RADIATIVE SYMMETRY BREAKING WITH NEW HIGGS (AND GAUGE) BOSONS

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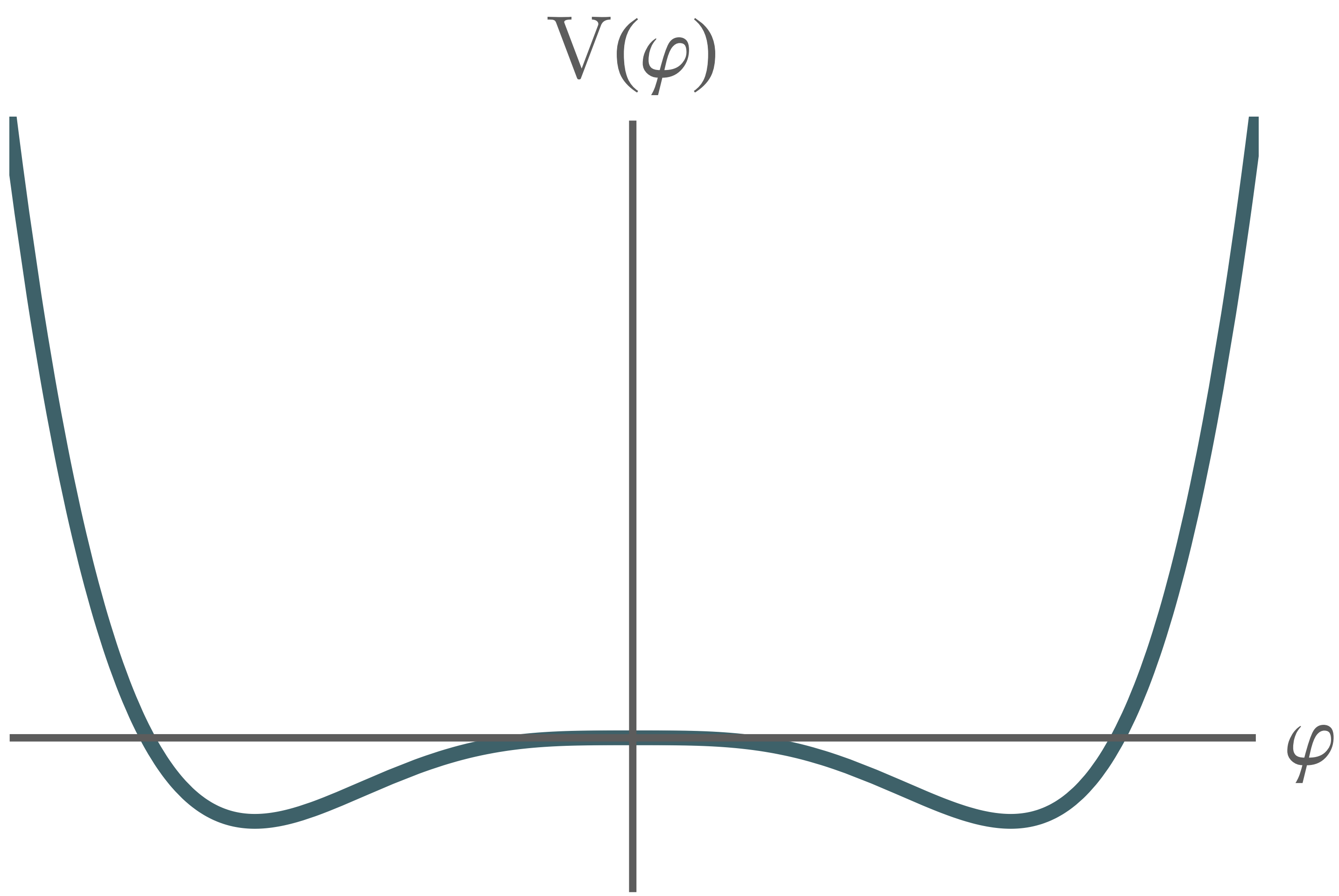
Utrecht University

in collaboration with:
Tomislav Prokopec, Michael G. Schmidt,
Leonardo Chataignier, Jonas Rezacek

Based on
JHEP 1808 (2018) 083
JHEP 1803 (2018) 014

Workshop on Multi-Higgs Models, Lisbon, 07.09.2018

SPONTANEOUS SYMMETRY BREAKING



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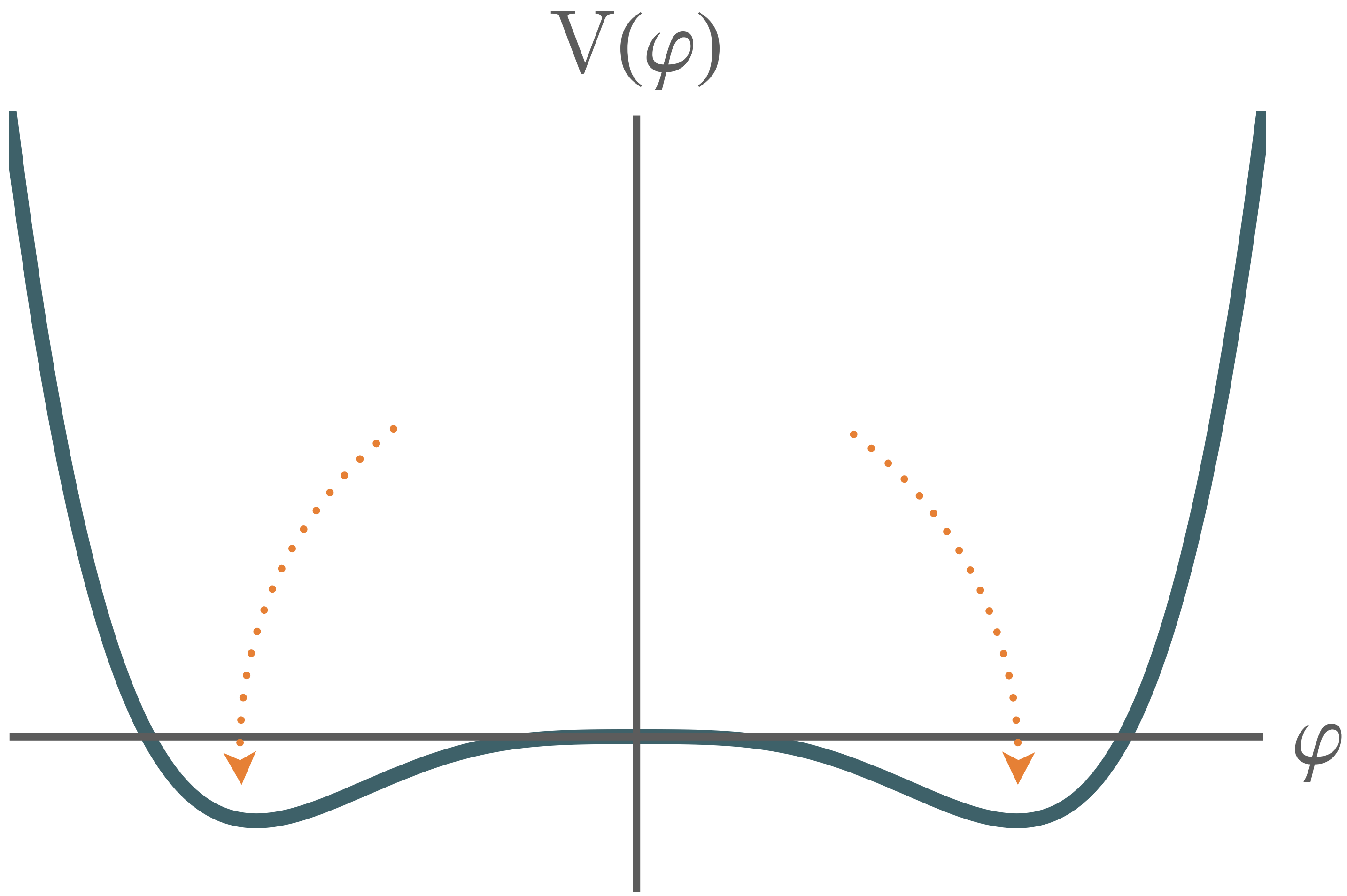
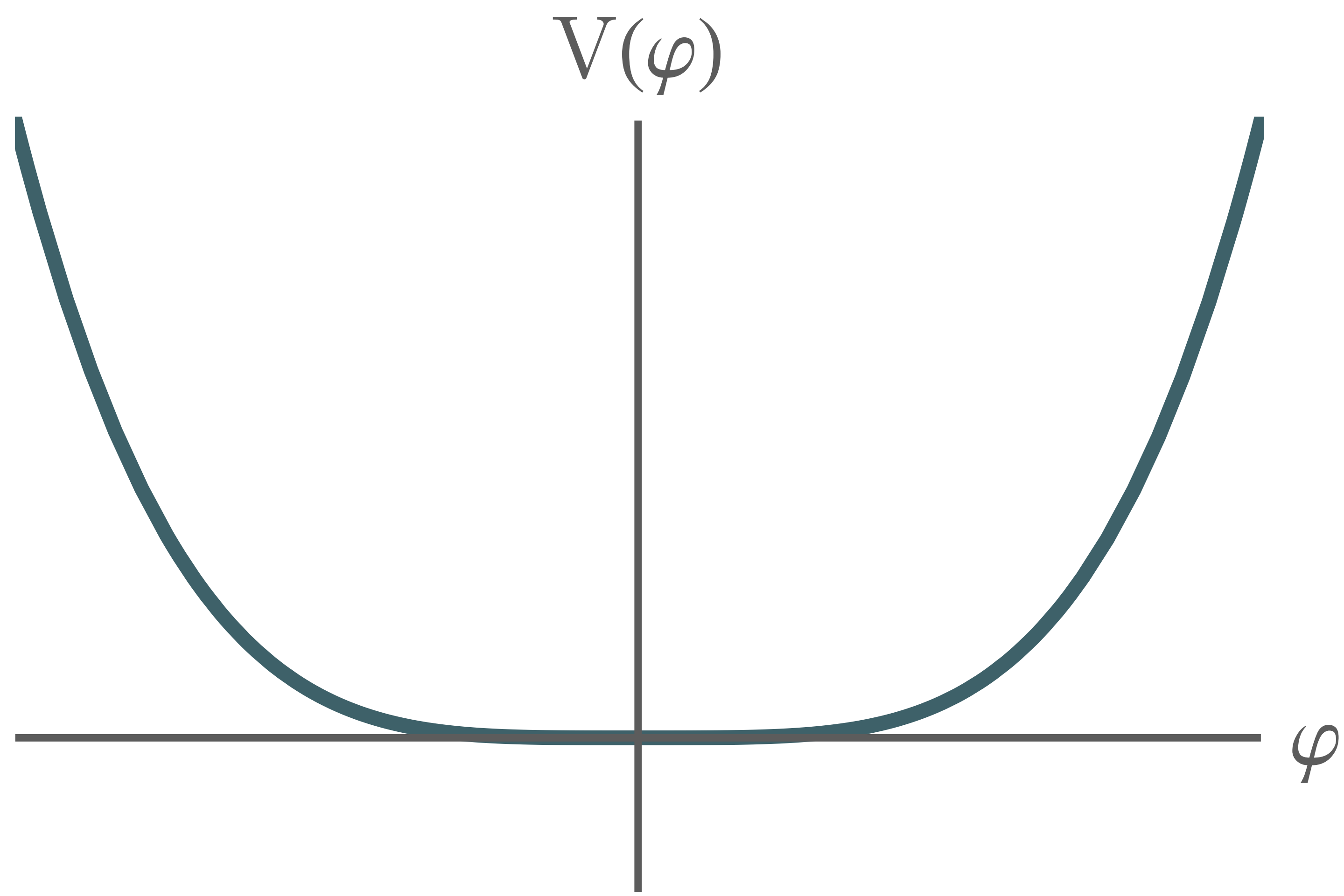
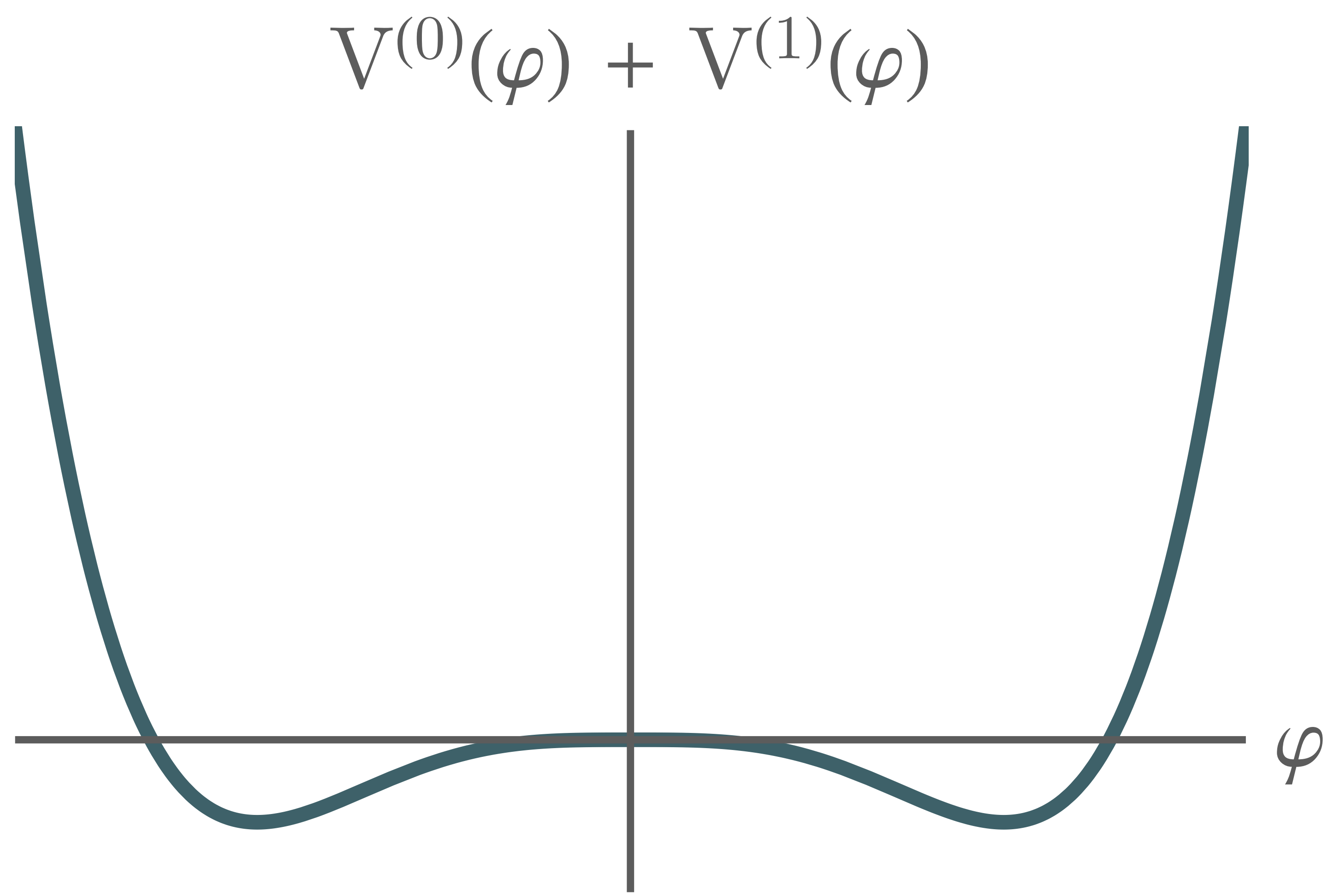


CLASSICAL CONFORMAL SYMMETRY?

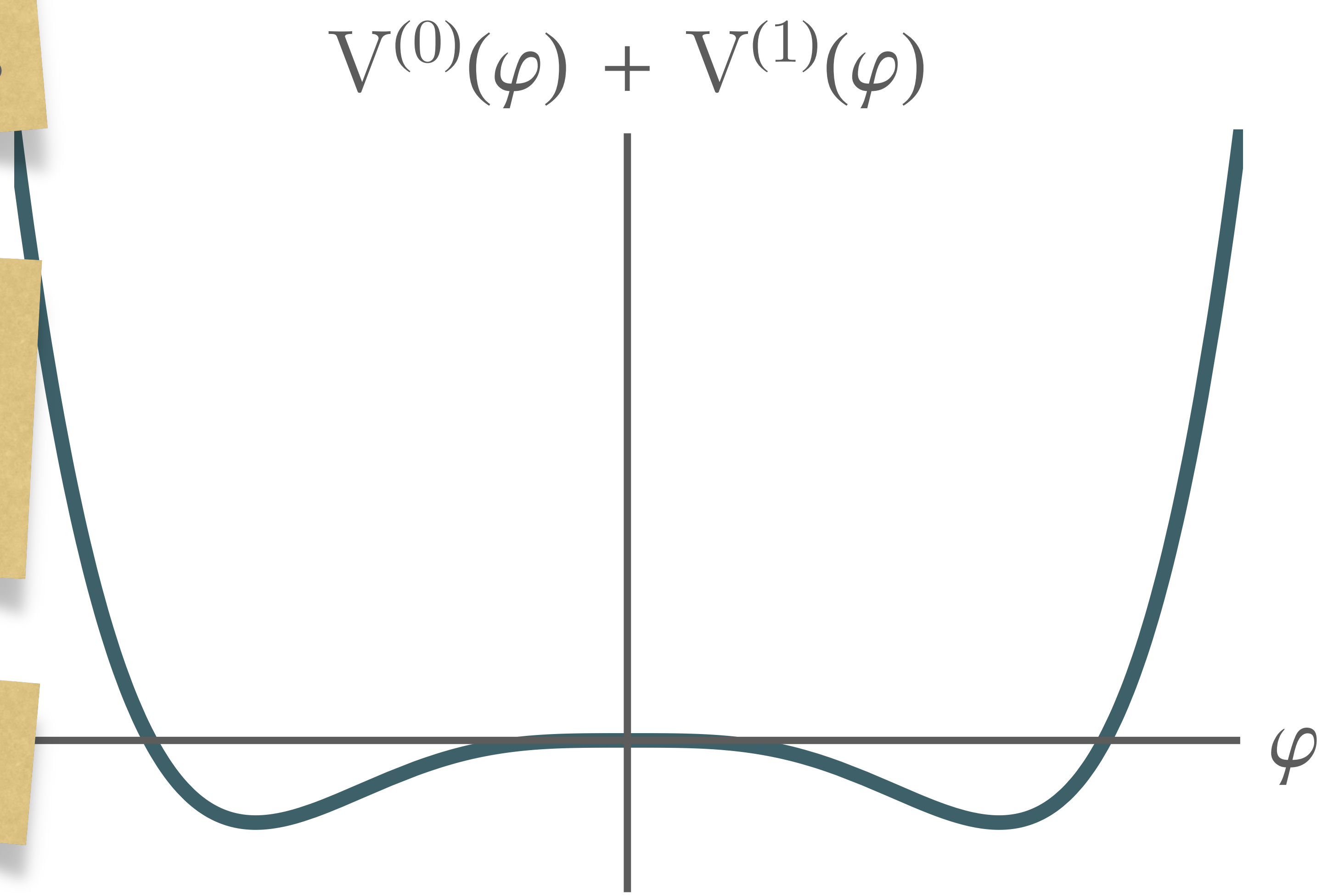


RADIATIVE BREAKING OF CONFORMAL SYMMETRY



RADIATIVE BREAKING OF CONFORMAL SYMMETRY

- dynamical generation of all mass scales
- alleviation of the hierarchy problem
- predictivity
- baryogenesis



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alleviation of the hierarchy problem

