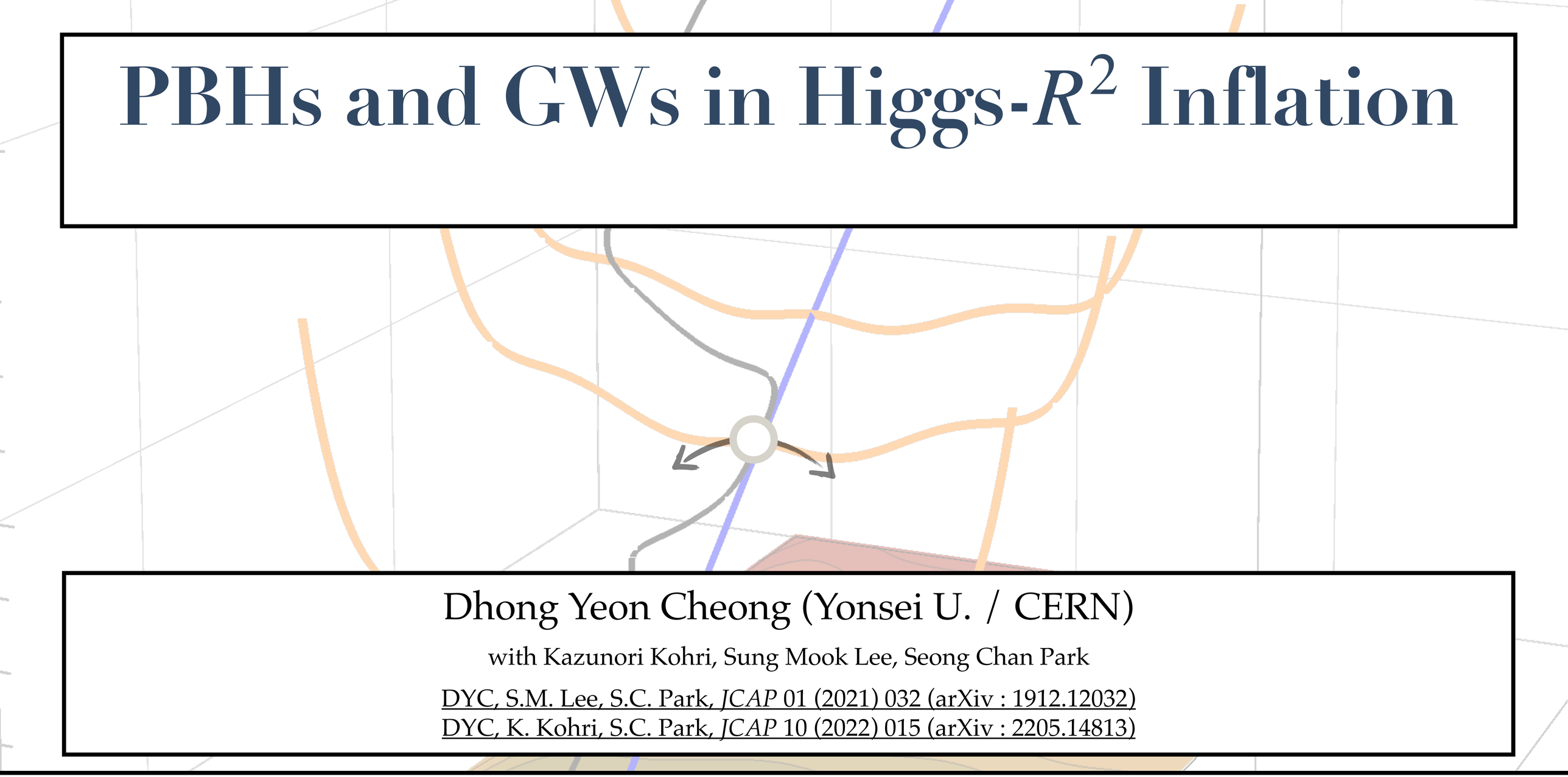
PBHs and GWs in Higgs-R^2 Inflation



Dhong Yeon Cheong (Yonsei U. / CERN)

with Kazunori Kohri, Sung Mook Lee, Seong Chan Park

DYC, S.M. Lee, S.C. Park, *JCAP* 01 (2021) 032 (arXiv : 1912.12032)

DYC, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015 (arXiv : 2205.14813)

