Higgs Inflation As A Mirage

Bethe Forum
Beyond the Standard Higgs-system
1/12/16, Bonn

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OUTLINE

- Context after LHC
- Review of the Higgs-inflation idea
  - Virtues
  - Challenges
    - Vacuum instability
    - EFT cutoff / Unitarity problem
- Simple UV Completion
  - what is gained / lost

Based on Barbón, Casas, Elias-Miró, J.R.E. '15

BSM STATUS

- Higgs discovered, close to SM-like

$+$

- No trace of BSM so far $\Rightarrow$ $\Lambda >$ few TeV ?

$+$

- Holding on to naturalness

$$V = \frac{1}{2} \underbrace{m^2}_{\sim \frac{1}{(4\pi)^2}\Lambda^2} h^2 + \frac{1}{4}\lambda h^4 \Rightarrow \langle h \rangle^2 \sim \frac{m^2}{\lambda} \sim \text{EW}$$

BSM STATUS

- Higgs discovered, close to SM-like

$+$

- No trace of BSM so far $\Rightarrow$ $\Lambda >$ few TeV ?

$+$

- Holding on to naturalness

$\Downarrow$

$\Lambda \sim$ few TeV

BSM STATUS / THIS TALK

- Higgs discovered, close to SM-like

+

- No trace of BSM so far $\Rightarrow$ $\Lambda \gg$ few TeV ?

+

- Disregarding naturalness

$\Downarrow$

$\Lambda \sim M_{Pl}$?

A non-trivial possibility.

BSM STILL NEEDED

- ★ Neutrino masses
- ★ Matter-antimatter asymmetry
- ★ Dark Matter
- ★ Dark Energy
- ★ Inflation

$\Lambda \gg m_{EW}$ OK

BSM STILL NEEDED

- ★ Neutrino masses
- ★ Matter-antimatter asymmetry
- ★ Dark Matter
- ★ Dark Energy
- ★ Inflation ← Can we get it within the SM ?

HIGGS INFLATION PROPOSAL

SLOW-ROLL INFLATION

Can explain flatness, homogeneity and isotropy of our Universe through a period of exponential expansion driven by a scalar field ϕ with nearly constant $V(\phi)$

$$\ddot{\phi} + 3H\dot{\phi} = -V' \qquad H^2 = \frac{1}{3M_P^2}\left(V + \frac{1}{2}\dot{\phi}^2\right)$$

Slow-roll $$3H\dot{\phi} \simeq -V' \qquad H^2 \simeq \frac{V}{3M_P^2}$$

Holds if $$\epsilon \equiv \frac{1}{2}M_P^2\left(\frac{V'}{V}\right)^2 \qquad \eta \equiv M_P^2\frac{V''}{V} \qquad \ll 1$$

Scale factor: $a \to e^{Ht}a_0$ $\qquad H \equiv \dot{a}/a$

* e-folds of expansion $$N_e = \int_{t_i}^{t_e} H\,dt = \frac{1}{\sqrt{2}}\int\frac{d\phi/M_P}{\sqrt{\epsilon}} \sim 60$$

HIGGS INFLATION??

Can the only SM scalar play the role of inflaton?

Looks hopeless as the potential

$$V_{SM}(h) \sim \frac{1}{4}\lambda h^4$$

is too steep ($\lambda \sim 10^{-13}$ is required)

Only hope: $V_{SM}(h)$ deviates from this simple behaviour at high field values.

Minimality wants this to happen in the SM

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Higgs inflation idea:

Non-minimal coupling of h to gravity can flatten $V(h)$

HIGGS AS INFLATON

Bezrukov, Shaposhnikov '07 (Spokoiny '84)
(Salopek, Bond, Bardeen '89)

SM+Gravity: $S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 R + \mathcal{L}_{SM} \right]$

$\mathcal{L}_{SM} \supset g^{\mu\nu} (D_\mu H)^\dagger D_\nu H - V(H)$

We can also add for the Higgs a direct coupling to R:

$$\delta S = -\int d^4x \sqrt{-g}\, \xi\, |H|^2 R$$

ξ New dimensionless coupling

Note $M_P^2 \to M_P^2 + \xi v^2$

Impact on low-energy suppressed by E/M_P, v/M_P

BOUND ON ξ

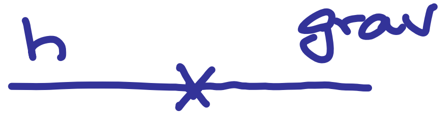
Atkins, Calmet '12

From LHC Higgs physics

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P}\gamma_{\mu\nu}$$

Graviton

$$\xi |H|^2 R \Rightarrow \xi \frac{v}{M_P} h \Box \gamma^{\mu}_{\mu}$$



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

Graviton (singlet) admixture in h

$\Rightarrow$ Reduction of all rates

$$\left(\xi \frac{m_h}{M_P}\right)^2 < O(0.1) \Rightarrow |\xi| \lesssim 10^{15}$$

Room for improvement !

Can you do better ?

HIGGS AS INFLATON

But $\xi h^2 R$ can be very important at large h

Most transparent way to see the effect :

Remove $\xi h^2 R$ using a re-scaling of the metric :

$$g^J_{\mu\nu} \to g^E_{\mu\nu} / \underbrace{\left(1 + \xi h^2/M_P^2\right)}_{e^\sigma}$$

How this works :

$$\sqrt{-g_J} \longrightarrow \sqrt{-g_E}\, e^{-2\sigma}$$

$$g_J^{\mu\nu}(\partial_\mu h)^2 \longrightarrow e^\sigma g_E^{\mu\nu}(\partial_\mu h)^2$$

$$R_J \to e^\sigma \left(R_E + 3 g_E^{\mu\nu} \sigma_{;\mu\nu} - \frac{3}{2} g_E^{\mu\nu} \sigma_{;\mu} \sigma_{;\nu}\right)$$

HIGGS AS INFLATON

$$\int d^4x \sqrt{-g_J} \left\{ -\frac{1}{2} \underbrace{(M_P^2 + \xi h^2)}_{m_P^2 e^{\sigma}} R_J + \frac{1}{2} g_J^{\mu\nu} \partial_\mu h \partial_\nu h - V_{SM}(h) \right\}$$

"Jordan frame"

$$\Big\downarrow \; g_{\mu\nu}^J \to g_{\mu\nu}^E e^{-\sigma}$$

$$\int d^4x \sqrt{-g_E}\, e^{-2\sigma} \left\{ -\frac{1}{2} M_P^2 e^{\sigma} \cdot e^{\sigma} \left[R_E + 3 g_E^{\mu\nu} \sigma_{;\mu\nu} - \frac{3}{2} g_E^{\mu\nu} \sigma_{,\mu} \sigma_{,\nu} \right] \right.$$
$$\left. + \frac{1}{2} e^{\sigma} g_E^{\mu\nu} \partial_\mu h \partial_\nu h - V_{SM}(h) \right\}$$

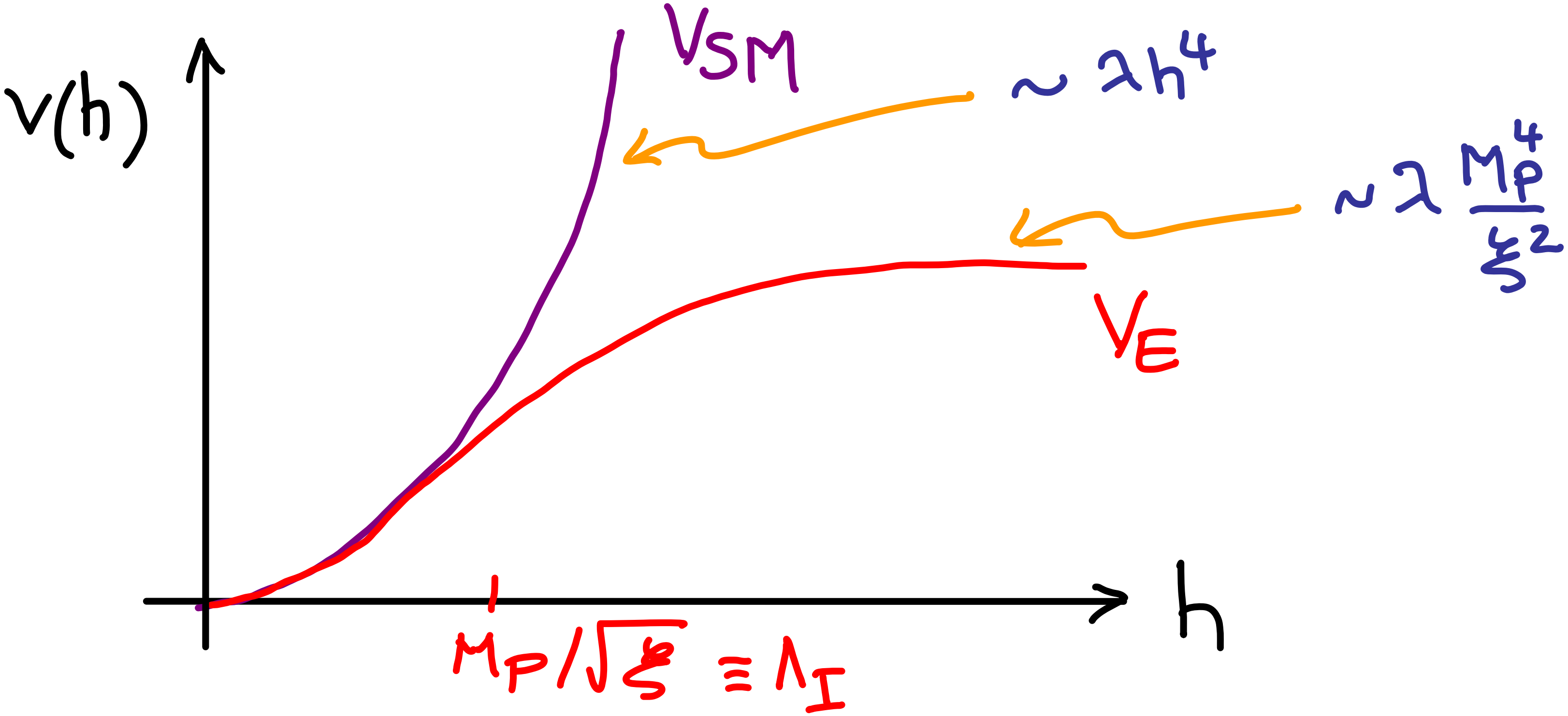
"Einstein frame"

$$= \int d^4x \sqrt{-g_E} \left\{ -\frac{1}{2} M_P^2 R_E + \frac{1}{2} K^2(h) \partial_\mu h \partial^\mu h - e^{-2\sigma} V_{SM}(h) \right\}$$

