PBH and GW in Higgs-R^2 inflation

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2022 CAU BSM workshop (Feb 7-10)

This talk is based on

- **Inflation by nonminimal 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
- **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 *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 (2111.00825, JCAP to appear)
- **Festina-Lente Bound**, S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, Min-Seok Seo (2111.04010, JHEP to appear)
- more to come soon

Higgs-R^2 model

- An EFT model based on the SM Higgs field & Gravity with $R + \xi H^\dagger H R + R^2 + \cdots$ 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 looks natural ($\lambda/\xi^2 \sim 10^{-10}$ during inflation) and perturbatively 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.

- The very specific potential of the model provides the enhanced curvature & isocurvature perturbation, which result in sizable production of PBH (and GW), which may explain the dark matter in the universe.

- 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.

The Higgs in the SM

An elementary scalar uniquely observed in nature

Goldstone

$$H \sim \begin{pmatrix} G^+ \\ (v + h + G^0)/\sqrt{2} \end{pmatrix} \qquad (1,2,\tfrac{1}{2})$$

vev

physical Goldstone

$SU(3) \times SU(2) \times U(1)$

The potential

The most general, gauge invariant, renormalizable potential includes two free parameters (λ, v)

$$V_{\text{Higgs}} = \lambda(|H|^2 - v^2/2)^2$$

$$H \sim \begin{pmatrix} G^+ \\ (v+h+G^0)/\sqrt{2} \end{pmatrix} \quad = \frac{\lambda}{4}h^4 + \lambda v h^3 + \lambda v^2 h^2$$

In unitary gauge

$$v = \sqrt{1/\sqrt{2}G} = 246.22 \text{ GeV}$$

$$\lambda = \frac{m_h^2}{2v^2} = \frac{125^2}{2 \times 246^2} \approx \frac{1}{8}$$

The SM Higgs potential

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

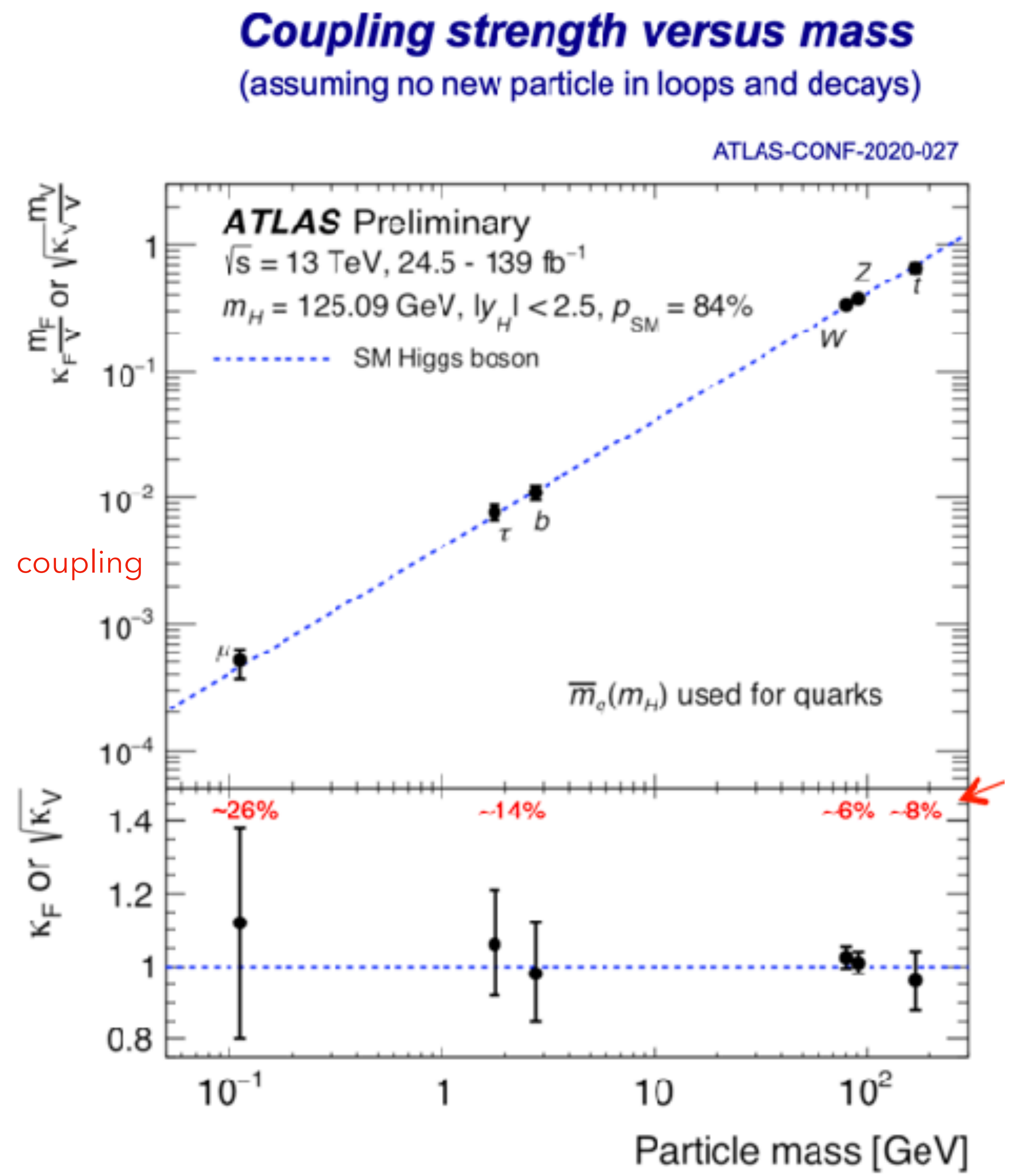
Predicted Predicted Measured

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!



Global shape of Higgs potential

- Taking RG running of λ, and also higher order operators,

$$V_{\rm eff}(h) = \Lambda_{\rm DE} + \frac{\lambda(h)}{4}h^4 + \frac{c_6}{\Lambda^2}h^6 + \frac{c_8}{\Lambda^4}h^8 + \cdots .$$

- 1 : the unique EW vacuum
- 2″ : inflection point
- 2, 2′ : 2nd dS vacuum at UV
- 3 : 2nd vacuum with AdS

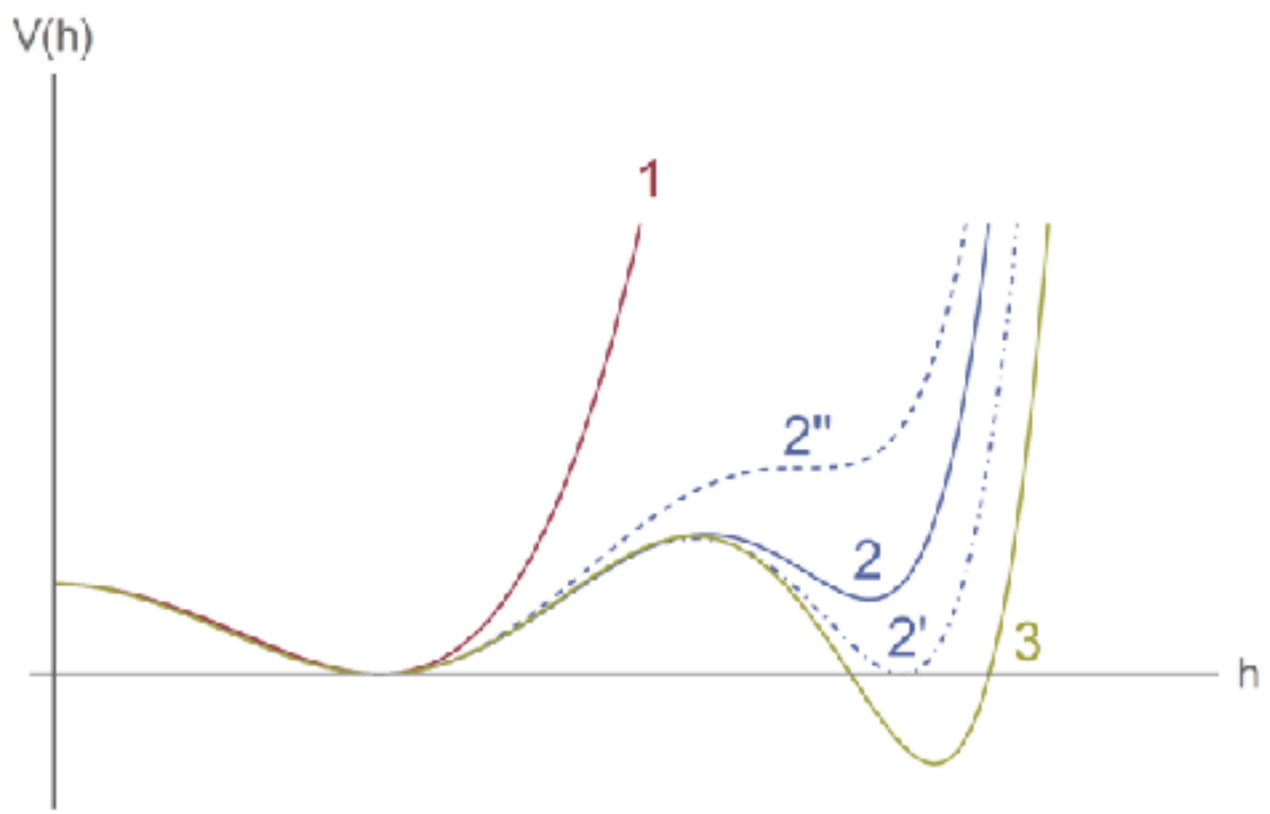
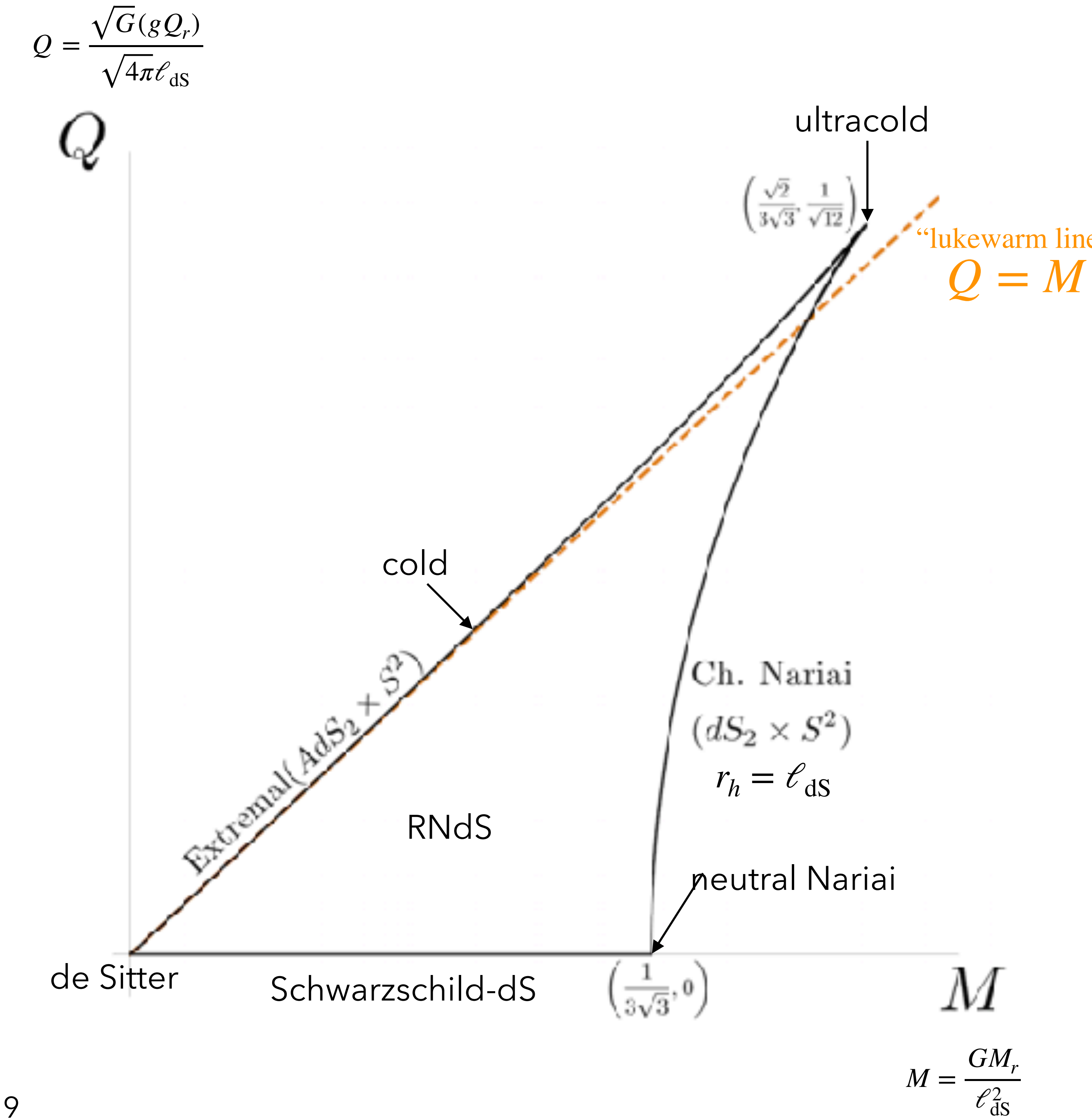


Figure 1: Schematic shape of the Higgs potential.

Festina-Lente bound

M. Montero, T. V. Riet, C. Vafa, G. Venken (1910.01648, 2106.07650)

- To check the consistency of the theory, it is useful to consider the decay of charged BH in dS space
- Charged BH in dS space has a phase diagram of 'shark fin' shape
- By Hawking radiation/ Schwinger process, BH decays and remains naked singularity unless $m_q^4 > 8\pi\alpha q^2 V$ for a charged particle in the theory.



