Spacetime curvature and Higgs stability before and after inflation

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arXiv:1506.04065

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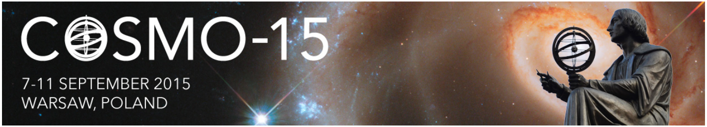


Outline

1. Introduction
2. Higgs stability during inflation
3. Higgs stability after inflation
4. Conclusions

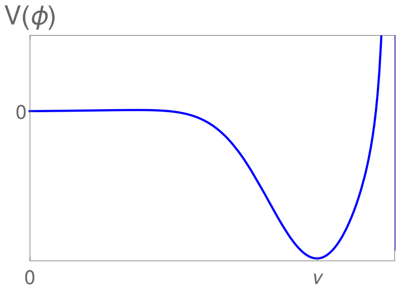
1 Introduction

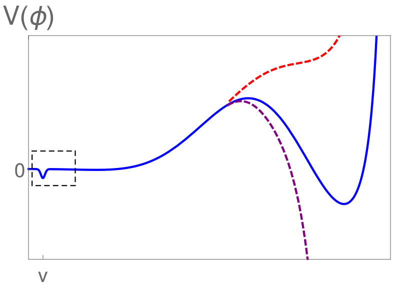
2 Higgs stability during inflation

3 Higgs stability after inflation

4 Conclusions

Standard Model Higgs potential





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- A vacuum at $\phi \neq v$ incompatible with observations
- *Meta* stable at 99% CL

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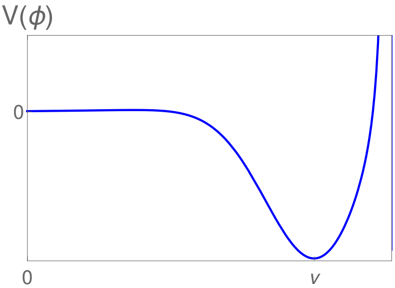

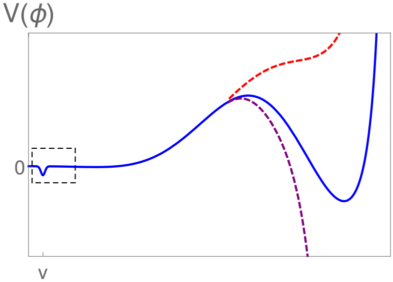

- Sensitive to M_h and M_t

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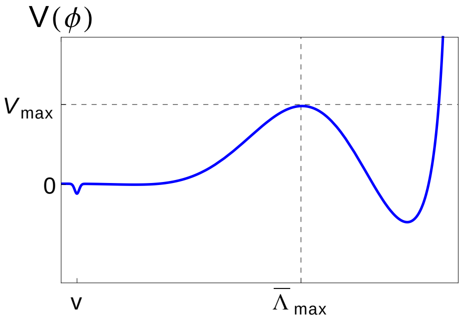
- What about the early Universe (inflation, reheating)?
- New physics needed to stabilize the vacuum?

The early Universe and the Standard Model

- Assume the SM to be valid and decoupled from inflation
  - Higgs subdominant, $\phi \ll M_{\rm pl}$
- Curvature can induce fluctuations of the Higgs $\Delta\phi \sim H$
  - Important if $\overline{\Lambda}_{\rm max} \lesssim H$
  - State of the art calculations [1]: $\overline{\Lambda}_{\rm max} \sim 10^{11}\,{\rm GeV}$



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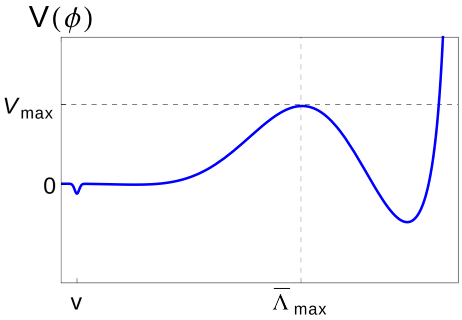

BICEP2/Keck/Planck

$H \lesssim 10^{14}\text{GeV}$

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Potential during inflation

- Fluctuations may be treated as stochastic variables [2]
- Probability density $P(t,\phi)$ from the Fokker-Planck equation

$$\dot{P}(t,\phi) = \frac{1}{3H}\frac{\partial}{\partial\phi}\left[P(t,\phi)V'_{\rm eff}(\phi)\right] + \frac{H^3}{8\pi^2}\frac{\partial^2}{\partial\phi^2}P(t,\phi)$$

- For large H the potential gets large curvature corrections ?!

