Origin of mass scales in scale-symmetric extension of Standard Model

Corfu2022

Paulina Michalak   in collaboration with prof. Zygmunt Lalak

31.08.2022

Faculty of Physics
University of Warsaw

Outline

1. Scale symmetric extension of Higgs sector
2. Origin of mass scales
3. Temperature corrections
4. Time evolution of the fields
5. Conclusions

Scale symmetric extension of Higgs sector

Authors

D. M. Ghilencea: 2104.15118, 1904.06596, 1812.08613...

P. G. Ferreira, C. T. Hill and G. G. Ross: 1801.07676, 1603.05983, 1906.03415...

D. M. Ghilencea, Z. Lalak and P. Olszewski: 1612.09120, 1608.05336...

M. Shaposhnikov and A. Shkerin: 2108.05897, 1804.06376...

...

Scale symmetric extension of Higgs sector

$$\frac{\mathcal{L}}{\sqrt{g}} = -\frac{1}{12}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)R + \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 + \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - V(\phi_0, \phi_1)$$

$$V(\phi_0, \phi_1) = \lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4$$

$$\boxed{\phi_0 \to \text{"dilaton"} \qquad \phi_1 \to \text{Higgs neutral component}}$$

Scale symmetric extension of Higgs sector

$$\frac{\mathcal{L}}{\sqrt{g}} = -\frac{1}{12}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)R + \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 + \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - V(\phi_0,\phi_1)$$

$$V(\phi_0,\phi_1) = \lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4$$

$$\boxed{\phi_0 \to \text{“dilaton”} \qquad \phi_1 \to \text{Higgs neutral component}}$$

$$\lambda_2 \gg |\lambda_1| \gg \lambda_0$$

$$\lambda_2 > 0, \quad \lambda_1 < 0, \quad \lambda_0 > 0$$

Ground state and the mass spectrum

$$\frac{\mathcal{L}}{\sqrt{g}} = -\frac{1}{12}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)R + \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 + \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - V(\phi_0,\phi_1)$$

$$V(\phi_0,\phi_1) = \lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4$$

Ground state and the mass spectrum

$$\frac{\mathcal{L}}{\sqrt{g}} = -\frac{1}{12}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)R + \frac{1}{2}\partial_\mu\phi_0\partial^\mu\phi_0 + \frac{1}{2}\partial_\mu\phi_1\partial^\mu\phi_1 - V(\phi_0,\phi_1)$$

$$V(\phi_0,\phi_1) = \lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4$$

$\mathcal{L} \Rightarrow$ EOMs $\Rightarrow$ stationary points:

$$\langle\phi_1^2\rangle = -\frac{\lambda_1}{2\lambda_2}\langle\phi_0^2\rangle, \qquad \underbrace{\lambda_0 = \frac{\lambda_1^2}{4\lambda_2}}_{V(\langle\phi_0\rangle,\langle\phi_1\rangle)=0}, \qquad \langle R\rangle = 0$$

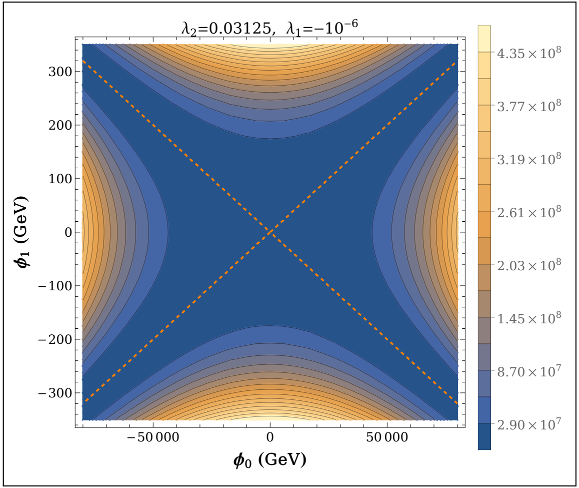
Ground state and the mass spectrum

$$\langle \phi_1^2 \rangle = -\frac{\lambda_1}{2\lambda_2} \langle \phi_0^2 \rangle$$

$$\lambda_0 = \frac{\lambda_1^2}{4\lambda_2}$$

$$\Downarrow$$

$$V = \lambda_2 \phi_0^4 \left(\frac{\phi_1^2}{\phi_0^2} + \frac{\lambda_1}{2\lambda_2} \right)^2$$