Minimally coupled h with modified action

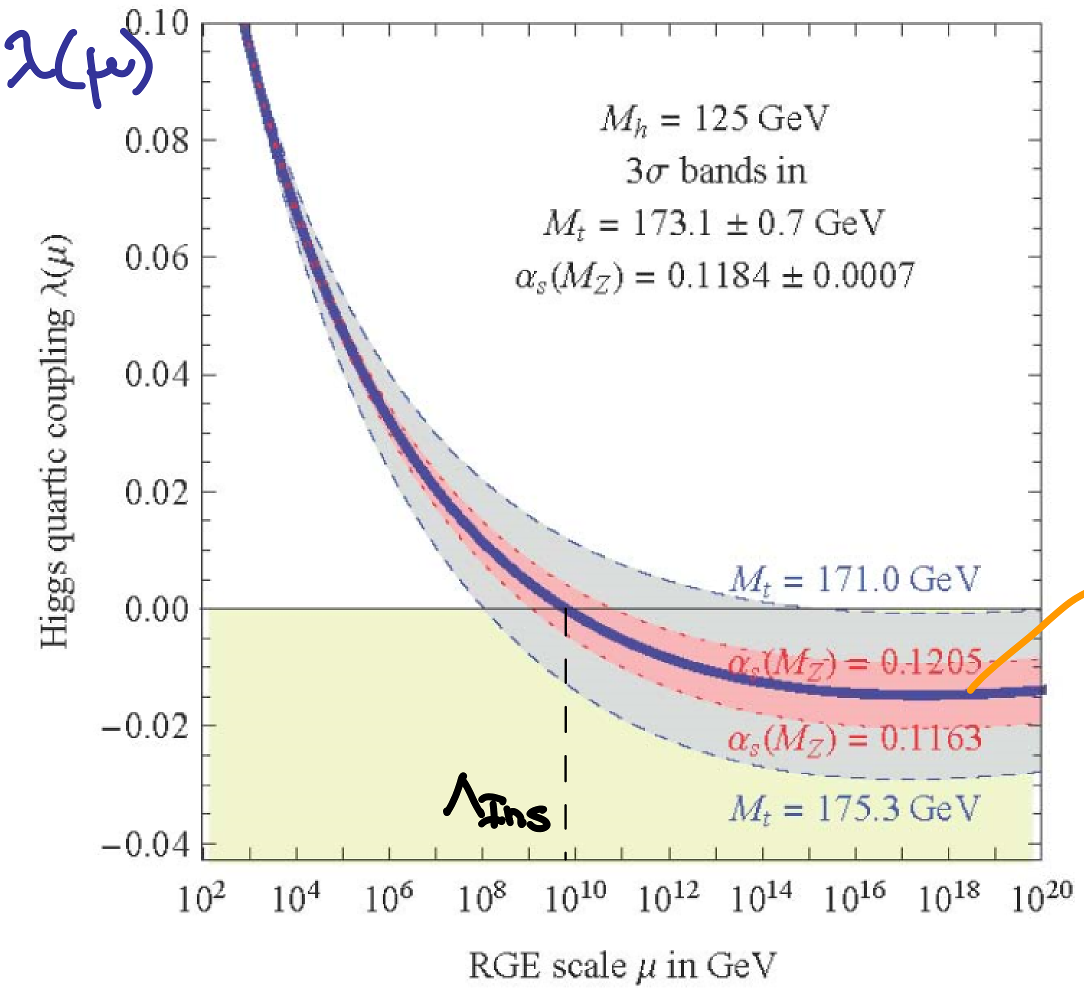
HIGGS AS INFLATON

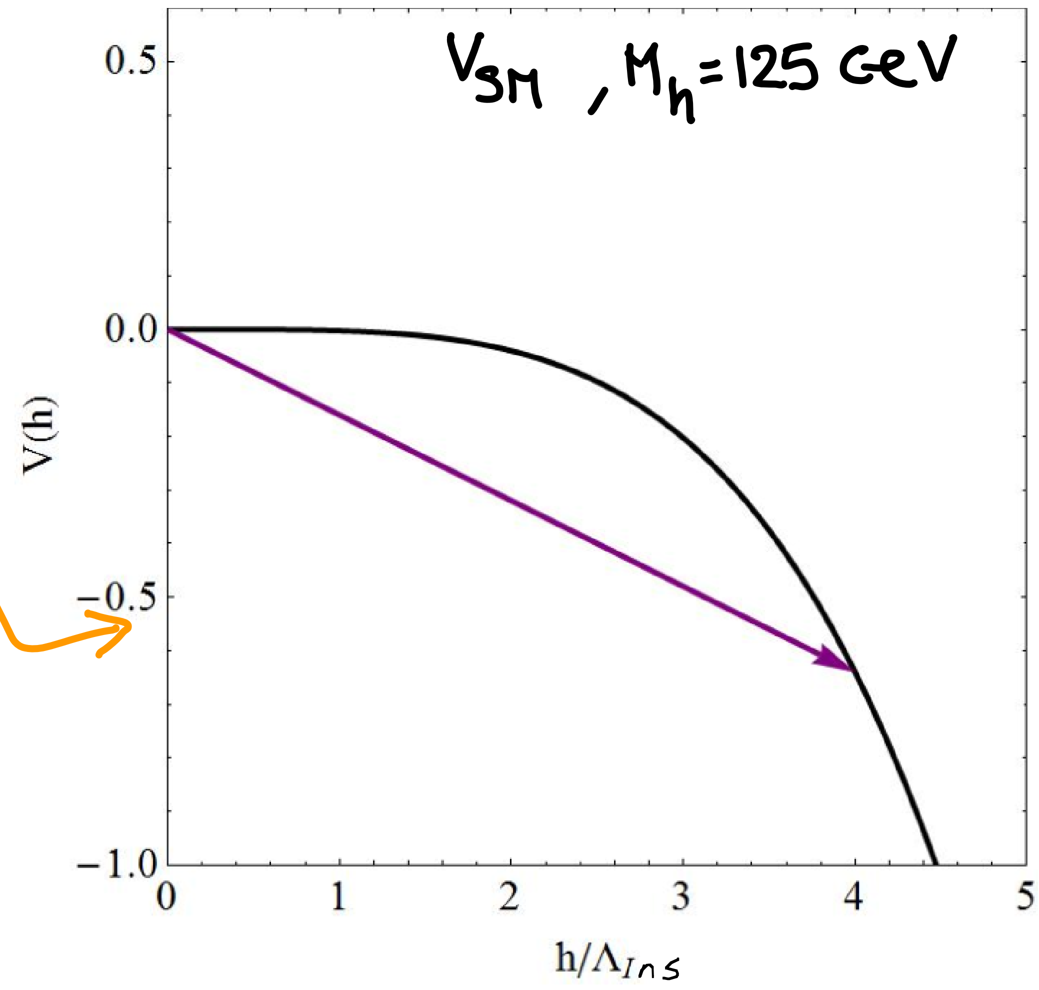
Potential : $e^{-2\sigma} V_{SM}(h) = \dfrac{V_{SM}(h)}{(1+\xi h^2/M_P^2)^2}$



A very predictive model of inflation !