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- Example: $V_{\rm eff}(\phi)$ for a self-interacting scalar field

$$V_{\rm cl}(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \frac{1}{2}\xi R\phi^2$$

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- Large $\log$'s problematic, $\Rightarrow$ RG improvement

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Effects from RG running

- The SM includes a non-minimal ξ-term
  - Always generated by running in curved space
  - Virtually unbounded by the LHC, $\xi_{\rm EW} < 10^{15}$ [3]

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running scale, $\phi \gg m$

$$\mu^2 \sim \phi^2 + R$$

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- Leading potential contributions:

Flat space, $\phi \gg m$

$$V_{\mathrm{eff}}(\phi) \approx \frac{\lambda(\phi)}{4}\phi^4$$

Curved space, $H \gg \phi \gg m$

$$V_{\mathrm{eff}}(\phi) \approx \frac{\lambda(H)}{4}\phi^4 + \frac{\xi(H)}{2}R\phi^2$$

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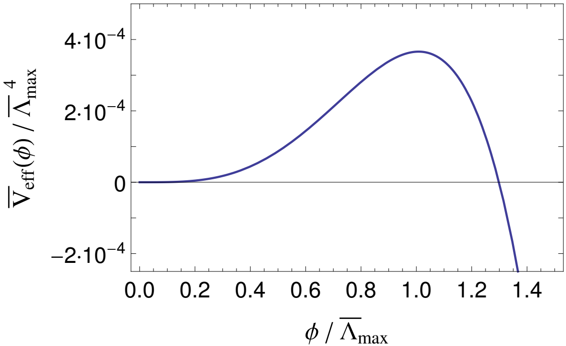
Full 1-loop result

$$V_{\text{eff}}(\phi, R) = -\frac{1}{2}m^2(\mu)\phi^2 + \frac{1}{2}\xi(\mu)R\phi^2 + \frac{1}{4}\lambda(\mu)\phi^4$$

$$+\sum_{i=1}^{9}\frac{n_i}{64\pi^2}M_i^4(\phi)\left[\log\frac{|M_i^2(\phi)|}{\mu^2} - c_i\right] \quad ; \quad \begin{aligned} M_i^2(\phi) &= \kappa_i\phi^2 - \kappa_i' + \theta_i R \\ \mu^2 &= \phi^2 + R \end{aligned}$$

Φ	i	n_i	κ_i	κ_i'	θ_i	c_i
$W^{\pm}$	1	2	$g^2/4$	0	$1/12$	$3/2$
	2	6	$g^2/4$	0	$-1/6$	$5/6$
	3	-2	$g^2/4$	0	$-1/6$	$3/2$
Z^0	4	1	$(g^2+g'^2)/4$	0	$1/12$	$3/2$
	5	3	$(g^2+g'^2)/4$	0	$-1/6$	$5/6$
	6	-1	$(g^2+g'^2)/4$	0	$-1/6$	$3/2$
t	7	-12	$y_t^2/2$	0	$1/12$	$3/2$
ϕ	8	1	3λ	m^2	$\xi - 1/6$	$3/2$
χ_i	9	3	λ	m^2	$\xi - 1/6$	$3/2$

Stability (Minkowski)



- For large H $(\sim 10^3\overline{\Lambda}_{\rm max})$, the SM is not stable [5]

[5] Kobakhidze & Spencer-Smith (2014); Hook et. al. (2014); Fairbairn & Hogan (2014); Enqvist, Meriniemi & Nurmi (2014); Zurek, Kearney & Yoo (2015)