Ground state and the mass spectrum

mass matrix:

$$M^2 = \begin{pmatrix} \lambda_1 \left(2\phi_1^2 + \frac{3\lambda_1}{\lambda_2}\phi_0^2\right) & 4\lambda_1\phi_1\phi_0 \\ 4\lambda_1\phi_1\phi_0 & 2\left(6\lambda_2 + \lambda_1\phi_1^2\phi_0^2\right) \end{pmatrix}$$

Goldstone $\rightarrow$ flat direction

$$m_G^2 = 0$$

massive “Higgs”

$$m_H^2 = -4\lambda_1\left(1 - \frac{\lambda_1}{2\lambda_2}\right)\langle\phi_0^2\rangle$$

Higgs potential parameters and Planck mass

$$m_H^2 = -4\lambda_1\left(1 - \frac{\lambda_1}{2\lambda_2}\right)\langle\phi_0^2\rangle = (125\ \mathrm{GeV})^2$$

$$\langle\phi_1^2\rangle = -\frac{\lambda_1}{2\lambda_2}\langle\phi_0^2\rangle = (250\ \mathrm{GeV})^2$$

Higgs potential parameters and Planck mass

$$m_H^2 = -4\lambda_1\left(1 - \frac{\lambda_1}{2\lambda_2}\right)\langle\phi_0^2\rangle = (125\ \mathrm{GeV})^2$$

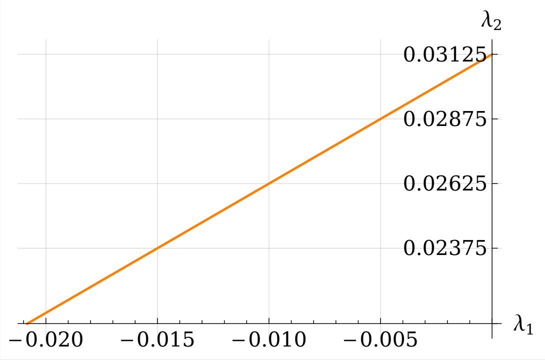
$$\langle\phi_1^2\rangle = -\frac{\lambda_1}{2\lambda_2}\langle\phi_0^2\rangle = (250\ \mathrm{GeV})^2$$

$$\Downarrow$$

$$\lambda_2 = \tfrac{1}{32}\left(1 + 16\lambda_1\right)$$

$$\lambda_2 \gg |\lambda_1|$$

$$\lambda_2 = 0.03125, \quad |\lambda_1| = \mathcal{O}(10^{-7}) - \mathcal{O}(10^{-26})$$



Higgs potential parameters and Planck mass

$$-\frac{1}{12}\left(\xi_0\phi_0^2+\xi_1\phi_1^2\right)R \quad\Longleftrightarrow\quad -\frac{1}{2}M_P^2 R$$

Higgs potential parameters and Planck mass

$$-\frac{1}{12}\left(\xi_0\phi_0^2+\xi_1\phi_1^2\right)R \quad\Longleftrightarrow\quad -\frac{1}{2}M_P^2 R$$

$$\frac{1}{6}\left(\xi_0\phi_0^2+\xi_1\phi_1^2\right)\xrightarrow{\text{ground state}}\frac{1}{6}\left(\xi_0-\frac{\lambda_1}{2\lambda_2}\xi_1\right)\langle\phi_0^2\rangle = M_P^2$$

