Higgs inflation, update

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5 Dec 2019

IBS-PNU Joint Workshop on Physics beyond the Standard Model
December 4-7, 2019 at the Paradise Hotel, Busan

Reasons for BSM

- DM
- Matter genesis
- Inflation
- and whatever theoretical problems you like to solve

Observation: Our old good friend, **Higgs**, is even greater than we had expected.

thoughts: Maybe, we don't need BSM.

Higgs inflation

- Electroweak symmetry breaking (1965)
- Inflation (2010)

Higgs full power

- Electroweak symmetry breaking (1965)
- Inflation (2010)
- Reheating & Preheating (2015, 2018, 2019)
- Dark matter by PBH (2018,2019)
- $\Lambda \geq M_P$ (2015, 2018)
- dS conjecture (2019)
- Baryogenesis (2020(?))

References

- **Clockwork for Higgs inflation** SCP, C.S Shin EPJC 79 (2019) no.6, 529
- **On the violent preheating in the mixed Higgs-R^2 inflationary 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 arXiv:1904.05699
- **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 to appear
- **Leptogenesis in Higgs inflation**, Kuwahara, Omura, SCP to appear

Outline

- Review: Higgs, Higgs+R^2 inflation and f(R)
- Discussions
  - ☑ Fine-tuning problem in Higgs inflation
  - ☑ Cut-off scale
  - ☑ PBH production
  - ☑ (more) Preheating, Palatini, Swampland conjecture…

NM-inflation

slow-roll inflation with nm-coupling in Jordan frame

non-minimal coupling

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

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

In Einstein frame: $U=\frac{M_{\rm Pl}^4}{(M^2+K(\phi))^2}V(\phi)$

Condition for large field inflation: $\partial_\phi K>0,\ \partial_\phi V>0 \quad \lim_{\phi\to\infty}\frac{V}{K^2}=Const>0.$

SCP-Yamaguchi JCAP(2008)

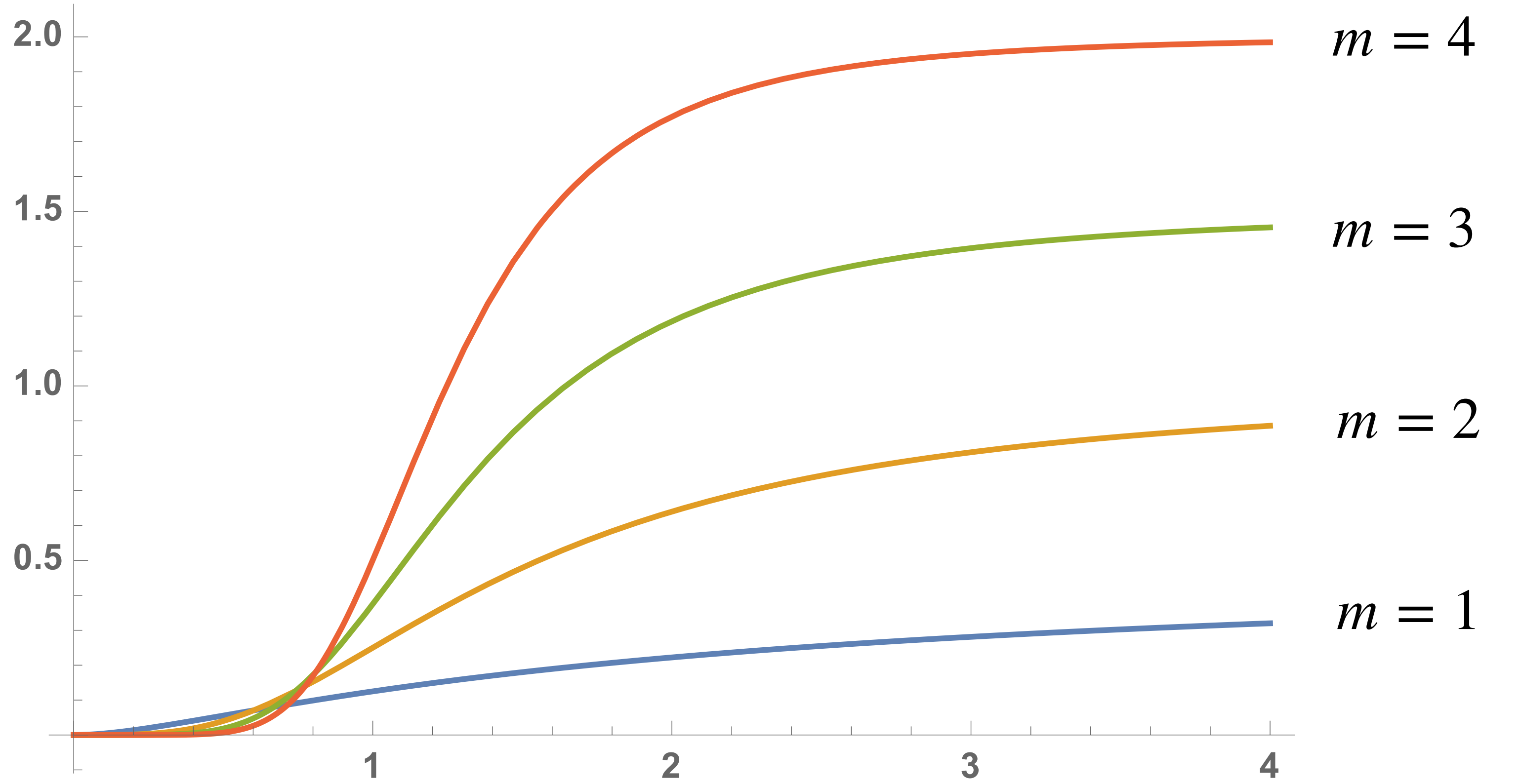
NM-inflation

$$V(h) = \frac{\lambda}{2m} h^{2m}$$

$$K(h) = \xi h^m$$

$$U = \frac{M_{\rm Pl}^4 \lambda}{2ma^2}\left(1 + \frac{M^2}{a}\phi^{-m}\right)^{-2}$$

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



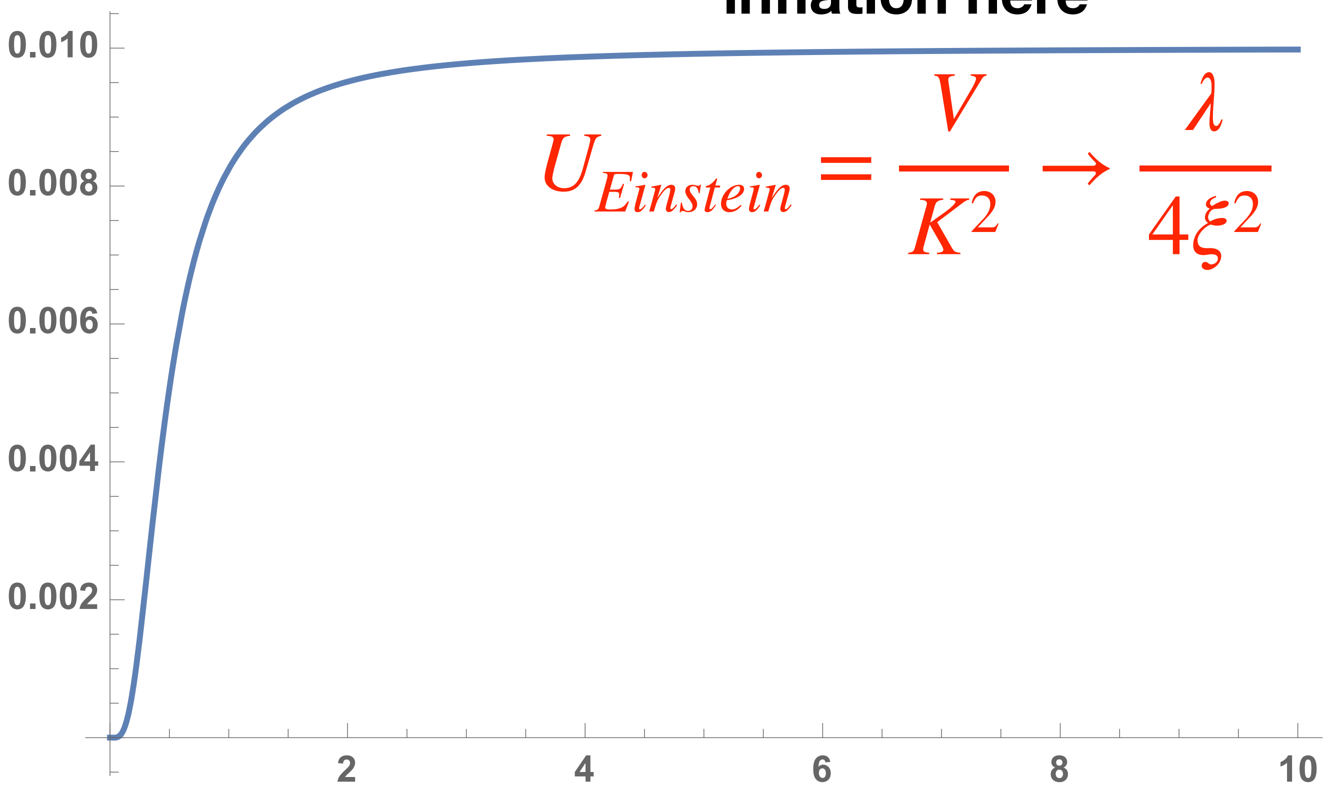
SCP-Yamaguchi JCAP(2008)

'Higgs' inflation

a particular case of NM inflation with m=2

$$V(h) = \frac{\lambda}{4}(h^2 - v^2)^2$$

$$K(h) = \xi h^2$$



$$U_{Einstein} = \frac{V}{K^2} \to \frac{\lambda}{4\xi^2}$$

Bezrukov-Shaposhnikov, PLB(2007)

