SM vacuum stability in the early universe

Sami Nurmi

University of Jyväskylä

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Based on:

Herranen, Markkanen, SN, Rajantie, PRL 113 (2014) 211102

Herranen, Markkanen, SN, Rajantie, PRL 115 (2015) 241301

Markkanen, Stopyra, SN, Rajantie, JHEP 1806 (2018) 040

Hardwick, Markkanen, SN, arxiv: 1904.11373

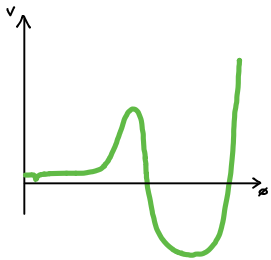
Enqvist, Meriniemi, SN, JCAP 1407 (2014) 025

Enqvist, Rusak, SN, Weir, JCAP 1602 (2016) 02 057

SM in flat spacetime

- 6 quarks, 6 leptons, 3 gauge fields + Higgs
- 19 parameters, all measured
- Can be extrapolated up to M_p

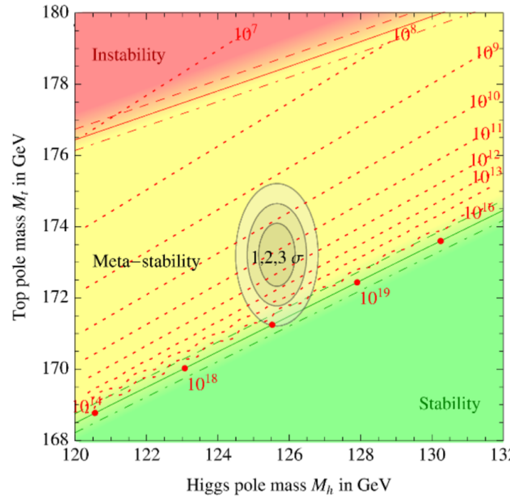
EW vacuum metastable



$\lambda = 0$ at $\mu = 6.6 \cdot 10^{9}\,\text{GeV}$

$\tau = \Gamma^{-1} \gg 10^{10}$ yrs

(Elias-Miro et.al. 11, Buttazo et.al. 13, Degrassi et.al. 12)



(Buttazo et.al. 13)

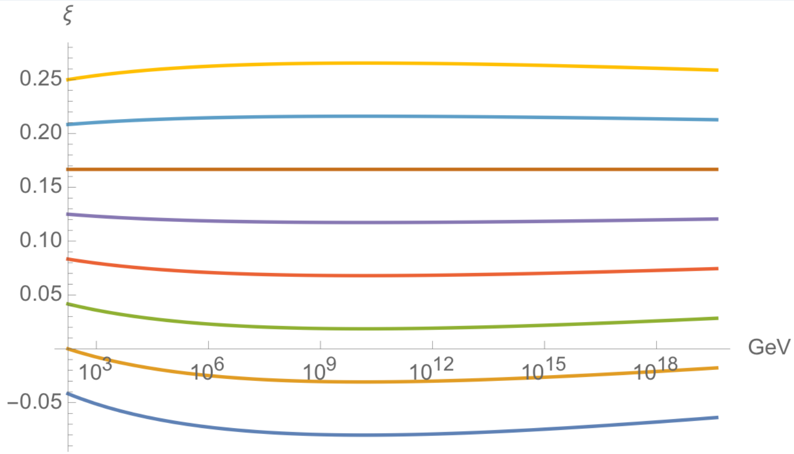
SM in curved spacetime

One new term allowed by symmetries

$$\mathcal{L} = \mathcal{L}_{SM} + \xi R \Phi^\dagger \Phi$$

(Chernikov & Tagirov 1968)

Running: $$\frac{d\xi}{d\ln\mu} = \frac{1}{16\pi^2}\left(\xi - \frac{1}{6}\right)\left(12\lambda + 6y_t^2 - \frac{3}{2}g'^2 - \frac{9}{2}g^2\right)$$



Cannot set $\xi = 0$ over all scales

$\Rightarrow$ last unknown SM coupling

Constraints on ξ

$$R = -8\pi G T = 3H^2(1-3w)$$

Today: $H_0 = 10^{-33}\,eV$ Very small

LHC: $|\xi| < 2.6 \cdot 10^{15}$ (Atkins & Calmet 12)