Higgs + gravity + c.c. (1)

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

- The EW vacuum (where we reside in) is consistent with FL bound with a tiny CC
- FL bound:
  $$\Lambda_{cc} \leq \frac{Gm_e^4}{\alpha} \sim 10^{-90}M_P^2$$
- well consistent with the observed value
  $$\Lambda_{cc}^{\rm obs} \simeq 2.8 \times 10^{-122}M_P^2$$

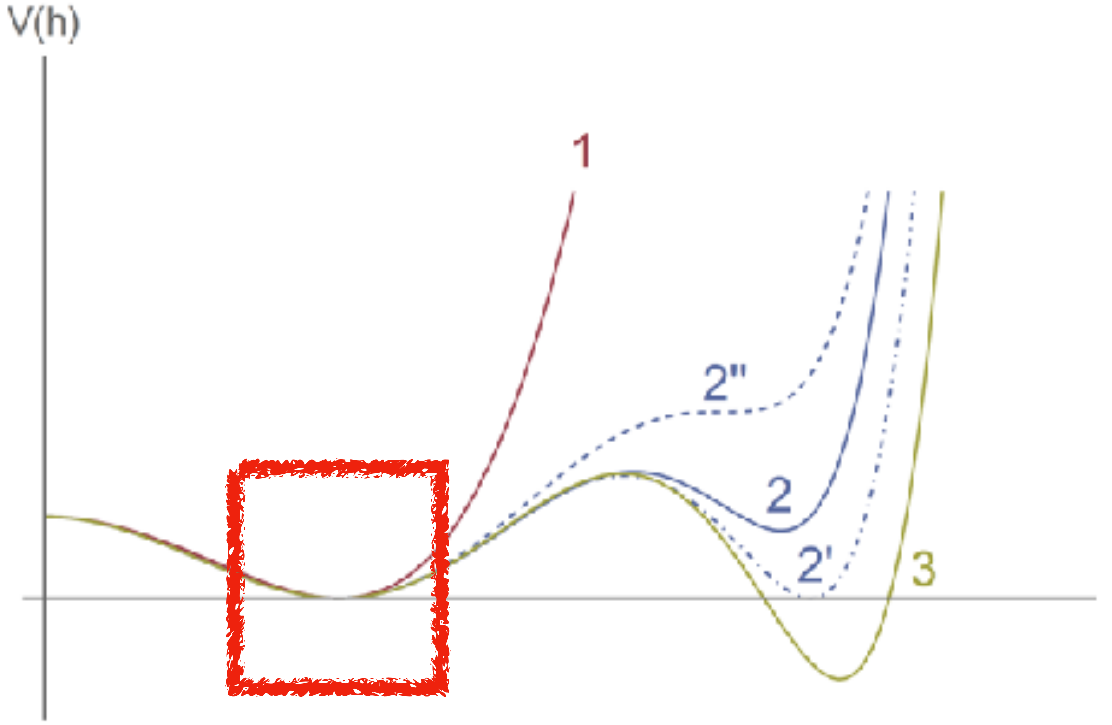


Figure 1: Schematic shape of the Higgs potential.

Higgs + gravity + c.c. (1')

- In SM, $m_q = y_q \langle H \rangle$ therefore, we can learn about $V(H)$ taking the electron mass into account!

$$\min_{i\in\mathrm{SM}} \frac{m_i^4}{8\pi\alpha_i} = \frac{y_e^4 v_{\mathrm{UV}}^4/4}{8\pi\alpha_{\mathrm{EM}}} \geq \frac{\lambda_{\mathrm{eff}}(v_{\mathrm{UV}})}{4} v_{\mathrm{UV}}^4$$

$$\Rightarrow \quad \lambda_{\mathrm{eff}}(v_{\mathrm{UV}}) \leq \frac{y_e^4}{8\pi\alpha_{\mathrm{EM}}} \simeq \mathcal{O}\left(10^{-22}\right).$$

S.M.Lee, D.Y.Cheong, S.C.Hyun, SCP, M.-S.Seo
2111.04010, JHEP accepted

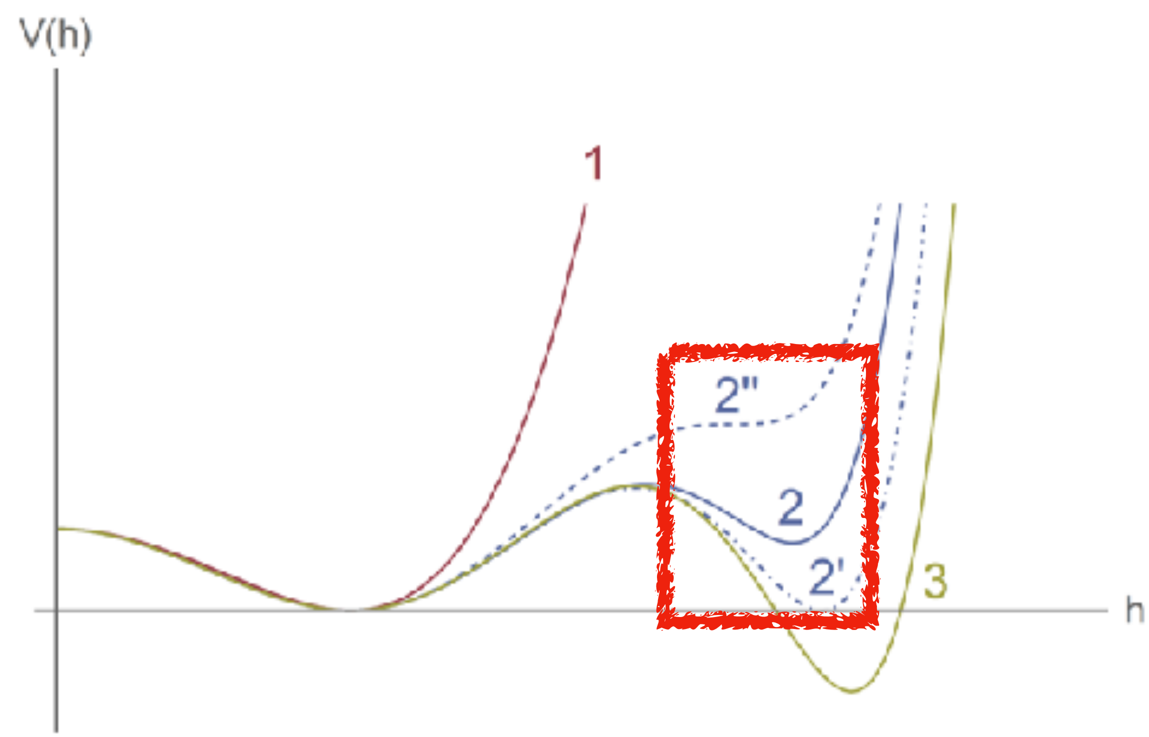


Figure 1: Schematic shape of the Higgs potential.

Higgs + gravity + c.c. (2)

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

- Note $[\xi H^\dagger H] = Mass^2$, $[R^2] = Mass^4$
- both terms are consistent with the SM gauge symmetry and Lorentz symmetry therefore naturally appear in EFT => Indeed, they can be radiatively induced by loop effects
- GB term (~mass^4) can be also included but does not contribute local physics unless non-minimally coupled as in $\xi' H^\dagger H(GB)$.
- Higher order terms e.g. $R^3 + R^4 + \cdots$ are often neglected but could be important when we consider high scale physics

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

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

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

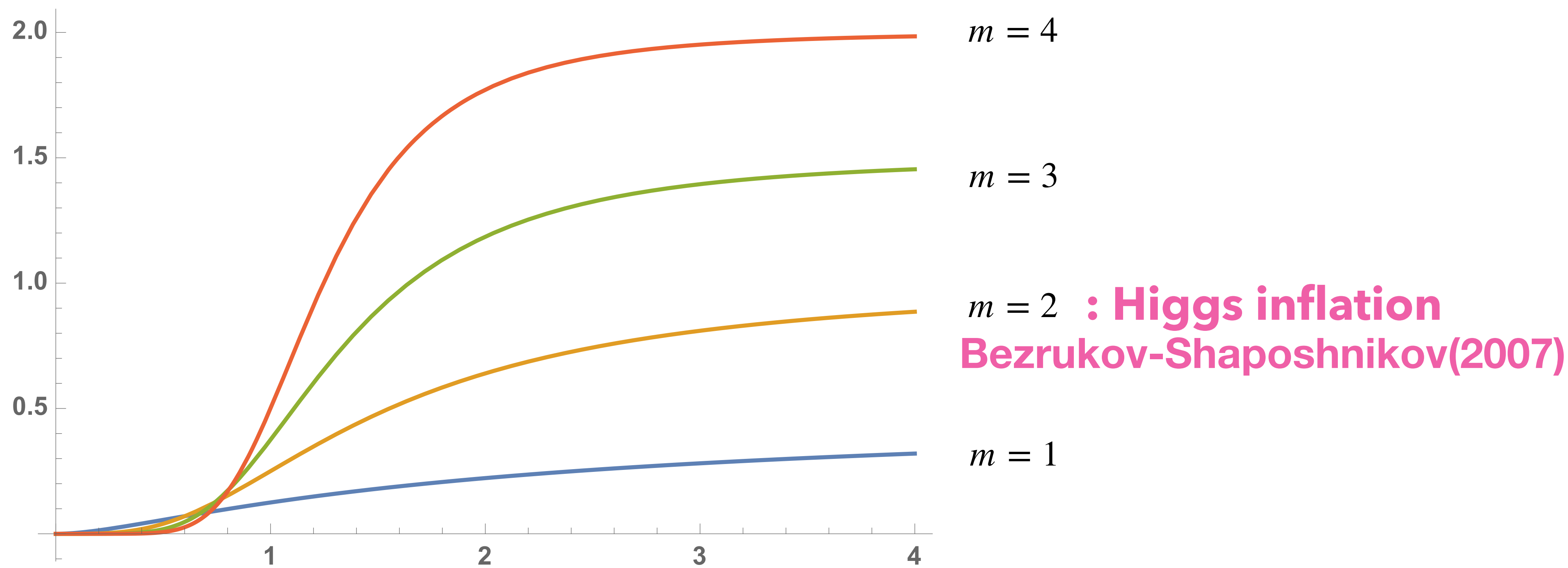
$\partial_\phi K > 0, \ \partial_\phi V > 0$

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

SCP, S. Yamaguchi (2007)

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

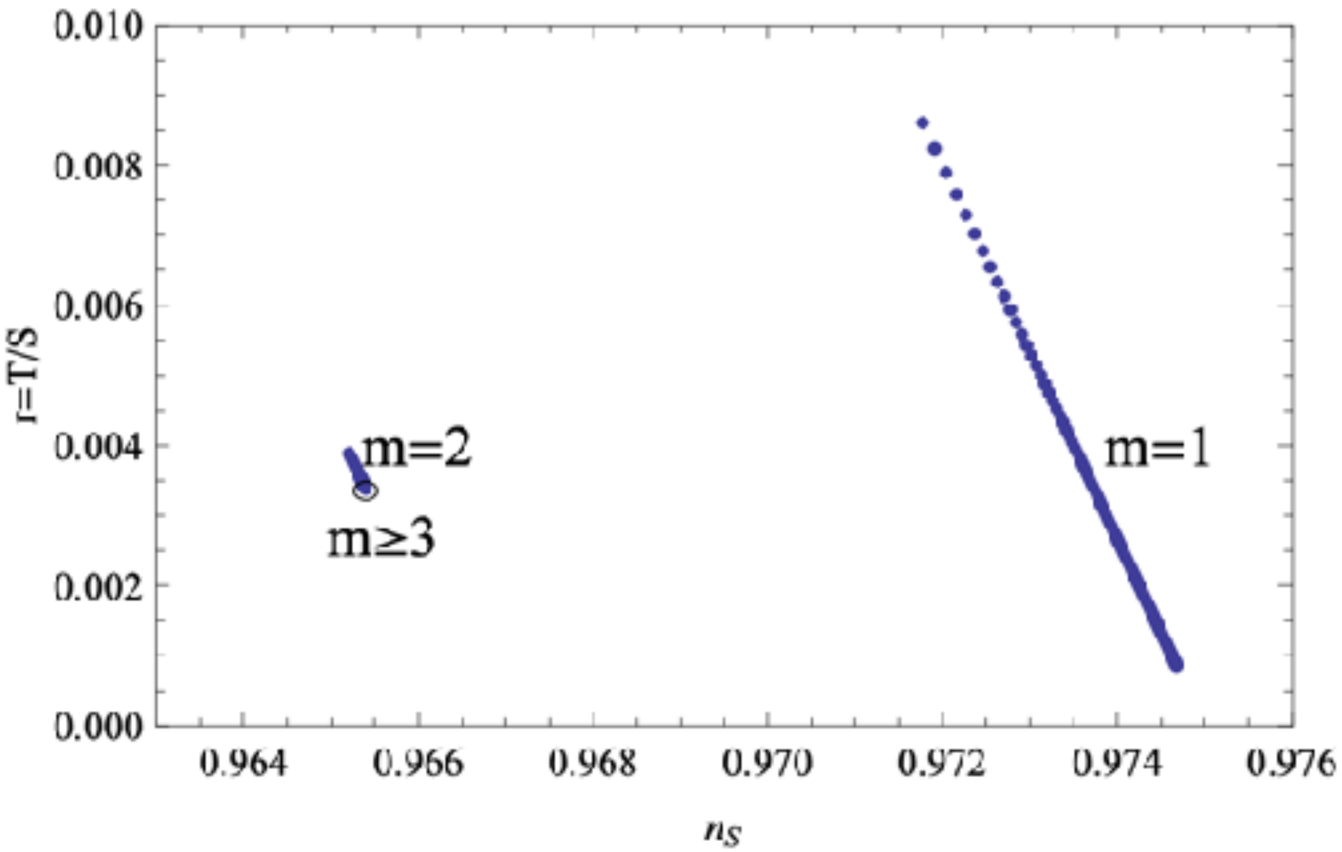
$$\lim_{\phi \to \infty} \frac{V}{K^2} = Const > 0.$$



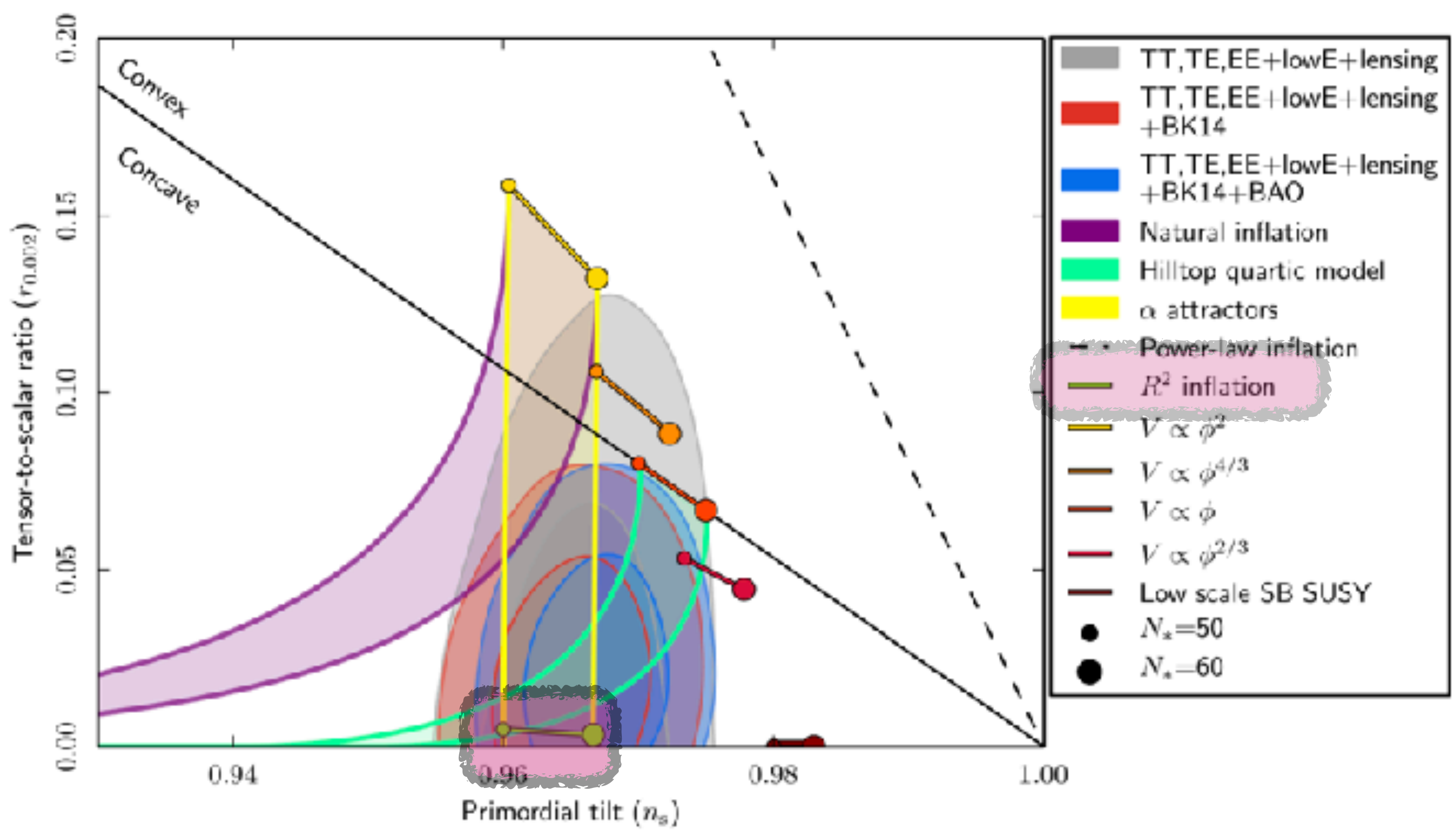
SCP, Yamaguchi (2007)

