Higgs valleys, stability and inflation

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Does the Higgs play any role in inflation?

Inflation is typically modelled with a scalar field -inflaton- sustaining a positive energy density. Planck's measurements discard potentials involving monomials ϕ^n, $n \geq 2$.

$$A_s = (2.142 \pm 0.049) \cdot 10^{-9}, \quad n_s = 0.9667 \pm 0.0040, \quad r < 0.09$$

The Standard Model has an elementary scalar field, the Higgs, whose quanta (or the quanta of something very much like the Higgs) have been detected at the LHC. The only thing compatible with an elementary scalar that we know!

Does the Higgs play any role at all in inflation?

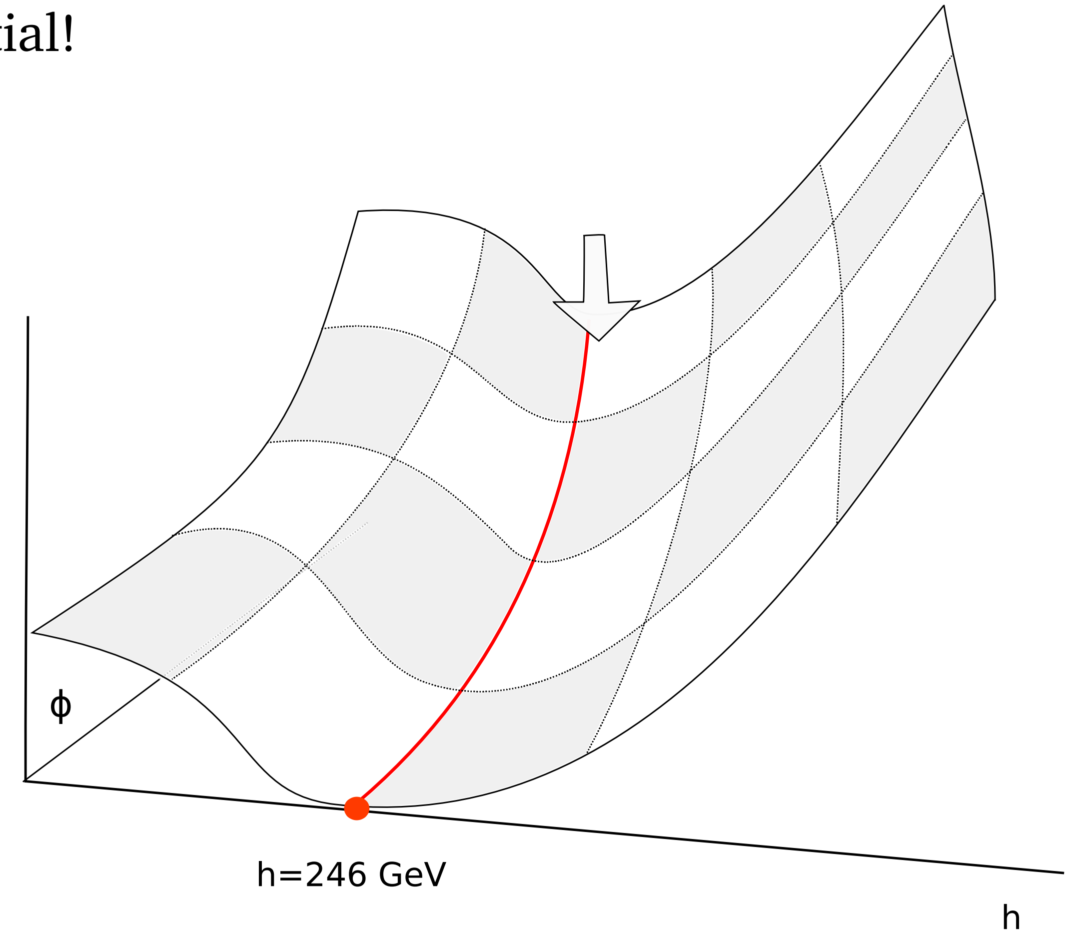
Can we avoid hierarchies of scales between the inflaton and Higgs potentials?

(e.g. in ϕ^2 inflation the mass is 10^{-6} $M_P >> m_h$)

Standard approach: H plays no role

The Higgs is stabilized inside its vacuum, while the inflaton rolls.