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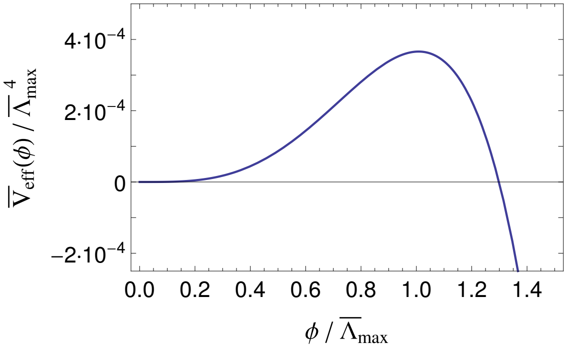

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How does including curvature change this?

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Stability (curved) I

- First attempt, set $\xi_{\rm EW} = 0$ and $H \sim 10^3\overline{\Lambda}_{\rm max}$

$$V_{\rm eff}(\phi) \approx \frac{\lambda(\mu)}{4}\phi^4 + \frac{\xi(\mu)}{2}R\phi^2$$

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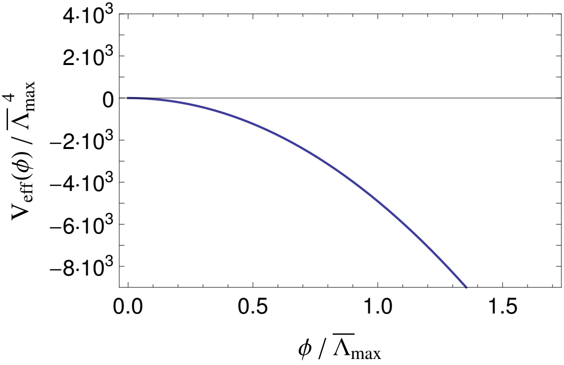

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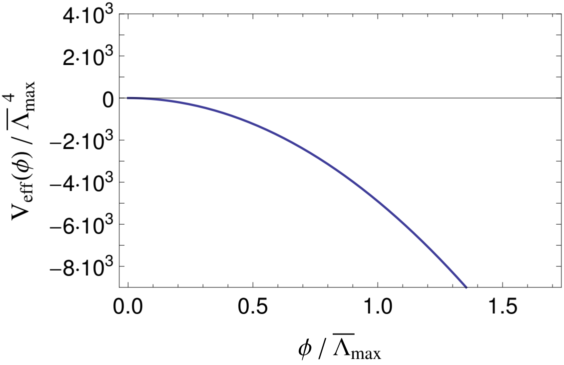

- For large H one has $\lambda(\mu) < 0$, since $\mu^2 = \phi^2 + R$
- ξ Can become positive or negative depending on $\xi_{\rm EW}$

Stability results (curved space) II

- Now choosing $\xi_{\rm EW} = 0.1$ [6]

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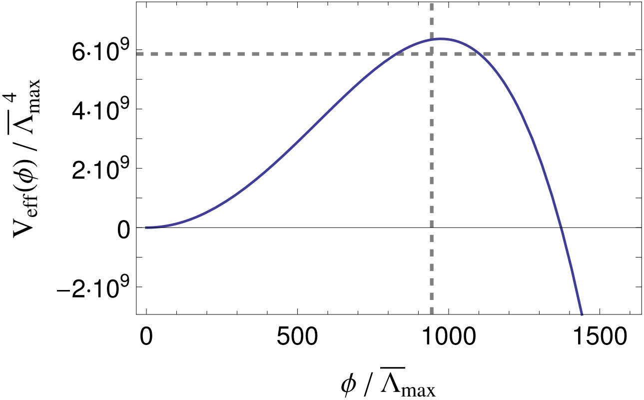

$$\Lambda_{\max}^2 \simeq \frac{\xi}{|\lambda|} R$$

$$V_{\max}^{1/4} \simeq V_{\rm tree}^{1/4}(\Lambda_{\max})$$

- $V_{\max}(\text{curved}) \gg V_{\max}(\text{flat})$ (and at a higher scale)