Predictions of NM-inflation

SCP-Yamaguchi (2007)



'Best fit model' of the Planck data



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

$R^2 \leftrightarrow \lambda\phi^4$ with nm coupling

Equivalence of Starobinsky & 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)

In general,
f(R) <=> Non-minimally coupled scalar theory

see Masahide's talk yesterday

The theory $S = \int d^4x \sqrt{-g}\, f(R)$ is equivalent

to a scalar + gravity theory 'Trick' for $f(R)$

$$S = \int d^4x \sqrt{-g} \; [f(\phi) + f'(\phi)(R - \phi)]$$

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

$$f(R) \quad \Rightarrow$$

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

$K(\phi) = f'(\phi)$ nm term

A fine tuning problem ?

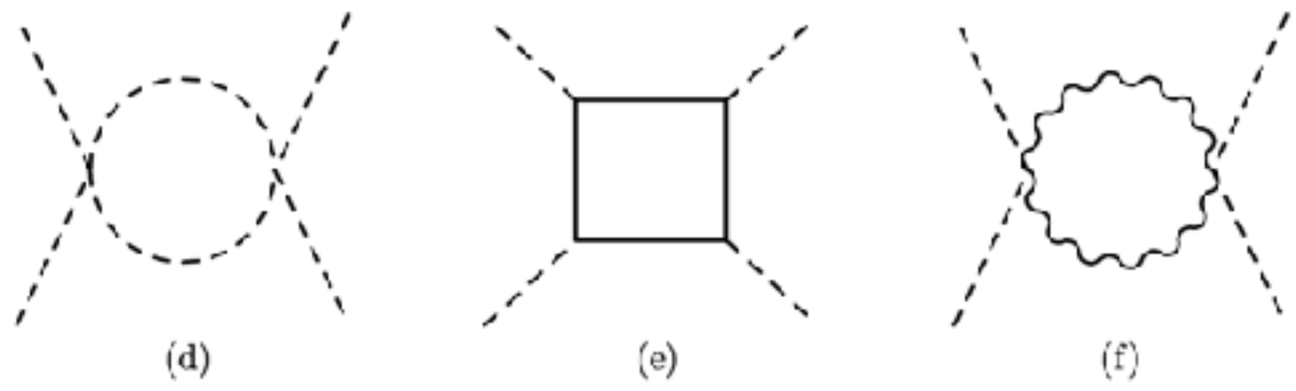
To fit $\frac{\delta T}{T} \sim \frac{U^{3/2}}{HU'} \sim 10^{-5}$ or $\frac{U}{\epsilon} \sim (0.027 M_P)^4$ (COBE)

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

Q. Why so small?

RG running of λ

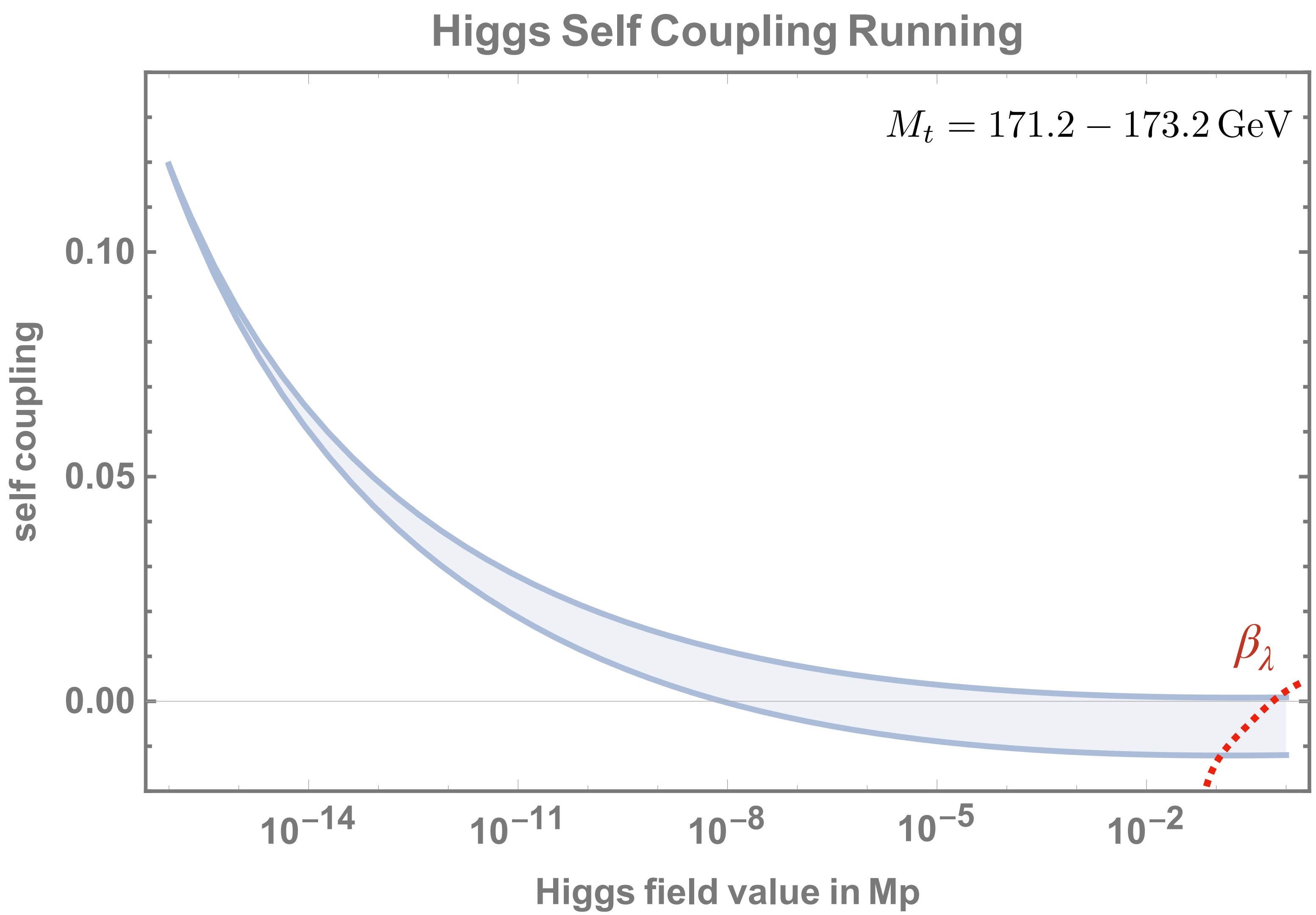
Simone, Hertzberg, Wilczek (PLB 2009), Hamada, Kawai, Oda, SCP (PRL 2014)



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

< 0 ==> weaker at higher energies!!

RG running of λ



Higgs Criticality!

$$\lambda \approx 0 \approx \lambda'$$

Hamada, Kawai, Oda, SCP (PRL 2014)

Near criticality

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

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

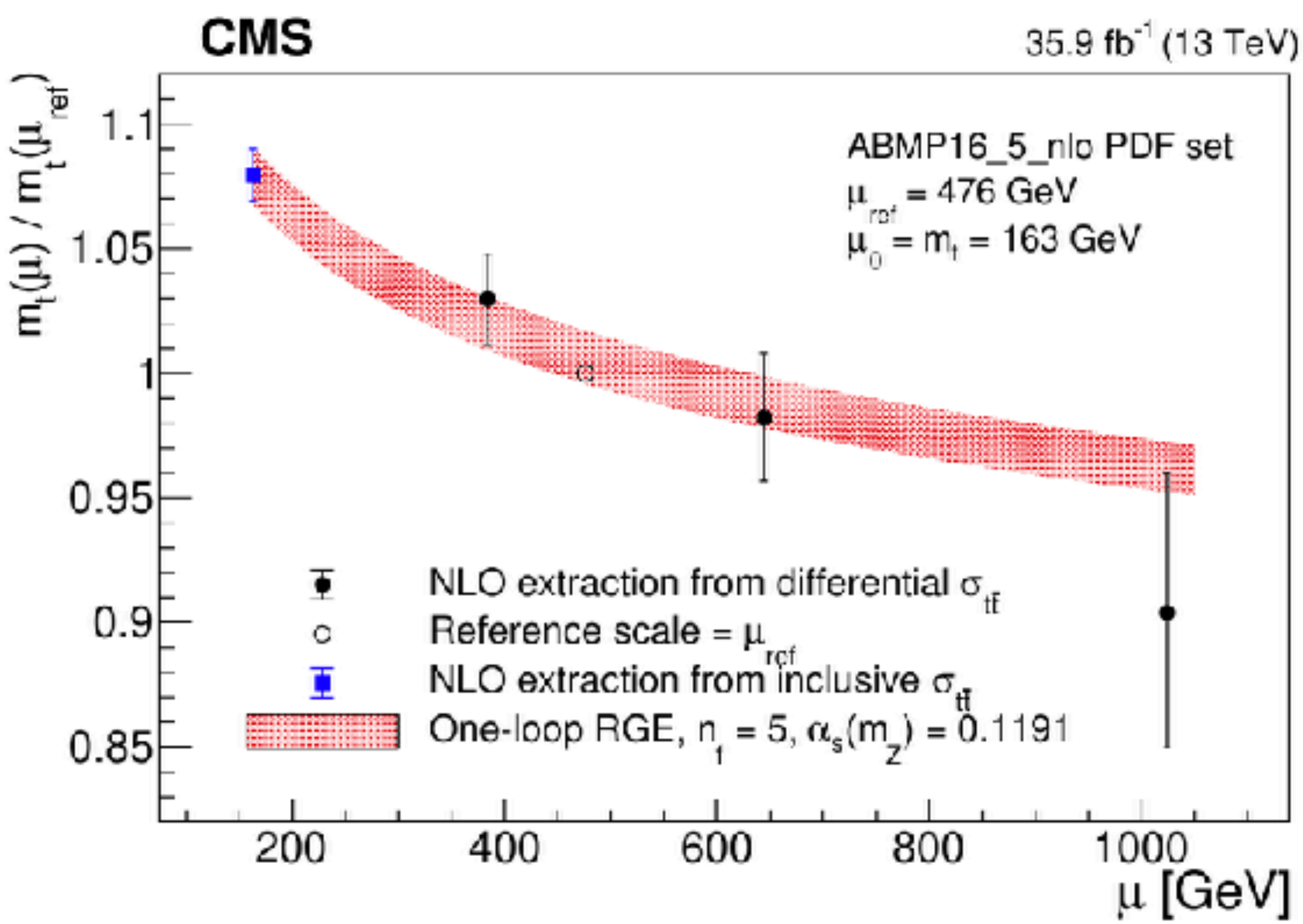
$\xi \sim \mathcal{O}(10-100), \lambda(\mu_{crit}) \sim \mathcal{O}(10^{-8}-10^{-6})$

fits the data!

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

Clockwork

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

no fine-tuning here $\xi_i \sim 1$ $\quad q \sim 1$

this breaks the CW shift symmetry

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

zero mode as inflaton $\quad \phi_1 \sim \frac{1}{q^N}\phi_{(0)}$

$$\lambda_{eff} \sim \frac{\lambda}{q^{4N}} \sim \frac{\lambda}{10^{10}} \ll 1$$

close look at the action

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

The model is $f(R,h)$ type equivalent to a (R,h,s) theory!

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

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

'Trick' for $f(R)$

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

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

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

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

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

(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)

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

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

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

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

cutoff scale of Higgs-R^2 theory

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) unitarize 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.

