NON-MINIMALLY COUPLED INFLATON AND EW VACUUM STABILITY

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1608.08848, 1711.10554, ongoing work

WHY ARE WE HERE?

THE HIGGS FIELD

- Scalar field in the SM.

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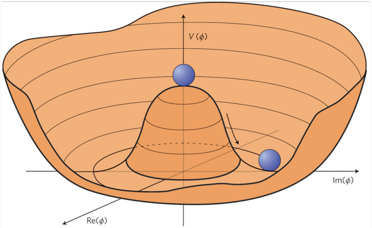

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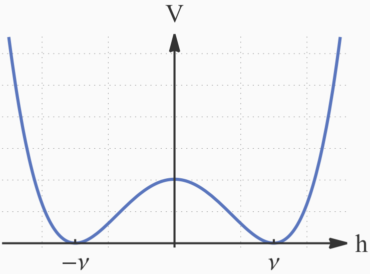

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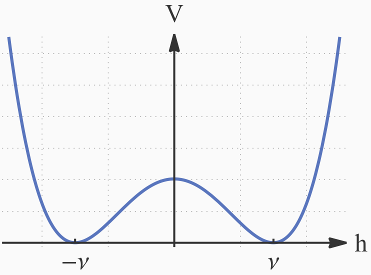

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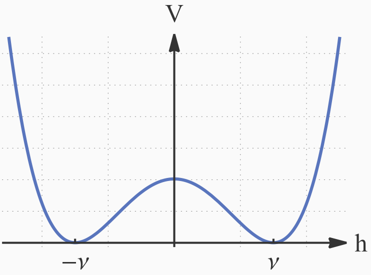

- Obtains a vacuum expectation value $\langle h \rangle = \nu \approx 246$ GeV.
- Particle masses:

$$M_H = 125.09 \pm 0.32\text{GeV}$$

$$M_{\text{top}} = 173.34 \pm 0.76\text{GeV}$$

$$\ldots$$

RUNNING OF THE COUPLINGS

- Renormalization group evolution:

$$
\begin{aligned}
\mu^2 \frac{\mathrm{d}\lambda_h}{\mathrm{d}\mu^2} &\equiv \beta_{\lambda_h} = \frac{1}{16\pi^2}\left(12\lambda^2 + 6\lambda y_t^2 - 3y_t^4\right) + \ldots \\
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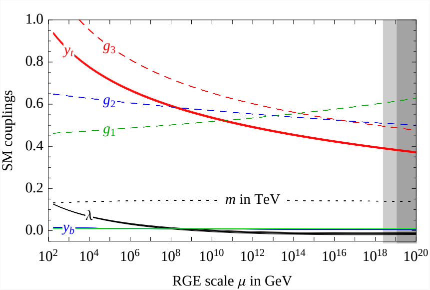
- Couplings run with energy.
- At high energies the RG improved effective potential $V(h) \simeq \frac{\lambda_h(h)}{4} h^4$.



RUNNING OF THE HIGGS SELF-COUPLING

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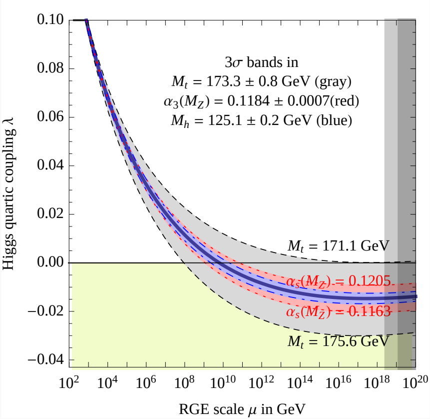

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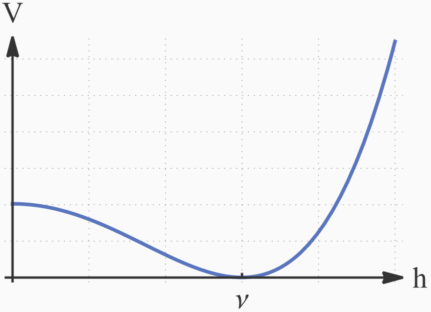

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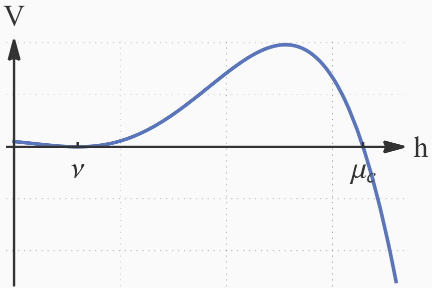

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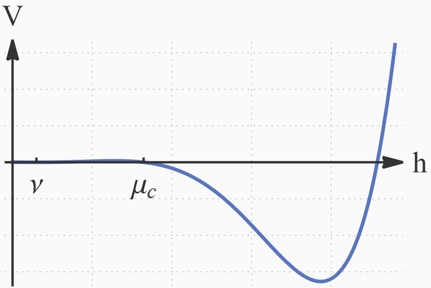

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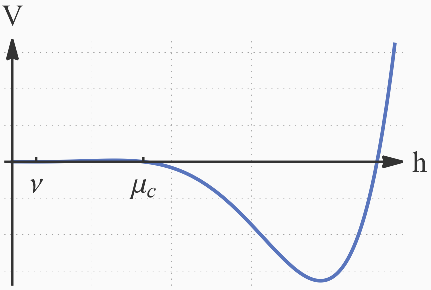
- Universe occupies an energetically disfavoured state.