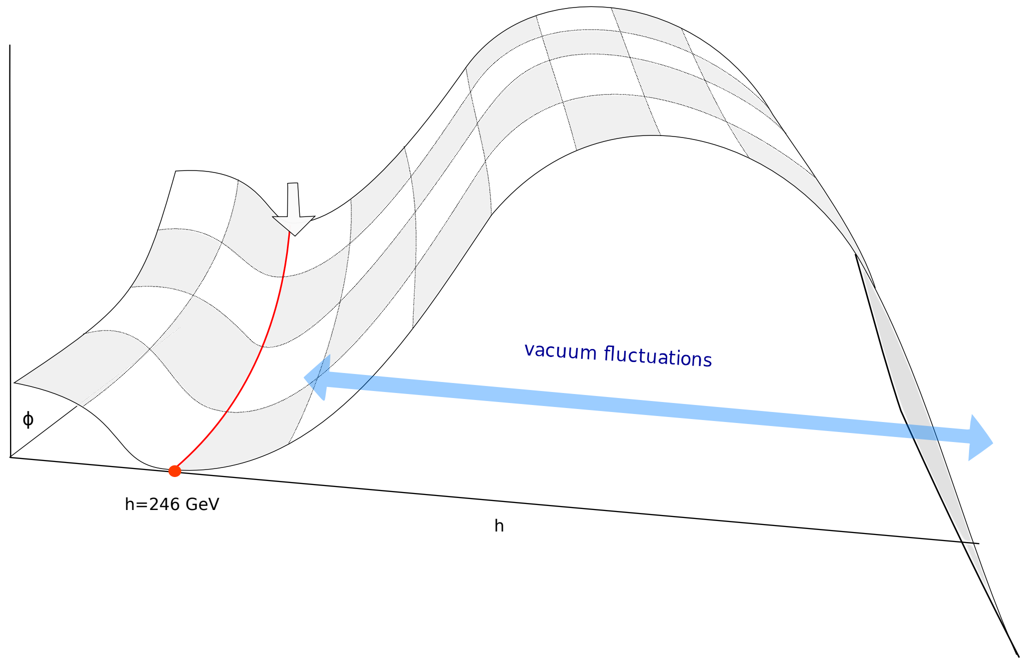
Note that this implies that inflation takes place in a straight valley in the 2-field potential!



Standard approach: H plays no role

Even if the Higgs plays no role in the inflationary dynamics, it can be affected by it.

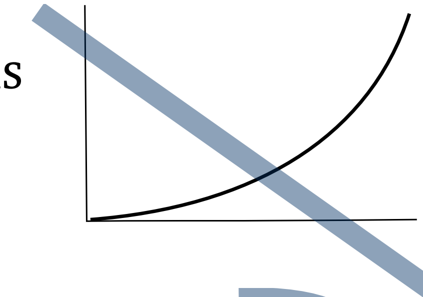
The small mass of the Higgs makes it susceptible of large fluctuations during inflation, which can destabilize the Higgs vacuum.



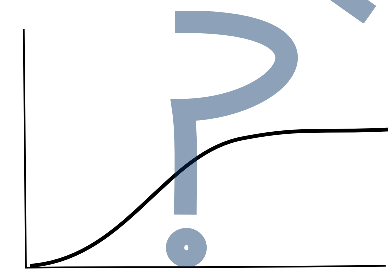
But this can be an advantage, for example to generate the baryon asymmetry during the relaxation to the low energy vacuum.

Alternative approach: H drives inflation

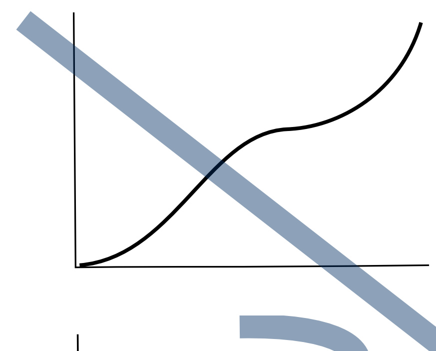
The SM potential is too steep to support enough efolds of inflation.



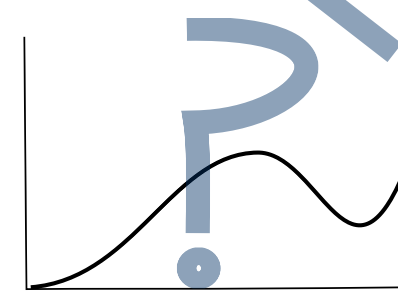
A nonminimal coupling to gravity can flatten out the potential, but requires large, nonperturbative value of the coupling.



Tuning the top mass to have a plateau still does not work due to the impossibility of fitting A_s and N.



