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Inflation, Electroweak Vacuum Stability and Direct Searches at LHC

Mindaugas Karčiauskas

Enqvist, MK, Lebedev, Rusak, Zatta (2016)
Ema, MK, Lebedev, Zatta (2017)
Ema, MK, Lebedev, Rusak, Zatta (2019)

Higgs Mass and SM Consistency

1. SM is consistent up to m_{Pl}:

   Higgs mass: $M_h = 125.09 \pm 0.24$ GeV   Aad et al. (2015)

   (Meta) stability region: 111 GeV $< M_h < 175$ GeV

2. No other states discovered

- EW vacuum metastability
  - $\lambda = 0$ at $\sim 10^{10}$ GeV
  - $V_{\mathrm{max}}^{1/4} \sim 10^{9}$ GeV
- Lifetime $\gg$ age of the Universe

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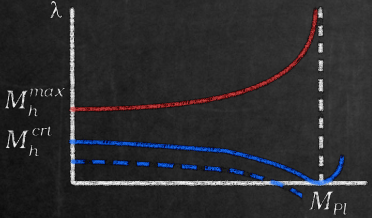

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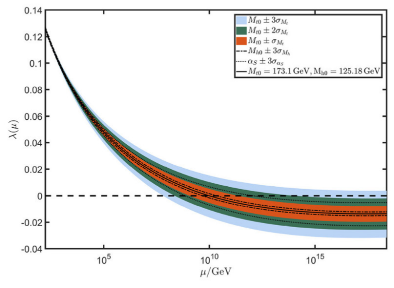
Tanabashi et al. (2018)



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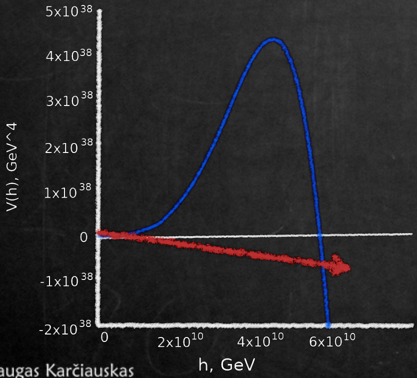

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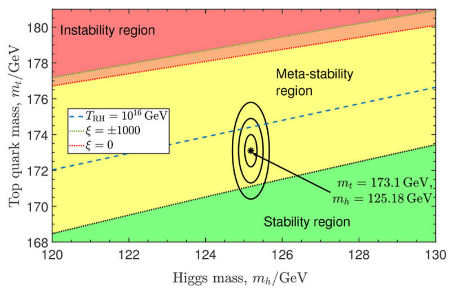

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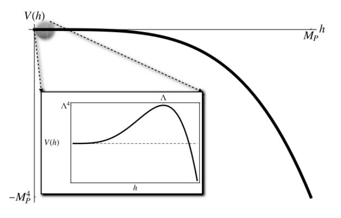
Lebedev & Westphal (2013)



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Questions:

1. Why isn't Higgs in an energetically favourable state?
2. How EW vacuum survived inflation? (If $r > 10^{-4}$)

The Model

- Answers the two questions
- Minimal: SM + GR + inflaton
- Stable up to the unitarity breaking scale (Planck scale ?)
- Has possible implication for LHC new physics searches

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- Generally expect all operators in a Lagrangian that are
  - Lorentz invariant
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$$S=\int \mathrm{d}^4x\sqrt{-\hat{g}}\left[\frac{1}{2}\Omega^2\hat{R}-\frac{1}{2}\hat{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-\frac{1}{2}\hat{g}^{\mu\nu}\partial_\mu h\partial_\nu h-V\left(\phi,h\right)\right]$$

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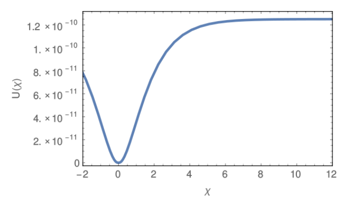

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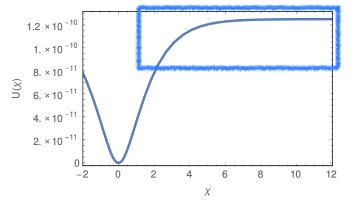