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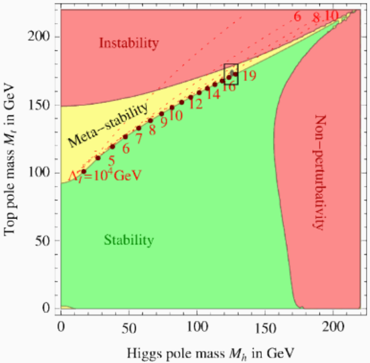
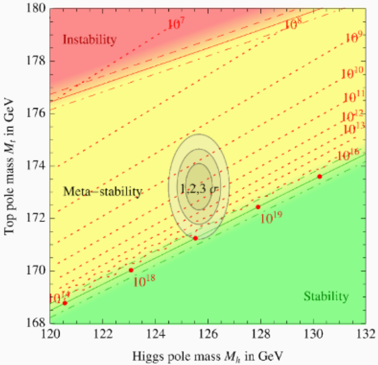
    - Why did we end up in an energetically disfavoured state?

STABILITY OF THE ELECTROWEAK VACUUM





- Precision calculations suggest our vacuum is metastable: $t_{\mathrm{decay}} \gg t_{\mathrm{universe}}$

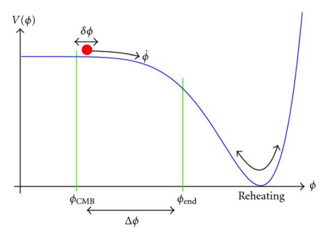
Buttazzo et al. '13

- No immediate problem.

WHERE DID WE COME FROM? INFLATION.

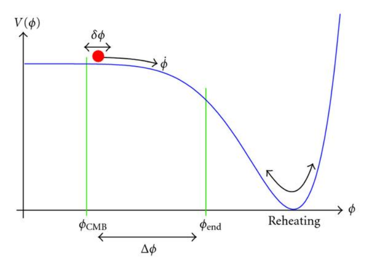
- An almost-exponential expansion of the universe $a \sim e^{Ht}$.
- Driven by a scalar field ϕ slowly rolling down a flat potential slope:

$$\frac{M_P^2}{2}\left(\frac{V'}{V}\right)^2,\ M_P^2\frac{V''}{V} \ll 1$$



- Once inflation ends the field starts to oscillate around the minimum of its potential and eventually decays into radiation.
- Simplest model: $V = \frac{1}{2}m^2\phi^2$.

- Meanwhile, quantum fluctuations are stretched beyond the horizon.



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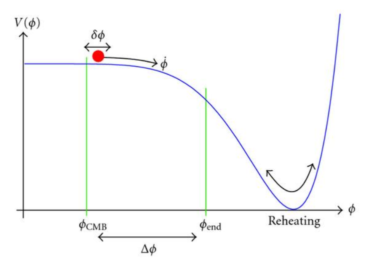
    - Consider fluctuations $\phi(x) = \bar{\phi}(t) + \delta\phi(x)$:

$$\ddot{\delta\phi} + 3H\dot{\delta\phi} + \left[\frac{k^2}{a^2} + V''(\bar{\phi})\right]\delta\phi = 0$$



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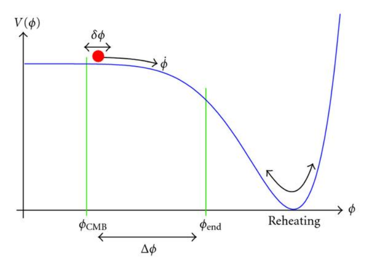
    - Inside the horizon ($k \gg aH$): $\delta\ddot{\phi} + \frac{k^2}{a^2}\delta\phi = 0$. Solution

$$\delta\phi \simeq \frac{1}{\sqrt{2k/a}} e^{-i\int \frac{k}{a} dt}$$



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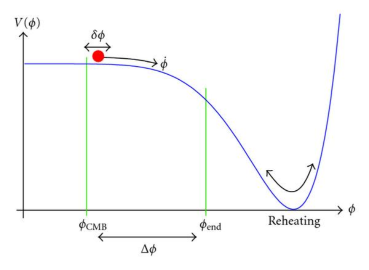

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$$\delta\phi \simeq \mathrm{constant} \simeq \frac{H_*}{\sqrt{2k^3}}$$

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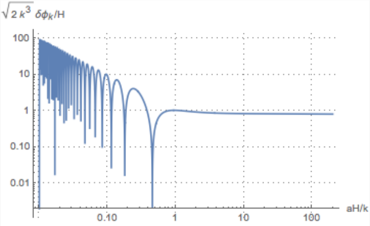

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- The SM Higgs is light during inflation.
- Stochastic formalism: field averaged on superhorizon scales obeys Langevin equation

Starobinsky '82

$$\dot{h} + \frac{V'(h)}{3H} = f(t); \qquad \langle f(t) f(t') \rangle = \frac{H^3}{4\pi^2} \delta(t - t').$$

- Equilibrium probability distribution at the end of inflation

$$P(h) \propto \exp\left(-\frac{2\lambda \pi^2 h^4}{3H^4} \right).$$

- Equilibrium value of the field $\sqrt{\langle h^2 \rangle} \sim \lambda^{-1/4} H$.
- If $H > \mu_c$ the field is driven into the true vacuum during inflation!