False vacuum inflation: Tuning the top mass away from the plateau generates a false vacuum which drive inflation. A graceful exit and the generation of scalar perturbations require new fields.



Higgs false vacuum inflation

Hybrid models allow graceful exit [Masina, Notari, Fairbairn]:

$$V(H,S) = -m_H^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2 - \frac{m_S^2}{2}S^2 + \frac{\lambda_S}{4!}S^4 + \frac{\lambda_{SH}}{2}H^\dagger H S^2$$

Problems with mh=125 GeV? Analyses assumed V ~constant in orthogonal direction, and yet a large value of $\varepsilon \sim (V'/V)^2$ is needed to fit A_s. Correcting this, one can fit A_s, n_s inside the false-vacuum valley.

$$A_s = \frac{1}{24\pi^2 M_P^4}\frac{V}{\epsilon}$$

But careful estimates of the height of plateau imply that one cannot achieve r<2.96

$$V = 3.3 \cdot 10^{66}\,\mathrm{GeV}^2 \Rightarrow r = \frac{2}{3\pi^2 M_P^4}\frac{V}{A_s} = 2.96$$

New valleys trapping H far from its SM VEV?

Valleys that extend in the Higgs direction can appear in the same hybrid models.

These valleys appear at tree-level and don't require tuning m_t!
They can support inflation compatible with Planck-BICEP's results.

Large excursions in the Higgs direction imply that stability constraints apply.

We start from the SM coupled to a heavy singlet getting a large VEV.

$$V(H,S) = -m_H^2 H^\dagger H + \frac{\lambda}{2}(H^\dagger H)^2 - \frac{m_S^2}{2}S^2 + \frac{\lambda_S}{4!}S^4 + \frac{\lambda_{SH}}{2}H^\dagger H S^2$$

$$m_S^2 \gg \frac{1}{2}\langle H^0 H^0 \rangle \equiv v_h^2 = 246^2\,\mathrm{GeV}^2,\ \lambda_S \ll 1$$

Near $H=0$, the potential is minimum for

$$S^2 \sim \frac{6 m_S^2}{\lambda_S} \gg v_h^2$$

A valley in the *H* direction

Recovering the SM Higgs at low energies

Low energy physics must be compatible with a SM Higgs with

$$H^0 = \frac{1}{\sqrt{2}} h,\ m_h = 125\ \mathrm{GeV},\ v_h = 246\ \mathrm{GeV}$$

The potential at the bottom of the S-valley should reproduce the SM Higgs potential.

This fixes m^2_H, λ in terms of other parameters:

