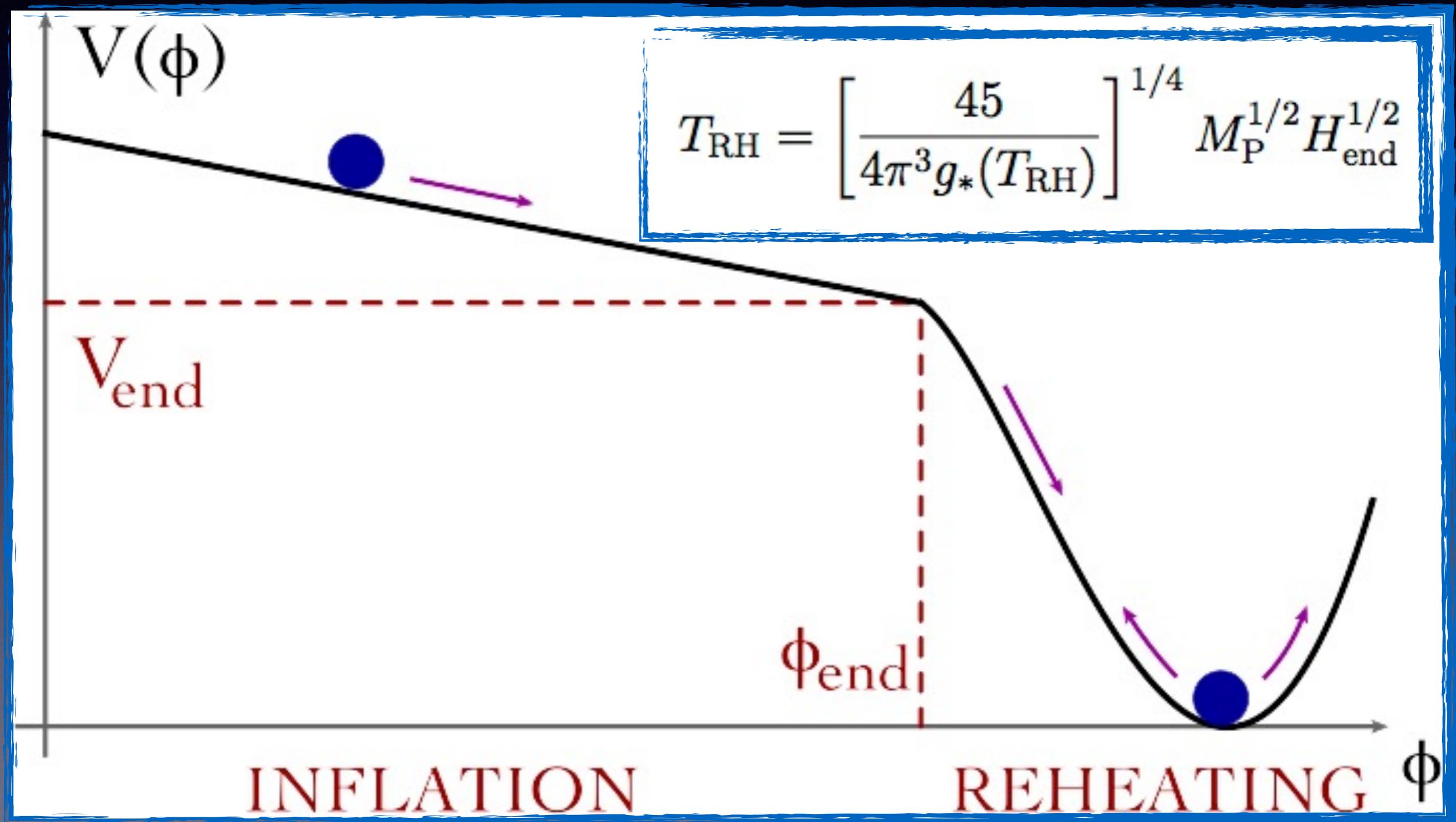
Inflation and the reheating temperature



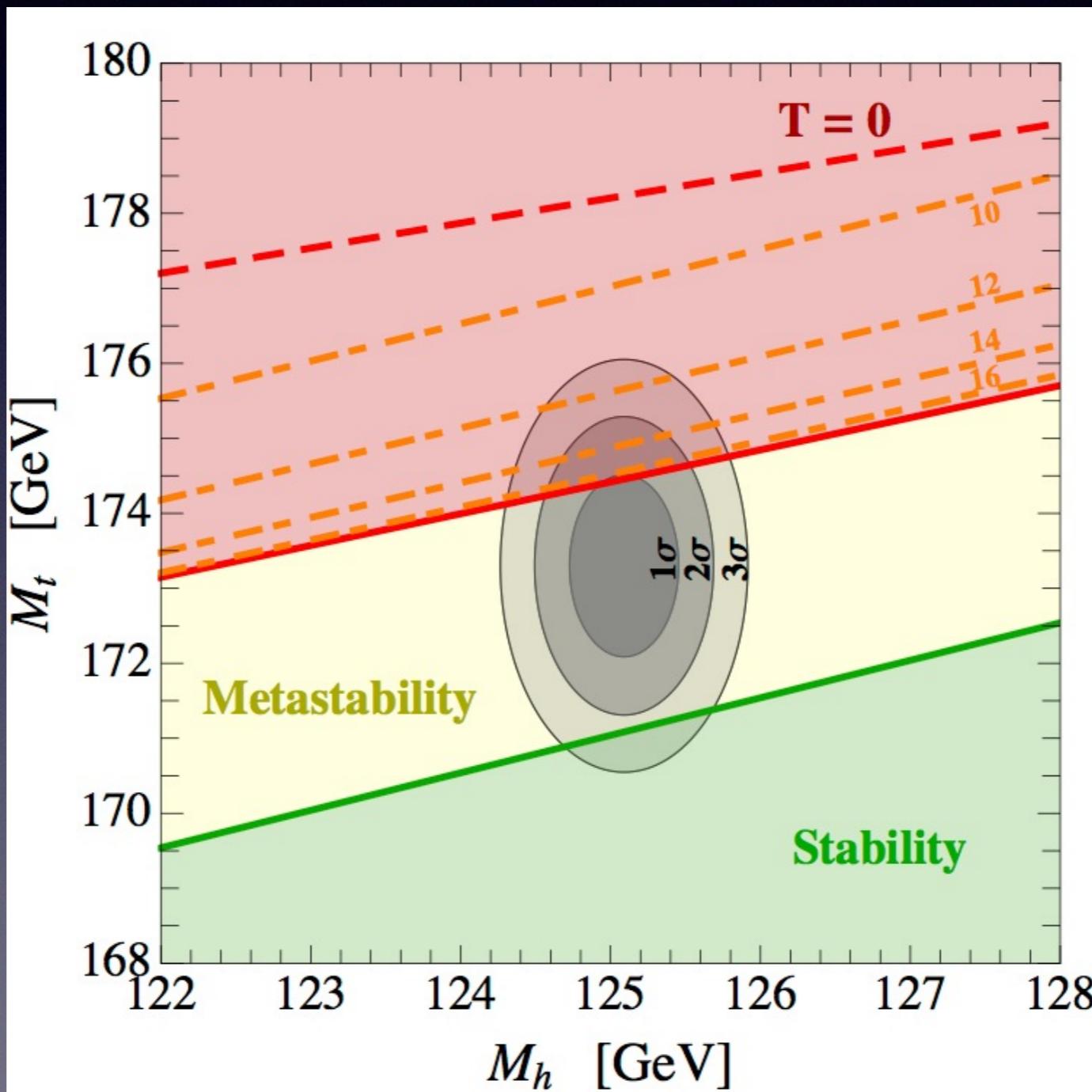
Inflation and the reheating temperature



Inflation and the reheating temperature



Inflation and the reheating temperature



What are the experimental limits on the reheating temperature ?