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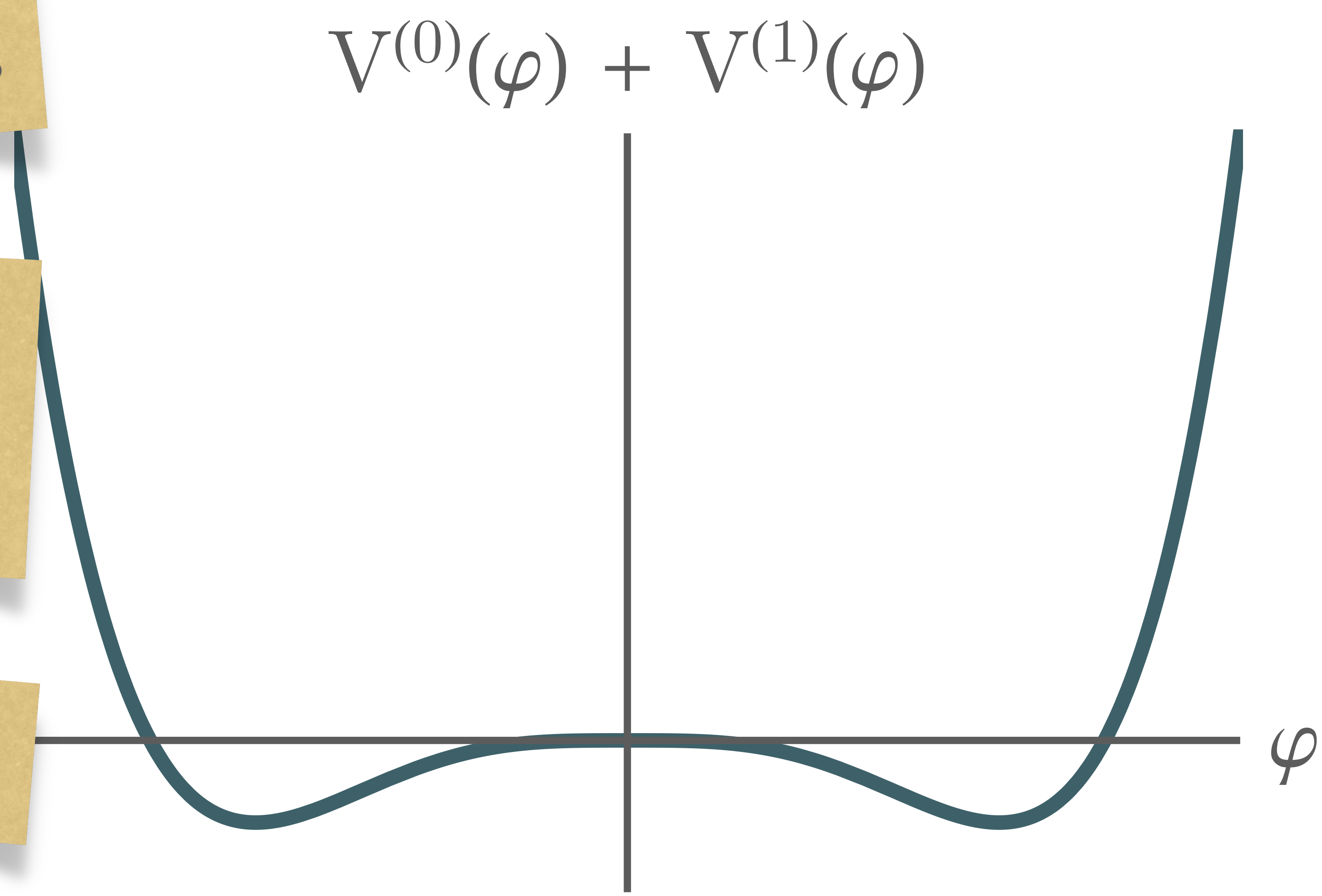
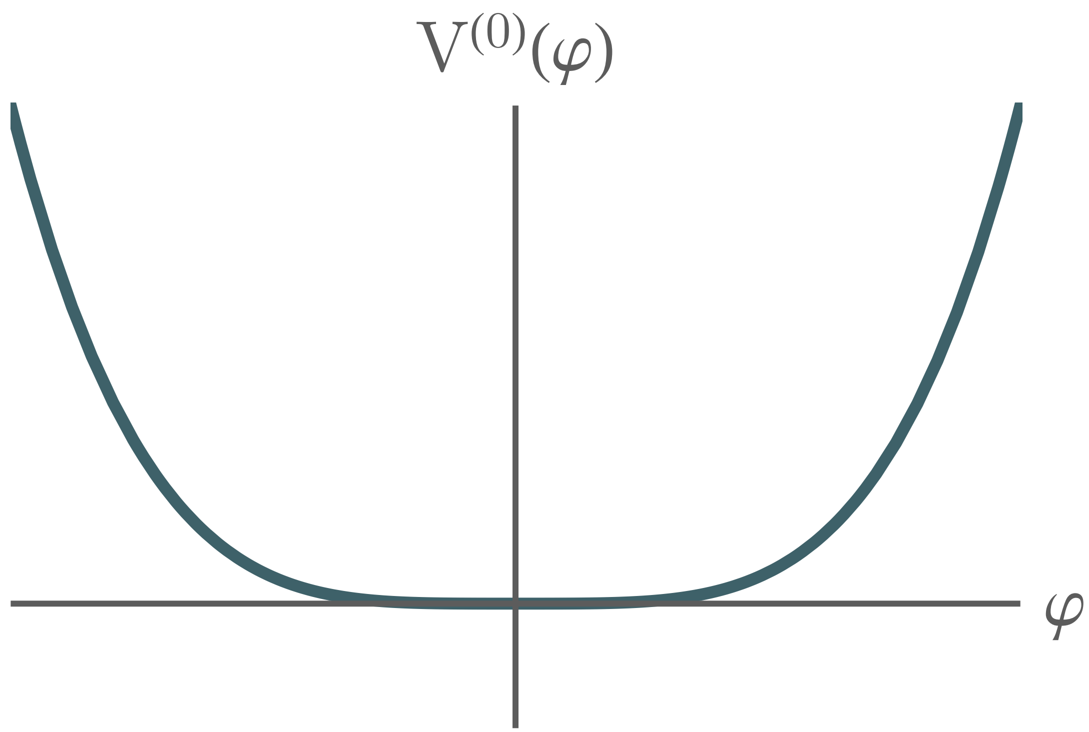


viable model

methods of analysing RSB

RADIATIVE SYMMETRY BREAKING (RSB)

RADIATIVE SYMMETRY BREAKING

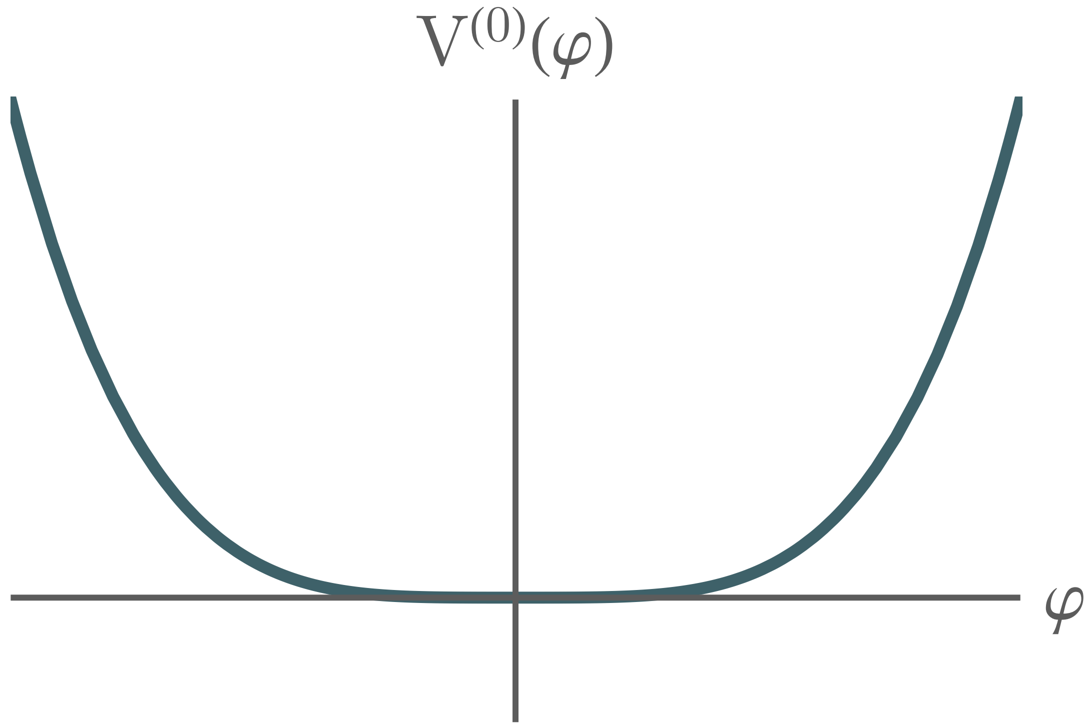


$$V^{(0)}(\varphi) = \frac{1}{4}\lambda\varphi^4$$

[S. Coleman, E. Weinberg, PRD 7 (1973) 1888]

RADIATIVE SYMMETRY BREAKING

Pure scalar theory



$$V^{(0)}(\varphi) = \frac{1}{4}\lambda\varphi^4$$

$$V^{(1)}(\varphi) = \frac{9\lambda^2\varphi^4}{64\pi^2}\left(\log\frac{3\lambda\varphi^2}{\mu^2} - \frac{3}{2}\right)$$

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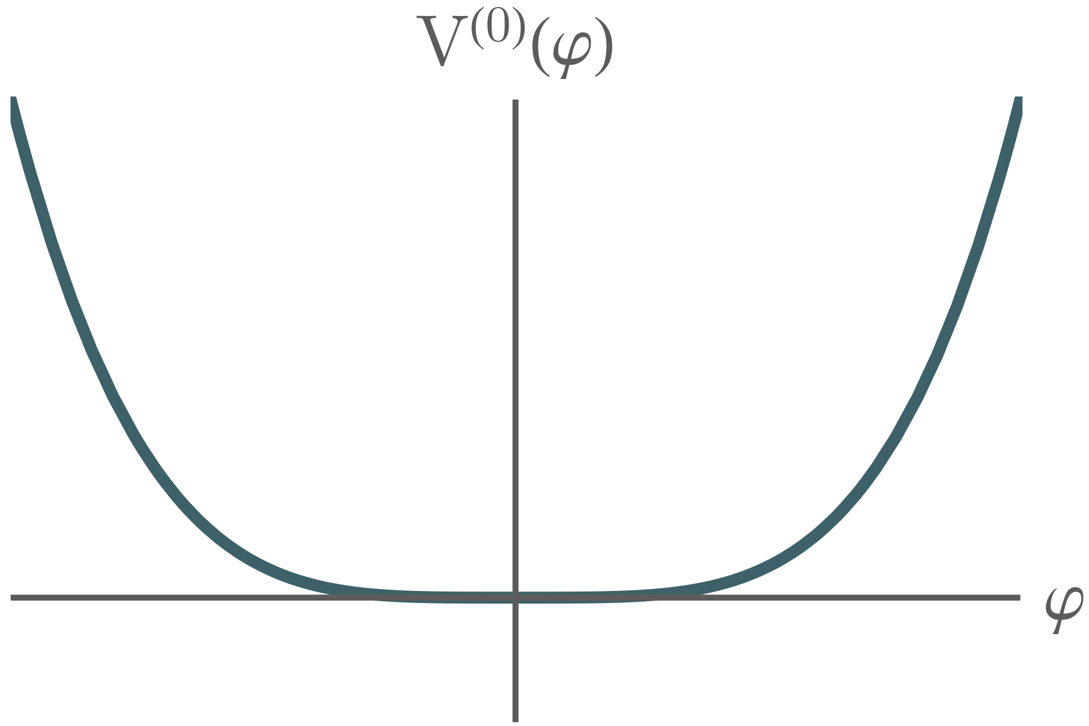

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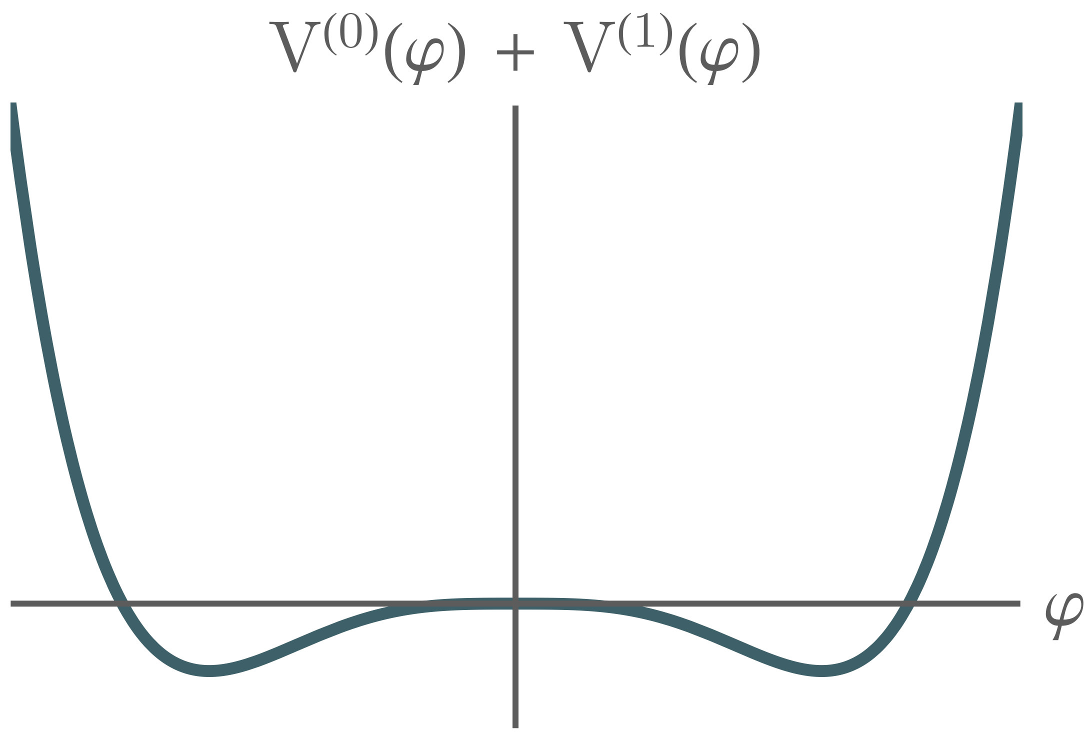
RADIATIVE SYMMETRY BREAKING

scalar QED



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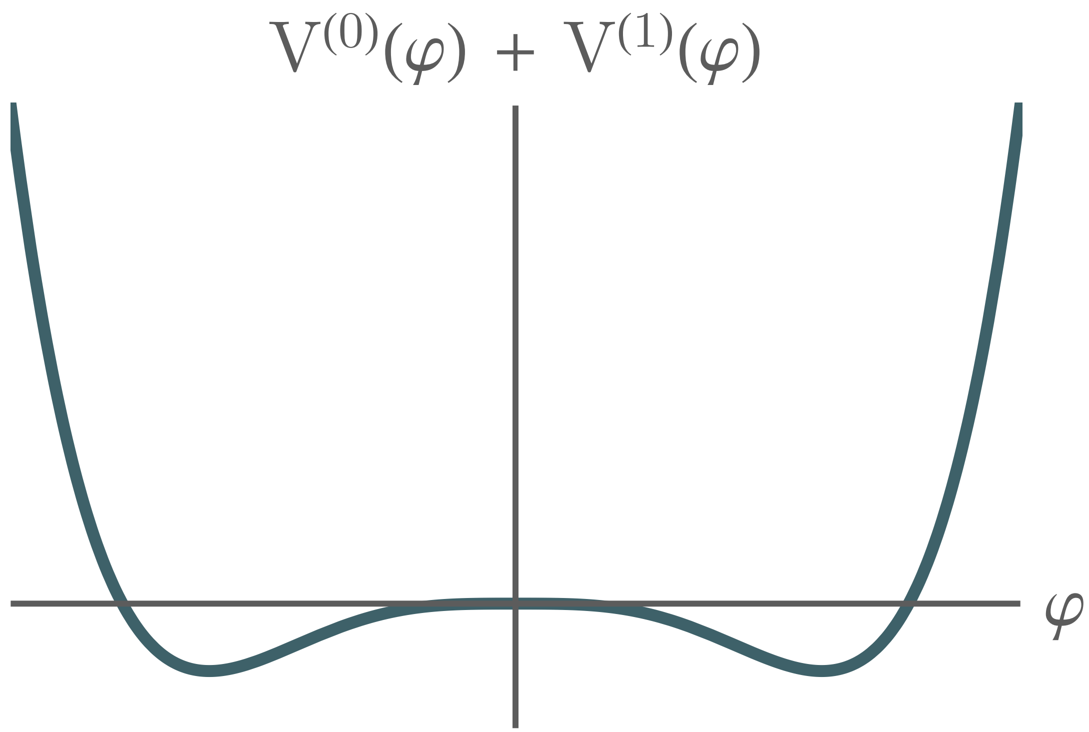

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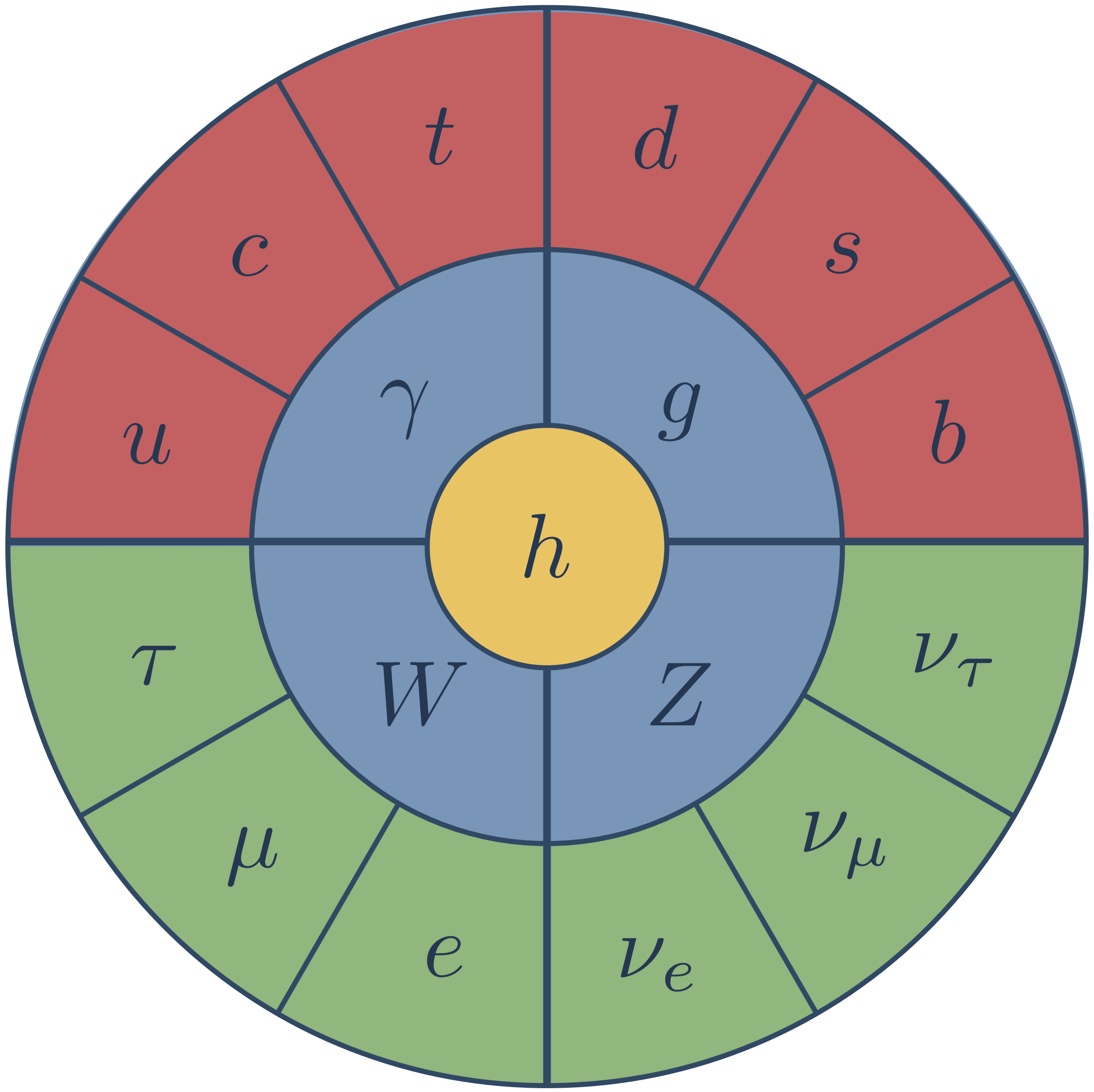
Hierarchy of couplings crucial, $\lambda \sim e^4$

[S.Coleman, E. Weinberg, PRD 7 (1973) 1888]

CONFORMAL STANDARD MODEL?



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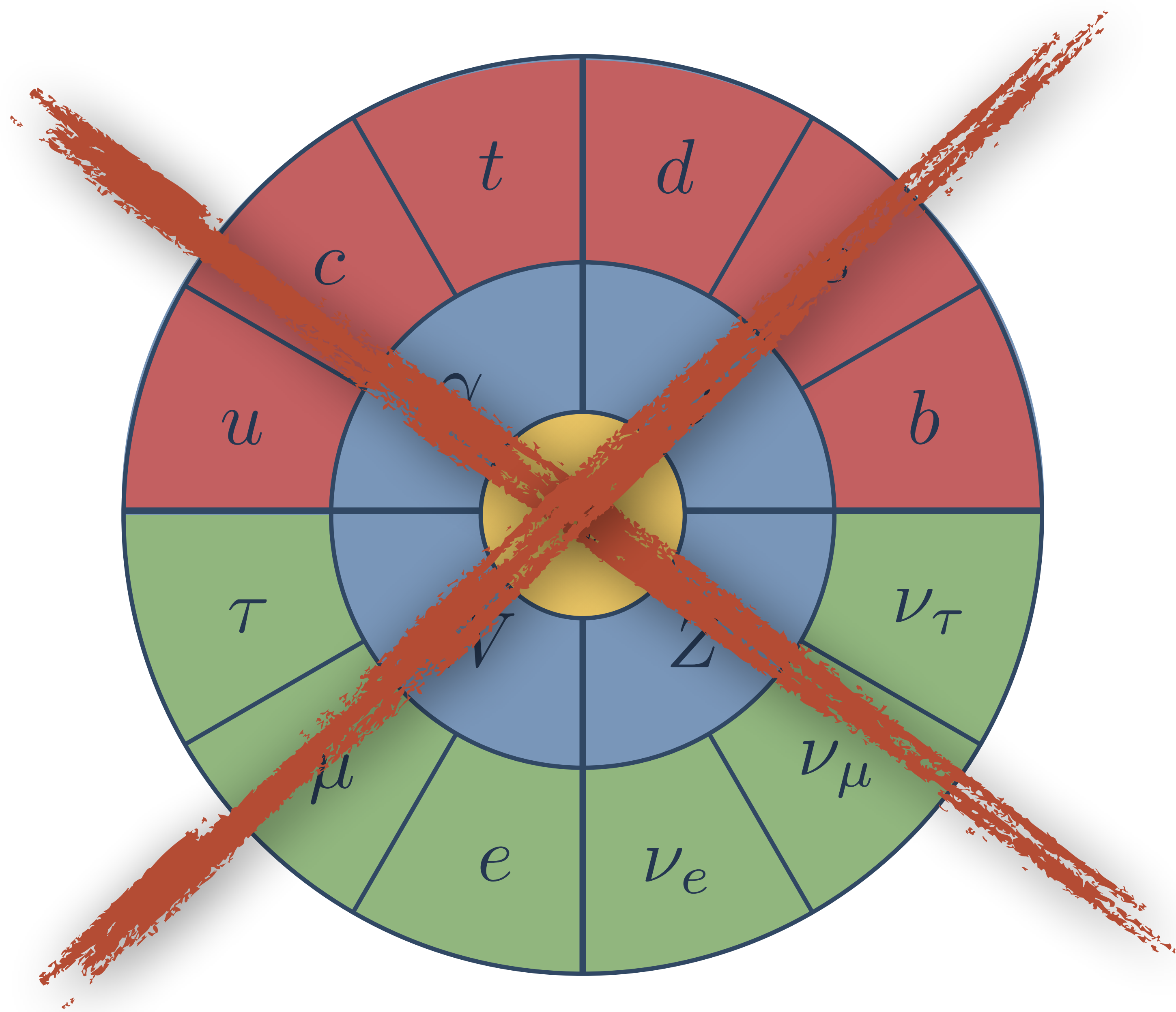
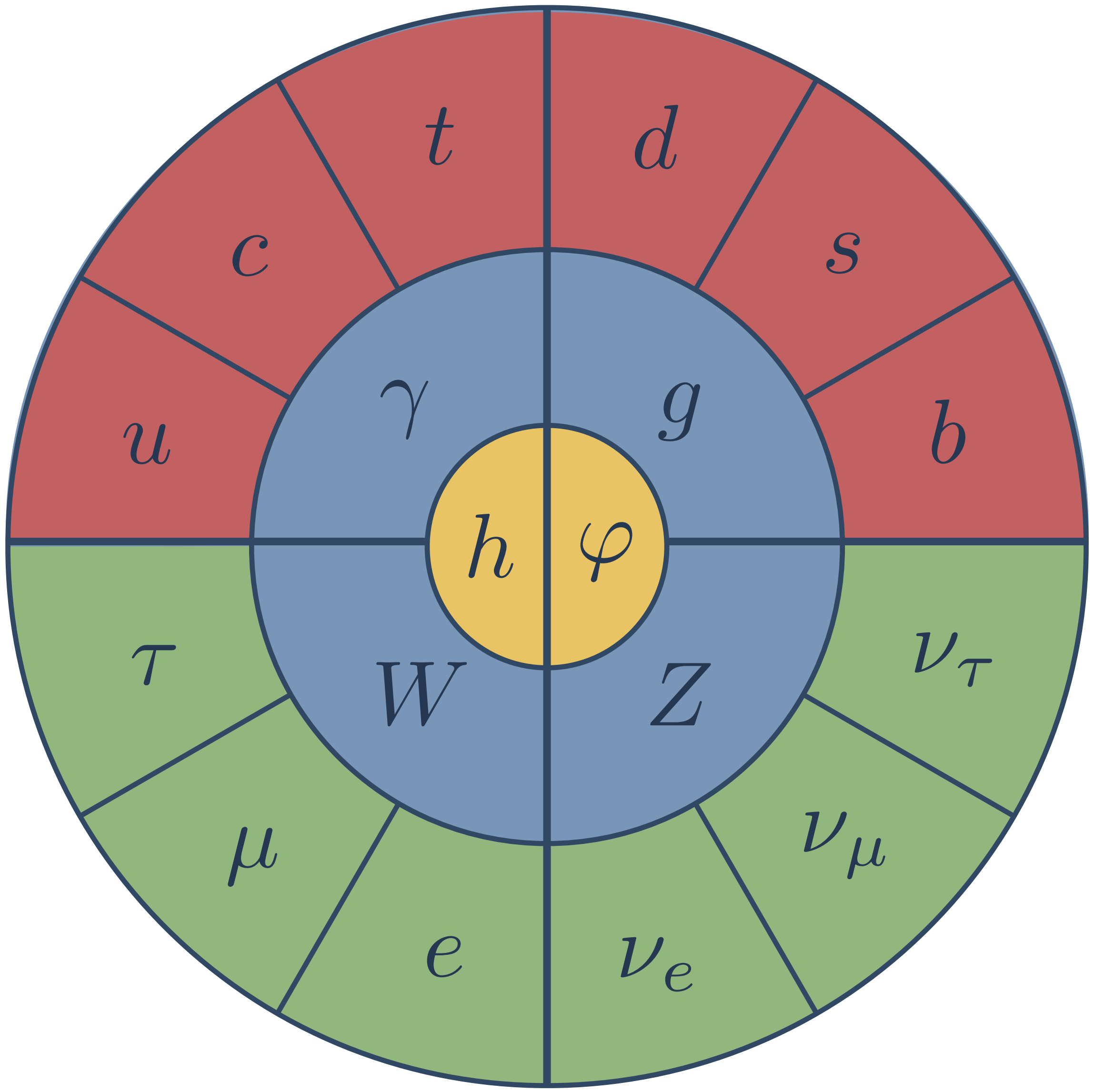