MODEL: Higgs-R^2

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}G_{ab}g^{\mu\nu}\nabla_\mu\phi^a\nabla_\nu\phi^b - U(\phi^a)\right],$$

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

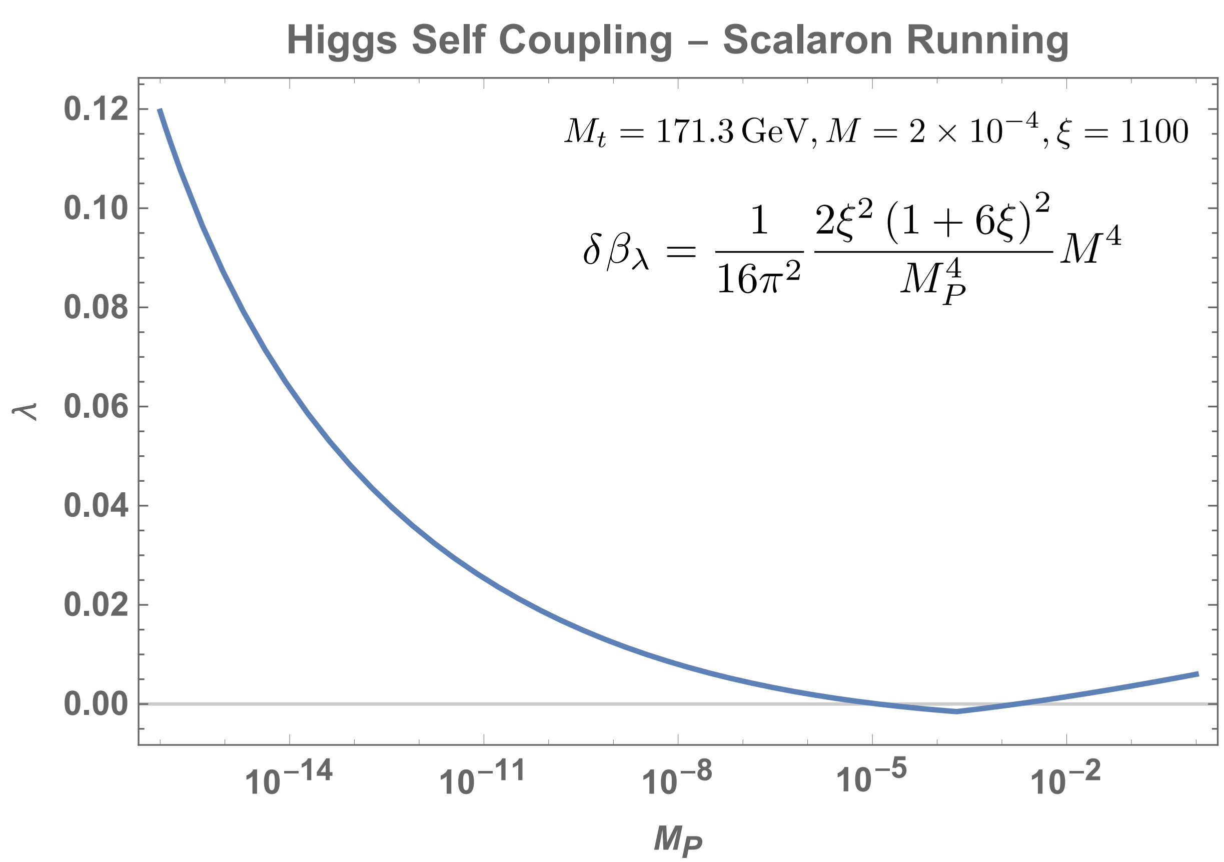
3 parameters: (M, ξ, λ)

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

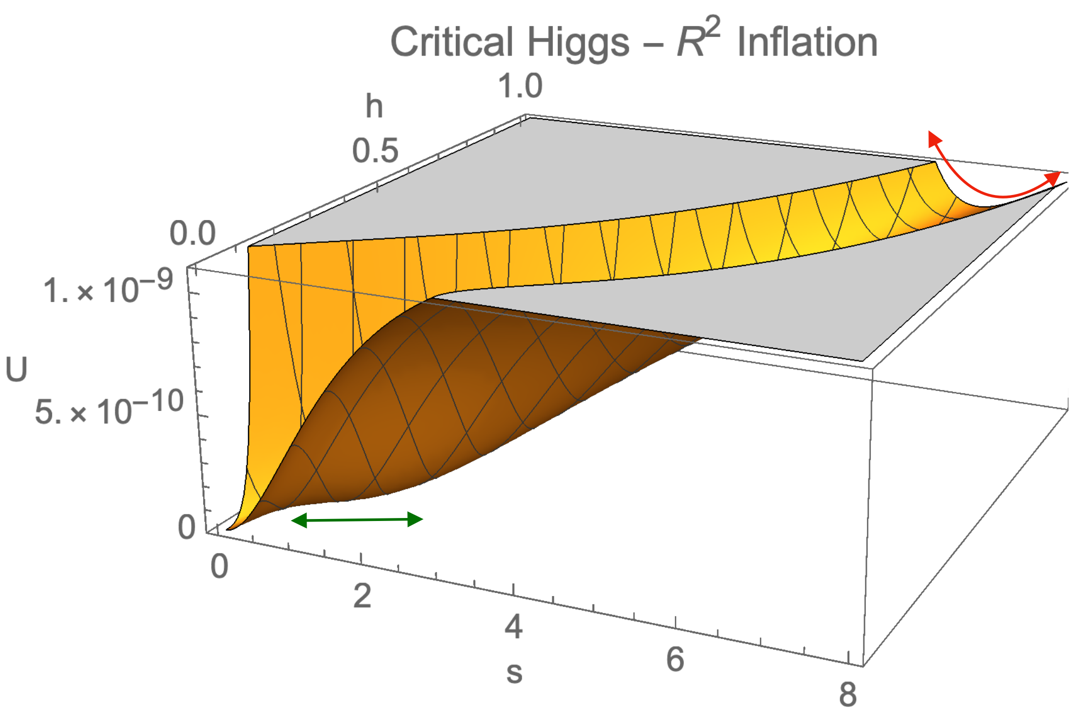


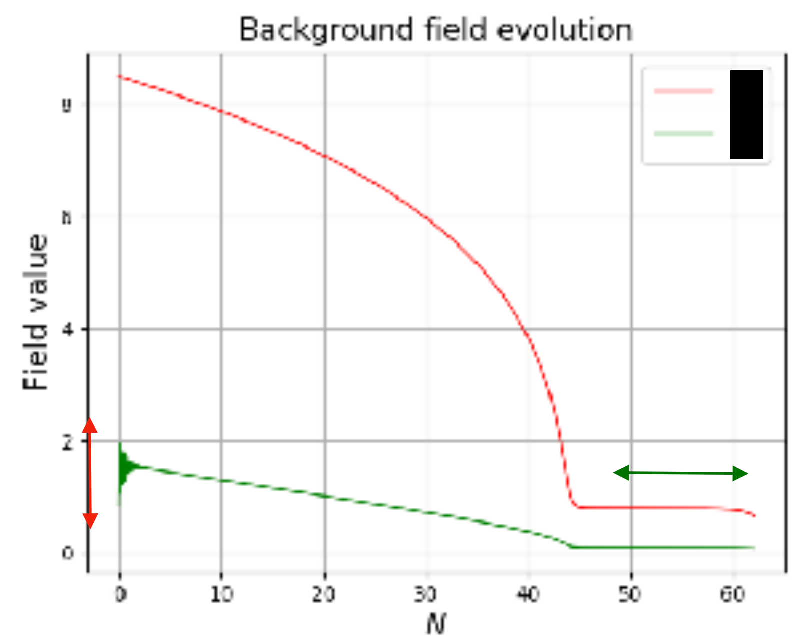
D.Gorbunov, A.Tokareva
Phys.Lett. B788 (2019) 37-41

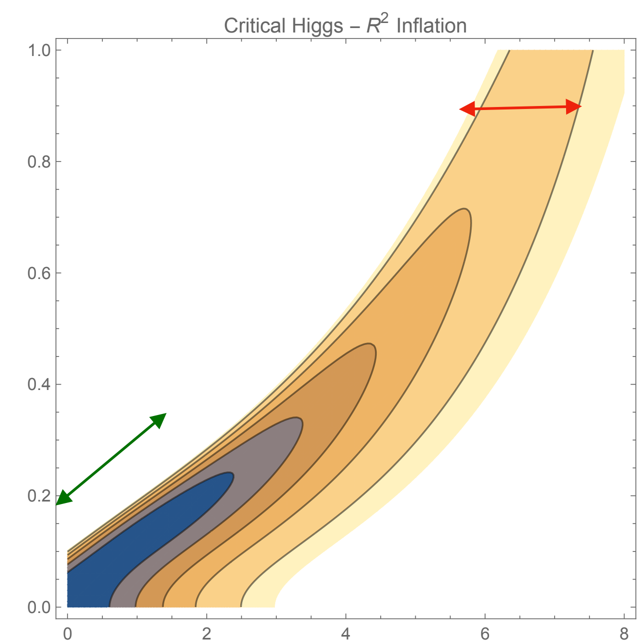
Inflaton potential

Benchmark Parameters

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



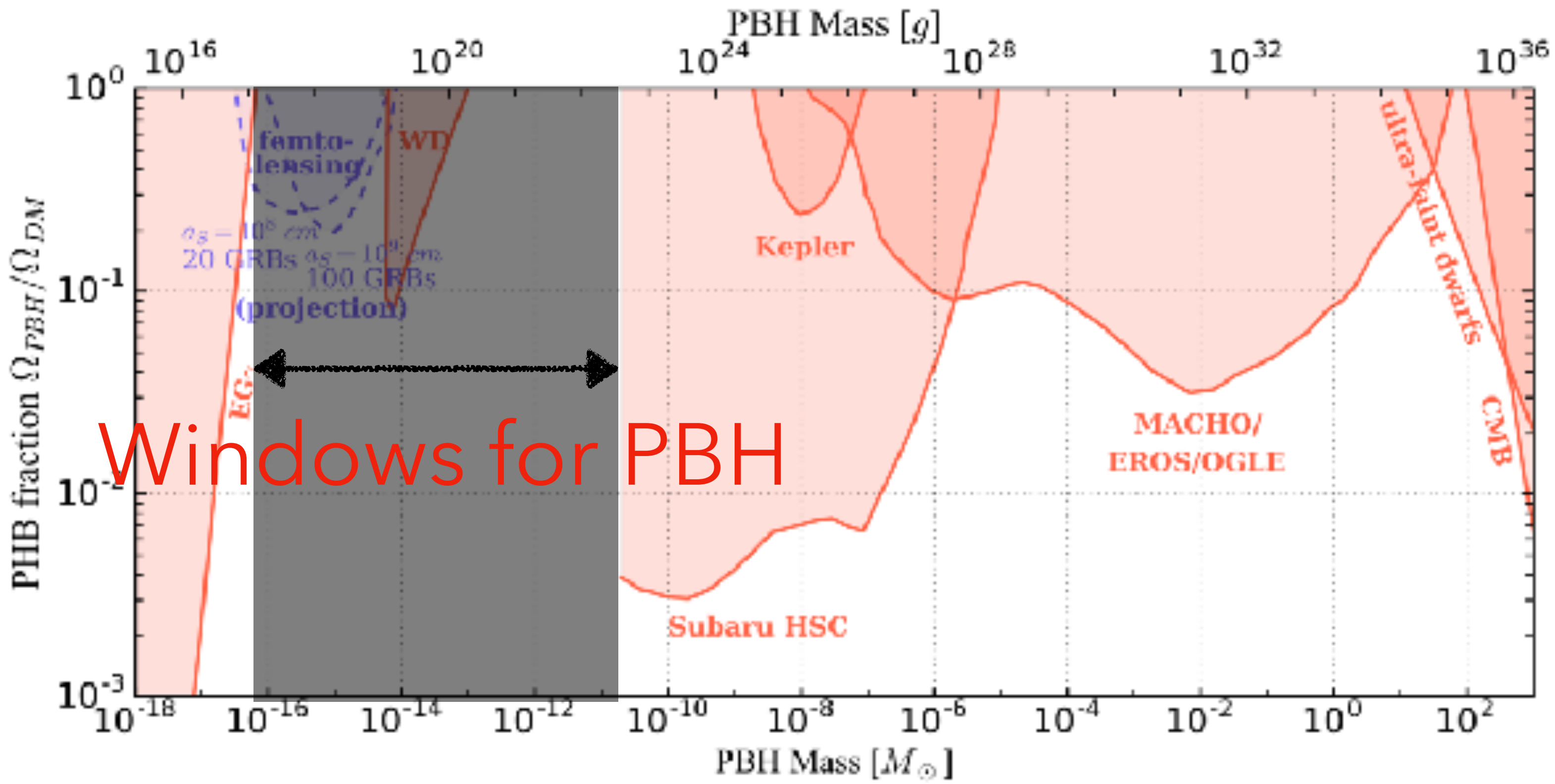




Two plateaus!

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

PBH DM



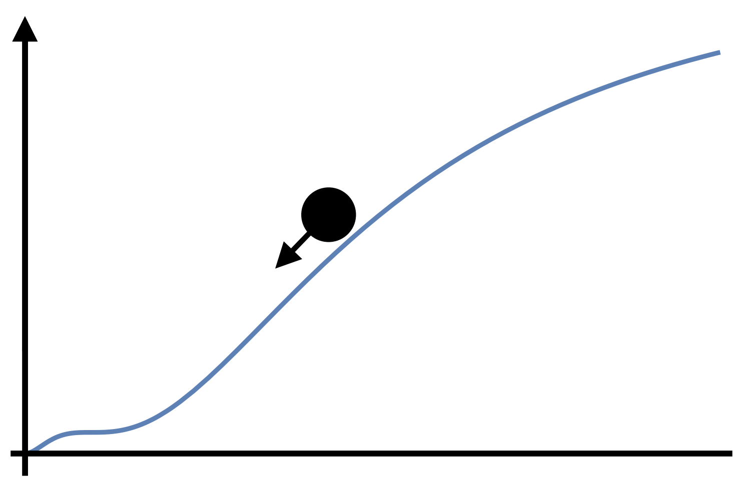
Q. Can we have PBH here?

Figure from 1807.11495

Critical Higgs-R^2 inflation

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

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



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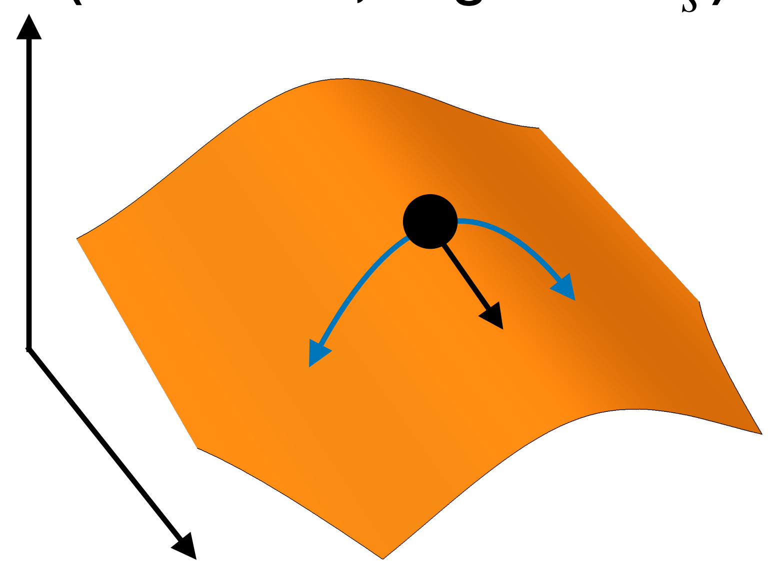
2. Tachyonic instability
(Multi-field, negative m_s^2)



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Enhanced Curvature Perturbation at small scales
GW & PBH Production?