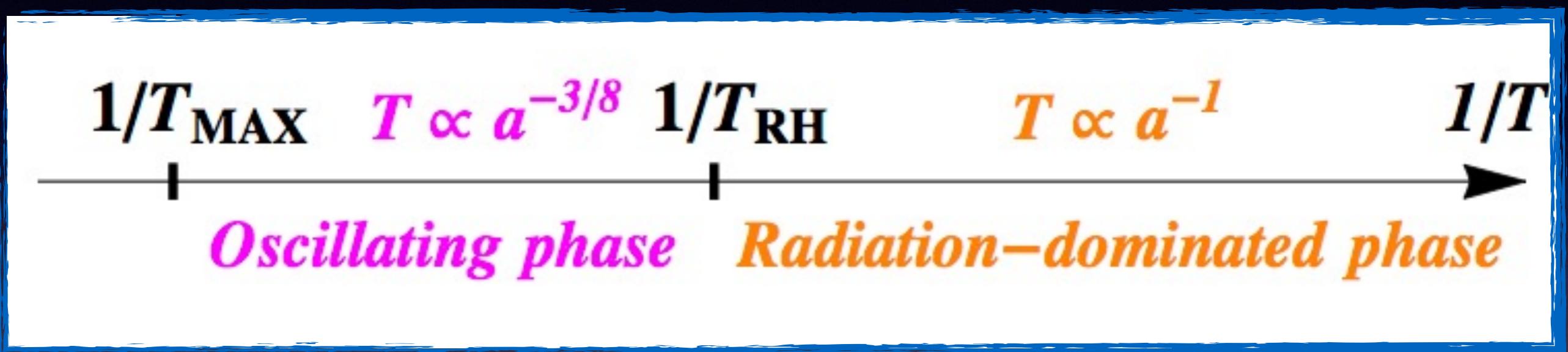
Despite its relevance in our understanding of the early Universe, very little is known about the actual value of the reheating temperature. An obvious lower bound can be obtained requiring a successful Big Bang Nucleosynthesis: 10 MeV

What are the experimental limits on the reheating temperature ?

The Hubble parameter at the end of inflation can be constrained using the limit on the tensor-to-scalar ratio of the amplitudes produced during inflation: 10^{16} GeV

$$T_{\text{RH}} = \left[\frac{45}{4\pi^3 g_*(T_{\text{RH}})} \right]^{1/4} M_{\text{P}}^{1/2} H_{\text{end}}^{1/2}$$