CONFORMAL STANDARD MODEL + SINGLET?



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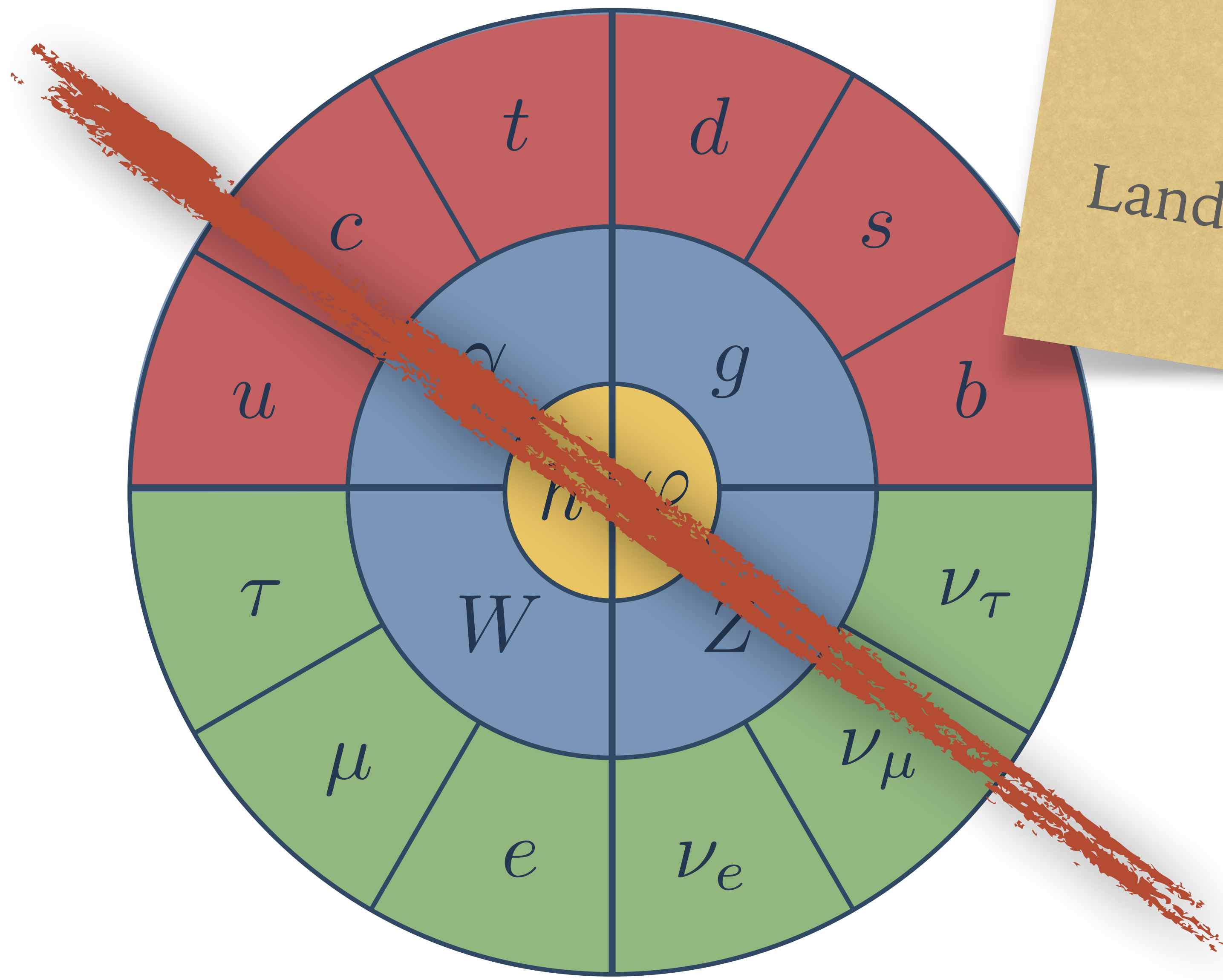


Large scalar coupling

↓

Landau pole at low energy

SU(2)CSM

SU(2)CSM

cSM:
$SU(2)_L \times U(1)_Y$
Φ

Hidden sector:
$SU(2)_X$
Ψ

$$V^{(0)}(\Phi, \Psi) = \lambda_1 \left(\Phi^\dagger \Phi\right)^2 + \lambda_2 \left(\Phi^\dagger \Phi\right)\left(\Psi^\dagger \Psi\right) + \lambda_3 \left(\Psi^\dagger \Psi\right)^2,$$

[See also: T. Hambye, A. Strumia, PRD88 (2013) 055022, C.D. Carone, R.Ramos, PRD88 (2013) 055020, V.V. Khoze, C. McCabe, G. Ro, JHEP 08 (2014) 026, S. Di Chiara, K. Tuominen, JHEP 1511 (2015) 188]

SU(2)CSM

SU(2)CSM

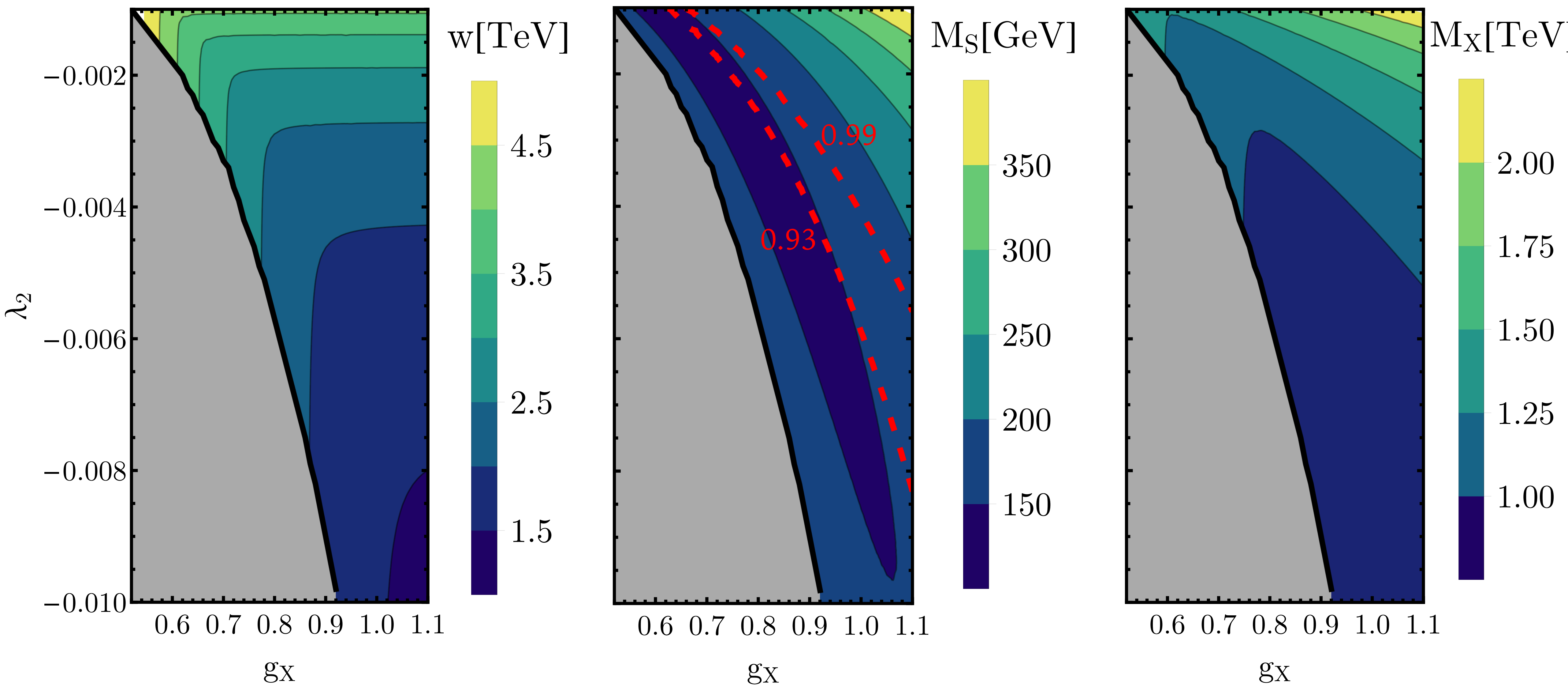
Perturbative, stable and self-consistent up to the Planck scale

All masses generated radiatively

DM candidate

Potential for baryogengesis

RADIATIVE SYMMETRY BREAKING IN SU(2)CSM



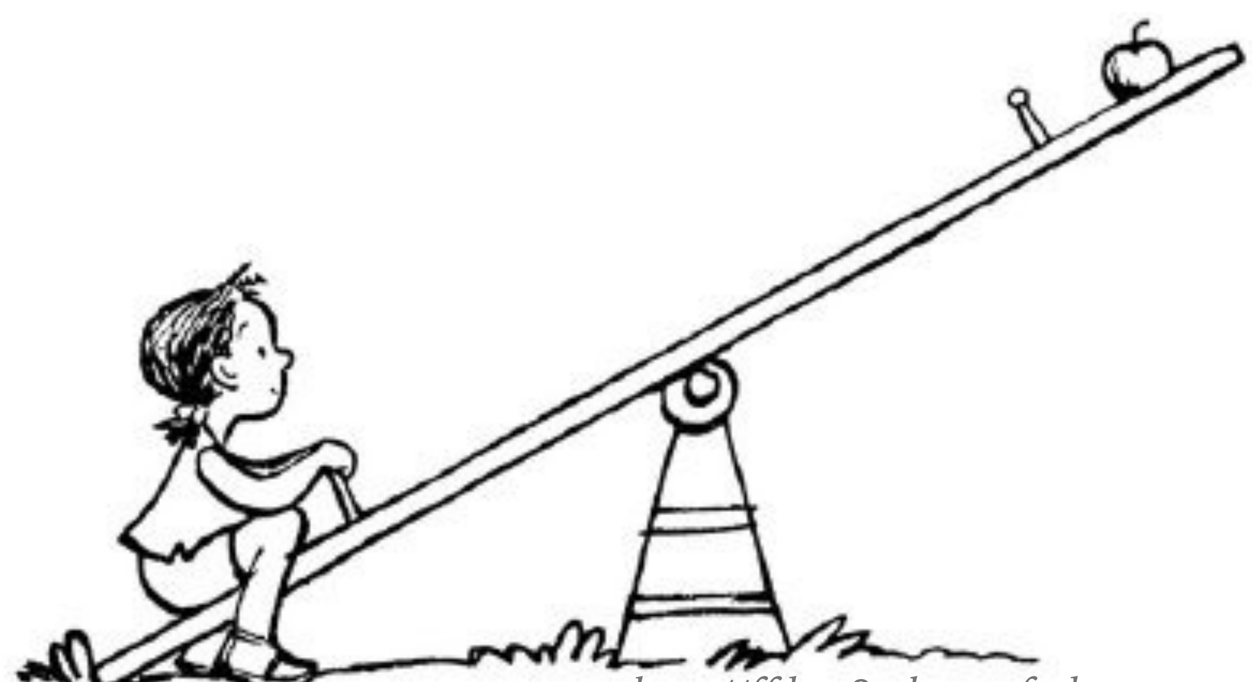
The VEV of the new scalar much greater than 246 GeV

[T. Robens and T. Stefaniak, Eur. Phys. J. C76 (2016) 268]

METHODS FOR STUDYING RSB

COMPLICATIONS DUE TO EXTRA SCALARS

- Minima along different directions possible
- Hierarchy of couplings not clear
- Many energy scales present



http://ffden-2.phys.uaf.edu

METHODS OF STUDYING RSB

Coleman-Weinberg method

COLEMAN-WEINBERG: EXPLICIT MINIMISATION

$$\frac{\partial V}{\partial h}\bigg|_{h=v,\varphi=w} = \lambda_1 v^3 + \frac{1}{2}\lambda_2 v w^2 + \frac{\partial V^{(1)}}{\partial h}\bigg|_{h=v,\varphi=w} = 0,$$

$$\frac{\partial V}{\partial \varphi}\bigg|_{h=v,\varphi=w} = \lambda_3 w^3 + \frac{1}{2}\lambda_2 v^2 w + \frac{\partial V^{(1)}}{\partial \varphi}\bigg|_{h=v,\varphi=w} = 0.$$

- Natural scale: $\mu = v = 246\,\mathrm{GeV}$
- Assume $V^{(0)} \sim V^{(1)}$
- Neglect scalar contributions to one-loop potential

METHODS OF STUDYING RSB

Coleman-Weinberg method

Sequential approach

SEQUENTIAL SYMMETRY BREAKING

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Ψ is a "Higgs" for the SM Higgs field

[T.Hambye, A.Strumia, PRD88 (2013) 055022]

SEQUENTIAL SYMMETRY BREAKING

cSM:
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Hidden sector:
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MULTI-HIGGS APPROVED

$$V^{(0)}(\Phi, \Psi) = \lambda_1 \left(\Phi^\dagger \Phi\right)^2 + \quad \lambda_2 \left(\Phi^\dagger \Phi\right) w^2 \quad + \lambda_3 \left(\Psi^\dagger \Psi\right)^2 ,$$

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[T.Hambye, A.Strumia, PRD88 (2013) 055022]

METHODS OF STUDYING RSB

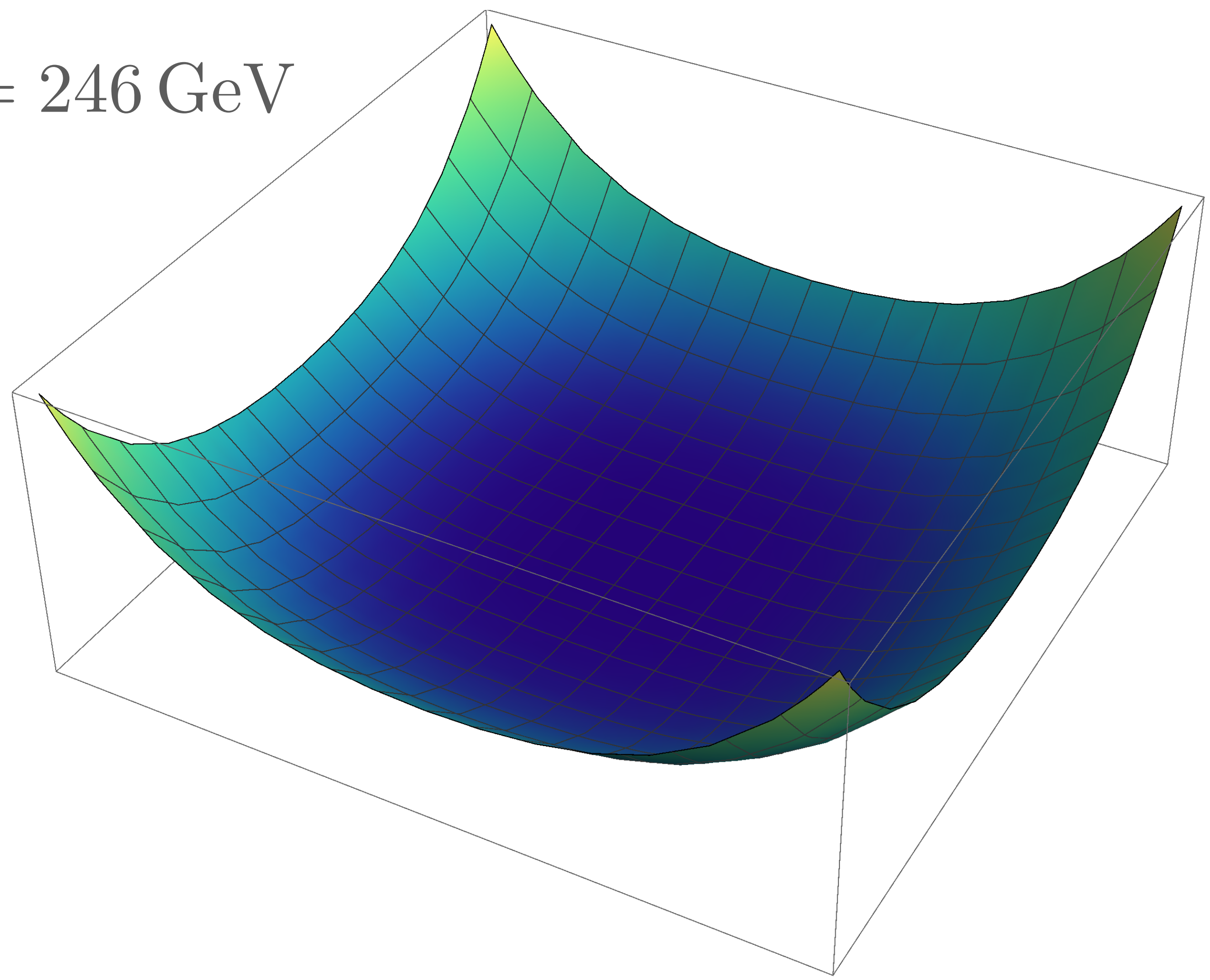
Coleman-Weinberg method

Sequential approach

Gildener-Weinberg method

GILDENER-WEINBERG METHOD

$\mu = 246\,\mathrm{GeV}$



If $\lambda_i \sim \mathcal{O}(g^2)$

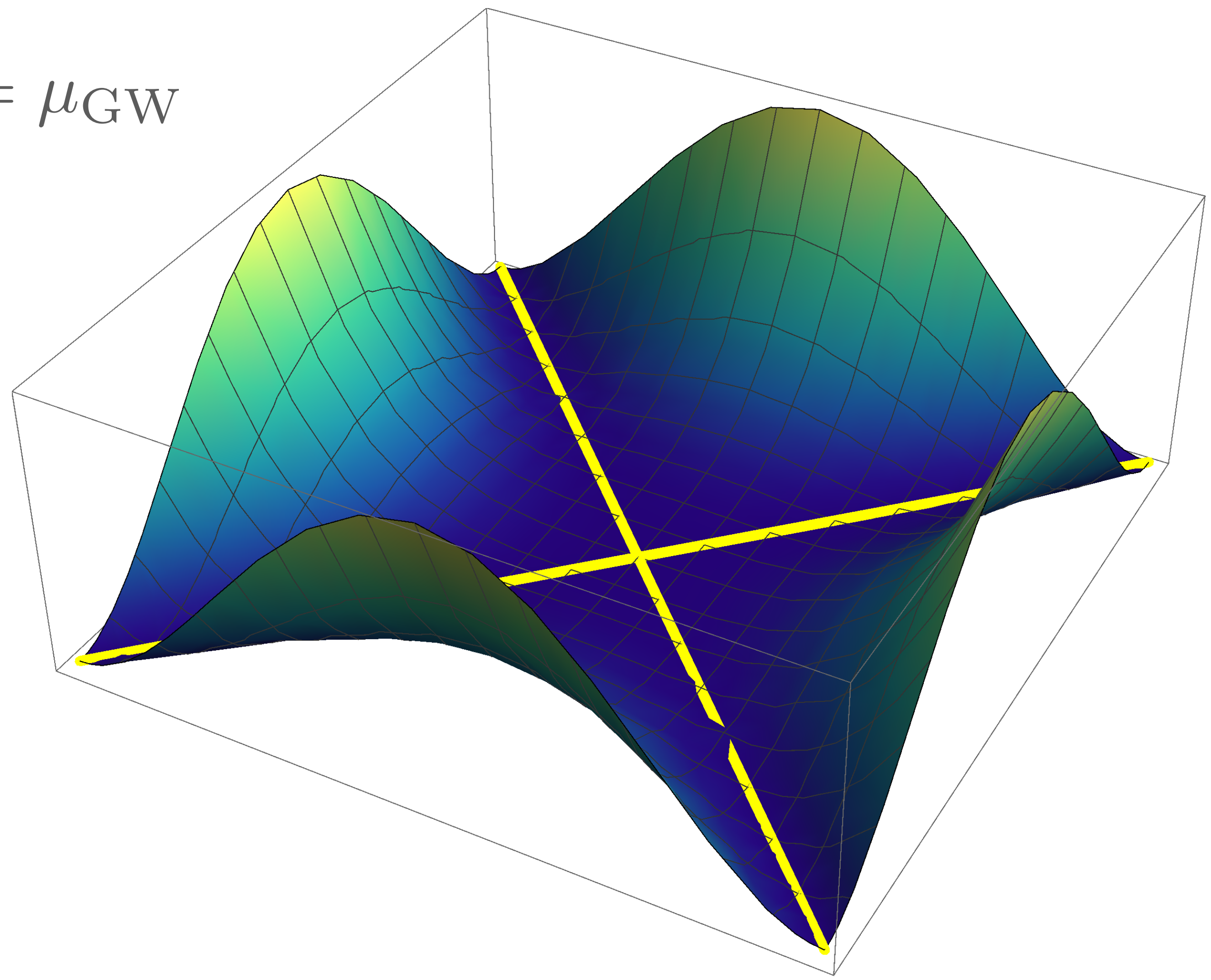
↓

$V^{(0)} \gg V^{(1)}$

[E. Gildener, S. Weinberg, PRD 13 (1976) 3333]