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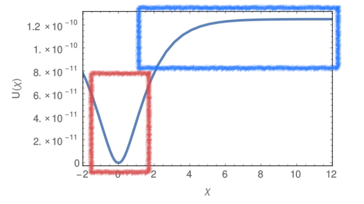

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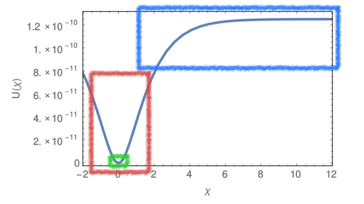
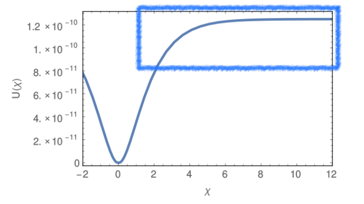


Inflation



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- CMB normalisation: $\lambda_\phi / \xi_\phi^2 \simeq 5 \times 10^{-10}$
- Unitarity cutoff: $\sim \xi_\phi^{-1}$
- No significant radiative corrections

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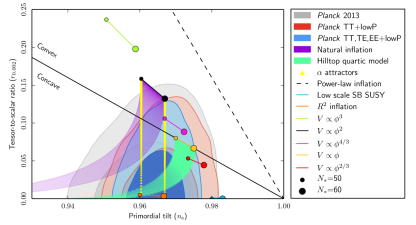
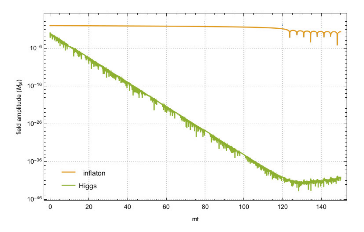
- n_s agrees with Planck and $r \simeq 3\times10^{-3}$
  - potentially observable



Ade et al. (2016)

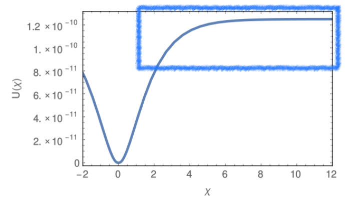
Higgs During Inflation

- Initially $h \sim 0.1\ m_{\rm Pl}$



Preheating and Reheating

$$\phi_{\mathrm{end}} \simeq \frac{1}{\sqrt{\xi_\phi}}$$



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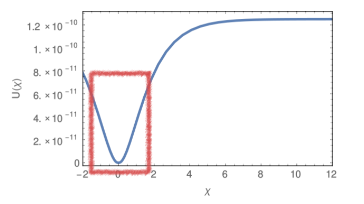

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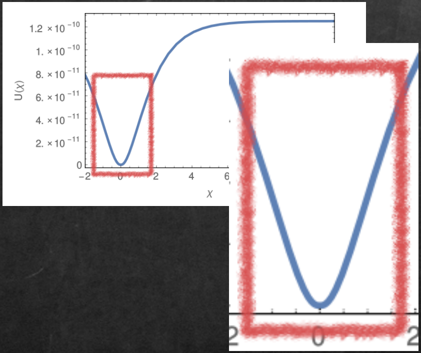

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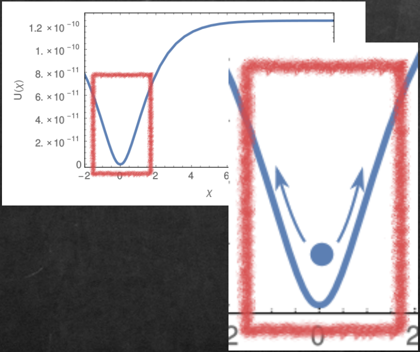

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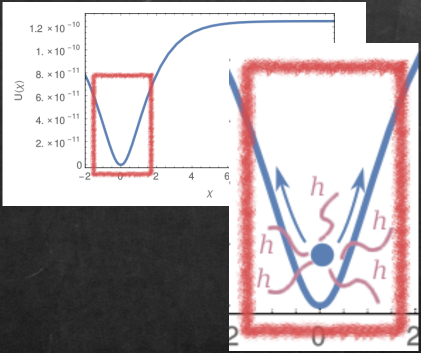

