# HIGGS INFLATION AS A MIRAGE

CERN-TH
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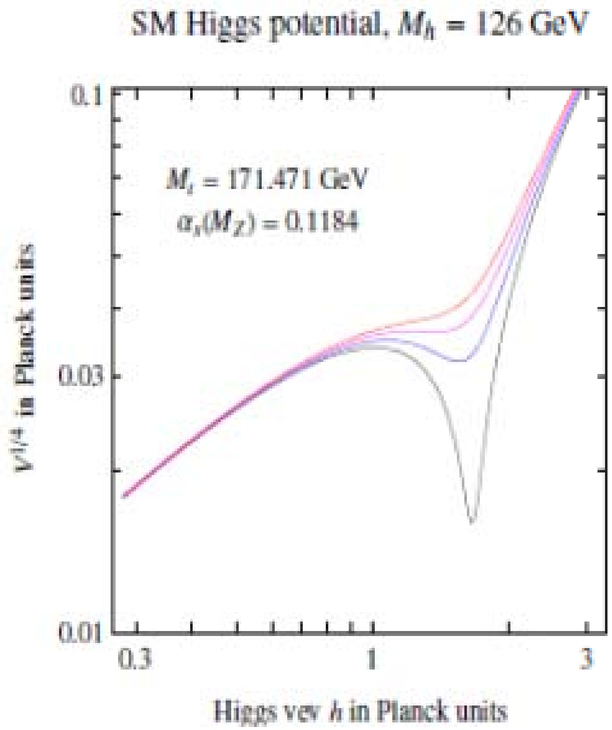
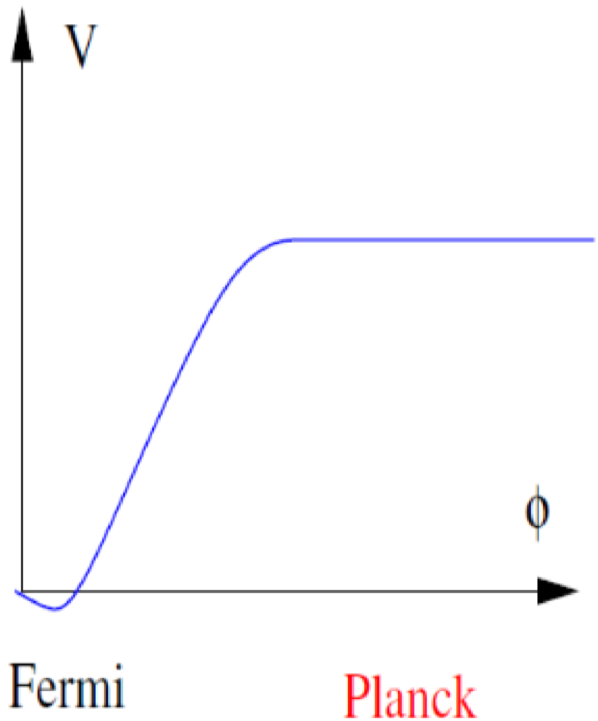
J.R. Espinosa
ICREA, IFAE
Barcelona

# OUTLINE

★ Review of the idea



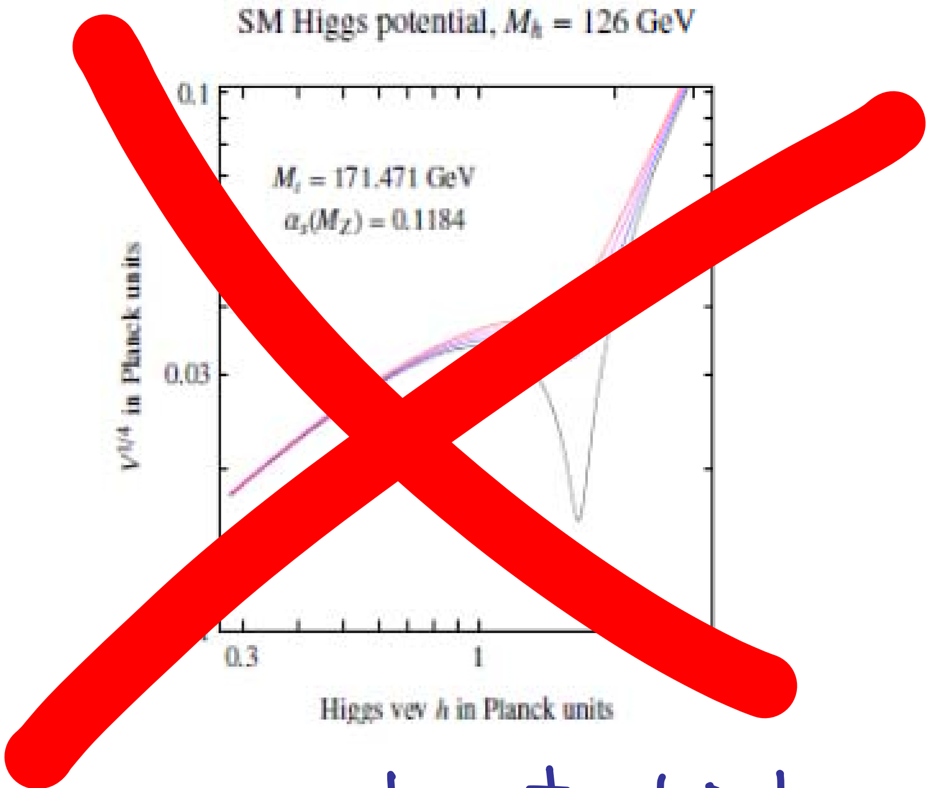




Tuned potential

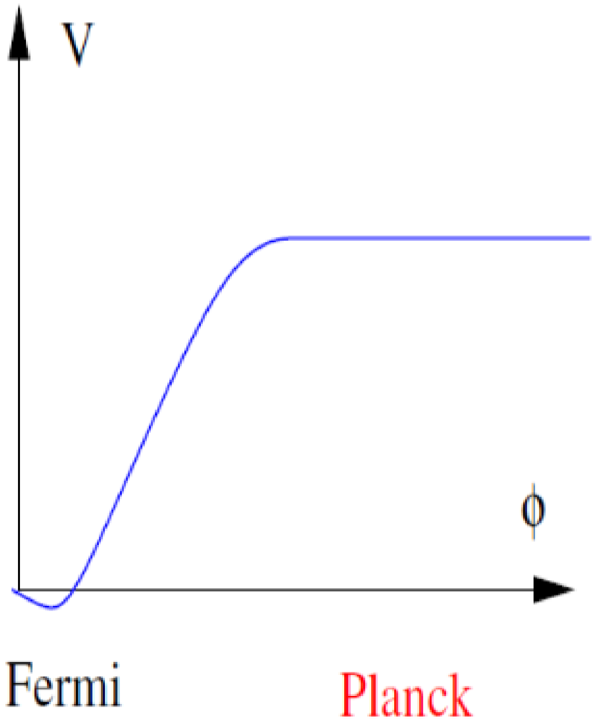
Nonminimal coupling $\xi |H|^2 R$

# OUTLINE

★ Review of the idea




Tuned potential




Nonminimal coupling $\xi |H|^2 R$

# OUTLINE

★ Review of the idea

- Virtues
- Challenges

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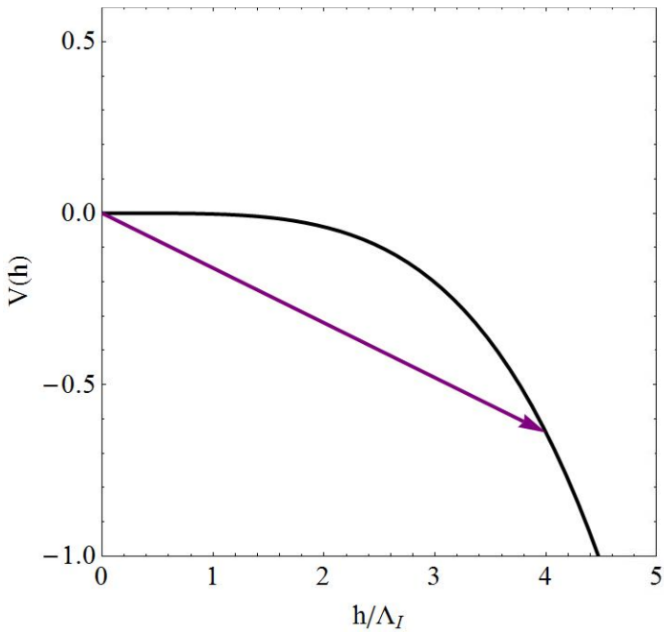
★ Review of the idea

- Virtues
- Challenges

● Vacuum instability

Isn't the potential
badly behaved in the UV?



# OUTLINE

★ Review of the idea

- Virtues
- Challenges

- Vacuum instability
- EFT cutoff for $V(h)$ / Unitarity problem

Background dependent cutoffs ?