'Higgs' inflation

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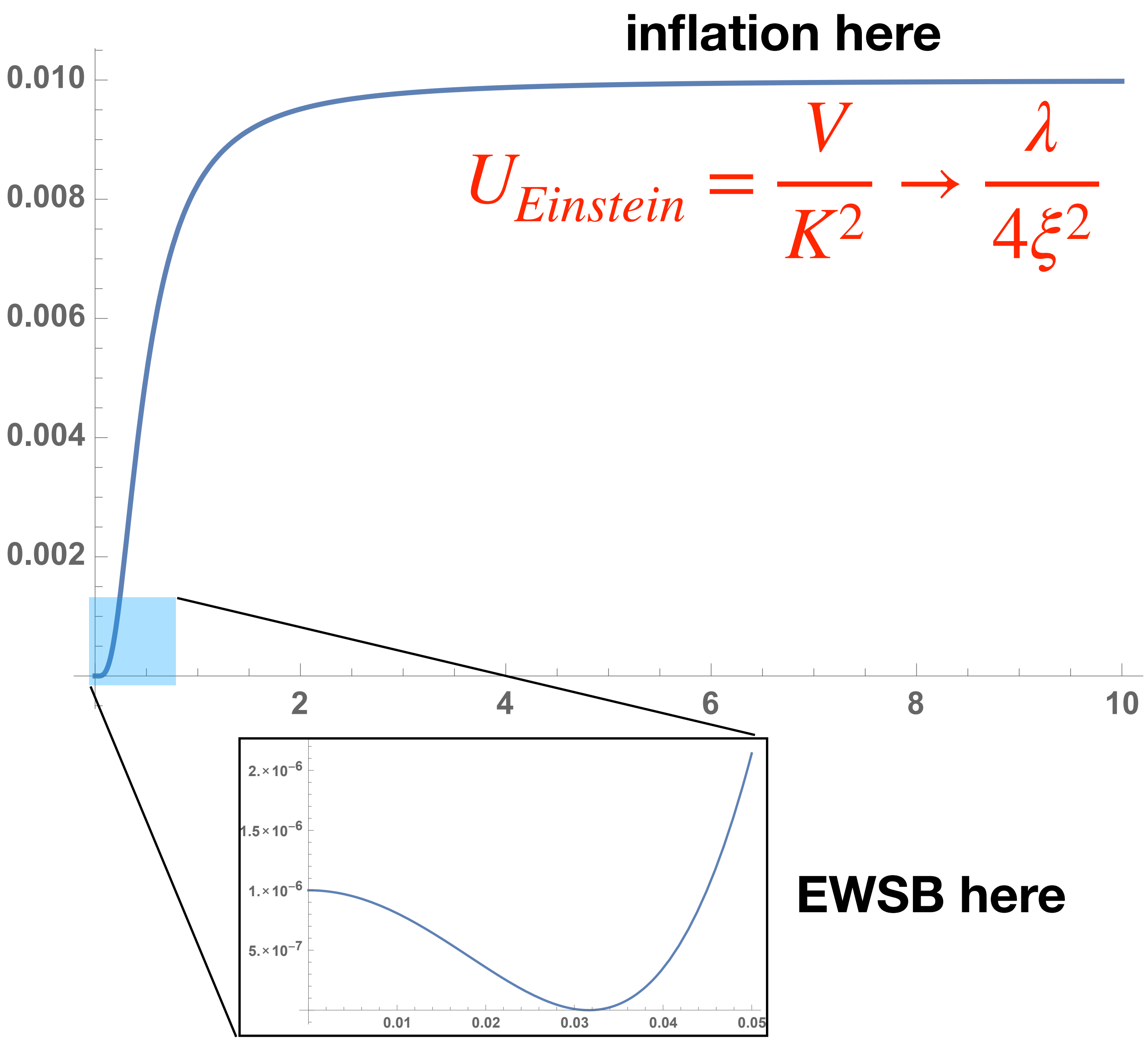
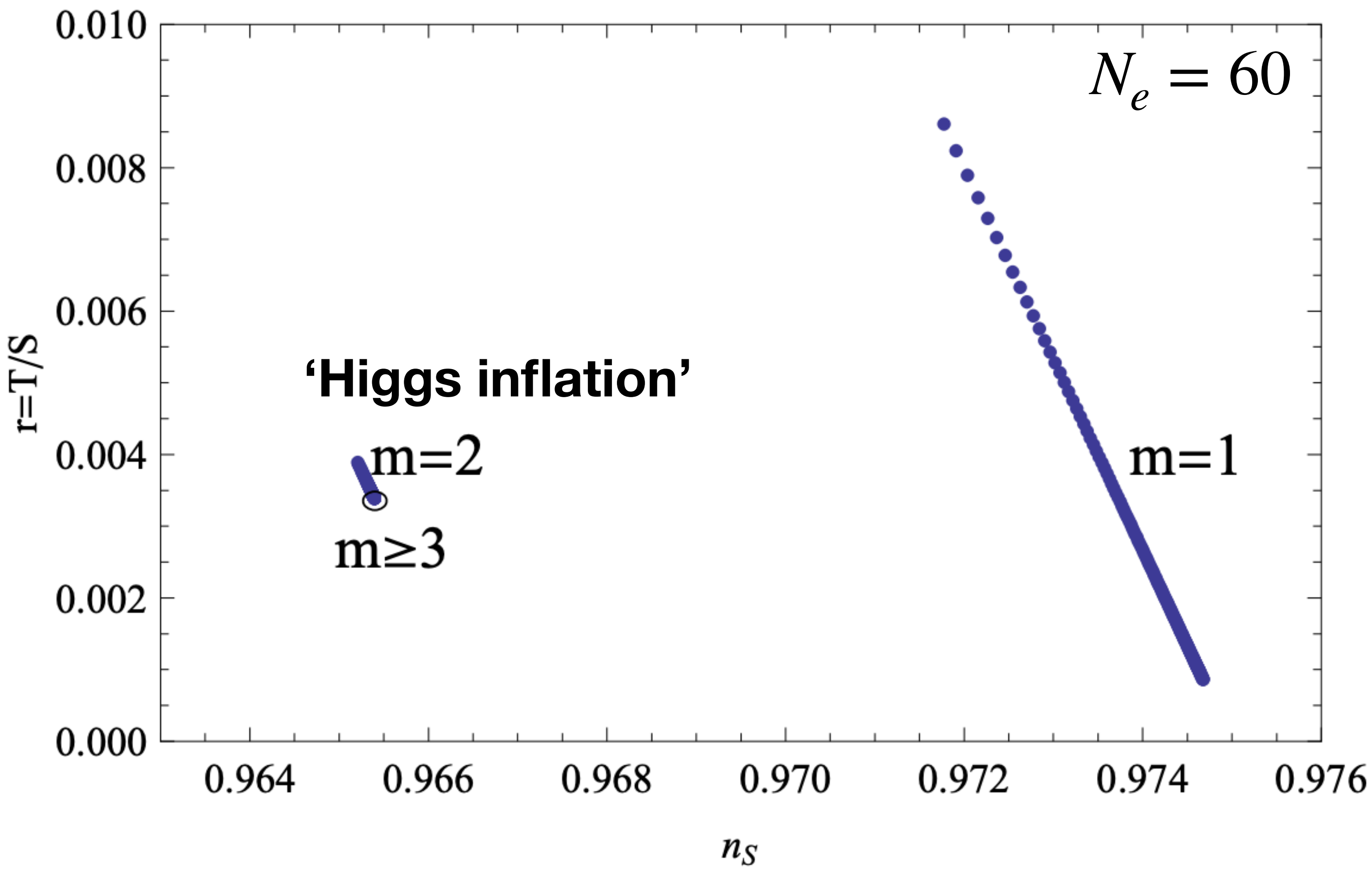
$$K(h) = \xi h^2$$



$$U_{Einstein} = \frac{V}{K^2} \rightarrow \frac{\lambda}{4\xi^2}$$

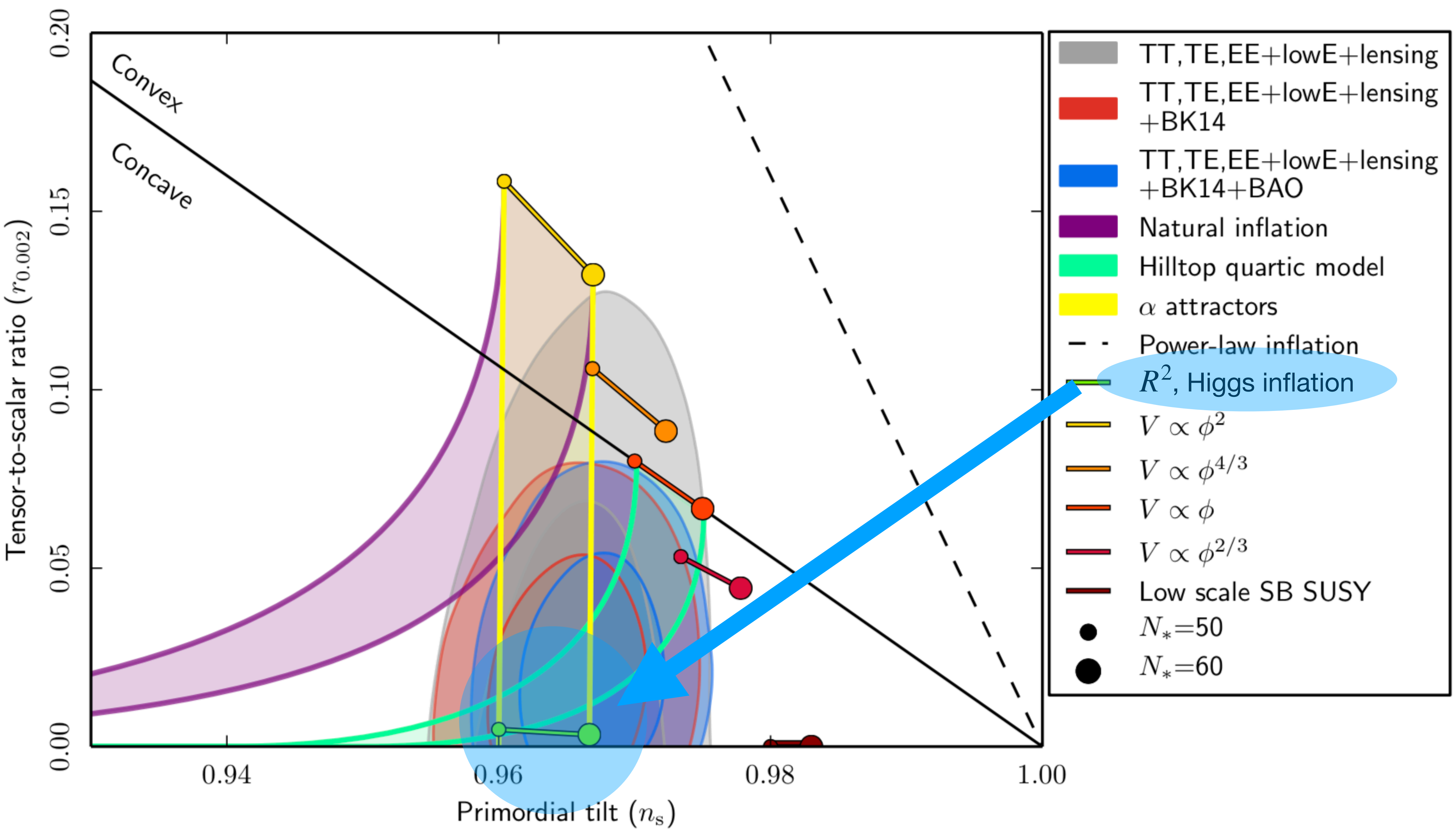
Bezrukov-Shaposhnikov, PLB(2007)