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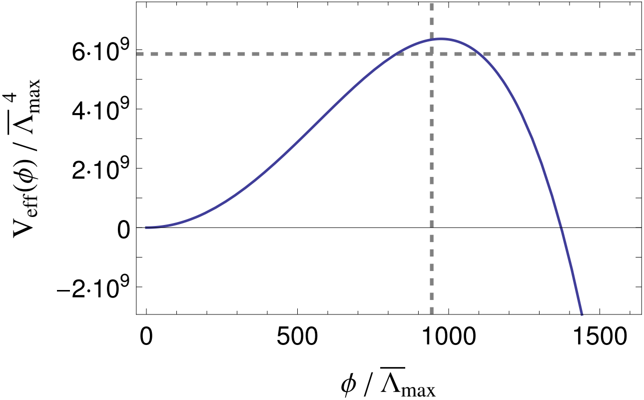

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$$P \sim \exp\left[-8\pi^2\left(V_{\rm max}/3H^4\right)\right] \quad \Rightarrow$$ **Stable!**

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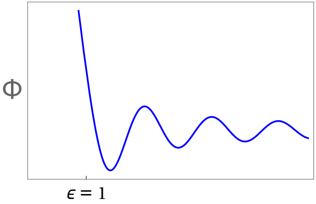
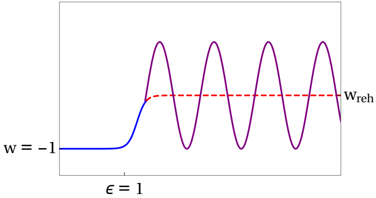
Reheating

- Energy is transferred to the SM $\Rightarrow$ thermalization
- A very complicated and dynamical process [7]
  - Explosive particle production (*Pre*heating)





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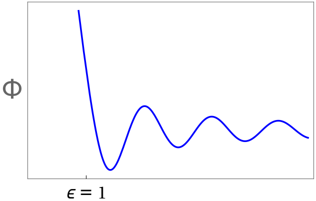
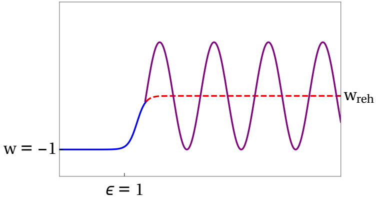




- The Higgs always feels reheating via gravity

$\Rightarrow$ New stability constraints !

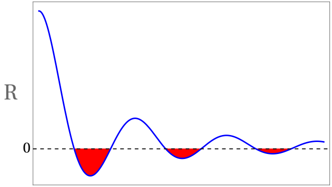
- Two effects:
  - A rapid drop in w, *on average*
  - Oscillations in the complete solution

[7] Kofman, Linde & Starobinsky (1997)

Oscillating R

- The curvature oscillates during reheating (Planck units)

$$G_{\mu\nu} = T_{\mu\nu} \quad \Rightarrow \quad R = \left[4V_{\rm inf}(\Phi) - \dot{\Phi}^2\right]$$



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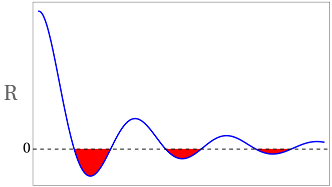

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- *Parametric (tachyonic) resonance* via the Mathieu equation

$$\frac{d^2 f(z)}{dz^2} + \left[A_{\mathbf{k}} - 2q\cos(2z)\right] f(z) = 0, \qquad z = t\, M_{\rm inf}$$

$\Rightarrow$ Exponential amplification, $n_{\mathbf{k}} \propto \exp\{\mu_{\mathbf{k}}\}$ [8]

[8] Kofman, Dufaux, Felder, Peloso & Podolsky (2006); Bassett & Liberati (1997)