GILDENER-WEINBERG METHOD

$\mu = \mu_{\mathrm{GW}}$



$V^{(0)} = 0$
along the flat direction

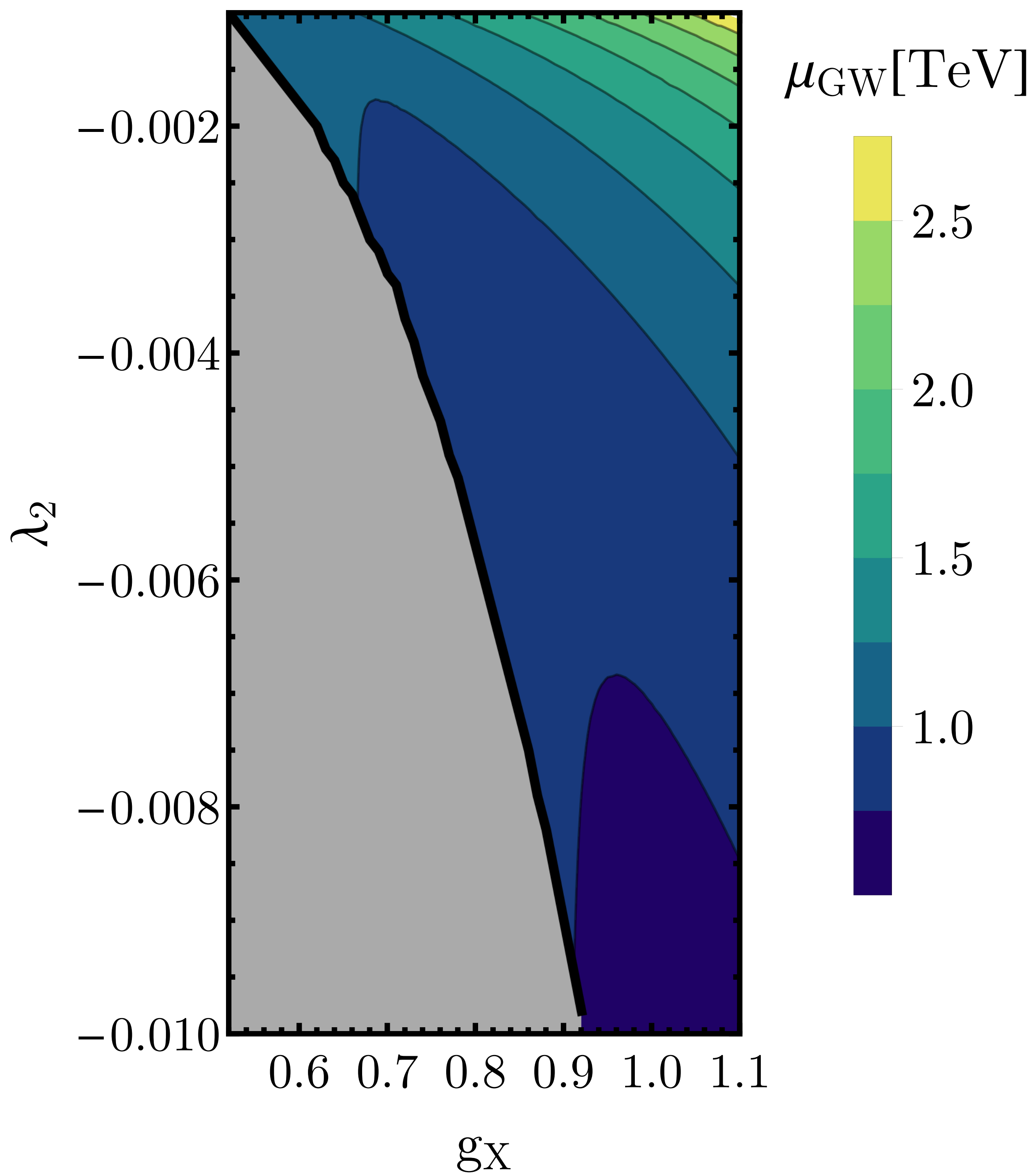
↓

$V^{(1)}$ dominant

↓

1-d analysis possible

GW SCALE

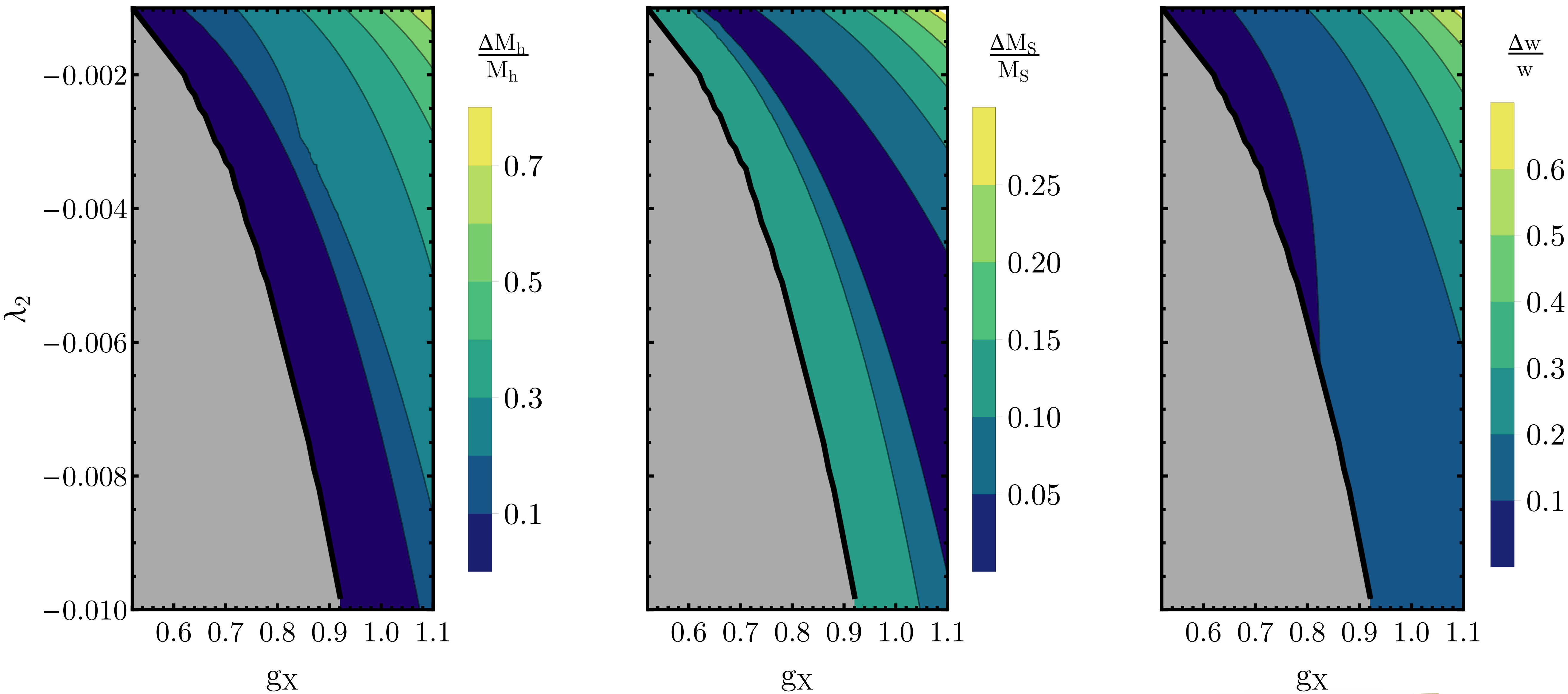


The GW scale is much higher than the EW scale

METHODS OF STUDYING RSB

Coleman-Weinberg method	Sequential approach	Gildener-Weinberg method
$\mu = v$	$\mu = w \approx 10v$	$\mu = \mu_{\mathrm{GW}}$
$V^{(0)} \sim V^{(1)}$	λ_2 small	$V^{(0)} \gg V^{(1)}$
$\lambda_i \sim \mathcal{O}(g^4)$	$\lambda_3 \sim \mathcal{O}(g_X^4)$	$\lambda_i \sim \mathcal{O}(g^2)$

GILDENER-WEINBERG VS COLEMAN-WEINBERG



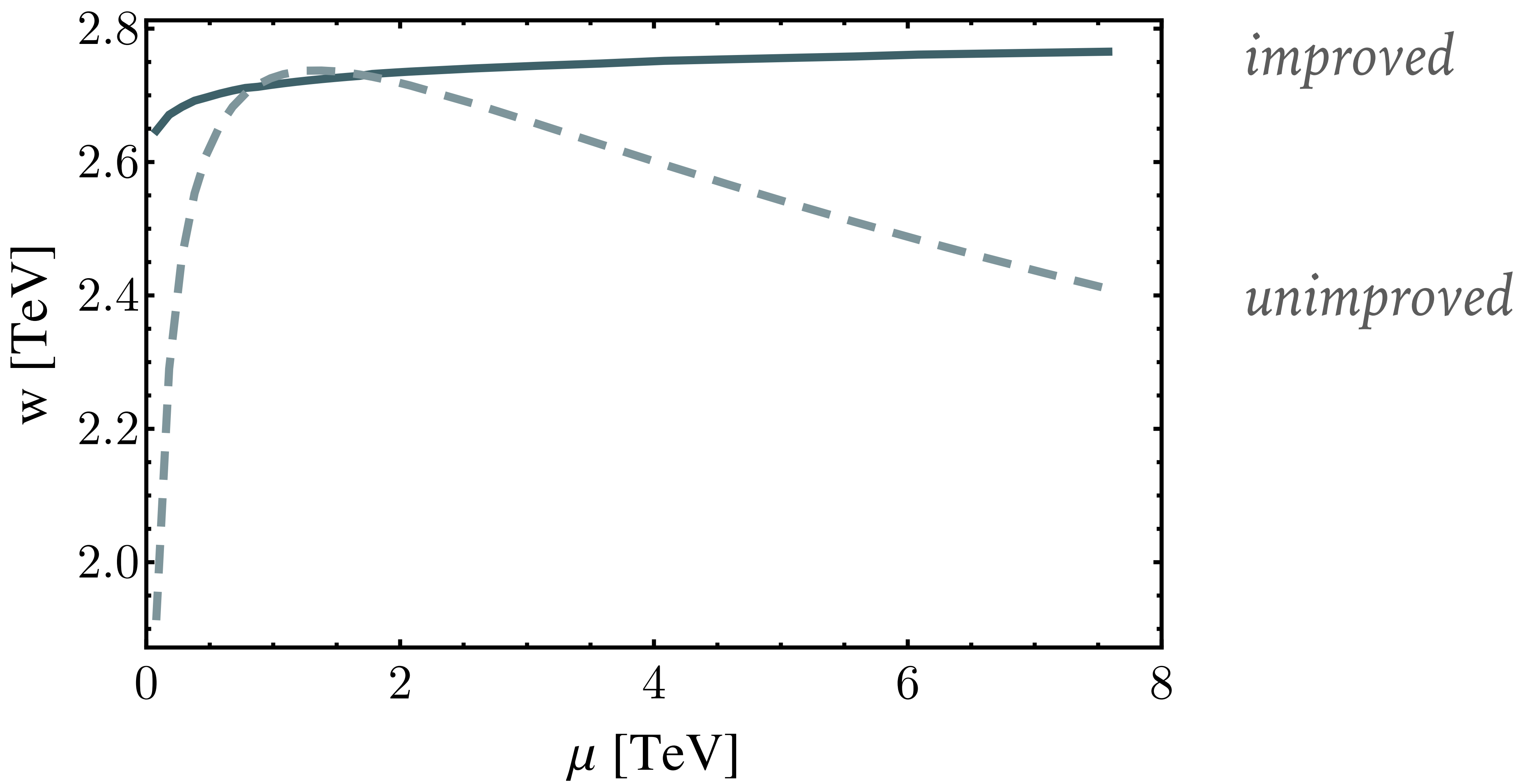
Huge differences between methods due to scale dependence

RENORMALISATION-GROUP-IMPROVED POTENTIAL

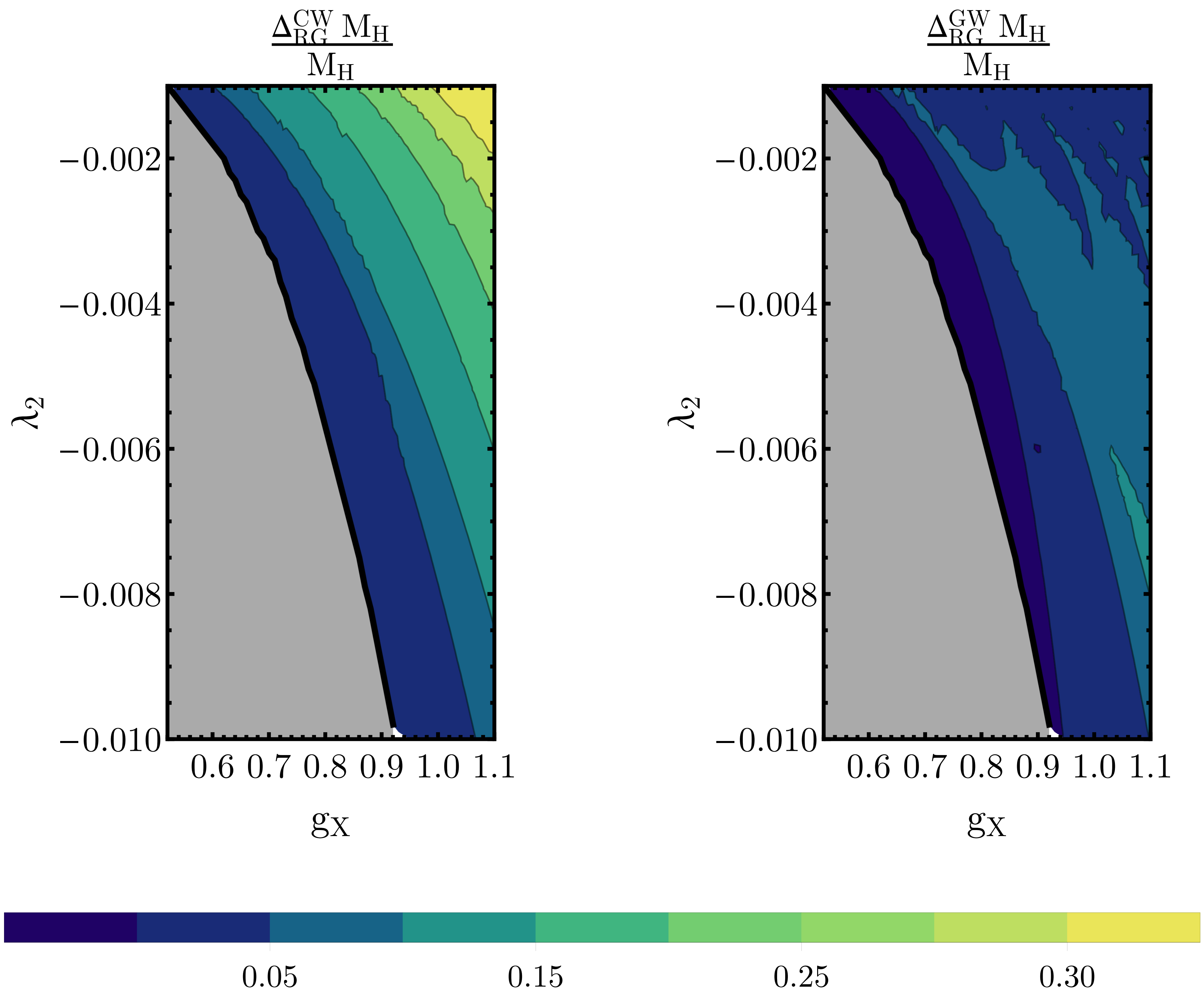
Choose the (field-dependent) RG scale such that $V^{(1)} = 0$

[T.Prokopec, L.Chataignier, M.G.Schmidt, BŚ, JHEP 1808 (2018) 083]

RUNNING VEVS



RESULTS FROM RG IMPROVED POTENTIAL



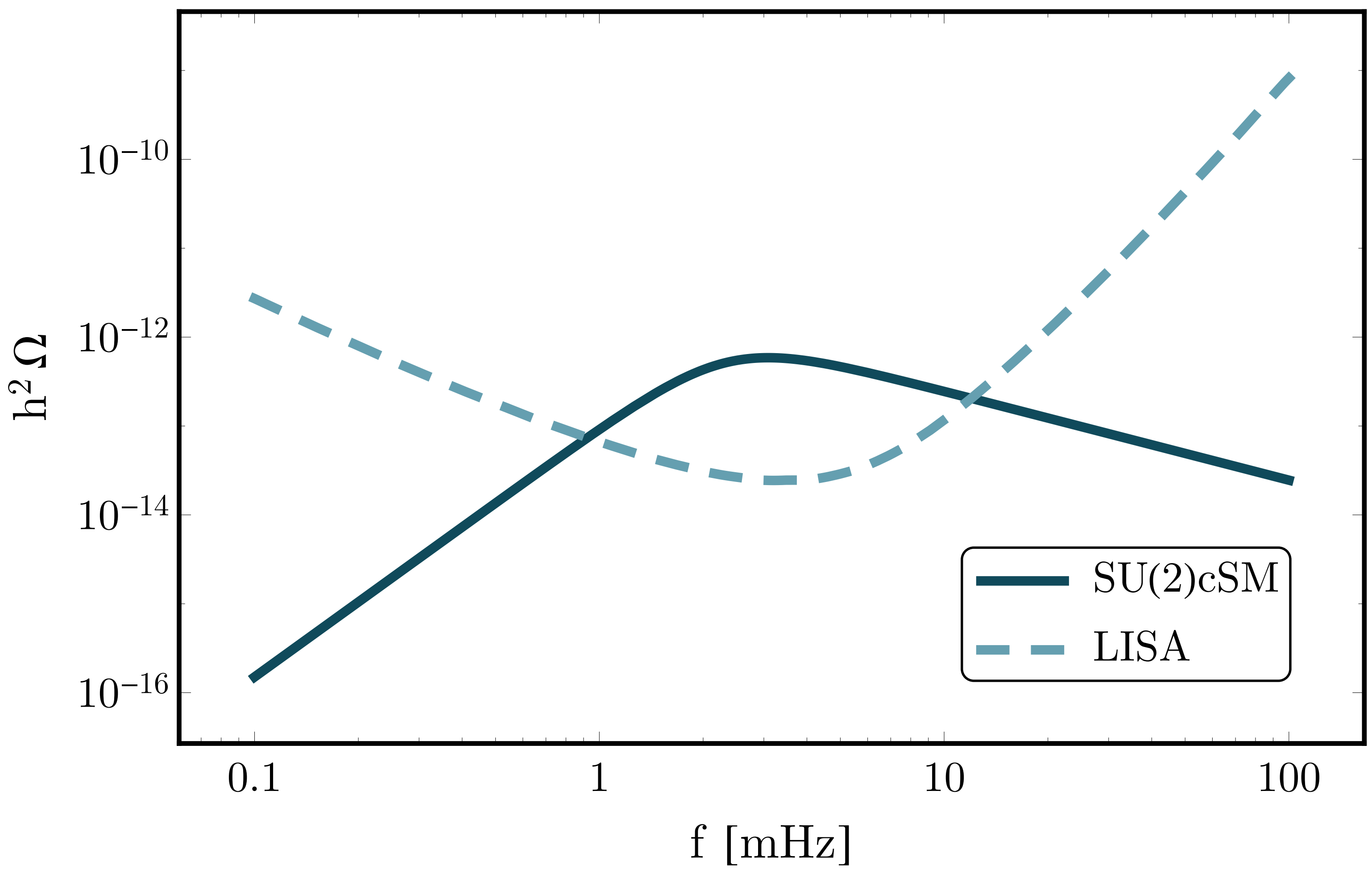
Preliminary

THERMAL EFFECTS

[T.Prokopec, J.Rezacek, BŚ, in progress, J.Rezacek, Msc thesis 2018, Utrecht University]

PHASE TRANSITIONS AND GRAVITATIONAL WAVES

potentially observable gravitational wave spectrum



[J.Rezacek, Msc thesis 2018, Utrecht University]

CONCLUSIONS AND OUTLOOK

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SU(2)cSM - viable, perturbative, stable up to the Planck scale, DM candidate, potential for baryogengesis and observable gravitational waves

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Radiative symmetry breaking analysis requires care, especially in the context of scale dependence

RG improvement has potential to improve the analysis

Self-energies?