Predictions of NM-inflation



SCP-Yamaguchi JCAP(2008)

The best fit model for Planck DATA



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

Equivalence of Starobinsky & Higgs

R² <=> Higgs

unimportant during slow-roll

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

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

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

Starobinsky (1980)

More generically

f(R) <=> NM inflation

Note:

The theory with $S = \int d^4x \sqrt{-g} f(R)$ **is equivalent to a scalar theory** $\int d^4x \sqrt{-g} f(\phi) + f'(\phi)(R - \phi)$

ϕ : **auxiliary**

$$\delta\phi : f''(\phi)(R - \phi) = 0$$

$$R = \phi$$

equivalent scalar theory

$$f(R)$$

$$V(\phi) = f'(\phi)\phi - f(\phi)$$
$$K(\phi) = f'(\phi)$$

Fine tuning

A fine tuning problem

To fit $$\frac{\delta T}{T} \sim \frac{U^{3/2}}{HU'} \sim 10^{-5}$$ or $$\frac{U}{\epsilon} \sim (0.027 M_P)^4$$ (COBE)

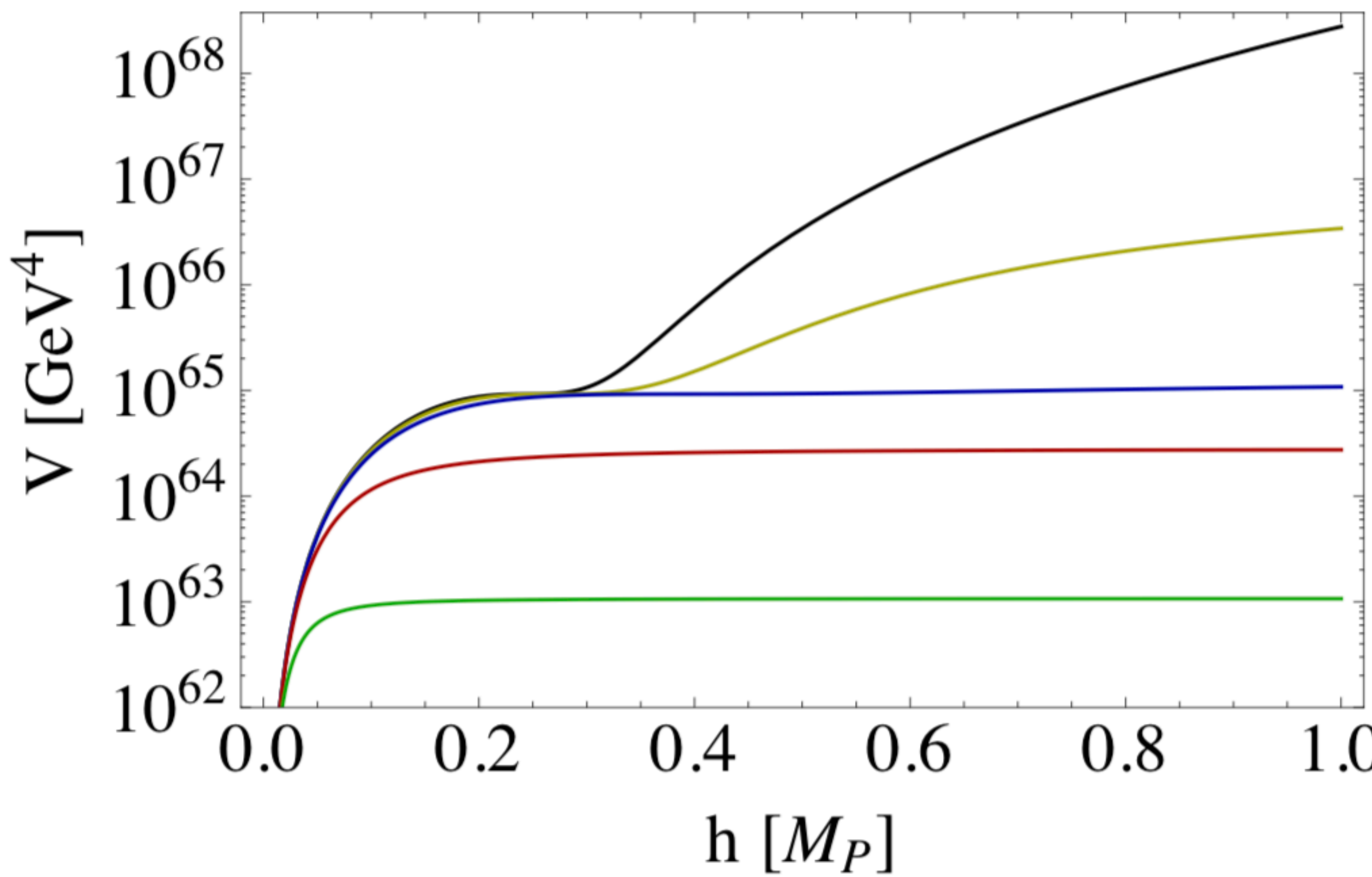
we need

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

Q. Why so small?

Critical Higgs inflation

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



Potential becomes flat due to quantum correction

$\lambda(\mu_{crit}), \lambda'(\mu_{crit}) \sim 0$

$m_t^{\text{pole}} \simeq 170 - 172$ GeV

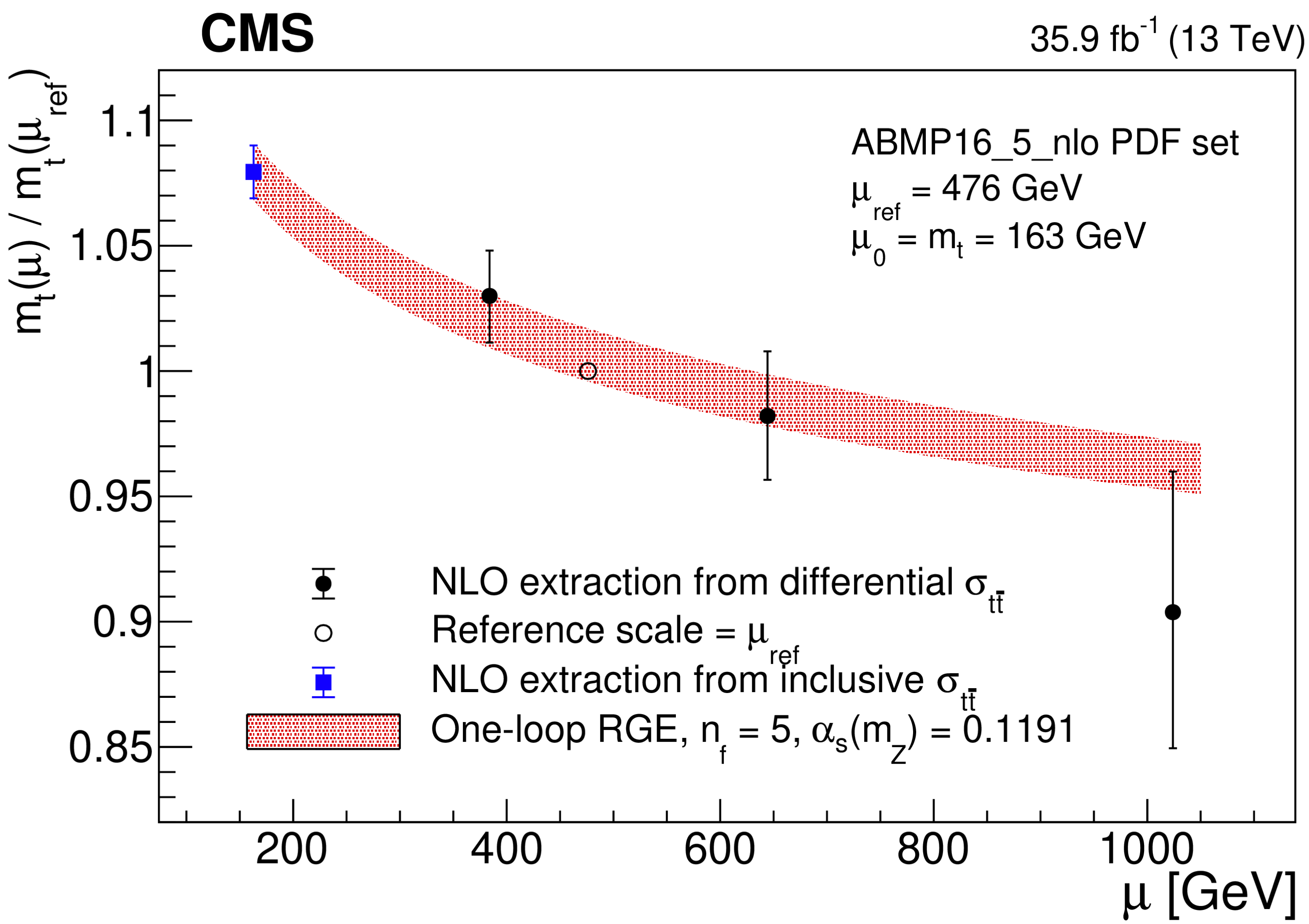
Near criticality

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

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

e.g. $\xi \sim \mathcal{O}(10-100), \lambda(\mu_{crit}) \sim \mathcal{O}(10^{-8}-10^{-6})$