1. Near-Inflection Point

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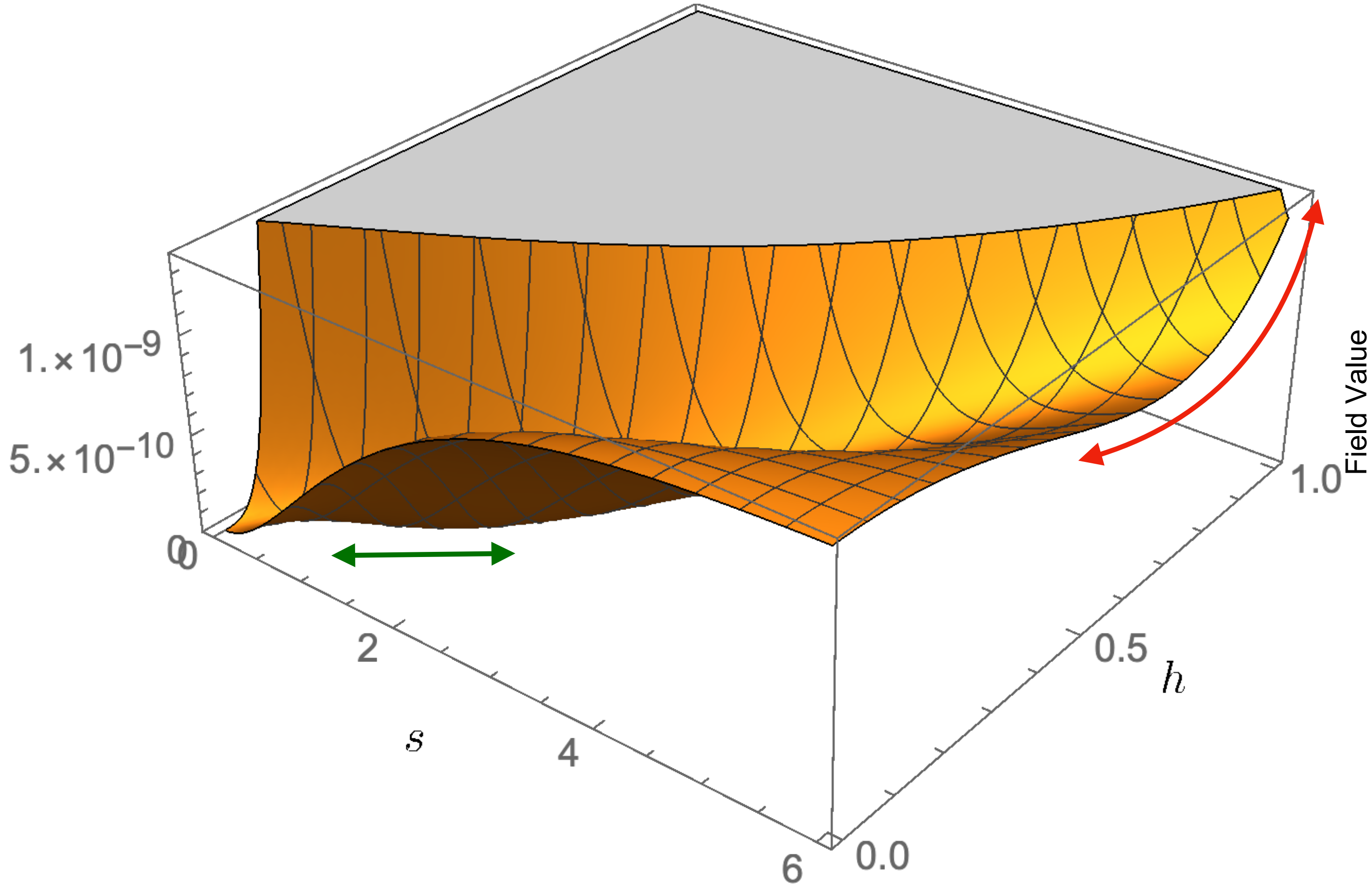
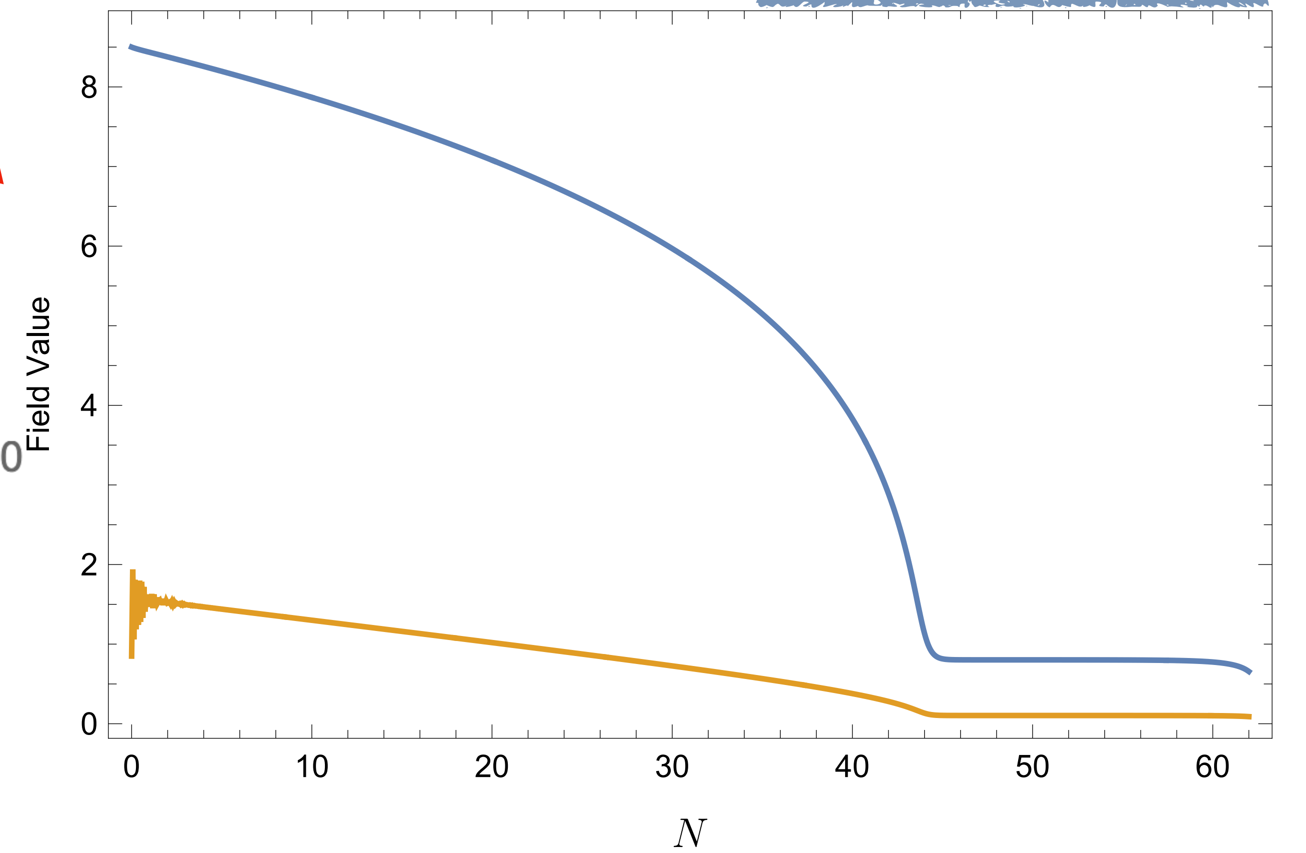
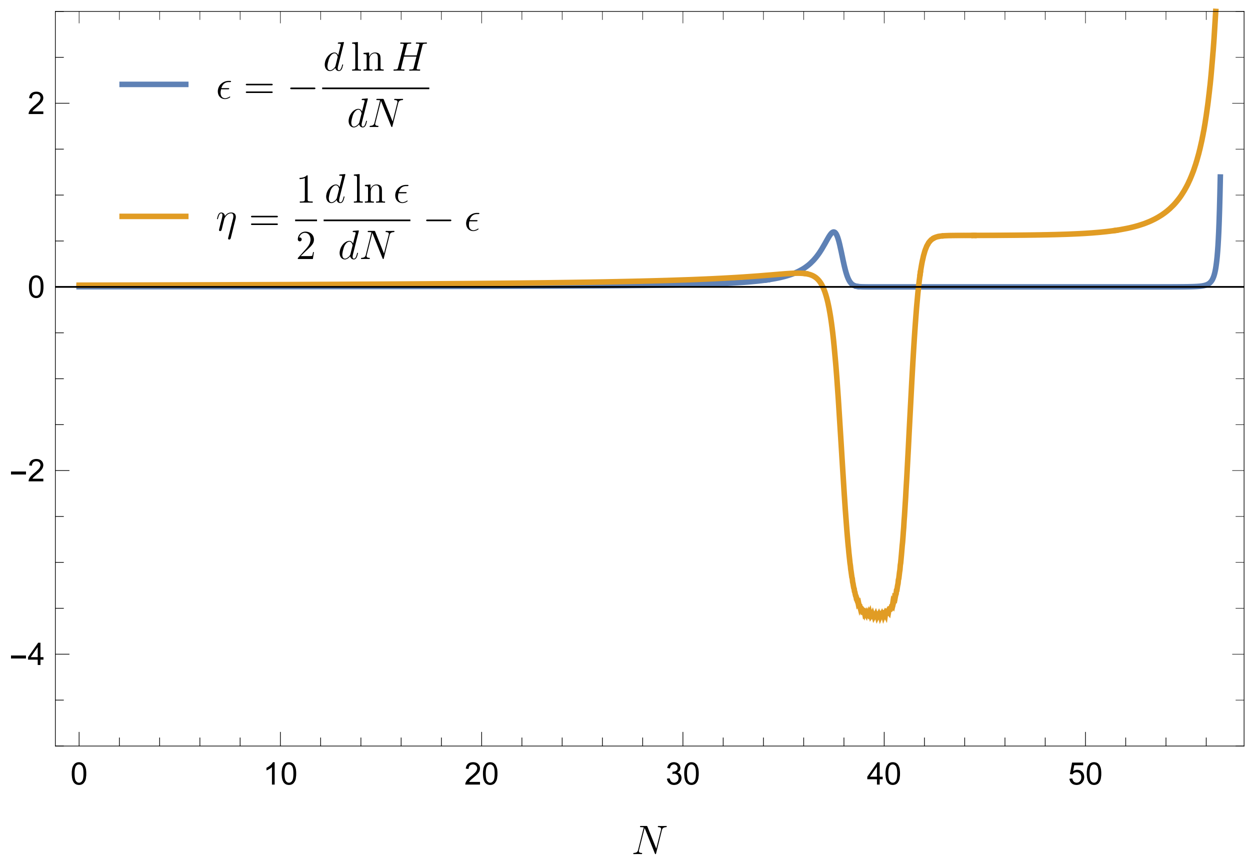
$M = 4.2 \times 10^{-5} M_P$
$\xi = 79$
$h_{\min} = 0.15 M_P$
$b = 2 \times 10^{-5}$
$\lambda_{\min} = 4.11087 \times 10^{-6}$

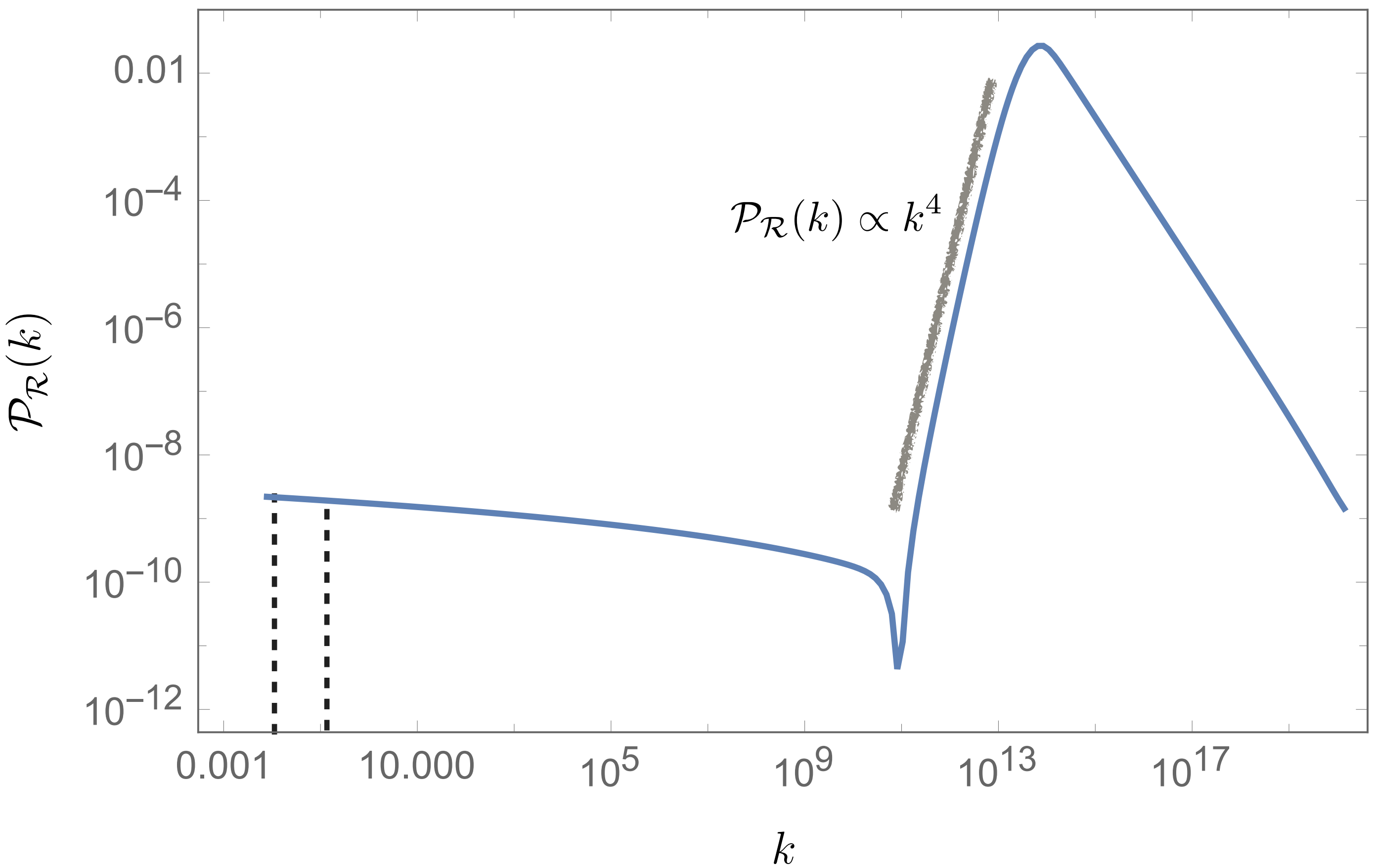




- Valley structure : Inflaton rolls along the “minimum” $D_h U = 0$ throughout inflation.
- 2nd plateau from the saddle point
- Ultra-slow-roll phase for about $\Delta N_{USR} \sim O(10)$ efolds.