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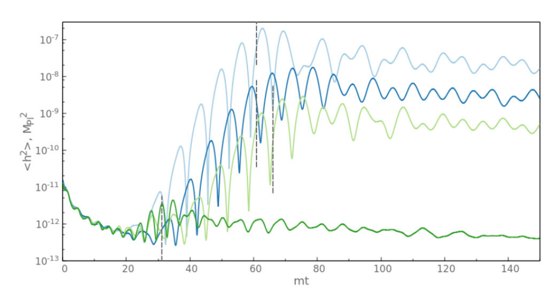
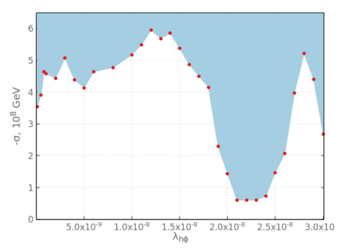
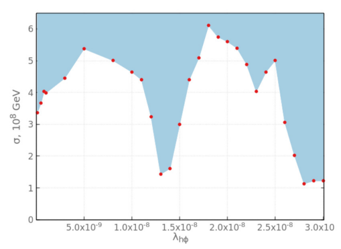


10-7
10-8
10-9
10-10
10-11
10-12
10-13
<h2>, Mpl2
0
20
40
60
80
100
120
140
mt

Preheating

$$\mathcal{L} \supset \sigma h^2 \phi$$



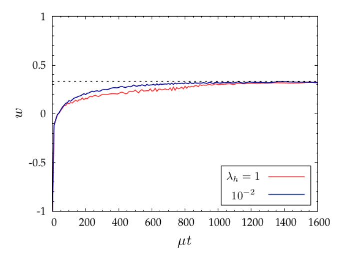


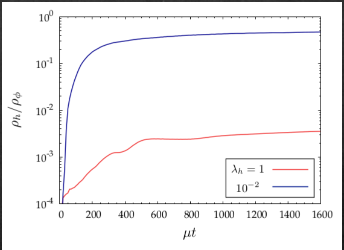
Reheating

- Reheating temperature
  $T_{\rm reh} \sim 10^{12}$ GeV

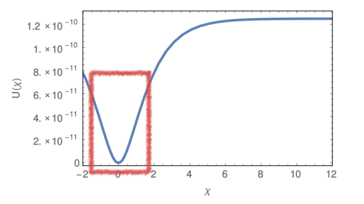
- Trilinear interaction $\sigma h^2 \phi$ is essential

$$\phi \quad \rightarrow \quad hh$$





Electroweak Scale



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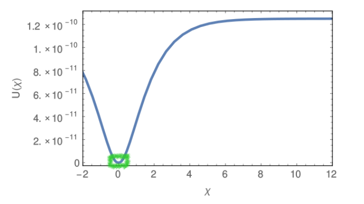

Electroweak Scale

- R can be neglected
- Rotate to mass eigenstates

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$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} h - v \\ \phi \end{pmatrix}$$

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2\lambda_h v^2 &= m_1^2 \cos^2\vartheta + m_2^2 \sin^2\vartheta \\
\lambda_{h\phi} v^2 - \mu_\phi^2 &= m_1^2 \sin^2\vartheta + m_2^2 \cos^2\vartheta \\
\sigma v &= \frac{1}{4}\sin 2\vartheta \left(m_1^2 - m_2^2\right)
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- For $\vartheta > 0$ λ_h is larger than SM $\Rightarrow$ no metastability
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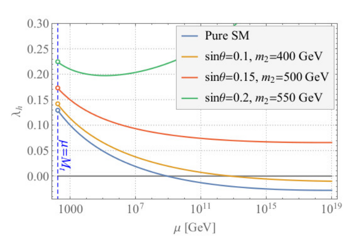