# OUTLINE

- ★ Review of the idea
  - Virtues
  - Challenges
    - Vacuum instability
    - EFT cutoff for $V(h)$
- ★ Simple UV Completion

Based on Barbón, Casas, Elias-Miró, J.R.E.
[hep-ph/1501.02231]

# REFERENCES

Bezrukov, Shaposhnikov '07

Barvinsky, Kamenshchik, Starobinsky; García-Bellido, Figueroa, Rubio; De Simone, Hertzberg, Wilczek; Magnin, Sibiryakov; Burgess, Lee, Trott; Barbón, JRE; Kiefer; Clark, Liu, Love, ter Veldhuis; Wetterich; Einhorn, Jones; Steinwachs; Lerner, McDonald; Ferrara, Kallosh, Linde, Marrani, Van Proeyen; Giudice, Lee; George, Mooij, Postma; Salvio; Burgess, Patil, Trott;

+ . . . many more

J.L.F. Barbón, A. Casas, J. Elias-Miró, J.R.E.

# HIGGS INFLATION??

Can the only SM scalar play the role of inflaton?

Looks hopeless as the potential

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

does not support slow-roll (it requires $\lambda \sim 10^{-10}$)

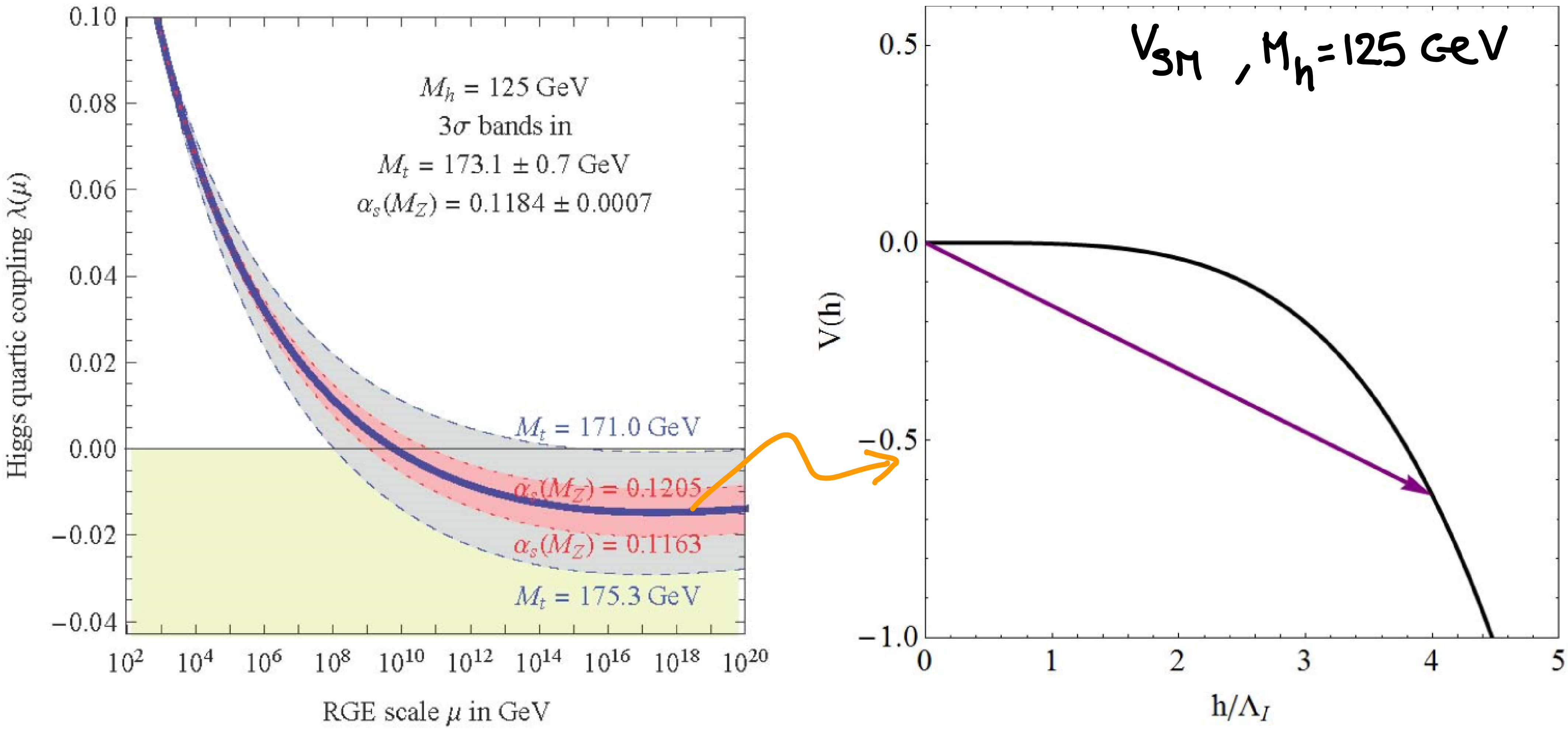
Only hope: $V_{SM}(h)$ deviates from this simple behaviour at high field values.

Minimality wants this to happen in the SM

Higgs inflation idea:

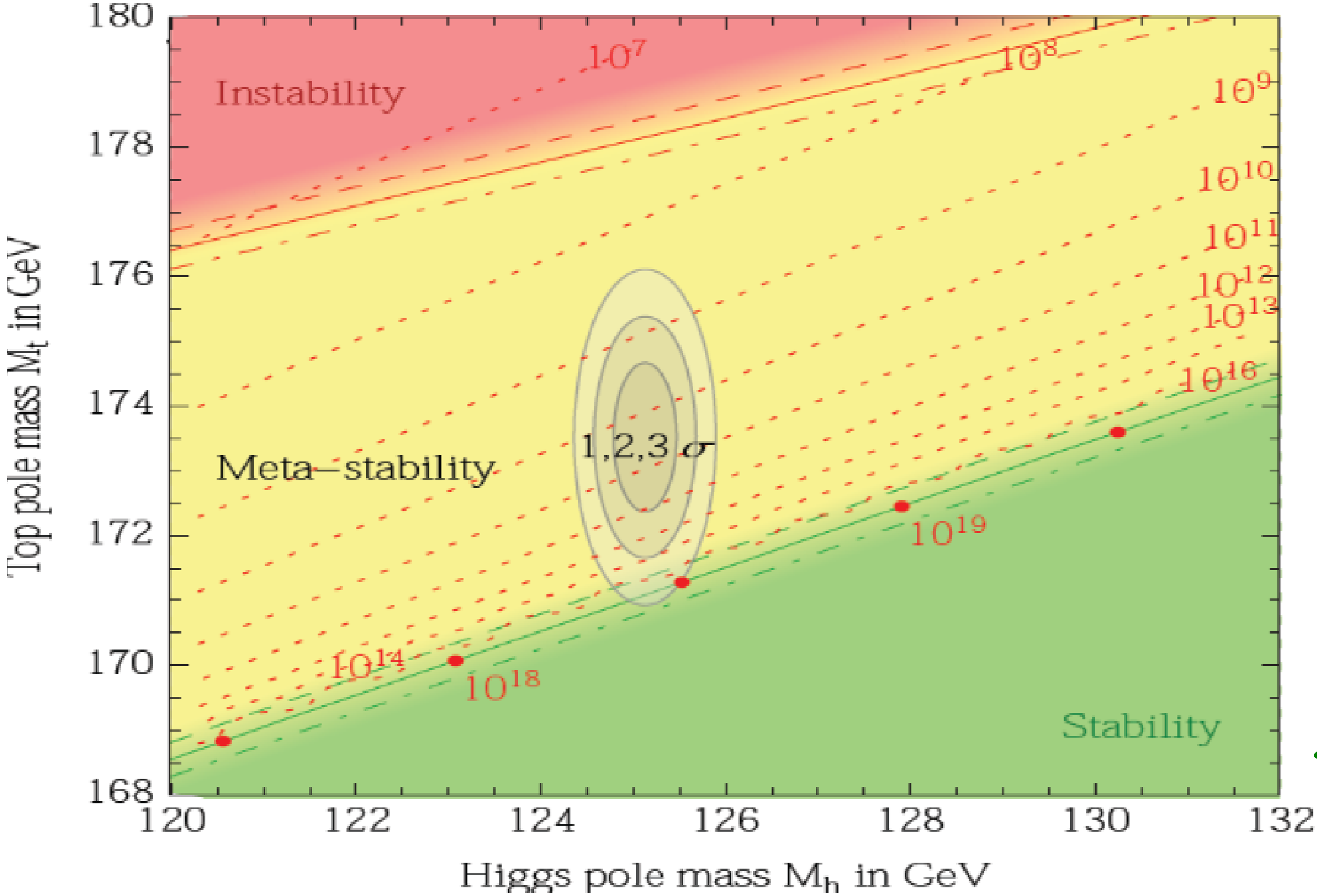
Non-minimal coupling of $h$ to gravity can flatten $V(h)$