1. Near-Inflection Point





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USR phase induced by $\lambda(h)$

Growing mode in $\mathscr{R}_k$

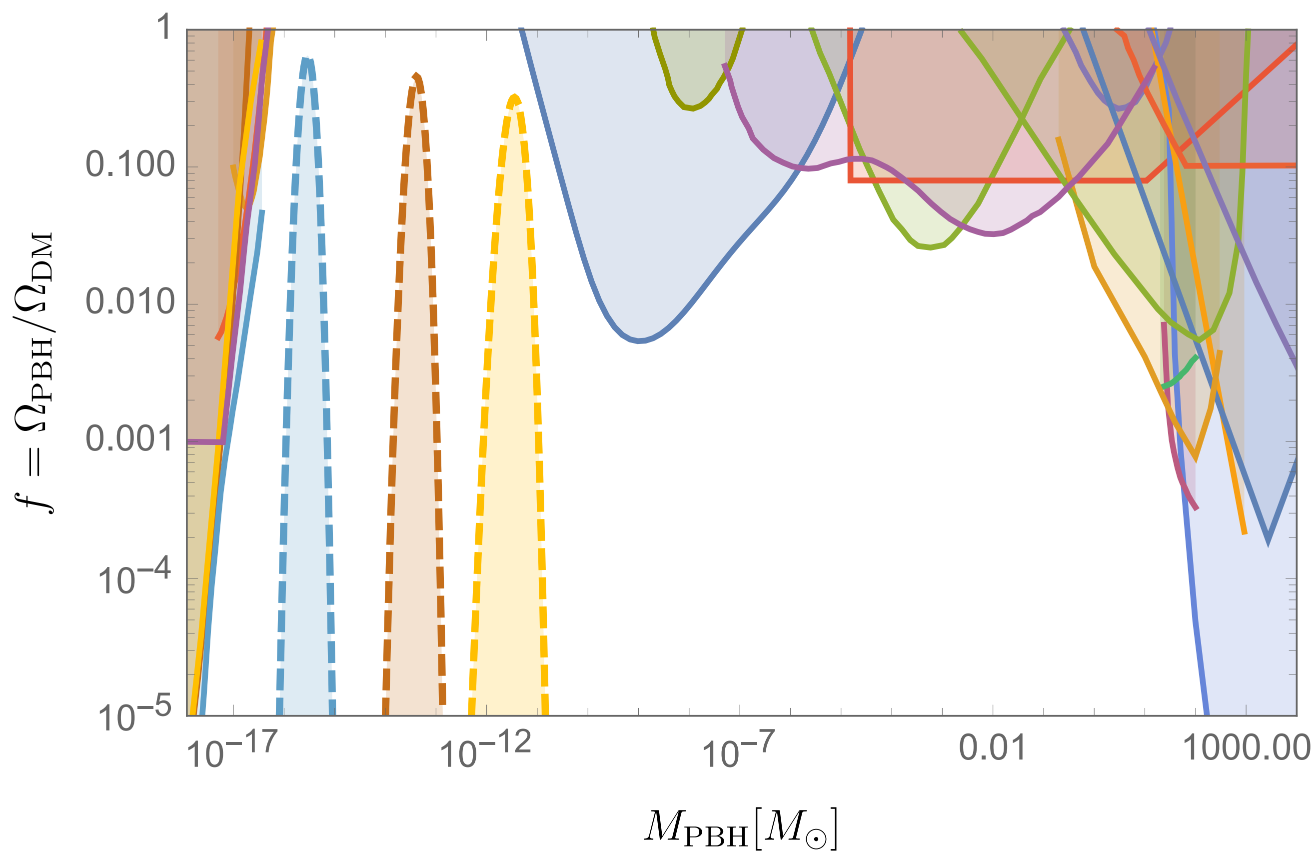
Distinctive USR growth

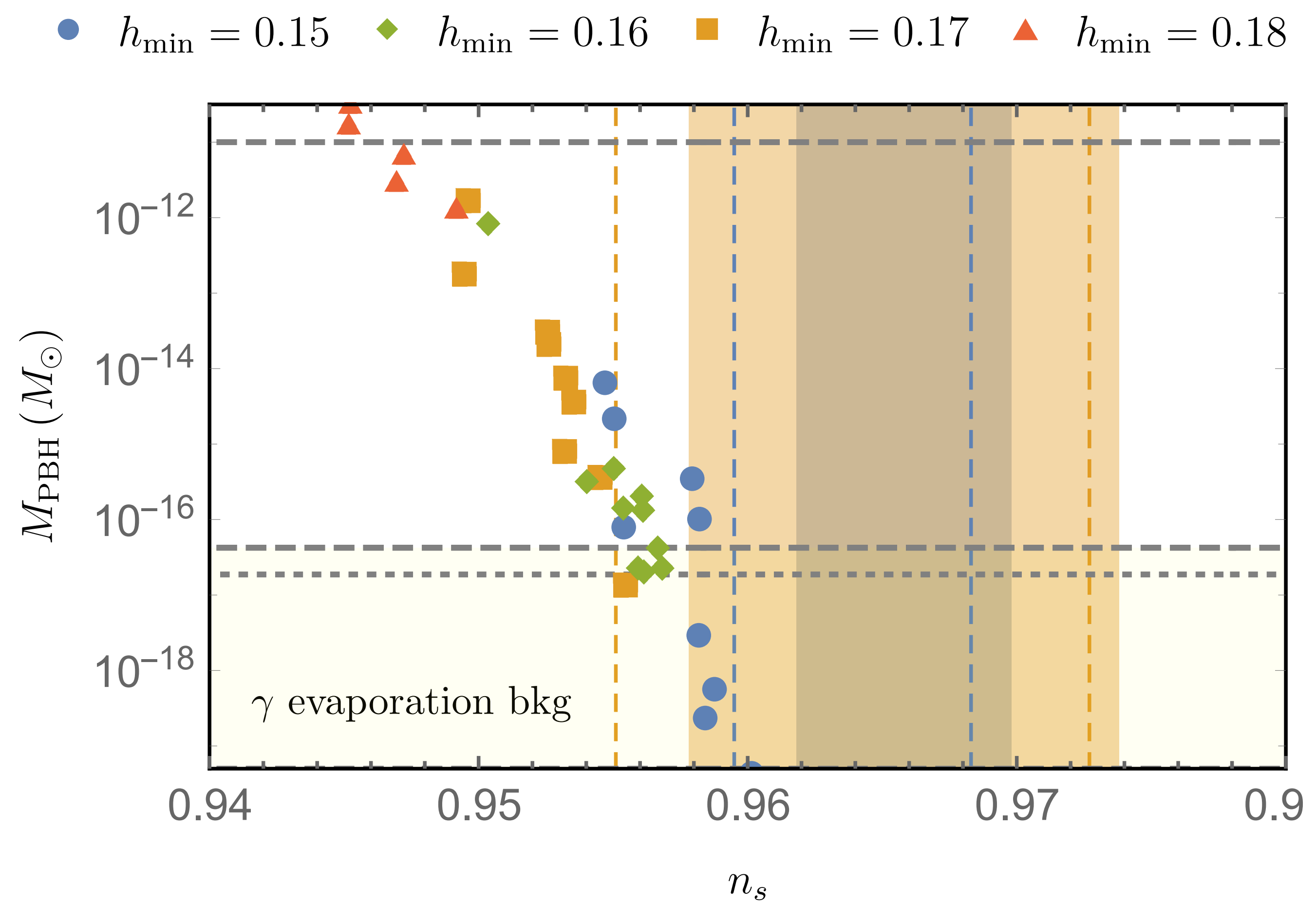
$\mathscr{P}_{\mathscr{R}} \propto k^4$

Small Scale Pert. produce PBHs and GWs!

Induced by the running of λ.

1. Near-Inflection Point





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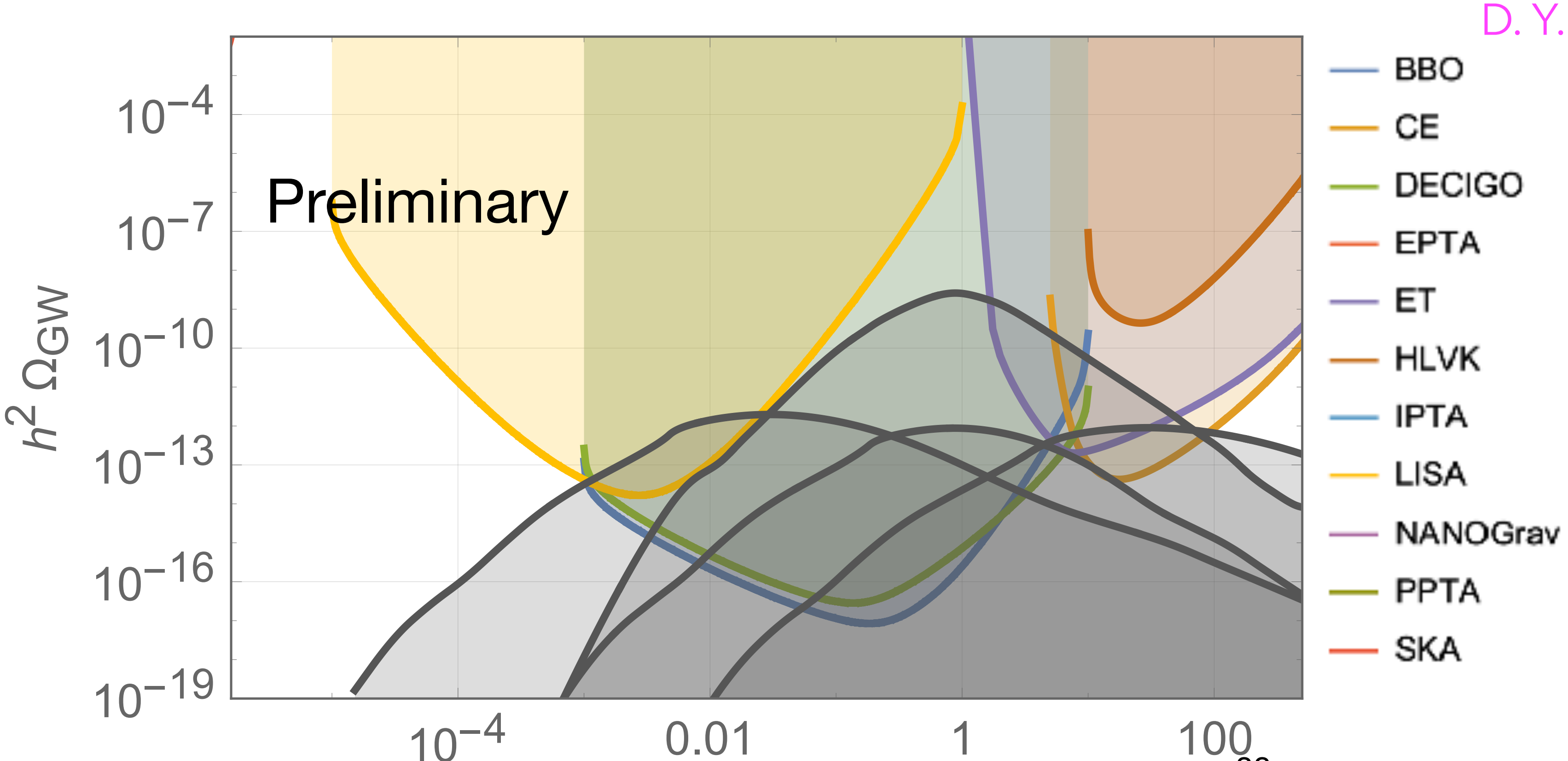


PBHs compatible for a suitable amount of DM.

Slight tension due to the prolonged USR.

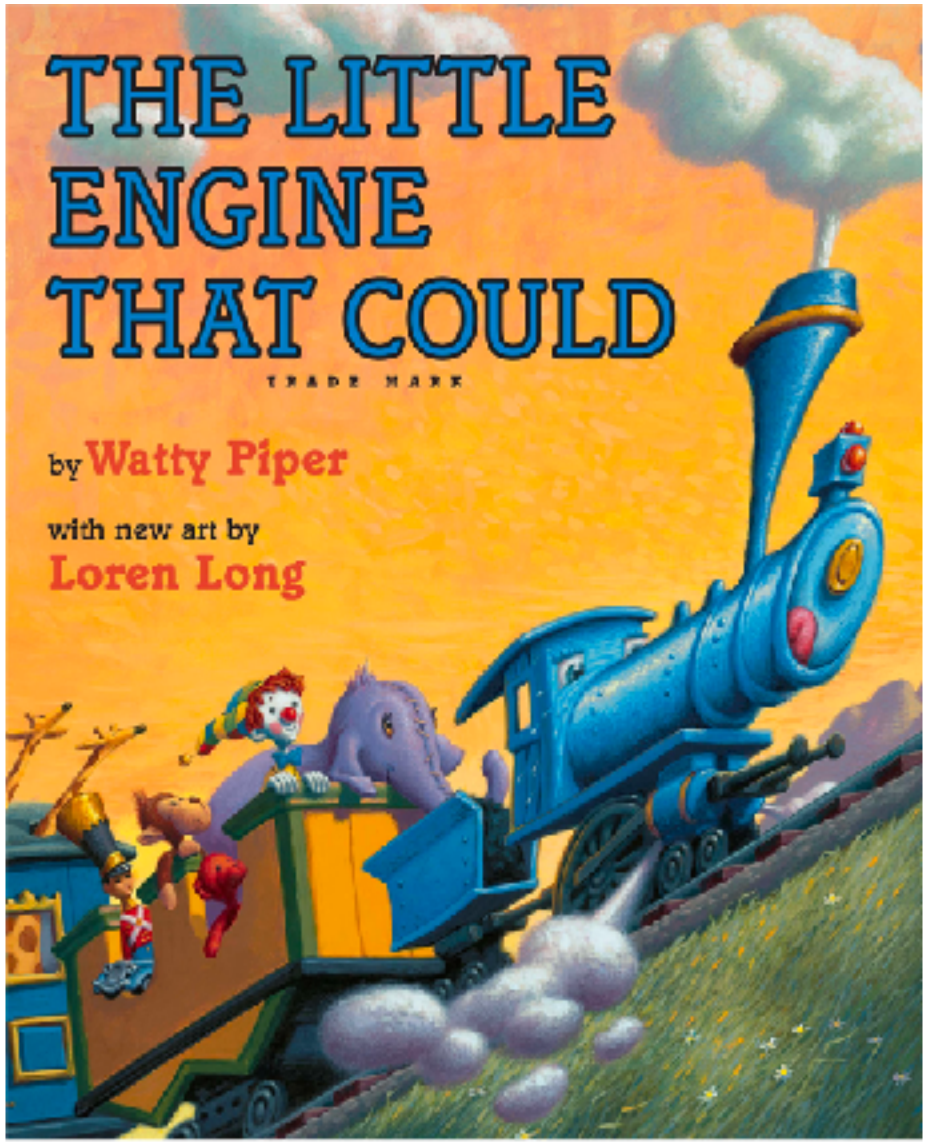
LISA, DECIGO, CE, ET available to probe wider parameter range compared to PBHs.

Tachyonic Instability

Apparently, this is not the end of the phenomenology the critical Higgs-R^2 inflation can exhibit.

Critical Higgs-R^2 inflation can exhibit turns in the trajectory.

Inflaton climbs the hill at $s = 0$, leading to tachyonic perturbation growth!