Beyond instantaneous reheating

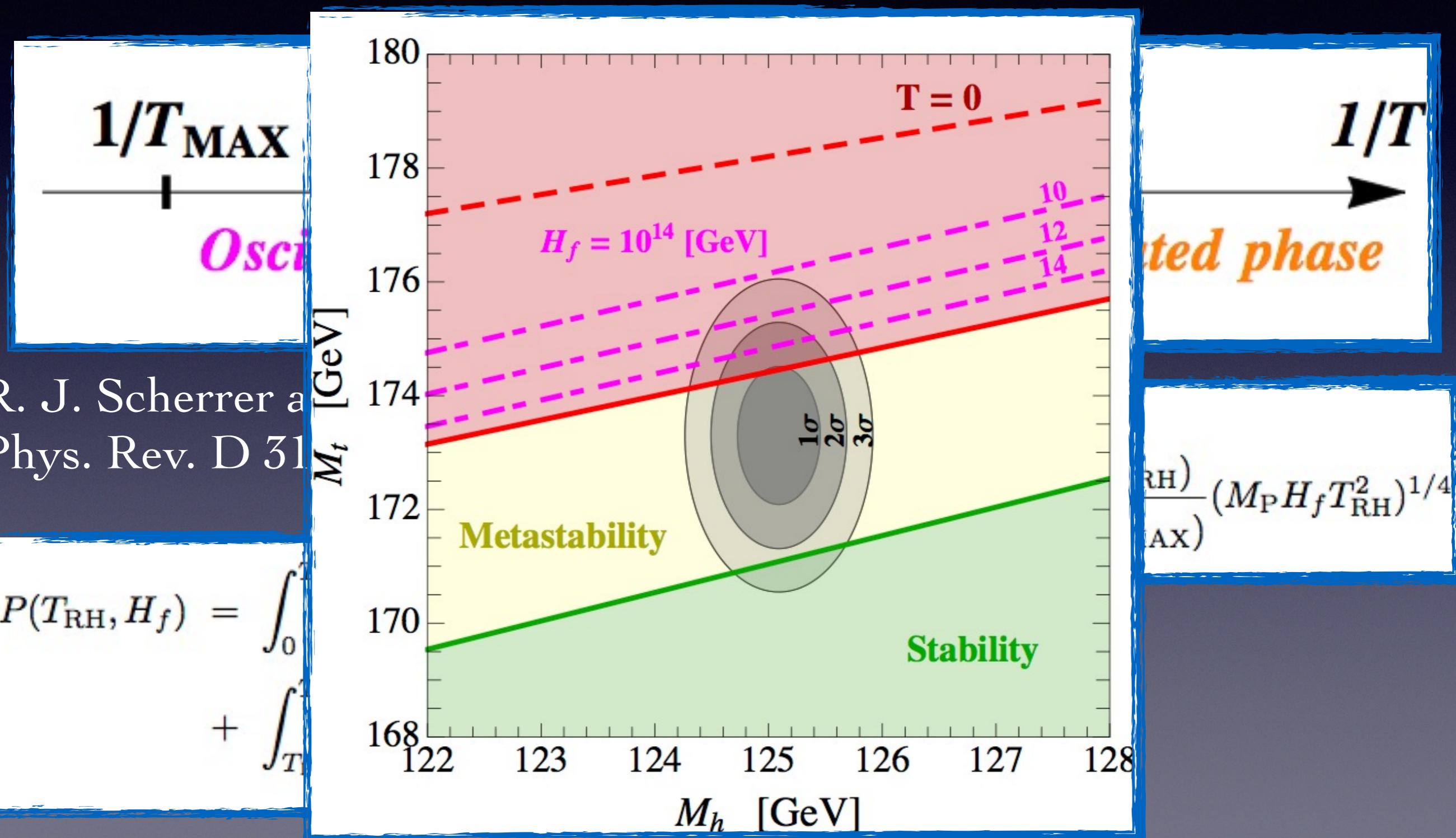


R. J. Scherrer and M. S. Turner,
Phys. Rev. D 31 (1985) 681

$$P(T_{\text{RH}}, H_f) = \int_0^{T_{\text{RH}}} \frac{dP(T')}{dT'} \Big|_{\text{eq. (11)}} dT' + \int_{T_{\text{RH}}}^{T_{\text{MAX}}} \frac{dP(T')}{dT'} \Big|_{\text{eq. (17)}} dT'$$

$$T_{\text{MAX}} = \left(\frac{3}{8}\right)^{2/5} \left(\frac{5}{\pi^3}\right)^{1/8} \frac{g_*^{1/8}(T_{\text{RH}})}{g_*^{1/4}(T_{\text{MAX}})} (M_P H_f T_{\text{RH}}^2)^{1/4}$$

Beyond instantaneous reheating



What about theory ?

Baryogenesis via leptogenesis:
larger than 10^{10} GeV

e.g.: S. Davidson, E. Nardi and Y. Nir, Phys. Rept. 466, 105 (2008)

What about theory ?

High value of the reheating temperature protects the Higgs field from large quantum fluctuations during inflation

$$10^7 \text{ GeV} - 10^{17} \text{ GeV}$$

Espinosa, Giudice, Morgante,
Riotto, Senatore, Strumia, Tetradis, arXiv:1505.04825

Prospects [Computational side]

PHYSICAL REVIEW D

VOLUME 47, NUMBER 8

15 APRIL 1993

Effective potential and first-order phase transitions: Beyond leading order

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(Received 11 December 1992)

Scenarios for electroweak baryogenesis require an understanding of the effective potential at finite temperature near a first-order electroweak phase transition. Working in the Landau gauge, we present a calculation of the dominant two-loop corrections to the ring-improved one-loop potential in the formal limit $g^4 \ll \lambda \ll g^2$, where λ is the Higgs self-coupling and g is the electroweak coupling. The limit $\lambda \ll g^2$ ensures that the phase transition is significantly first order, and the limit $g^4 \ll \lambda$ allows us to use high-temperature expansions. We find corrections from 20% to 40% at Higgs-boson masses relevant to the bound computed for baryogenesis in the minimal standard model. Though our numerical results seem to still rule out minimal standard model baryogenesis, this conclusion is not airtight because the loop expansion is only marginal when corrections are as big as 40%. We also discuss why superdaisy approximations do not correctly compute these corrections.

PACS number(s): 11.15.Kc, 05.70.Fh, 12.15.Cc, 98.80.Cq

NLO thermal corrections
potential and kinetic term (*)

Prospects

[Computational side]

(*) NLO thermal corrections
potential and kinetic term

$$\Gamma_\beta[\phi] = \int_\beta \left\{ \frac{1}{2} [1 + Z_2(\phi, T)] e^{2\Gamma(\phi)} (\partial_\mu \phi) (\partial^\mu \phi) - V_{\text{eff}}(e^{\Gamma(\phi)} \phi, T) \right\}$$

