Higgs Inflation

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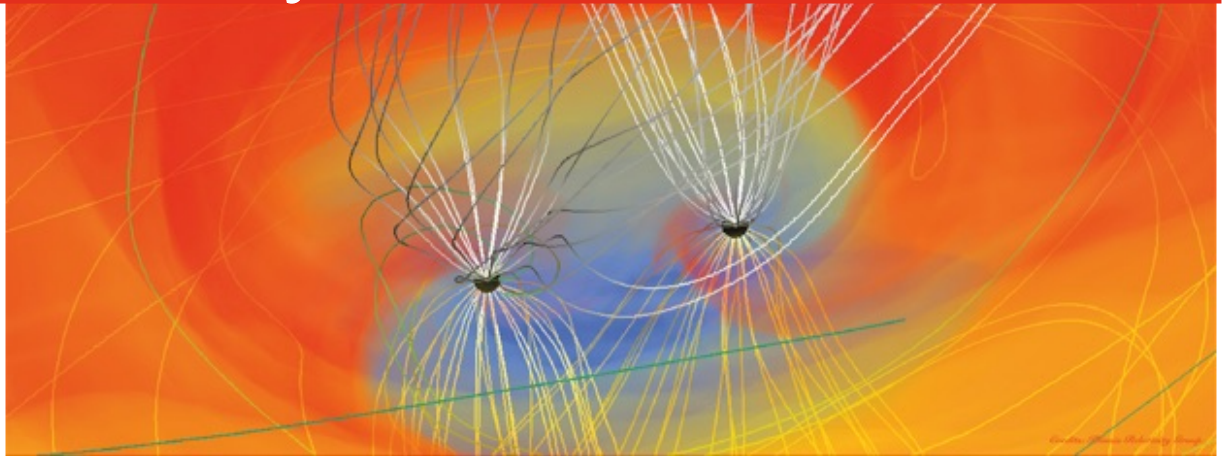


Outline

- Why Higgs Inflation?
- Phenomenology of Higgs Inflation
- Challenges in Higgs inflation: higher dimensional operators and possible vacuum metastability
- Beyond naive power counting: effective field theory of Higgs Inflation
- Higgs inflation and vacuum metastability
- Symmetries of UV completion?
- Conclusions

Why Higgs Inflation?

SM of particle physics:

- The Standard Model is complete: the last particle - Higgs boson, predicted by the SM, has been found
- No significant deviations from the SM have been observed
- With experimental values of the masses of the top quark and of the Higgs boson the SM is a self-consistent effective field theory all the way up to the quantum gravity Planck scale

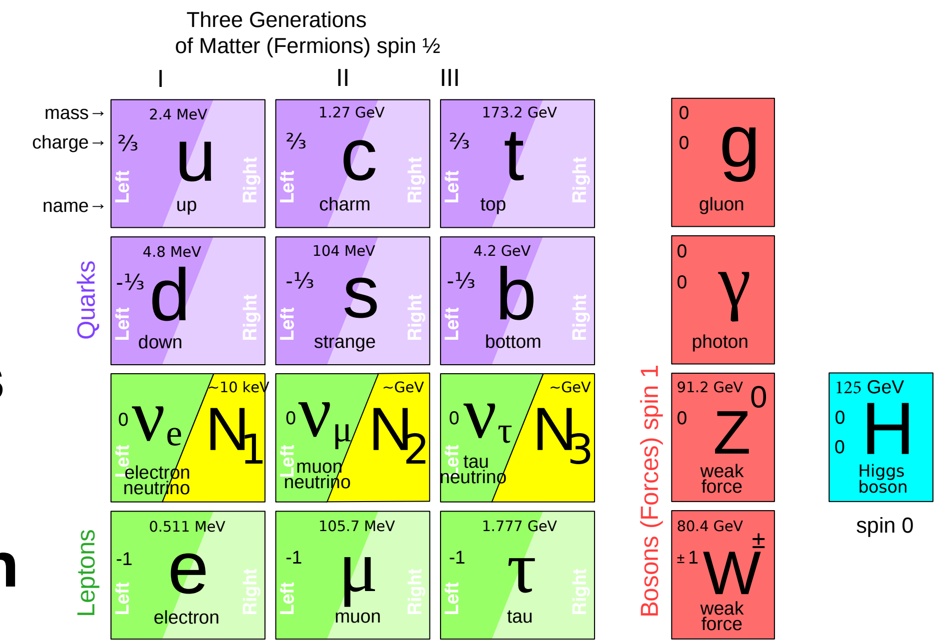
- Though the SM is not the final theory, its drawbacks on the experimental and cosmological front (neutrino masses, dark matter and baryon asymmetry of the Universe) can be cured in a minimal way by adding 3 Majorana fermions - "Heavy Neutral Leptons (HNLs)" with masses below the Fermi scale

- As the Higgs boson in the Standard Model is described by a fundamental scalar field, the most economic (not necessarily right!) picture of the particle theory arises if the Higgs inflates the Universe.

Lightest HNL N1, keV range - dark matter

Heavier N2 and N3, GeV range - neutrino masses and baryogenesis

Higgs boson: EW symmetry breaking and inflation



νMSM

Phenomenology of Higgs Inflation

Starting point: the Standard Model and gravity Lagrangian

$$S_G = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R\right)$$

should contain a non-minimal coupling of the Higgs field h to gravity, with arbitrary parameter ξ, to be fixed (as any other parameter of the SM) by observations.

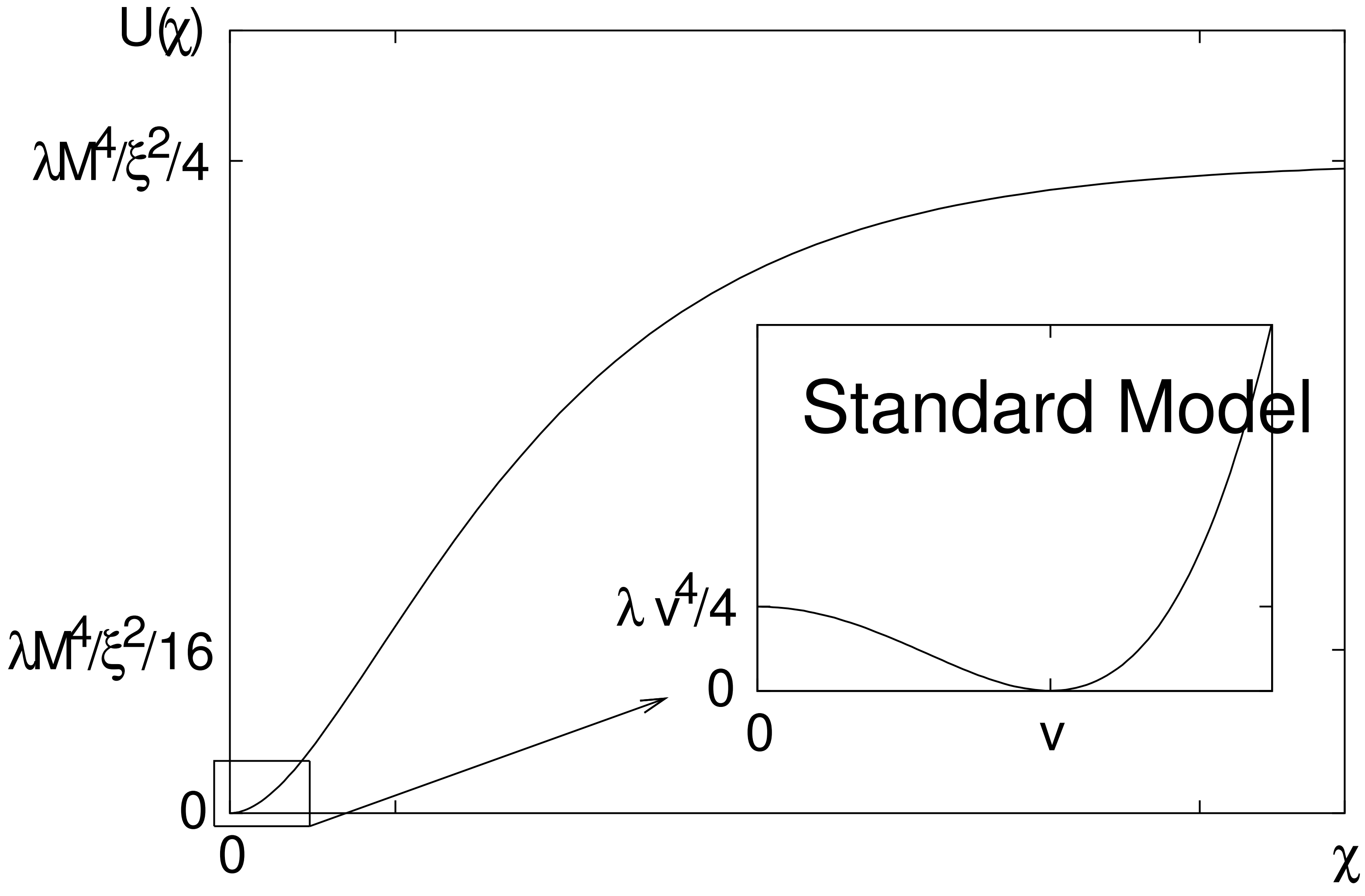
- Interesting physics: gravity strength as well as particle masses are determined by the Higgs field, if