Inflation: $H \lesssim 10^{14}\,GeV$ (Planck + BKEP2/Keck 18)

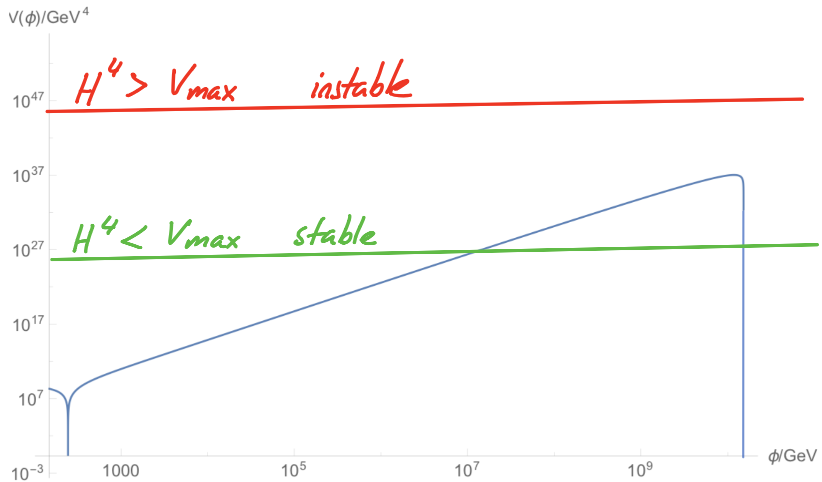
Potentially large contribution to effective mass

$$m_{eff}^2 = m_h^2 + 6\xi H^2$$

Higgs during inflation

Assume: inflaton decoupled from the Higgs (e.g. R^2-inflation + SM)

Higgs fluctuates $\langle \delta\phi \rangle \sim H^4$, $V'' < H^2$



Transition over the barrier if $H > V_{max}$

(Espinosa et.al 08,
Lebedev, Westphal 13,
Kobakhidze, Spencer-Smith 13,
Fairbairn, Hogan 14,
Hook et. al. 14,
Enqvist, Meriniemi, SN 14)

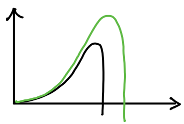
Sensitive to ξ

Inflation $R = 12H^2$

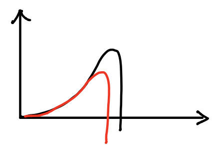
- $\frac{\xi}{2} R \phi^2 \implies$ effective mass $m_{eff}^2 \supset 12 \xi H^2$

- Tree level (Espinosa et.al. 08)

$\xi > 0$ stabilizing effect



$\xi < 0$ destabilizing effect



- QM analysis: ξH^2 enters also in loop logs

  $\implies$ running of all couplings affected

SM eff. pot. in curved space (UV limit)

One-loop

$$V_{\rm SM}^{\rm eff}(\varphi(\mu)) = -\frac{1}{2}m^2(\mu)\varphi^2(\mu) + \frac{\xi(\mu)}{2}R\varphi^2(\mu) + \frac{\lambda(\mu)}{4}\varphi^4(\mu) + V_\Lambda(\mu) - 12\kappa(\mu)H^2 + \alpha(\mu)H^4$$
$$+\frac{1}{64\pi^2}\sum_{i=1}^{31}\left\{n_i\mathcal{M}_i^4(\mu)\left[\log\left(\frac{|\mathcal{M}_i^2(\mu)|}{\mu^2}\right) - d_i\right] + n_i' H^4\log\left(\frac{|\mathcal{M}_i^2(\mu)|}{\mu^2}\right)\right\}$$