Prospects

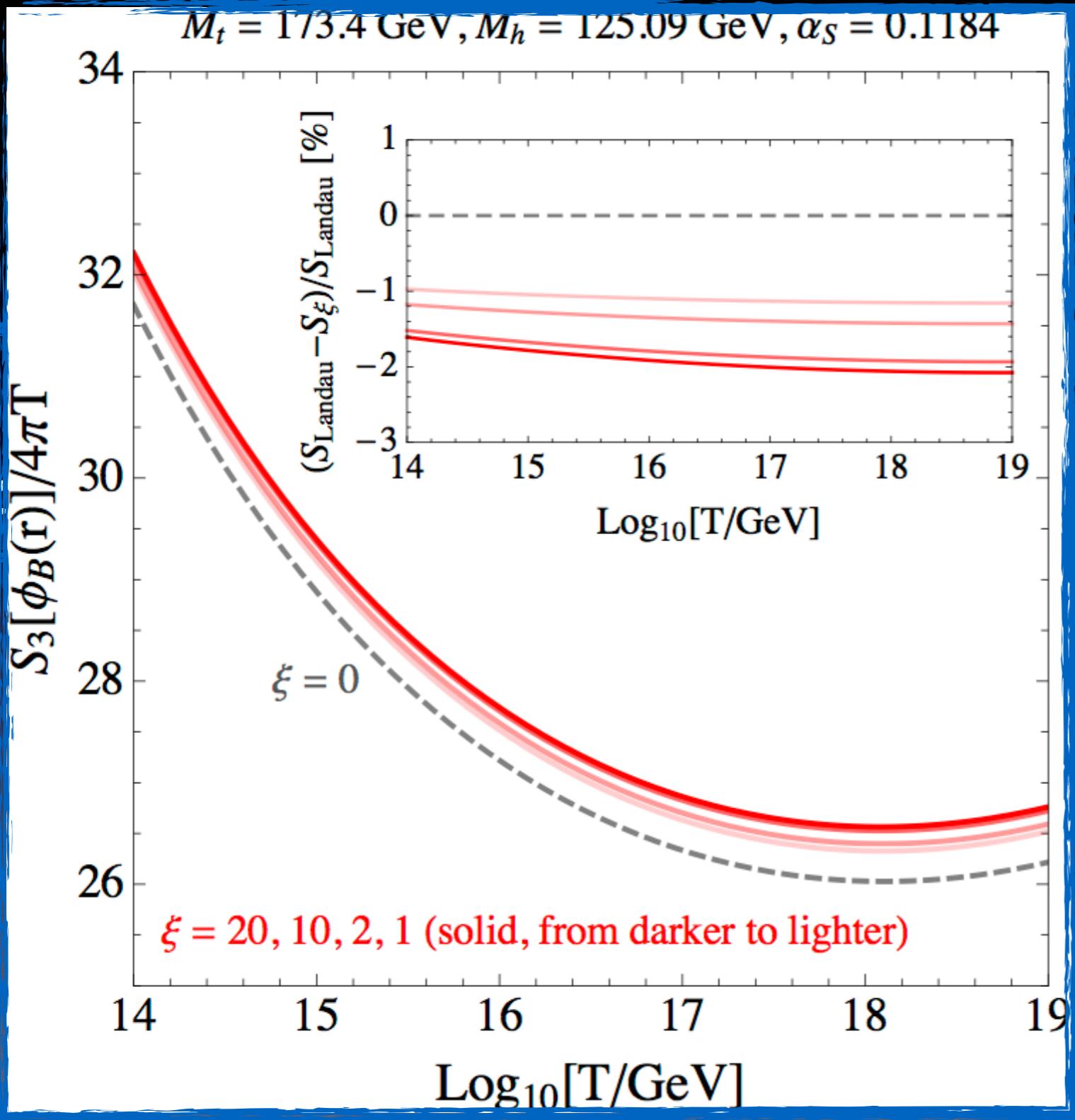
[Computational side]

(*) NLO thermal corrections
potential and kinetic term

$$\Gamma_\beta[\phi] = \int_\beta \left\{ \frac{1}{2} [1 + Z_2(\phi, T)] e^{2\Gamma(\phi)} (\partial_\mu \phi) (\partial^\mu \phi) - V_{\text{eff}}(e^{\Gamma(\phi)} \phi, T) \right\}$$

Neglecting Z introduces a
gauge dependence
(violation of Nielsen identity)

pol^{*}
 ζ



side]