Running top mass
(measured for the first time)



~ consistent with the critical Higgs

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

Clockwork Higgs inflation

SCP, C.S Shin EPJC (2019)

$$S_J = \int d^4x\sqrt{-g}\left(\frac{M_P^2}{2}(1+K(\phi))R - \frac{1}{2}\sum_i(\partial\phi_i)^2 - V_{CW} - V_{inf}\right)$$

CW structure: $K = \sum_{i=1}^{N+1}\xi_i\phi_i^2$ $\quad V_{CW} = \sum_{i=1}^{N}\frac{m^2}{2}(\phi_{i+1} - q\phi_i)^2$ $\quad V_{inf} = \frac{\lambda}{4}\phi_1^4$

$\xi_i \sim 1$ $\quad q \sim 1$

no fine-tuning here $\quad$ **this breaks the CW shift symmetry**

$$\delta\phi_i : \phi_{i+1} \sim q\phi_i \Rightarrow \phi_{N+1} \sim q\phi_N \sim q^2\phi_{N_1}\cdots \sim q^N\phi_1 \qquad \phi_1 \sim \frac{1}{q^N}\phi_{(0)}$$

zero mode (inflaton)

$$\frac{\lambda_{eff}}{\xi^2} \sim 10^{-10} \Longleftarrow \lambda_{eff} \sim \frac{\lambda}{q^{4N}} \sim \frac{\lambda}{10^{10}} \Longleftarrow$$

Cutoff scale

Pure Higgs inflation

- Naïve cutoff scale from the expansion of U(h) near $h = 0 + \delta h$ (or EW vacuum)
- $V(h) = \lambda h^4 - \frac{\lambda}{\Lambda^2} h^6 + \cdots, \Lambda \sim M_P/\xi$ [Burguess et. al. (2010)]
- Note: This is NOT a problem for inflationary dynamics when $h = h_{inf} + \delta h$.

Cutoff scale of Higgs-R^2

Unitary gauge $f(R) = R + R^2$

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

'Trick' for $f(R)$

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

New NM coupling

New scalar potential

Higgs-Scalaron

$$(*) \;=\; \frac{M_P^2}{2}\Omega^2(S),$$

New NM coupling

$$\Omega^2 \;\equiv\; 1+\xi\frac{h^2}{M_P^2}+\frac{\chi}{3m_s^2} \equiv e^{\sqrt{\frac{2}{3}}\frac{s}{M_P}}$$

s: Scalaron

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

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

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

Higgs-Scalaron potential

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

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

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

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

NOTE: expansion near (h,s)=(0,0) (cf) (h_{inf},s_{inf})

Cut-off scale

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

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

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

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

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

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

‘light’ scalaron erases the low-cutoff issue

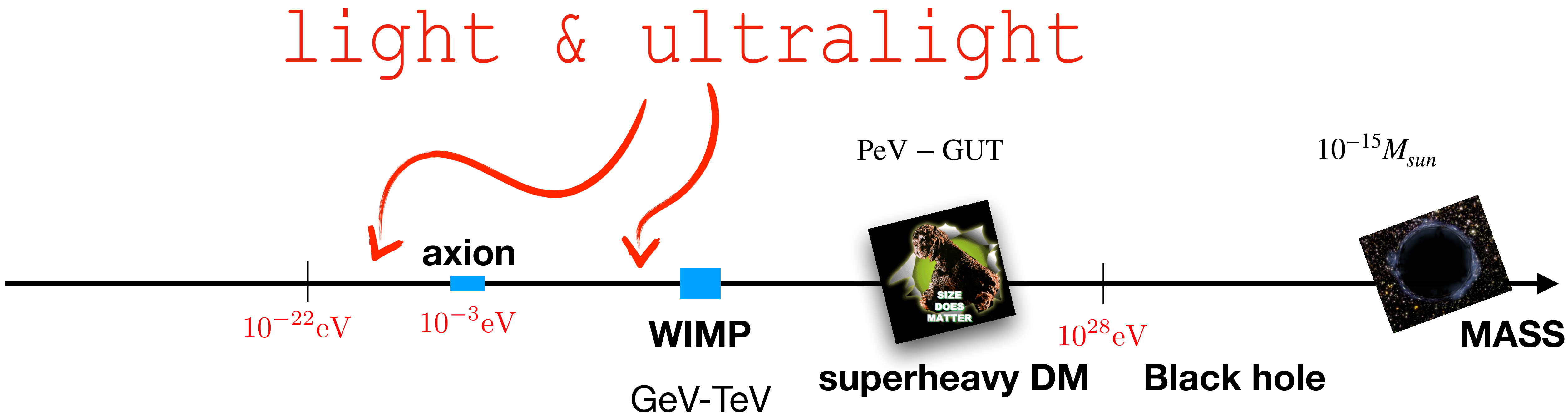
(Just as the Higgs does for the SM)

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

↑

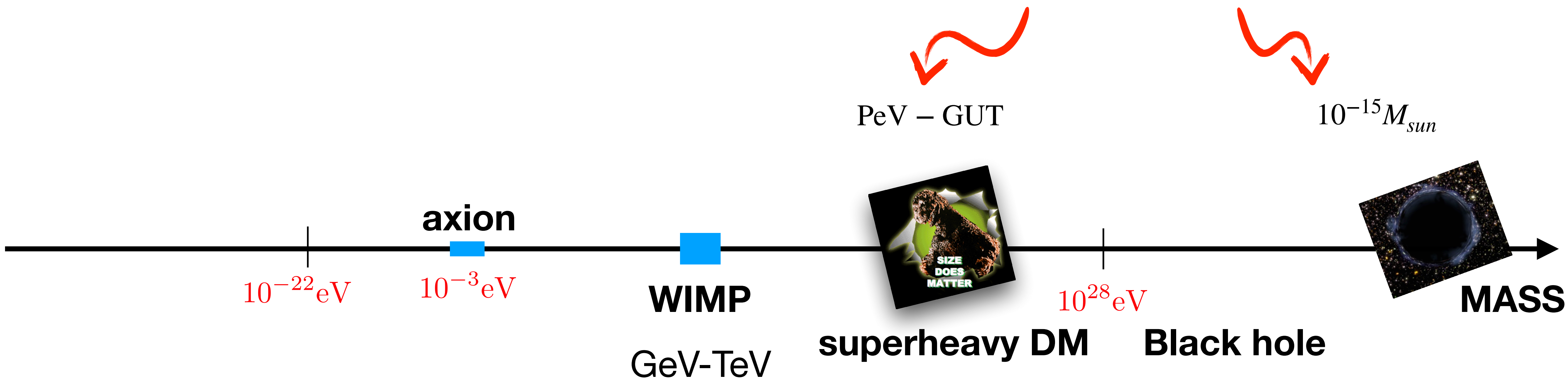
$$M_P/\xi > m_s$$

PBH



light & ultralight
PeV – GUT
$10^{-15} M_{sun}$
axion
10^{-22}eV
10^{-3}eV
WIMP
GeV-TeV
SIZE DOES MATTER
superheavy DM
10^{28}eV
Black hole
MASS

SUPERHEAVY DM



PBH DM

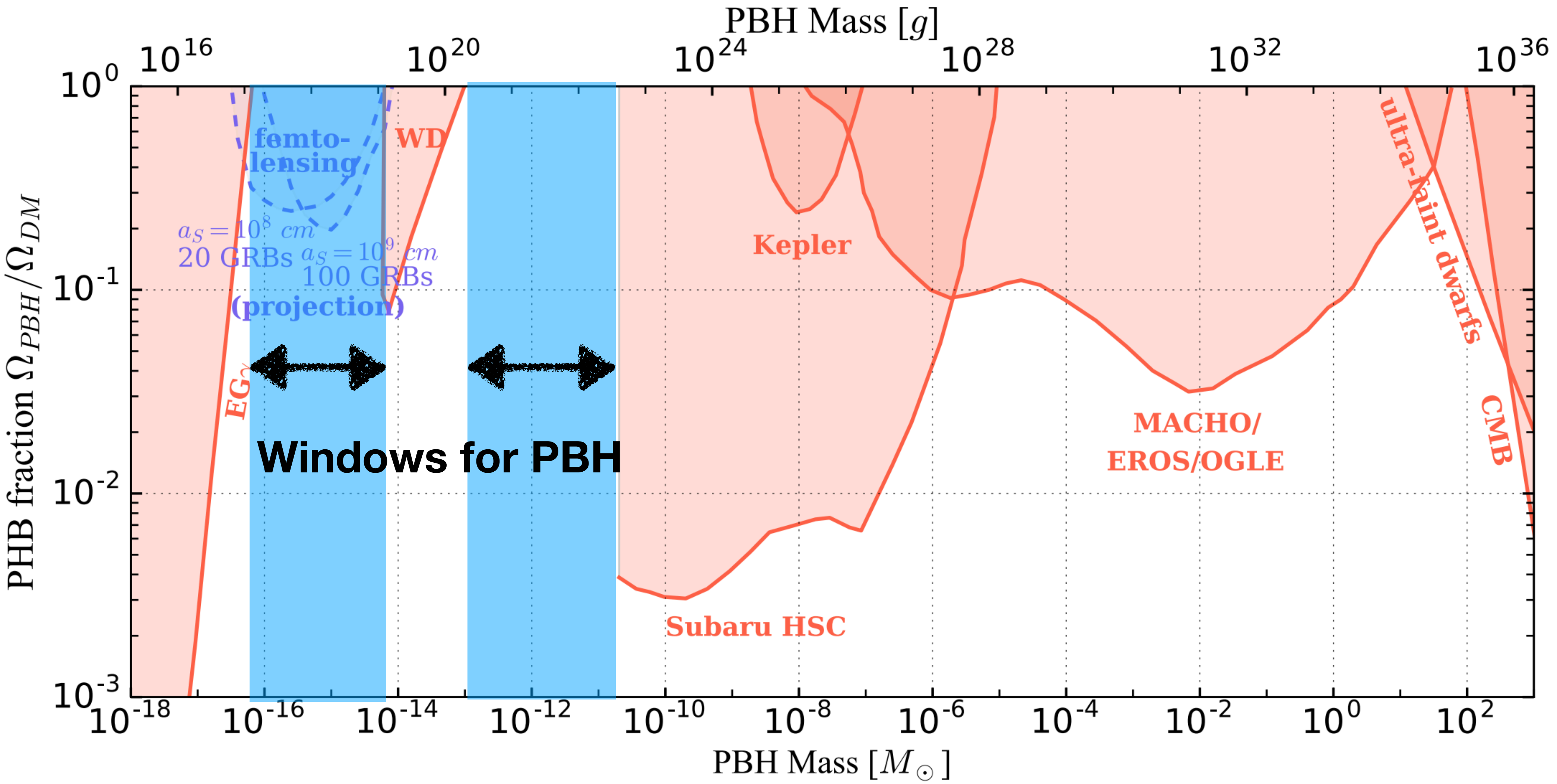


Figure from 1807.11495

PBH in Higgs-R^2 inflation

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{M_P^2}{2}\left(R_J + \frac{\xi h^2}{M_P^2}R_J + \frac{R_J^2}{6M^2}\right) - \frac{1}{2}g^{\mu\nu}\nabla_\mu h\nabla_\nu h - \frac{\lambda(\mu)}{4}h^4\right]$$