HOW TO RESOLVE THIS?

SOLUTIONS

- Scale of inflation must be low: $H_{\rm inf} < 10^{10}$ GeV.
    - However, $H_{\rm inf}$ up to 10^{13} GeV still consistent with observations.
- Critical scale must be high.
    - Top mass is lower than its central value.
    - New physics stabilizes the potential during inflation.
        1. Higgs inflaton coupling
        $$\delta\mathcal{L} = -\frac{\lambda_{h\phi}}{4}\phi^2 h^2 - \frac{\sigma_{h\phi}}{2}\phi h^2$$
        this talk
        2. Non-minimal coupling to gravity
        $$\delta\mathcal{L} = -\xi R h^2$$
        eg. 1407.3141, 1602.00483, 1703.04681

COUPLING TO THE INFLATON

$$V_{h\phi} = \frac{\lambda_{h\phi}}{4}\phi^2 h^2 + \frac{\sigma_{h\phi}}{2}\phi h^2$$

- Quantum corrections must not spoil the flatness of the inflaton potential:

$$\lambda_{h\phi} < 10^{-6}.$$

- New instability scale

$$\tilde{\mu}_c \sim \sqrt{\frac{\lambda_{h\phi}\phi^2 + 2\sigma_{h\phi}\phi}{|\lambda_h|}}.$$

- ϕ, m, H Can be obtained from cosmological observatiobs.
- λ_h can be calculated from SM RG running.
- Higgs is stabilized for $\lambda_{h\phi} > 10^{-10}$, $|\sigma_{h\phi}| < \lambda_{h\phi} M_P$.

Enqvist E., Karciauskas M., Lebedev O., SR, Zatta M., 2016

WHAT HAPPENS AFTER INFLATION?

- Once inflation ends the inflaton starts to oscillate around the mimimum of the potential.

$$\phi(t) = \frac{\Phi_0}{a^3} \sin(mt).$$

- Can be thought of as a condensate of massive particles at rest; perturbative decay

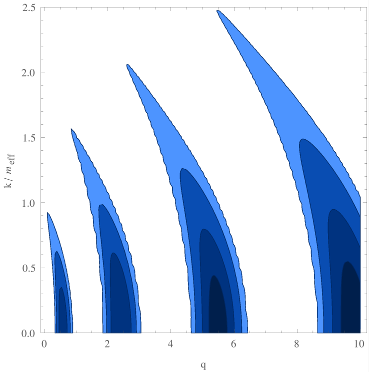
$$\Gamma(\phi \to hh) = \frac{\sigma_{h\phi}^2}{32\pi m}.$$

- Reheating when $H \sim \Gamma$ with reheating temperature $T \sim \sqrt{\Gamma M_P}$.
- Not the whole story!

- The equation of motion for the (rescaled) Higgs modes ($\sigma_{h\phi} = 0$)

$$\ddot{h}_k + \left[\frac{k^2}{a^2} + 4q(t)\sin^2(mt) + 3\lambda_h a^{-3}\langle h^2\rangle\right] h_k = 0$$

- Mathieu-type equation.
- Characterised by resonance parameter $q(t) = \frac{\lambda_{h\phi}\Phi^2(t)}{2m^2}$.
- Within the blue bands modes are amplified $h_k \sim e^{\mu t}$.
- In white regions oscillating modes $h_k \sim e^{i\int \omega_k dt}$.



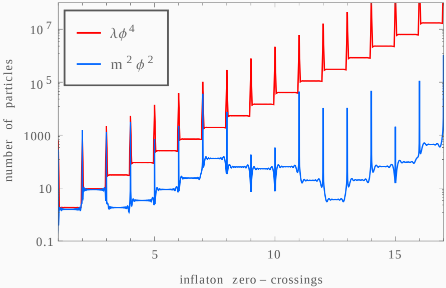
- The particle number density $n_\kappa^{j+1} = |\beta_k^{j+1}| \simeq e^{2\pi\mu_\kappa^j} n_\kappa^j$ with Floquet index

$$\mu_\kappa^j \equiv \frac{1}{2\pi} \ln\left[1 + 2W_\kappa^j - 2\sin\theta_{\mathrm{tot}^j}\sqrt{W_\kappa^j(1+W_\kappa^j)}\right], \qquad W = e^{-\pi\kappa^2}$$

- The Higgs evolves as

$$\langle h^2 \rangle = \frac{3^j m^2 \kappa_{\mathrm{max}}^3}{2^{5/2} e \pi^{3/2} a^3 \sqrt{q}}$$

- Production ends when $q \sim 1/4$.



EFFECT OF THE SELF-COUPLING

- Naively: vacuum is safe if the resonance shuts down before $\langle h^2 \rangle \sim \tilde{\mu}_c^2$.
- After only a single zero-crossing $\sqrt{\langle h^2 \rangle} > \mu_c^{\mathrm{SM}}$.
- $\lambda_h(\sqrt{\langle h^2 \rangle}) < 0$ throughout the resonance.
- $3\lambda_h \langle h^2 \rangle$ contributes a tachyonic mass term. This is larger than the inflaton contribution for a time Δt near the zero-crossing