# CH. 1 EW VACUUM METASTABILITY




Degrassi et al '12

# EW VACUUM META STABILITY




Degrassi '12
Buttazzo '13

Higgs inflation requires stability

stability requires marginal values of $M_h$ & $M_t$

# HIGGS AS INFLATON

Bezrukov, Shaposhnikov '07

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:

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

New dimensionless coupling

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

Can be very important at large $H$

# HIGGS AS INFLATON

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"

$$\Big\downarrow \; g^J_{\mu\nu} \to g^E_{\mu\nu} e^{-\sigma}$$

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

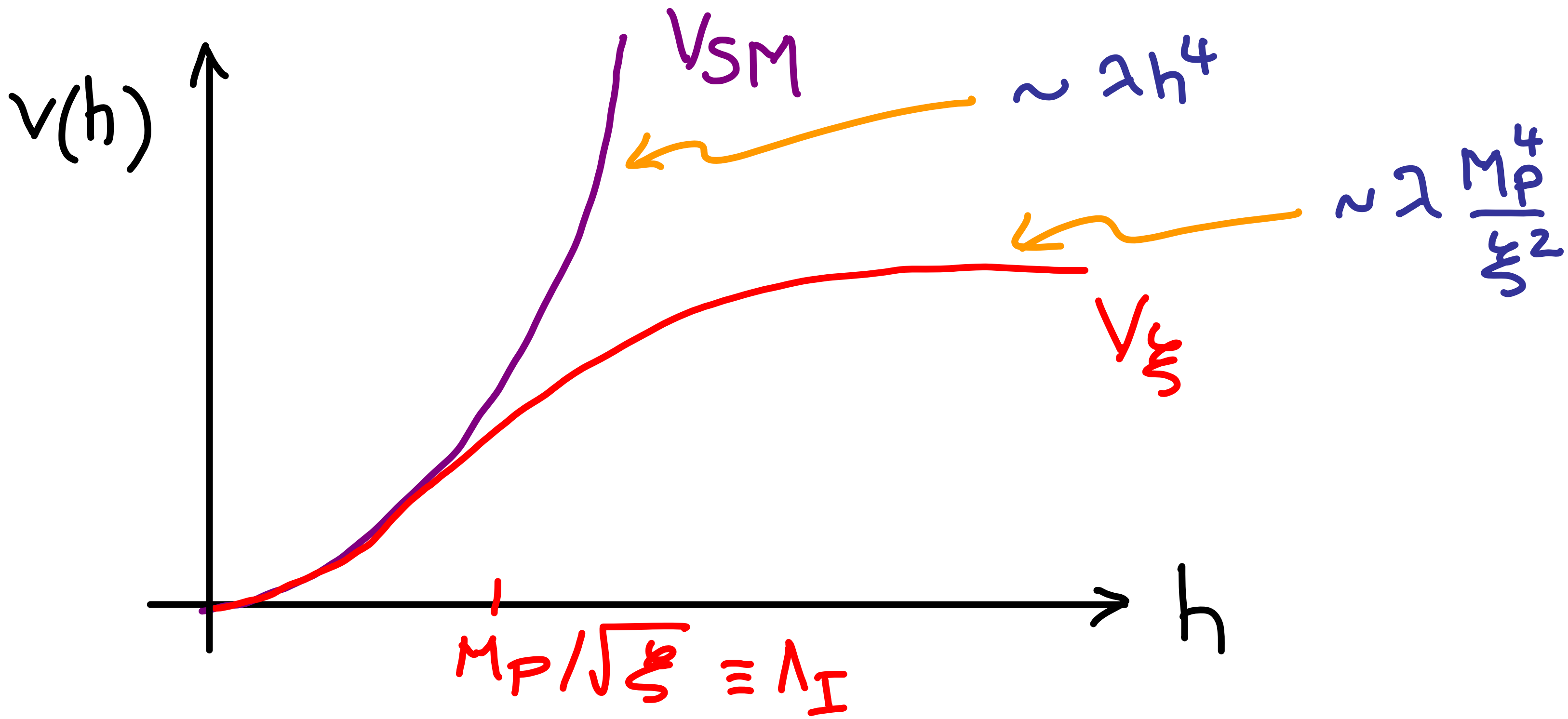
"Einstein frame"

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

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 !

# PREDICTIONS

The slow-roll conditions are easy to satisfy

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

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

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

Inflation $\left\{ \begin{array}{ll} \text{ends at} & h_{end} \simeq \frac{M_P}{\sqrt{\xi}} \\ \text{55 efolds} & h_* \simeq 9\frac{M_P}{\sqrt{\xi}} \end{array} \right.$

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

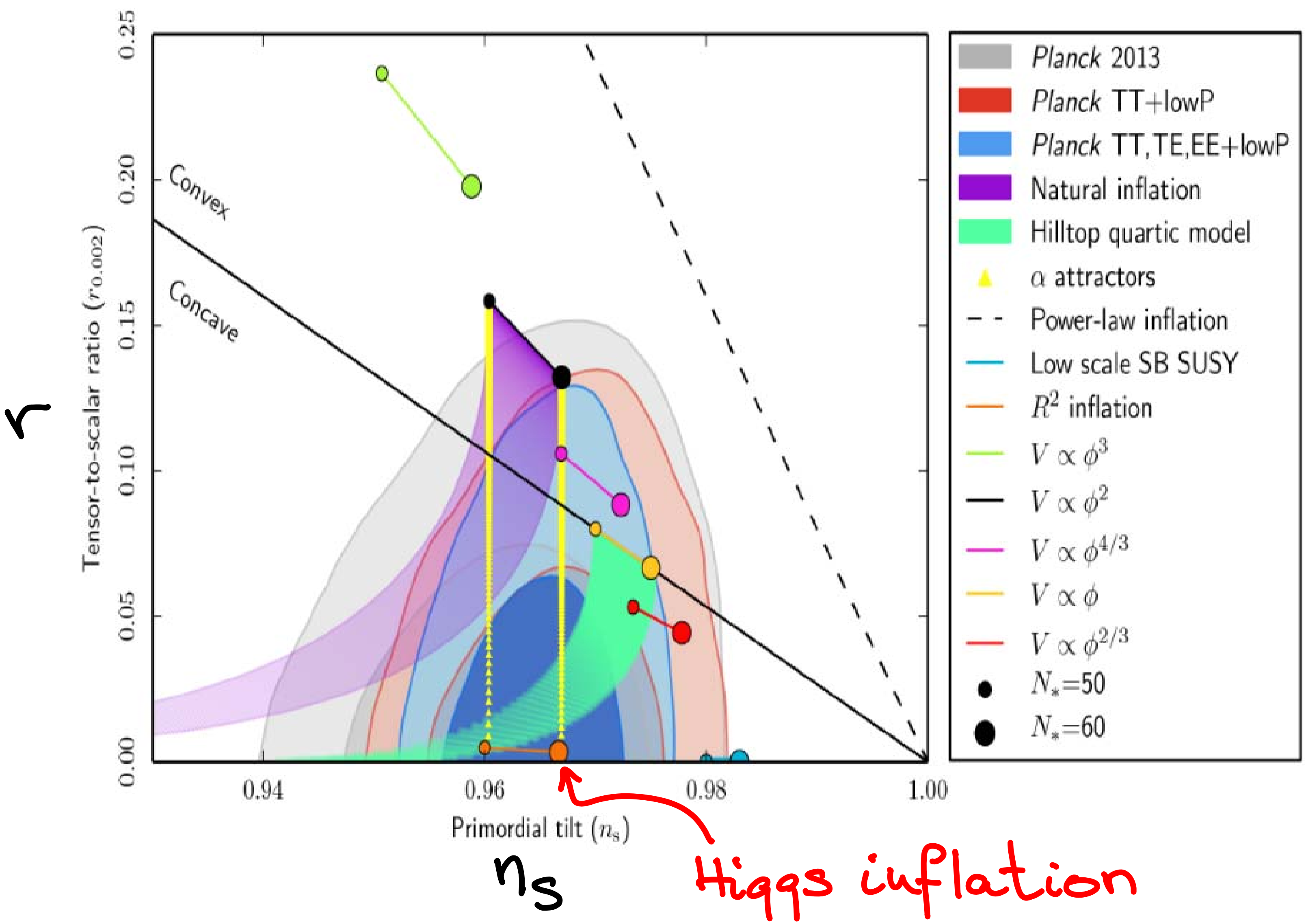
$\boxed{\xi \sim 10^4\sqrt{\lambda}}$ $\quad \xi \gg 1$