$$\xi h^2 \gg M_P^2$$

- the theory is scale invariant in this limit, leading to flat potential for the Higgs field, exactly what is needed for inflation!

Importance of non-minimal coupling for inflation: Spokoiny; Salopek, Bond, Bardeen;…
Higgs inflation: Bezrukov, MS; derivative coupling of Higgs to gravity: Germani, Kehagias

- Higgs potential in the Einstein frame, with χ being canonically normalised scalar field related to the Higgs field :



Stage 1

Initial condition for inflation - chaotic (Linde):

- Field configurations with "large" $h > \frac{M_P}{\sqrt{\xi}}$,

corresponding to the plateau of the effective potential enter eventually into inflationary regime

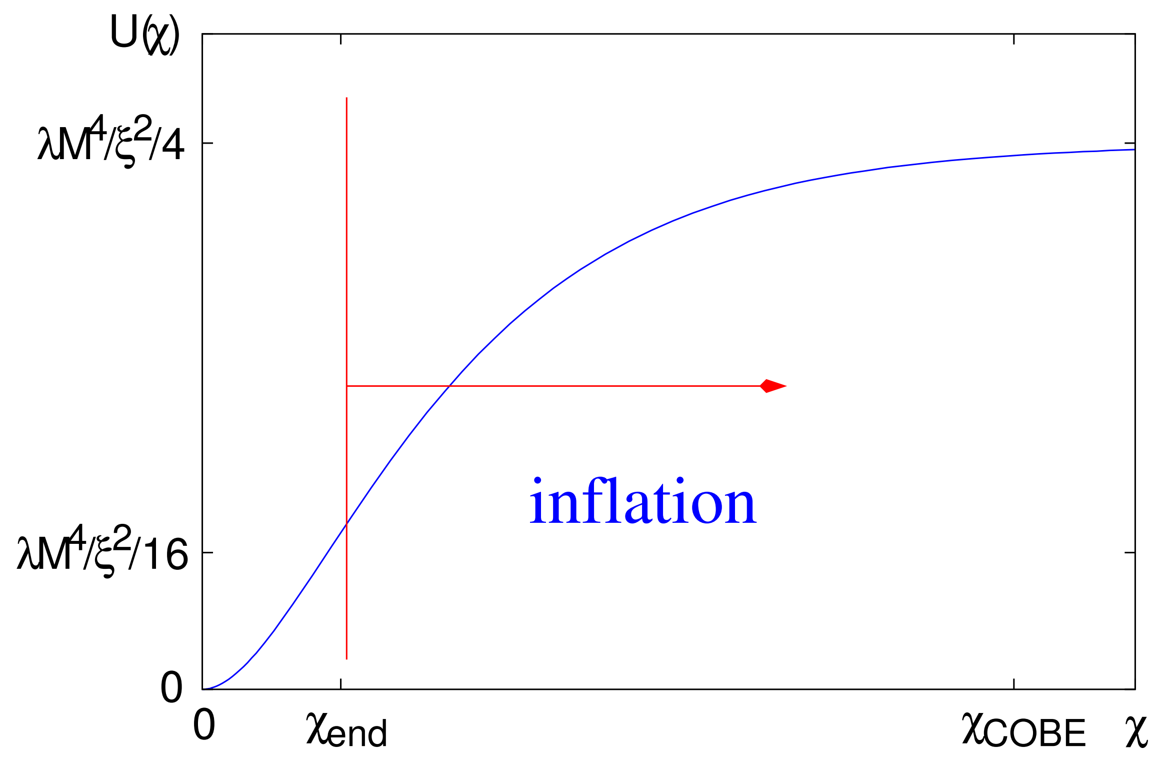
- Field configurations with "small" $h < \frac{M_P}{\sqrt{\xi}}$ are not inflating

- Inflationary regime is "generic" and "natural"