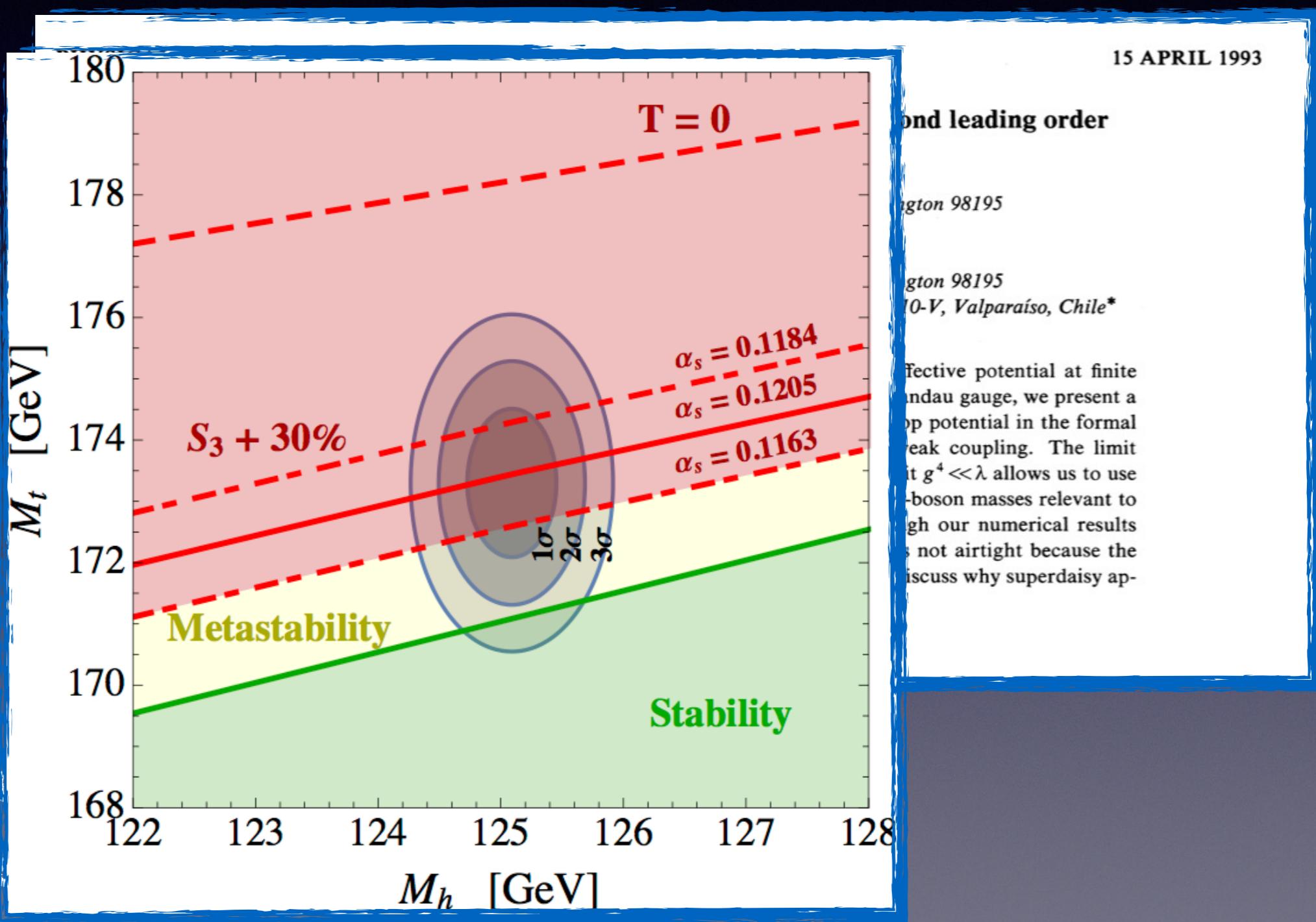
$$(\partial^\mu \phi) - V_{\text{eff}}(e^{\Gamma(\phi)} \phi, T) \}$$

See

M. Garny and T. Konstandin, arXiv:1205.3392,
for the analysis in the context of the abelian Higgs model

Prospects

[Computational side]



Prospects

[Interpretational side]

Interplay with inflation
before-after reheating

Conclusions

(In)stability of the Higgs potential
in the SM still an open issue ?

Interplay with the physics
of the early Universe is crucial