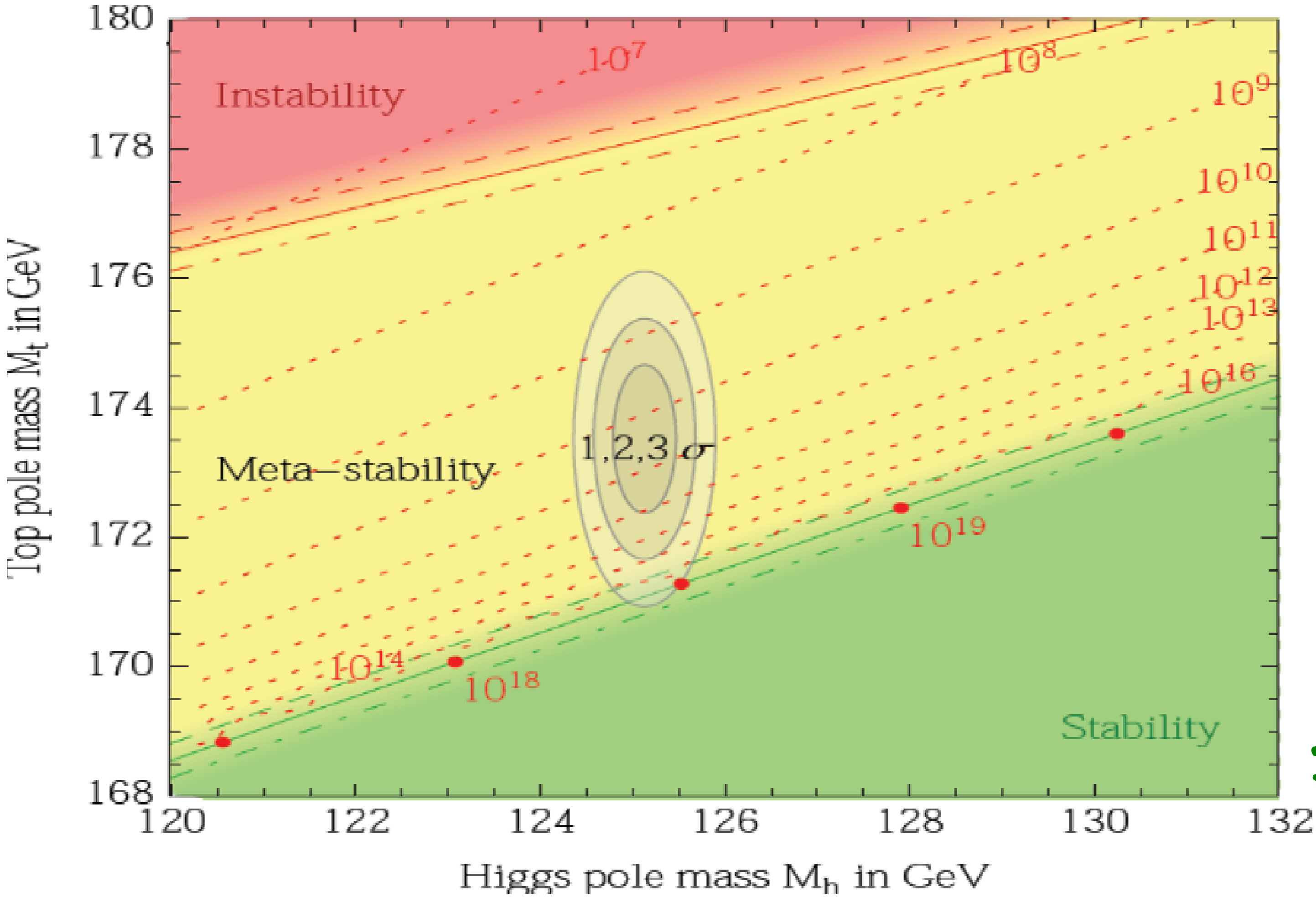
CH. 1 SM POTENTIAL INSTABILITY





Degrassi et al '12

EW VACUUM META STABILITY



Degrassi et al '12
Buttazzo et al '13

Higgs inflation requires stability

stability requires marginal values of M_h & M_t

INFLATIONARY OBSERVABLES

Primordial origin of inhomogeneities by inflationary stretching of the quantum fluctuations of the inflaton and the metric

Spectrum of scalar perturbations

$$P_s(k) \sim \left(\frac{\delta\rho}{\rho}\right)^2 \propto c\left(\frac{V}{\epsilon}\right)\cdot\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$n_s = 1-6\epsilon+2\eta \qquad (n_s \simeq 1)$$

Spectrum of tensor perturbations

$$P_t(k) \propto cV\left(\frac{k}{k_*}\right)^{n_T} \qquad (n_T \simeq 0)$$

INFLATION

Spectrum of scalar perturbations

$$P_s(k) \sim \left(\frac{\delta\rho}{\rho}\right)^2 \propto C\left(\frac{V}{\epsilon}\right)\cdot\left(\frac{k}{k_*}\right)^{n_s-1}$$

Amplitude

$\sim 10^{-5}$ $\Rightarrow \frac{V}{\epsilon} \approx (0.0276\, M_P)^4$

Spectral index

$$n_s = 1 - 6\epsilon + 2\eta \approx 0.968$$

Spectrum of tensor perturbations

$$P_t(k) \propto C V \left(\frac{k}{k_*}\right)^{n_T}$$

Amplitude

$V < (2 \times 10^{16}\, \mathrm{GeV})^4$ or

t-to-s ratio:

$$r = \frac{P_t(k_*)}{P_s(k_*)} = 16\epsilon < 0.10$$

HIGGS INFLATION PREDICTIONS

The slow-roll conditions are easy to satisfy

near $h \gtrsim \frac{M_P}{\sqrt{\xi}} \equiv \Lambda_I \Rightarrow V(\chi) \simeq \frac{\lambda M_P^4}{4\xi^2}\left(1 - e^{-\frac{2\chi}{\sqrt{6}M_P}}\right)^2$

$\Rightarrow \epsilon \simeq \frac{4M_P^4}{3\xi^2 h^4}$

$\simeq 2 \times 10^{-4}$ at h_*

Inflation $\begin{cases} \text{ends at} & h_{end} \simeq \frac{M_P}{\sqrt{\xi}} \\ \text{55 efolds} & h_* \simeq 9\frac{M_P}{\sqrt{\xi}} \end{cases}$

$\frac{\delta\rho}{\rho} \Rightarrow \frac{V}{\epsilon} \sim \frac{\lambda}{\xi^2}$ fixed

$\boxed{\xi \sim 10^4\sqrt{\lambda}}$

$\xi \gg 1$

$n_s = 1 - 6\epsilon + 2\eta$

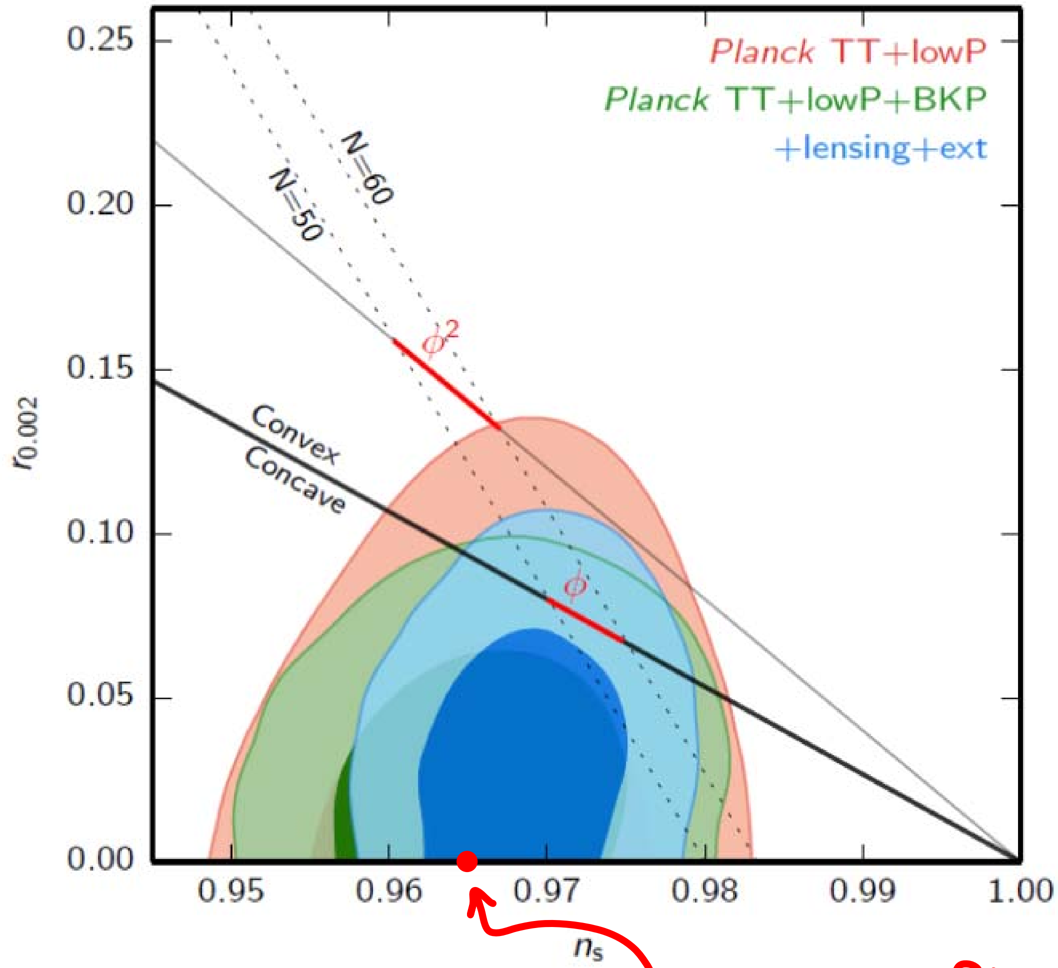
$\boxed{n_s \sim 0.965}$

$r = 16\epsilon$ quite small

$\boxed{r \sim 0.003}$

PREDICTiONS

Planck '15



r

n_s

Higgs inflation

GREAT SUCCESS!!

A HIDDEN ASSUMPTION

The plateau is caused by a functional tuning

$$\delta\mathcal{L} \sim \xi f(h) R - V_{SM}(h) \longrightarrow \quad V_E(h) = \frac{V_{SM}(h)}{\left(1+\xi f(h)\right)^2}$$

works only if $f(h) \sim h^2$ ⇨ $V_E(h) \xrightarrow[h\to\infty]{}$ constant

This restriction is equivalent to assuming a

SHIFT SYMMETRY

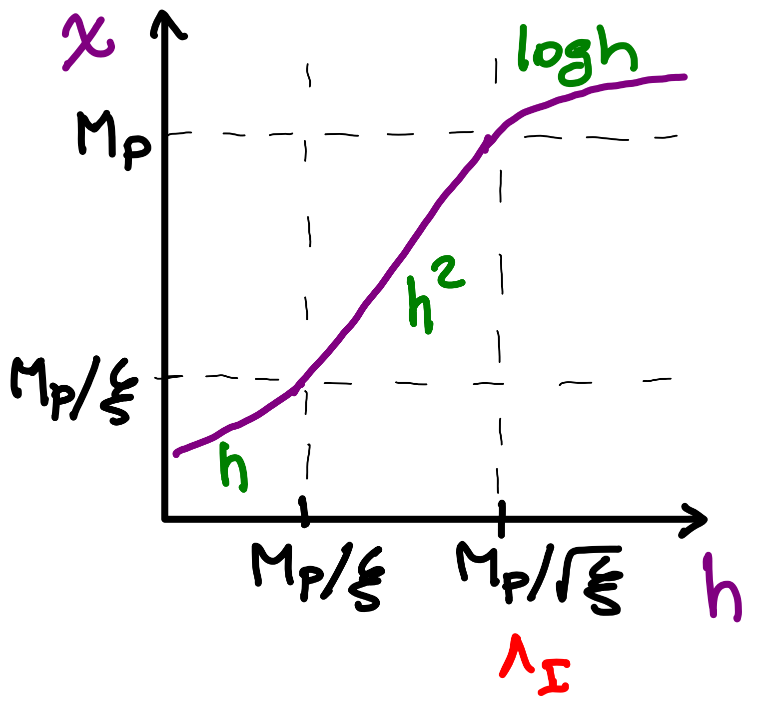
for h in the UV theory (at large field values).