nonminimal coupling

R^2 term

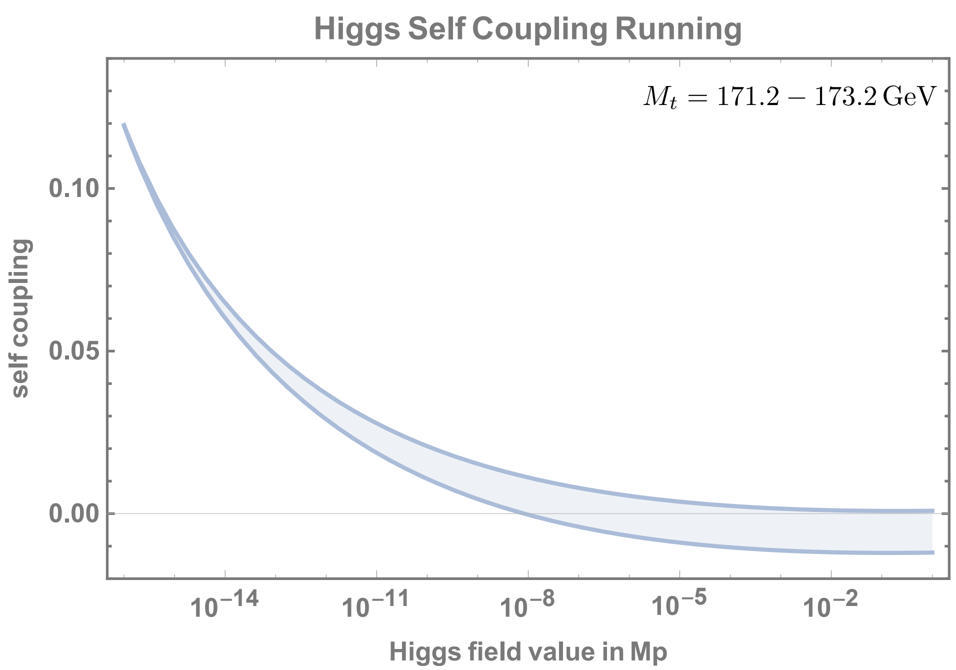
Higgs potential

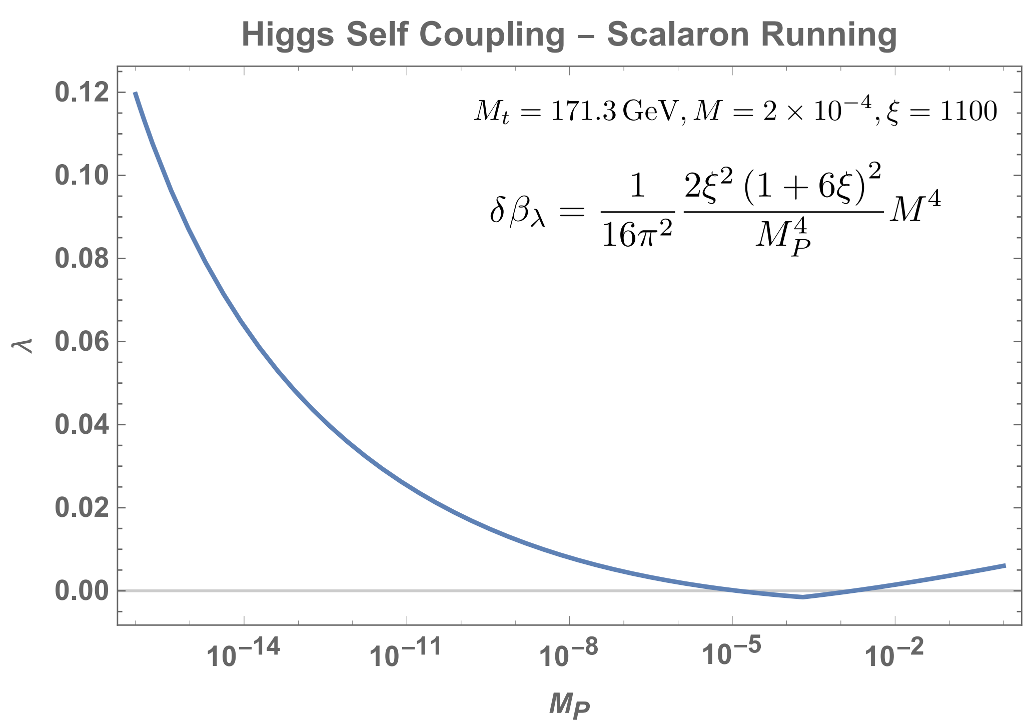
$$\lambda(\mu) = \lambda_{\rm min} + \frac{\beta_2}{(16\pi^2)^2}\ln^2\left(\frac{\mu}{\mu_{\rm min}}\right)$$

Einstein Action

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\nabla_\mu s\nabla_\nu s - \frac{1}{2}e^{-\omega(s)}g^{\mu\nu}\nabla_\mu h\nabla_\nu h - U(s,h)\right]$$

$$U(s,h) \equiv e^{-2\omega(s)}\left\{\frac{3}{4}M_P^2M^2\left(e^{\omega(s)} - 1 - \frac{\xi h^2}{M_P^2}\right)^2 + \frac{\lambda(\mu)}{4}h^4\right\}.$$





Scalaron effect on λ-running

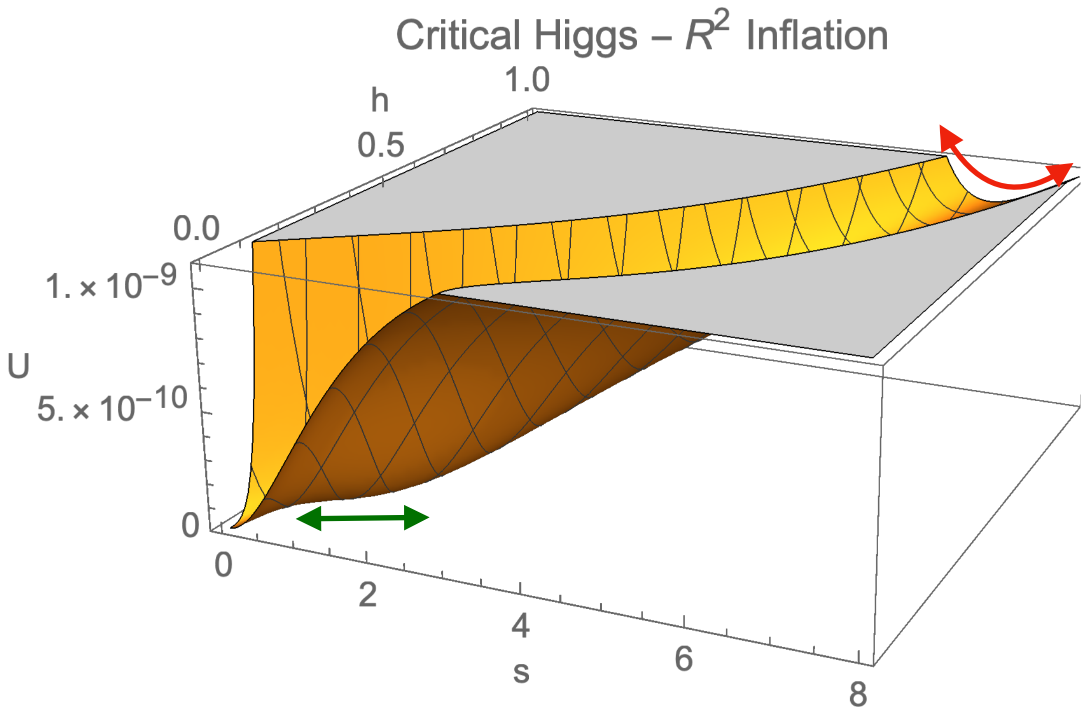
[D.Gorbunov, A.Tokareva Phys.Lett. B788 (2019) 37-41]