Higgs potential parameters and Planck mass

$$\langle \phi_1^2 \rangle = -\frac{\lambda_1}{2\lambda_2}\langle \phi_0^2 \rangle = (250\ \mathrm{GeV})^2$$

$$\lambda_2 = \frac{1}{32}\left(1 + 16\lambda_1\right)$$

$$\frac{1}{6}\left(\xi_0 - \frac{\lambda_1}{2\lambda_2}\xi_1\right)\langle \phi_0^2 \rangle = M_P^2$$

$$\Downarrow$$

$$\lambda_1 = \frac{-0.0625 \cdot \xi_0}{\xi_0 - \xi_1 + 1.43 \cdot 10^{34}}$$

Higgs potential parameters and Planck mass

$$\langle \phi_1^2 \rangle = -\frac{\lambda_1}{2\lambda_2}\langle \phi_0^2 \rangle = (250 \text{ GeV})^2$$

$$\lambda_2 = \frac{1}{32}\Big(1 + 16\lambda_1\Big)$$

$$\frac{1}{6}\left(\xi_0 - \frac{\lambda_1}{2\lambda_2}\xi_1\right)\langle \phi_0^2 \rangle = M_P^2$$

$$\Downarrow$$

$$\lambda_1 = \frac{-0.0625 \cdot \xi_0}{\xi_0 - \xi_1 + 1.43 \cdot 10^{34}}$$

$$\xi_0 \gg \xi_1$$

$$\xi_0 < \mathcal{O}(10^{15})$$

$$\boxed{\begin{aligned} &\xi_0 = 10^5, \quad \xi_1 = 0.1, \quad \lambda_1 = -4.37 \cdot 10^{-31}, \\ &\xi_0 = 10^{10}, \quad \xi_1 = 0.1, \quad \lambda_1 = -4.37 \cdot 10^{-26}, \\ &\xi_0 = 10^{15}, \quad \xi_1 = 0.1, \quad \lambda_1 = -4.37 \cdot 10^{-21}. \end{aligned}}$$

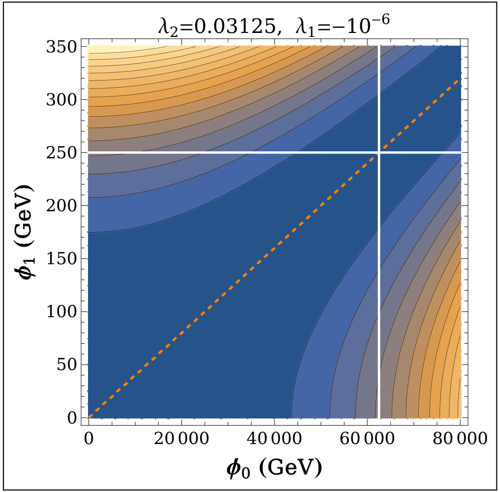
$$\lambda_1 \phi_0^2 \phi_1^2$$

Origin of mass scales

Origin of mass scales

NO MASS SCALES $\Rightarrow$ $\langle \phi_i \rangle$

$$\langle \phi_1^2 \rangle \sim \langle \phi_0^2 \rangle$$
$$m_H^2 \sim \langle \phi_0^2 \rangle$$
$$M_P^2 \sim \langle \phi_0^2 \rangle$$



Temperature corrections

Adding temperature

$$V \quad \rightarrow \quad V + \underbrace{\delta V_T + \delta V_{ring}}_{T \text{ dependent}}$$

Adding temperature

$$V \quad \rightarrow \quad V + \underbrace{\delta V_T + \delta V_{ring}}_{T \text{ dependent}}$$

$$V \rightarrow V + \frac{1}{2}\phi_1^2 \cdot \left(\lambda_2 + \frac{\lambda_1}{6} + \frac{g_1^2}{16} + \frac{3g_2^2}{16} + \frac{h_t^2}{4}\right)T^2 + \frac{1}{2}\phi_0^2 \cdot \frac{\lambda_1}{6}T^2$$