see also Linde; Gorbunov, Panin

Stage 2

Slow roll of the Higgs field $h > \frac{M_P}{\sqrt{\xi}}$

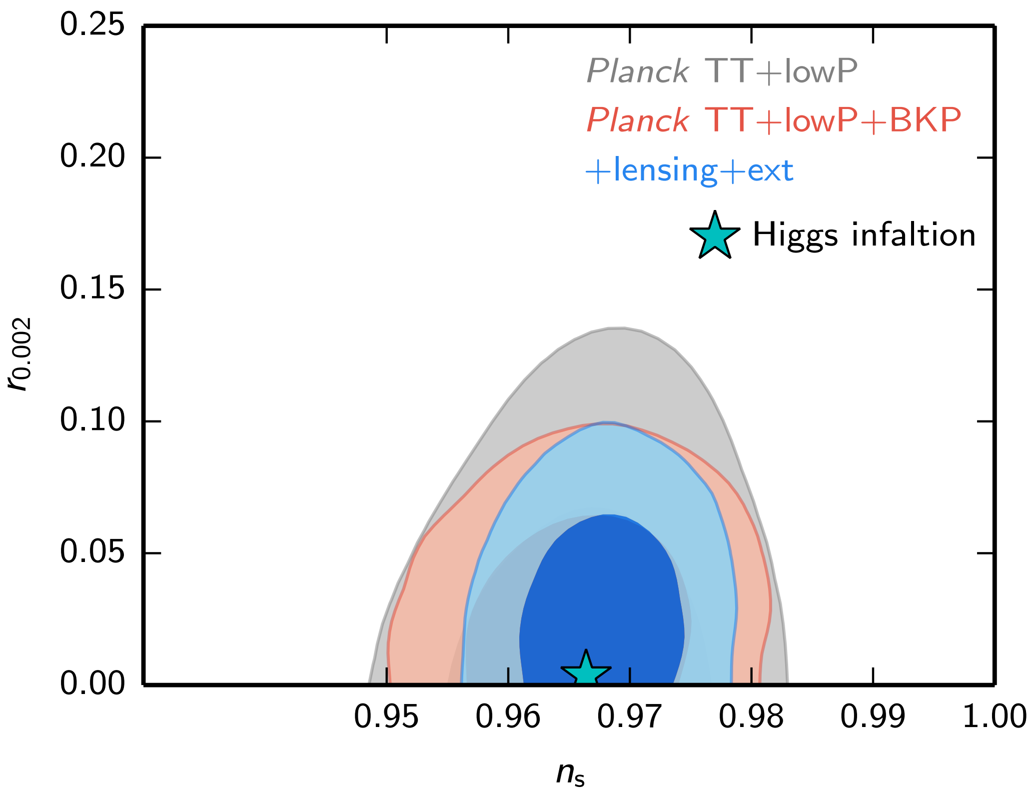


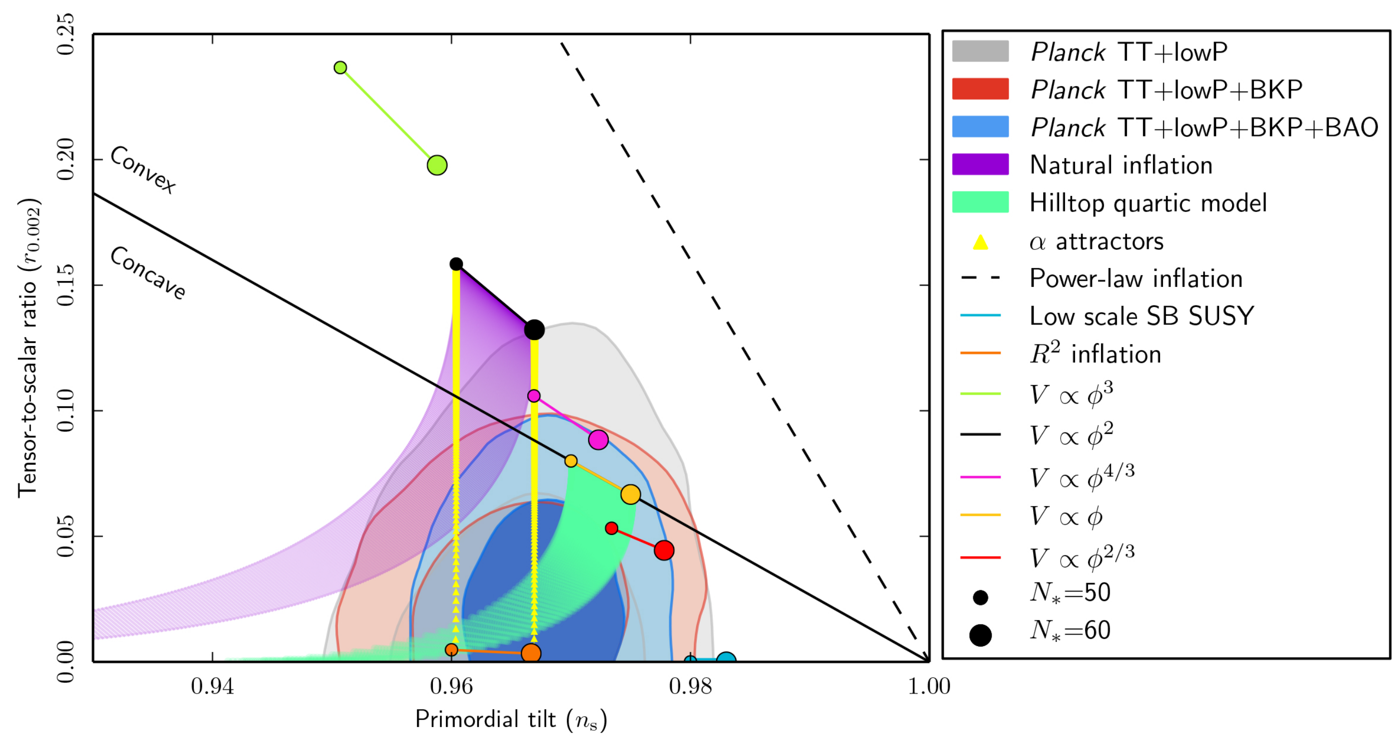
- Makes the Universe flat, homogeneous and isotropic
- Produces fluctuations leading to structure formation: clusters of galaxies, etc

Predictions

- Cobe normalisation: $\xi = 49000\sqrt{\lambda}$, numerically large ξ
- Gaussian perturbations
- Prediction for inflationary observables:

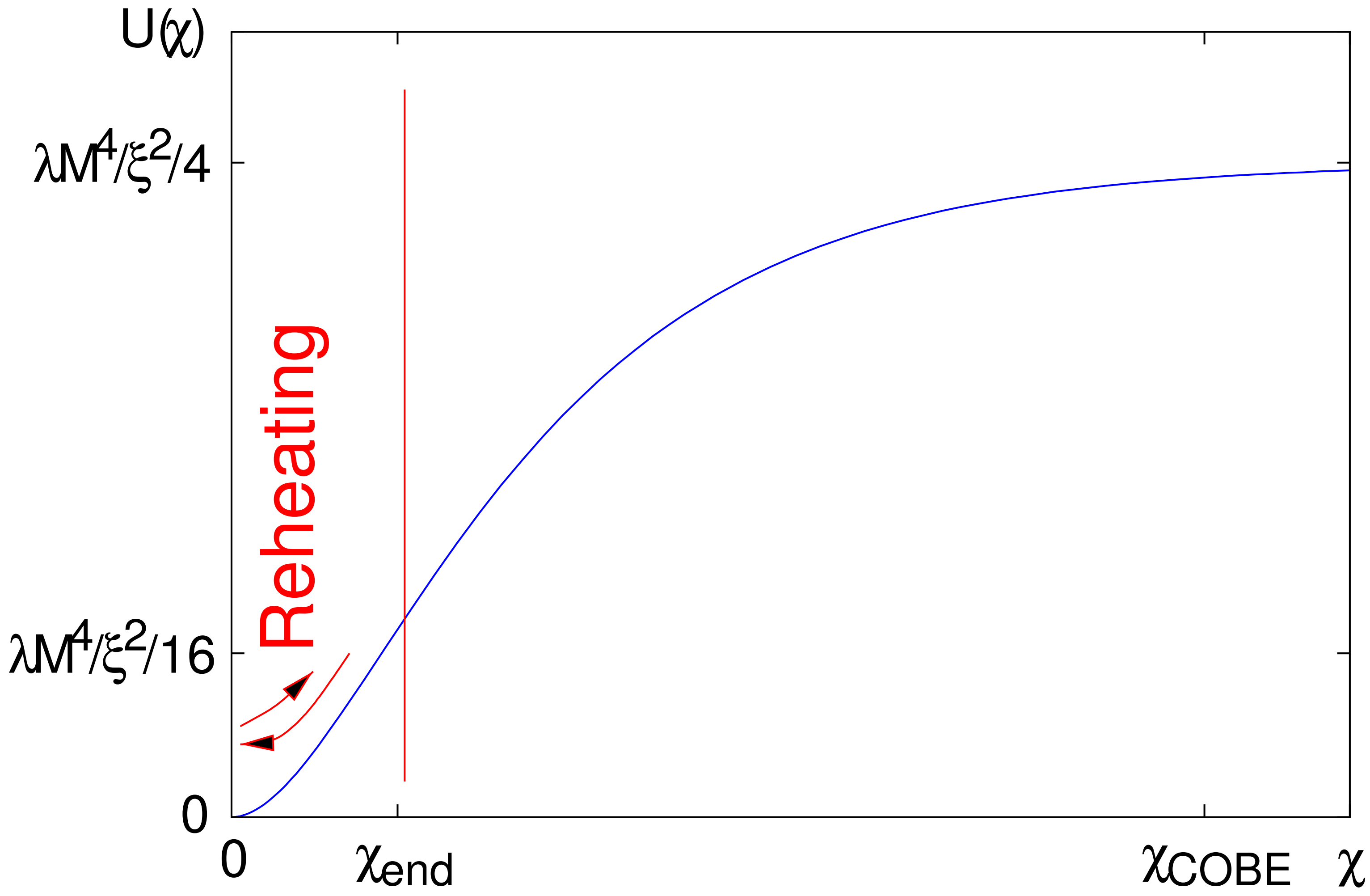
$$n_s = 0.97,\ r = 0.0033$$





Stage 3

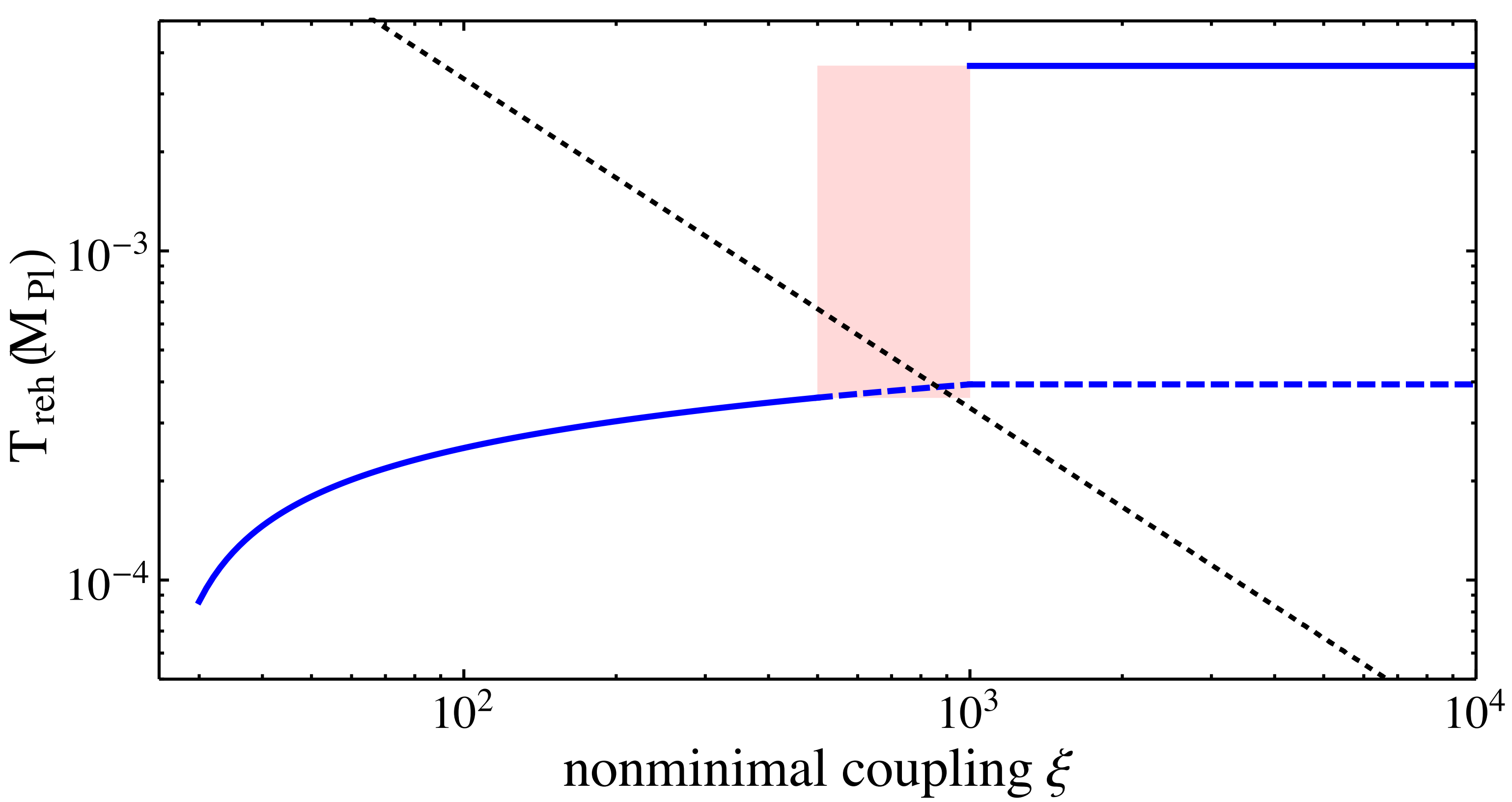
- Heating of the Universe : energy stored in the Higgs field goes into the particles of the Standard Model - Higgs makes the Big Bang



- The process of reheating is computable, as the Higgs couplings to the particles of the SM are known!

- first analysis: reheating temperature is high, $T_r \simeq (3.3 - 8.3) \times 10^{13}$ GeV, Bezrukov, Gobunov, MS; Garcia-Bellido, Figueroa, Rubio

- important observation: longitudinal W and Z bosons are copiously produced, making the reheating temperature even higher, $\sim 5 \times 10^{15}$ GeV, Higgs field makes almost no oscillations: instantaneous preheating. DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis; Ema, Jinno, Mukaida, Nakayama



Sfakianakis and van de Vis '18

Stage 4

- Radiation dominated stage of the Universe expansion starts, and later baryon asymmetry of the Universe and Dark Matter are created. In the framework of νMSM, BAU generation occurs around the electroweak cross-over and sphaleron freeze-out, $T \simeq 130$ GeV and sterile neutrino DM creation around the QCD cross-over $T \simeq 100$-300 MeV.

Challenges in Higgs inflation

1. Classical theory of the Higgs inflation should be promoted to the quantum theory of Higgs inflation. Any theory of inflation involves gravity which is non-renormalisable. An approach to every type of inflation (and HI in particular) should be formulated if the framework of some effective theory and be self-consistent.

2. The SM parameters are measured at small energies ~ 100 GeV, whereas inflation takes place at high energies: radiative corrections and RG running must be accounted for. What happens if the SM vacuum is metastable?

Challenge 1: Higher dimensional operators

Important: the energy domain of perturbative validity of the scalar-gravity theory with non-minimal coupling

$$S_G = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \frac{\xi h^2}{2}R + \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}h^4\right)$$

Take some background field h, and consider all sorts of scattering reactions at energy E. Define the "cut-off" scale E = Λ at which the perturbative expansion breaks down. For zero h background

$$\Lambda \sim \frac{M_P}{\xi}$$

due to kinetic mixing of the Higgs and the metric (Burgess, Lee, Trott ; Barbon and Espinosa). This may be dangerous for the Higgs inflation, as the typical scale of it is $M_P/\sqrt{\xi} \gg \Lambda$, $\xi \gg 1.$

Several ways to proceed:

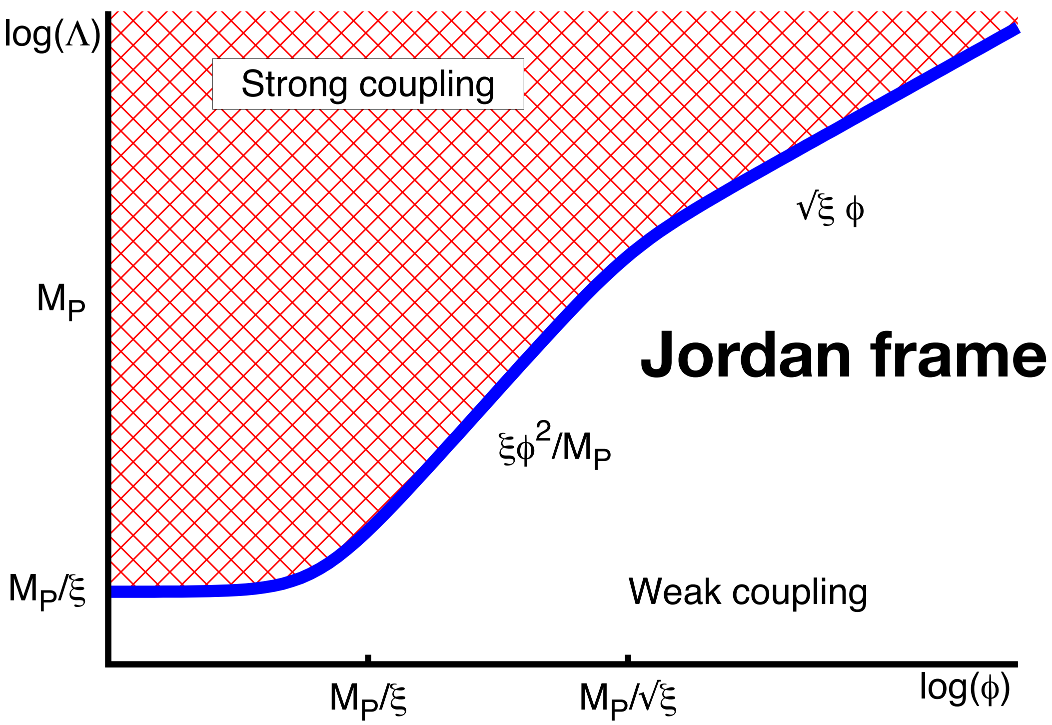
- Add new physics (new fields) and construct a theory in such a way that for zero Higgs and other fields backgrounds the inflation occurs in a weak coupling regime (Giudice, Lee, and many generalisations, e.g. for Higgs-Starobinsky inflation: Bezrukov, Gorbunov, Shepherd, Tokareva)

- Go beyond naive power counting: a refined effective field theory of Higgs Inflation

Beyond naive power counting: effective field theory of Higgs Inflation

In fact, the cutoff is background dependent (Bezrukov, Magnin, M.S., Sibiryakov; see also Ferrara, Kallosh, Linde, A. Marrani, Van Proeyen).