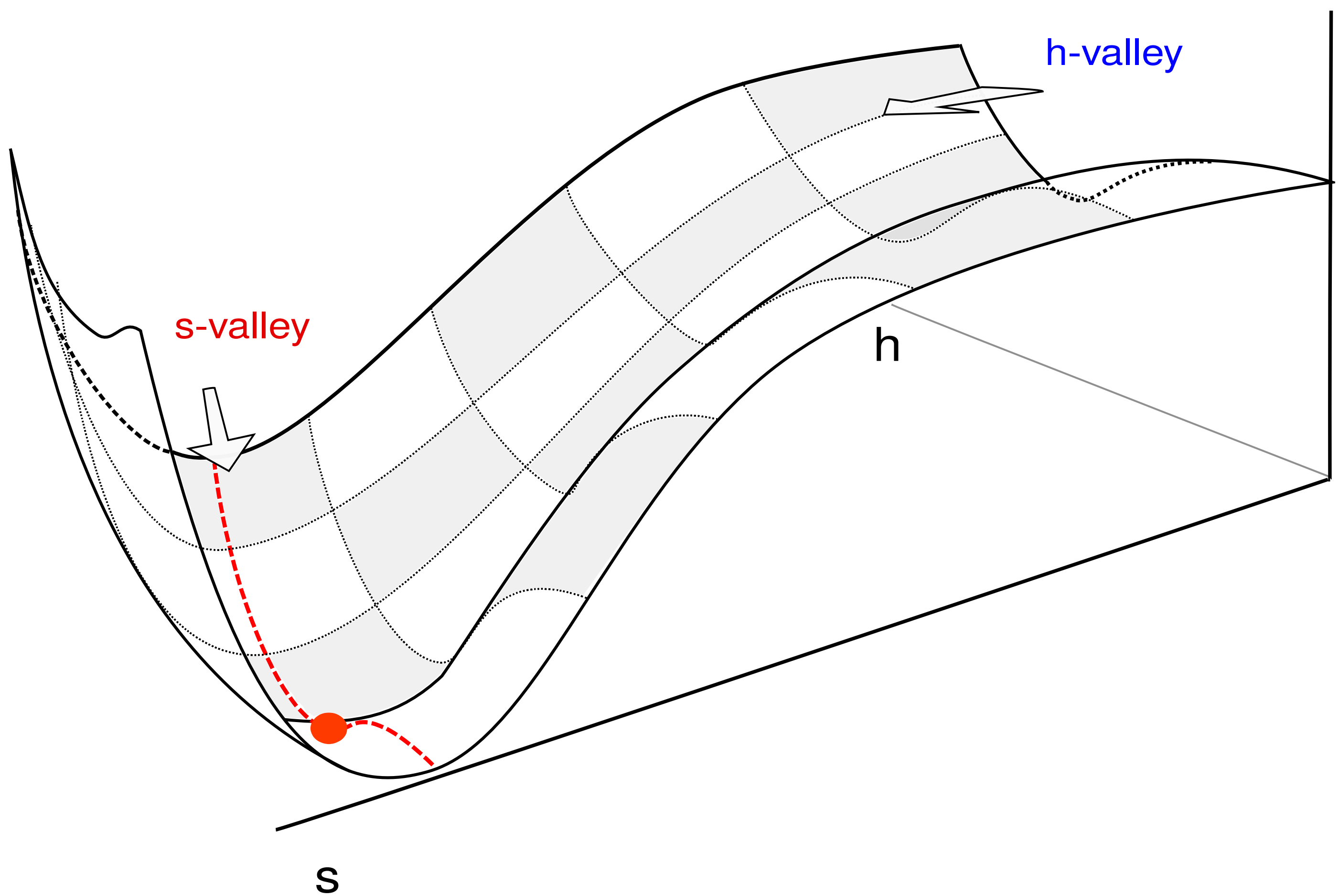
$$m_H^2 = \tilde{m}_H^2 + \frac{3\lambda_{SH}}{\lambda_S} m_S^2$$

$$\lambda = \tilde{\lambda} + \frac{3\lambda_{SH}^2}{\lambda_S}$$

$$\tilde{m}_H^2 \sim 7800^2\ \mathrm{GeV}^2,\ \tilde{\lambda} \sim 0.26$$

Valleys in the absence of Higgs-singlet coupling

Minima in the S direction define a valley. Similarly the minima in the h direction define a valley with h=246 GeV. This is like a standard single-field inflation scenario, S being the inflaton.



The Higgs-singlet interaction deforms valleys

$m_H^2 = \tilde{m}_H^2 + \frac{3\lambda_{SH}}{\lambda_S} m_S^2$ can become of the order of $m^2_S >> v^2_h$

