Higgs-R^2 cosmology

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The LIO international conference & France-Korea STAR workshop

Lyon June 23, 2022

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Contents

- Inflation & particle physics model
- Higgs inflation
    - non-minimal coupling & $f(R)$ gravity
    - Higgs-R^2 model
    - Phenomenology :PBH & GW ,Reheating, Leptogenesis
- Conclusions

refs

- **Inflation by non-minimal coupling** SCP, Yamaguchi JCAP (2008)
- **Higgs Inflation after the Results from BICEP2** Hamada, Kawaii, Oda, SCP, PRL 112, 241301 (2014)
- **Higgs inflation from Standard model criticality** Hamada, Kawaii, Oda, SCP, PRD 91, 053008 (2015)
- **Clockwork for Higgs inflation** SCP, C.S Shin EPJC 79 (2019) no.6, 529
- **Preheating in Higgs-R^2 model**, M. He, R. Jinno, K. Kamada, SCP, A. Starobinsky, J. Yokoyama PLB791 (2019) 36-42
- **Higgs inflation in metric and Palatini formalisms**, R. Jinno, M. Kubota, K-y. Oda, SCP *JCAP* 03 (2020) 063
- **Higgs Inflation and the Refined dS Conjecture** D. Y. Cheong, S. M. Lee, SCP PLB 789 (2019) 336-340
- **PBH in Higgs inflation**, D. Y. Cheong, S. M. Lee, SCP *JCAP* 01 (2021) 032
- **Beyond the Starobinsky model**, H.M.Lee, D.Y.Cheong, SCP Phys.Lett.B 805 (2020) 135453
- **Leptogenesis in Higgs inflation**, S. M. Lee, D. Y. Cheong, SCP *JHEP* 03 (2021) 083
- **Reheating of general nm inflation** S. M. Lee, D. Y. Cheong, SCP (*JCAP* 02 (2022) 02, 029)
- **Festina-Lente Bound**, S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, Min-Seok Seo (*JHEP* 02 (2022) 100)
- **Non-minimally assisted inflation**, S.C.Hyun, Jinsu Kim (CERN), SCP, T. Takahashi (*JCAP* 05 (2022) 05, 045)
- **PBH & GW in Higgs-R^2 inflation**, D. Y. Cheong, K. Kohri (KEK), SCP, 2205.14813
- **Festina-Lente for dark photon**, K. Ban, D. Y. Cheong, H. Okada (APCTP), H. Otsuta (IBS), J-C Park, SCP, 2206.00890
- and more

Inflation

Hot big bang

- Universe started from a hot and dense state then cooled down by expansion
- BBN & CMB (observationally confirmed)

Initial conditions for Hot big bang

-Flat, homogeneous & isotropic Universe

-No exotics such as monopoles

-Need seed for structures

Inflation

-The period of Exponential expansion

-(size after inflation) /(size before inflation) $\sim e^{60}$

Expanding Universe

- FRW Metric $ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$
- Scale factor determines Physical length $\Delta\ell = a(t)\Delta r$
- $\dot{a} > 0$ for expanding universe
- Friedmann eq. : $H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$
- $\rho_1 > \rho_2 \rightarrow H_1 > H_2 \rightarrow \ell_1 > \ell_2$ a local patch with larger energy density grows faster and becomes larger

Chaotic inflation [Linde, 1983]

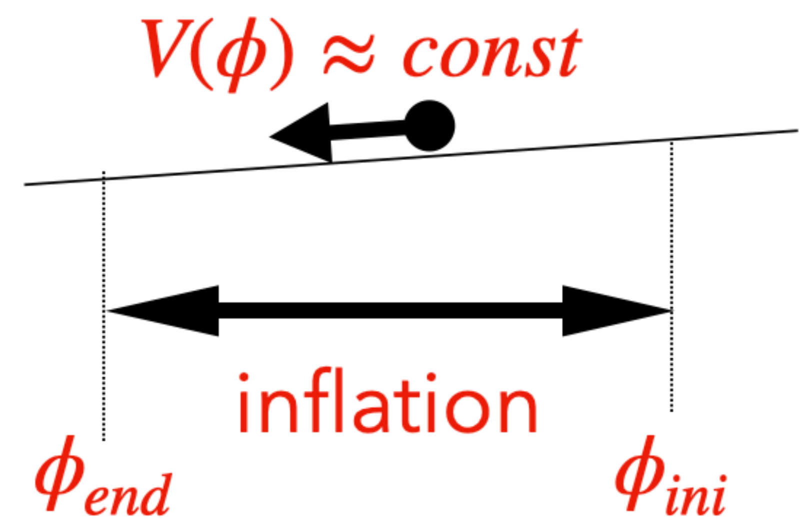
Money earns more money…

Exponential Expansion

- $H(t)^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$: Friedmann equation
- $\rho = const$, $H = const$ => sol. $a(t) = a(t_0)e^{H(t-t_0)}$
- $\frac{a(t_{end})}{a(t_{ini})} = e^{H(t-t_0)} \sim e^{60}$ "60-efolds" for successful inflation

Particle Physics modeling

- **A scalar field (=inflaton) having a flat potential**
- $\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \approx V(\phi) \approx const\,.$



$\{\varepsilon, |\eta|\} \ll 1.$

slow-roll parameters

$$\epsilon_V \equiv \frac{M_{pl}^2}{2}\left(\frac{V'}{V}\right)^2 \quad , \quad |\eta_V| \equiv M_{pl}^2 \frac{|V''|}{V}$$

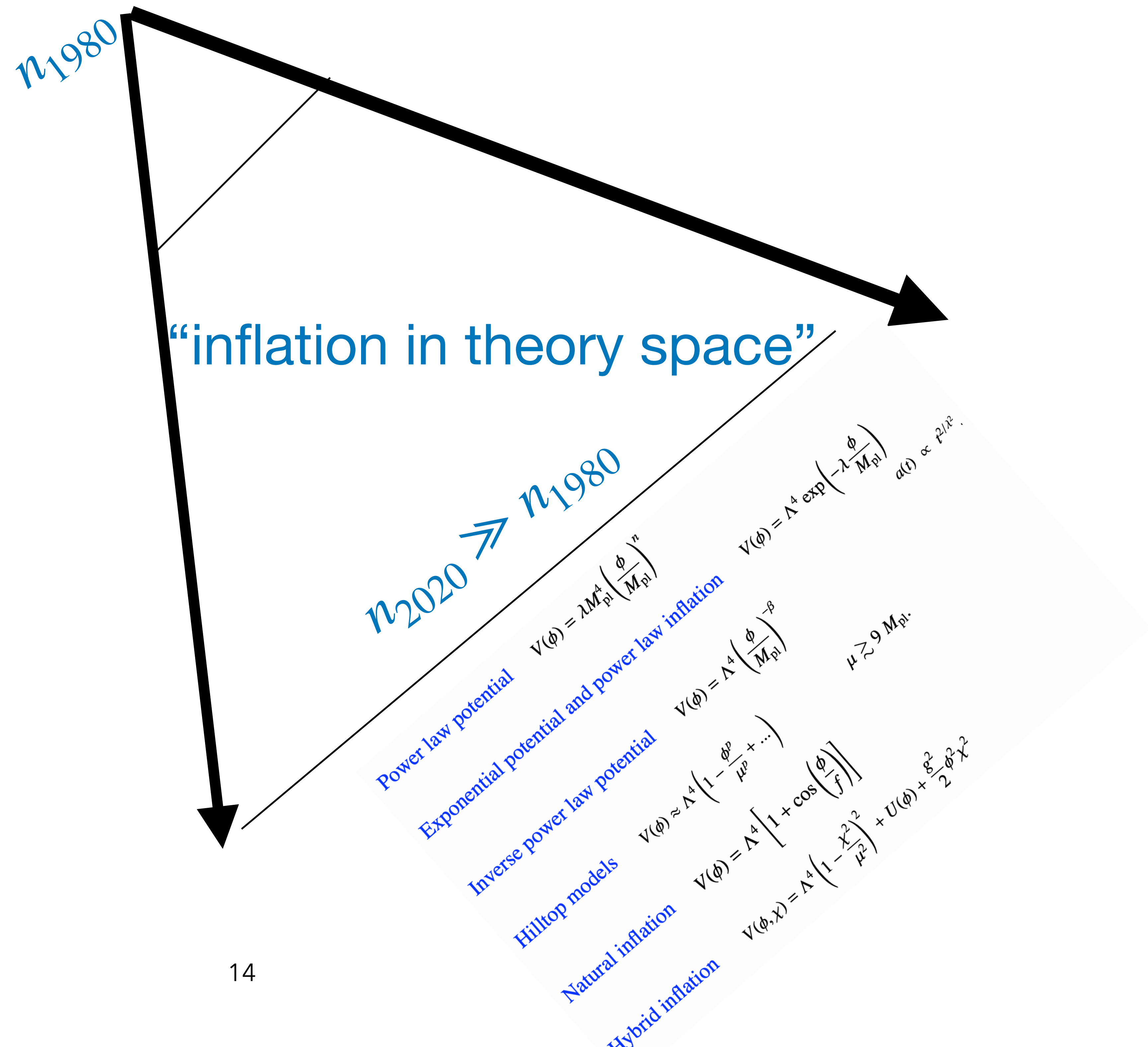
cosmological perturbation

observables e.g. $n_s, r, f_{NL}, \cdots$

Many models

Guth, Linde, Sato, Starobinsky

- old
- new
- chaotic
- natural
- blah
- blah blah
- Higgs-R^2 inflation



A special choice: Higgs inflation

- The only observed scalar (probably elementary but composite is not ruled out)
- $H \sim \begin{pmatrix} G^+ \\ (v+h+G^0)/\sqrt{2} \end{pmatrix} \quad \left(1_{SU(3)} \otimes 2_{SU(2)_L}\right)_{\frac{1}{2}}$
- Her properties have been well measured (only 2 parameters in potential)

$$V(H) \approx \lambda \left(H^\dagger H - v^2/2\right)^2$$

$$v = \sqrt{1/\sqrt{2}G_F} = 246.22 \text{ GeV}, \ \lambda = \frac{m_h^2}{2v^2} = \frac{125^2}{2 \times 246^2} \approx \frac{1}{8}$$

The SM Higgs potential

$$V_{\text{Higgs}} \simeq \frac{1}{32}h^4 + \frac{246\ \text{GeV}}{8}h^3 + \frac{1}{2}(125\ \text{GeV})^2 h^2$$

Predicted   Predicted   Measured

(Future colliders)