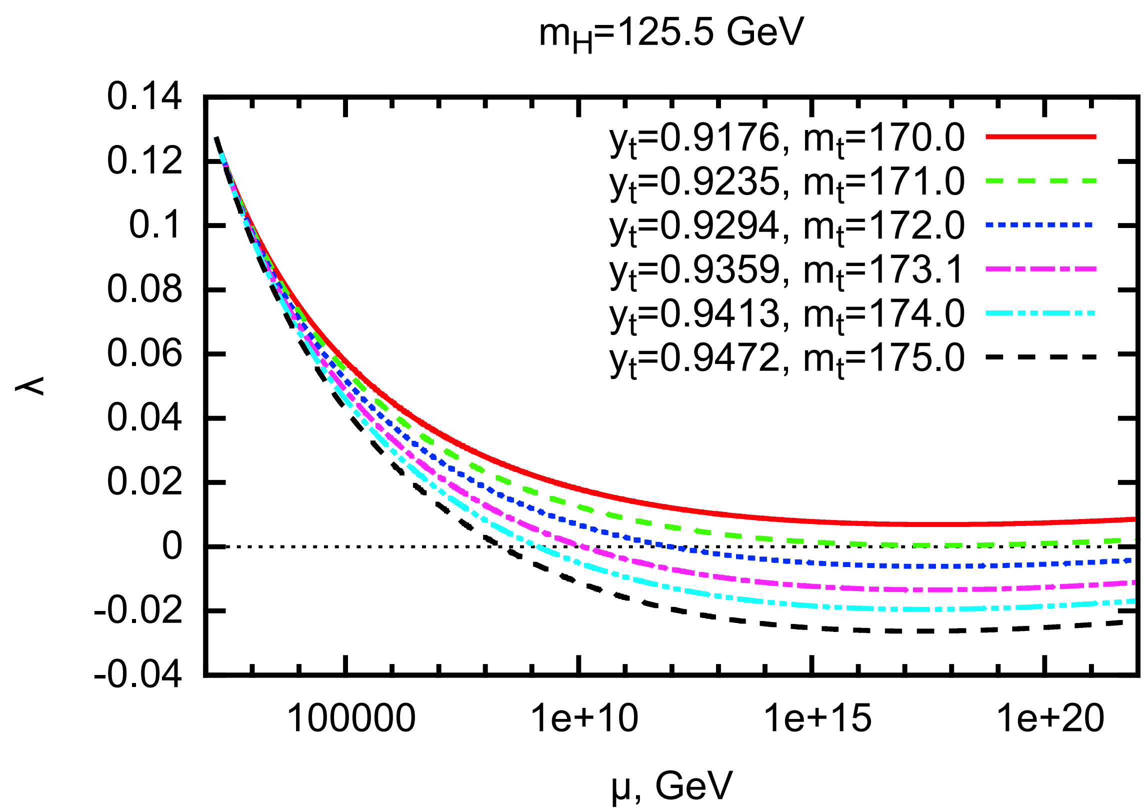
$$\Lambda(h) \simeq \begin{cases} \frac{M_P}{\xi}\,, & \text{for } h \lesssim \frac{M_P}{\xi}\,, \\ \frac{h^2\xi}{M_P}\,, & \text{for } \frac{M_P}{\xi} \lesssim h \lesssim \frac{M_P}{\sqrt{\xi}}\,, \\ \sqrt{\xi}h\,, & \text{for } h \gtrsim \frac{M_P}{\sqrt{\xi}}\,. \end{cases}$$



Cutoff is higher than the relevant dynamical scales throughout the the inflationary epoch. The Higgs-inflation occurs in the weakly coupled regime. The same statement may be also valid for reheating stage: self healing of the amplitudes: Calmet and Casadio

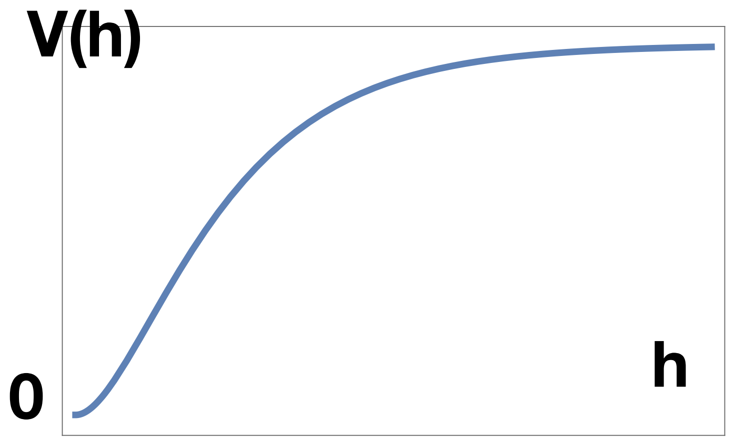
Challenge 2: possible vacuum metastability

Behaviour of the scalar self-coupling λ: depending on the top quark Yukawa coupling, λ may cross zero at energies as small as 10^{11} GeV (for larger m_t) or never cross it (for smaller m_t). For all admissible SM parameters, $|\lambda| \sim 0.01$ in inflationary region, much smaller than at low energies