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

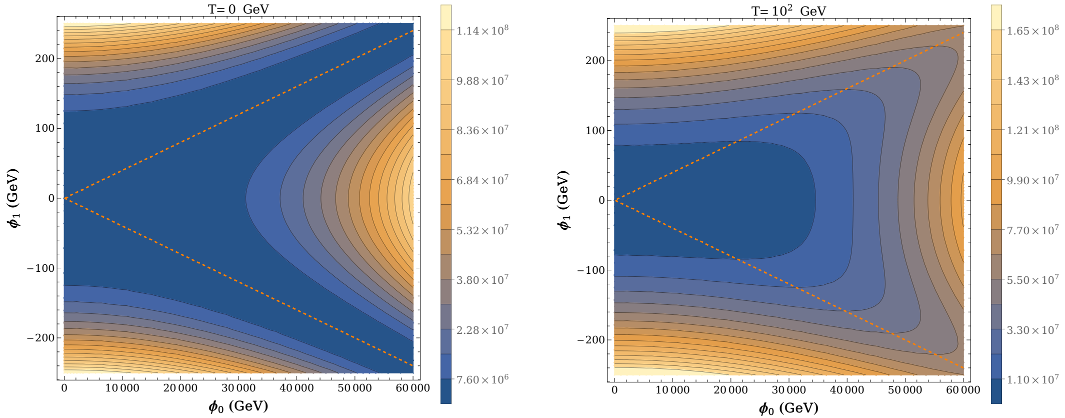
Adding temperature

$$V \quad \rightarrow \quad V + \underbrace{\delta V_T + \delta V_{ring}}_{T \text{ dependent}}$$

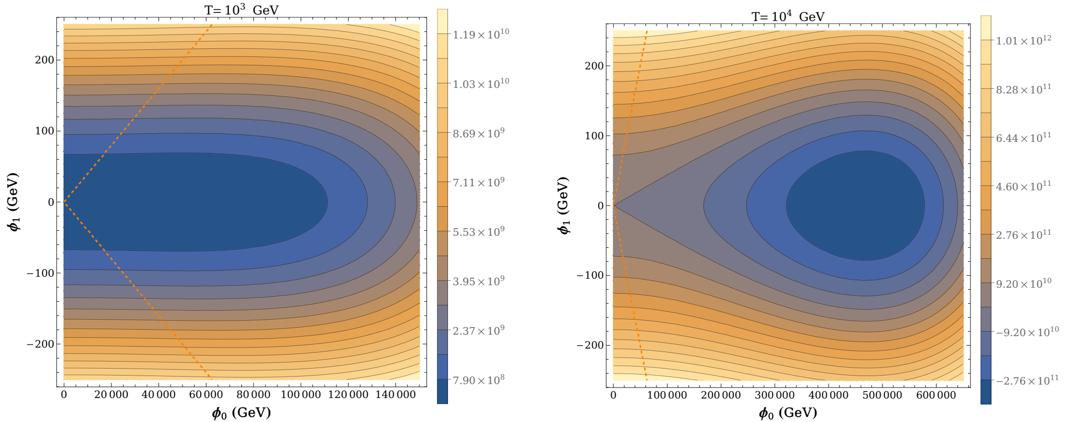
$$V \rightarrow V + \frac{1}{2}\phi_1^2 \cdot \left(\lambda_2 + \frac{\lambda_1}{6} + \frac{g_1^2}{16} + \frac{3g_2^2}{16} + \frac{h_t^2}{4}\right)T^2 + \frac{1}{2}\phi_0^2 \cdot \frac{\lambda_1}{6}T^2$$

SCALE SYMMETRY BROKEN!