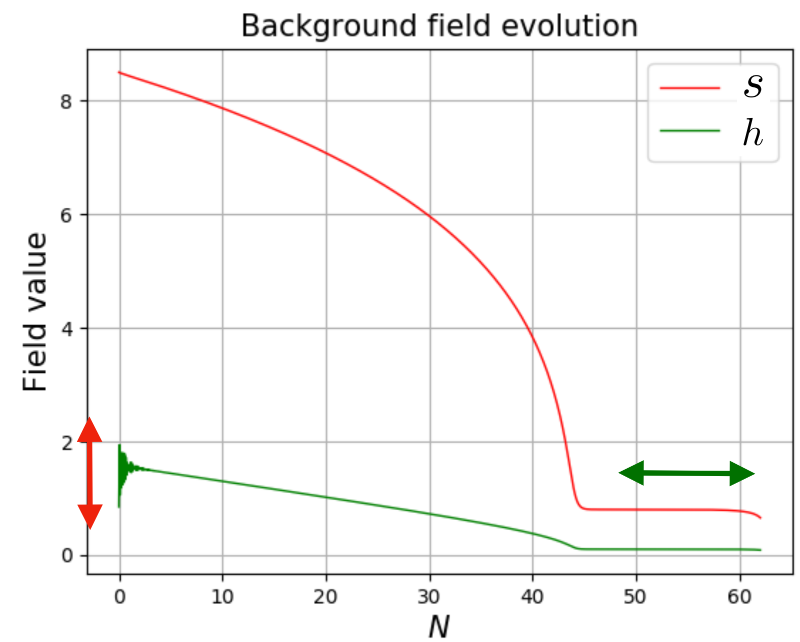
Our parameters indicate $\mu = h$

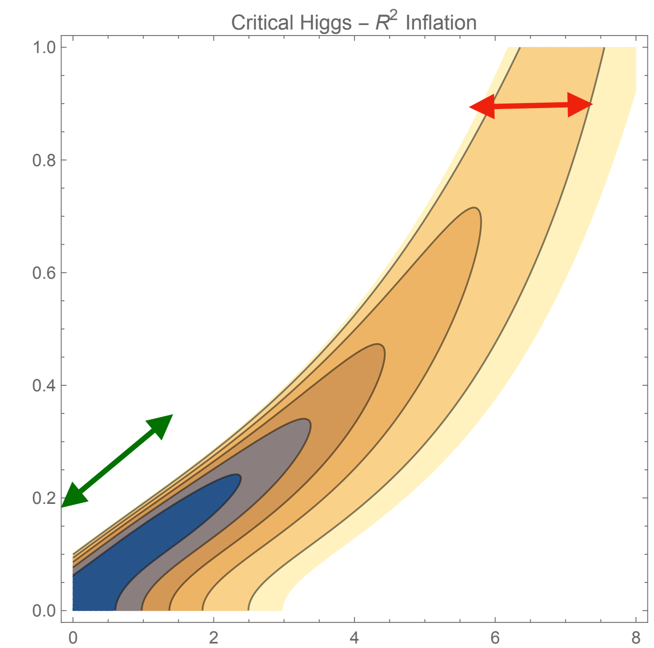
PBH in Higgs-R² inflation

Benchmark Parameters

$$M = 4.2 \times 10^{-5} M_P, \;\; \xi = 79, \;\; \lambda_{\rm min} = 4.10514 \times 10^{-6}, \;\; \beta_2 = 0.5, \;\; h_{\rm min} = 0.15$$







- Valley structure, quasi-single-field inflation
- Near inflection point (local min) in the tangential direction, USR $\partial_\sigma U \approx 0 \;\&\; \partial_{\sigma\sigma} U \approx 0$

$$\frac{U\left(\phi_{\rm CMB}\right)}{U\left(\phi_{\rm PBH}\right)} \approx 10 \qquad \Delta N_e \approx 10 \text{ e-folds}$$

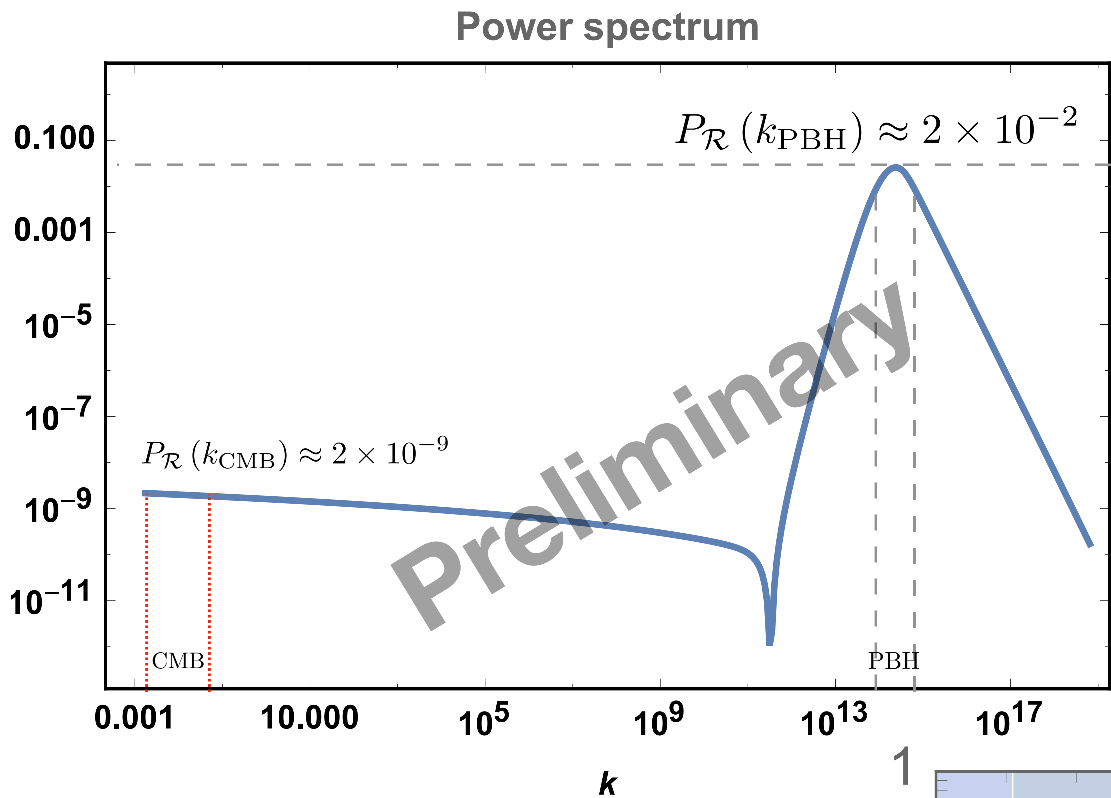
Simple SR analysis fails ⟶ USR crucial in $\mathcal{P}_{\mathcal{R}}(k)$

Power spectrum needs to take full orders into account

Calculate power spectrum using δN

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{k^3}{2\pi^2} \frac{\partial N}{\partial \phi^I} \frac{\partial N}{\partial \phi^J} \left\langle \delta\phi^I \delta\phi^J \right\rangle \Big|_{k=aH}$$

PBH in Higgs-R^2 inflation



$n_s = 0.958$ at benchmark parameters.

$$\frac{P_\mathcal{R}(k_{\rm PBH})}{P_\mathcal{R}(k_{\rm CMB})} \approx 10^7$$

$\delta_c = 0.4 - 0.5$ in RD

$f_{\rm PBH} = \mathcal{O}(0.1-1)$ with $M_{\rm PBH} \approx 1.01\times10^{-16} M_\odot$