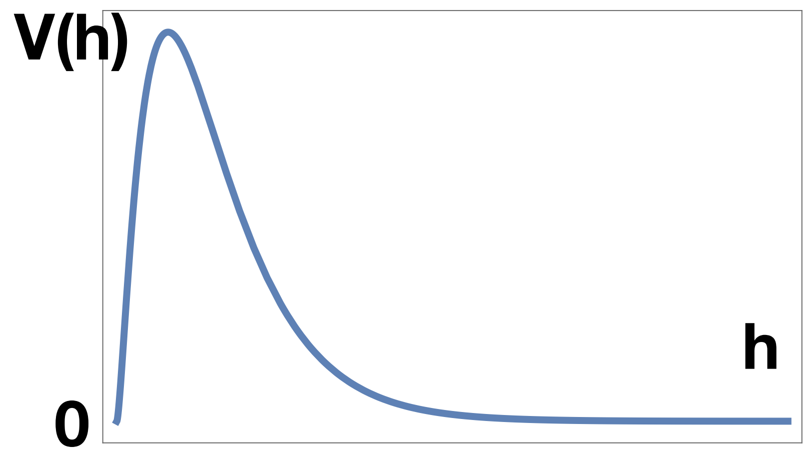


This behaviour may change the form of the Higgs potential at large h

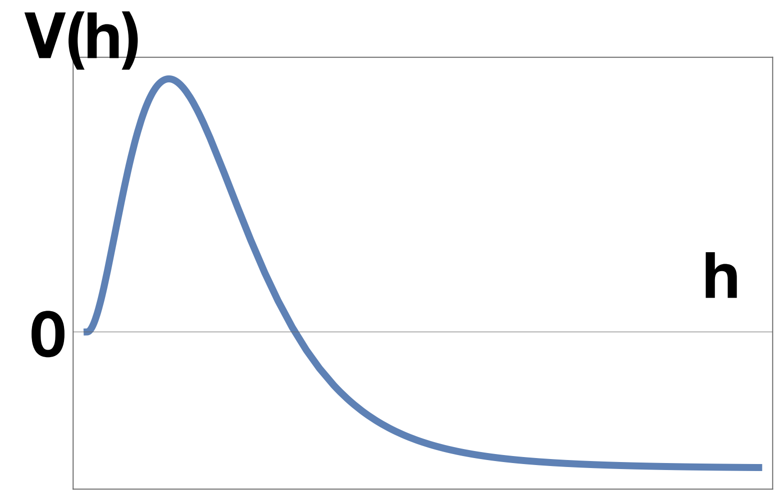
Naive RG: $V(h)=\lambda(h)h^4$



Stability



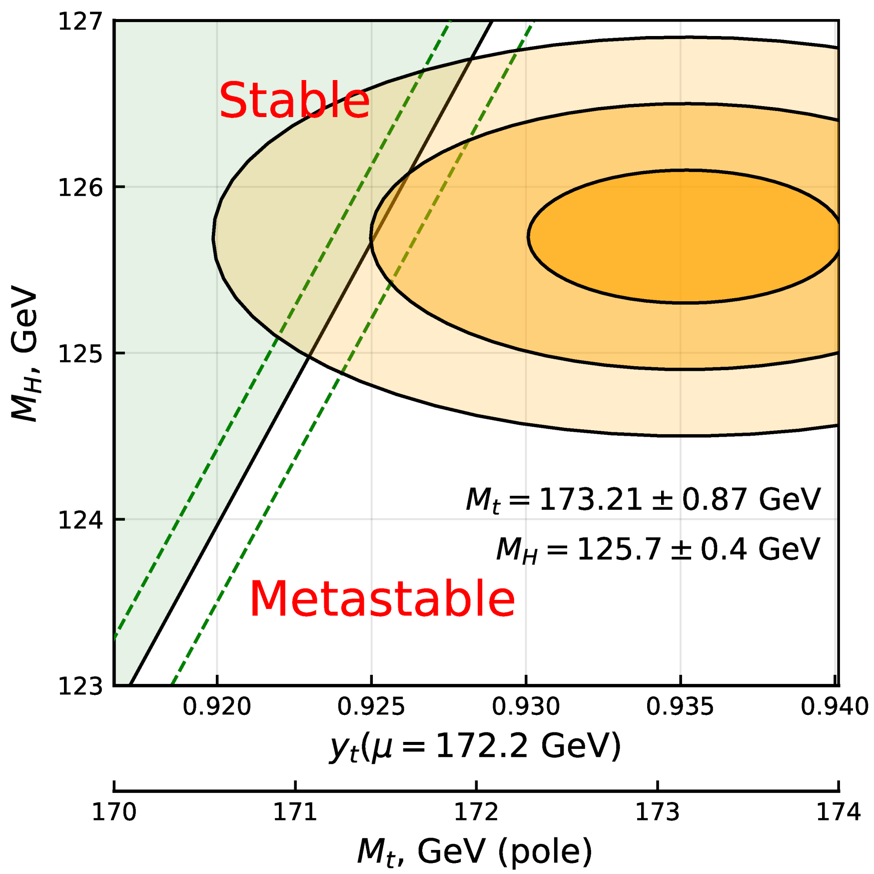
Criticality



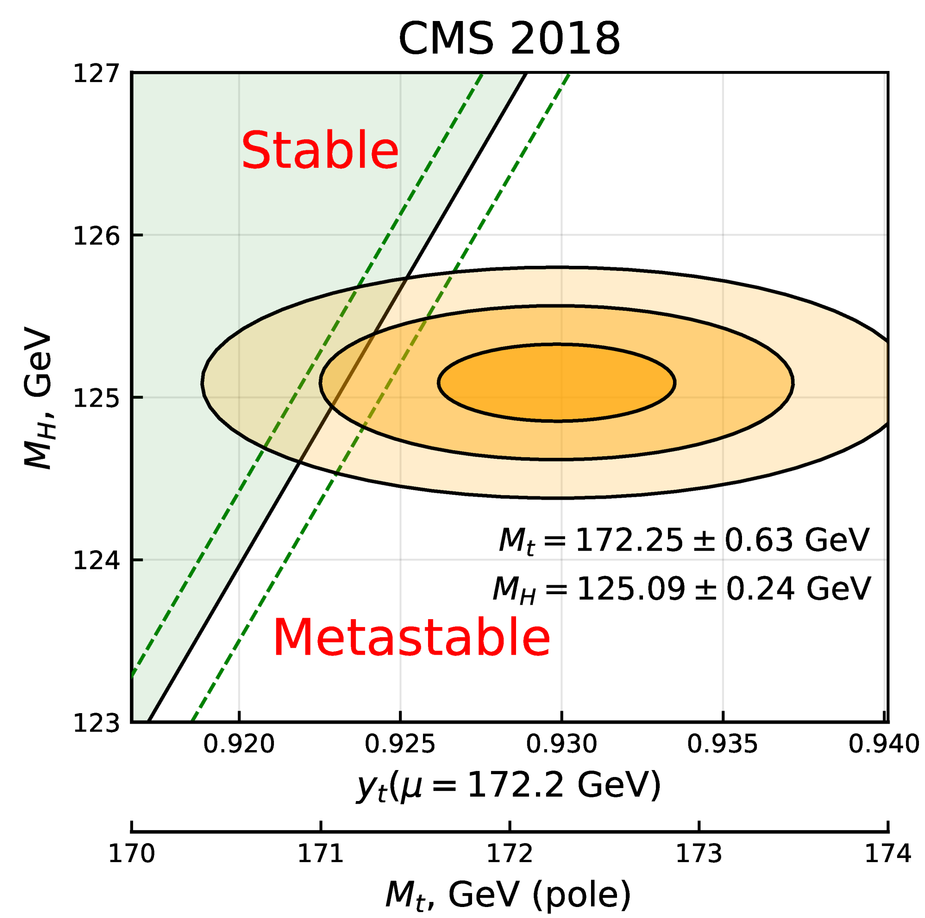
Metastability

- Marginal evidence (less than 2σ) for the SM vacuum metastability given uncertainties in relation between Monte-Carlo top mass and the top quark Yukawa coupling

2015



Time evolution of SM vacuum metastability



Radiative corrections in Higgs Inflation

The minimal setup, working for renormalisable theories: add to the Lagrangian all counter-terms necessary to make the theory finite. The theory is predictable: everything is expressed via few parameters.

The HI theory is not renormalisable - how to deal with radiative corrections? The minimal approach: add to the Lagrangian all counter-terms necessary to make the theory finite. The theory is not predictable for all energy scales, as the number of appearing structures - counter-terms is infinite. However, if the energy scale is well below the dynamical cutoff Λ(h), the reliable computations can be done and ignorance of UV completion can be parametrised by the unknown coefficients - finite part of counter-terms (Bezrukov, Magnin, MS, Sibiryakov; Burgess, Patil, Trott …). RG evolution of coupling constants from the Fermi to inflation scale is possible. Studies of RG evolution: Simone, Hertzberg, Wilczek; Barvinsky, Kamenshchik, Kiefer, Starobinsky, Steinwachs…