The SM Higgs potential

The Higgs is responsible for
-masses of elementary particles

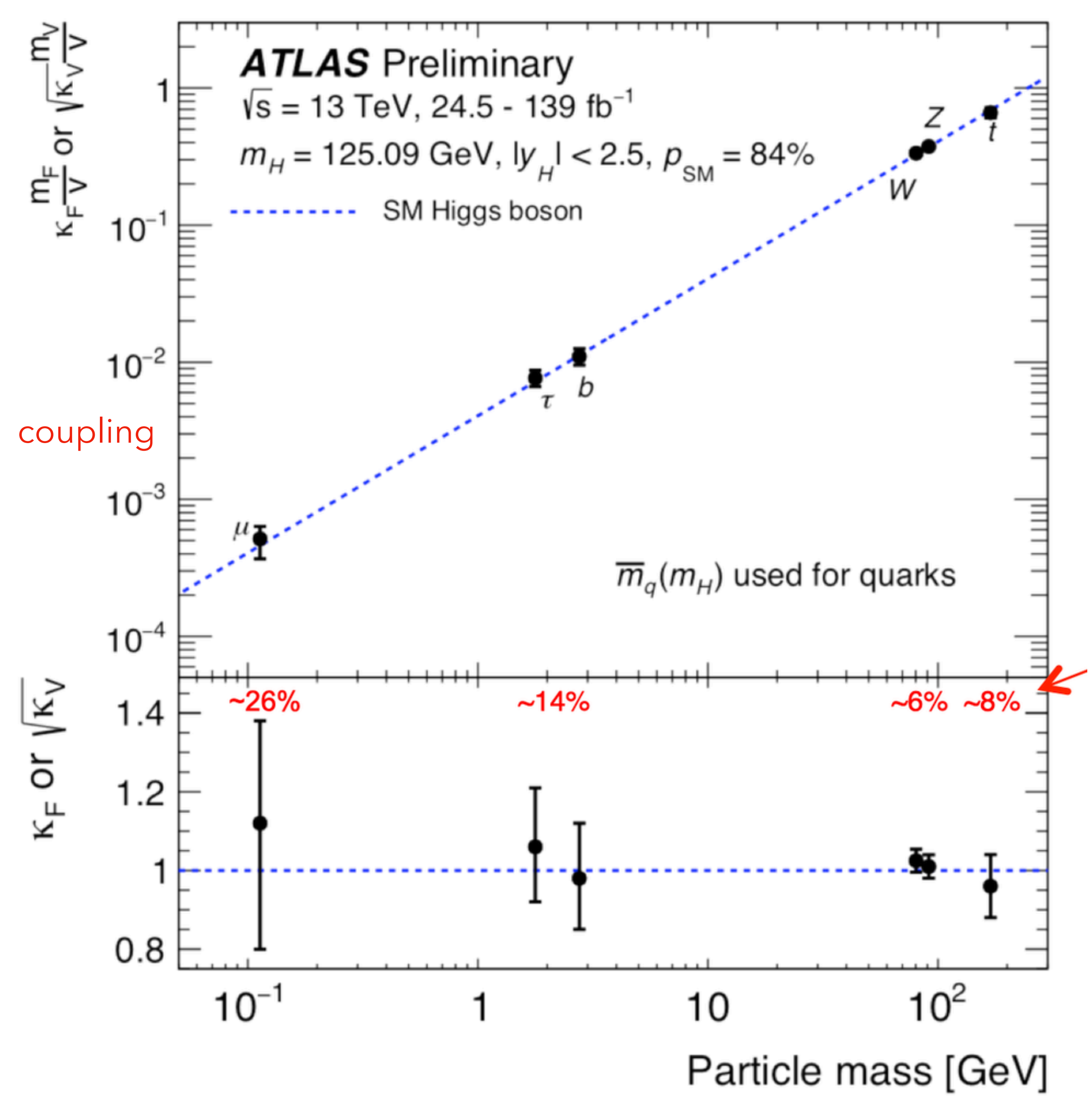
a linear relation

$$m_\psi, m_Z \propto \langle H \rangle$$

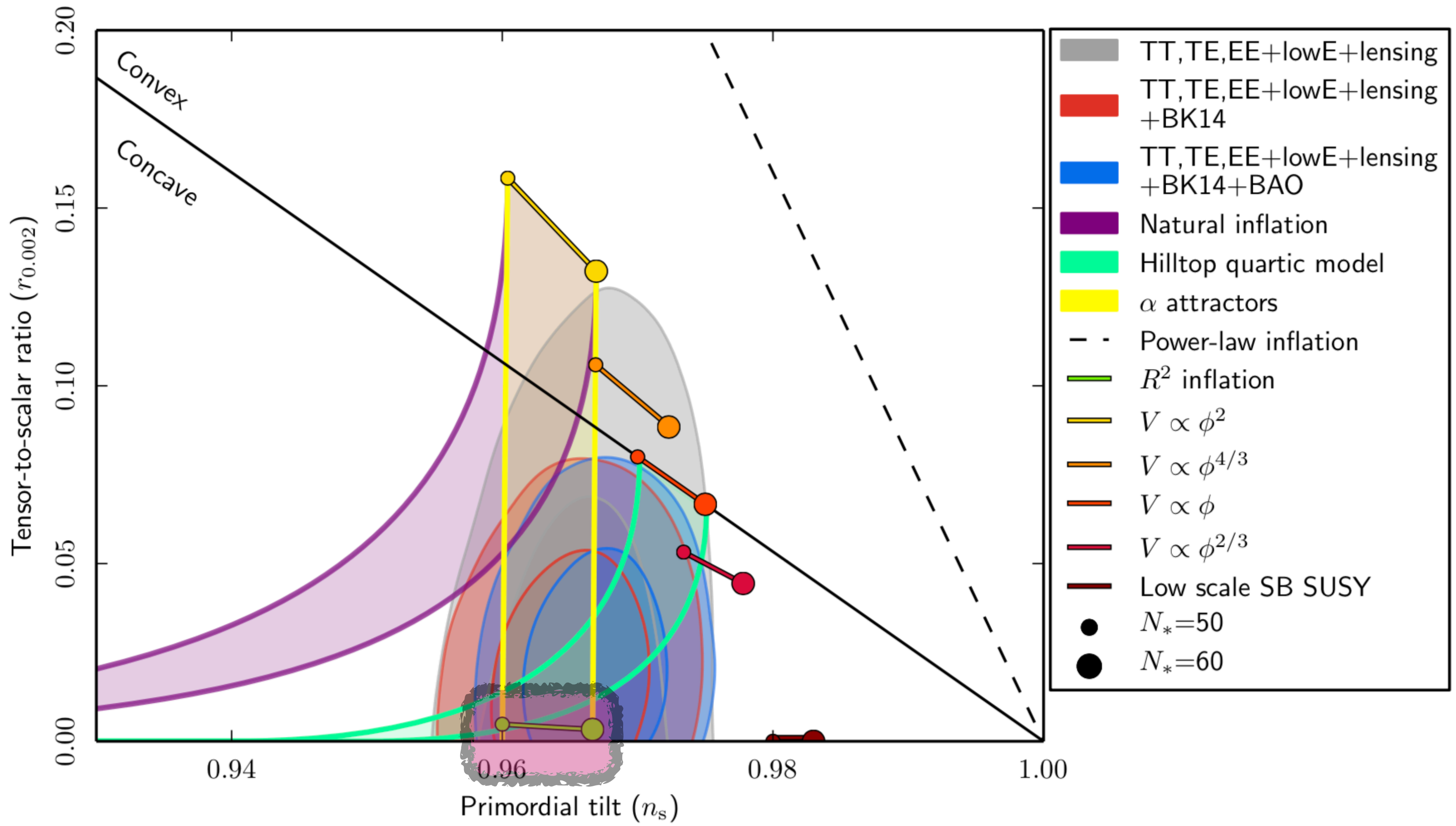
Beautifully confirmed
by the LHC!

Coupling strength versus mass
(assuming no new particle in loops and decays)

ATLAS-CONF-2020-027



'Best fit model' of the Planck data



Higgs inflation

Y. Akrami et.al [Planck Collaboration] (2018)

well motivated & observationally preferred

certainly worth looking into details!

Higgs inflation

Non-minimal coupling ($\ni$ Higgs inflation)

SCP, S. Yamaguchi (2007)

non-minimal coupling (general Kahler)

$$S = \int d^4x \sqrt{-g} \left[-\frac{M^2 + K(\phi)}{2} R + \frac{1}{2}(\partial\phi)^2 - V(\phi) \right]$$

-Jordan frame action is not canonically normalized

-$[K(\phi)] = Mass^2$

e.g. $K(\phi) = M_P^2(\phi/M_P)^{2+n}$

or $K(\phi) = M^2(1 - \cos(\phi/M))$ or many possibilities

Weyl transformation :
Jordan frame -> Einstein frame

SCP, S. Yamaguchi (2007)

$$S = \int d^4x\sqrt{-g}\left[-\frac{M^2+K(\phi)}{2}R + \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

Weyl:

$$g_{\mu\nu} = e^{-2\omega} g^E_{\mu\nu}, \qquad e^{2\omega} := \frac{M^2+K(\phi)}{M_{\rm Pl}^2}.$$

$$R \to e^{-2\omega}(R_E - 2(D-1)\nabla^2\omega - (D-2)(D-1)(\partial\omega)^2)$$

The potential in Einstein frame $U = \dfrac{M_{\rm Pl}^4}{(M^2+K(\phi))^2}V(\phi)$

Condition for 'flat' potential: $\partial_\phi K > 0,\ \partial_\phi V > 0$

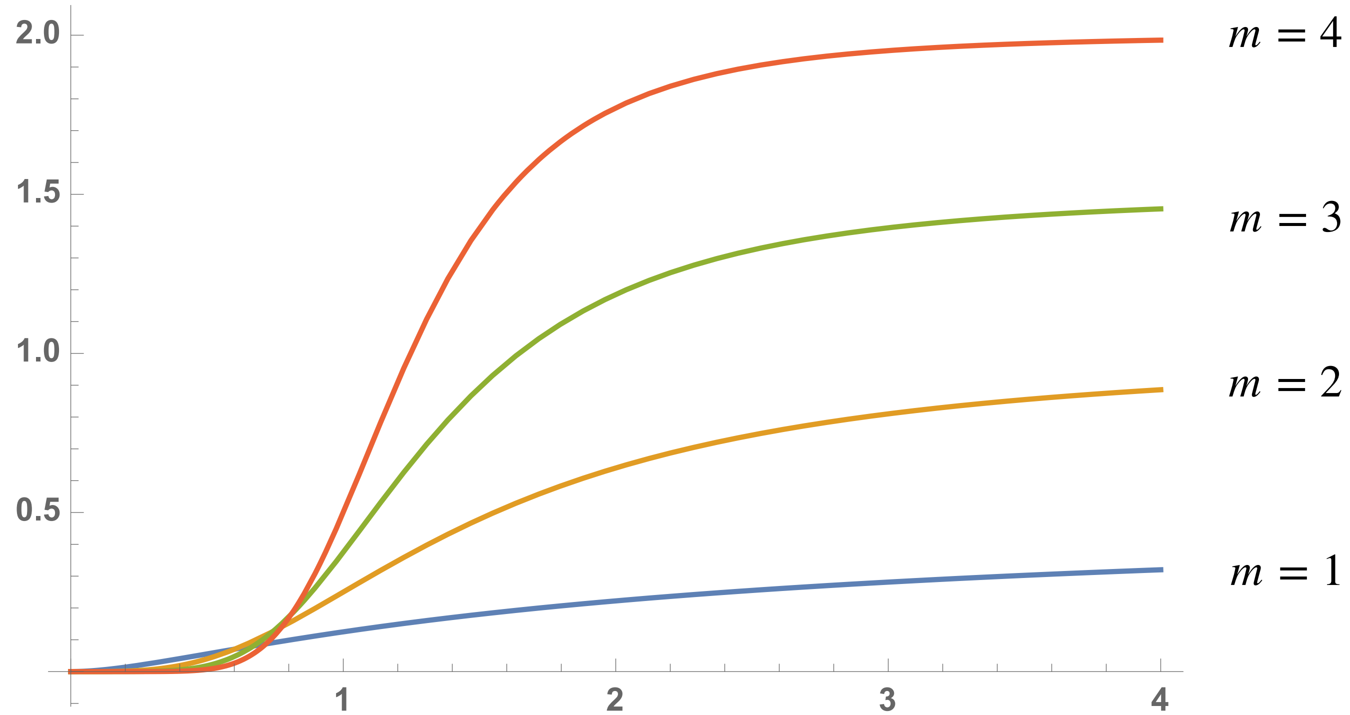
$$\lim_{\phi\to\infty}\frac{V}{K^2} = Const > 0.$$