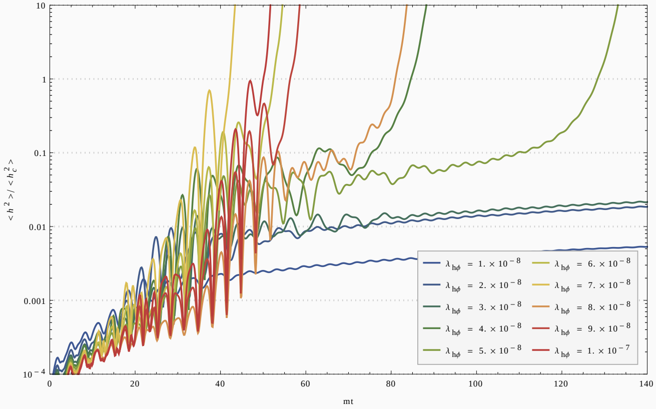
$$\Delta t = \sqrt{\frac{6|\lambda_h|\langle h^2 \rangle}{\lambda_{h\phi} \Phi^2 m^2}}.$$

- Condition for stability $\sqrt{3|\lambda_h|\langle h^2 \rangle}|\Delta t| < 1$.
- Bound on the Higgs-inflaton coupling $\lambda_{h\phi} < 3 \times 10^{-8}$.

Enqvist E., Karciauskas M., Lebedev O., SR, Zatta M., 2016

AMPLIFICATION OF THE HIGGS

- The higgs is rapidly amplified during the resonance.



- Analytic bound $\lambda_{h\phi} \lesssim 3 \times 10^{-8}$.

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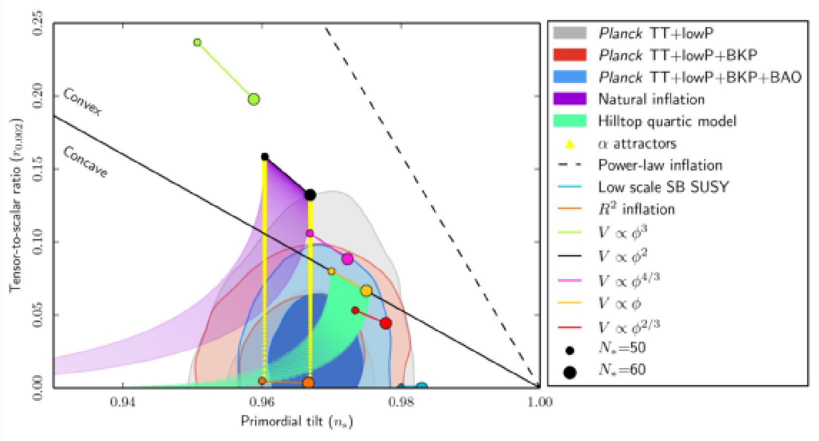
Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Planck TT+lowP
Planck TT+lowP+BKP
Planck TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
Low scale SB SUSY
R^2 inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
N_*=50
N_*=60

NON-MINIMALLY COUPLED INFLATON

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- Jordan frame action

$$S = \int \mathrm{d}^4x\sqrt{-g_J}\left[\frac{M_{\rm pl}^2}{2}\Omega^2(\phi_J)R_J - \frac{1}{2}g_J^{\mu\nu}\partial_\mu\phi_J\partial_\nu\phi_J - V(\phi_J)\right]$$

$$\Omega^2(\phi_J) = 1 + \xi\frac{\phi_J^2}{M_{\rm pl}^2}, \qquad V(\phi_J) = \frac{\lambda}{4}\phi_J^4$$

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$$d\phi_E \equiv \frac{\sqrt{1 + \xi(1 + 6\xi) \frac{\phi_J^2}{M_{\rm pl}^2}}}{\Omega^2} d\phi_J, \qquad V_E \equiv \frac{\lambda}{4} \left(\frac{\phi_J}{\Omega} \right)^4$$

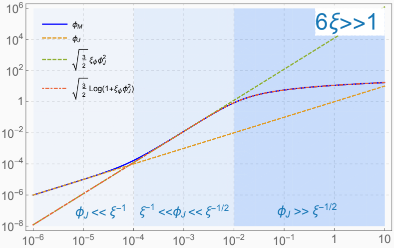
NON-MINIMALLY COUPLED INFLATON

- Einstein frame field

$$\frac{\phi_{\mathrm{E}}}{\mathrm{M}_{\mathrm{pl}}} = \sqrt{\frac{1+6\xi}{\xi}}\,\mathrm{arsinh}\left(\sqrt{\xi(1+6\xi)}\,\frac{\phi_{\mathrm{J}}}{\mathrm{M}_{\mathrm{pl}}}\right) - \sqrt{6}\,\mathrm{arsinh}\left(\sqrt{\frac{6\xi^2}{1+\xi\phi_{\mathrm{J}}^2/\mathrm{M}_{\mathrm{pl}}^2}}\,\frac{\phi_{\mathrm{J}}}{\mathrm{M}_{\mathrm{pl}}}\right)$$

- Einstein frame field

$$\frac{\phi_E}{M_{\rm pl}} = \sqrt{\frac{1+6\xi}{\xi}}\,\mathrm{arsinh}\left(\sqrt{\xi(1+6\xi)}\,\frac{\phi_J}{M_{\rm pl}}\right) - \sqrt{6}\,\mathrm{arsinh}\left(\sqrt{\frac{6\xi^2}{1+\xi\phi_J^2/M_{\rm pl}^2}}\,\frac{\phi_J}{M_{\rm pl}}\right)$$