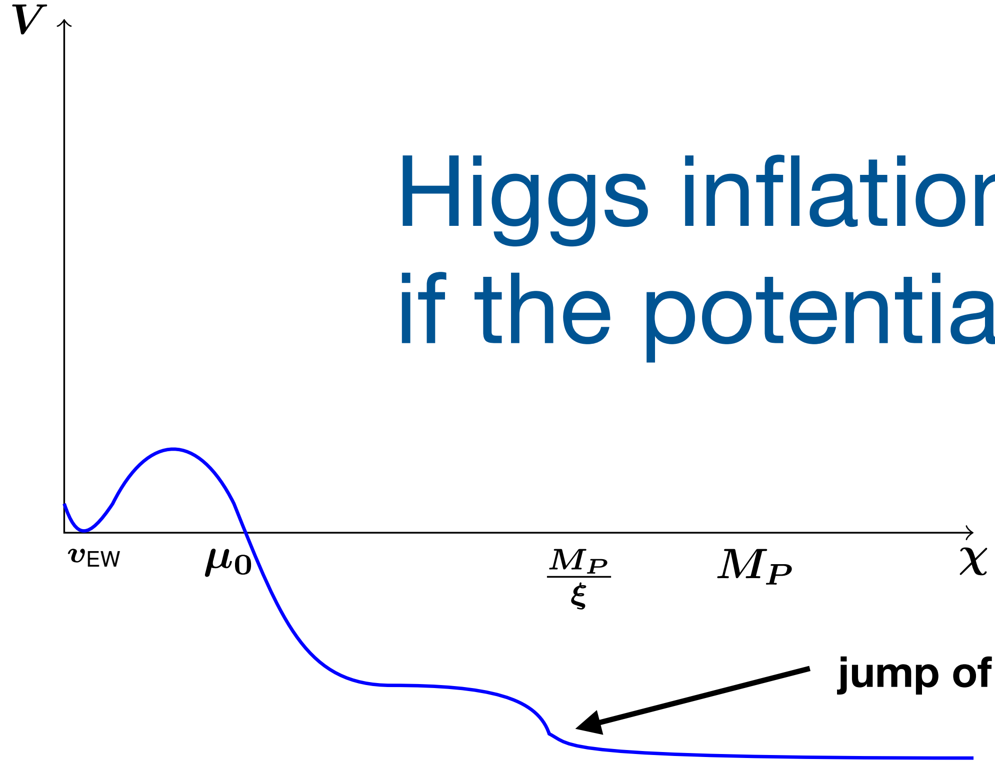
Summary of the outcome of this program:

- The inflationary Higgs potential is well defined for $h \lesssim \frac{M_P}{\xi}$ and is expressed via low energy SM parameters

- The inflationary Higgs potential is well defined for $h \gtrsim \frac{M_P}{\xi}$ and is expressed via SM low energy parameters and unknown matching coefficients for all coupling constants describing the “jumps” of couplings at the field value $h \simeq \frac{M_P}{\xi}$

- The predictions of HI for $n_s = 0.97$ and $r=0.0033$ remain the same almost for all parameters (for a detailed study of the parameter space see Enckell, Enkvist, Nurmi; Bezrukov, Pauly, Rubio) except for one very specific point corresponding to the “critical” Higgs inflation. Studies of radiative corrections: Fumagalli, Mooij, Postma,…

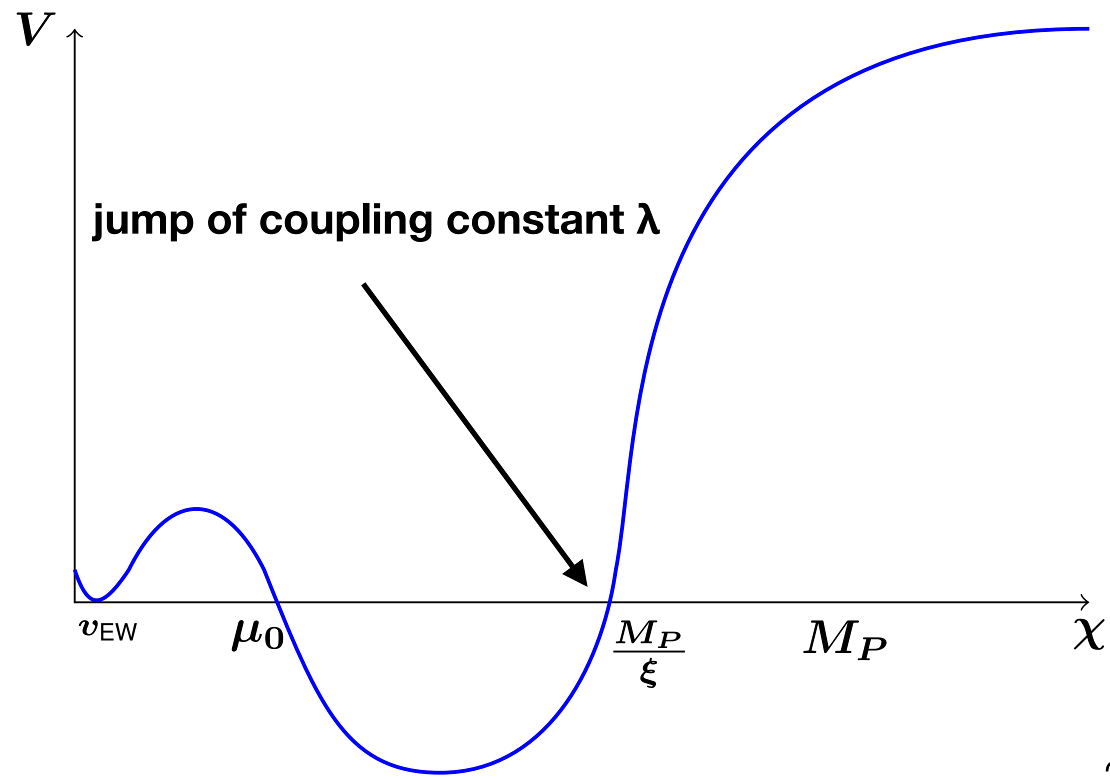
- For some choice of these matching coefficients HI can be realised even for metastable vacuum



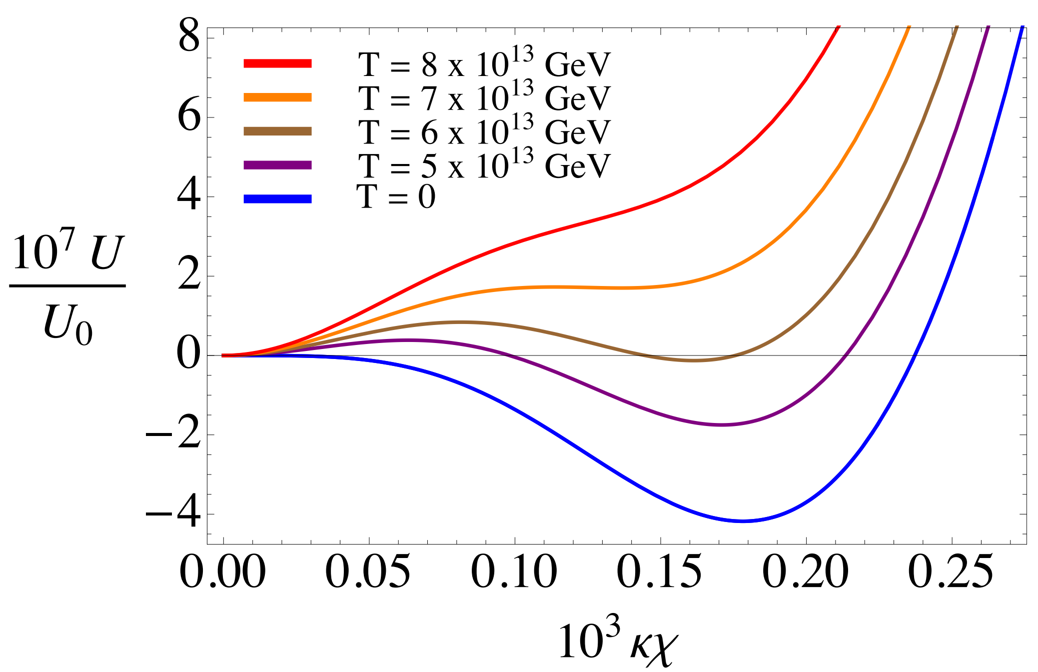
Higgs inflation does not work if the potential has this form

Bezrukov, Rubio, MS

Higgs inflation still works if the potential has this form, as reheating brings the Higgs field to the origin.