Perturbed action in second order

Perturbed action up to second order in the comoving gauge $S^{(2)} = \int dt d^3x \mathscr{L}^{(2)}$

$$\mathscr{L}^{(2)} = a^3 \left[M_P^2 \epsilon \left(\dot{\mathscr{R}}^2 - \frac{(\partial \mathscr{R})^2}{a^2} \right) + 2\dot{\sigma}\eta_\perp \dot{\mathscr{R}} Q_{iso} + \frac{1}{2} \left(\dot{Q}_{iso}^2 - \frac{(\partial Q_s)^2}{a^2} - m_{iso}^2 Q_{iso}^2 \right) \right]$$

Slow roll parameters : $\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\sigma}^2}{2M_P^2 H^2}, \eta_\parallel \equiv -\frac{\ddot{\sigma}}{H\dot{\sigma}}, \eta_\perp \equiv \frac{U_{iso}}{\dot{\sigma}H}, \dot{\theta} = H\eta_\perp$.

Unit vectors : $e_\sigma^a \equiv \dot{\phi}^a / \dot{\sigma}, e_{iso}^a \perp e_\sigma^a, \dot{\sigma}^2 \equiv (G_{ab}\dot{\phi}^a\dot{\phi}^b)$.

Isocurvature mass : $m_{iso}^2 = U_{ss} - \dot{\theta}^2 + \epsilon H^2 M_P^2 \mathbb{R}_{ab} G^{ab}$

with $U_{ss} \equiv e_{iso}^a e_{iso}^b \nabla_a \nabla_b U$ and $\mathbb{R}_{ab}$ being the Ricci scalar of the field space metric

Perturbation equations

Redefining $\mathscr{R} = \frac{H}{\dot{\sigma}} Q_\sigma$, $S = \frac{H}{\dot{\sigma}} Q_{iso}$, the perturbation equations yield

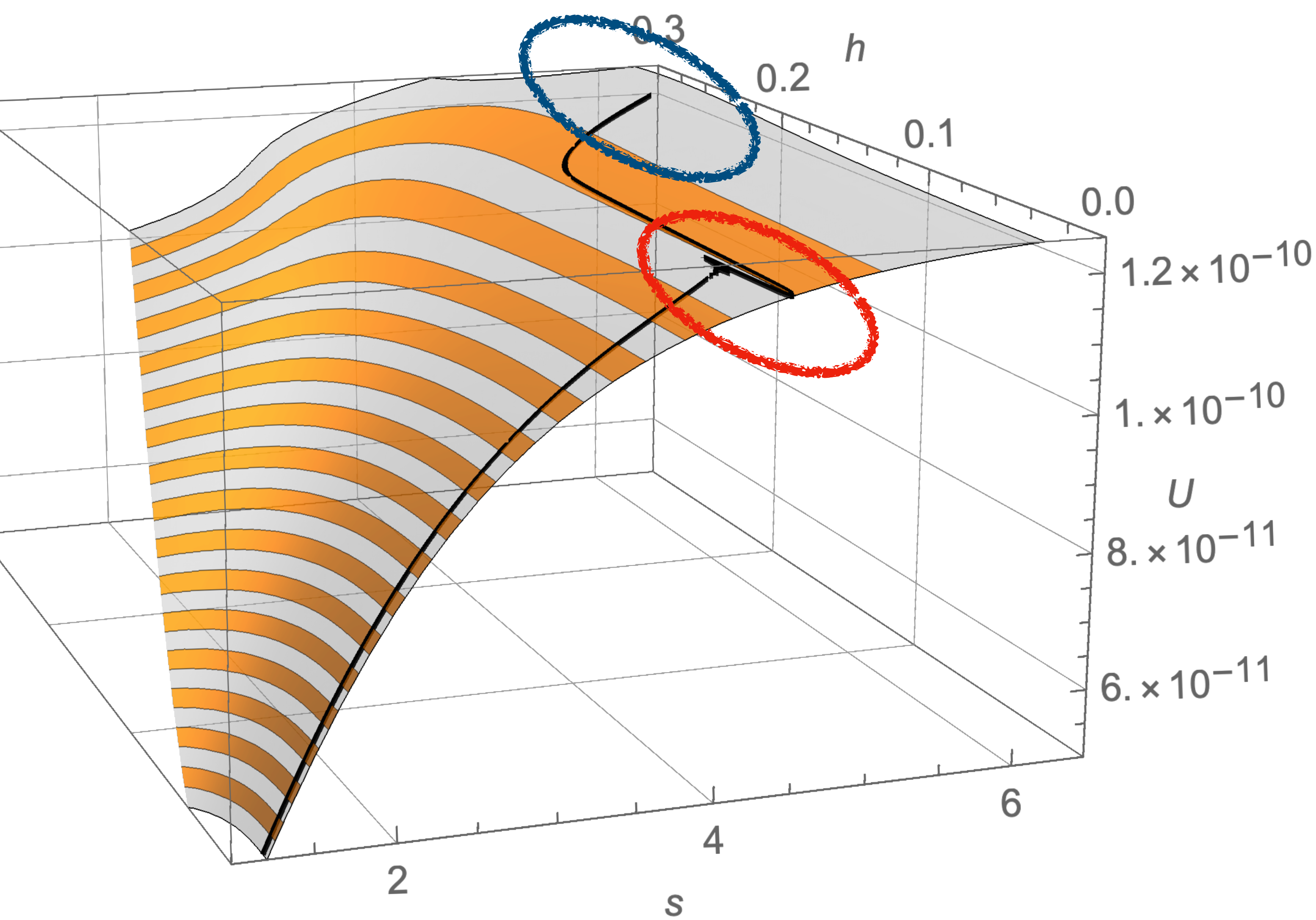
$$\ddot{Q}_\sigma + 3H\dot{Q}_\sigma + \left(\frac{k^2}{a^2} + m_\sigma^2\right) Q_\sigma = (2H\dot{\eta_\perp Q_{iso}}) - \left(\frac{\dot{H}}{H} + \frac{U_\sigma}{U}\right) 2H\eta_\perp Q_{iso}$$

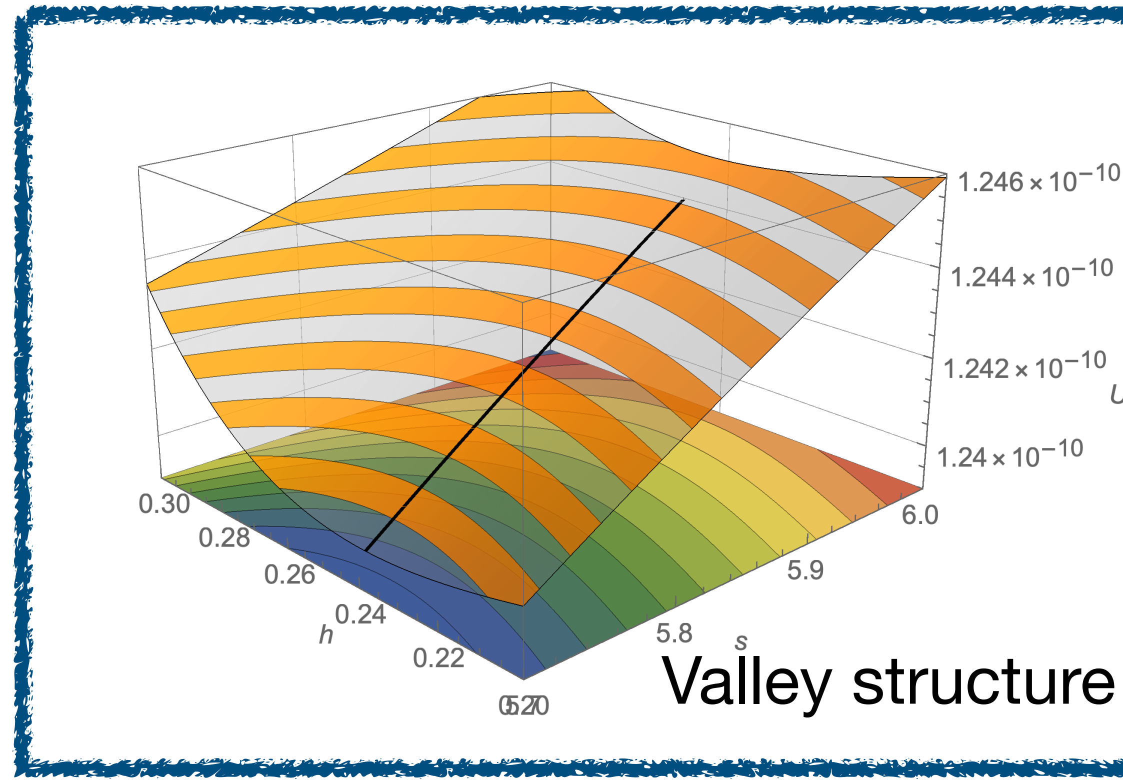
$$\ddot{Q}_{iso} + 3H\dot{Q}_{iso} + \left(\frac{k^2}{a^2} + m_{iso}^2\right) Q_{iso} = -2\dot{\sigma}\eta_\perp \dot{\mathscr{R}}$$

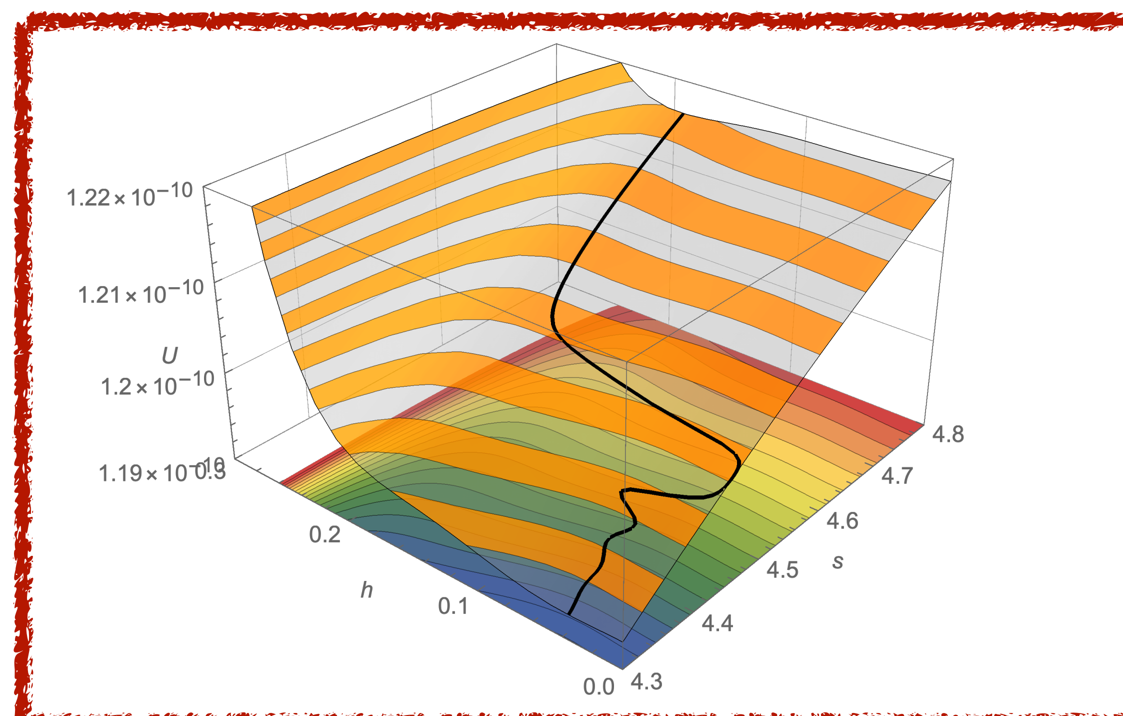
$m_{iso}^2 < 0$ leads to tachyonic growth of Q_{iso} , then gets sourced to Q_σ through turns in the trajectory.

Negative m_{iso}^2 at the "hill" of the potential at $s = 0$, $m_{iso}^2 \simeq -3M_P^2 M^2 \xi \left(1 - e^{-\sqrt{\frac{2}{3}}\frac{s}{M_P}}\right)$