Ψ	i	n_i	d_i	n_i'	$\mathcal{M}_i^2$
$W^\pm$	1	2	3/2	−34/15	$m_W^2 + H^2$
	2	6	5/6	−34/5	$m_W^2 + H^2$
	3	−2	3/2	4/15	$m_W^2 - 2H^2$
Z^0	4	1	3/2	−17/15	$m_Z^2 + H^2$
	5	3	5/6	−17/5	$m_Z^2 + H^2$
	6	−1	3/2	2/15	$m_Z^2 - 2H^2$
q	7 − 12	−12	3/2	38/5	$m_q^2 + H^2$
l	13 − 15	−4	3/2	38/15	$m_l^2 + H^2$
h	16	1	3/2	−2/15	$m_h^2 + 12(\xi - 1/6)H^2$
χ_W	17	2	3/2	−4/15	$m_\chi^2 + \zeta_W m_W^2 + 12(\xi - 1/6)H^2$
χ_Z	18	1	3/2	−2/15	$m_\chi^2 + \zeta_Z m_Z^2 + 12(\xi - 1/6)H^2$
c_W	19	−2	3/2	4/15	$\zeta_W m_W^2 - 2H^2$
c_Z	20	−1	3/2	2/15	$\zeta_Z m_Z^2 - 2H^2$

Ψ	i	n_i	d_i	n_i'	$\mathcal{M}_i^2$
γ	21	1	3/2	−17/15	H^2
	22	3	5/6	−17/5	H^2
	23	−1	3/2	2/15	$-2H^2$
g	24	8	3/2	−136/15	H^2
	25	24	5/6	−136/5	H^2
	26	−8	3/2	16/15	$-2H^2$
ν	27 − 29	−2	3/2	19/15	H^2
c_γ	30	−1	3/2	2/15	$-2H^2$
c_g	31	−8	3/2	16/15	$-2H^2$

(Markkanen, SN, Rajantie, Stopyra 18)

Stability condition

Horizon crossing: $\delta\phi_k \sim \frac{H}{2\pi}$ + squeezing $\Longrightarrow$ **IR part $\bar{\phi}$ stochastic**

(Starobinsky 82, Starobinsky & Yokoyama 94)

Distribution $P(\bar{\phi}, t)$:

$$\frac{\partial P}{\partial t} = \frac{1}{3H}\frac{\partial}{\partial\bar{\phi}}\left(\frac{V'_{\text{eff}}}{Z}P\right) + \frac{1}{2}\frac{\partial^2}{\partial\bar{\phi}^2}(GP)$$

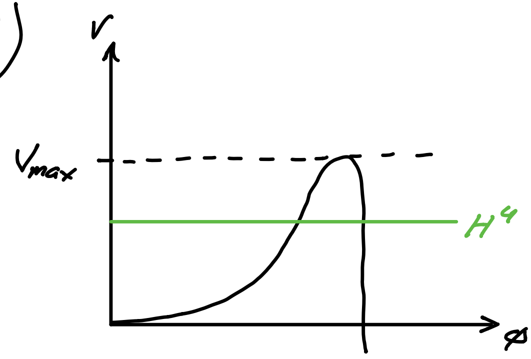
QFT UV limit $\rightarrow V_{\text{eff}}, Z$

(Hardwick, Markkanen, SN 19)

de Sitter $\Longrightarrow P(\bar{\phi}) = \exp\left(-\frac{V_{\text{eff}}(\bar{\phi})}{8\pi^2 H^4}\right)$