⇨ The plateau is not an automatic result

HIGGS AS INFLATON

Kinetic term:

$$\frac{1}{2}\underbrace{\frac{\left[1+(\xi+6\xi^2)h^2/m_p^2\right]}{\left[1+\xi h^2/m_p^2\right]^2}}_{K^2(h)}(\partial h)^2 \longrightarrow \frac{1}{2}(\partial\chi)^2$$



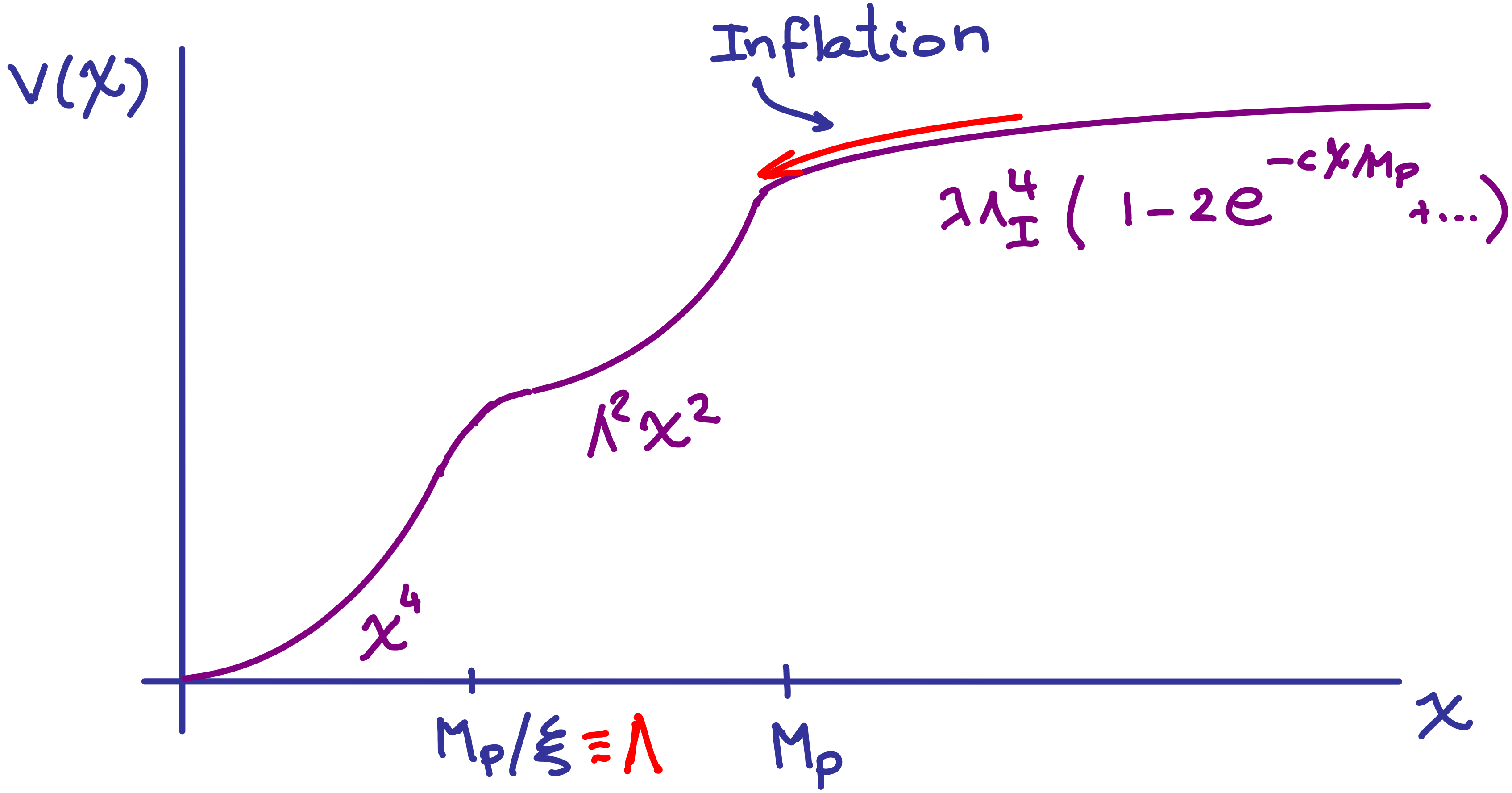
by the field redefinition $\chi(h)$

with $\frac{d\chi}{dh} = K(h)$

- New scale M_P/ξ
- $h = M_P/\sqrt{\xi} \Rightarrow \chi = M_P$
- χ couplings $\neq$ h couplings ($\to 0$ at high χ)

SCALES

As a function of the canonical field χ



Non-trivial RG improvement. Postma et al '13 '14 '15 '16

In the plateau, χ decouples asymptotically. $\rightarrow$ Higgsless SM!

CH. 2

EFT CUTOFF ($\xi \gg 1$)

Burgess, Lee, Trott '09. Barbón, JRE '09

We are dealing with a non renormalizable effective theory with a UV cutoff:

Jordan frame: $g_{\mu\nu} = \eta_{\mu\nu} + \frac{1}{M_P}\gamma_{\mu\nu}$ ← Graviton

$$\xi h^2 R = \frac{\xi}{M_P} h^2 \eta^{\mu\nu}\partial^2\gamma_{\mu\nu} + \ldots \Rightarrow \Lambda \sim \frac{M_P}{\xi}$$

Einstein frame:

$$\frac{1}{2}K^2(h)(\partial h)^2 \supset -3\frac{\xi^2}{M_P^2}h^2(\partial h)^2 \Rightarrow \Lambda \sim \frac{M_P}{\xi}$$

$$\boxed{\Lambda \sim \frac{M_P}{\xi} \ll \Lambda_I \sim \frac{M_P}{\sqrt{\xi}}}$$

Can't trust the plateau region

FIELD-DEPENDENT CUTOFF ?

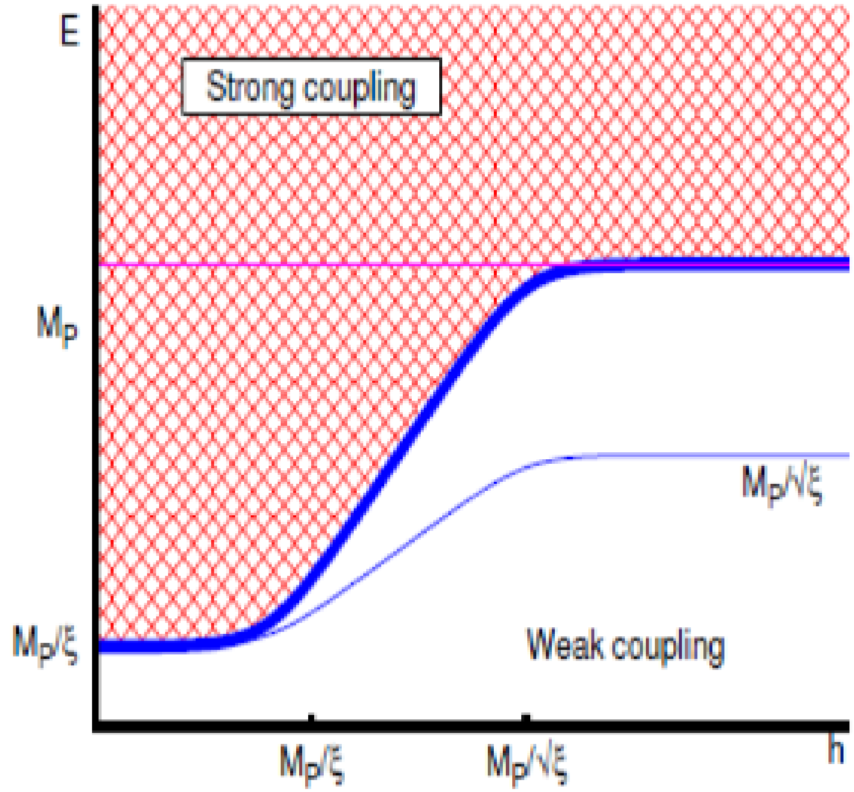
Bezrukov, Magnin, Shaposhnikov, Sibiryakov '10

Previous analysis done at EW vacuum $h \ll M_P/\xi$

Isn't the cutoff different at large h ?

$$\Lambda = \frac{M_P + (\xi + 6\xi^2) h^2/M_P}{\xi\left(1 + \xi h^2/M_P^2\right)}$$

growing to safe values



Bezrukov

FIELD-DEPENDENT CUTOFF ?

Really ?? cutoff ≡ threshold of ignorance.

$\Lambda = \frac{M_P}{\xi}$ ⇨ New physics enters at Λ, either new degrees of freedom or strong coupling

How could raising the h background change that ?

Maybe that new physics is sensitive to h ...