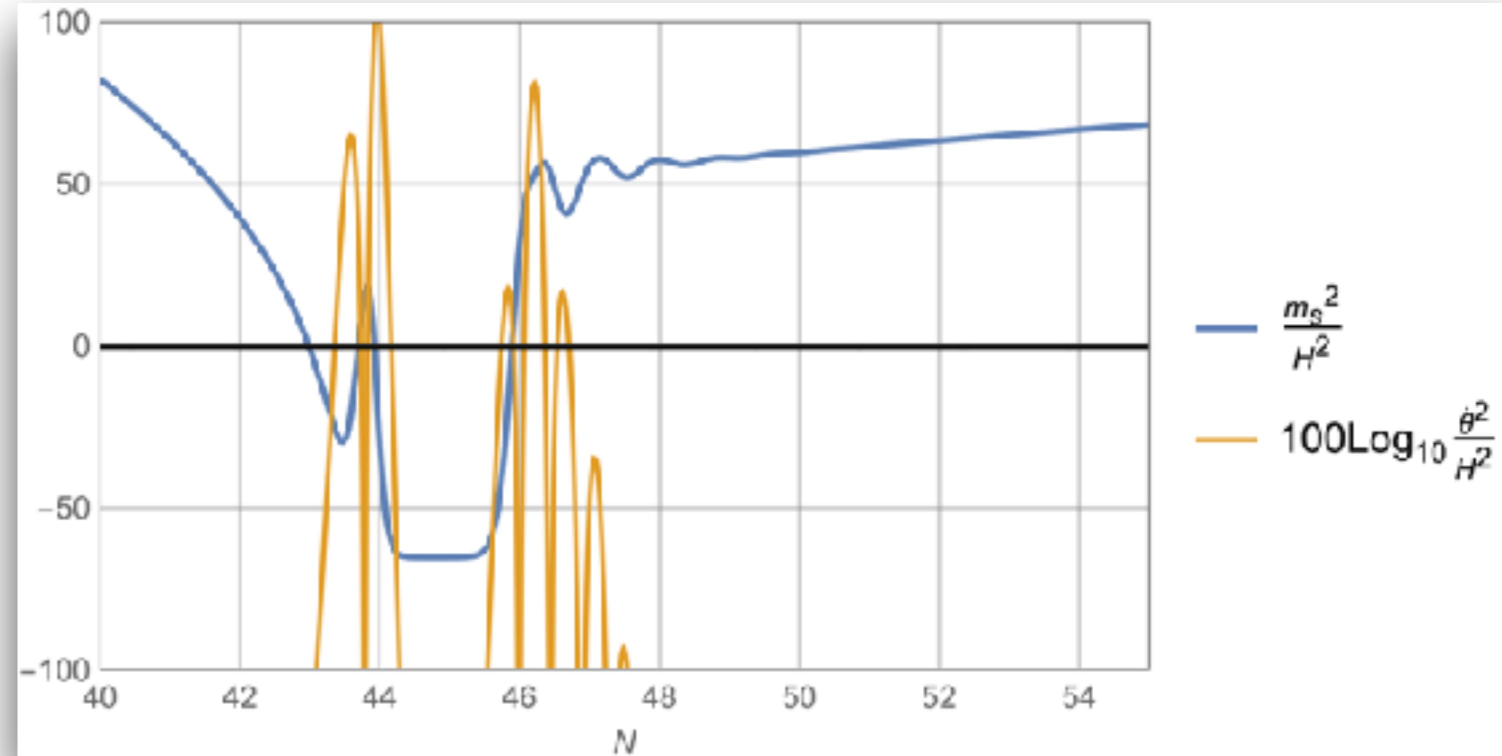
Trajectory $\xi = 3.2$





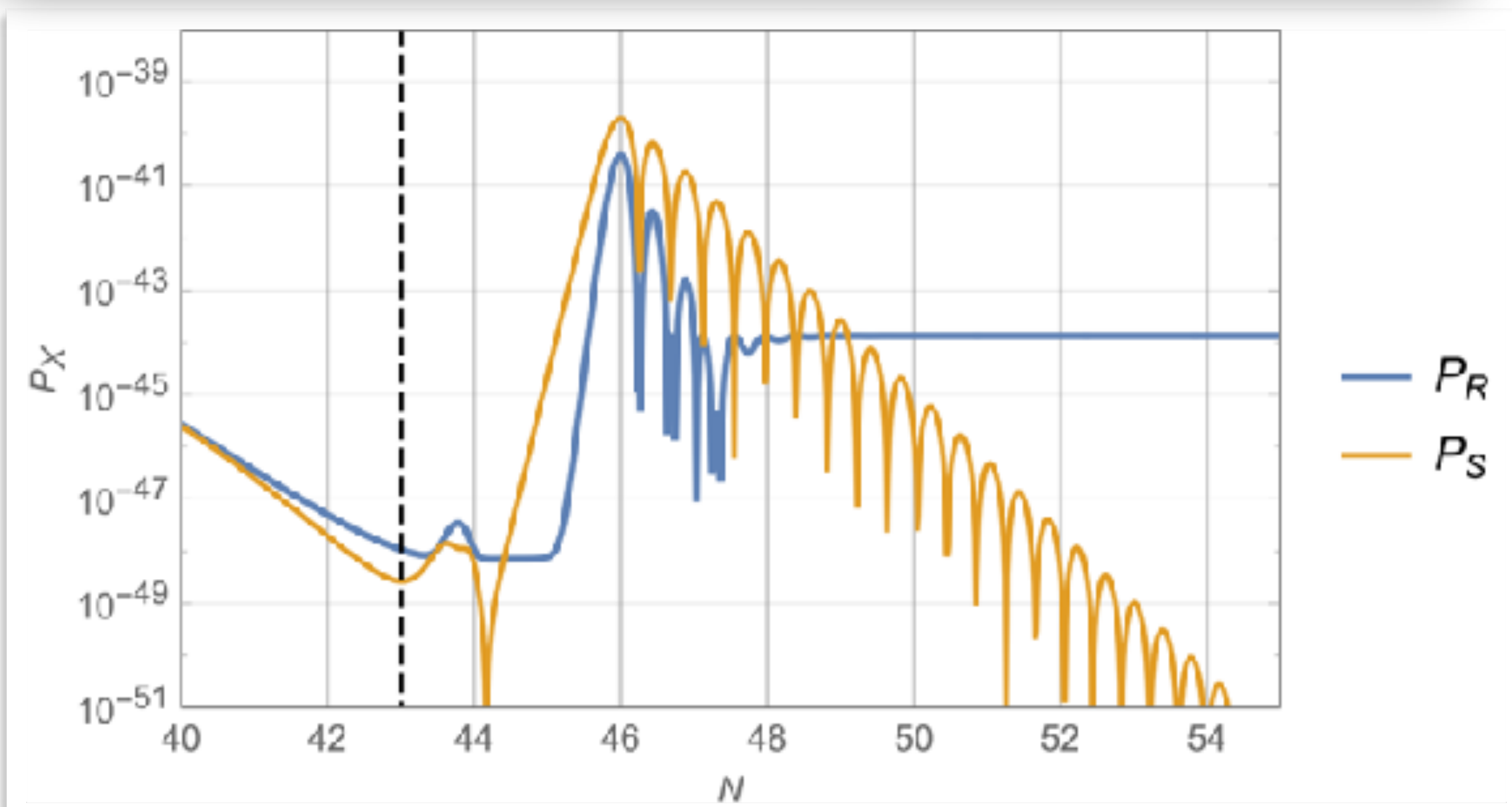


Perturbations



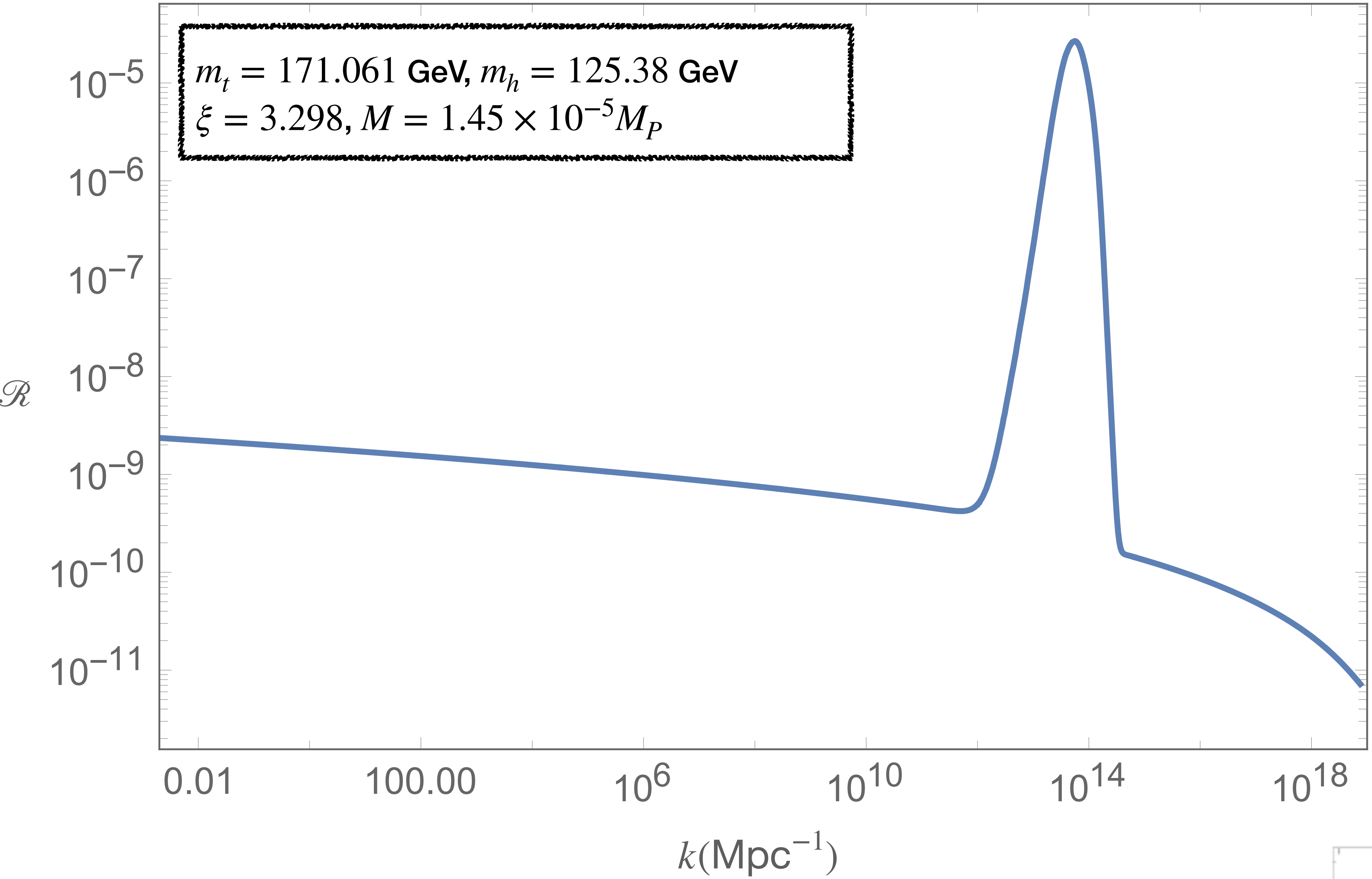
Temporal $m_{iso}^2 < 0$ stage

Turn rates transfer perturbations



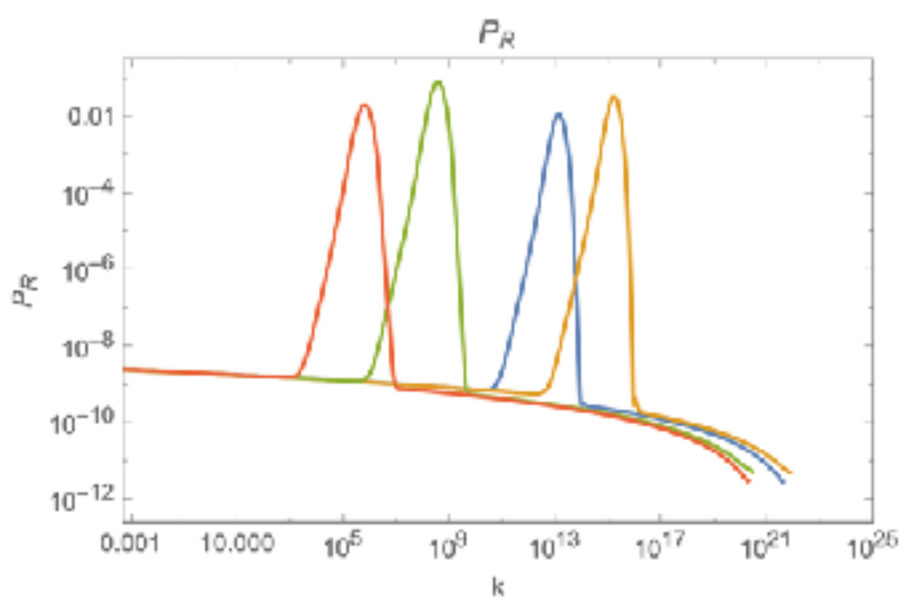
Tachyonic growth in both isocurvature and curvature perturbations.

Perturbations and GWs, an Example

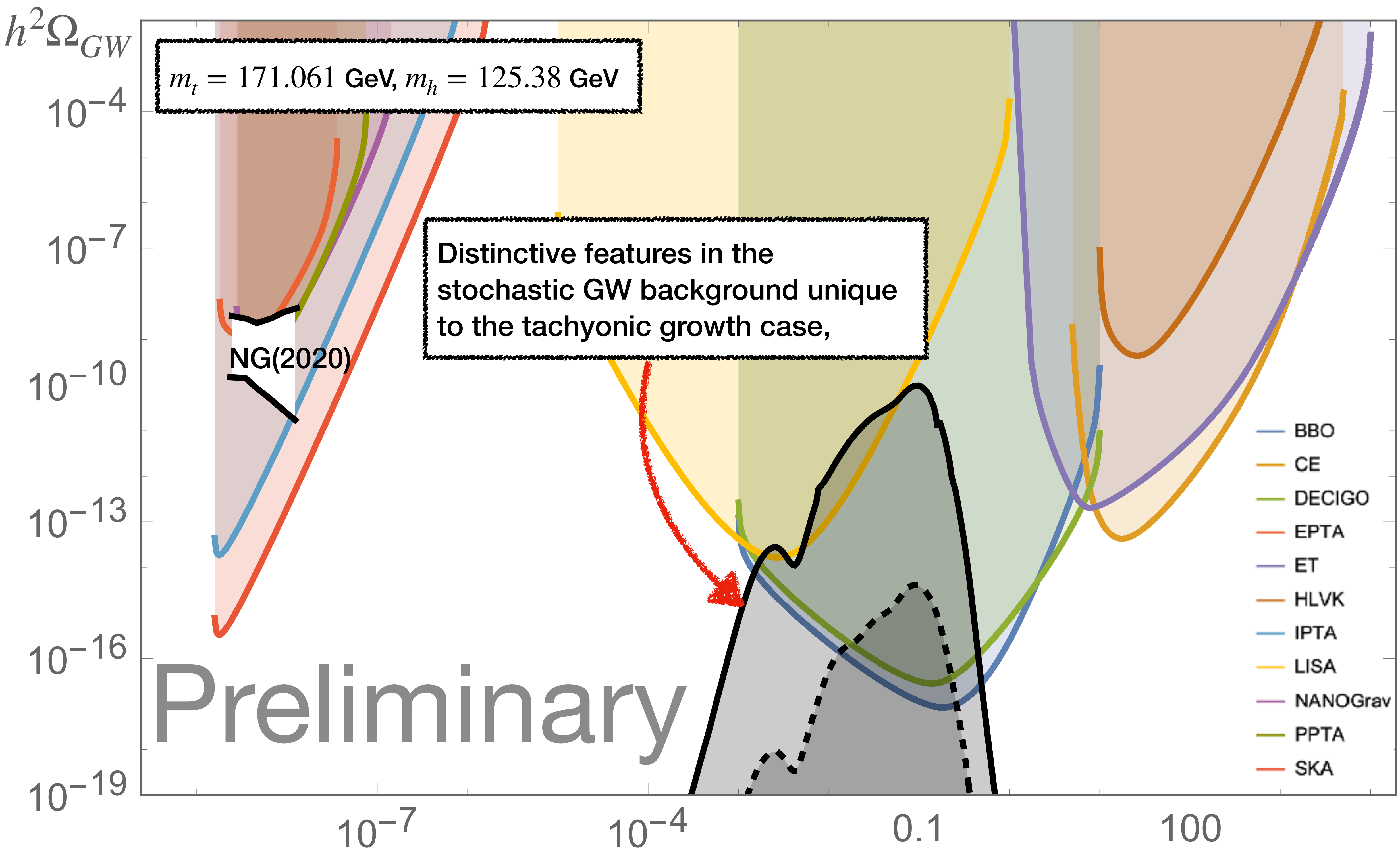


Rapid growth in the curvature power spectrum compared to USR cases

Compatible parameters with current CMB, LHC



Perturbations and GWs, an Example



ξ =3.2981, M = $1.45\times10^{-5}M_p$ .... ξ =3.298, M = $1.45\times10^{-5}M_p$

Summary

- Higgs-R^2 (or equivalently Higgs-Scalaron) with $m_s < M_P/\xi$ is a unitary theory up to $\Lambda \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2 m_s^2}\right) M_P$
- provides successful inflation with $n_s \simeq 0.962,\ r \sim 0.003$
- The potential $V(s, h)$ allows
    - ❋ inflection point for USR near criticality ($\xi \gtrsim O(10)$)
    - ❋ valley + hill for Tachyonic instabilty ($\xi \sim O(1)$)
    - ❋ note $\lambda(\mu_i) \ll \lambda(\mu_{EW})$ due to RG running
- Both support enhancement in curvature and/or isocurvature perturbation => leads to PBH & GW production
- PBH can be the whole dark matter. GW can be subject to be observed in the future experiments.