$n_s = 1 - 6\epsilon + 2\eta$ $\quad \boxed{n_s \sim 0.965}$

$r = 16\,\epsilon$ quite small $\quad \boxed{r \sim 0.003}$

# PREDICTIONS

Planck '15



# A HIDDEN ASSUMPTION

The plateau is caused by a functional tuning

$$\xi f(h) R - V_{SM}(h) \longrightarrow V_E(h) = \frac{V_{SM}(h)}{(1+\xi f(h))^2}$$

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

This restriction is equivalent to assuming a

SHIFT SYMMETRY

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

$\Rightarrow$ The plateau is not an automatic result

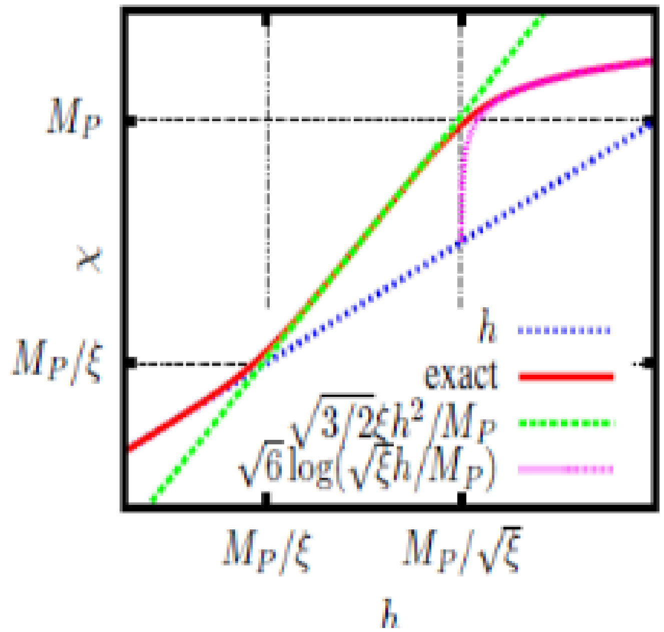
# HIGGS AS INFLATON

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 $\chi(h)$

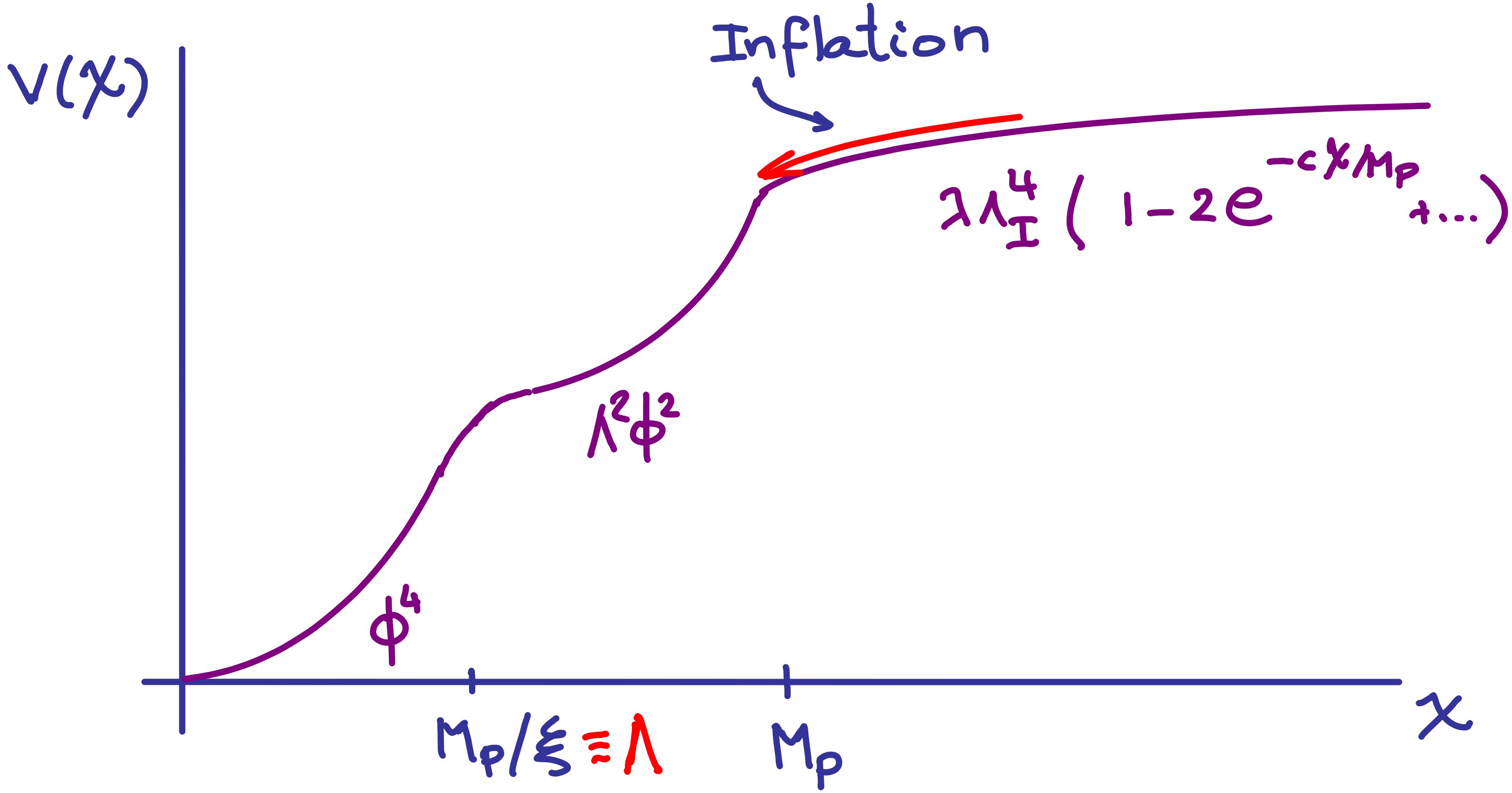
with $\frac{d\chi}{dh} = K(h)$




Bezrukov

# SCALES

As a function of the canonical field $\chi$




In the plateau, $\chi$ decouples asymptotically → 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 ?

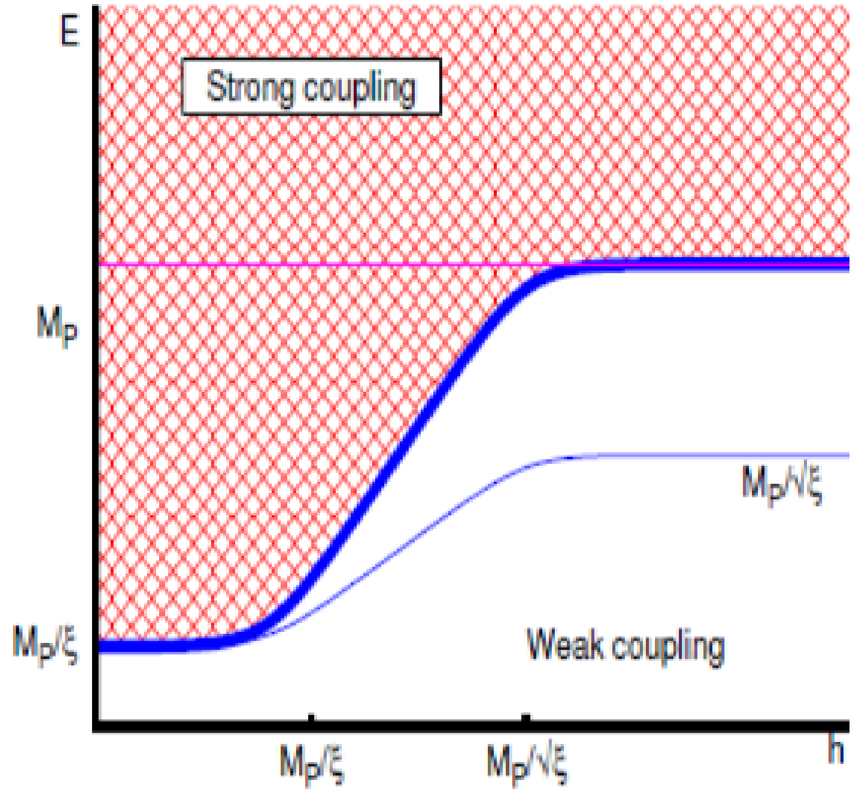
Bezrukov, Magnin, Shaposhnikov, Sibiryakov '10

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 $\Lambda$, either new degrees of freedom or strong coupling

How could raising the $h$ background change that ?

Maybe that new physics is sensitive to $h$ ...