Fluctuations from parametric resonance

- Resonance may give large fluctuations,
  $\Rightarrow$ Instabilities ?!
- After *one* oscillation, with $\mathbf{k} < aH$

$$n_{\mathbf{k}} \sim \exp\left\{\sqrt{\xi}\frac{2\Phi_0}{M_{\rm pl}}\right\}$$

- For example for quadratic inflation

$$\Rightarrow \quad \frac{2\Phi_0}{M_{\rm pl}} \approx 0.6$$

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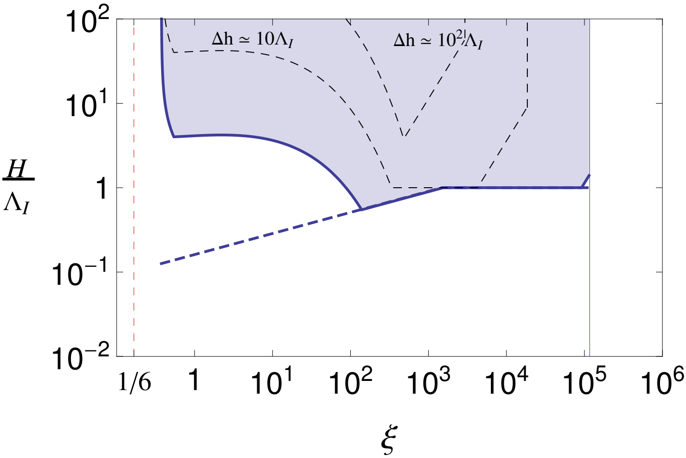
Superhorizon modes, $\mathbf{k} < aH$

$$\Rightarrow \quad \Delta\phi^2 \sim \left(\frac{H}{2\pi}\right)^2 \frac{\exp\left\{\sqrt{\xi}\frac{2\Phi_0}{M_{\rm pl}}\right\}}{\sqrt{\xi}}$$

- Potentially a huge effect, $\Delta\phi \gg \Lambda_I$

- However, the resonance may be shut off by backreaction

Stability results, reheating



Interactions

$\lambda\langle\hat{\phi}^2\rangle \ll \xi R,$

if $\lambda > 0$

Gravity

$\rho_{\rm Hig} \ll 3M_{\rm pl}^2 H^2$

$\Rightarrow$ For $H \gtrsim \Lambda_I \sim 10^{11}$GeV, ξ is constrained to be $\sim 1/6$

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Thank You!

Sensitivity to the choice of μ

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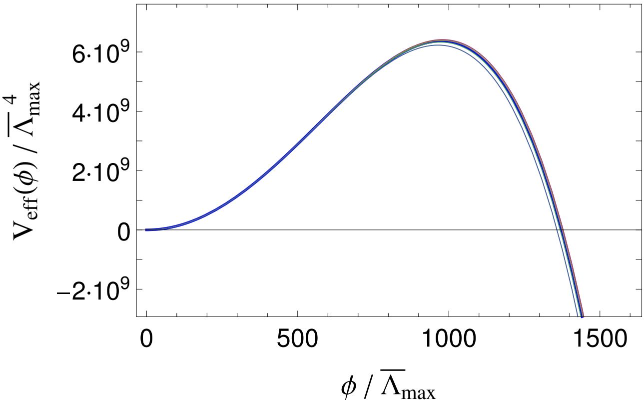
$$\mu^2 = \alpha\phi^2 + \beta R \qquad \alpha, \beta \in \{0.1 \cdots 10\}$$



Potential during inflation II

Quantum field theory on a curved background

- Example: self-interacting scalar field in curved space

$$S = -\int d^4x\sqrt{-g}\,\left[\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}m^2\phi^2 + \frac{\xi}{2}R\phi^2 + \frac{\lambda}{4!}\phi^4\right]\ ;\ R = 12H^2$$

- For a constant field

$$\frac{\delta S}{\delta\phi} = 0 \quad \Leftrightarrow \quad V'(\phi) = 0 \quad \Rightarrow \quad V(\phi) = \int^{\phi} V'(\phi)$$

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- Quantum correction to LO in fluctuations, $\hat{\phi} \to \langle\hat{\phi}\rangle + \hat{\phi} \equiv \phi + \hat{\phi}$

$$V'(\phi) = \underbrace{m^2\phi + \xi R\phi + \frac{\lambda}{6}\phi^3}_{\text{classical}} + \underbrace{\frac{\lambda}{2}\phi\langle\hat{\phi}^2\rangle}_{\text{quantum}}$$

- Same calculation in flat and curved space
  - The only difference is the form of the mode