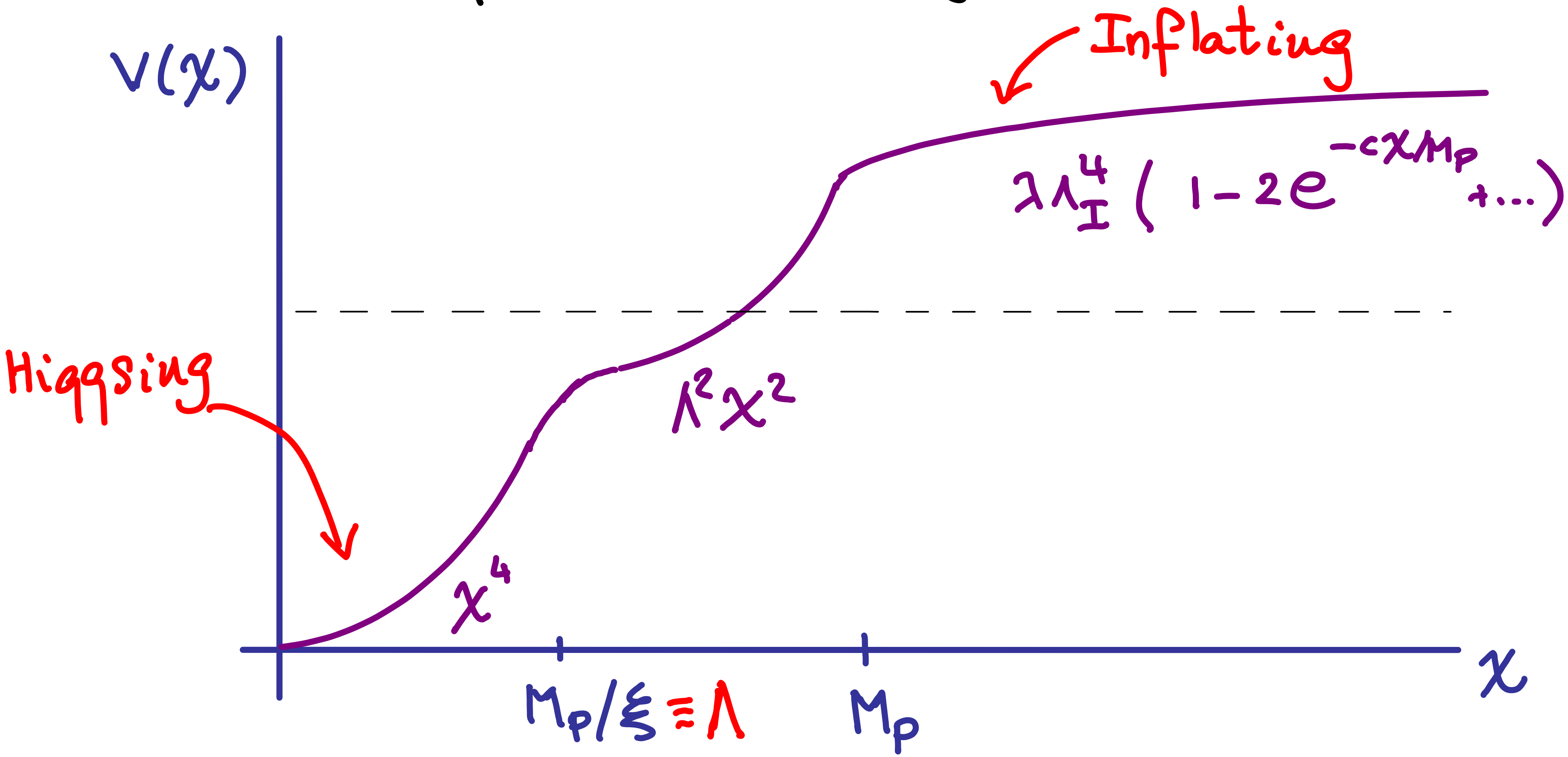
e.g. $M_i^2 \sim \Lambda^2 + \kappa_i h^2$

That is precisely the danger:

Such new physics will have an impact on $V(h)$ above Λ !

UNITARITY LOST

Root of the problem: the Higgs serves double duty:



Higgsing requires unitarizing $W_L W_L$ scattering and works if Higgs has SM couplings. True only below $(4\pi)\Lambda$

UNITARIZING HIGGS INFLATION

Barbón, Casas, Elías-Miró, JRE '15

Model that UV completes H.I. above Λ with the following ingredients/achievements :

1) New massive d.o.f. at/below Λ, decoupling which

⇨ Low-energy EFT ≃ Higgs inflation

2) Unitarizes Goldstone scatterings above Λ

3) No large ξ as input

4) As simple as possible

5) Can help with the stability challenge for H.I.

Alternative to the Giudice-Lee model

UNITARIZING HIGGS INFLATION

Barbón, Casas, Elias-Miró, JRE '15

Massive field ϕ, a singlet

$$\mathcal{L}_J = -\frac{1}{2} M_P^2 R + \mathcal{L}_{SM} - g M_P \phi R + \frac{1}{2}(\partial_\mu \phi)^2 - U(\phi, H)$$

$$U(\phi,H) \downarrow \quad \frac{1}{2} m^2 \phi^2 - \mu \phi |H|^2$$

All irrelevant ops. controlled by M_P ✓ $\quad (g \sim O(1))$

No strong coupling thresholds below M_P

⇨ Unitarity under control up to M_P

Mass parameters m^2, μ :

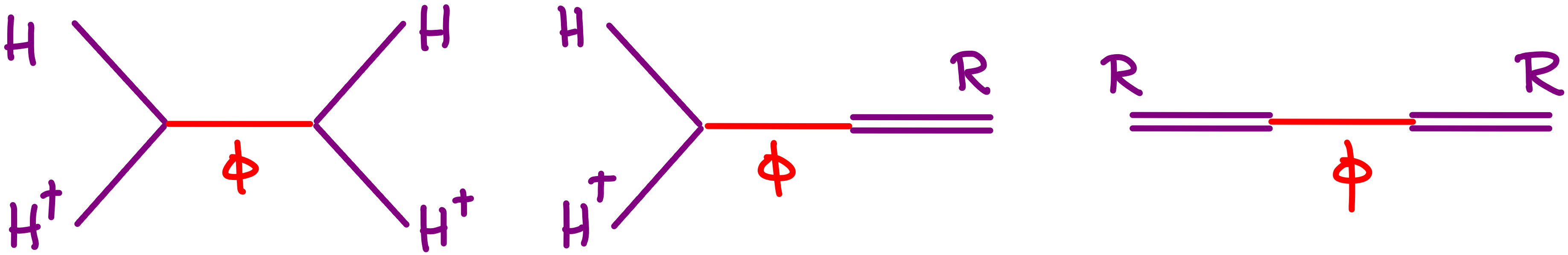
$$m_{EW} \ll \mu \lesssim m \ll M_P$$

USES OF THE MODEL / PLAN

- Decouple heavy ϕ $\Rightarrow$ EFT Higgs inflation
- Compare inflationary predictions of EFT potential with complete model
- Address challenges of original Higgs inflation
- What do we gain / loose

EFT BELOW m

Integrating out ϕ produces the operators :



$$\delta\lambda = -\frac{\mu^2}{2m^2} \qquad \xi |H|^2 R \qquad \gamma R^2$$

$$\Downarrow \qquad\qquad \Downarrow \qquad\qquad \Downarrow$$

$$\lambda = \lambda_{UV} + \delta\lambda \qquad \xi = \frac{\mu g M_P}{m^2} \qquad \gamma = \frac{g^2 M_P^2}{m^2}$$

ξ calculable in terms of UV parameters ✓

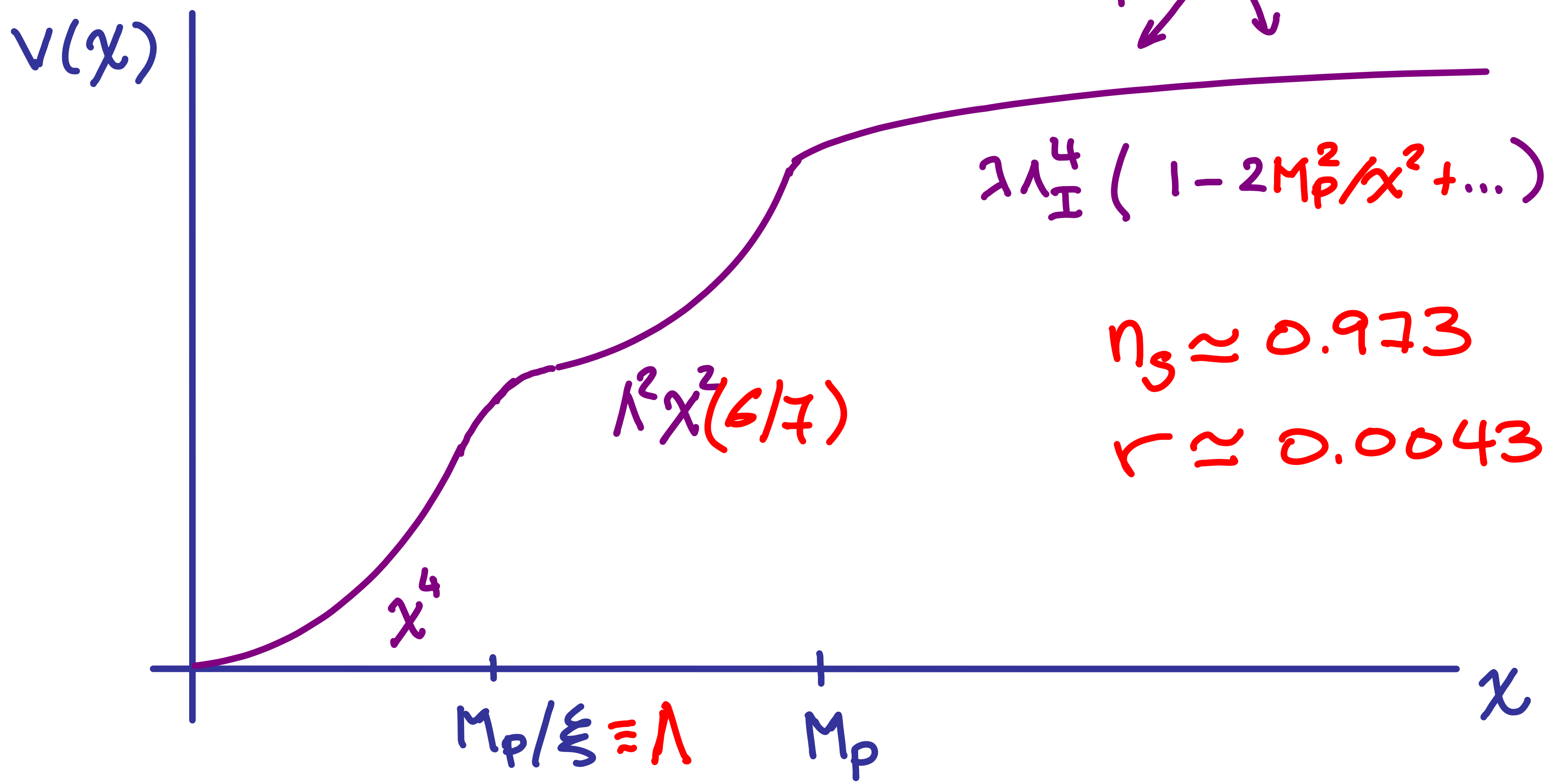
$\xi \gg 1$ easy to achieve ✓

$\Lambda \equiv \frac{M_P}{\xi} = \frac{m^2}{\mu g} \gtrsim m$ $\quad\phi$ indeed appears below Λ