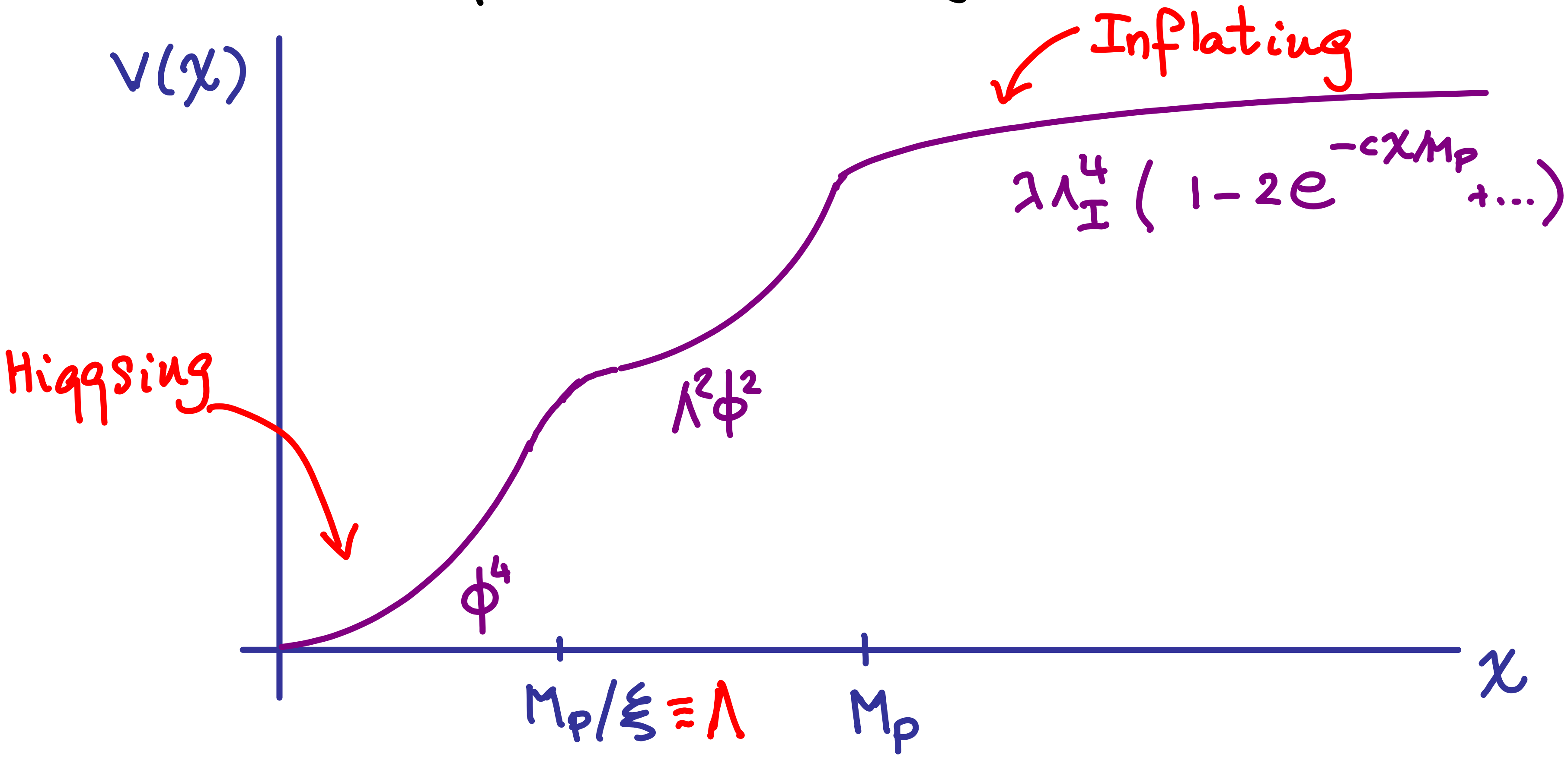
e.g. $M_i^2 \sim \Lambda^2 + k_i h^2$

That is precisely the danger !

Such new physics will have an impact on $V(h)$ above $\Lambda$

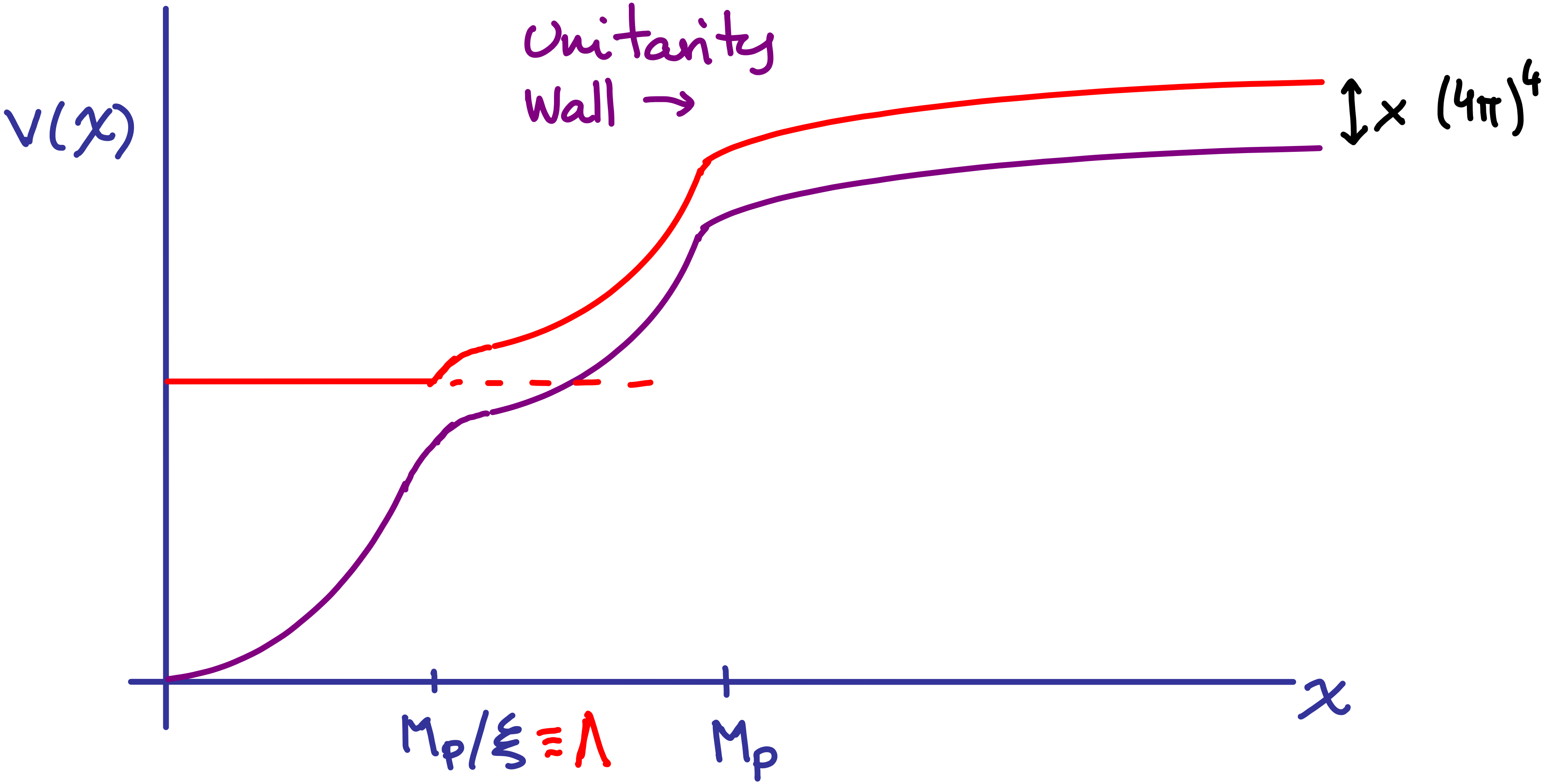
# UNITARITY LOST

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 $(4\pi)\Lambda$

# 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.

# UNITARIZING HIGGS INFLATION

Barbón, Casas, Elias-Miró, JRE '15

Model that UV completes H.I. above $\Lambda$ with the following ingredients/achievements :

1) New massive d.o.f. at/below $\Lambda$, decoupling which
⇨ Low-energy EFT ≃ Higgs inflation
2) Unitarizes Goldstone scatterings above $\Lambda$
3) No large $\xi$ as input
4) As simple as possible
5) Can help with the stability challenge for H.I.