ex) $V \sim \phi^{2m}, K \sim \phi^m$

NM-inflation with monomial functions, $V \sim h^{2m}, K \sim h^m$

$$S = \int d^4x\sqrt{-g}\left[-\frac{M^2+K(\phi)}{2}R + \frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$$\lim_{\phi\to\infty}\frac{V}{K^2} = Const > 0.$$

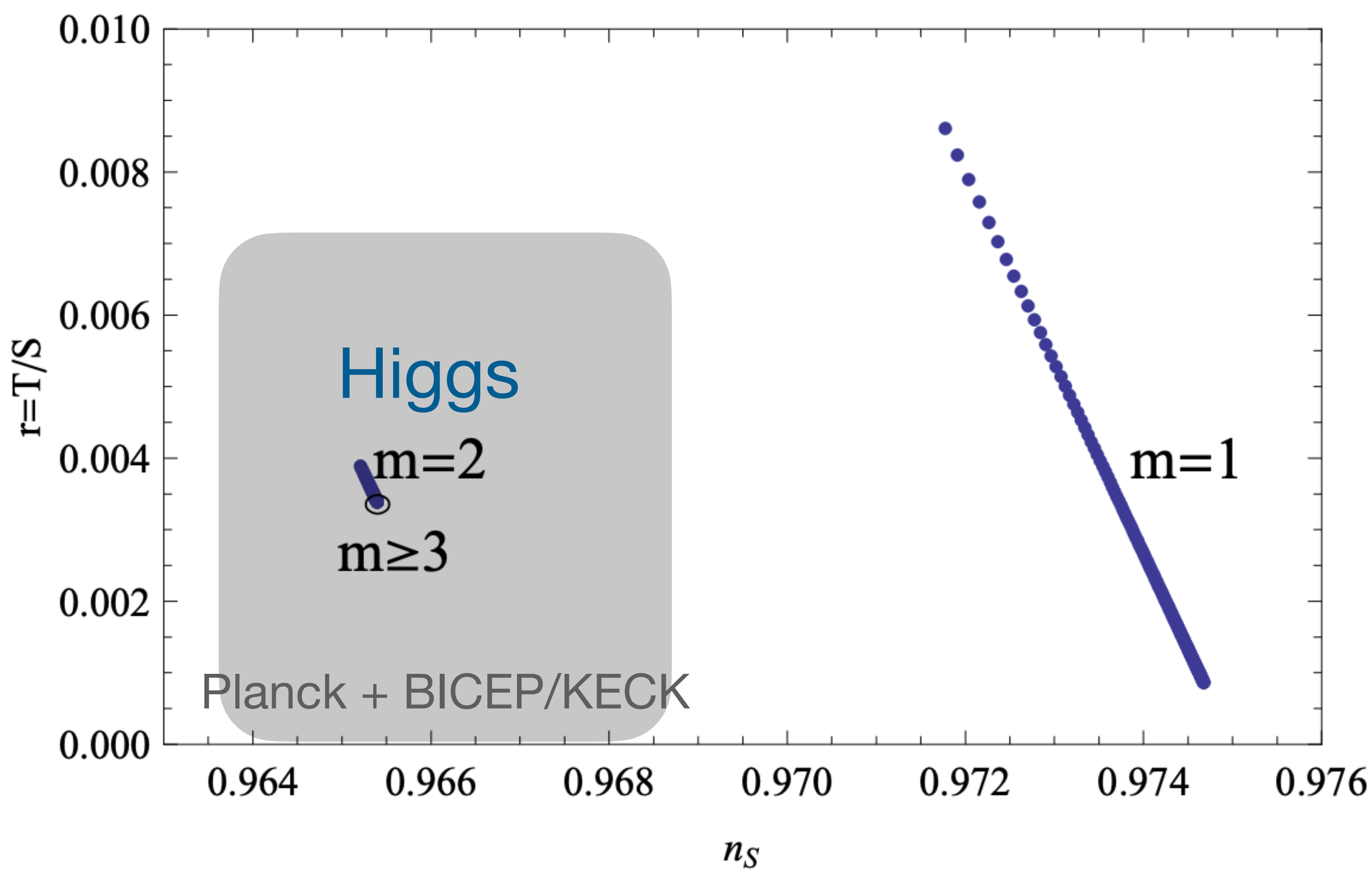


: Higgs inflation

SCP, Yamaguchi (2007)

Predictions of NM-inflation

SCP-Yamaguchi (2007)



Well consistent with Planck data!

Starobinsky & nm theory are equivalent

unimportant during slow-roll

$$S_{Higgs} = \int d^4x\sqrt{-g}\,\left[\frac{1}{2}\left(M_P^2 + \xi\phi^2\right)R + \frac{1}{2}(\partial\phi)^2 - \frac{\lambda}{4}\phi^4\right]$$

n=2

EOM for auxiliary field

$$\delta\phi : \xi\phi R - \lambda\phi^3 = 0 \;\Rightarrow\; \phi^2 = \frac{\xi R}{\lambda}$$

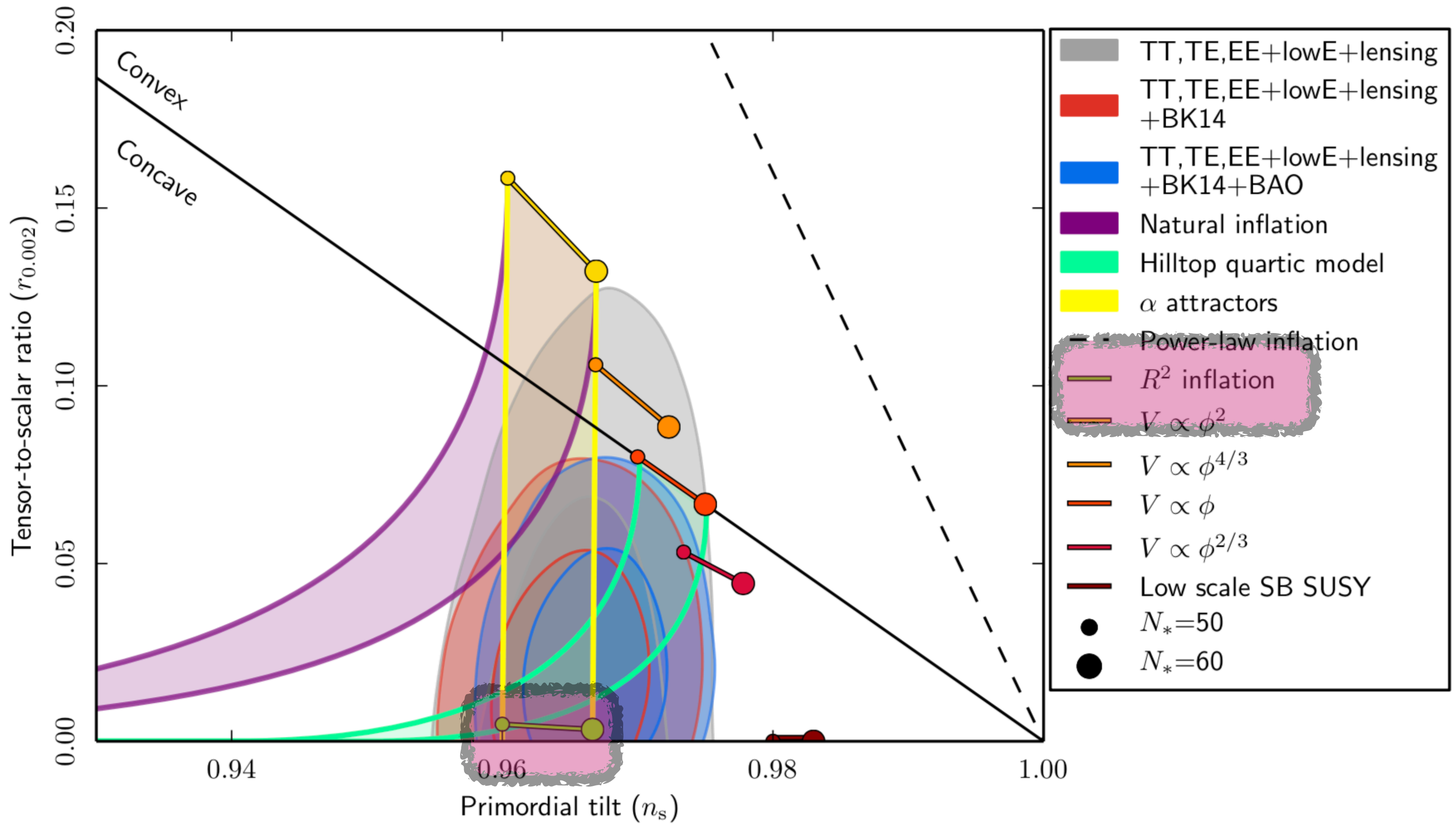
$$S_{Starobinski} = \int d^4x\sqrt{-g}\,\frac{1}{2}\left(M_P^2 R + \frac{\xi^2}{4\lambda}R^2\right)$$

Starobinsky (1980)

$\frac{\xi^2}{\lambda} \sim 10^{10}$ for Planck normalization $\delta T/T \sim 10^{-5}$

**will discuss this issue later

'Best fit model' of the Planck data



Higgs inflation

Y. Akrami et.al [Planck Collaboration] (2018)

$$\frac{\xi^2}{\lambda} \sim 10^{10}$$ for Planck normalization $\delta T/T \sim 10^{-5}$

**will discuss this issue later

Before going into further details, I want to introduce

some useful tricks for $f(R)$

(ex) Starobinsky: $f(R) = R + \beta R^2$

Claim#1 : A $f(R)$ gravity theory is equivalent to a non-minimally coupled gravity + non-dynamical scalar theory.