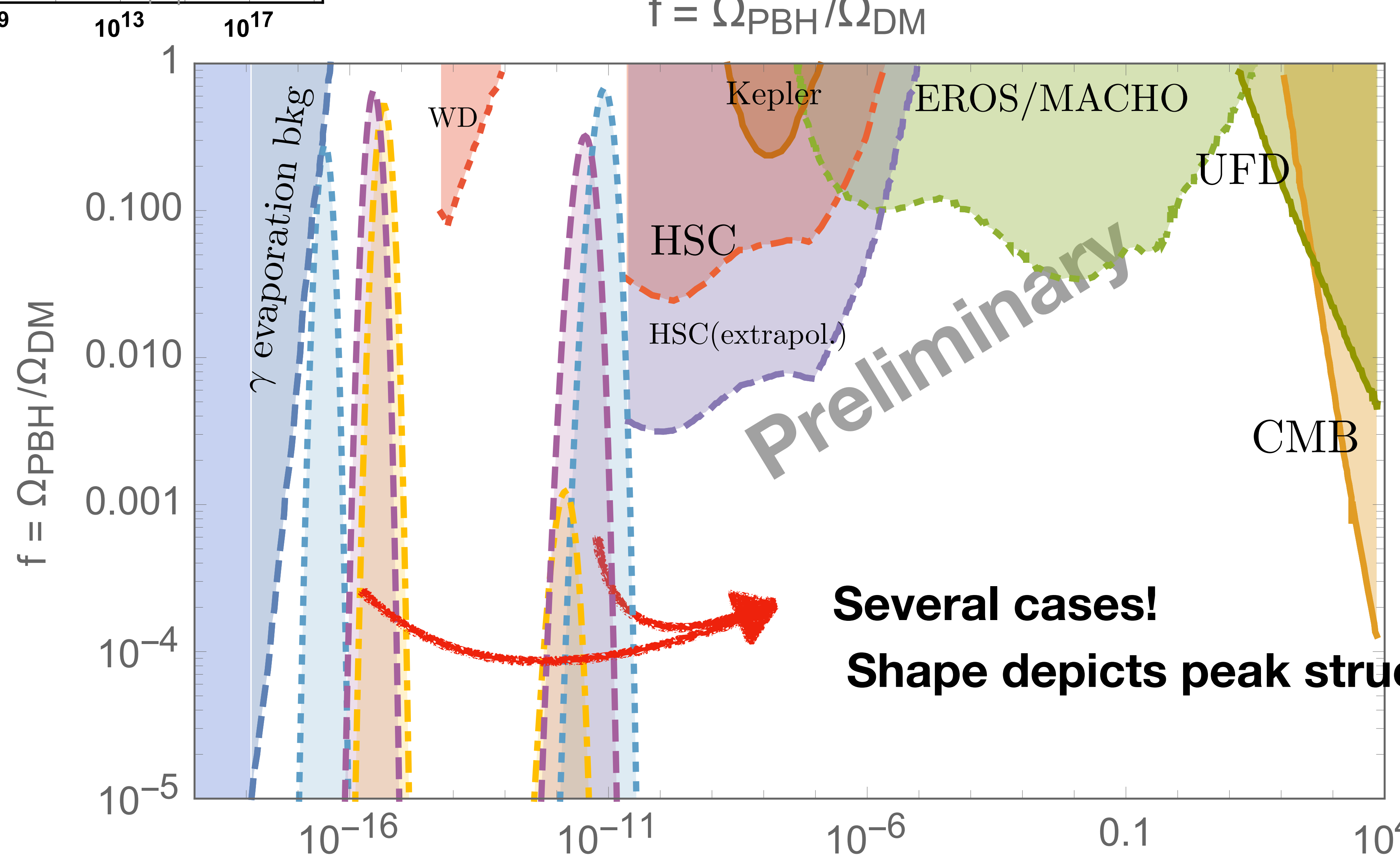
Parameter region

$M \sim \mathcal{O}(10^{-5})\, M_\odot$

$\xi \sim \mathcal{O}(10-100)$

$\beta_2 = 0.5$

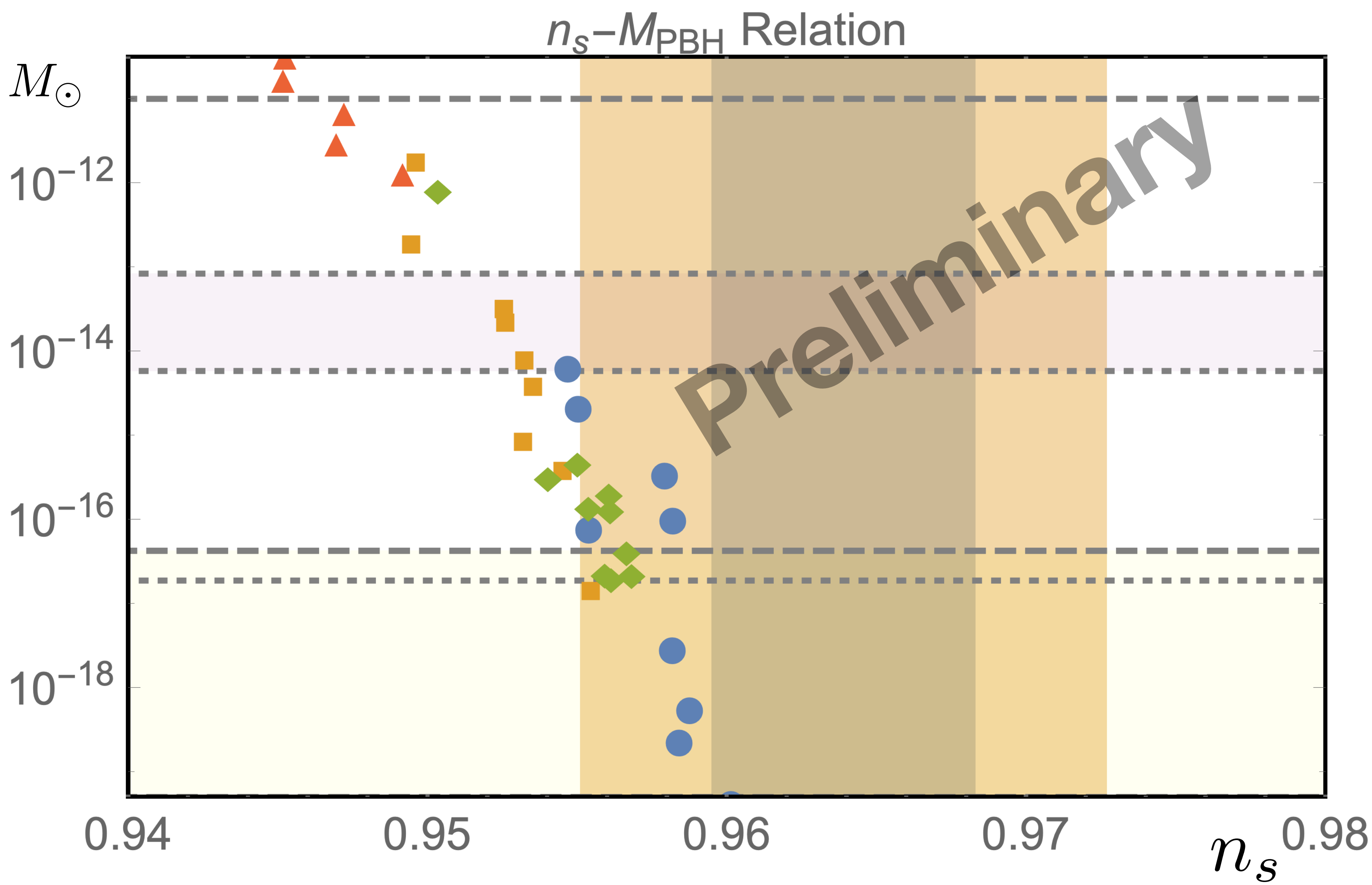
$h_{\rm min} \sim \mathcal{O}(0.1)\, M_P$



Several cases!

Shape depicts peak structure

PBH in Higgs-R^2 inflation

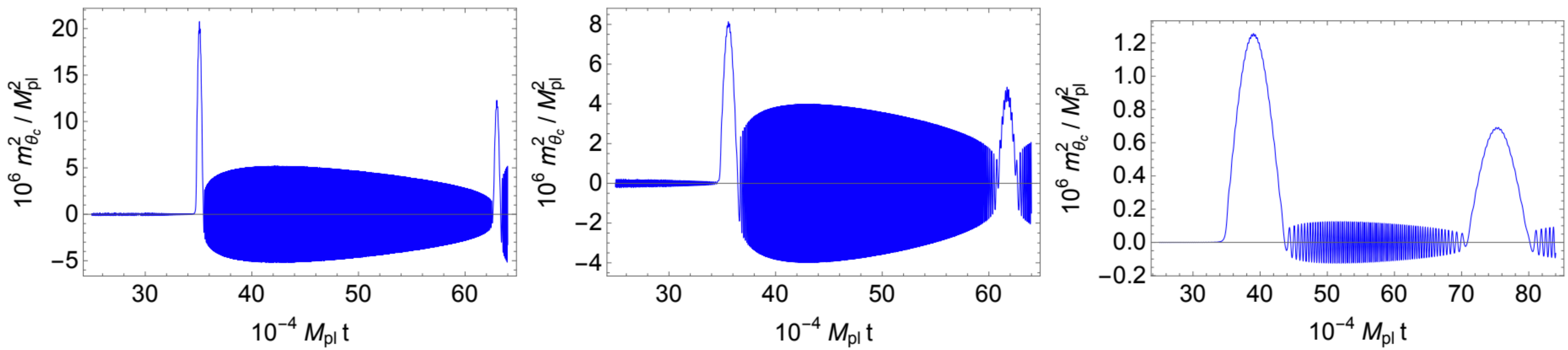


At least 2σ consistency with Planck, desired PBH mass achievable.

Further constrainable through future CMB observations (CMB-S4, Litebird, etc) and femtolensing, GW observations.

More

Preheating of Higgs-R² inflation



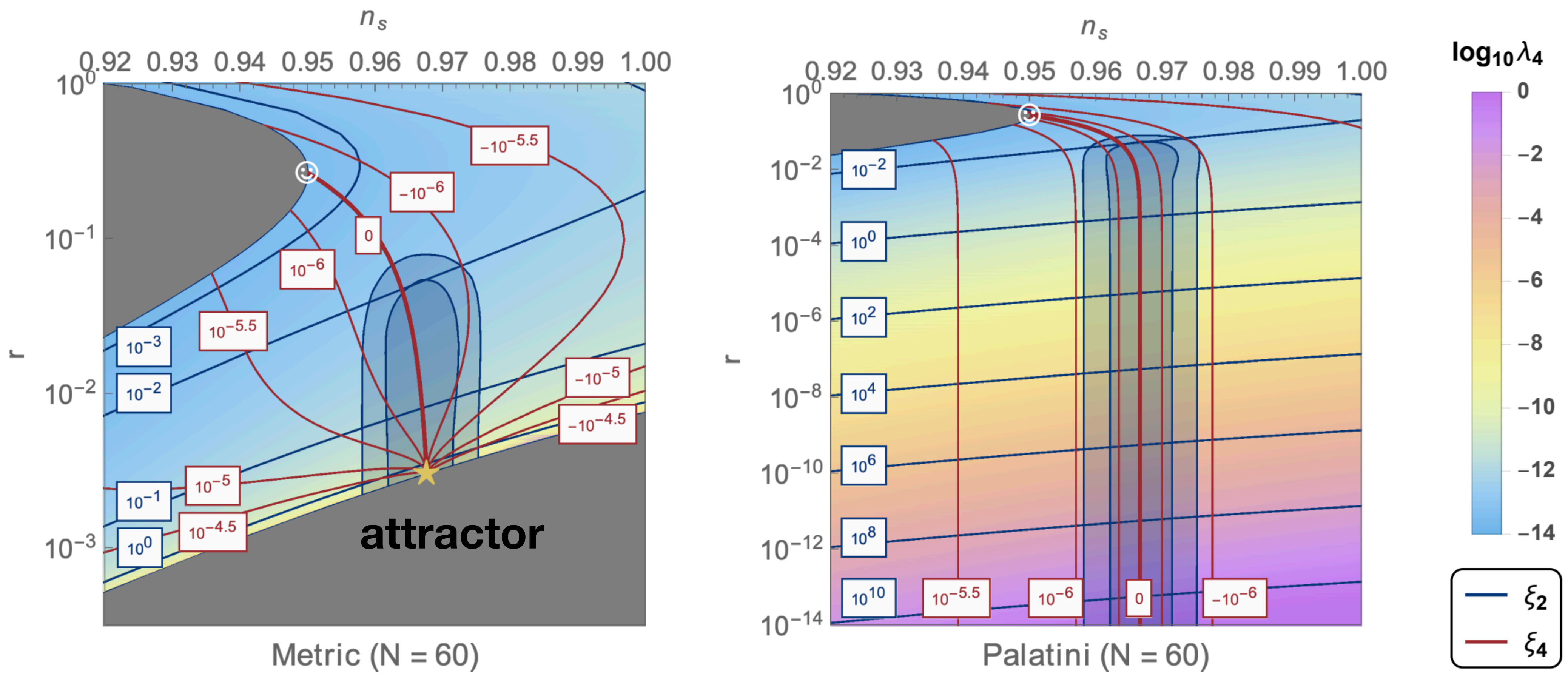
'peak' showed up! but not too efficient

$T_{RH} > 10^{12}\mathrm{GeV}$ **: fully consistent with e.g. Leptogensis**

M. He, R. Jinno, K. Kamada, SCP, A. Starobinsky, J. Yokoyama PLB791 (2019)

Einstein vs Palatini

$$R_{\rm J} = \begin{cases} \Omega^2 \left[R + 3\Box \ln \Omega^2 - \dfrac{3}{2} (\partial \ln \Omega^2)^2 \right] & \text{(metric)}, \\ \Omega^2 R(\Gamma) & \text{(Palatini)}, \end{cases}$$