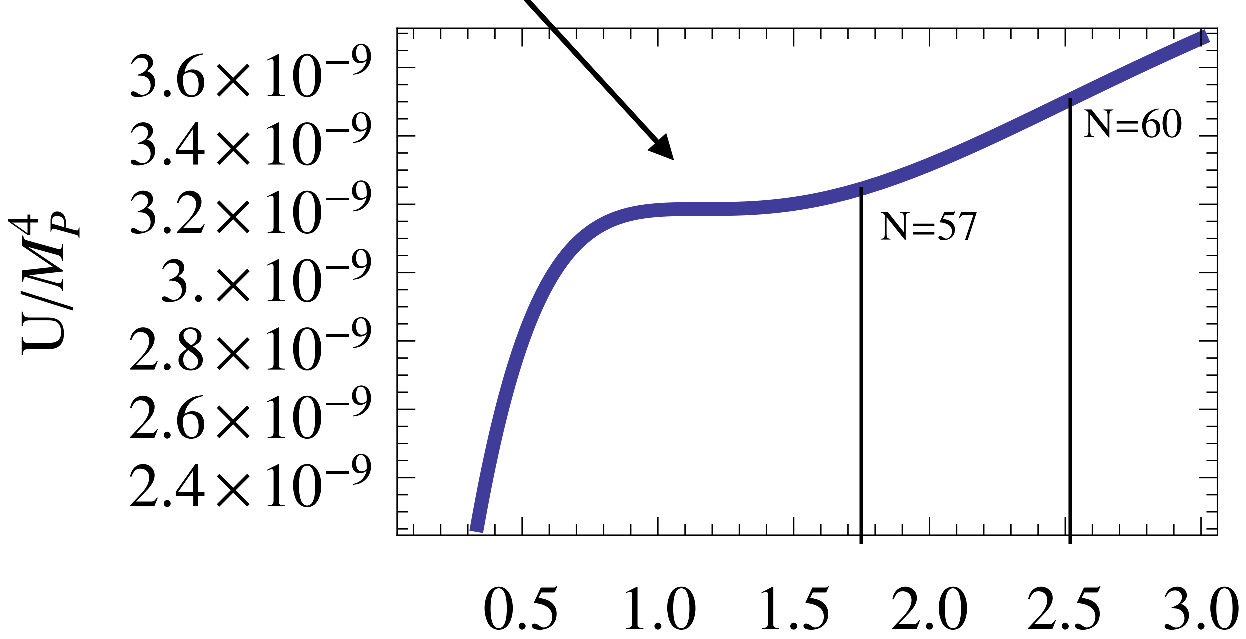


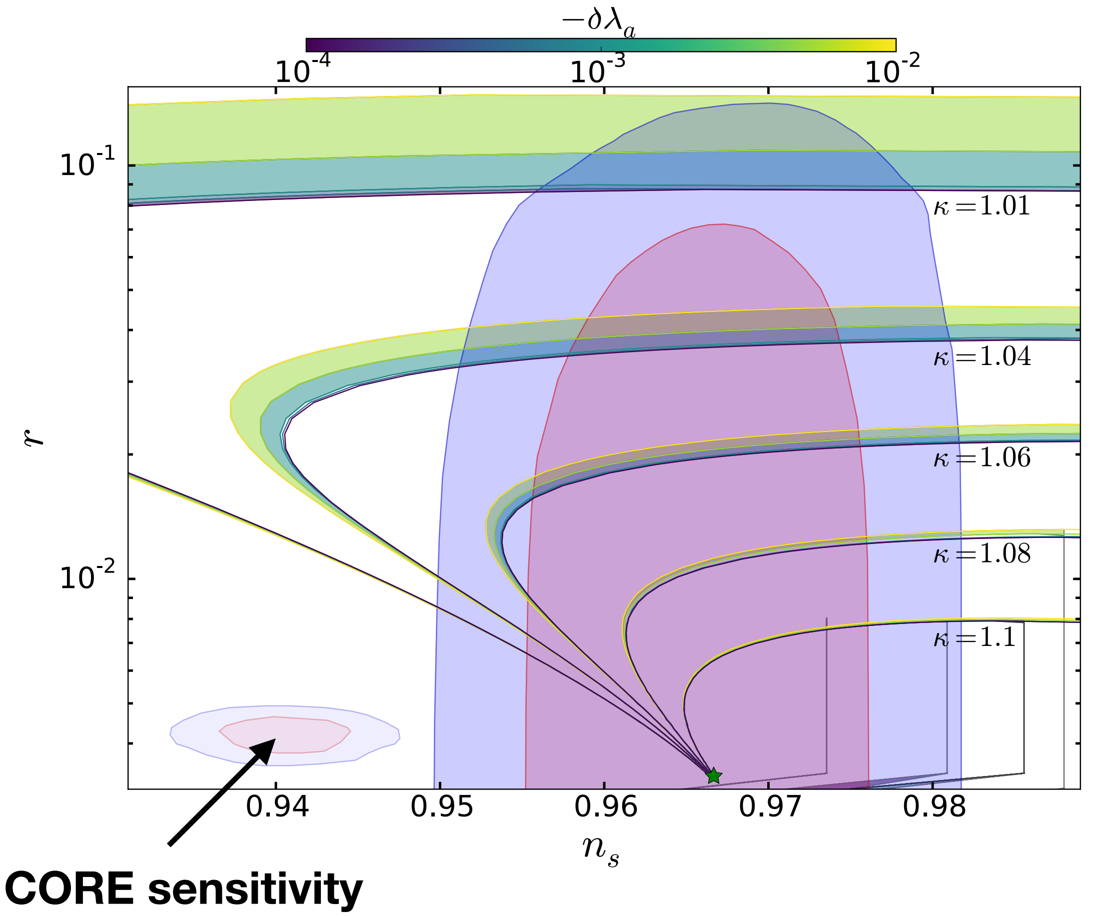
Symmetry restoration



Critical Higgs Inflation

For a very particular choice of top and Higgs masses, and of the matching coefficients the Higgs potential can develop an inflection point: $V'(h_0) = V''(h_0) = 0$





Hamada, Kawai, Oda, Park; Bezrukov, MS; Bezrukov, Pauly, Rubio, …

Primordial Black Holes? Garcia-Bellido; Rubio,…

Symmetries of UV completion?

- The successful models of inflation (Starobinsky, Higgs, α - attractors) all share the same feature: constant potential in the Einstein frame at large values of the canonically normalised scalar field:

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4}M_P^4\right)$$

- The theory has a shift symmetry, $\phi \to \phi$+const. In the Jordan frame the action is scale-invariant,

$$S = \int d^4x\sqrt{-g}\left(-\frac{\xi h^2}{2}R + \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}h^4\right)$$

- Perhaps, the Nature is scale-invariant? The scale-invariant Higgs-dilaton inflation (scale invariance is broken spontaneously) requires dynamical generation of the Planck scale and is based on the action

$$S = \int d^4x\sqrt{-g}\left(-\frac{\xi_h h^2 + \xi_\chi \chi^2}{2}R + \frac{1}{2}(\partial h)^2 + \frac{1}{2}(\partial\chi)^2 - \frac{\lambda}{4}h^4\right)$$

For cosmology of scale-invariant theory see Garcia-Bellido, Rubio, MS, Zenhausern; Trashorras, Nesseris, Garcia-Bellido; Ferreira, Hill, Ross,…

Conclusions

The Standard Model is a natural theory and is in the great shape.

natural [nach-er-*uh*l, nach-r*uh*l] SHOW IPA

SYNONYMS | EXAMPLES | WORD ORIGIN SEE MORE SY

adjective

1. existing in or formed by nature (opposed to artificial):
   a natural bridge.
2. based on the state of things in nature; constituted by nature

Perhaps, its success, together with the measurements of inflationary parameters is telling us that the Higgs boson

- is responsible for the EW symmetry breaking
- inflated the Universe
- produced density perturbations leading to structure formation, and
- is the origin of the hot Big Bang

To distinguish experimentally Higgs inflation from Starobinsky or α-attractors we should know better n_s and r!