(proof) Explicitly,

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\, f(R) \sim \frac{1}{2}\int d^4x\sqrt{-g}\,\left[f(\phi) + f'(\phi)(R-\phi)\right] .$$

"Trick" : Take ϕ as an auxiliary field. Eq. of motion by varying $\delta\phi$ is $\delta\mathscr{L} = f'\delta\phi + f''(\phi)(R-\phi)\delta\phi - f'(\phi)\delta\phi \propto -f''(\phi)(R-\phi) = 0 \;\therefore\; R = \phi$. It leads to the original action. *(Q.E.D.)*

(NOTE)

$$S \equiv \int d^4x\sqrt{-g}\left[\frac{1}{2}\Omega^2(\phi)R - V(\phi)\right]$$ where $\Omega^2(\phi) = f'(\phi), V(\phi) = \frac{1}{2}\left(\phi f'(\phi) - f(\phi)\right)$.

The theory looks

Claim #2 A non-minimally coupled gravity + scalar theory is equivalent to Einstein gravity + scalar theory

(proof)

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}\Omega^2(\phi)R - V(\phi)\right]$$ is Weyl-transformed

$g_{E\mu\nu} = \Omega^2(\phi)g_{\mu\nu}$ to $S_E = \int d^4\sqrt{-g_E}\left[\frac{1}{2}R_E - \frac{1}{2}g_E^{\mu\nu}\partial_\mu s\partial_\nu s - V_E(s)\right]$

with $s \equiv \sqrt{\frac{3}{2}}\ln\Omega^2 = \sqrt{\frac{3}{2}}\ln f'(\phi)\Big|_{\phi=\phi(s)}$ dynamical field = scalaron

Potential in Einstein frame: $V_E(s) = \dfrac{V(\phi(s))}{\Omega^4(\phi(s))} = \dfrac{\phi f' - f}{2(f')^2}\Bigg|_{\phi=\phi(s)}$

Claim #1 + Claim #2
=> $f(R)$ equivalent to (Einstein+ scalar)

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\, f(R) \sim S_E = \int d^4\sqrt{-g_E}\left[\frac{1}{2}R_E - \tfrac{1}{2}g_E^{\mu\nu}\partial_\mu s\partial_\nu s - V_E(s)\right]$$

$$s \equiv \sqrt{\frac{3}{2}}\ln\Omega^2 = \sqrt{\frac{3}{2}}\ln f'(\phi)\Big|_{\phi=\phi(s)} \quad \text{and} \quad V_E(s) = \frac{V(\phi(s))}{\Omega^4(\phi(s))} = \frac{\phi f' - f}{2(f')^2}\Bigg|_{\phi=\phi(s)}$$

(ex) $f(R) = R + \frac{\beta}{2}R^2$

$$M_P \equiv \frac{1}{\sqrt{8\pi G}} = 1$$

$[R] \sim L^{-2} \sim M^2$ and set $\frac{\beta}{2} = \frac{1}{6m_s^2}$

(scalaron mass)

$$s = \sqrt{\frac{3}{2}}\,\ln f'(\phi)\Big|_{\phi=\phi(s)} = \sqrt{\frac{3}{2}}\,\ln(1+\beta\phi)$$

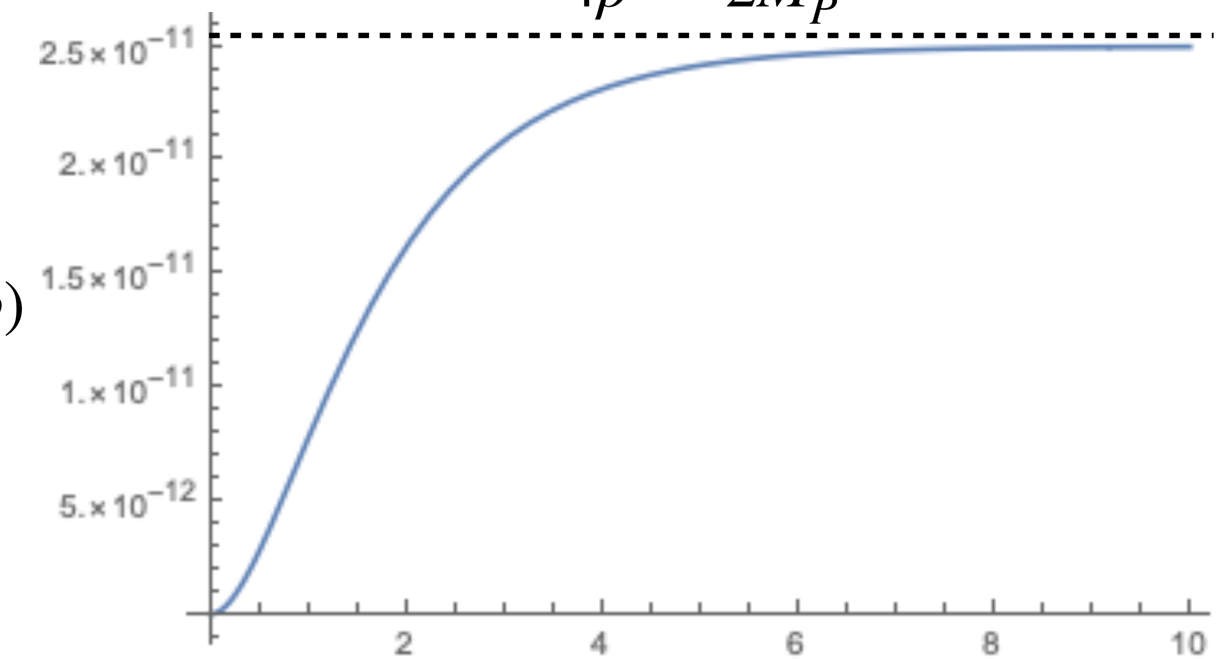
or $\phi = \frac{1}{\beta}\left[e^{\sqrt{2/3}s} - 1\right]$

$$V_E(s) = \frac{V(\phi(s))}{\Omega^4(\phi(s))} = \frac{\phi f' - f}{2(f')^2}\Bigg|_{\phi=\phi(s)}$$

$$= \frac{\beta\phi^2(s)}{4\left(1+\beta\phi(s)\right)^2} = \frac{1}{4\beta}\left(1 - e^{-\sqrt{2/3}s}\right)^2$$

$m_s \sim 10^{-5}M_P$

$\frac{1}{4\beta} = \frac{3m_S^2}{2M_P^2} \sim 10^{-10}$ **[COBE]**



Starobinsky (1980)

(ex) $f(R) = R + \frac{\beta}{2}R^2 + \frac{\gamma}{3}R^3, \gamma \ll 1$

With a small γ, the potential is modified as

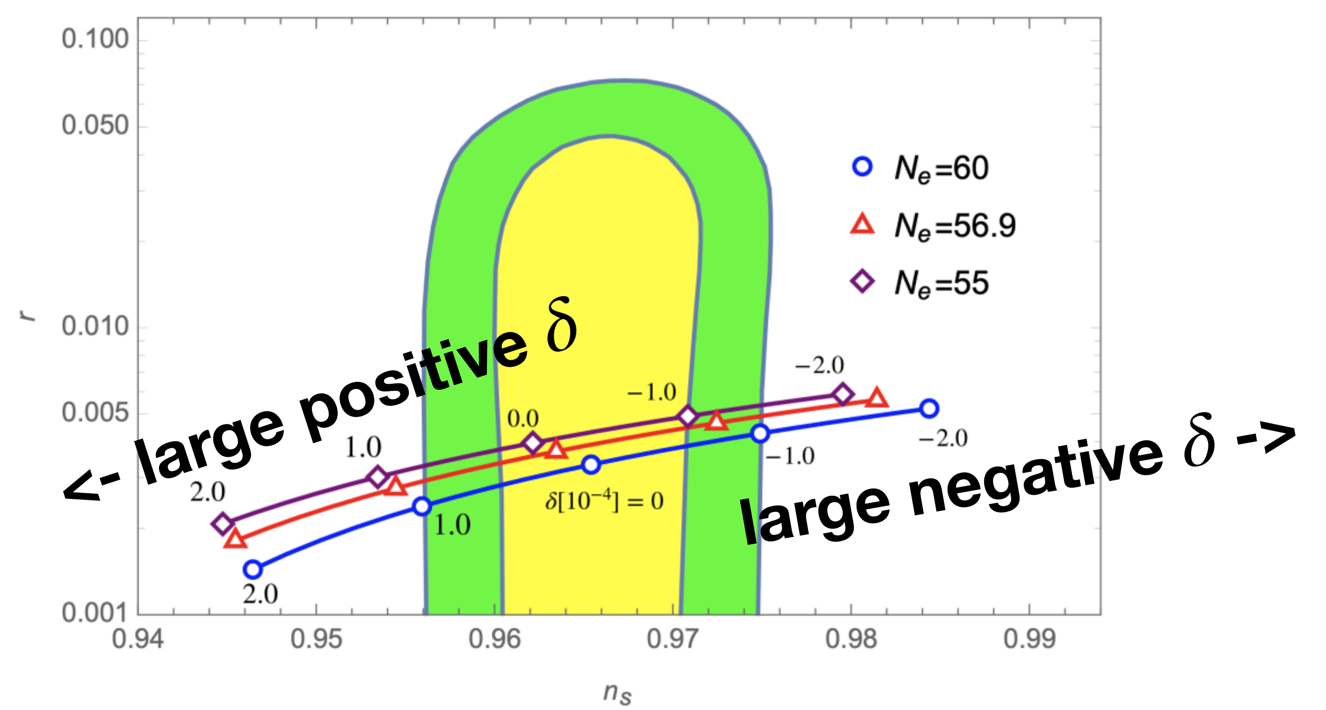
$$V_E(s) = V_0(s)\left[1 - \frac{2}{3}\frac{\gamma}{\beta}\left(\frac{\sigma(s)-1}{\beta}\right) + \cdots\right]$$