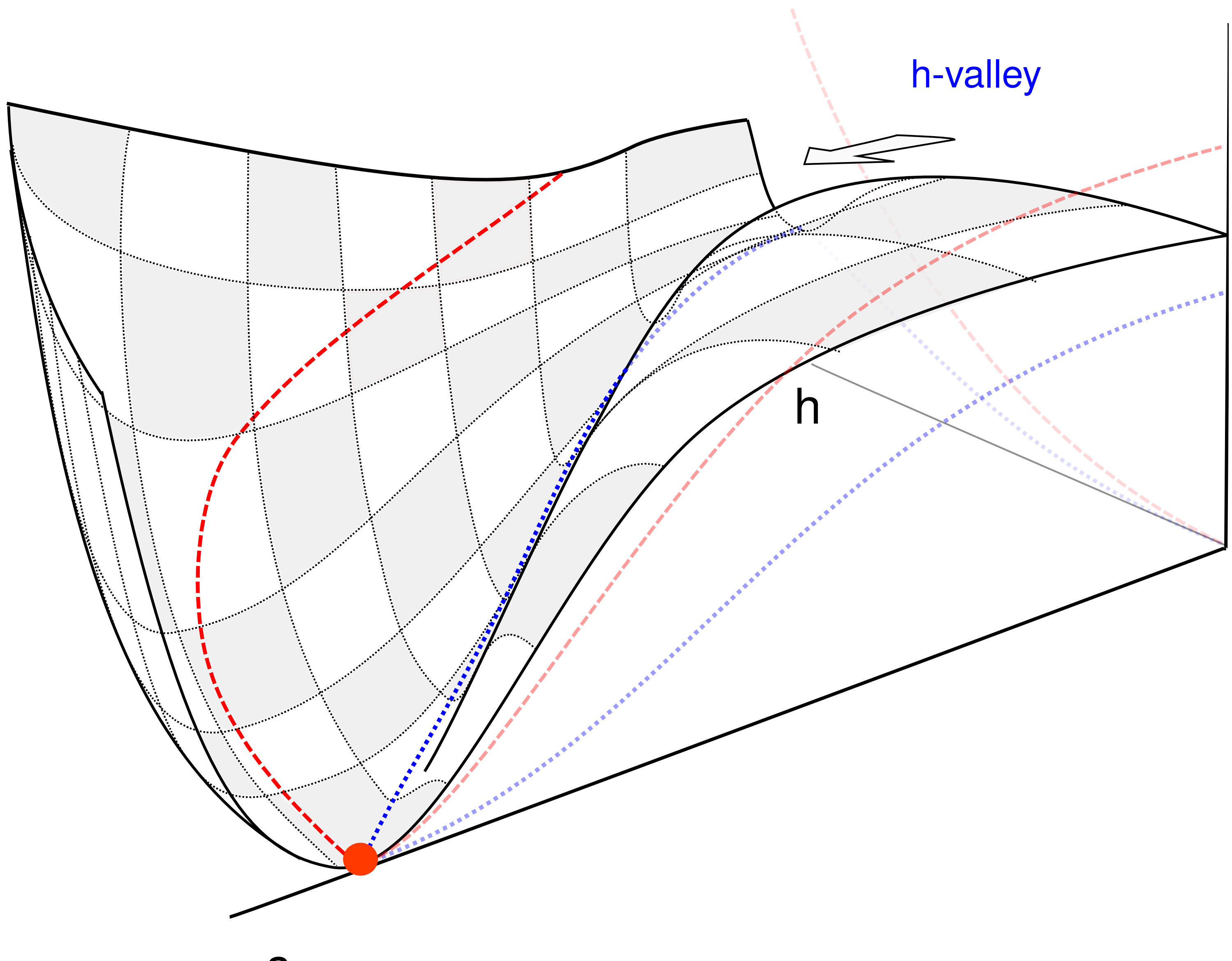
Effective mass in the *h* direction for fixed S, determining location of *h* minima:

$$m_{H,eff}^2 = -m_H^2 + \frac{1}{2}\lambda_{SH} S^2$$

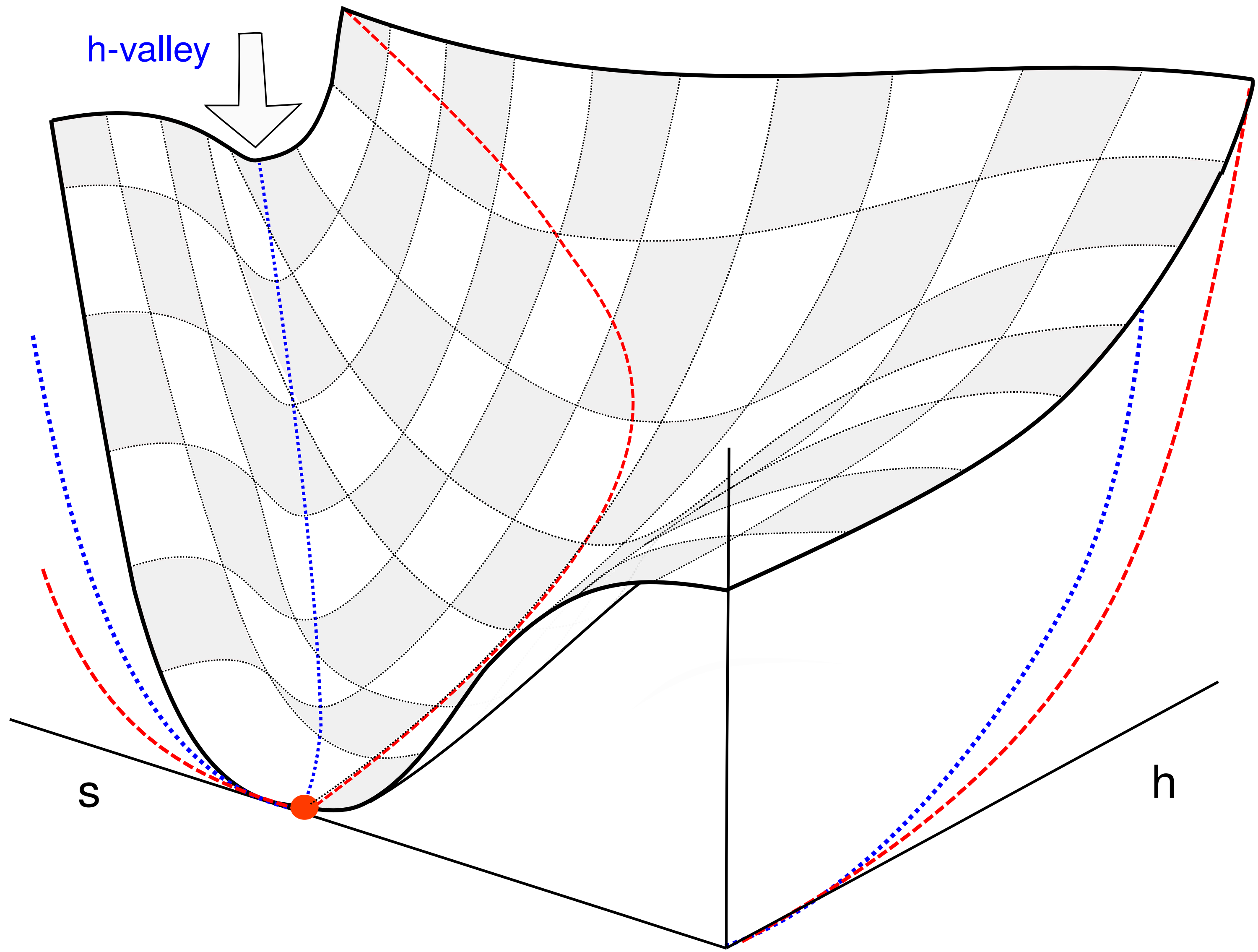
The *h*-valley is deformed towards large values of h. Similar to false vacuum inflation, but without tuning m_t.