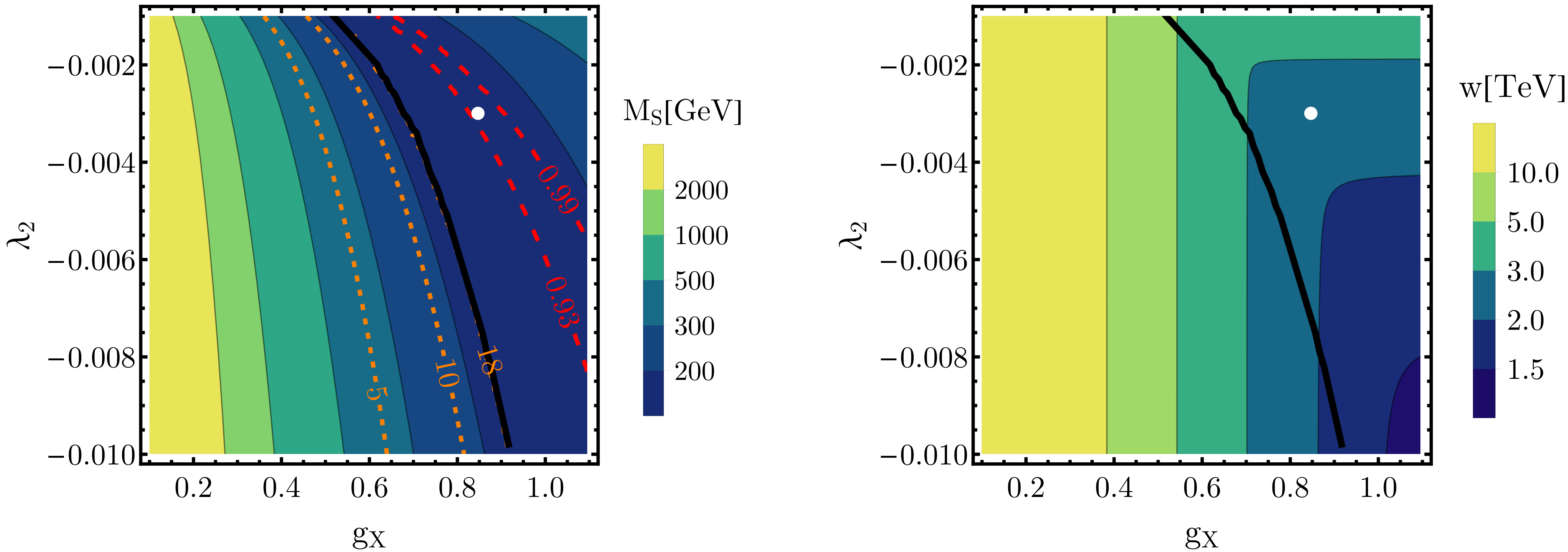
Detailed analysis of phase transitions, resummations of thermal effects

Source of CP violation?

THANK YOU

BACKUP SLIDES

BENCHMARK POINT



	μ [GeV]	λ_1	λ_2	λ_3	g_X	w [GeV]	$V^{(1)}_{\rm SM}$[GeV^4]	$V^{(1)}_{\rm X}$[GeV^4]	$V^{(1)}/V^{(0)}$
CW	246	0.1236	-0.0030	-0.0047	0.8500	2411	$2.38 \cdot 10^7$	$3.18 \cdot 10^{10}$	0.802
GW	940	0.1055	-0.0030	$2 \cdot 10^{-5}$	0.8141	2722	$6.28 \cdot 10^7$	-$1.08 \cdot 10^{10}$	551
RG	734	0.1085	-0.0030	-0.0008	0.8204	2680	$5.82 \cdot 10^7$	-$5.79 \cdot 10^7$	$-3 \cdot 10^{-5}$

METHOD OF CHARACTERISTICS

$$\mu \frac{\mathrm{d}V}{\mathrm{d}\mu}(\mu;\lambda,\phi) = \left(\mu \frac{\partial}{\partial \mu} + \sum_{i=1}^{N_\lambda} \beta_i \frac{\partial}{\partial \lambda_i} - \frac{1}{2} \sum_{a=1}^{N_\phi} \gamma_a \phi_a \frac{\partial}{\partial \phi_a} \right) V(\mu;\lambda,\phi) = 0$$

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Characteristic curves = RG flow

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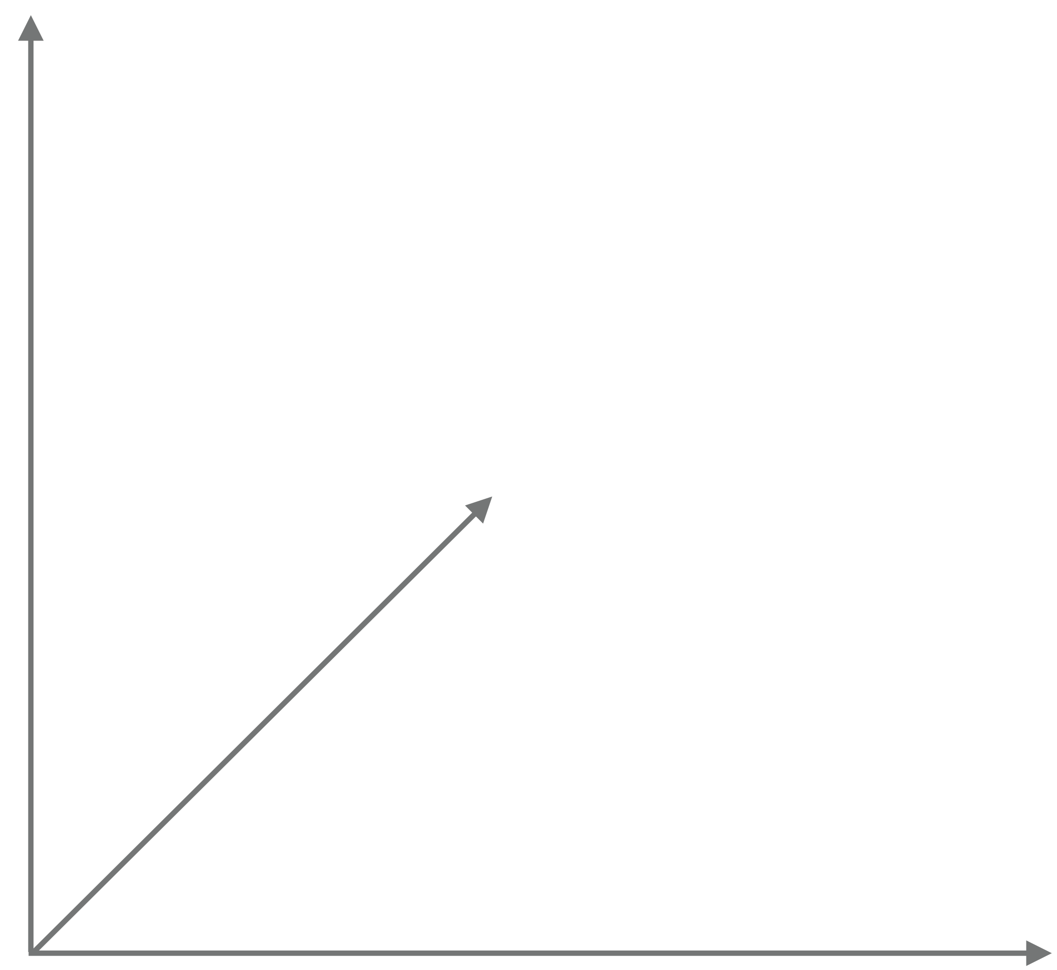

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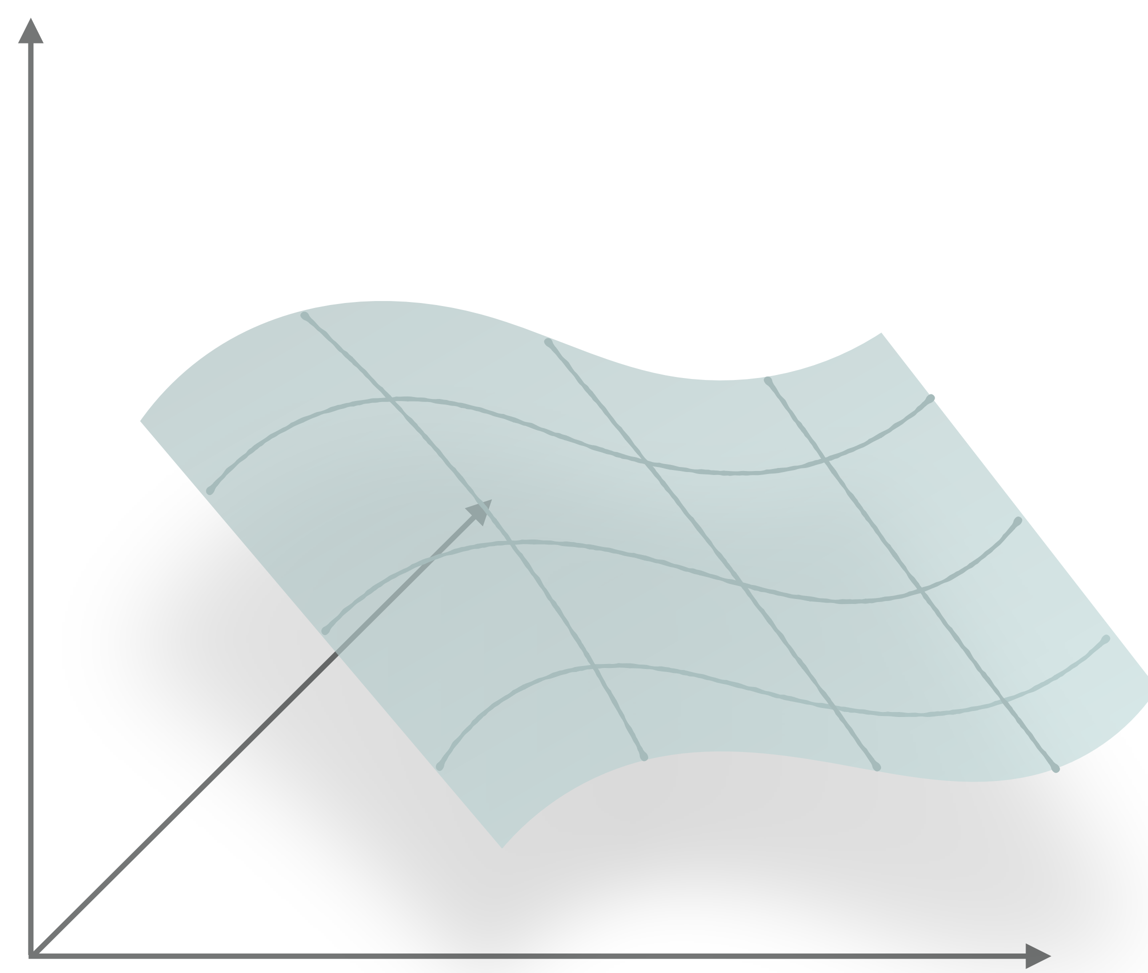

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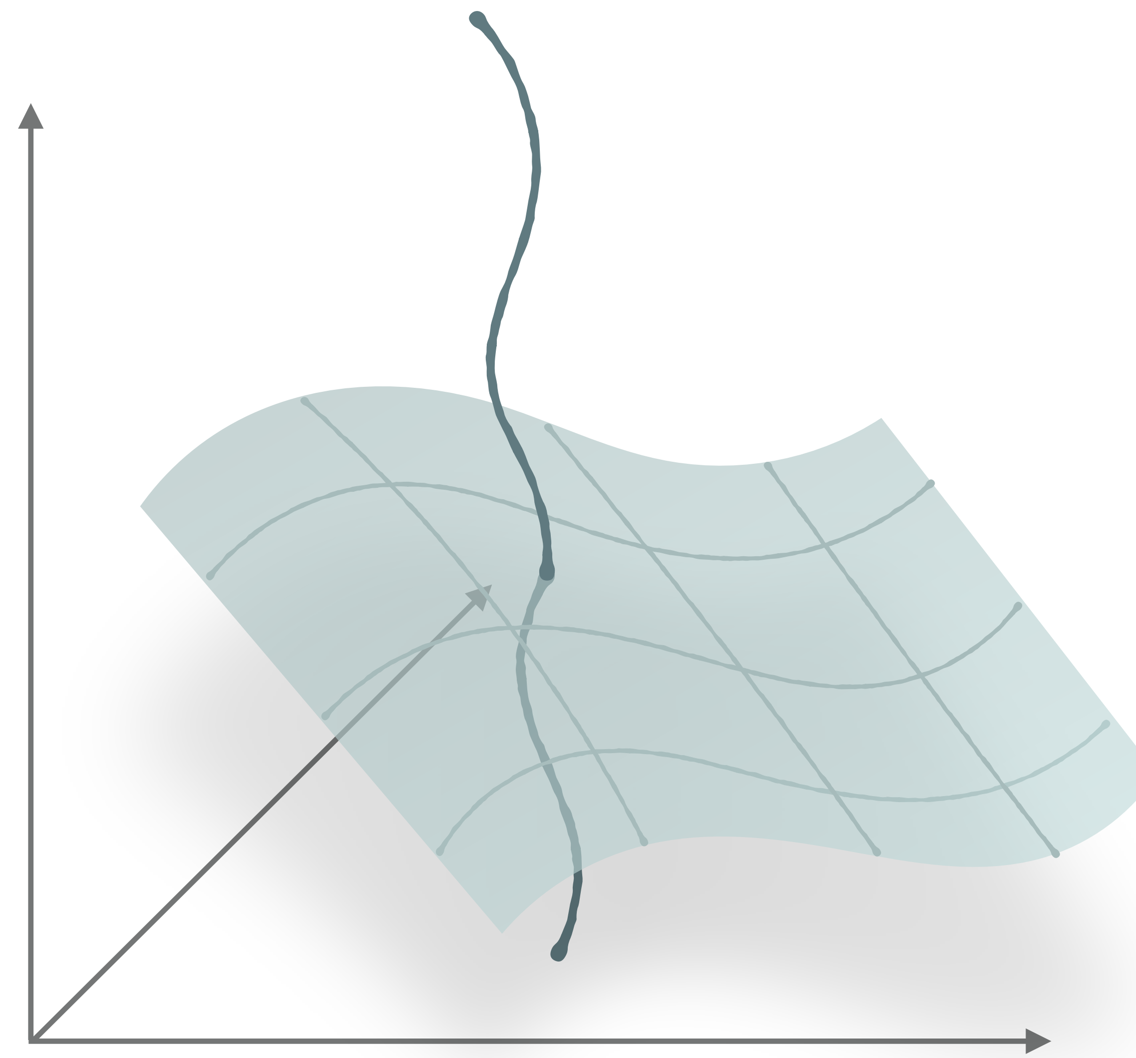

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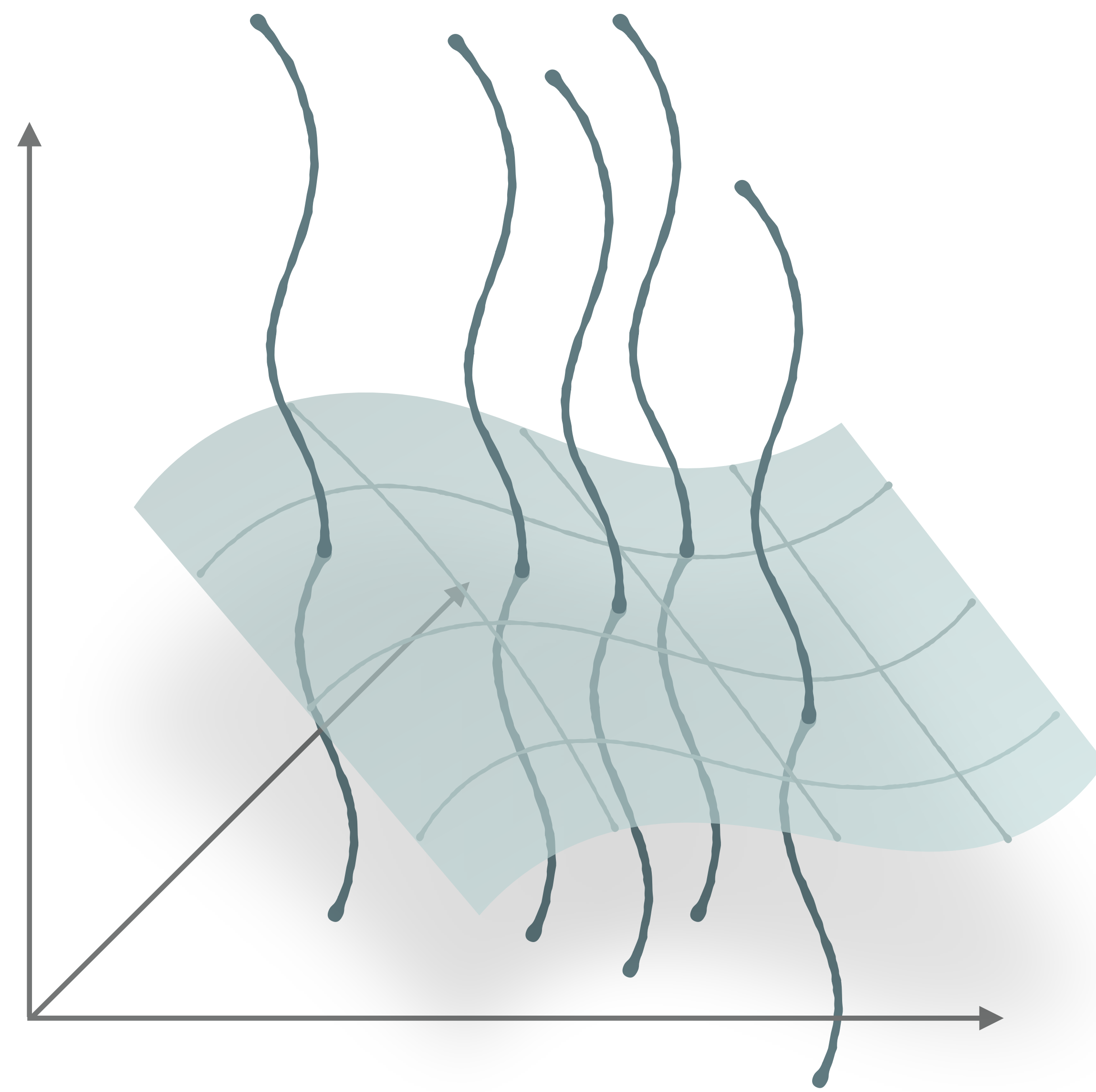

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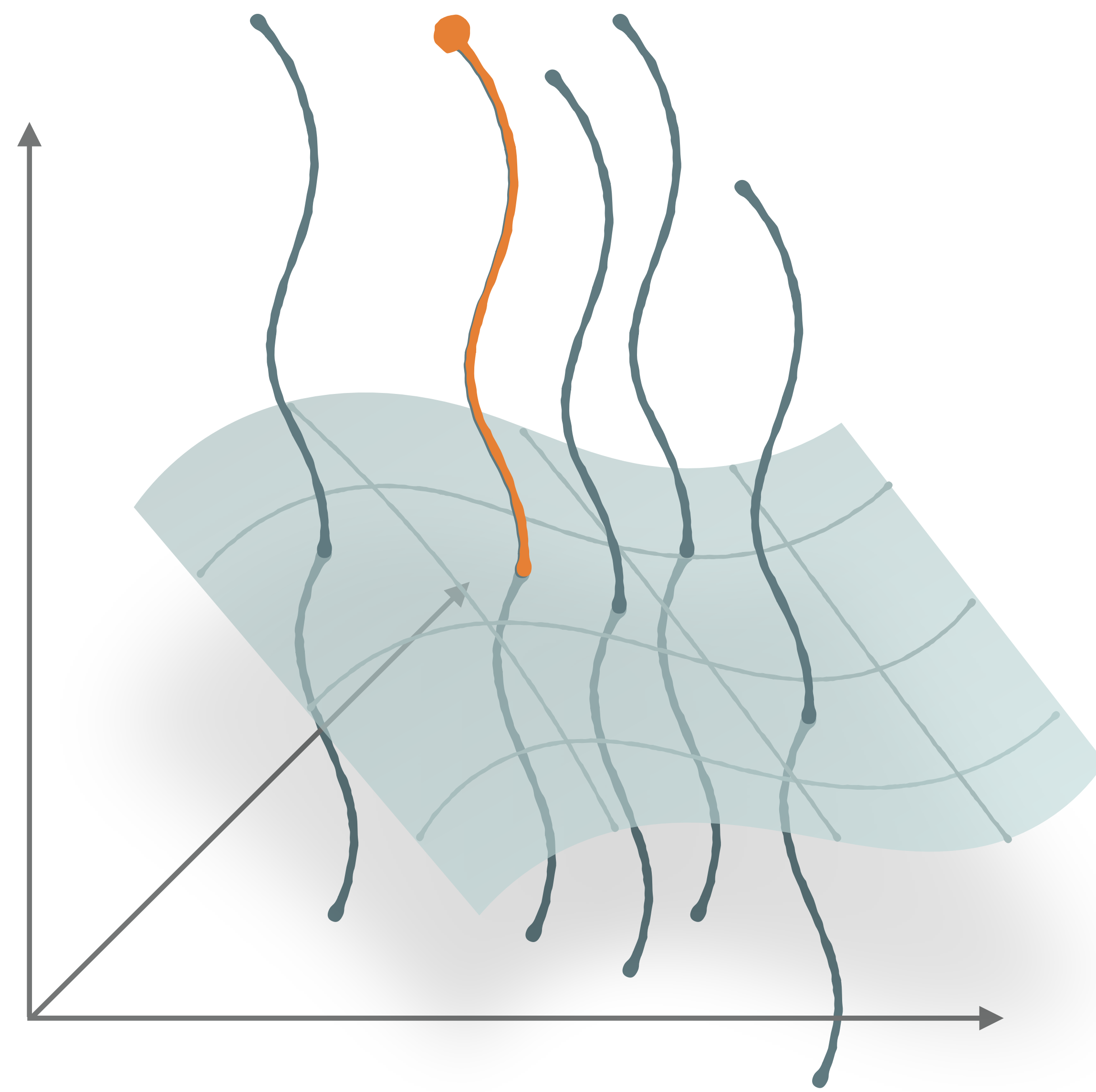