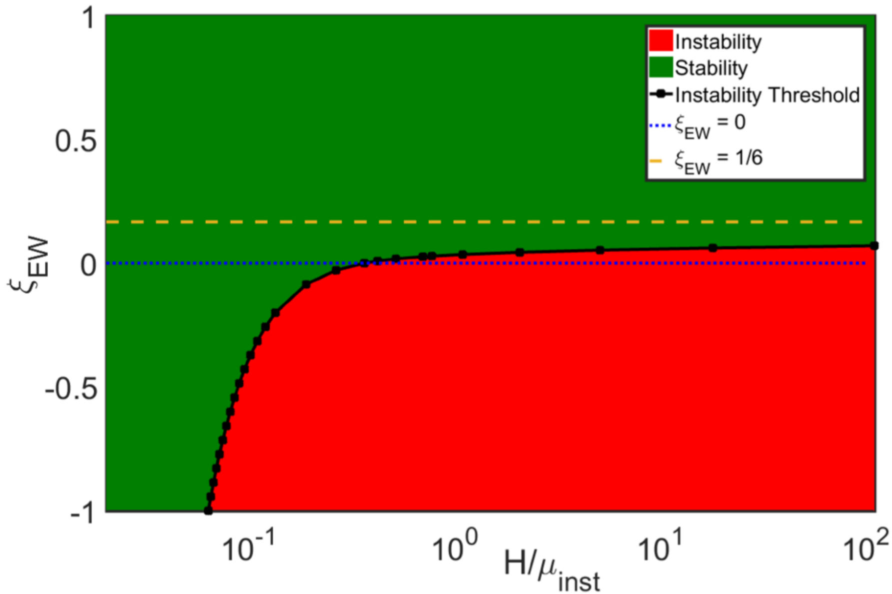
EW vacuum survives if

$$\frac{V_{max}}{8\pi^2 H^4} < 1$$



SM stability during inflation

(Markkanen, SN, Rajantie, Stopyra 18)



Must have $\xi \gtrsim 0.01$ if $H \gtrsim \mu_{inst} = 6.6 \cdot 10^9$ GeV

Stability during reheating

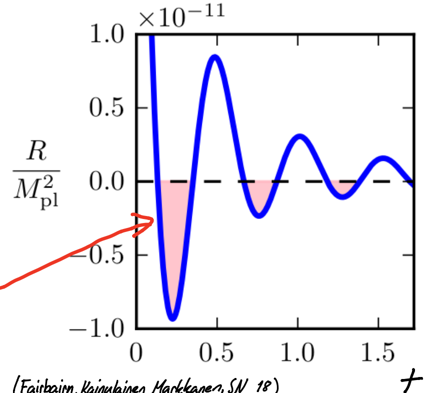
Inflaton χ oscillates

$$R = M_P^{-2}\left(4V(\chi) - \dot{\chi}^2\right)$$

$$m_h^2 \simeq 3\lambda h^2 + \xi R h^2 < 0$$

Tachyonic phase

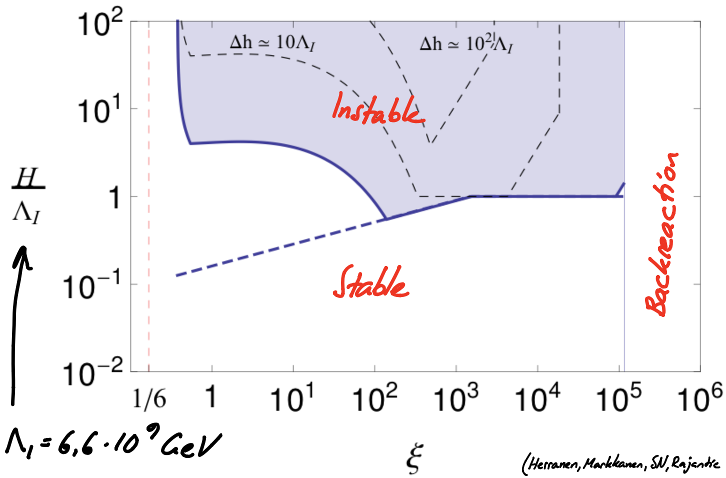
(Basset, Liberati 98, Tsujikawa et.al. 99)



(Fairbairn, Kainulainen, Markkanen, SN 18)

Exponential Higgs production: $\langle h^2 \rangle \sim \frac{H^2}{\sqrt{\xi}} e^{2\sqrt{\xi}}$ (Herranen, Markkanen, SN, Rajantie 15)

Upper bound for ξ



(Herranen, Markkanen, SN, Rajantie 15)

Assume:

inflaton $V = \frac{1}{2} m^2 \chi^2$

Lattice study: $\xi \lesssim 10$ (Ema et.al. 16, Figueroa et.al. 17)

Summary

- Minimal scenario: SM valid up to $E \sim M_p$ (DM, DE, inflaton decoupled of SM)
- Non-minimal Higgs coupling inavoidable

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\xi R h^2 \quad , \quad \frac{d\xi}{d\ln\mu} \neq 0$$

- Inflation + reheating: $0.01 \lesssim \xi \lesssim 10$

- Possible imprints? $\langle h^2 \rangle \sim H^2$ primordial Higgs condensate

(Enqvist, Meriniemi, SN 14; Enqvist, Rusak, SN, Wein 16)

PBH + GW (Espinosa et. al. 18)