EFT BELOW m

$$\mathcal{L}_{eff} = -\frac{1}{2}\left(M_p^2 + \xi h^2\right)R + \frac{1}{2}\left(1 + \xi^2\frac{h^2}{M_p^2}\right)(\partial_\mu h)^2 - \frac{\lambda}{4}h^4 + \dots$$

departure from H.I.



(R^2 subleading impact during inflation for small λ)

EFT vs. TRUE DYNAMICS

The previous EFT analysis is done extrapolating for $h > \Lambda$: a dangerous procedure in general.

Now we can compare with the UV theory

Two-field model : h, ϕ

$$\mathcal{L}_E = \frac{1}{2} \sum_{i,j=h,\phi} G_{ij}\, \partial_\mu \Phi_i \partial^\mu \Phi_j - V_E(h,\phi)$$

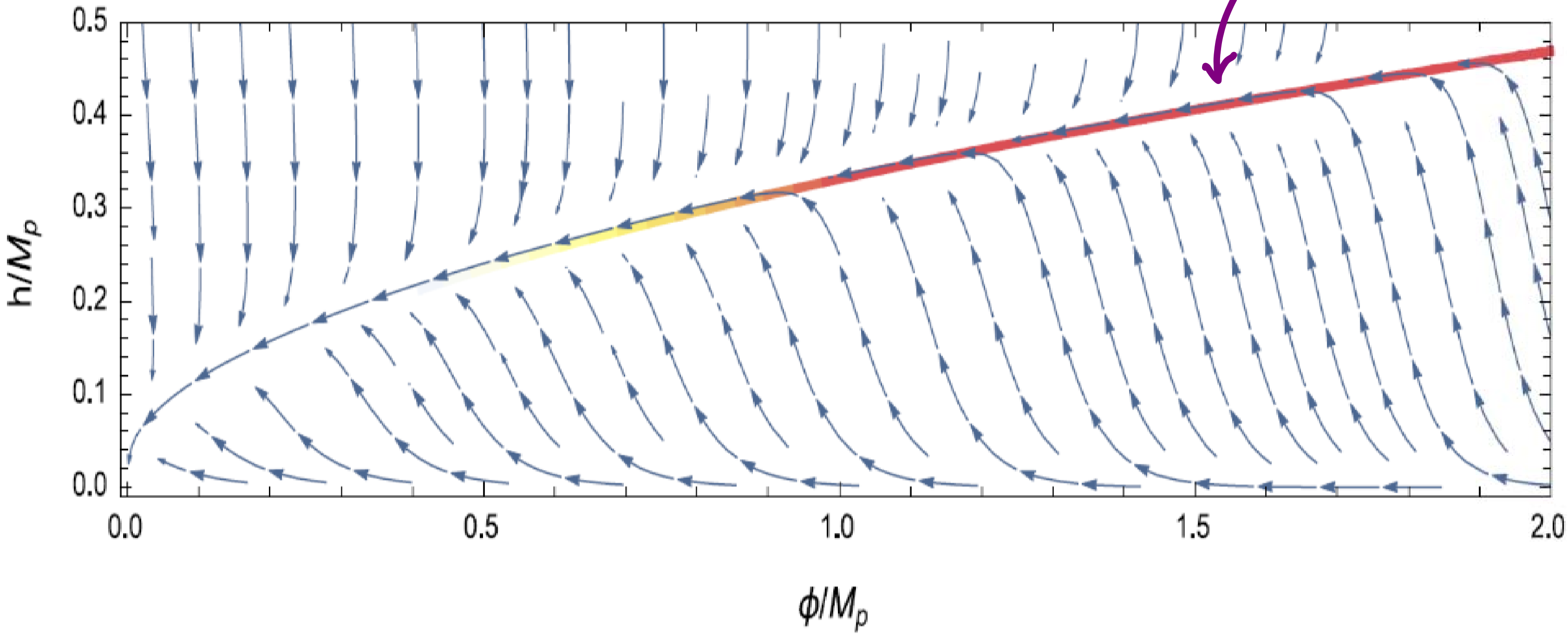
where now

$$g_{\mu\nu}\big|_J \longrightarrow \frac{1}{1+2\phi/M_P}\, g_{\mu\nu}\big|_E \qquad V_E = \frac{V_J(h,\phi)}{(1+2\phi/M_P)^2}$$

HIGH ENERGY THEORY

Potential in Einstein frame:

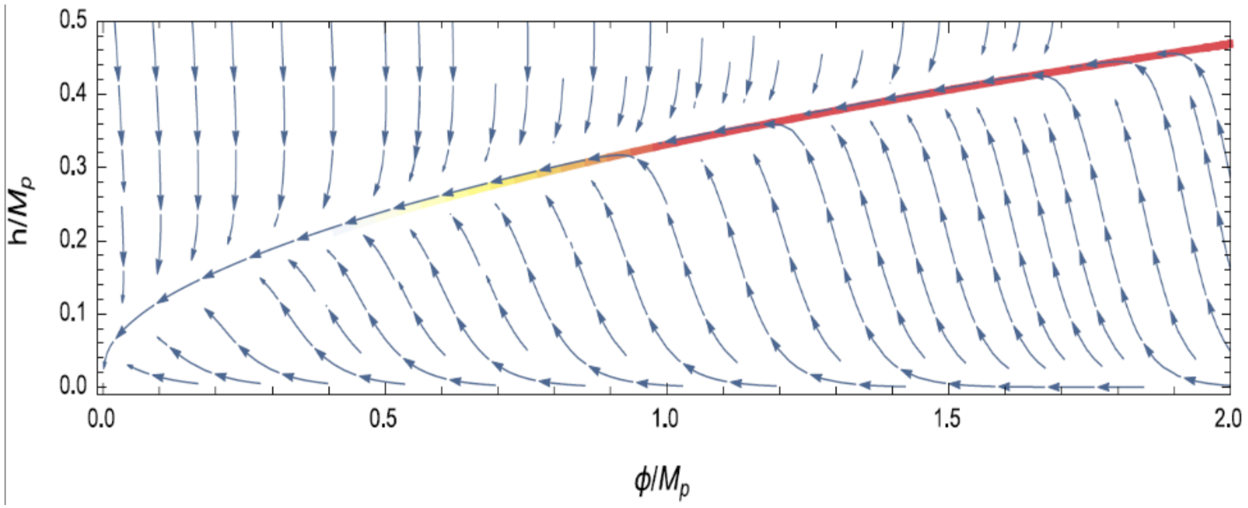
Flat Valley



Flatness results from $\phi R \leftrightarrow m^2\phi^2$ interplay.

UV shift symmetry still assumed but for ϕ ✓

HIGH ENERGY THEORY



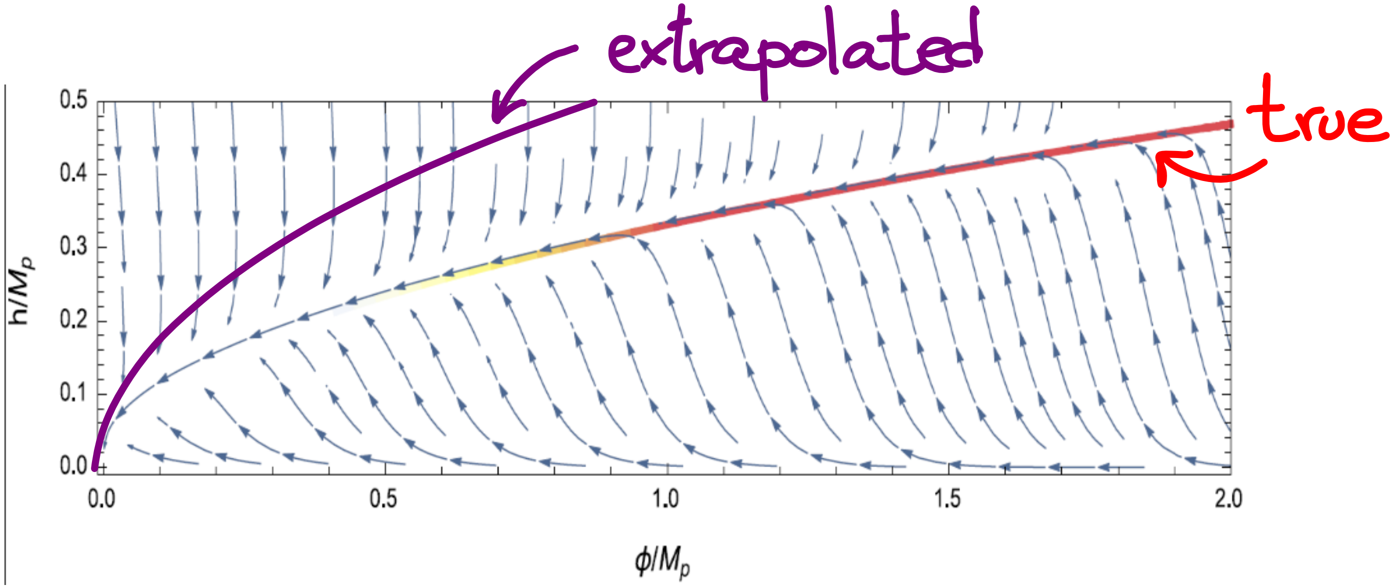
- Inflationary valley is narrow $m_\perp^2 \sim M_p \mu \gg H_I^2 \sim \frac{M_p^2}{\xi^2}$
  - ⇨ single field inflation
- Can parametrize in terms of h or ϕ but clearly the inflaton field is mostly ϕ, not h.