where

$$V_0(s) = \frac{1}{4\beta}\left(1 - \frac{1}{\sigma(s)}\right)^2$$ is

for $\gamma = 0$ with $\sigma(s) = e^{\sqrt{2/3}s}$

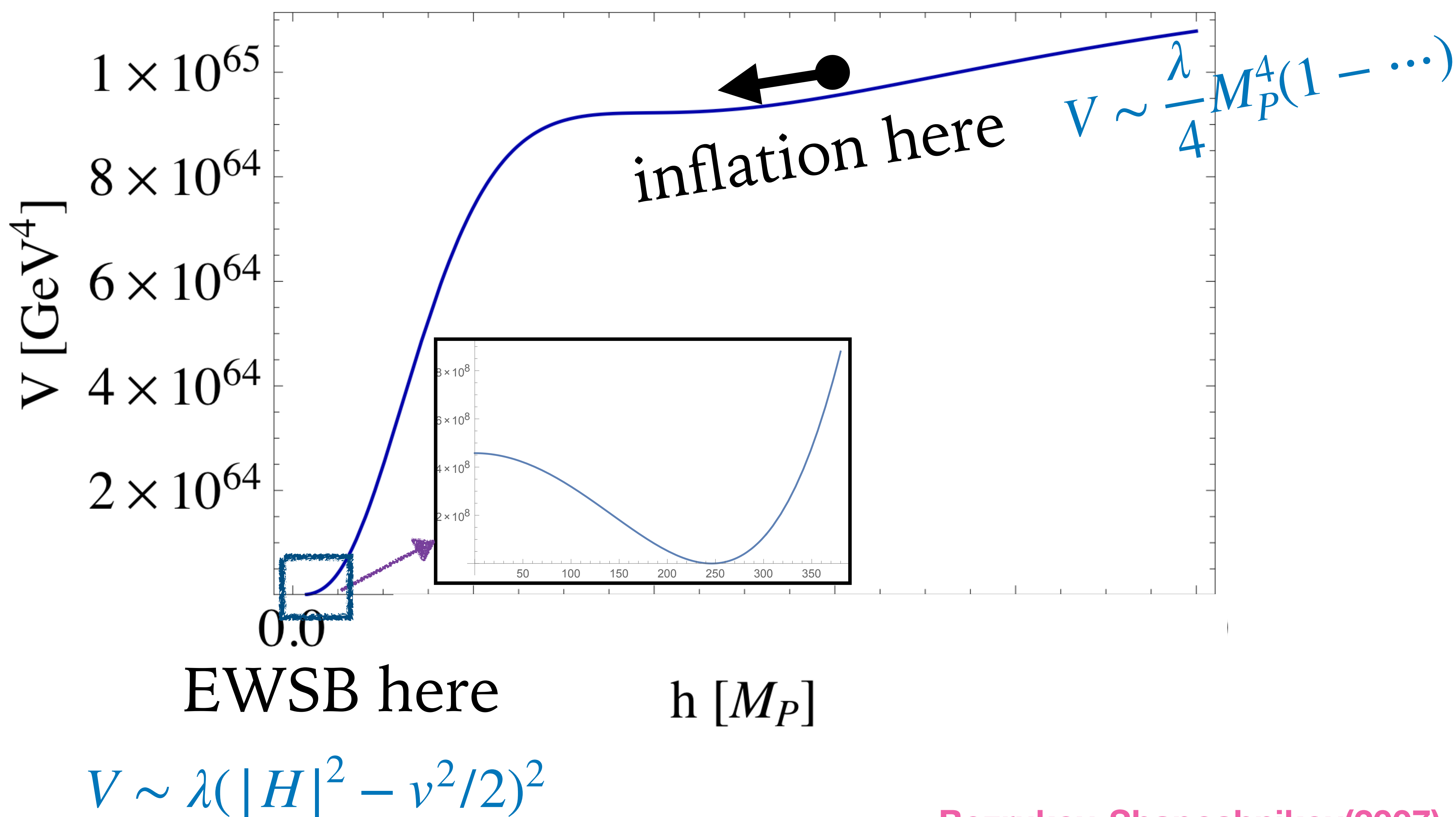
$\delta = \gamma/\beta^2$



D. Y. Cheong, H. M. Lee and SCP, 2002.07981 (PLB)

The gauge invariant action for the Higgs

$$S_{Higgs} = \int d^4x\sqrt{-g}\ \left[\frac{1}{2}\left(M_P^2 + 2\xi|H|^2\right)R + |D_\mu H|^2 - \lambda_H(|H|^2 - v^2/2)^2\right]$$



Bezrukov-Shaposhnikov(2007)
SCP, Yamaguchi (2007)

Planck normalization

we need $$\frac{\lambda}{4\xi^2} \sim 10^{-10}$$

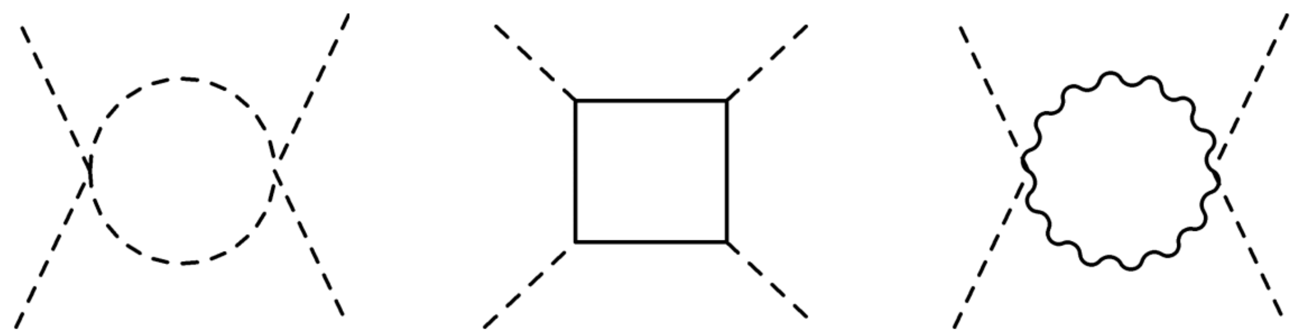
Q. Why so small?

1. $\xi \gg 1, \lambda \sim 1$: Bezrukov & Shaposhnikov (2007) not realistic & theoretically problematic

2. $\xi \sim 1,\ \lambda \ll 1$: Hamada, Kawai, Oda, SCP PRL (2014) critical Higgs

RG running of λ

Simone, Hertzberg, Wilczek (PLB 2009), Hamada, Kawai, Oda, SCP (PRL 2014)

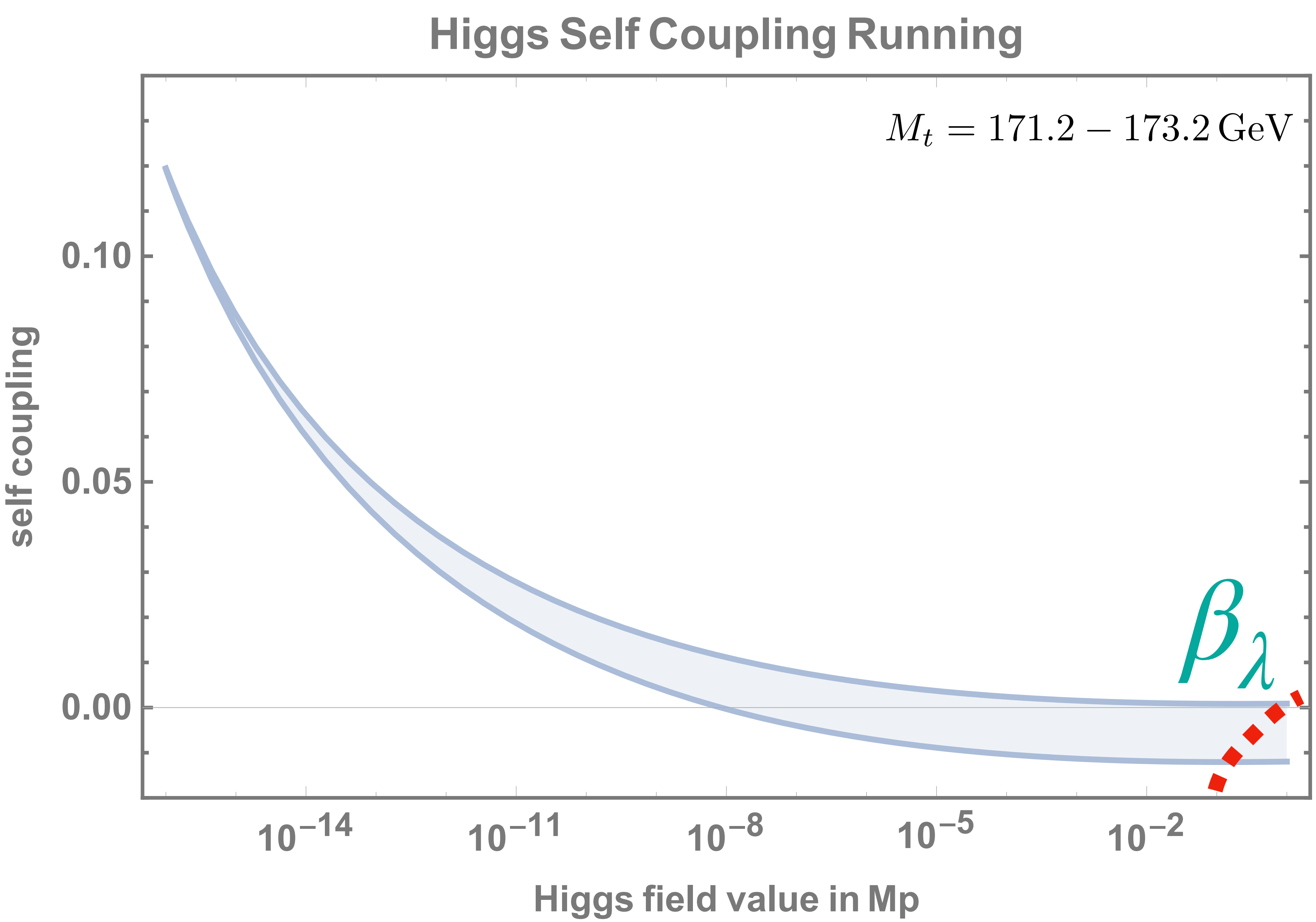


$$\begin{aligned}\beta_\lambda &= \frac{1}{(4\pi)^2}\left[24s^2\lambda^2 - 6y_t^4 + \frac{3}{8}\left(2g^4 + \left(g^2+g'^2\right)^2\right) + \left(-9g^2 - 3g'^2 + 12y_t^2\right)\lambda\right] \\ &+ \frac{1}{(4\pi)^4}\left[\frac{1}{48}\left(915g^6 - 289g^4g'^2 - 559g^2g'^4 - 379g'^6\right) + 30sy_t^6 - y_t^4\left(\frac{8g'^2}{3} + 32g_s^2 + 3s\lambda\right)\right. \\ &+ \lambda\left(-\frac{73}{8}g^4 + \frac{39}{4}g^2g'^2 + \frac{629}{24}sg'^4 + 108s^2g^2\lambda + 36s^2g'^2\lambda - 312s^4\lambda^2\right) \\ &+ \left. y_t^2\left(-\frac{9}{4}g^4 + \frac{21}{2}g^2g'^2 - \frac{19}{4}g'^4 + \lambda\left(\frac{45}{2}g^2 + \frac{85}{6}g'^2 + 80g_s^2 - 144s^2\lambda\right)\right)\right]. \qquad (33)\end{aligned}$$

< 0 ==> weaker at higher energies!!