NON-MINIMALLY COUPLED INFLATON

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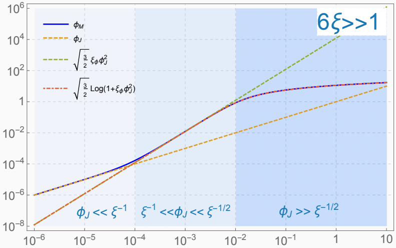
$$\frac{\phi_{\mathrm{E}}}{\mathrm{M_{pl}}} = \sqrt{\frac{1+6\xi}{\xi}}\,\mathrm{arsinh}\left(\sqrt{\xi(1+6\xi)}\,\frac{\phi_{\mathrm{J}}}{\mathrm{M_{pl}}}\right) - \sqrt{6}\,\mathrm{arsinh}\left(\sqrt{\frac{6\xi^2}{1+\xi\phi_{\mathrm{J}}^2/\mathrm{M_{pl}^2}}}\,\frac{\phi_{\mathrm{J}}}{\mathrm{M_{pl}}}\right)$$



- When $6\xi \gg 1$

$$\frac{\phi_{\mathrm{E}}}{\mathrm{M_{pl}}} \simeq \begin{cases} \frac{\phi_{\mathrm{J}}}{\mathrm{M_{pl}}}, & \phi_{\mathrm{J}}^2 \ll \frac{\mathrm{M_{pl}^2}}{6\xi_\phi^2} \\ \mathrm{sign}(\phi_{\mathrm{J}})\sqrt{\frac{3}{2}}\xi_\phi\left(\frac{\phi_{\mathrm{J}}}{\mathrm{M_{pl}}}\right)^2, & \frac{\mathrm{M_{pl}^2}}{6\xi_\phi^2} \ll \phi_{\mathrm{J}}^2 \ll \frac{\mathrm{M_{pl}^2}}{\xi_\phi} \\ \mathrm{sign}(\phi_{\mathrm{J}})\sqrt{\frac{3}{2}}\log\left[1+\xi_\phi\left(\frac{\phi_{\mathrm{J}}}{\mathrm{M_{pl}}}\right)^2\right], & \phi_{\mathrm{J}}^2 \gg \frac{\mathrm{M_{pl}^2}}{\xi_\phi} \end{cases}$$

NON-MINIMALLY COUPLED INFLATON

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$$V_E(\phi_E) \simeq \begin{cases} \frac{\lambda}{4}\phi_E^4, & \phi_J^2 \ll \frac{M_{\rm pl}^2}{6\xi_\phi^2} \\ \frac{\lambda M_{\rm pl}^2}{6\xi_\phi^2}\phi_E^2, & \frac{M_{\rm pl}^2}{6\xi_\phi^2} \ll \phi_J^2 \ll \frac{M_{\rm pl}^2}{\xi_\phi} \\ \frac{\lambda M_{\rm pl}^4}{4\xi_\phi^2}\left(1 - e^{-\sqrt{\frac{2}{3}}\frac{|\phi_E|}{M_{\rm pl}}}\right)^2, & \phi_J^2 \gg \frac{M_{\rm pl}^2}{\xi_\phi} \end{cases}$$

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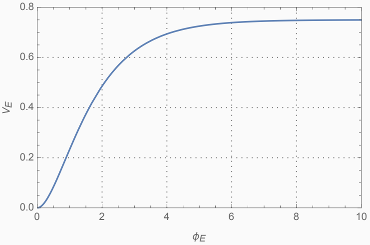
- Flat potential for large field values ⇒ inflation.



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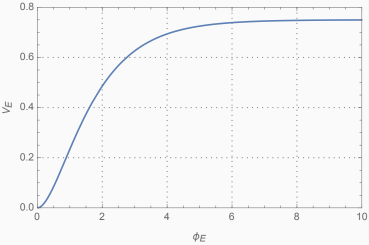
- Flat potential for large field values $\Rightarrow$ inflation.
- Spectrum fixes $\frac{\lambda}{\xi^2} \sim 5 \times 10^{-10}$.



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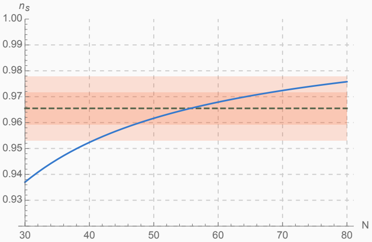
- Gives the right spectral index n_s.



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- Flat potential for large field values $\Rightarrow$ inflation.
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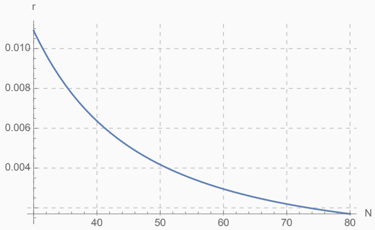
- Gives the right spectral index n_s.
- Negligible tensor-to-scalar ratio r.