Close cousin of the Giudice-Lee model

# UNITARIZING HIGGS INFLATION

Barbón, Casas, Elias-Miró, JRE '15

Massive field $\phi$, a singlet

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

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

No strong coupling thresholds below $M_P$

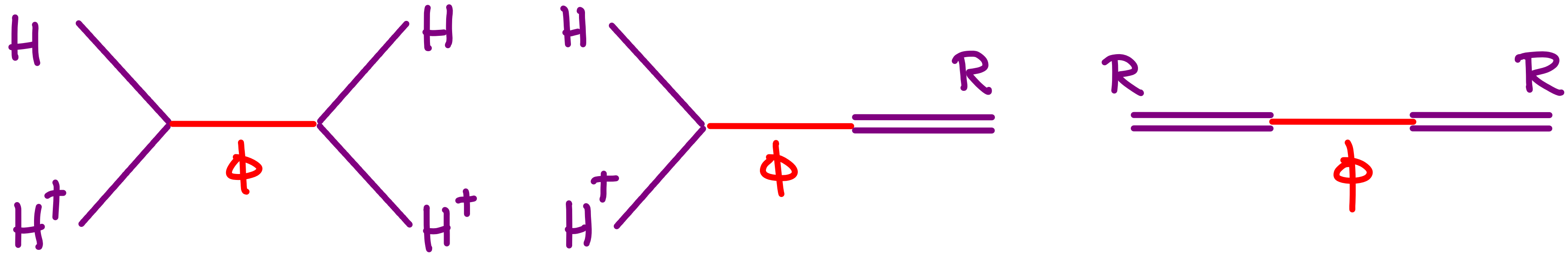
⇨ Unitarity under control up to $M_P$

Mass parameters $m^2, \mu$ :

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

# EFT BELOW m

Integrating out $\phi$ produces the operators :




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

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

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

$\xi$ calculable in terms of UV parameters ✓

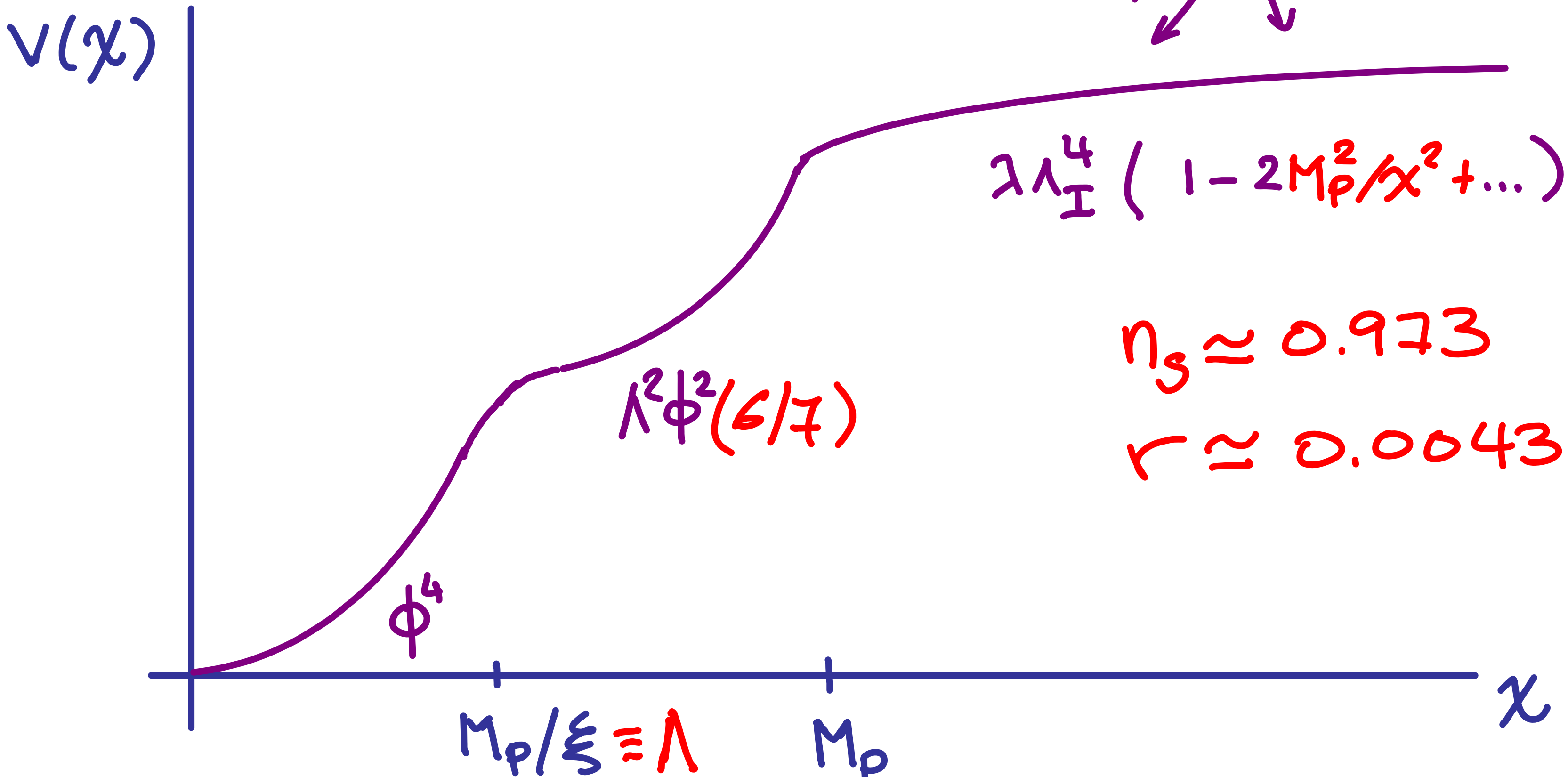
$\xi \gg 1$ easy to achieve ✓

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

# 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 $\lambda$ )

# 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: $h, \phi$

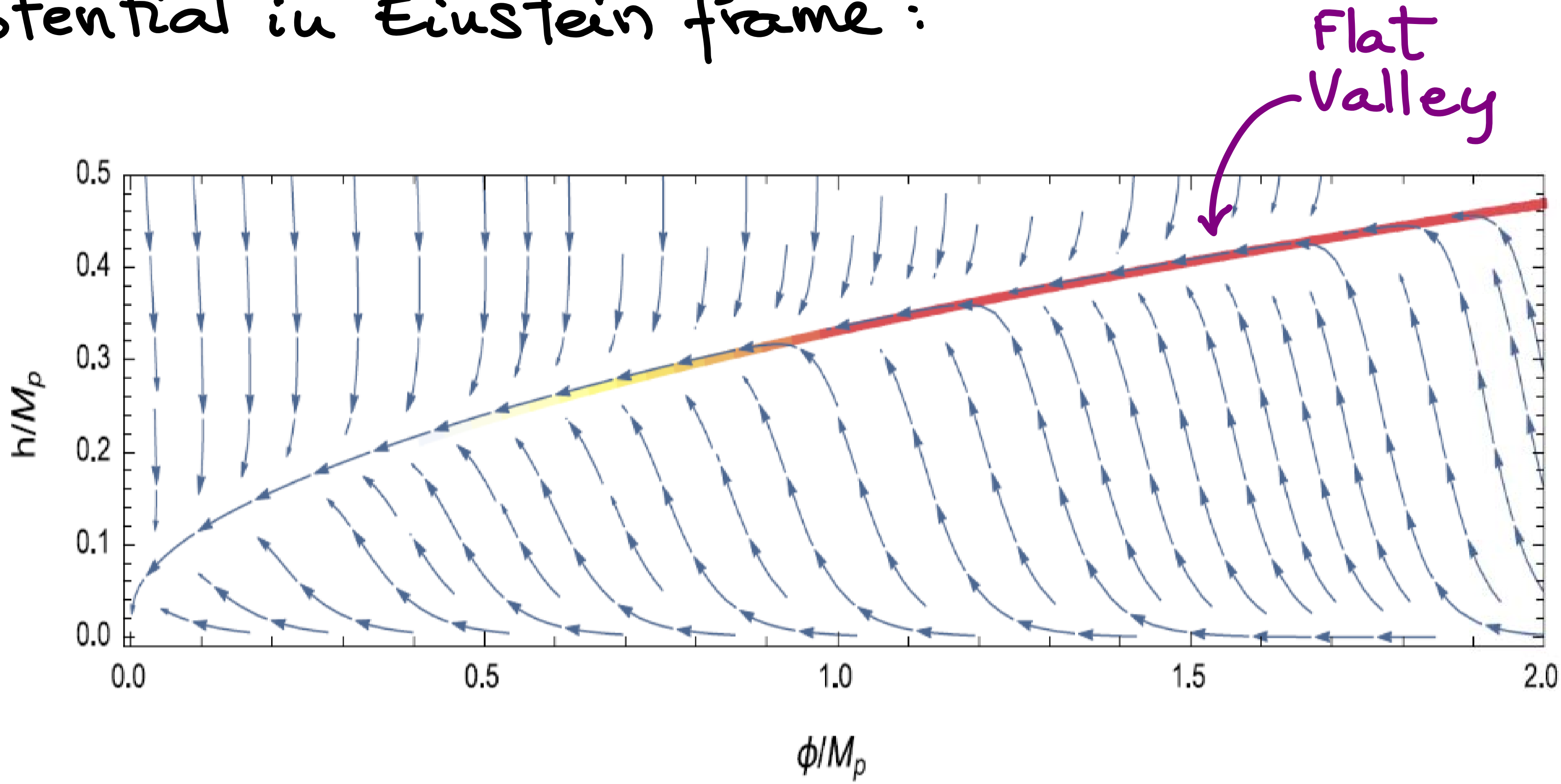
$$\mathcal{L}_E = \frac{1}{2} \sum_{i,j=h,\phi} G_{ij}\, \partial_\mu \Phi_i \partial^\mu \Phi_j - V_E(h,\phi)$$