MULTI-FIELD MODELS

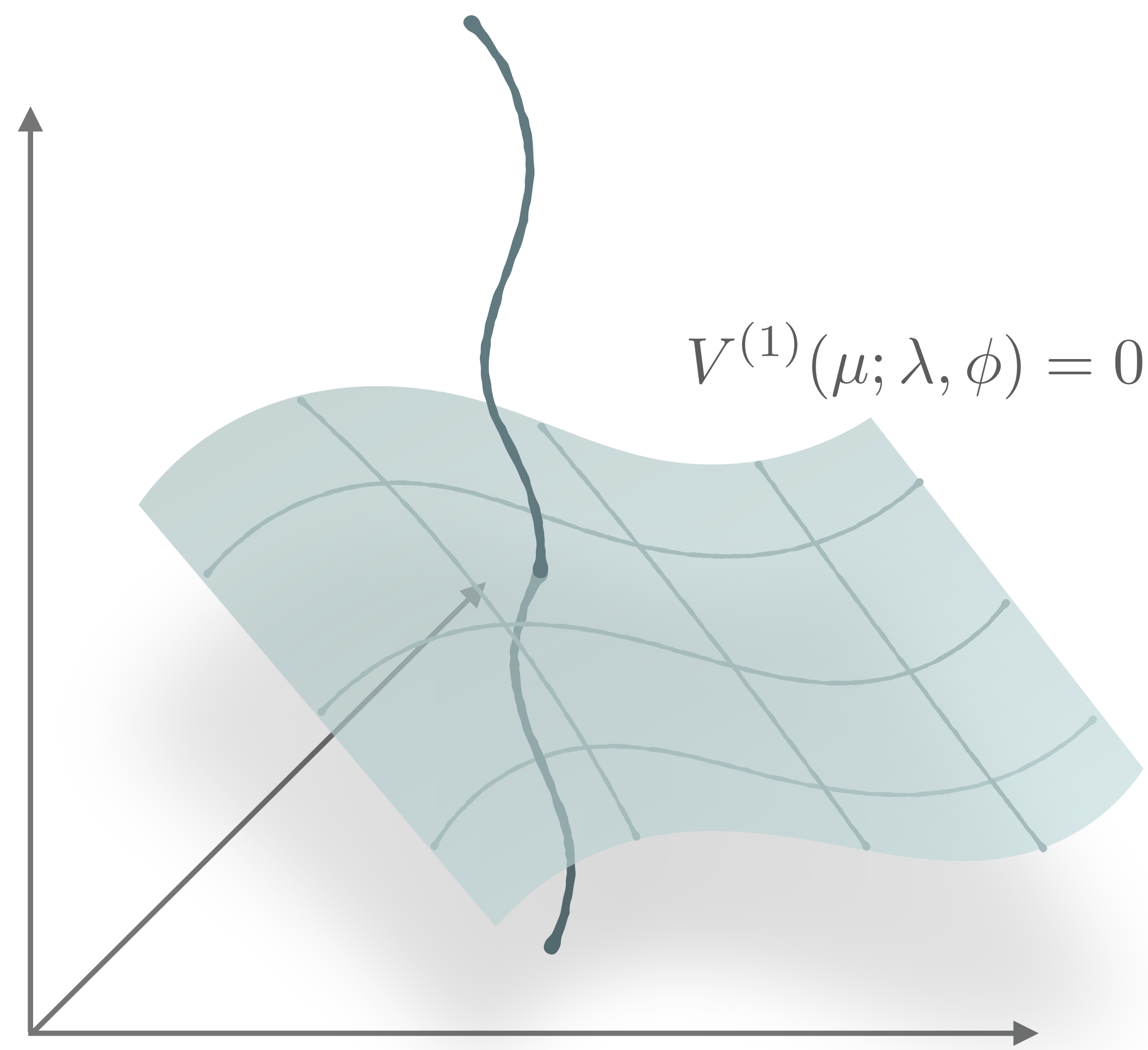
$$V^{(1)}(\mu, \lambda, \phi) = \frac{1}{64\pi^2} \sum_a n_a m_a^4(\lambda, \phi) \left[\log \frac{m_a^2(\lambda, \phi)}{\mu^2} - \chi_a \right]$$

To compute $V(\mu, \lambda, \phi)$

t_* Run to the tree-level surface

Evaluate

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$



MULTI-FIELD MODELS

$$V^{(1)}(\mu, \lambda, \phi) = \frac{1}{64\pi^2} \ldots \left[\log \frac{m_a^2(\lambda, \phi)}{\mu^2} - \chi_a\right]$$

M. Sher, Electroweak Higgs potentials and vacuum stability

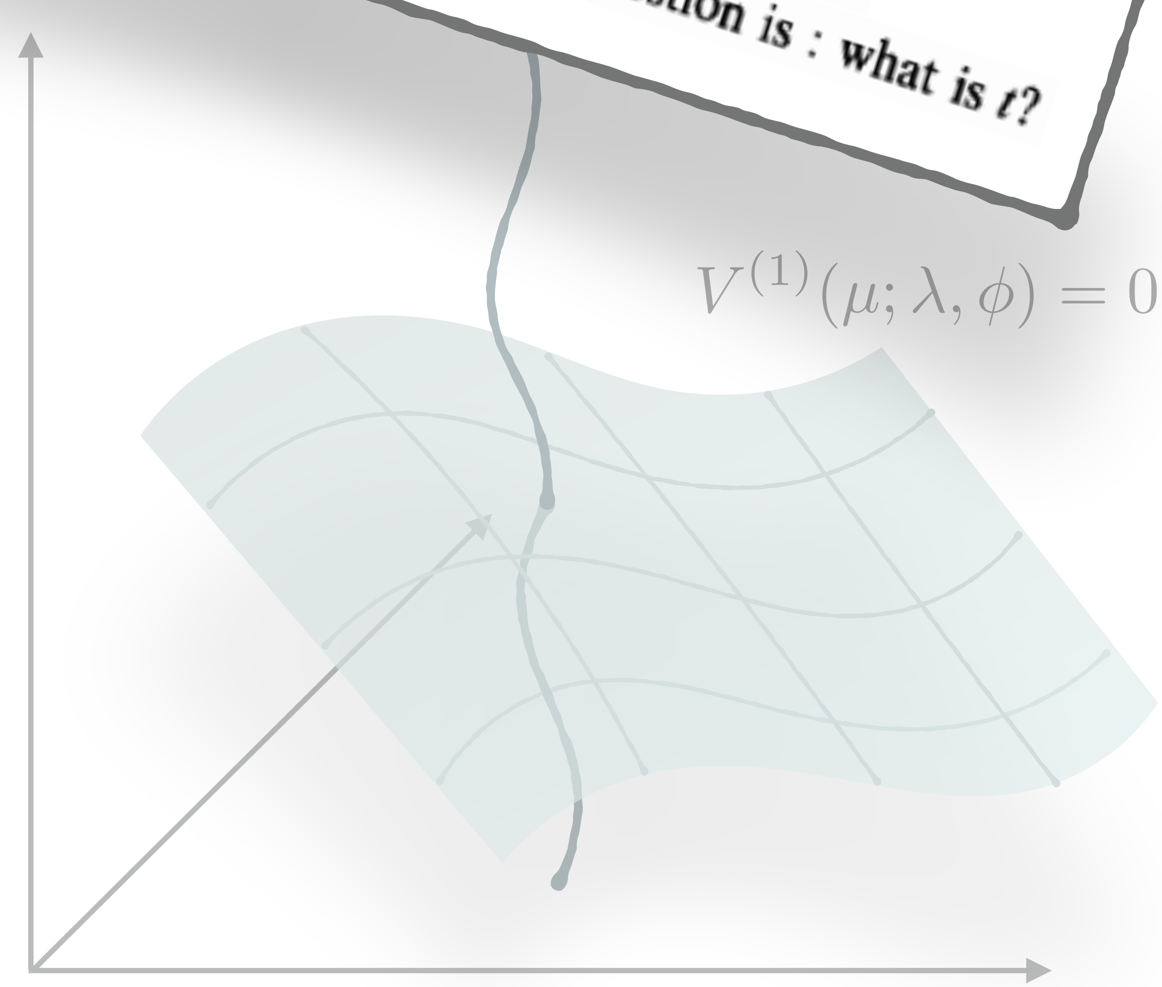
The form of this solution is not surprising; the only question is : what is t?

To compute $V(\mu, \lambda, \phi)$

t_* Run to the tree-level surface

Evaluate

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$



MULTI-FIELD MODELS

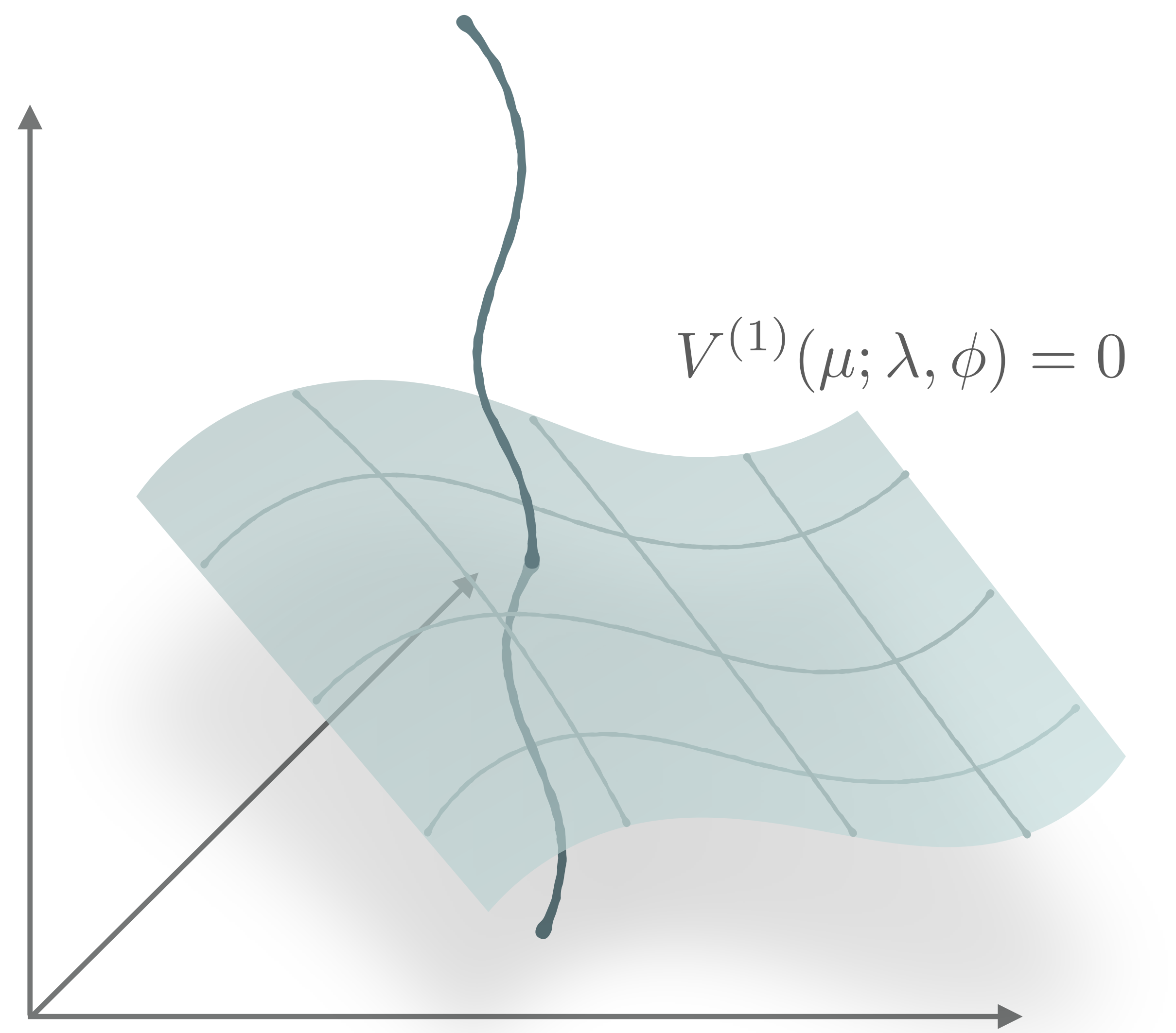
$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$

What is t_*?

$$V^{(1)}(\bar{\mu}(t_*); \bar{\lambda}(t_*), \bar{\phi}(t_*)) = 0$$

To leading order in $\hbar$

$$t_*^{(0)} = \frac{V^{(1)}(\mu, \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)}$$



*SUBTLETIES

- Properties of the tree-level hypersurface
- Existence and uniqueness of t_*
- Resummation

[L. Chataignier, T. Prokopec, M. G. Schmidt, BŚ, JHEP 1803 (2018) 014]

VACUUM STABILITY

$$\lim_{\phi\to\infty} V(\phi) = ?$$

One-loop potential unsuitable for this issue → need of improvement

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$

VACUUM STABILITY

$$\lim_{\phi \to \infty} V(\phi) = ?$$

One-loop potential unsuitable for this issue $\longrightarrow$ need of improvement

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$

Enough to consider tree-level conditions evaluated at large scale.

WHY RGE?

Loop expansion parameters: $\lambda, \ \lambda \log \frac{\phi^2}{\mu^2}$

$\xrightarrow{\text{RGE}}$ Scale independence of the effective potential

RG improved potential expansion parameter: $\bar{\lambda}\left(\log \frac{\phi^2}{\mu^2}\right)$

LEADING LOGS

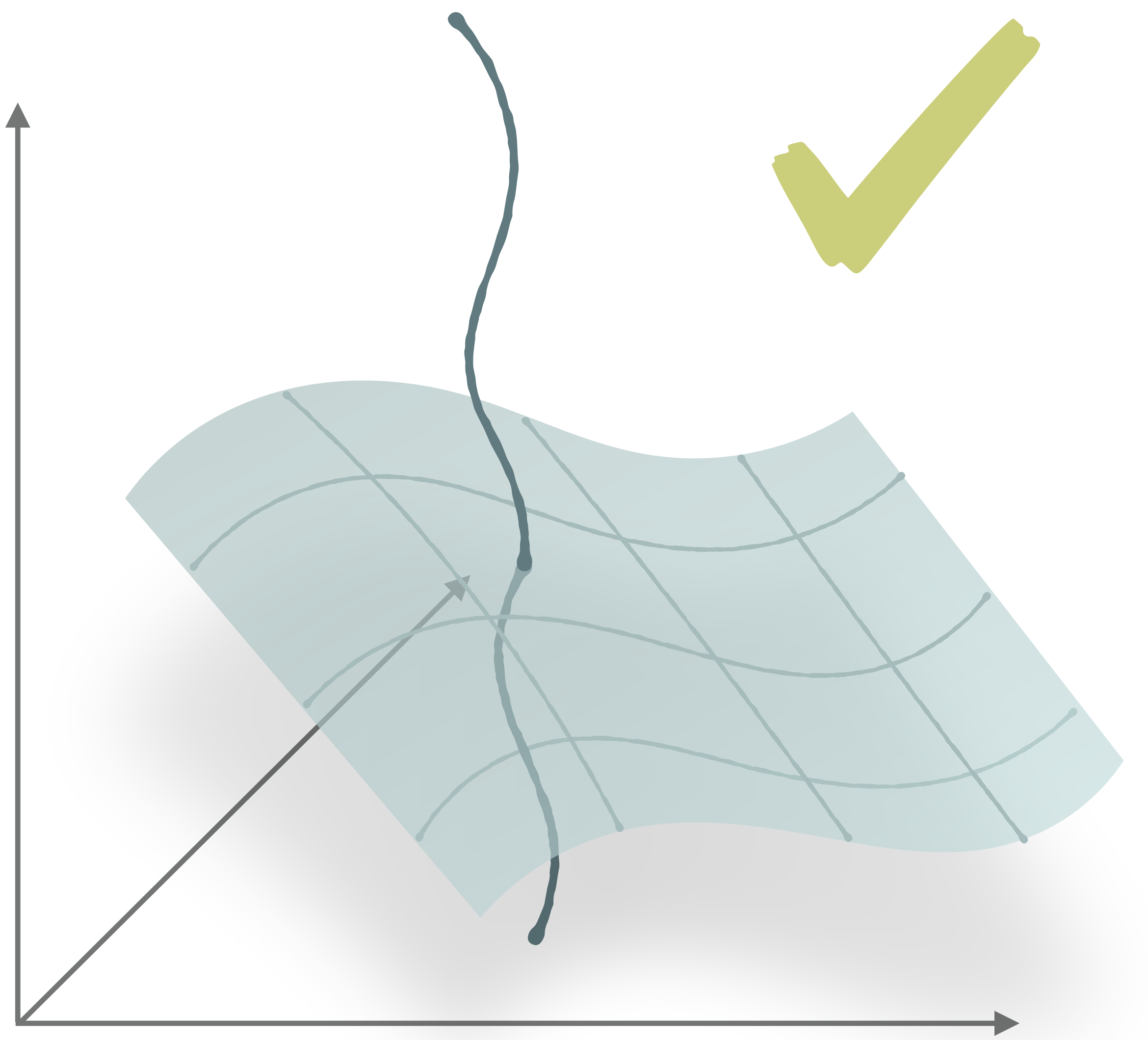
	1-loop	$\lambda \log$		
λ	2-loop	$\lambda^2 \log$	$\lambda^2 \log^2$	
	3-loop	$\lambda^3 \log$	$\lambda^3 \log^2$	$\lambda^3 \log^3$

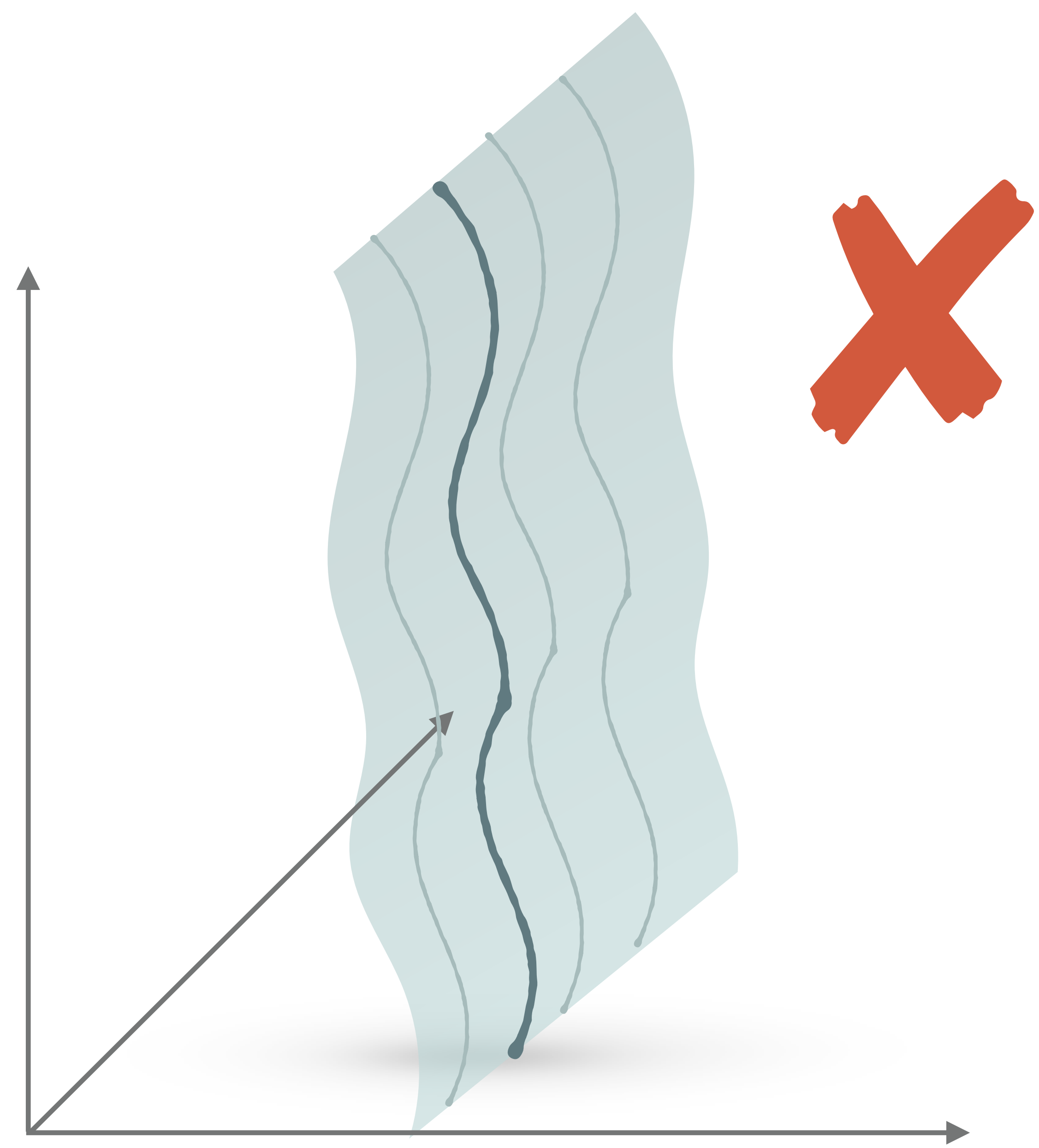
LEADING LOGS

	1-loop	$\lambda \log$		
λ	2-loop	$\lambda^2 \log$	$\lambda^2 \log^2$	
	3-loop	$\lambda^3 \log$	$\lambda^3 \log^2$	$\lambda^3 \log^3$

VALIDITY OF THE METHOD

Boundary surface must be non-characteristic





VALIDITY OF THE METHOD

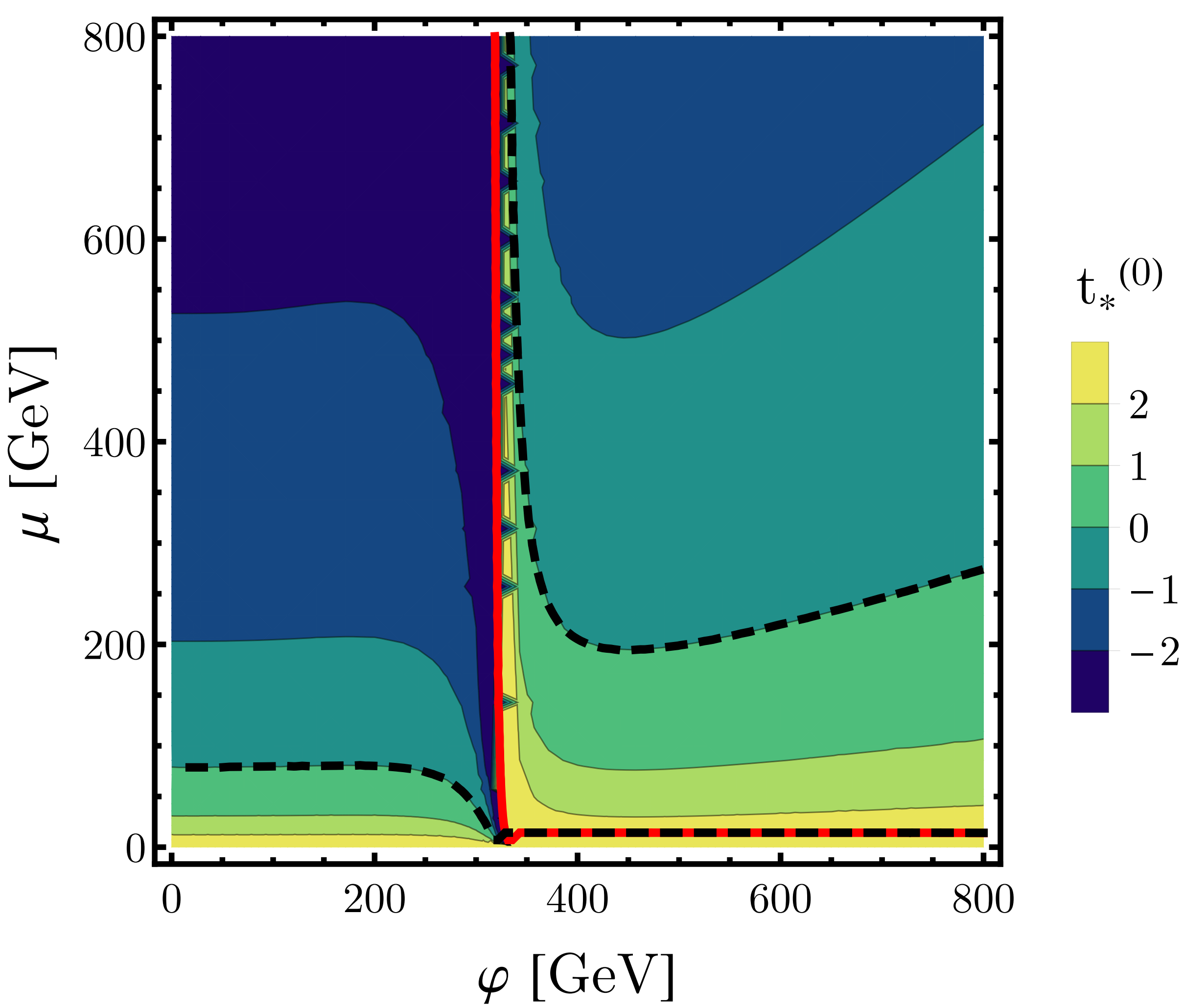
Is there a unique solution for t_* ?