Higgs criticality! $\lambda \approx 0 \approx \lambda'$

consistent with the current particle physics measurements



see A. Strumia's talk

Near criticality

$$\lambda(\mu_{crit}) \ll \lambda(\mu_{EW}) \sim \frac{1}{8}$$

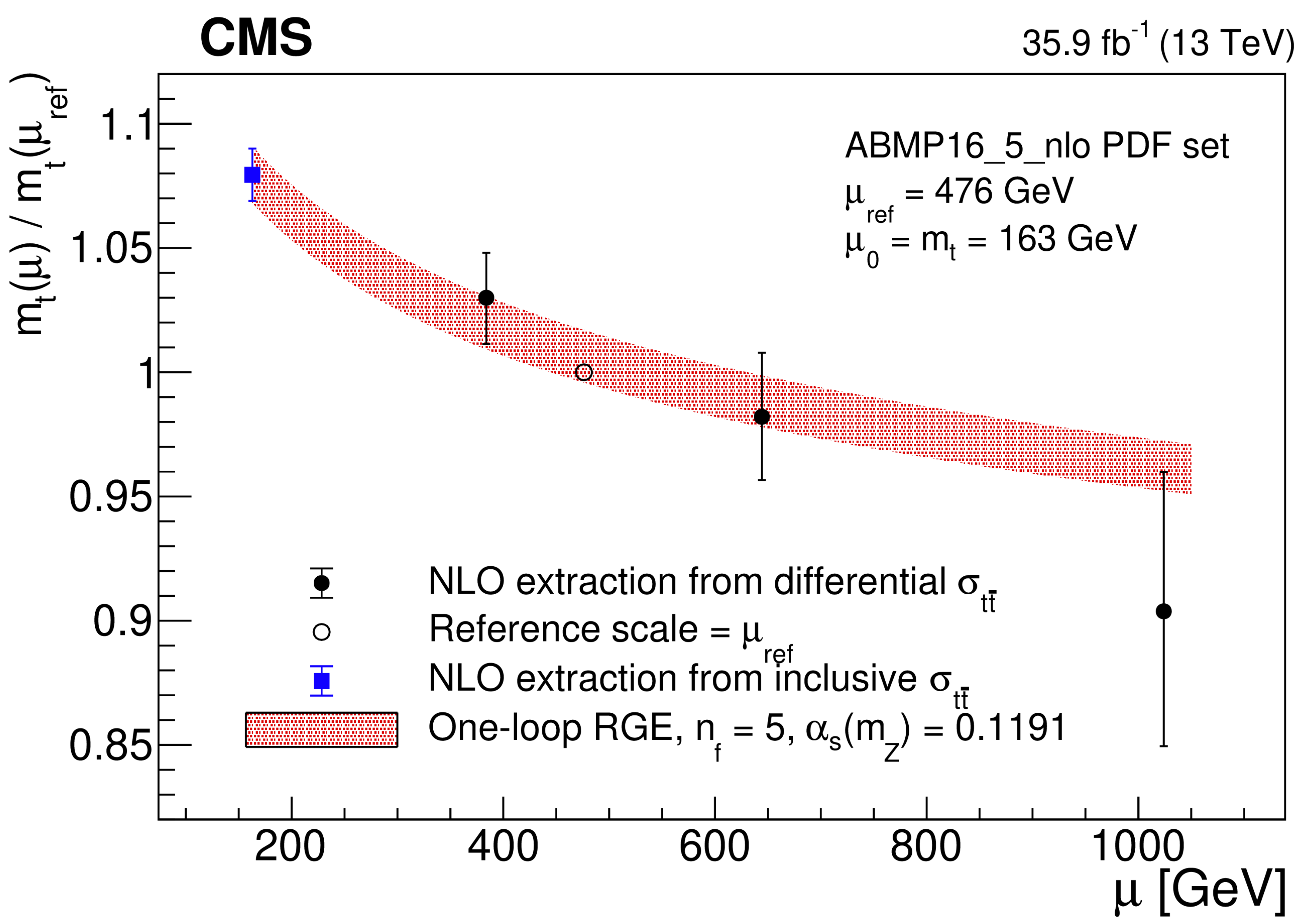
$$\left.\frac{\lambda}{\xi^2}\right|_{\mu_{crit}} \ll \left.\frac{\lambda}{\xi^2}\right|_{\mu_{EW}}$$

fits the Planck data!

$\sim 10^{-10}$

Y. Hamada, H. Kawai, K.-y. Oda, SCP PRL (2014), PRD(2015)

Running top mass
(measured for the first time in 2019)



consistent with the critical Higgs!

CMS-TOP-19-007 ; CERN-EP-2019-189

Finally, Higgs + R^2

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2 + 2\xi H^\dagger H}{2}(R + 2\Lambda_{cc}) + \frac{M_P^2}{12m_S^2}R^2 + \mathscr{L}_{Higgs}\right]$$

- $[\xi H^\dagger H] = Mass^2$, $[R^2] = Mass^4$: both terms are consistent with the gauge symmetries and Lorentz symmetry therefore natural in EFT
- **radiatively induced at loop levels**
- **cut-off** $\Lambda_{Higgs+R^2} \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 m_s^2}\right)M_P$ **> Planck! with** $m_s < M_P/\xi$

(details later..)

$(h, R) \sim (h, \chi)$

$$S_J = \int d^4x \sqrt{-g} \left[\frac{M_P^2 + \xi h^2}{2} R + \frac{M_P^2}{12 m_s^2} R^2 - \frac{1}{2} g^{\mu\nu} \partial_\mu h \partial_\nu h - \frac{g^2}{4} g^{\mu\nu} W_\mu^+ W_\nu^- (h+v)^2 + \cdots - \frac{\lambda}{4} h^4 + \mathcal{L} \right].$$

'Trick' for $f(R)$

$$\begin{aligned} S_J &= \int d^4x \sqrt{-g} \left[\frac{M_P^2 + \xi h^2}{2} \chi + \frac{M_P^2}{12 m_s^2} \chi^2 + \left(\frac{M_P^2 + \xi h^2}{2} + \frac{M_P^2}{6\mu^2} \chi \right) (R - \chi) \right. \\ &\quad \left. - \frac{1}{2} g^{\mu\nu} \partial_\mu h \partial_\nu h - \frac{g^2}{4} g^{\mu\nu} W_\mu^+ W_\nu^- (h+v)^2 + \cdots - \frac{\lambda}{4} h^4 + \mathcal{L} \right] \\ &= \int d^4x \sqrt{-g} \left[\underbrace{\left(\frac{M_P^2 + \xi h^2}{2} + \frac{M_P^2}{6 m_S^2} \chi \right)}_{(*)} R - \frac{M_P^2}{12 \mu^2} \chi^2 \right. \\ &\quad \left. - \frac{1}{2} g^{\mu\nu} \partial_\mu h \partial_\nu h - \frac{g^2}{4} g^{\mu\nu} W_\mu^+ W_\nu^- (h+v)^2 + \cdots - \frac{\lambda}{4} h^4 + \mathcal{L} \right], \end{aligned}$$

New NM coupling

New scalar potential

$(h,\chi) \sim (h,s)$ in Einstein frame

New NM coupling

$$(*) \;=\; \frac{M_P^2}{2}\Omega^2(S),$$
$$\Omega^2 \;\equiv\; 1+\xi\frac{h^2}{M_P^2}+\frac{\chi}{3m_s^2} \equiv e^{\sqrt{\frac{2}{3}}\frac{s}{M_P}}.$$

s: scalaron

Weyl $\quad g^E_{\mu\nu} = \Omega^2 g_{\mu\nu}, \quad g_E = \Omega^8 g.$

↓

$$S = \int d^4x\sqrt{-g_E}\left[\frac{M_P^2}{2}R_E - \frac{1}{2}(\partial_\mu s)^2 - \frac{1}{2}\Omega^{-2}(\partial_\mu h)^2 - V(h,s) + \cdots\right]$$

$$V(h,s) = \frac{\lambda}{4}\Omega^{-4}h^4 + \frac{3}{4}m_S^2M_P^2\left(1-\left(1+\frac{\xi h^2}{M_P^2}\right)\Omega^{-2}\right)^2$$

(Higgs-R^2) is equivalent to (Higgs-Scalaron)!

Perturbative cutoff of Higgs-R^2

$$V(h,s) = \frac{\lambda}{4}\Omega^{-4}h^4 + \frac{3}{4}m_S^2 M_P^2\left(1 - \left(1 + \frac{\xi h^2}{M_P^2}\right)\Omega^{-2}\right)^2$$

expand around (0,0)

$$V(h,s) = \frac{\lambda}{4}\sum_{k=0}^{\infty}\frac{(-2)^k}{k!}\left(\frac{\sqrt{2/3}}{M_P}\right)^k s^k h^4 + \frac{3}{4}m_S^2 M_P^2\left(1 - \left(1 + \frac{\xi h^2}{M_P^2}\right)\sum_{k=0}^{\infty}\frac{(-1)^k}{k!}\left(\frac{\sqrt{2/3}}{M_P}\right)^k s^k\right)^2$$

$$= \frac{\lambda}{4}h^4 + \frac{3\xi^2 m_s^2}{4M_P^2}h^4 + \frac{1}{2}m_s^2 s^2 - \frac{m_s^3}{\sqrt{6}M_P}s^3 + \frac{7m_s^2}{36M_P^2}s^4 - \frac{\sqrt{\frac{3}{2}}\xi m_s^2}{M_P^2}sh^2 + \frac{3\xi m_s^2}{2M_P^2}h^2 s^2$$

$$-\frac{\lambda}{\sqrt{6}M_P}sh^4 - \frac{m_s^2}{6\sqrt{6}M_P^3}s^5 + \left(\frac{\lambda}{3M_P^2} + \frac{\xi^2 m_s^2}{M_P^4}\right)h^4 s^2 + \frac{31m_s^2}{1620M_P^4}s^6 + \cdots,$$

$\Rightarrow$

$$\Lambda_{Higgs+R^2} \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 m_s^2}\right)M_P$$

more explicitly...

$$\Lambda_{h^4 s^{k+j}} \sim \left[\frac{4}{3}\frac{M_P^2}{\xi^2 m_s^2}\frac{1}{\sum C_k \sum C_j}\right]^{\frac{1}{k+j}} M_P \gtrsim M_P, \quad (k+j = 1, 2, \cdots)$$

$$\Lambda_{h^4 s^k} \sim \left[\frac{4}{\lambda \sum_k (2)^k C_k}\right]^{\frac{1}{k}} M_P \gtrsim M_P, \quad (k = 0, 1, 2, \cdots)$$

$$\Lambda_{s^{k+j>4}} \sim \left[\frac{3}{4\sum_k C_k \sum_j C_j}\frac{M_P^2}{m_s^2}\right]^{\frac{1}{k+j-4}} M_P \gtrsim M_P, \quad (k+j = 4, 5, \cdots)$$

$$\Lambda_{s^{k>4}} \sim \left[\frac{3}{2\sum_k C_k}\frac{M_P^2}{m_s^2}\right]^{\frac{1}{k-4}} M_P \gtrsim M_P, \quad (k = 5, 6, \cdots)$$

where $C_k = \frac{(-1)^k \sqrt{2/3}}{k!}$, $k = 0, 1, 2, \cdots$.

$$\Lambda \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 m_s^2}\right) M_P$$

scalaron (s) unitarizes the theory

(Just as the Higgs does for the SM)

$$\Lambda \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 m_s^2}\right) M_P > M_P$$

$$M_P/\xi > m_s$$

Therefore, we take Higgs-R^2 theory as a natural setup to UV complete the Higgs inflation model.