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:

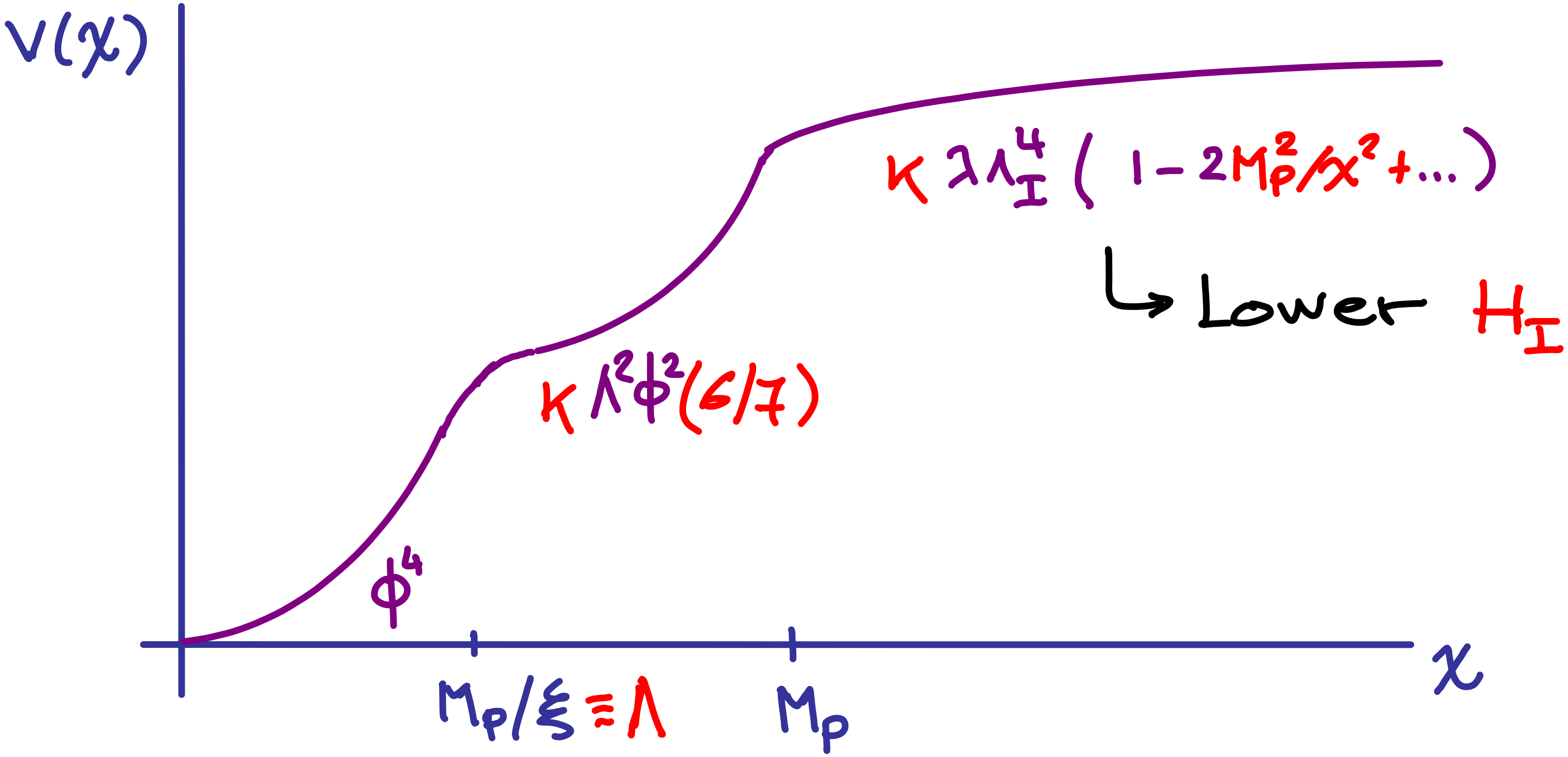



Flatness results from $\phi R \leftrightarrow m^2\phi^2$ interplay.

UV shift symmetry still assumed but for $\phi$ ✓

# HIGH ENERGY THEORY

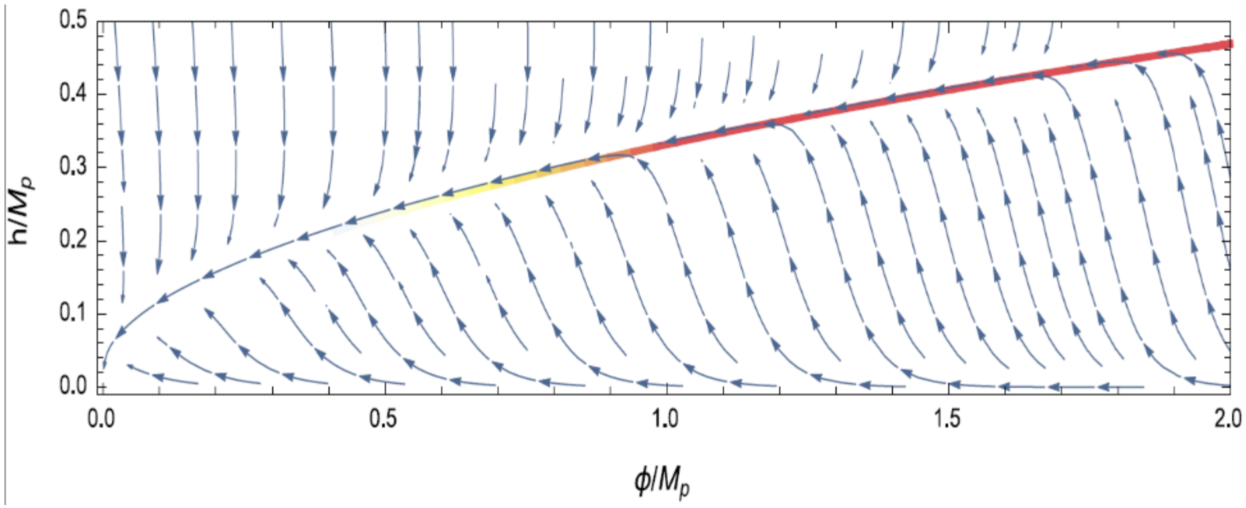
Missmatch factor wrt EFT: $\kappa \equiv 1 - \lambda/\lambda_{UV}$




Artifact of truncating EFT at two-derivatives.

But same slow-roll parameters: $n_s \simeq 0.973$
$r \simeq 0.0043$

# HIGH ENERGY THEORY




- Inflationary valley is narrow $\quad m_\perp^2 \sim M_p \mu \gg H_I^2 \sim \frac{M_p^2}{\xi^2}$

  ⇨ single field inflation

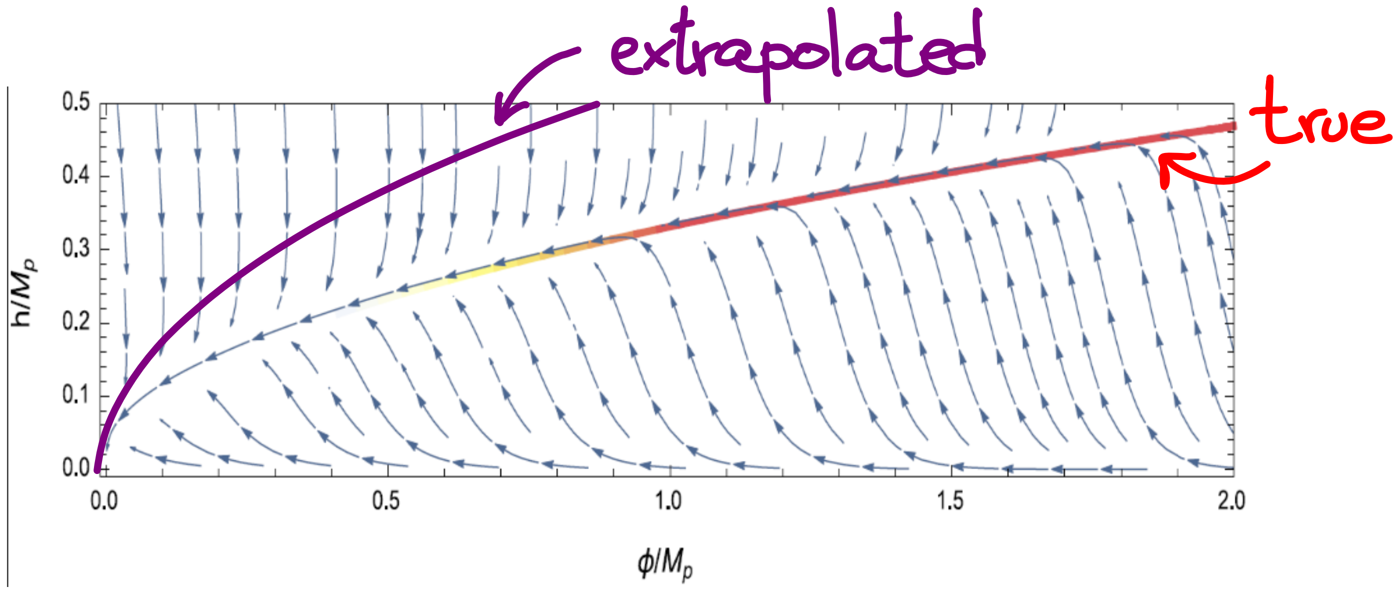
- Can parametrize in terms of $h$ or $\phi$ but clearly the inflaton field is mostly $\phi$, not $h$.