Since we can have $m^2_S \sim m^2_H$, the weak scale can arise from a single mass source by tuning dimensionless parameters λ_S, λ_{SH}. This tuning is radiatively stable.

Deformed valleys, $\lambda_{SH} > 0$



Deformed valleys, $\lambda_{SH} < 0$



Potentials along the lines of minima

All proportional to the SM quartic.

s-lines:
$$\frac{dV}{dS} = 0, \quad \begin{cases} V_{\text{s-valley}}(S) & = \frac{\tilde{\lambda}}{2} \left(\frac{\lambda_S}{6\,\lambda_{SH}}\right)^2 \left(S^2 - v_S^2\right)^2, \\ V_{\text{s-valley}}(h) & = \frac{\tilde{\lambda}}{8} \left(h^2 - v_h^2\right)^2 = V_{SM}(h) \end{cases}$$

h-lines:
$$\frac{dV}{dh} = 0, \quad \begin{cases} V_{\text{h-valley}}(S) & = \left(1 + \tilde{\lambda}\, \frac{\lambda_S}{3\lambda_{SH}^2}\right)^{-1} V_{\text{s-valley}}(S), \\ V_{\text{h-valley}}(h) & = \left(1 + \tilde{\lambda}\, \frac{\lambda_S}{3\lambda_{SH}^2}\right) V_{\text{s-valley}}(h) \end{cases}$$

Stability constraints

In the SM. Potential at large values of the field captured by the running λ:

$$V_{SM}(h) \sim \frac{1}{8}\tilde{\lambda}(h)h^4, \quad \beta_\lambda = -\frac{3}{4\pi^2}y_t^4 + \ldots$$

Instability at $\Lambda_I \sim 10^{13}$ GeV for m_t=173 GeV, m_h =125 GeV.

SM plus singlet. Stabilization by a scalar threshold effect? [Elias-Miró et al].

$$\lambda = \tilde{\lambda} + \frac{3\lambda_{SH}^2}{\lambda_S} > \tilde{\lambda}$$

Stability claimed for large enough $\delta = 3\lambda^2_{SH}/\lambda_S$, if

$$\lambda_{SH} > 0, \; m_S^2 \lesssim \Lambda_I^2$$

Using what we know about h-lines and s-lines: V>0 on them.