This seems inescapable if h still takes care of unitarizing Goldstone scattering (It was the same for Giudice-Lee)

HIGH ENERGY THEORY

★ Deep inside the valley the heavy field is mostly h while the EFT is constructed by decoupling ϕ...

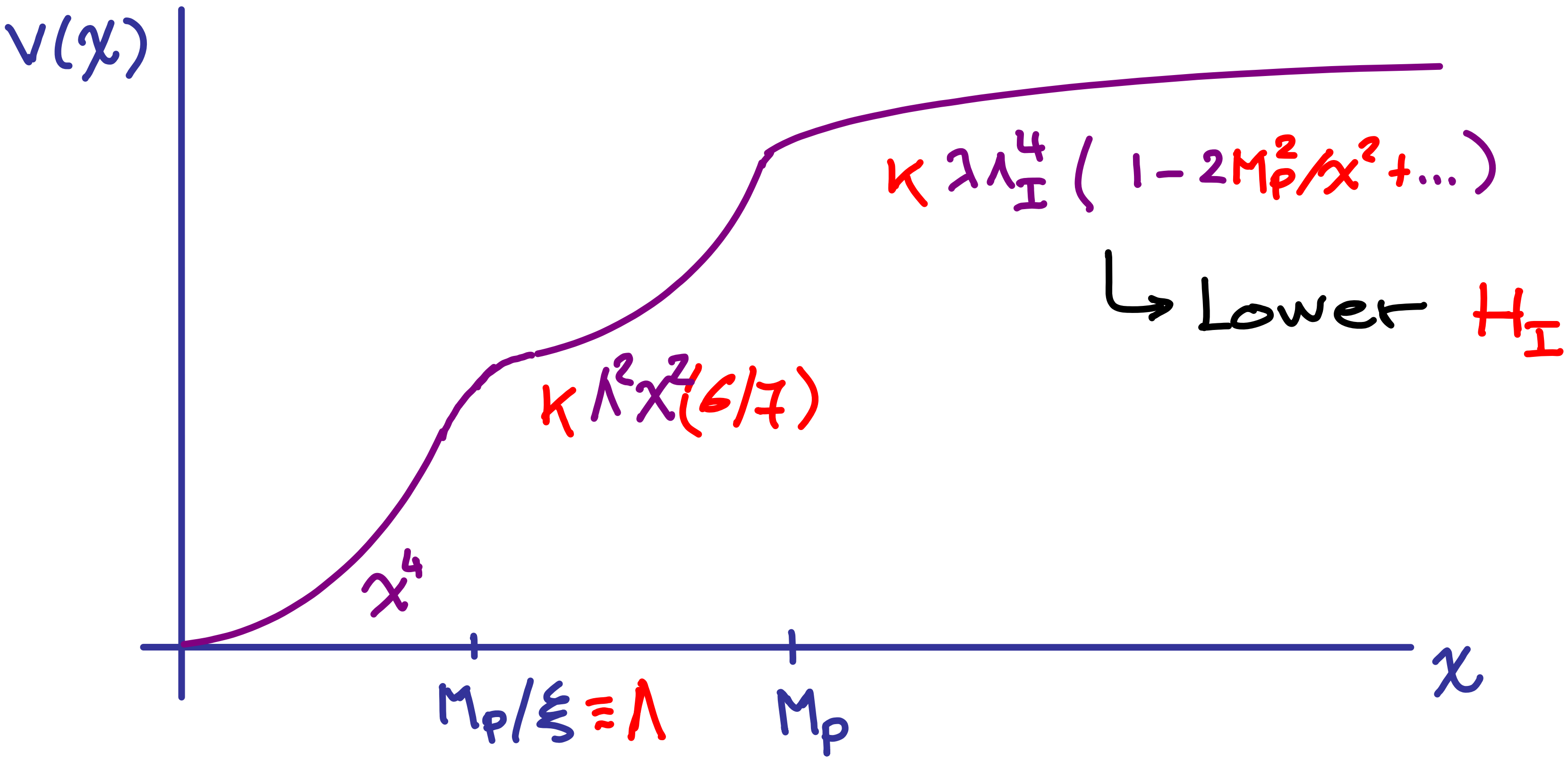
⇨ Deviation between the true inflationary trajectory and the extrapolated one (from $\partial V/\partial\phi = 0$)



The extrapolated path probes higher potential values.

HIGH ENERGY THEORY

Missmatch factor wrt EFT: $\kappa \equiv 1 - \lambda/\lambda_{UV}$



Artifact of truncating EFT at two-derivatives.

But same slow-roll parameters: $n_s \simeq 0.973$

$r \simeq 0.0043$

EFT vs HIGH ENERGY THEORY

EFT		HIGH ENERGY THEORY
Higgs inflation		ϕ-inflation
H_I	$>$	H_I
n_s, r	$=$	n_s, r

Requires knowledge of additional NR operator

ϕ-Loop corrections to V

Can't be included	Can be Included

STABILITY PROBLEM

Singlet field ϕ modifies the running of λ

$$\frac{d\lambda}{d\log Q} = \beta_\lambda^{SM} + \underbrace{\frac{1}{2\pi^2}(\lambda_{UV}-\lambda)(\lambda_{UV}+2\lambda)}_{>0}$$

This can stabilize the potential, provided

$$m < \Lambda_{inst} \sim 10^{11}\,\mathrm{GeV}$$

which requires $\mu < \xi \dfrac{\Lambda_{inst}^2}{g M_P}$

$\cancel{\mathcal{O}(1)}$

CONCLUSIONS

★ Can the SM scalar be responsible for cosmological inflation?

NO!

Inflation ⇨ BSM

★ The unitarity problem of Higgs inflation requires new dofs. at or below the scale $M_P/\xi \ll M_P$

CONCLUSIONS

- ★ Very simple model curing this problem

$$\delta\mathcal{L} \supset M_p \phi R - \mu \phi |H|^2 - \frac{1}{2} m^2 \phi^2$$

  - Shows how to get $\xi \gg 1$
  - Can help with the instability problem
  - Agrees with measured n_s and r
  - Still requires a shift symmetry in the UV

- ★ Such dof takes care of inflating so that h can unitarize $W_L W_L$

Higgs not really the inflaton

CONCLUSIONS

★ Predictions deviate from original Higgs inflation and from the naive EFT extrapolation

⇨ UV sensitivity

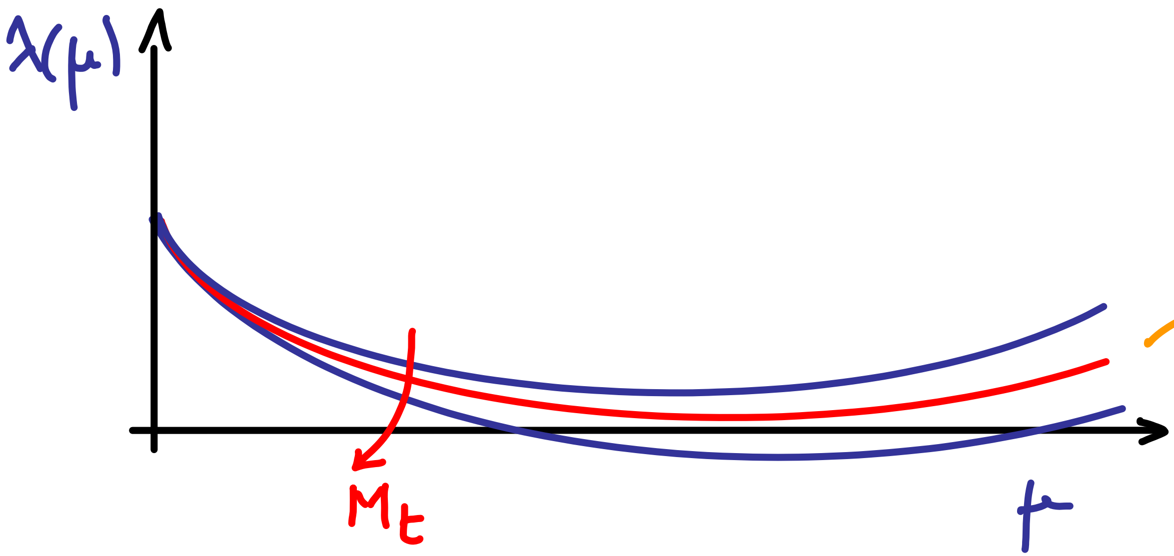
"Higgs inflation" just a mirage single-field projection from a more complicated landscape-like potential.