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 $\phi$...

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




The extrapolated path probes higher potential values.

# STABILITY PROBLEM

Singlet field $\phi$ modifies the running of $\lambda$

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

This can stabilize the potential, provided

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

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

(For an alternative solution, see: Bezrukov, Shaposhnikov, Rubio '14.)

# CONCLUSIONS

- The unitarity problem of Higgs inflation requires new dofs. at or below the scale $M_p/\xi \ll M_p$
- Very simple model curing this problem

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

  - Still requires a shift symmetry in the UV
  - Shows how to get $\xi \gg 1$
  - Can help with the instability problem
  - Agrees with measured $n_s$ and $r$
- Such dof takes care of inflating so that $h$ can unitarize $W_L W_L$

Higgs not really the inflaton

# CONCLUSIONS

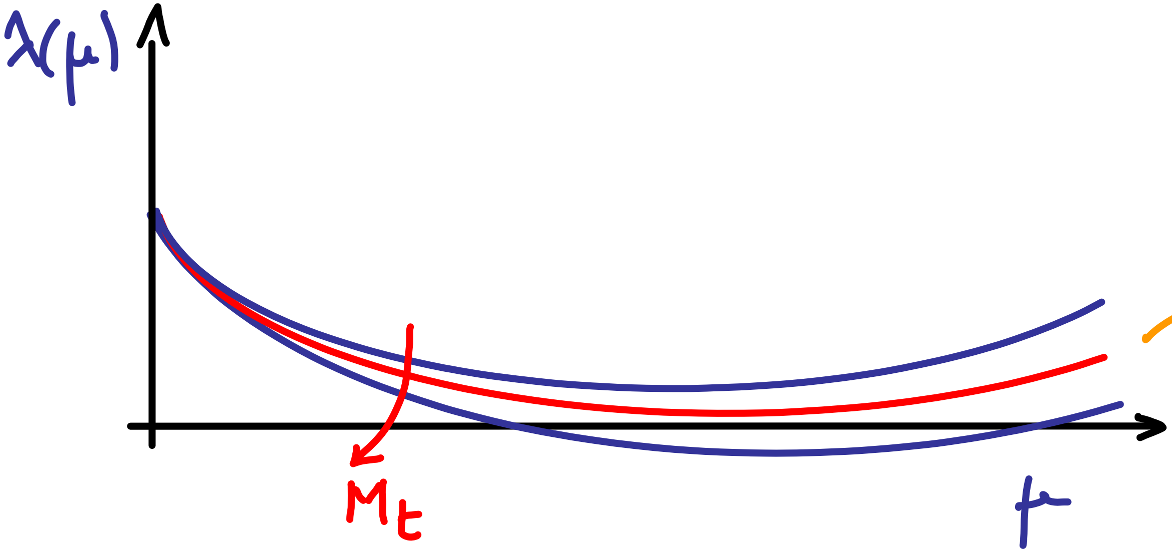
★ Predictions deviate from original Higgs inflation and from the naive EFT extrapolation
⇨ UV sensitivity

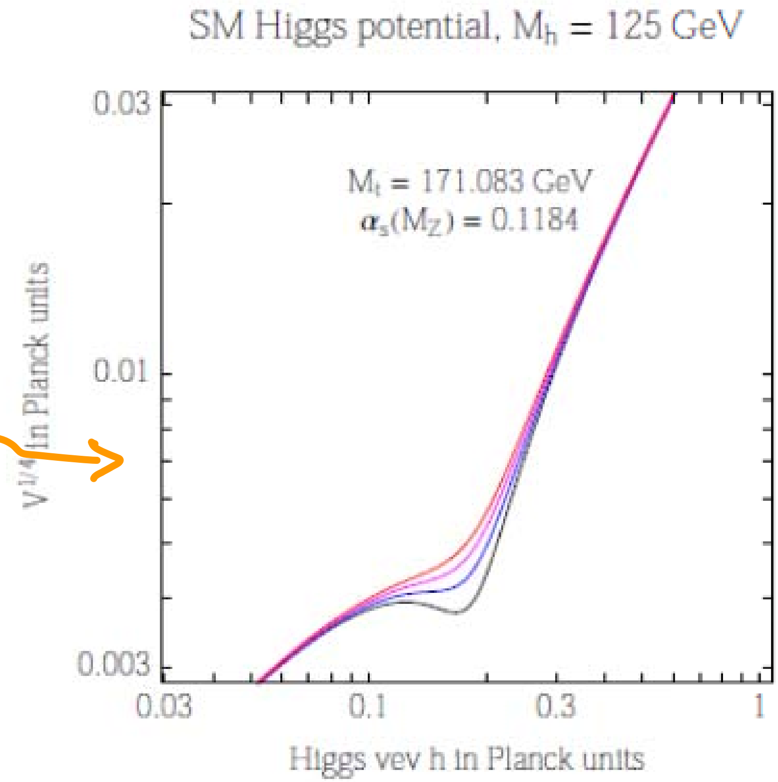
"Higgs inflation" could be just a mirage single-field projection from a more complicated landscape-like potential. Finding out that potential will be tough!

# 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 $\Delta h \gtrsim M_P$

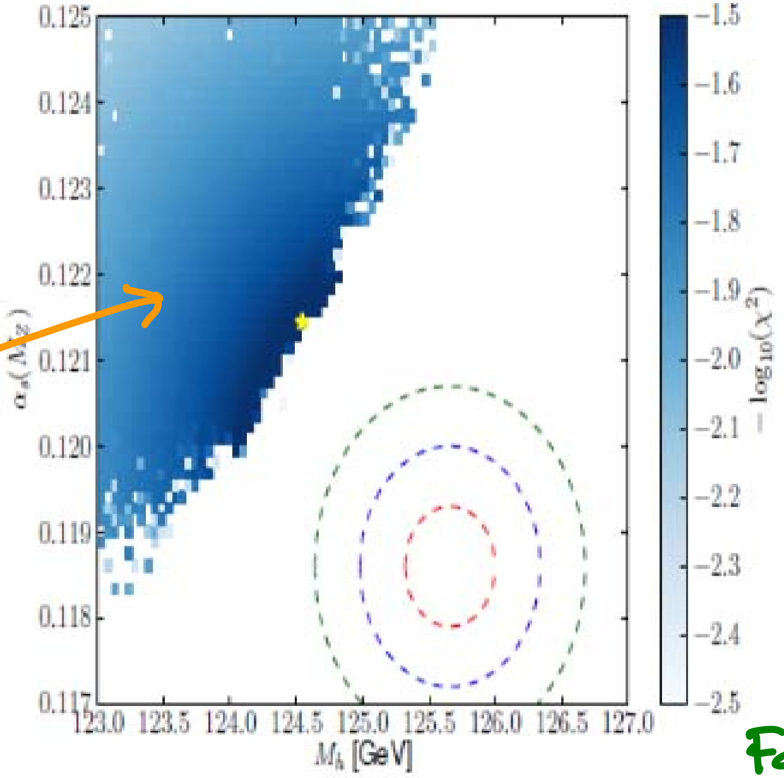
while the small plateau is much shorter

# 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

# GIUDICE-LEE MODEL

New d.o.f. $\sigma$, a singlet

$$\mathcal{L} \supset \frac{1}{2}(M^2 + \underbrace{\xi}_{\xi \gg 1} \sigma^2)R - \underbrace{V(\sigma)}_{\langle\sigma\rangle \neq 0} - \lambda_{H\sigma}\sigma^2 |H|^2$$

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

Induces $\xi|H|^2 R$ 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 $r \sim 1$.