Adding temperature

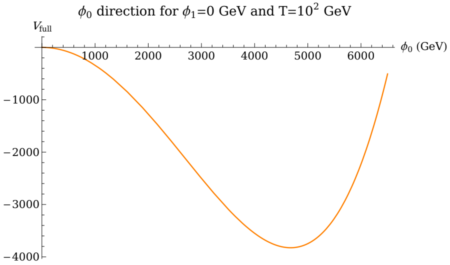


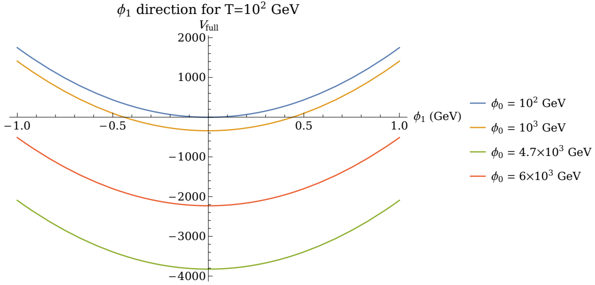
Adding temperature



Temperature minimum

$$\langle\phi_1^2\rangle_T = 0, \qquad \langle\phi_0^2\rangle_T \sim T^2$$





Time evolution of the fields

Equations of motion: $T = 0$

FLRW metric $\left(1, -a(t)^2, -a(t)^2, -a(t)^2\right)$

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 + 2\xi_0\phi_0^2 H^2 + \xi_0\phi_0^2\dot{H} + 4\lambda_0\phi_0^3 + 2\lambda_1\phi_0\phi_1^2 = 0$$
$$\ddot{\phi}_1 + 3H\dot{\phi}_1 + 2\xi_1\phi_1^2 H^2 + \xi_1\phi_1^2\dot{H} + 4\lambda_2\phi_1^3 + 2\lambda_1\phi_0^2\phi_1 = 0$$
$$\frac{1}{2}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)\left(2H + \dot{H}\right) - \frac{1}{2}\dot{\phi_0}^2 - \frac{1}{2}\dot{\phi_1}^2 + 2\left(\lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4\right) = 0$$

Equations of motion: $T = 0$

FLRW metric $(1, -a(t)^2, -a(t)^2, -a(t)^2)$

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 + 2\xi_0\phi_0^2 H^2 + \xi_0\phi_0^2\dot{H} + 4\lambda_0\phi_0^3 + 2\lambda_1\phi_0\phi_1^2 = 0$$

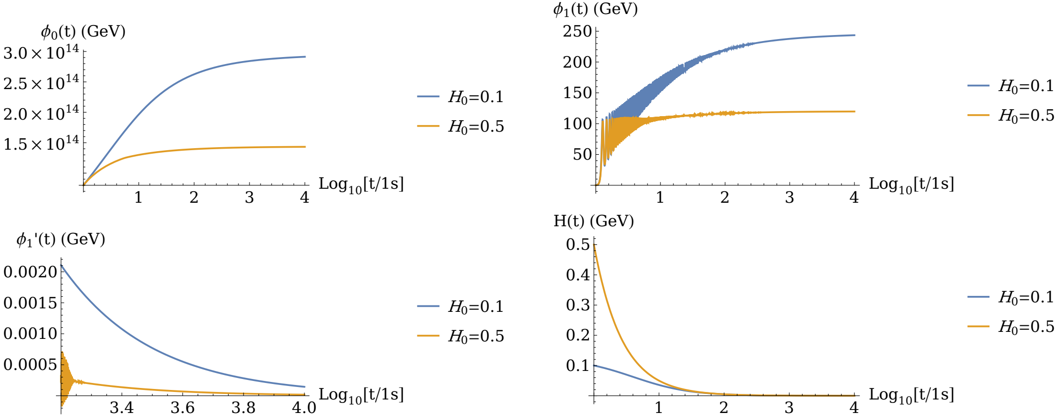
$$\ddot{\phi}_1 + 3H\dot{\phi}_1 + 2\xi_1\phi_1^2 H^2 + \xi_1\phi_1^2\dot{H} + 4\lambda_2\phi_1^3 + 2\lambda_1\phi_0^2\phi_1 = 0$$

$$\frac{1}{2}\left(\xi_0\phi_0^2 + \xi_1\phi_1^2\right)\left(2H + \dot{H}\right) - \frac{1}{2}\dot{\phi_0}^2 - \frac{1}{2}\dot{\phi_1}^2 + 2\left(\lambda_0\phi_0^4 + \lambda_1\phi_0^2\phi_1^2 + \lambda_2\phi_1^4\right) = 0$$

$$\langle\phi_1^2\rangle = -\frac{\lambda_1}{2\lambda_2}\langle\phi_0^2\rangle, \qquad \langle H\rangle = 0$$

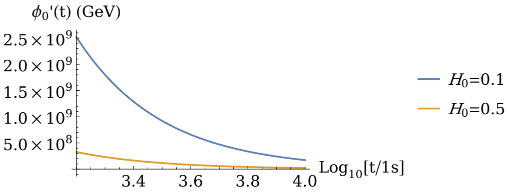
$T = 0$ evolution: realistic model

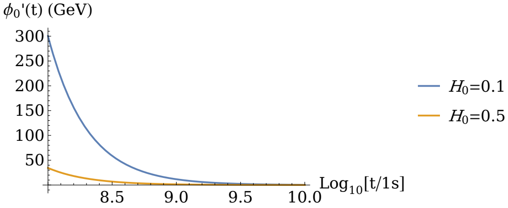
$$\lambda_2 = 0.03125, \quad \lambda_1 = -4.37 \cdot 10^{-26}, \quad \xi_0 = 10^{10}, \quad \xi_1 = 0.1$$