Flat space

$$ds^2 = -dt^2 + d\mathbf{x}^2$$

$$\left[-\Box + M(\phi)^2 \right] \hat{\phi} = 0$$

$$f_{\mathbf{k}} = \frac{1}{\sqrt{\omega}} e^{-i\omega t}$$

$$\omega^2 = \mathbf{k}^2 + M(\phi)^2$$

Curved space (FLRW)

$$ds^2 = -dt^2 + a^2(t) d\mathbf{x}^2$$

$$\left[-\Box + M(\phi)^2 + \xi R \right] \hat{\phi} = 0$$

$$f_{\mathbf{k}} = \frac{1}{\sqrt{W}} e^{-i \int^t W}$$

$$W^2 = \frac{\mathbf{k}^2}{a(t)^2} + M(\phi)^2 + \left(\xi - \frac{1}{6} \right) R$$

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$\left[-\Box + M(\phi)^2 \right] \hat{\phi} = 0$	$\left[-\Box + M(\phi)^2 + \xi R \right] \hat{\phi} = 0$
$f_{\mathbf{k}} = \frac{1}{\sqrt{\omega}} e^{-i\omega t}$	$f_{\mathbf{k}} = \frac{1}{\sqrt{W}} e^{-i \int^t W}$
$\omega^2 = \mathbf{k}^2 + M(\phi)^2$	$W^2 = \frac{\mathbf{k}^2}{a(t)^2} + M(\phi)^2 + \left(\xi - \frac{1}{6}\right) R$

$$V_Q(\phi) = \frac{M(\phi)^4}{64\pi^2} \left[\log \left(\frac{M(\phi)^2}{\mu^2} \right) - \frac{3}{2} \right] ; \qquad M(\phi)^2 = m^2 + \frac{\lambda}{2}\phi^2$$

$$V_Q(\phi) = \frac{\left[M(\phi)^2 + \left(\xi - \frac{1}{6}\right) R\right]^2}{64\pi^2} \left[\log \left(\frac{\left|M(\phi)^2 + \left(\xi - \frac{1}{6}\right) R\right|}{\mu^2} \right) - \frac{3}{2} \right]$$

Renormalization group improvement for $\lambda\phi^4$ theory

- Large $\log$'s perturbatively problematic
- However, the physical result must not depend on μ:

$$\frac{d}{d\mu}V_{\rm eff}(\phi)=0 \quad \Leftrightarrow \quad \left\{\mu\frac{\partial}{\partial\mu}+\beta_\lambda\frac{\partial}{\partial\lambda}+\gamma_\phi\phi\frac{\partial}{\partial\phi}\right\}V_{\rm eff}(\phi)=0$$

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optimal choice, curved space

$$\mu^2 = m^2 + \tfrac{\lambda}{2}\phi^2 + (\xi - \tfrac{1}{6})R$$

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$\Rightarrow$ Curvature induces running of the constants ! [10]

[9] Ford, Jones, Stephenson & Einhorn (1993)
[10] Zurek, Kearney & Yoo (2015); TM (2014)

Stability results (curved space) II

$$V_{\text{eff}}(\phi) \approx \frac{\lambda(\mu)}{4}\phi^4 + \frac{\xi(\mu)}{2}R\phi^2$$

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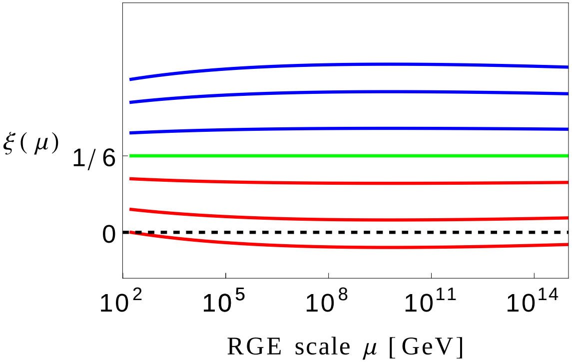
- ξ Can become positive or negative depending on ξ_{EW}



ξ_{EW}

$0,\ 0.05,\ 0.12,\ 1/6,\ 0.22,\ 0.28,\ 0.33$