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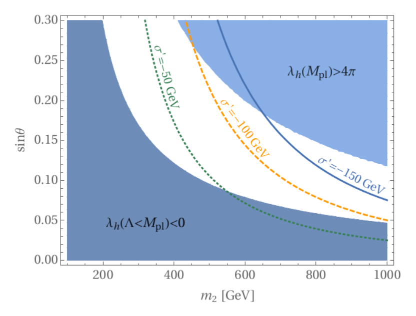
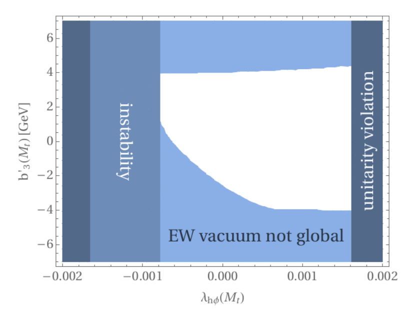
Electroweak Scale

- RG running
  - Perturbativity
  - Stability
  - EW vacuum is global

- For $\sigma \lesssim$ TeV and $m_2 \lesssim$ TeV stable EW vacuum

- For $\langle\phi\rangle$ up to $\sim 10\,\text{TeV}$
  - Mixing is governed by σ





Prospects for LHC

Universal reduction in the Higgs coupling to gauge bosons and fermions

$$\mathcal{L} \supset \frac{H_1 \cos\theta + H_2 \sin\theta}{v} \left[2 m_W^2 W_\mu^+ W^{\mu -} + m_Z^2 Z_\mu Z^\mu - \sum m_f \bar{f} f \right]$$

$$\Downarrow$$

$$\sigma\left(pp \to h_1\right) = \cos^2\theta \, \sigma_{\mathsf{SM}}\left(pp \to h_1\right)$$

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- Current constraints: $|\sin\theta| < 0.3$

  ATLAS: Aad et al. (2015)

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  - That corresponds to $|\sin\theta| < 0.1$

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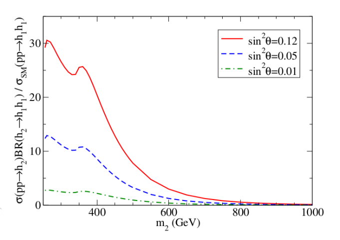
Lewis & Sullivan (2017)



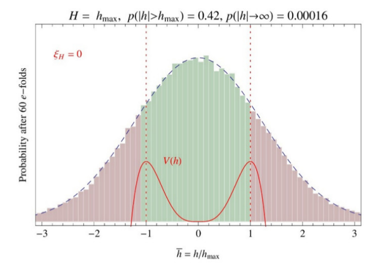
Summary

- A minimal model with generically expected interactions
  - The trilinear interaction is essential
  - Assume only one scale: dimensional parameters $\sim$ TeV
- Provides a consistent history of the Universe
- Solves EW vacuum metastability problem
- Suggests new signatures for the high luminosity LHC searches

Enqvist, MK, Lebedev, Rusak, Zatta (2016)
Ema, MK, Lebedev, Zatta (2017)
Ema, MK, Lebedev, Rusak, Zatta (2019)

Production of Infrared Modes

Espinosa et al. (2015)



- Langevin equation

$$\frac{\mathrm{d}h}{\mathrm{d}N} \simeq -\frac{\lambda h^3}{3H^2} + \frac{H}{2\pi}\xi\left(N\right)$$

- Safe energy scale for inflation

$$V_{\mathrm{inf}}^{1/4} \quad < \quad 10^{13}\ \mathrm{GeV}$$

- If GW are detected ($r > 10^{-4}$)

$$V_{\mathrm{inf}}^{1/4} \quad > \quad 10^{15}\ \mathrm{GeV}$$

Field Shift

- Field shift $\phi \to \phi' = \phi - u$ transform dimensional constants as

$$
\begin{aligned}
b_3' &= b_3 + 3\lambda_\phi u \\
{\mu_\phi'}^2 &= \mu_\phi^2 - 3\lambda_\phi u^2 - 2b_3 u \\
{\mu_h'}^2 &= \mu_h^2 - \frac{1}{2}\lambda_{h\phi} u^2 - 2\sigma u \\
b_1' &= b_1 + \lambda_\phi u^3 + b_3 u^2 - \mu_\phi^2 u \\
\sigma' &= \sigma + \lambda_{h\phi} u
\end{aligned}
$$

where

$$u \equiv \langle \phi \rangle$$

- Dimensionless constants do not change