(cf) Without s, $\Lambda_{Higgs} \sim \dfrac{M_P}{\xi}$ or $\dfrac{M_P}{\sqrt{\xi}}$ => problematic when $\xi \gg 1$

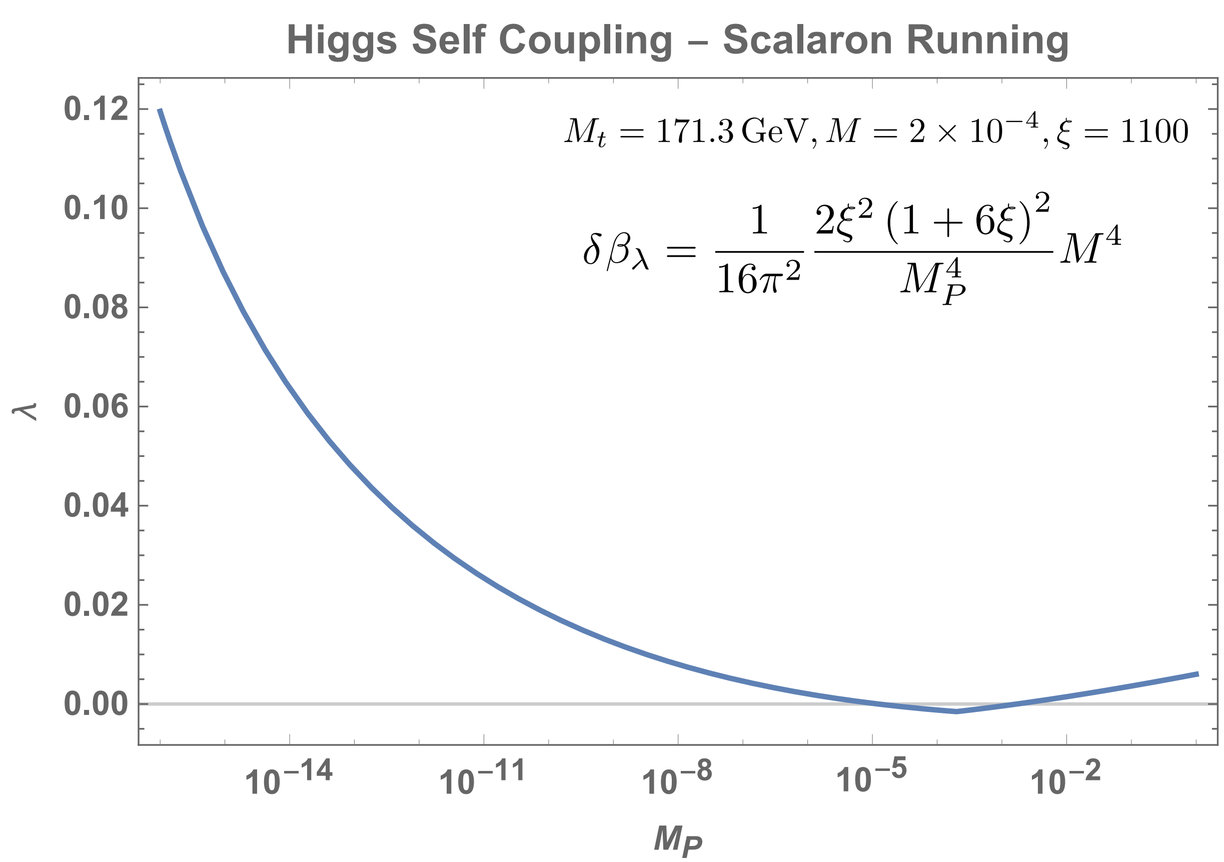
Espinosa (2009), Burgess (2010)

Running Parameters (M, ξ, λ)

scalaron mass $$\beta_\alpha = -\frac{1}{16\pi^2}\frac{(1+6\xi)^2}{18}, \qquad \alpha = \frac{M_P^2}{12M^2}$$

NM coupling $$\beta_\xi = -\frac{1}{16\pi^2}\left(\xi + \frac{1}{6}\right)\left(12\lambda + 6y_t^2 - \frac{3}{2}g'^2 - \frac{9}{2}g^2\right),$$

Higgs self coupling $$\beta_\lambda = \beta_{\rm SM} + \frac{1}{16\pi^2}\frac{2\xi^2(1+6\xi)^2 M^4}{M_P^4},$$



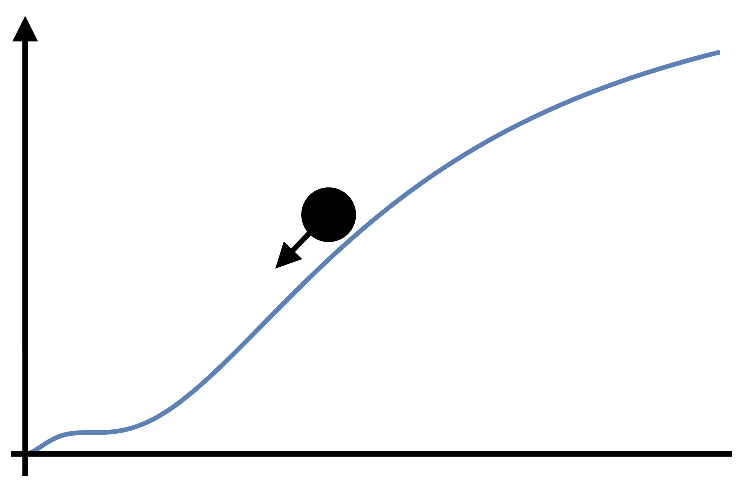
D.Gorbunov, A.Tokareva
Phys.Lett. B788 (2019) 37-41

Phenomenology of Higgs-R^2 inflation

Q. theory is given, what do you want to know?

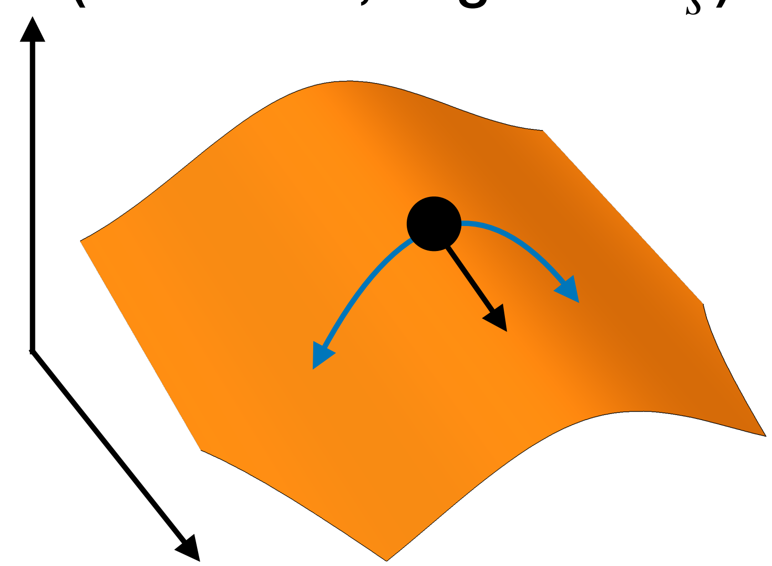
Evolution in Higgs-R^2 inflation

1. Near Inflection Point
(Effective single field, USR)



D. Y. Cheong, S. M. Lee, SCP JCAP 01 (2021) 032

2. Tachyonic instability
(Multi-field, negative m_s^2)

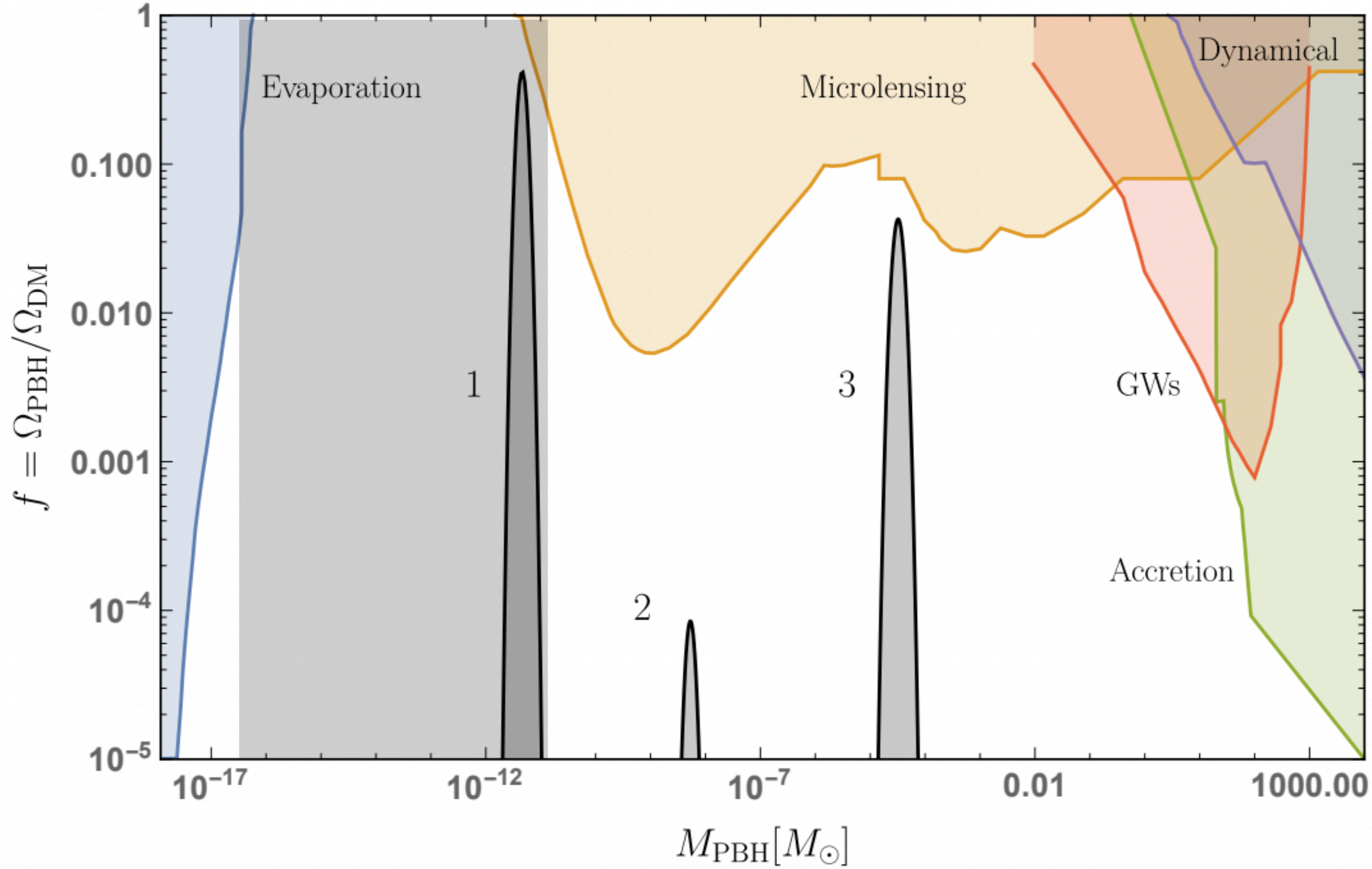


D. Y. Cheong, K. Kohri, SCP 2205.14813

Enhanced Curvature Perturbation at small scales
GW & PBH Production
==> see Dhong Yeon Cheong's talk

PBH as whole Dark Matter

window here! (no BSM?)