$T = 0$ evolution: realistic model

$$\phi_0(0) = 8 \cdot 10^{13}, \quad \dot{\phi}_0(0) = 5 \cdot 10^{13}, \quad \phi_1(0) = 0, \quad \dot{\phi}_1(0) = 10$$





$T \neq 0$ evolution

$$V \to V + \frac{1}{2}\phi_1^2 \cdot \left(\lambda_2 + \frac{\lambda_1}{6} + \frac{g_1^2}{16} + \frac{3g_2^2}{16} + \frac{h_t^2}{4}\right)T^2 + \frac{1}{2}\phi_0^2 \cdot \frac{\lambda_1}{6}T^2$$

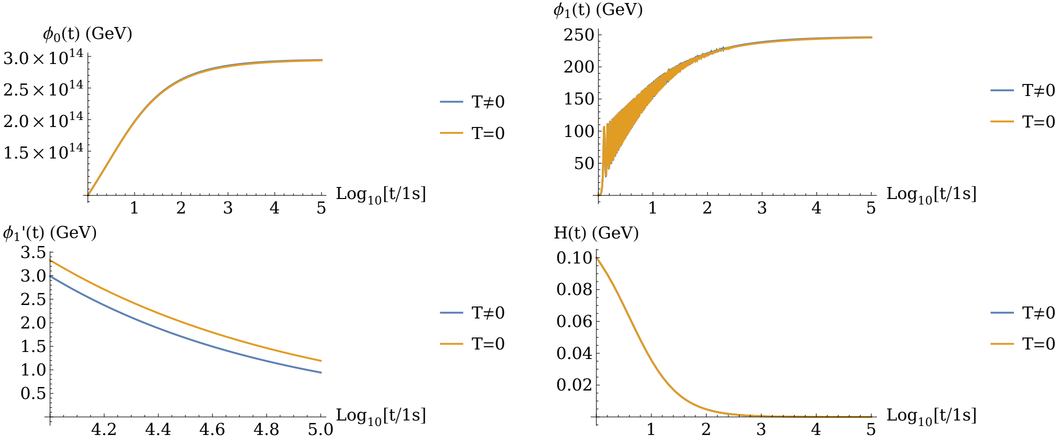
radiation domination:

$$T(t) = \frac{1.121 \cdot \mathrm{GeV} \cdot \sqrt{\mathrm{s}}}{\sqrt{t + t_0}}$$

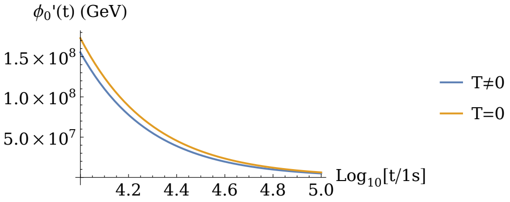
$$\boxed{\mathrm{H}_0 = 0.1, \quad T_0 = 10^4 \ \mathrm{GeV}}$$