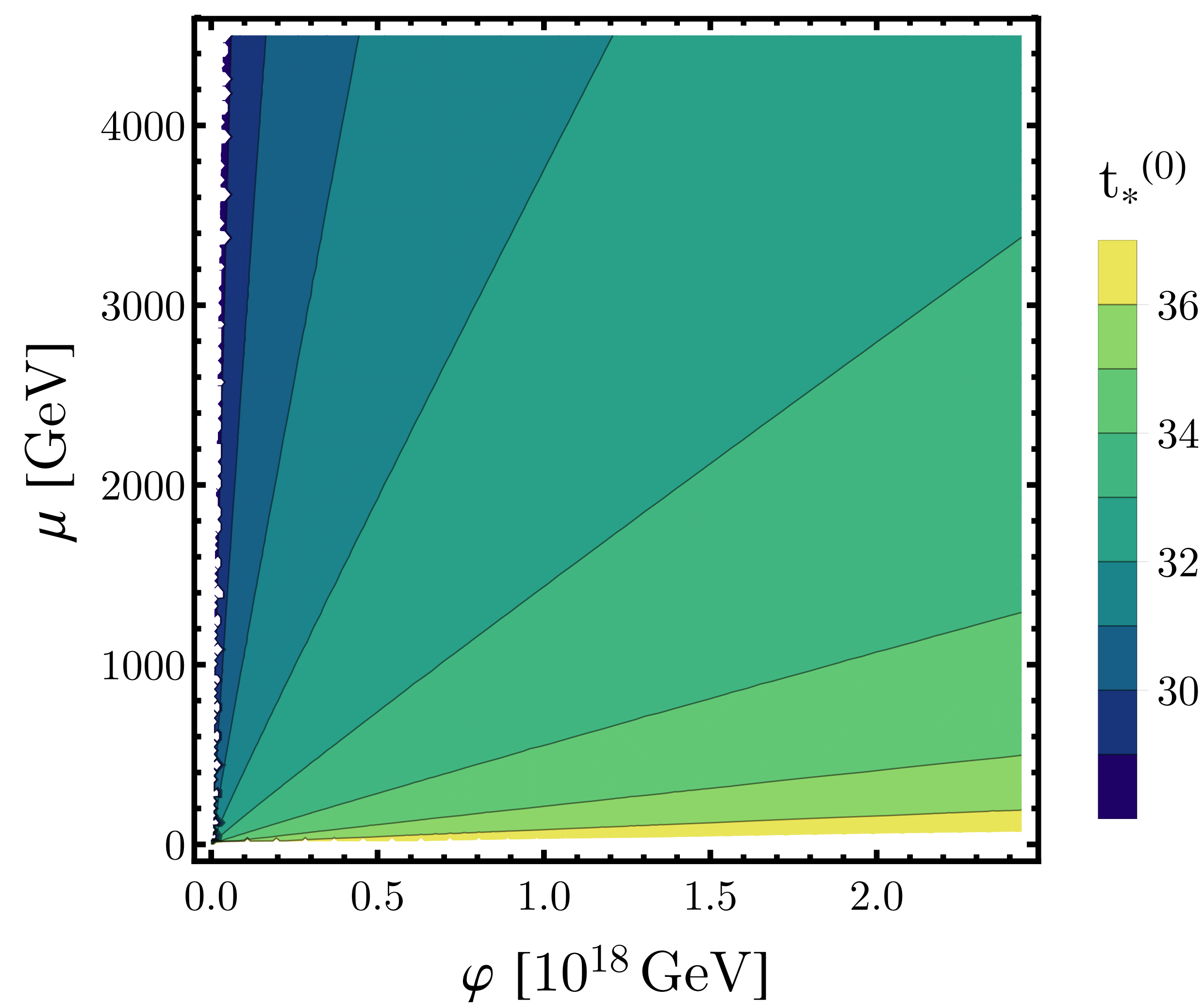
$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

VALIDITY OF THE METHOD

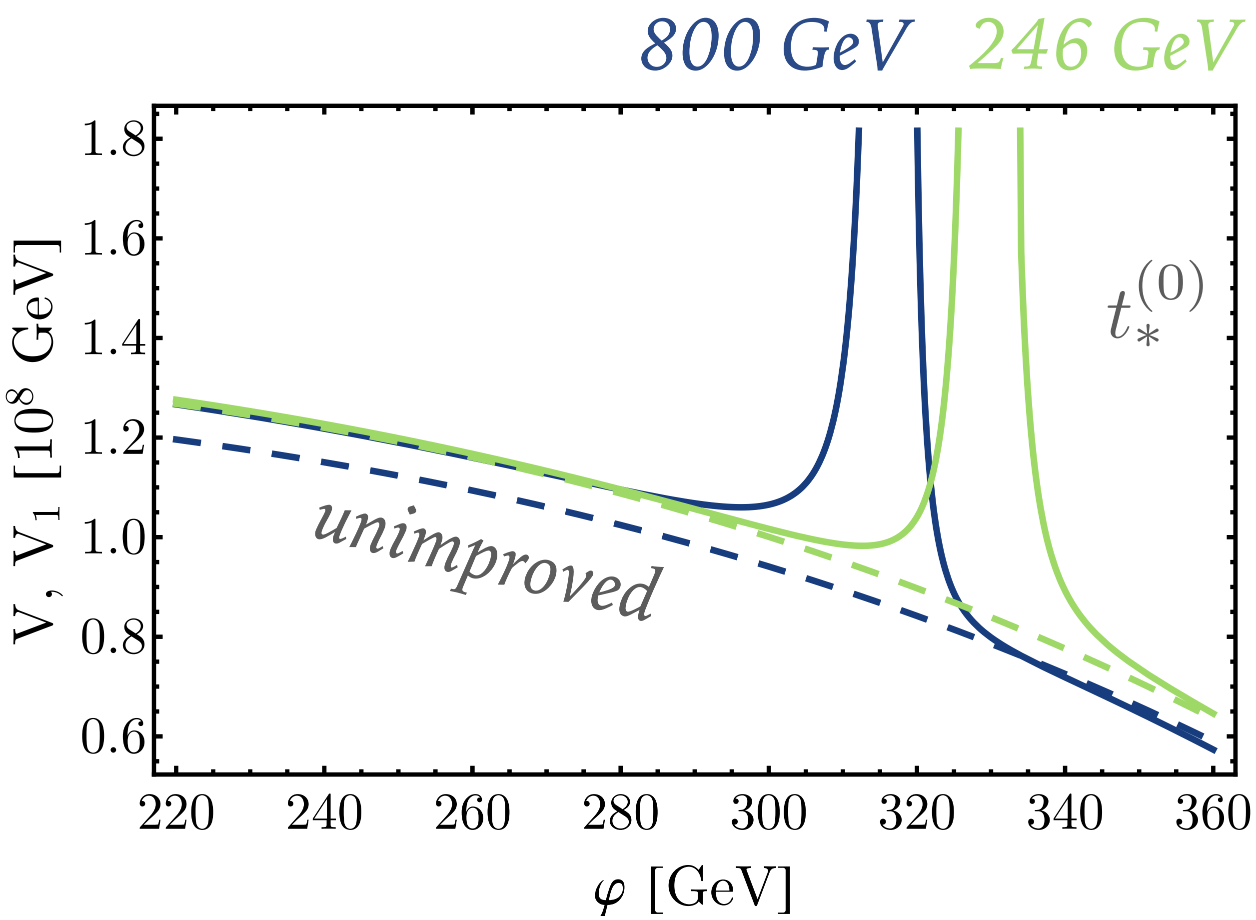
To first approximation $V^{(1)}(\mu; \lambda, \phi) = 0$ is characteristic when $\mathbb{B} = 0$

$\mathbb{B} = 0$ is characteristic.



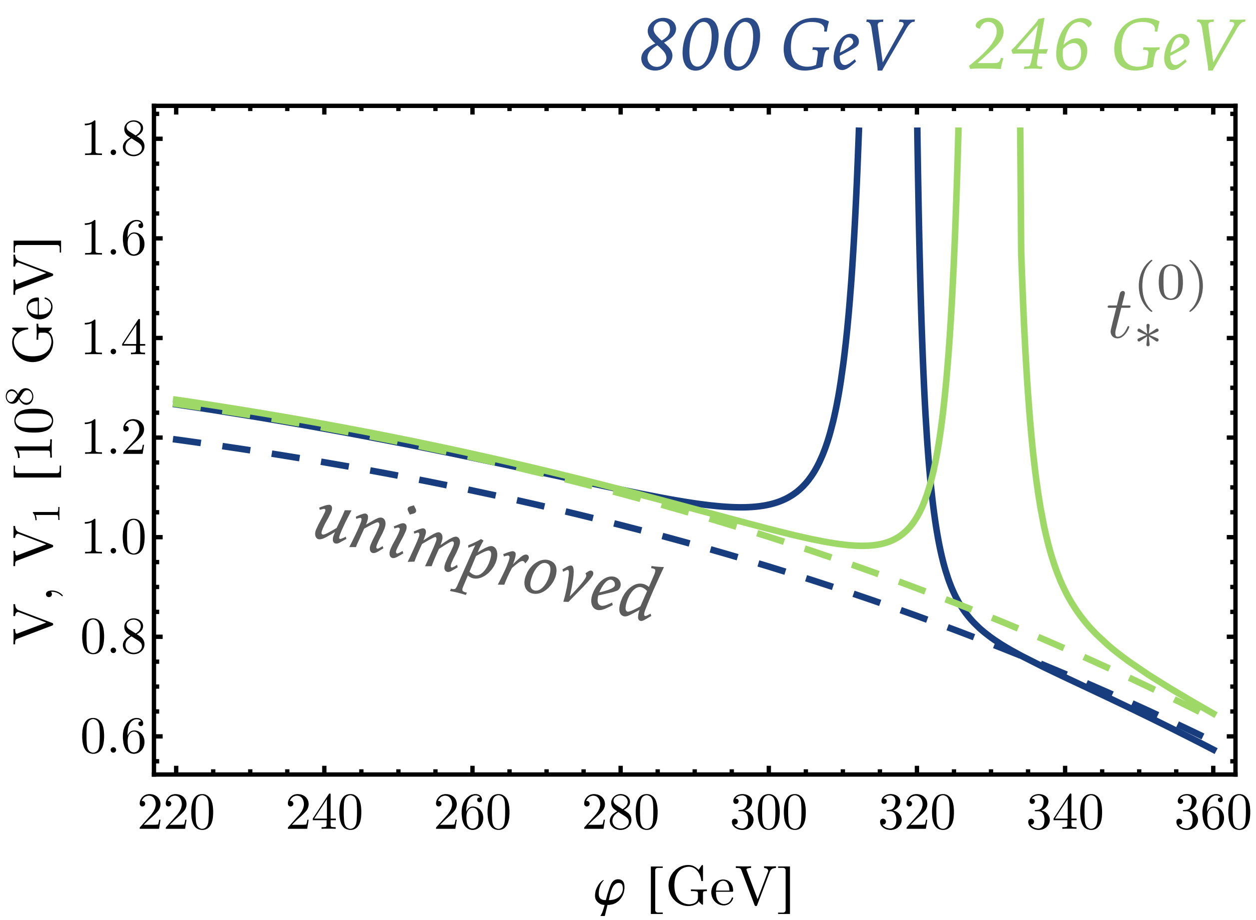


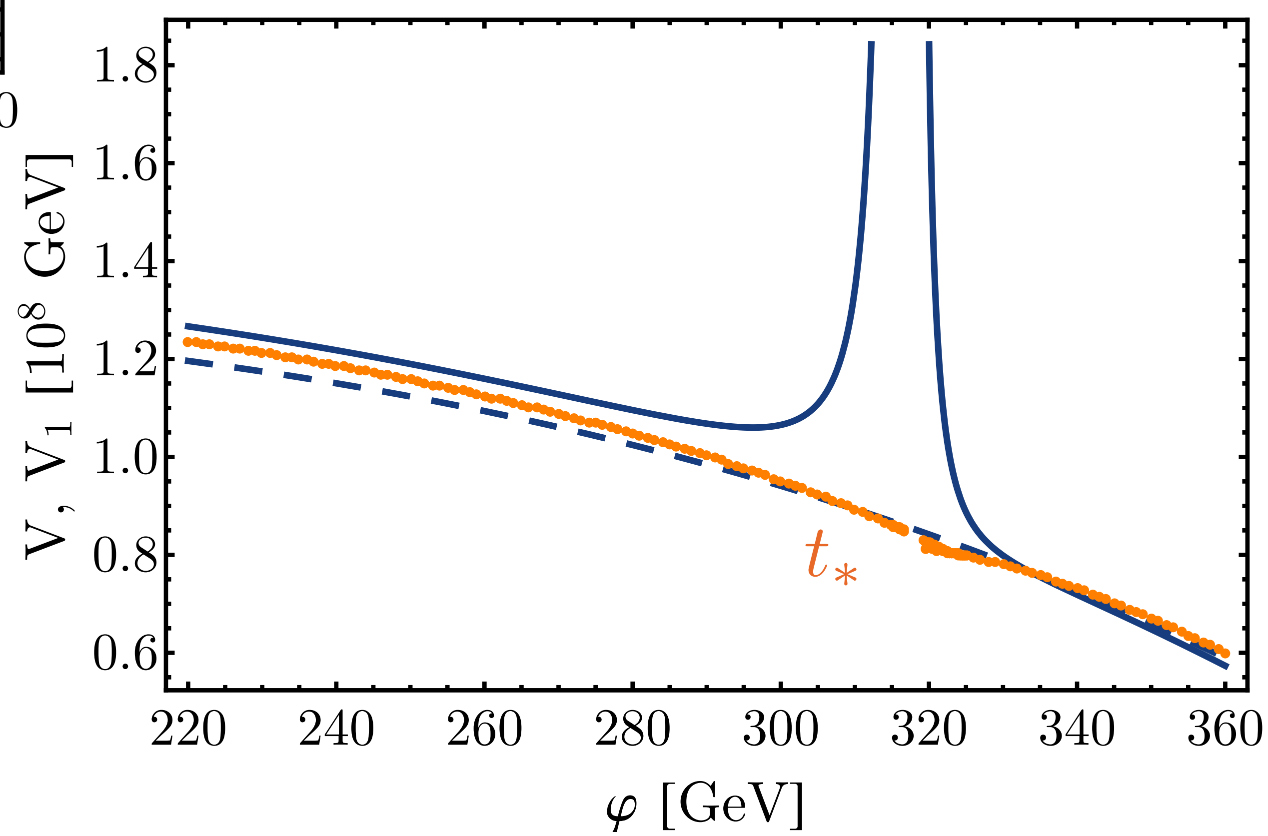
VALIDITY OF THE METHOD



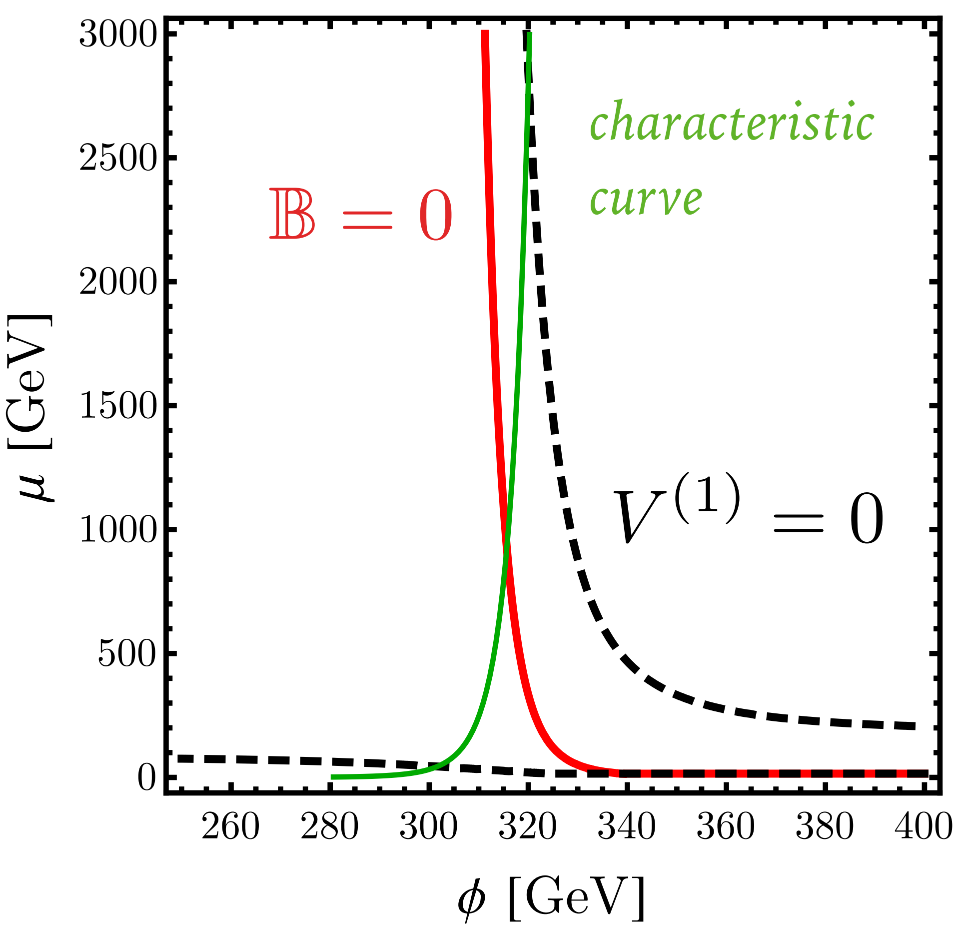
t_*

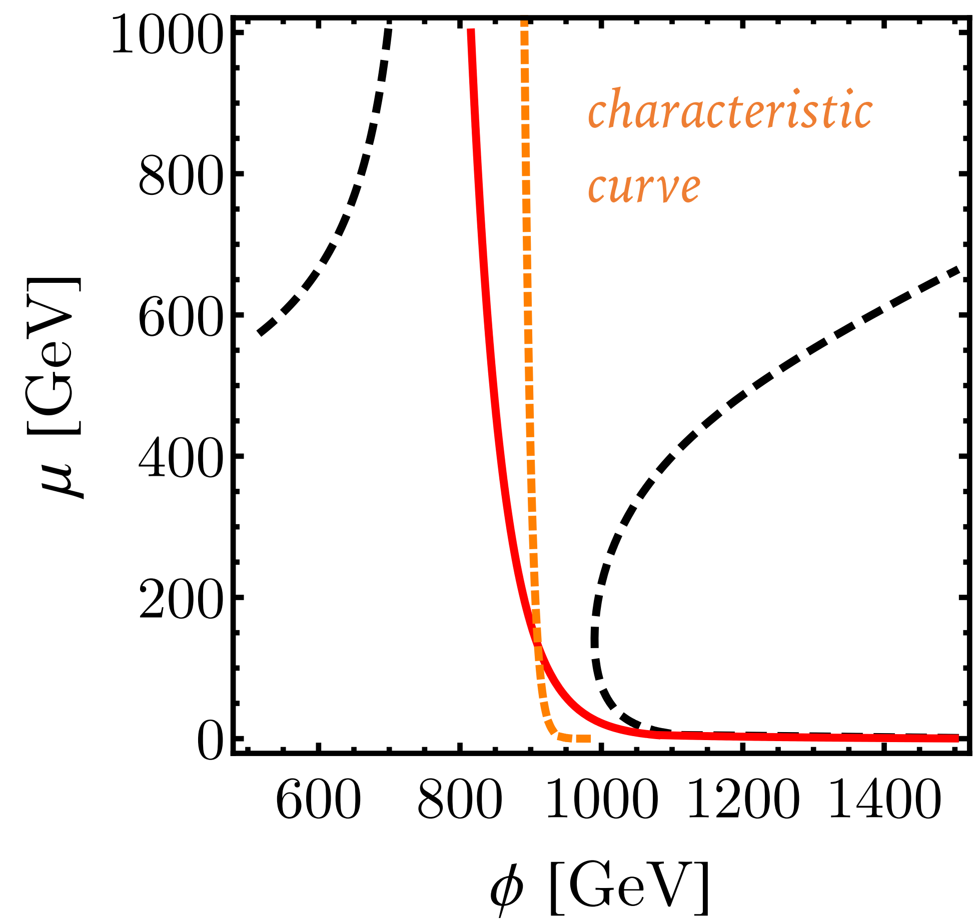
VALIDITY OF THE METHOD





VALIDITY OF THE METHOD





Higgs-Yukawa model

RESUMMATION

The leading logarithms are not resummed. And what is?