+GWs

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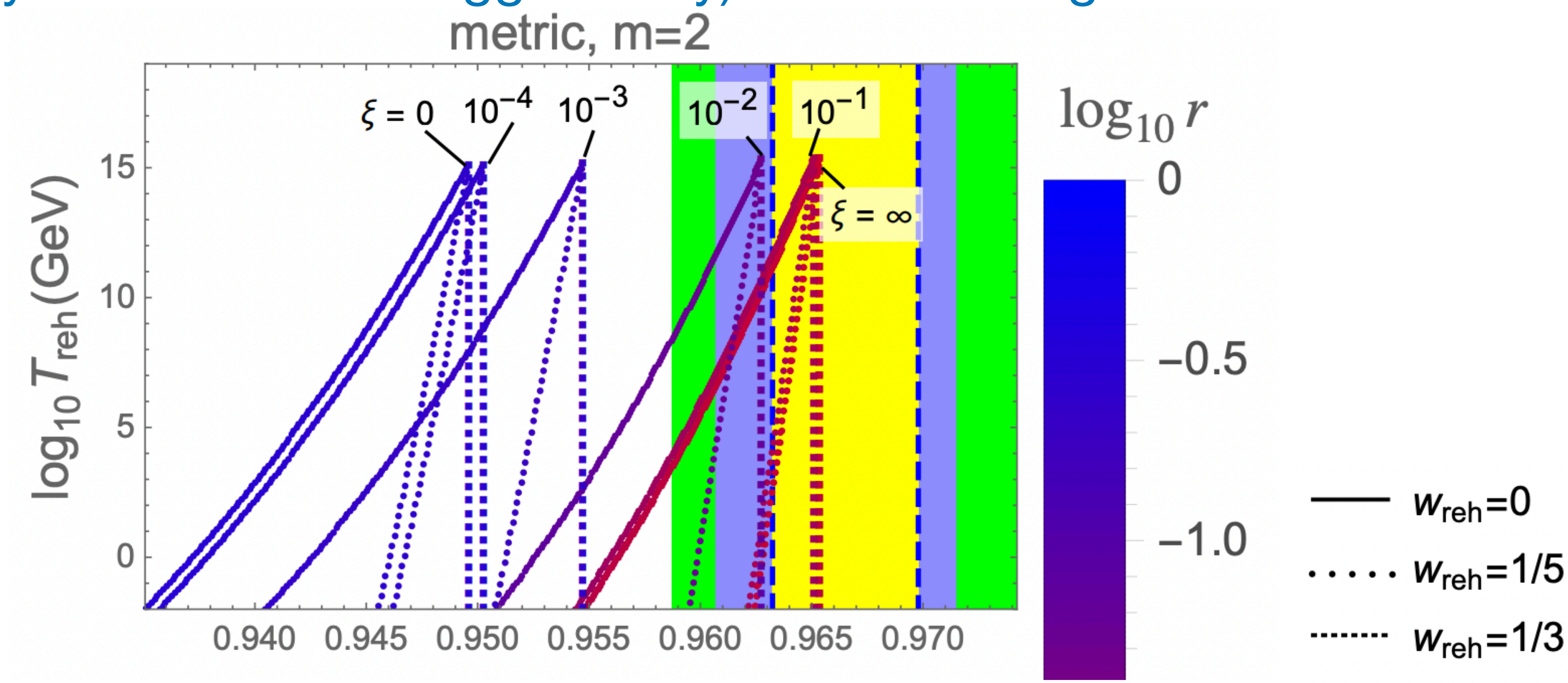
D. Y. Cheong, K. Kohri, SCP 2205.14813

Reheating

unlike other models, **reheating is built-in** in Higgs-R^2 inflation

He, Jinno, Kamada, SCP, Starobinsky, Yokoyama, *PLB* 791 (2019) 1812.10099
Cheong, Lee, SCP, JCAP 02 (2022) 2111.00825

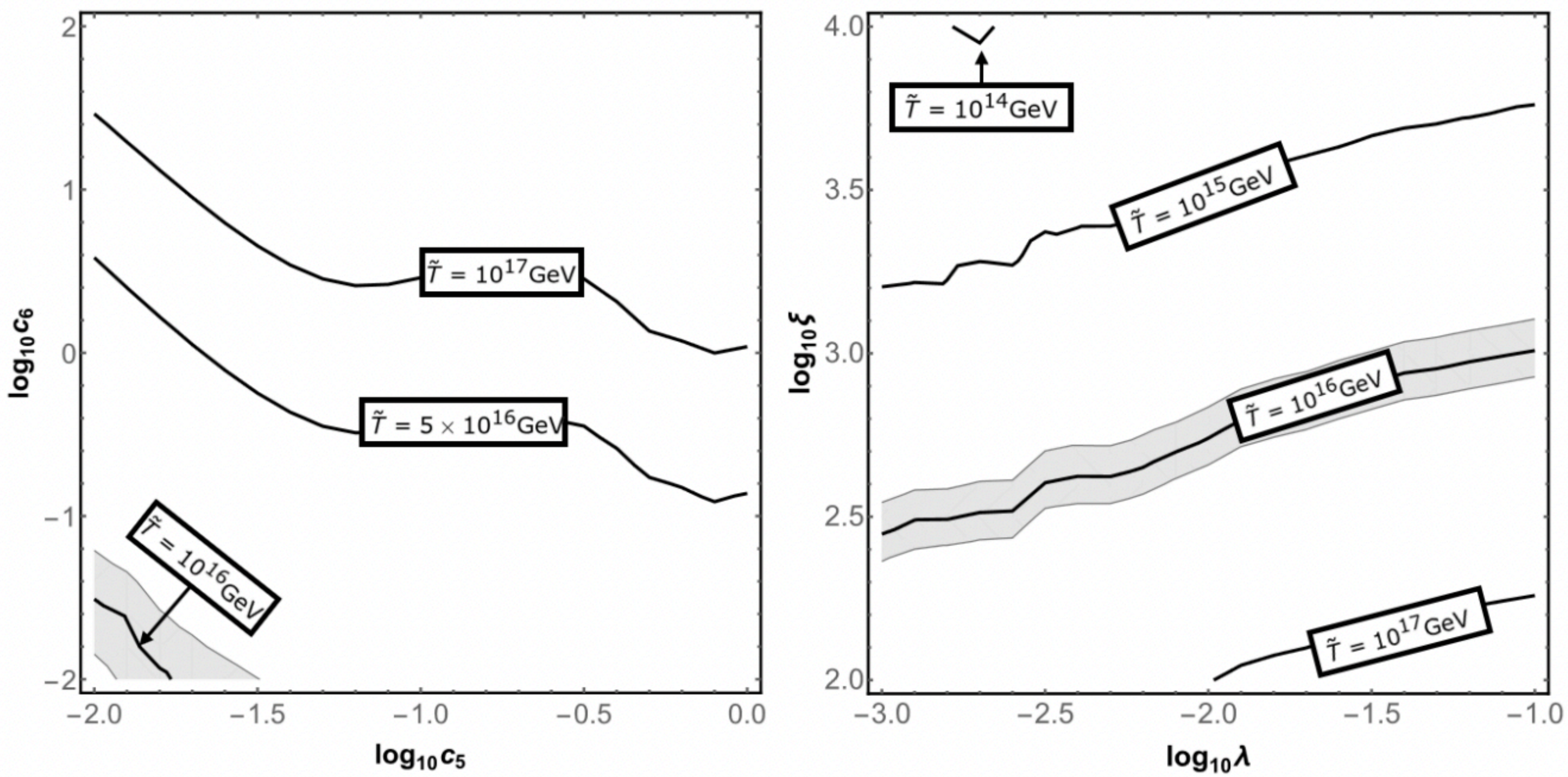
- Potential is given => dynamical evolution of inflation => (tachyonic instability + oscillation + Higgs decay) ==> reheating



- Palatini formulation (Levi-Civita connection) gives different predictions

Leptogenesis

Lee, Oda, SCP JHEP 03 (2021) , 2010.07563



$$\mathcal{L}_{\text{dim-5},J} = \frac{c_5}{M_P}(\overline{L}_J\widetilde{\Phi}_J)(\widetilde{\Phi}_J L_J)^\dagger,$$

$$\mathcal{O}_6 = -\frac{c_6}{M_P^2}\Phi_J^\dagger\Phi_J\partial_\mu j_L^\mu = \frac{c_6}{M_P^2}(\partial_\mu\phi_J^2)j_L^\mu = \frac{c_6}{M_P^2}(\partial_t\phi_J^2)j_L^0,$$

Lepton number violation

Rapid moving at
the end of inflation
(spontaneous CPT violation)

==> Spontaneous Leptogenesis

Conclusion

- An EFT model based on the SM Higgs field & Gravity $\mathscr{L}/\sqrt{g} \ni R + \xi H^\dagger H R + R^2 - \lambda (H^\dagger H)^2 + \cdots$ to provide the successful **cosmological inflation** (indeed the best fit model to the Planck data) in a way of **keeping the successful EWSB** in the SM.

- With the **RG running** effects, the model is natural ($\lambda/\xi^2 \sim 10^{-10}$ during inflation) and **unitary** with a high cutoff scale $\Lambda \sim \mathcal{O}\left(M_P^2/\xi^2 m_s^2\right) M_P > M_P$ thanks to the scalaron s associated with R^2.

- PBH dark matter, GW, leptogenesis, reheating … phenomenological studies are actively on-going

- The model links the EW scale and the inflationary scale via the common field, Higgs, so that we can **learn from both sides: particle physics@ colliders and cosmology & astrophysics**.