SPECTATOR DYNAMICS

- Consider a spectator field χ coupled to the inflaton. In the Jordan frame

$$S_\chi = \int \mathrm{d}^4x\sqrt{-g_J}\left[-\frac{1}{2}g_J^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}g^2\phi_J^2\chi^2\right].$$

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- In the Einstein frame this becomes

$$S_\chi = \int d^4x \sqrt{-g_E}\left[-\frac{1}{2}\Omega^{-2}g_E^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}g^2\Omega^{-4}\phi_J^2\chi^2\right].$$

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$$\ddot{X}_k + \omega_k^2 X_k = 0, \quad \omega_k^2 = \frac{k^2}{a^2} + g^2\left(\frac{\phi_J}{\Omega}\right)^2 + \partial_t^2 \log\frac{\Omega}{a^{3/2}} - \left(\partial_t \log\frac{\Omega}{a^{3/2}}\right)^2$$

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$$-\frac{\Omega^2}{\sqrt{-g_M}}\partial_\mu\left(\frac{\sqrt{-g_M}}{\Omega^2}g_M^{\mu\nu}\partial_\nu h\right)+\Omega^{-2}V_h'-\xi_h\Omega^{-2}R_J h=0$$

- Ricci scalar

$$R_J=\Omega^2\left(R_M+3\Box\log\Omega^2-\frac{3}{2}\partial_\mu\log\Omega^2\partial^\mu\log\Omega^2\right)$$

- Stability during inflation

$$\frac{m_{\mathrm{eff}}^2}{H_M^2}=12\left[\frac{\lambda_{h\phi}}{\lambda_\phi}\left(\frac{\phi_J}{M_{\mathrm{pl}}}\right)^{-2}-\xi_h\right]\gg 1$$

- Stabilized by inflaton if

$$\left(\frac{\lambda_{h\phi}}{\xi_\phi}\right)\gg\frac{\lambda_\phi(3N-4)}{48\xi_\phi^2}\approx 1.3..1.9\times 10^{-9}$$

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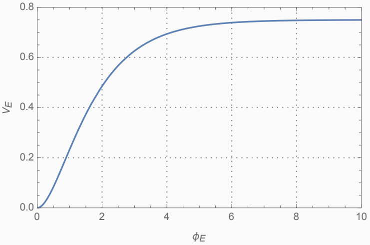

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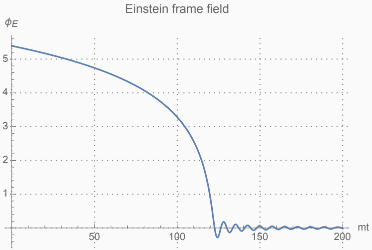

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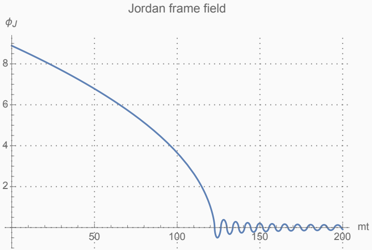

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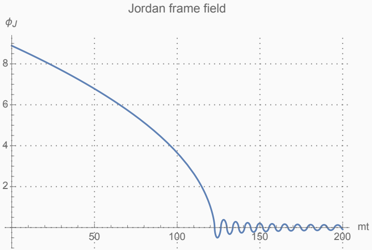

- Mapping between frames

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$$n_k^{j+1} \simeq e^{2\pi\mu_k^j} n_k^j, \qquad \mu_k^j \equiv \frac{1}{2\pi} \log\left[1 + 2C_k^j + 2\cos\theta_j \sqrt{C_k^j\left(1 + C_k^j\right)}\right].$$

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$$\langle h^2 \rangle \simeq 5 \times 10^{-2} \frac{\sqrt{q} m^2}{a^3} \left(\frac{\sqrt{a}}{\sqrt{a} - 1}\right)^{3/2} \left(\frac{5}{3}\right)^j$$

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- Constraints from stability

$$\frac{\lambda_{h\phi}}{\xi_\phi} < 4 \times 10^{-9} \frac{M_{\rm pl}}{\Phi_0}$$

HIGGS-INFLATON MIXING

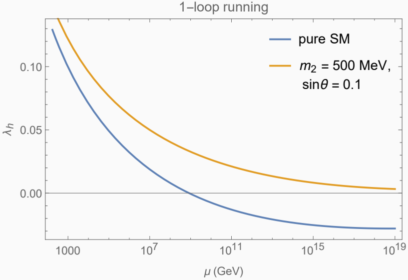
HIGGS-INFLATON MIXING

$$V(\phi, h) = \frac{\lambda_h}{4} h^4 - \frac{\mu_h^2}{2} h^2 + \frac{\lambda_{h\phi}}{2} h^2 \phi^2 + \sigma h^2 \phi + \frac{\lambda_\phi}{4} \phi^4 + \frac{b_3}{3} \phi^3 - \frac{\mu_\phi^2}{2} \phi^2 + b_1 \phi$$

- Low energy mass eigenstates h_1, h_2:

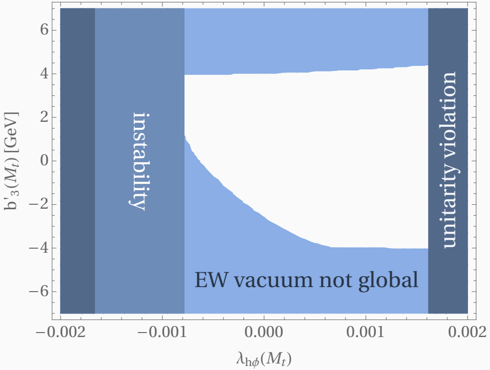
$$\begin{aligned} 2\lambda_h \nu^2 &= m_1^2 \cos^2\theta + m_2^2 \sin^2\theta, \\ \lambda_{h\phi}\nu^2 - \mu_\phi^2 &= m_1^2 \sin^2\theta + m_2^2 \cos^2\theta, \\ \sigma\nu &= \frac{\sin 2\theta}{4}\left(m_1^2 - m_2^2\right) \end{aligned}$$

- Higgs-inflaton mixing lifts the value of higgs self-coupling.
- Stability ensured with moderate values of $\sin\theta$, m_2.