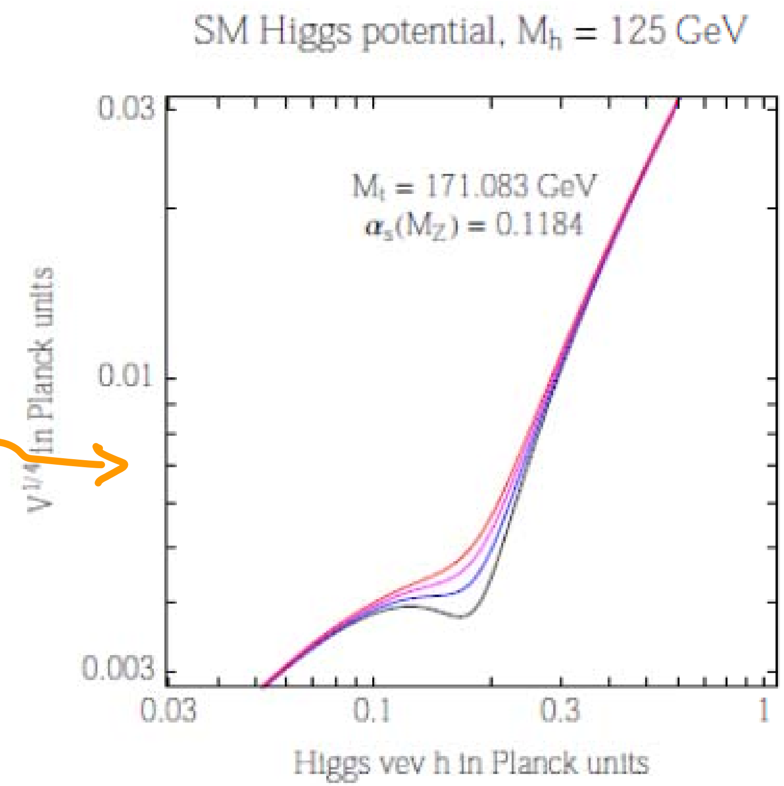
Finding out that potential will be tough!

HIGGS AS INFLATON (KINK)

Use kink in Higgs potential

Isidori et al. '07





Requires exquisite tuning ($1/10^6$) in M_t

HIGGS AS INFLATON (KINK)

First try : Slow-roll in the small plateau

$$\epsilon = \frac{1}{2} M_P^2 \left(\frac{V'}{V}\right)^2 \qquad \eta = M_P^2 \left(\frac{V''}{V}\right) \qquad \ll 1$$

Very predictive scenario

Given V, $\delta\rho/\rho \sim 10^{-5}$ $\Rightarrow$ $\frac{V}{\epsilon} \approx (0.0276\, M_P)^4 \Rightarrow \epsilon \gtrsim 10^{-3}$

$N_e = \frac{1}{\sqrt{2}} \int \frac{dh/M_P}{\sqrt{\epsilon}} \approx 60$ requires sizeable $\Delta h \gtrsim M_P$

while the small plateau is much shorter

use $\xi \sim O(10)$ for further flatenning

Bezrukov, Shaposhnikov'14
Hamada et al'14

Still : plateau at $h \lesssim M_{Pl}$: UV sensitive

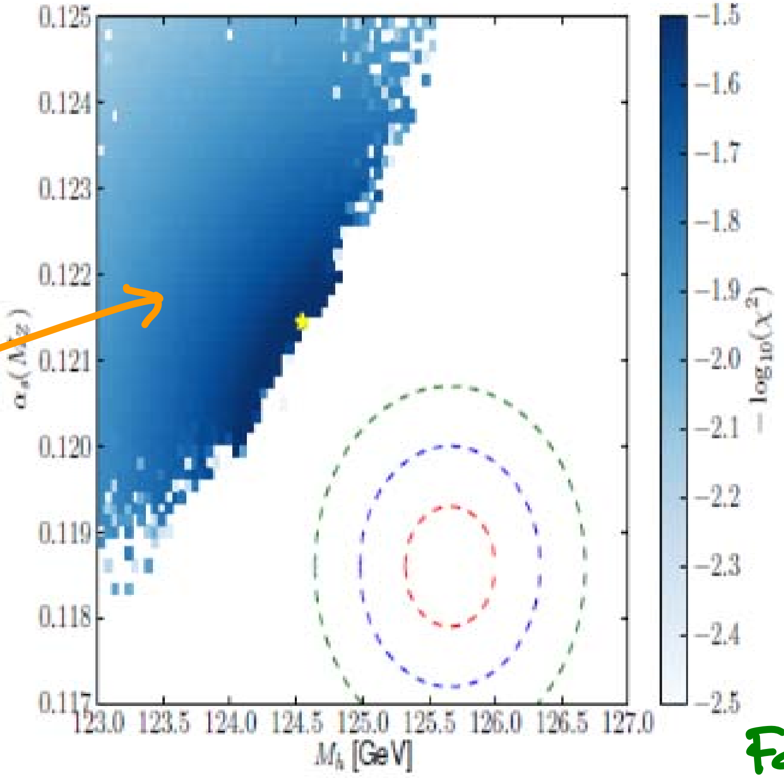
HIGGS AS INFLATON (KINK)

2nd try : False vacuum inflation ? Masina, Notari '12 ...

Similar to old inflation ⇒ Graceful exit problem

Need to add extra fields to the SM to solve this and even then :

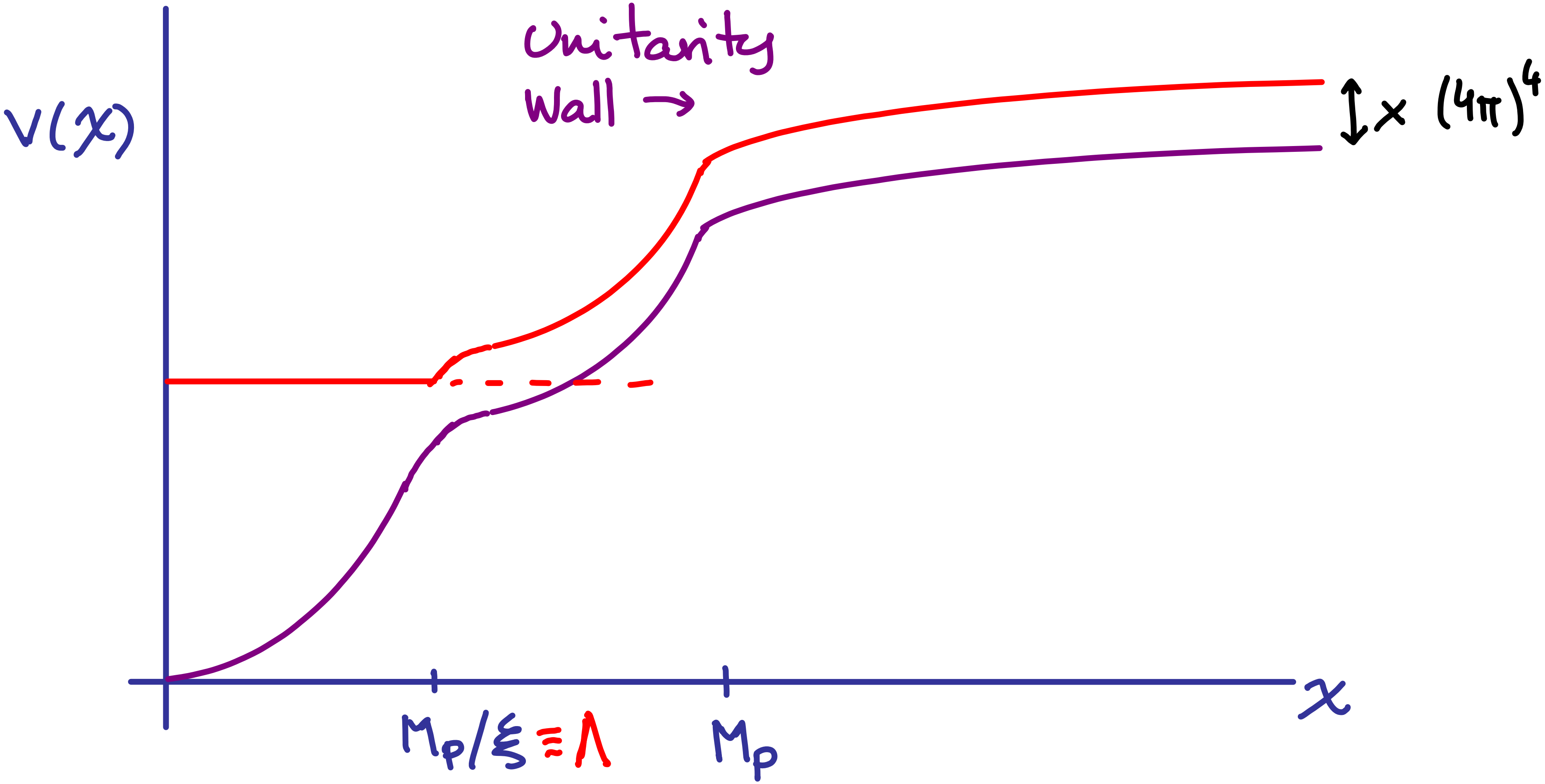
Good inflation predictions



SM+Singlet model

Fairbairn '14

UNITARITY LOST



Problem in the intermediate region. Can study it decoupling gravity ($M_p \to \infty$, $\xi \to \infty$, $\Lambda = M_p/\xi$ fixed). Should have a QFT solution.

GIUDICE-LEE MODEL

New d.o.f. σ, a singlet

$$\mathcal{L} \supset \frac{1}{2}(M^2 + \xi\sigma^2)R - V(\sigma) - \lambda_{H\sigma}\sigma^2|H|^2$$

$\xi \gg 1$ $\qquad$ $\langle\sigma\rangle \neq 0$: $M_P^2 = M^2 + \xi\langle\sigma\rangle^2$

Induces $\xi|H|^2R$ in the low-energy EFT

Modifies the unitarity cutoff to

$$\Lambda = (1 + 6r\xi)\frac{M_{Pl}}{\xi}$$

with $r = \xi\langle\sigma\rangle^2/M_{Pl}^2 \in (0,1)$ so that $\Lambda \sim M_{Pl}$ for $r \sim 1$.