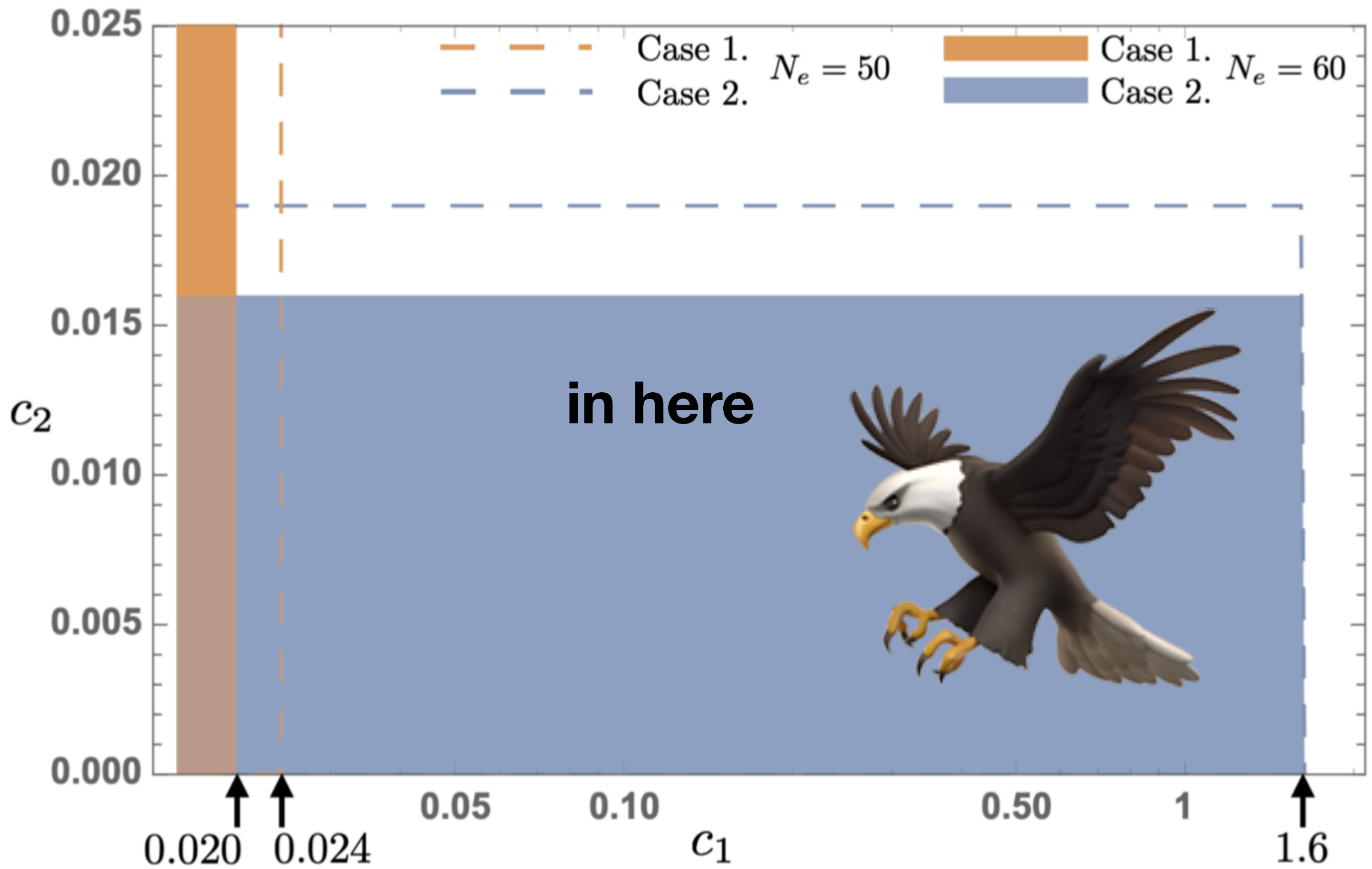
Jinno, Kubota, Oda, SCP 1904.05699

So, this is the result

$$\left|\nabla V\right| \geq c_1 \frac{V}{M_{\rm Pl}}$$

$$\nabla_i \nabla_j V \leq -c_2 \frac{V}{M_{\rm Pl}^2}$$

$c_1, c_2 \sim O(1)$, **positive**



D. Y. Cheong, S. M. Lee and **SCP**, Phys. Lett. B789 (2019) 336-340

Summary

- Higgs inflation is a theoretical framework providing cosmological inflation, dark matter (PBH) and EWSB.

- Various theoretical issues have been examined recently e.g. unitarity, violent preheating, fine-tuning, quantum gravity & , PBH dark matter…

- Higgs inflation still remains the best fitting, attractive and successful model of inflation based on particle physics (it lives in Landscape rather than Swampland)

Our old good friend, Higgs, is even greater than we had expected.

Maybe, we don’t need BSM

backups

Refined Swampland Conjecture

Ooguri, Palti, Shiu and Vafa arXiv:1810.05506

S. K. Garg and C. Krishnan arXiv:1807.05193

Any scalar potential V (ϕ) for scalar fields in a low energy effective theory of a consistent quantum gravity must satisfy at least one of the following conditions:

$$\left| \nabla V \right| \geq c_1 \frac{V}{M_{\mathrm{Pl}}}$$

$$\nabla_i \nabla_j V \leq -c_2 \frac{V}{M_{\mathrm{Pl}}^2}$$

$c_1, c_2 \sim O(1)$, **positive**

Q. 0.1 is O(1)? 0.01 is O(1)?


String Landscape
Low energy theories which has UV-completion that is consistent with Quantum gravity (string theory)

Swampland

The swampland is the set of (seemingly consistent) effective field theories, which cannot be obtained from a consistent string construction.

Eagle or Crocodile?

A theory living in Landscape

consistent with Quantum Gravity

A theory living in Swampland

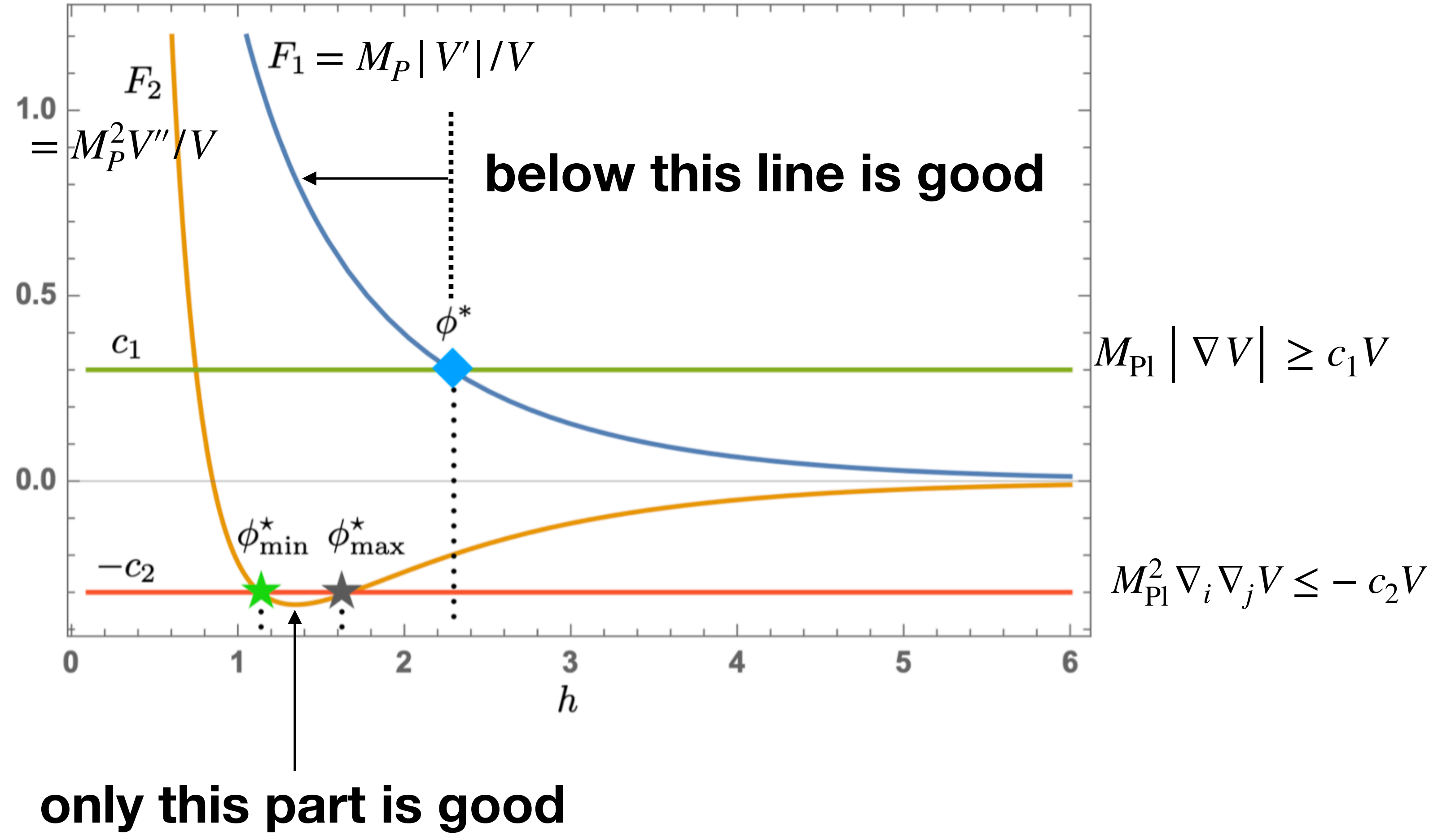
YONSEI

Is Higgs an eagle or Crocodile?

$$\left|\nabla V\right| \geq c_1 \frac{V}{M_{\rm Pl}}$$

$$\nabla_i \nabla_j V \leq - c_2 \frac{V}{M_{\rm Pl}^2}$$

$c_1, c_2 \sim O(1)$, **positive**



therefore Eagle if $\phi^* \lesssim \phi^\star_{\rm min} < \phi_{\rm max}$