Ema Y., Karciauskas M., Lebedev O., SR, Zatta M., 2016

- For inflation run the parameters to the inflationary scale.
- We require that no vacua deeper than the EW one develop at higher energies.

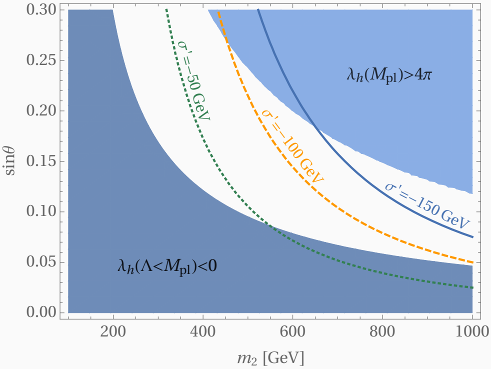


- We also require:
  1. overall stability: $\lambda_{h\phi} > -\sqrt{\lambda_h \lambda_\phi}$
  2. unitarity $\lambda_\phi \xi_\phi^2 \lesssim 1$
  3. perturbativity $\lambda_i > 4\pi$

Enqvist E., Karciauskas M., Lebedev O., SR, Zatta M., 2016

- For inflation run the parameters to the inflationary scale.
- We require that no vacua deeper than the EW one develop at higher energies.

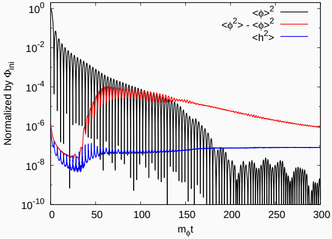
- We also require:
  1. overall stability: $\lambda_{h\phi} > -\sqrt{\lambda_h \lambda_\phi}$
  2. unitarity $\lambda_\phi \xi_\phi^2 \lesssim 1$
  3. perturbativity $\lambda_i > 4\pi$

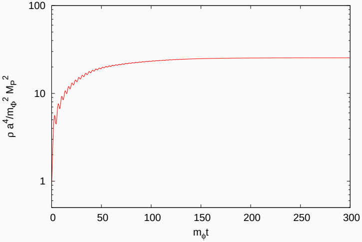


Enqvist E., Karciauskas M., Lebedev O., SR, Zatta M., 2016

HIGGS-INFLATON MIXING

- Within the allowed regions inflation proceeds as before.
- Higgs is stable both during inflation and preheating due to the mixing-induced running of λ.





- The model is viable for mixing of $\sin\theta \sim \mathcal{O}(0.1)$ and $m_2 \sim \mathcal{O}(100\text{GeV})$, offering prospects of collider detection.

Ema Y., Karciauskas M., Lebedev O., SR, Zatta M., 2016

SUMMARY

SUMMARY

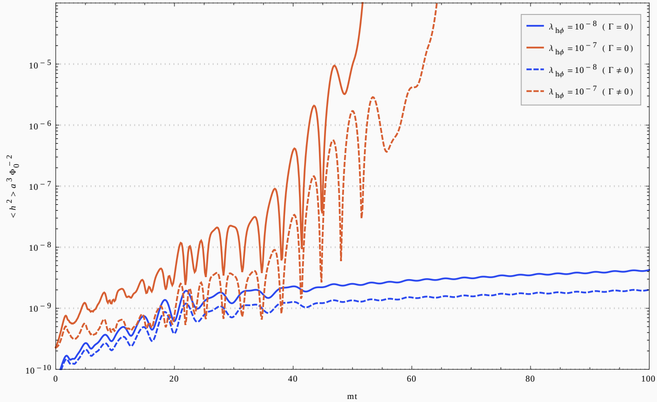
- High scale inflation pushes the higgs into the true vacuum.
- In order to avoid this need to couple higgs to something else: inflaton or spacetime curvature.
- This results in non-perturbative, resonant amplification of the higgs during preheating and may lead to destabilization.
- Thus preheating puts new constraints on such models and significantly reduces the available parameter space in this scenario.
- In non-minimally coupled inflation, the mixing between the higgs and the inflaton provides a viable model which could be accessible to collider searches in the near future.

Thank you!

WHAT ABOUT PERTURBATIVE DECAY?

- Higgs may decay between inflaton zero-crossing through

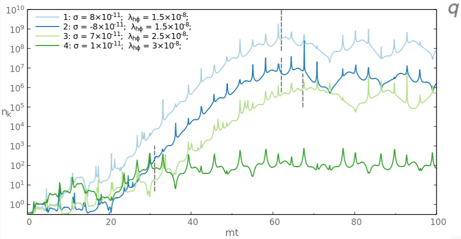
$$\Gamma = \frac{3y_t^2 m_{\mathrm{eff}}}{16\pi}.$$

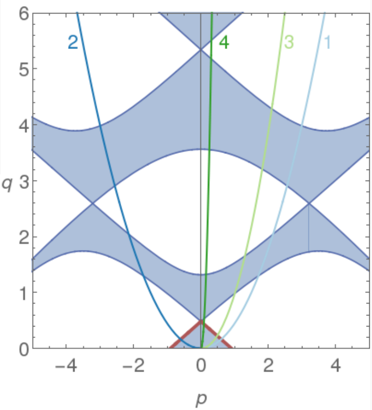


- If $\sigma_{h\phi} \neq 0$ then the inflaton contributes a tachyonic mass to the higgs every other oscillation while $2\sigma_{h\phi} > \lambda_{h\phi}\Phi$.