Stability can only be really achieved for

$$m_S^2 < \text{Min}\left\{\frac{\lambda\lambda_S}{6\lambda_{SH}}\Lambda_I^2, \frac{\lambda_{SH}}{2}\Lambda_I^2\right\}$$

Evading stability constraints

In the range of interest of parameters, we can stabilize valleys with large excursions in the h direction in two ways (keeping Higgs at 125 GeV) :

- $m_t < 172.1$ GeV. Compatible with latest combined CMS measurements

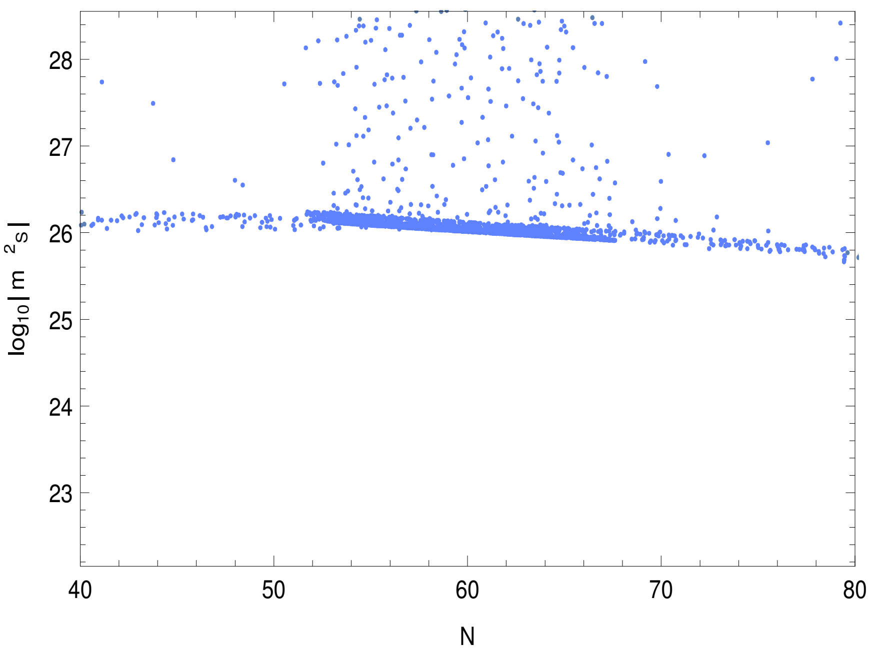
$$m_t = 172.38 \pm 0.38 \text{ GeV}$$

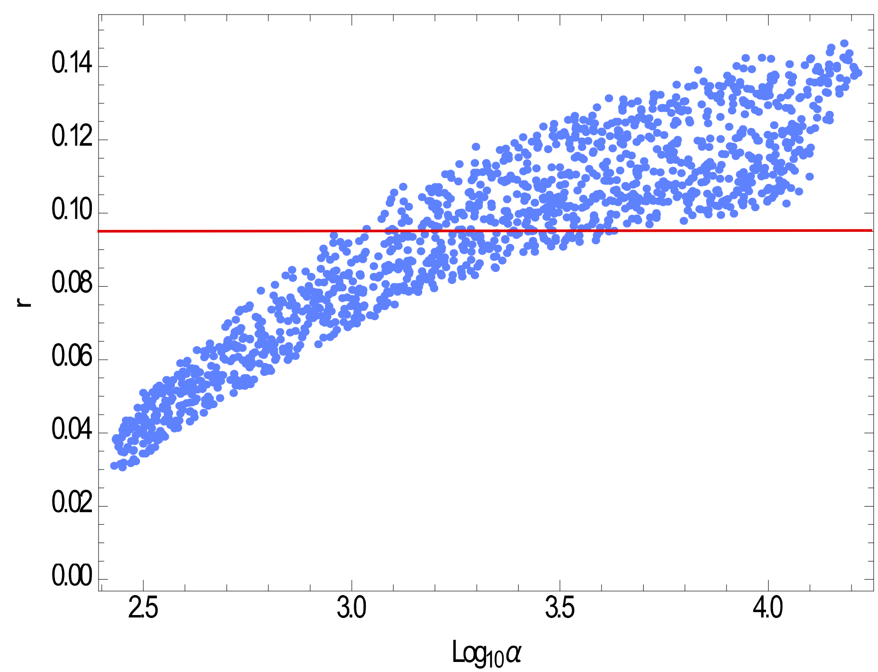
- Adding a second heavy singlet stabilized at the origin. Integrating it out gives S'=0, and so does not modify the shape of the valleys seen before. The model is stabilized by additional contributions to β_λ.

Inflation along the *h*-valleys

One-dimensional rolling along the valley is a very good approximation for large v_S (large curvature, transversal masses). Defining

$$\alpha = \frac{6 m_S^2}{\lambda_S M_P}$$





m^2_S near 10^{26} GeV preferred!