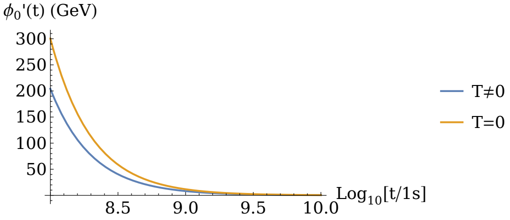
FACULTY OF PHYSICS UNIVERSITY OF WARSAW

$T \neq 0$ evolution: realistic model

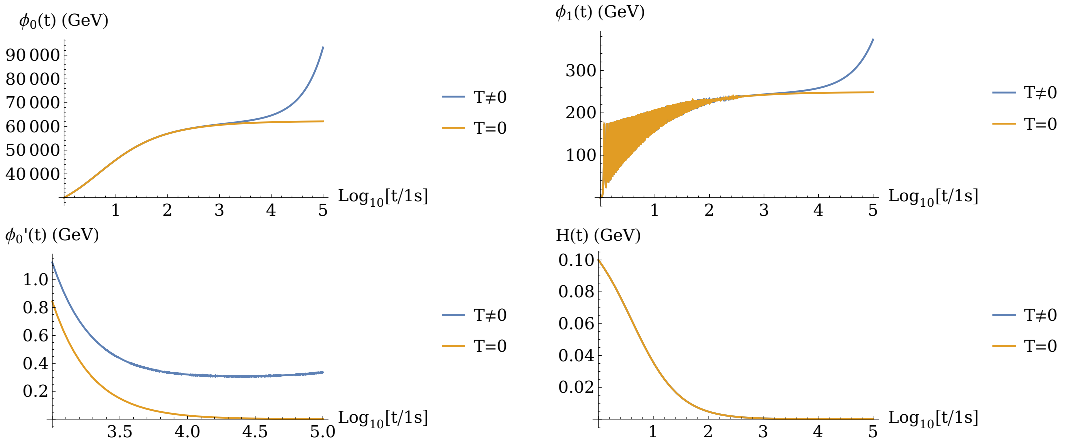


$T \neq 0$ evolution: realistic model





$T \neq 0$ evolution: bigger $|\lambda_1|$ values $\rightarrow$ $\lambda_1 = -10^{-6}$

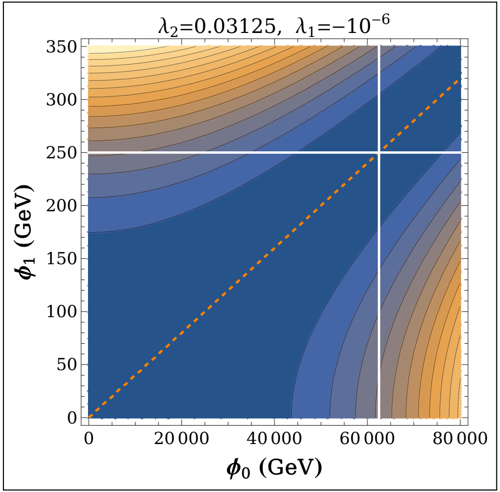


$T \neq 0$ evolution: bigger $|\lambda_1|$ values

$$V \to \lambda_1 \phi_0^2 T^2$$

$$-\frac{\partial V}{\partial \phi_0} \sim -\lambda_1 \phi_0 T^2$$

$$\lambda_1 < 0$$



Conclusions

Conclusions

scale symmetry $\Rightarrow$ origin of mass scales

Conclusions

scale symmetry $\Rightarrow$ origin of mass scales

broken at finite T $\rightarrow$ $\langle \phi_0^2 \rangle \sim T^2$

Conclusions

scale symmetry $\Rightarrow$ origin of mass scales

broken at finite T $\rightarrow$ $\langle \phi_0^2 \rangle \sim T^2$

cosmological evolution $\rightarrow$ $\langle \phi_1 \rangle = 250$ **GeV**

Thank You

Questions?

NATIONAL SCIENCE CENTRE
POLAND

GR5853

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

Backup slides: temperature minimum

$$\phi_0^2 = \left[\frac{\left(9.89\alpha - 3.63\lambda_2 - 6.91 \cdot 10^{-16} g_1^2 - 2.76 \cdot 10^{-15} h_t^2\right)}{\left(- 39.48\alpha + \lambda_2(\alpha \log(-\lambda_1) + 3.48\alpha + 43.53)\right)} + \right.$$

$$\left. + \frac{\lambda_2\left(6.58\alpha - 43.53\lambda_2 - 2.72 g_1^2 - 8.16 g_2^2 - 10.88 h_t^2\right)}{\lambda_1\left(- 39.48\alpha + \lambda_2(\alpha \log(-\lambda_1) + 3.48\alpha + 43.53)\right)} \right] \cdot T^2$$

$$\alpha = \sqrt{48\lambda_2 + 3g_1^2 + 9g_2^2 + 12h_t^2}$$