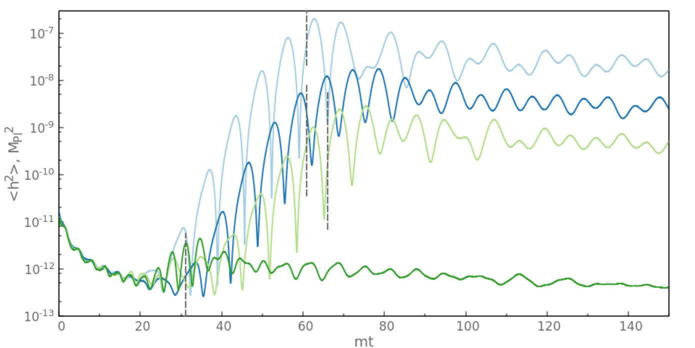
$$\ddot{h}_k + \left[\frac{4k^2}{a^2} + 2qm^2 + 2p\cos 2mt + 2qm^2 \cos 4mt + 3\lambda_h a^{-3}\langle h^2 \rangle \right] h_k = 0$$

- Whittaker-Hill-type equation.
- Again there are oscillating and exponentially growing solutions.
- Evolution of the number density





- Field evolution ($\lambda_h = 0$)

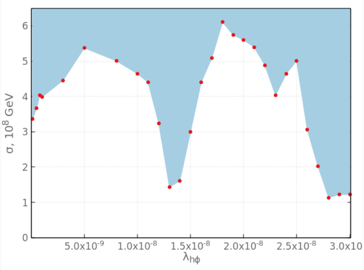


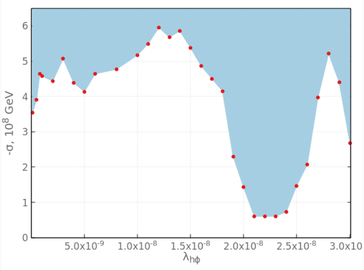
DESTABILIZATION WITH TRILINEAR COUPLINGS

- Critical scale at late times $\tilde{\mu}_c \simeq \frac{2|\sigma_{h\phi}|\Phi}{|\lambda_h|}$.
- Can evaluate the Higgs as before

$$\langle h^2 \rangle \simeq \frac{m^2}{2a^3} \frac{e^{\mu_* mt}}{\sqrt{|\sigma_{h\phi}|\Phi}}.$$

- Constraint on the coupling $|\sigma_{h\phi}| \lesssim 10^9$ GeV.





- Alternatively the Higgs may be stabilized during inflation via a non-minimal coupling to gravity

$$-\delta\mathcal{L} = \frac{1}{2}\xi R h^2.$$

- Critical scale $\tilde{\mu}_c^2 = \frac{2\xi R}{\lambda_h}$.
- During inflation $R \simeq 12H^2$ so $\xi \sim \mathcal{O}(0.1)$ can stabilize the potential.
- During preheating $R = 6(\dot{H} + 2H^2)$ oscillates $\Rightarrow$ similar dynamics as in the tachyonic preheating case.
- Constraint $\xi < 2.5\left(\frac{\sqrt{2}M_P}{\Phi_{\rm inf}}\right)^2$ (Ema et al. '16).

COMBINATION OF HIGGS-INFLATON AND HIGGS-GRAVITY COUPLINGS

Ema et. at '17

- If Higgs couples to both gravity and the inflaton

$$-\delta\mathcal{L} = \frac{1}{2}\lambda_{h\phi}\phi^2 h^2 + \frac{1}{2}\xi R h^2.$$

- In the Einstein frame

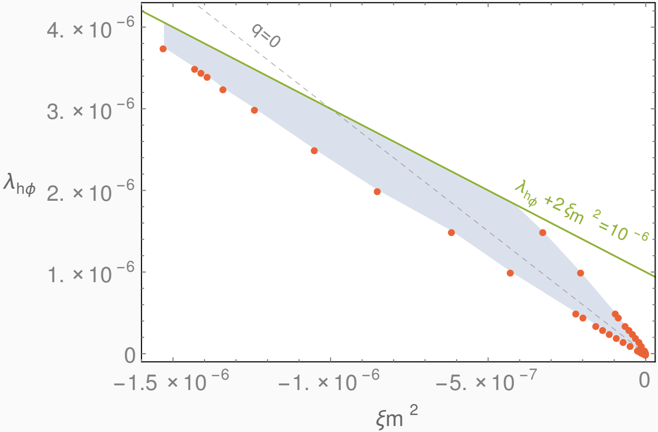
$$-\delta\mathcal{L} = \frac{1}{2}(\lambda_{h\phi} + 2\xi m^2)\phi^2 h_c^2.$$

- Stability during inflation

$$10^{-10} < \lambda_{h\phi} + 2\xi m^2 < 10^{-6}$$

- Resonance parameter $q = (\lambda_{h\phi} + 3\xi m^2)\Phi^2 m^{-2}$.
- Suppression of resonance for $\lambda_{h\phi} \simeq -3\xi m^2$.

COMBINED CASE: VACUUM STABILITY



COMBINED CASE: VACUUM STABILITY