Summary

- Inflationary models in which a field gets a large VEV are sensitive to Higgs physics, because Higgs interactions deform the valleys supporting inflation.
- The valleys can extend to large values of *h,* realizing the idea of Higgs false-vacuum-inflation at tree-level, without tuning the top mass.
- In these models, stability constraints apply to make inflation viable. Inflation cannot be blind towards Higgs physics! Threshold stabilization does not work for small couplings.
- All mass scales can be similar in the high energy theory.
- In contrast to the usual false-vacuum scenarios, ruled out by the bound $r<0.09$, one can achieve $r\geq 0.03$.

Outlook

- Could the Higgs field actually source isocurvature perturbations and nongaussianities? This can only happen when the valleys extend very far (several Planck masses?) in the Higgs direction.

Slow-rolling formulae

$$A_s[\phi] = \frac{\left(-6m_H^2\lambda_{SH} + 6\tilde{\lambda}m_S^2 + \tilde{\lambda}\phi^2\lambda_S\right)^4}{4608\pi^2\tilde{\lambda}^3\phi^2 M_P^6\lambda_S^2\left(\tilde{\lambda}\lambda_S + 3\lambda_{SH}^2\right)},$$

$$n_s^h[\phi] - 1 = -\frac{24\tilde{\lambda}M_P^2\lambda_S\left(2m_H^2\lambda_{SH} - 2\tilde{\lambda}m_S^2 + \tilde{\lambda}\phi^2\lambda_S\right)}{\left(-6m_H^2\lambda_{SH} + 6\tilde{\lambda}m_S^2 + \tilde{\lambda}\phi^2\lambda_S\right)^2},$$

$$r^h[\phi] = \frac{128\tilde{\lambda}^2\phi^2 M_P^2\lambda_S^2}{\left(-6m_H^2\lambda_{SH} + 6\tilde{\lambda}m_S^2 + \lambda\phi^2\lambda_S\right)^2},$$

$$N^h[\phi_i, \phi_f] = \frac{1}{8M_P^2}\left[\phi^2 + \left(-\frac{12m_H^2\lambda_{\mathrm{SH}}}{\lambda\lambda_S} + \frac{12m_S^2}{\lambda_S}\right)\log\left[\frac{\phi}{M_P}\right]\right]_{\phi_f}^{\phi_i}$$

Approximations

$\alpha \gg 1:$

$$A_s^h[N] \sim \frac{\lambda_S \alpha N^2}{18\pi^2} \pm \frac{\lambda_S N\sqrt{\alpha}}{27\sqrt{2}\pi^2}, \qquad A_s^s[N] \sim \frac{\tilde{\lambda}\lambda_S^2 N^2 \alpha}{54\pi^2\lambda_{SH}^2} \pm \frac{\tilde{\lambda}\lambda_S^2 N\sqrt{\alpha}}{81\sqrt{2}\pi^2\lambda_{SH}^2},$$

$$(n_s^h[N]-1) = (n_s^h[N]-1) \sim -\frac{2}{N} \pm \left(\frac{\sqrt{2}}{3N^2} + \frac{2}{\sqrt{N}}\right)\frac{1}{\sqrt{\alpha}}, \quad r^h[N] = r^s[N] \sim \frac{8}{N} \mp \frac{4(\sqrt{2}+12N^{3/2})}{3N^2\sqrt{\alpha}}.$$

$\alpha \ll 1,\ \lambda_{SH} > 0:$

$$A_s^h[N] \sim \frac{3\lambda_{SH}^2}{\tilde{\lambda}\lambda_S} A_s^h[N] \sim \frac{\alpha^2 \lambda_S e^{8N/\alpha}}{576\pi^2}, (n_s^h[N]-1) = \quad (n_s^h[N]-1) \sim -\frac{8}{\alpha},$$

$$r^h[N] = r^s[N] \sim 16e^{-8N/\alpha}.$$

$\alpha \gg 1:$

$$A_s^h[N](n_s^h - 1)^2 \sim \frac{2\lambda_S \alpha}{9\pi^2} = -\frac{4}{3\pi^2}\frac{m_S^2}{M_P^2},$$

$$\Rightarrow m_S^2 \sim -\frac{3\pi^2}{4} M_P^2 A_s (n_s - 1)^2 = -1.04 \cdot 10^{26}\ \mathrm{GeV},$$