$V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$ resums powers of t_*

one-field case

$$V(\mu; \lambda, \phi) = \frac{1}{4}\bar{\lambda}(t_*, \lambda)\phi^4 = \frac{1}{4}\phi^4 \sum_{n=0}^{\infty} \lambda^{n+1} \left[\frac{9\hbar}{16\pi^2} \log \frac{3\lambda\phi^2}{\mu^2}\right]^n + \cdots$$

multi-field case

$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

RESUMMATION

$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

RESUMMATION

$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

$$V^{(1)}(\mu, \lambda, \phi) = \mathbb{A} + \mathbb{B} \log \frac{\mathcal{M}^2}{\mu^2}$$

pivot log

μ-independent

RESUMMATION

$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

$$V^{(1)}(\mu, \lambda, \phi) = \mathbb{A} + \mathbb{B} \log \frac{\mathcal{M}^2}{\mu^2}$$

pivot log

μ-independent

$V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$ resums powers of the pivot log.

RESUMMATION

$$t_* = \frac{V^{(1)}\left(\mu, \bar{\lambda}(t_*), \bar{\phi}(t_*)\right)}{2\mathbb{B}\left(\bar{\lambda}(t_*), \bar{\phi}(t_*)\right)} \approx \frac{V^{(1)}(\mu; \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)} + \mathcal{O}(\hbar)$$

$$V^{(1)}(\mu, \lambda, \phi) = \mathbb{A} + \mathbb{B} \log \frac{\mathcal{M}^2}{\mu^2}$$

pivot log

μ-independent

$V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$ resums powers of the pivot log.

If $\left|\log \frac{\mathcal{M}^2}{\mu^2}\right| \gg \max_a \left\{ \left| \log \frac{m_a^2(\lambda, \phi)}{\mathcal{M}^2} \right| \right\}$ these are the dominant terms.

GENERALISATION TO HIGHER ORDERS

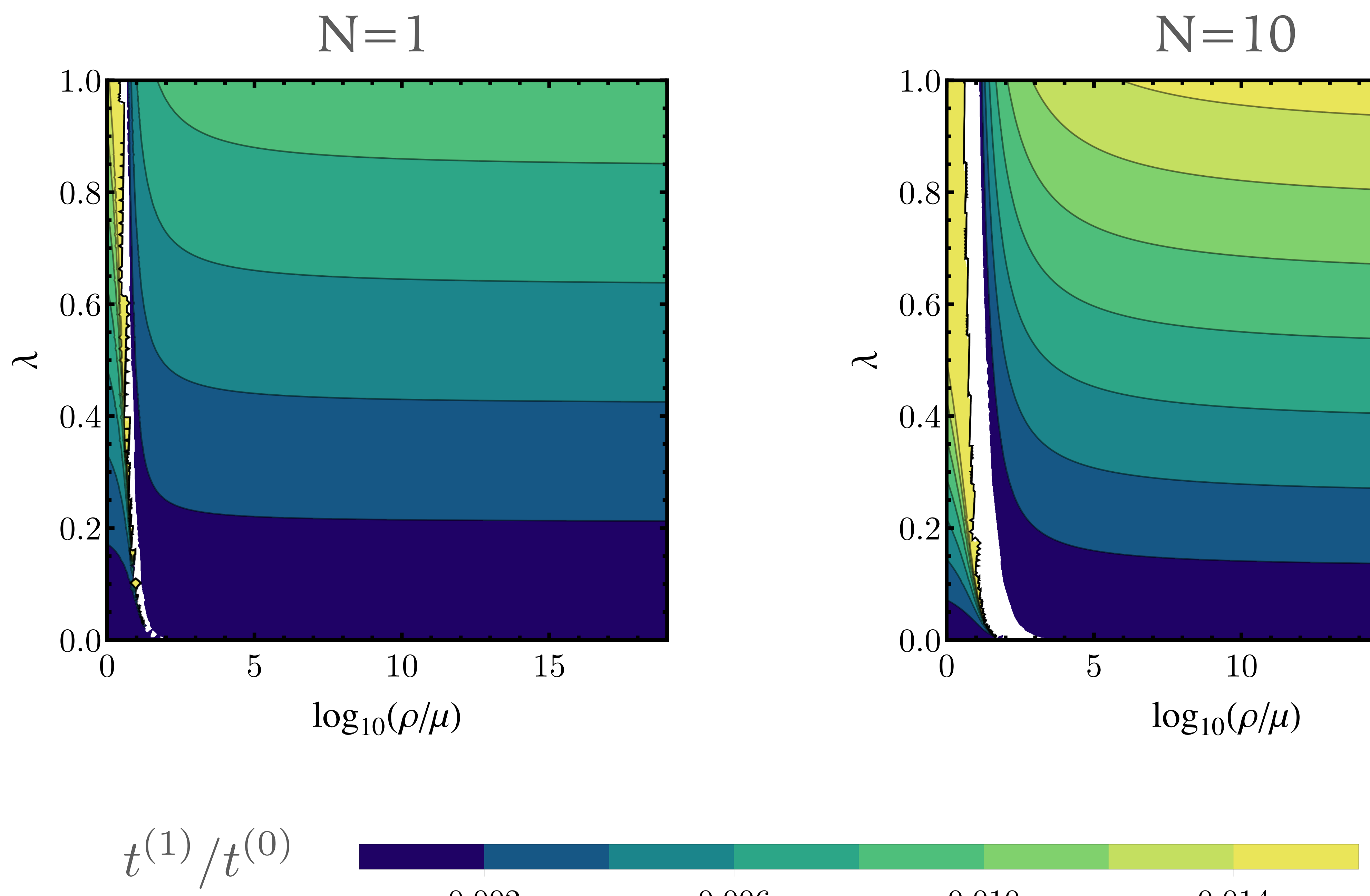
$$V(\mu;\lambda,\phi) = V^{(0)}(\lambda,\phi) + q(\mu,\lambda,\phi) = V^{(0)}(\lambda,\phi) + \sum_{l=1}^{\infty} \hbar^l V^{(l)}(\mu,\lambda,\phi)$$

$$q(\bar{\mu}(t_*),\bar{\lambda}(t_*),\bar{\phi}(t_*)) = 0$$

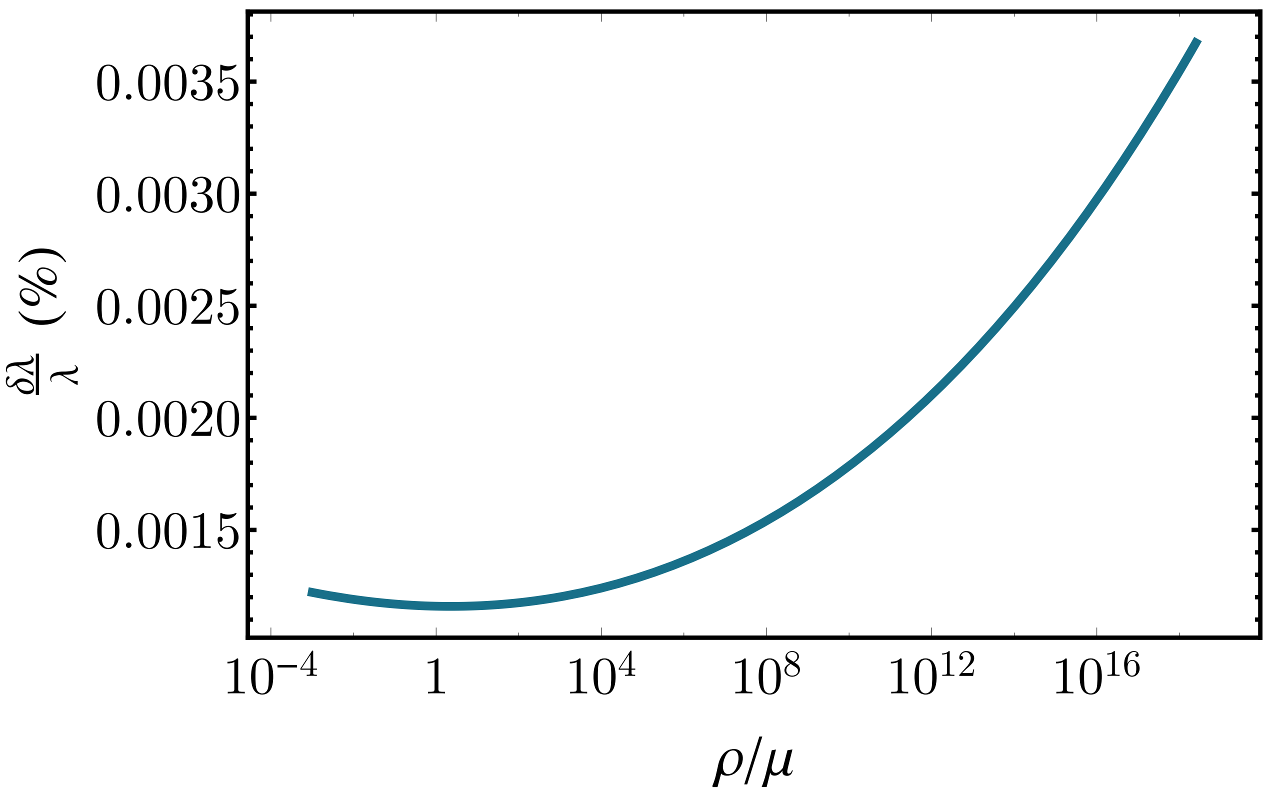
Solve for t_* perturbatively in $\hbar$

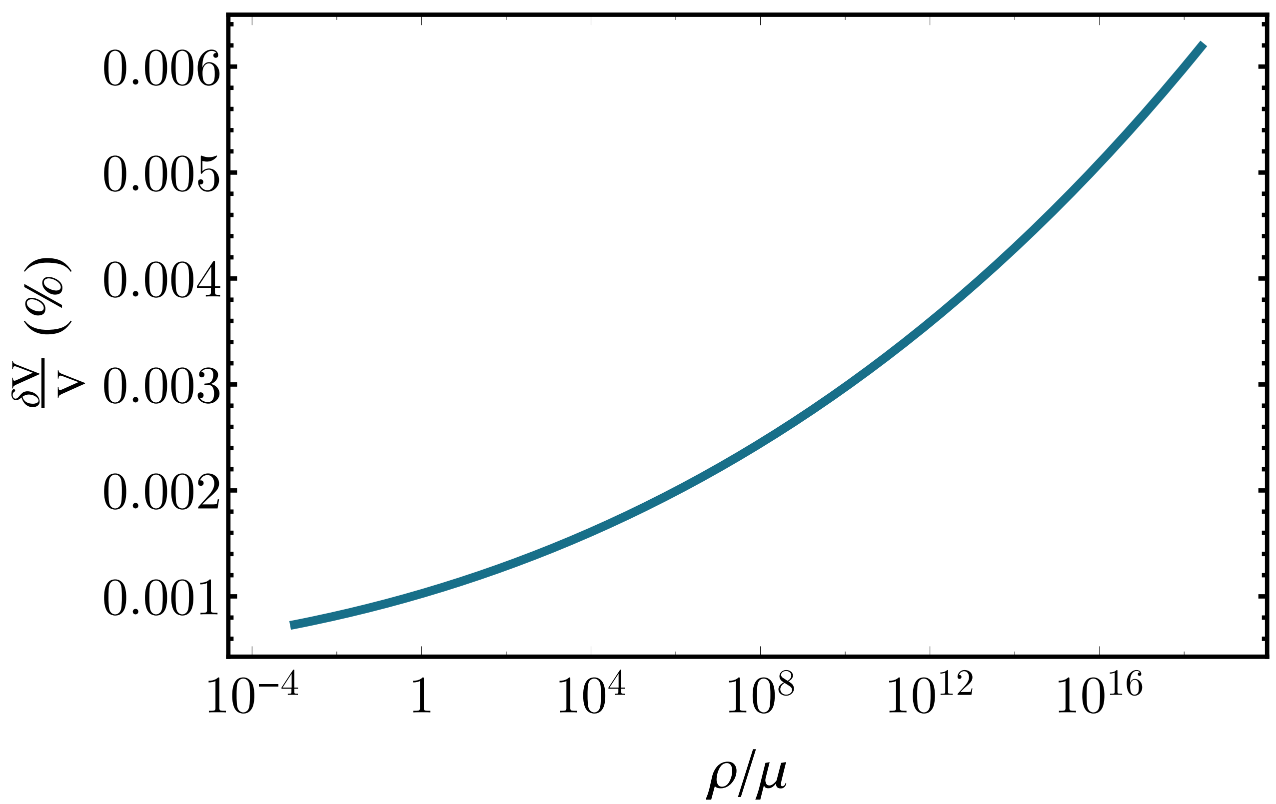
$$t_*^{(1)} = \frac{V^{(2)}(\mu,\lambda,\phi) - \left[\mathrm{d}^{(2)}V^{(0)}\right]_{t=0} t_*^{(0)} - \frac{1}{2}\left[\left(\mathrm{d}^{(1)}\right)^2 V^{(0)}\right]_{t=0}\left(t_*^{(0)}\right)^2}{\left[\mathrm{d}^{(1)}V^{(0)}\right]_{t=0}}$$

O(N)-SYMMETRIC MODEL AT TWO-LOOP LEVEL



O(N)-SYMMETRIC MODEL AT TWO-LOOP LEVEL





RECAP

To compute $V(\mu, \lambda, \phi)$

t_*

Evaluate

$$V(\mu, \lambda, \phi) = V^{(0)}(\bar{\lambda}(t_*), \bar{\phi}(t_*))$$

Solve numerically

$$V^{(1)}(\bar{\mu}(t_*); \bar{\lambda}(t_*), \bar{\phi}(t_*)) = 0$$

Use approximation

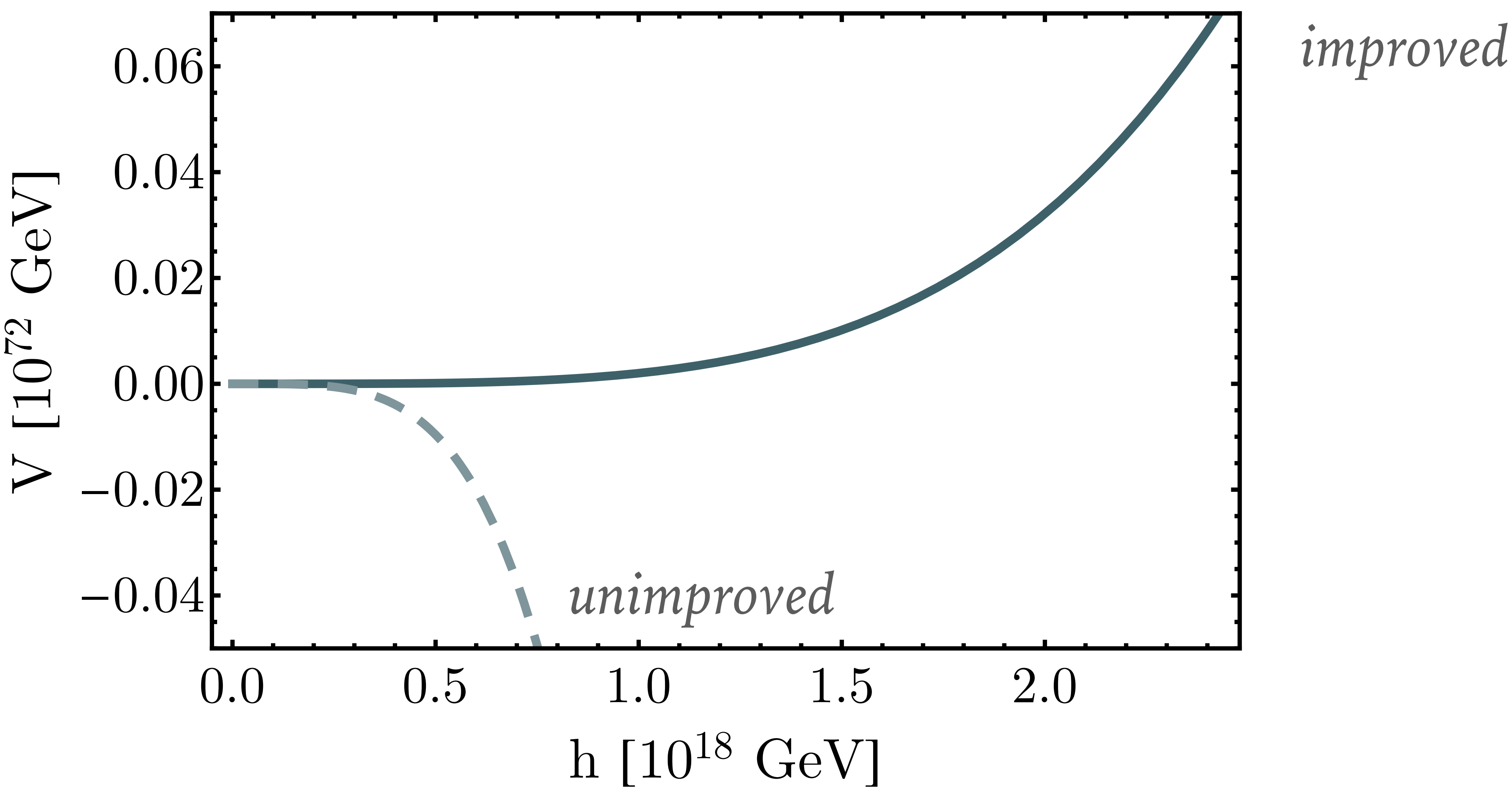
$$t_*^{(0)} = \frac{V^{(1)}(\mu, \lambda, \phi)}{2\mathbb{B}(\lambda, \phi)}$$

No explicit logs!

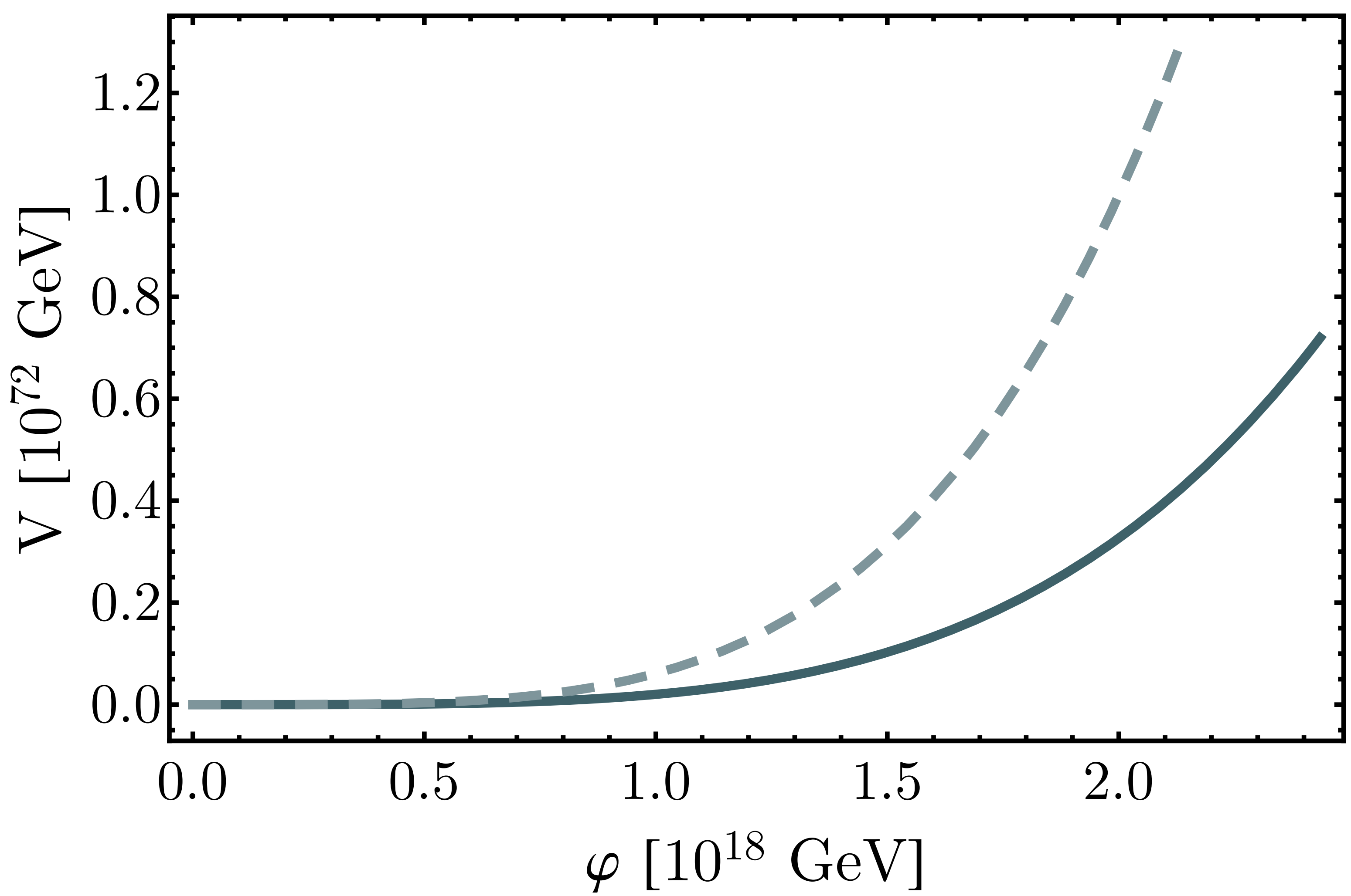
Form preserved at higher orders difference can only come from running

VACUUM STABILITY IN SU(2)CSM

Tree-level vacuum stability conditions satisfied at the Planck scale



VACUUM STABILITY IN SU(2)CSM



RUNNING VEVS