OKC@15 Conference

Stockholm, Sweden, Oct 18th, 2023

연세대학교 YONSEI UNIVERSITY

Outline

Higgs-R^2 inflation + SM Higgs Running

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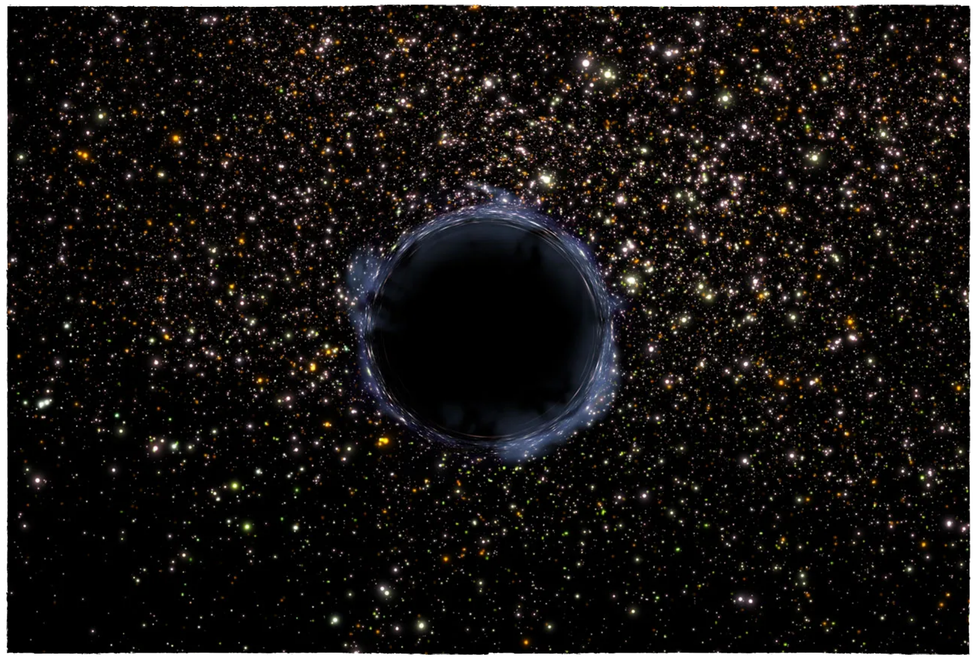
Observational Consequences!

Outline

Higgs-R^2 inflation + SM Higgs Running



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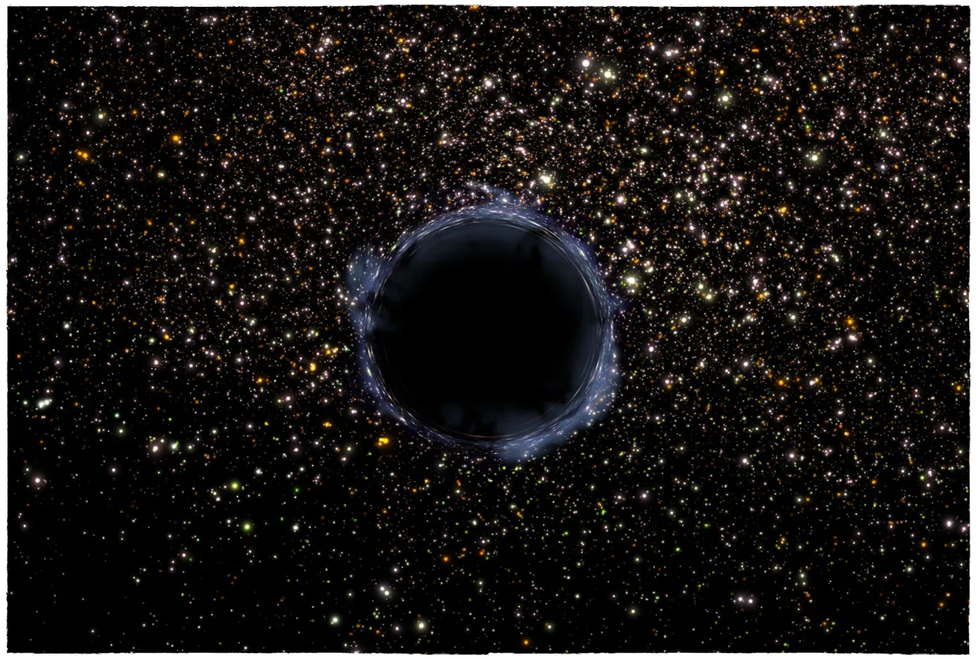
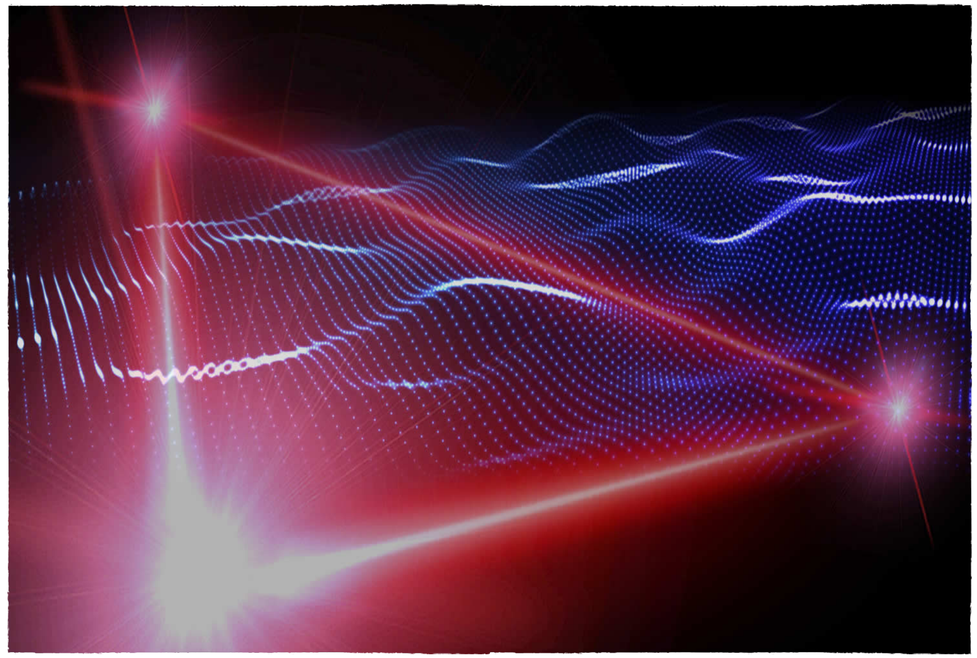


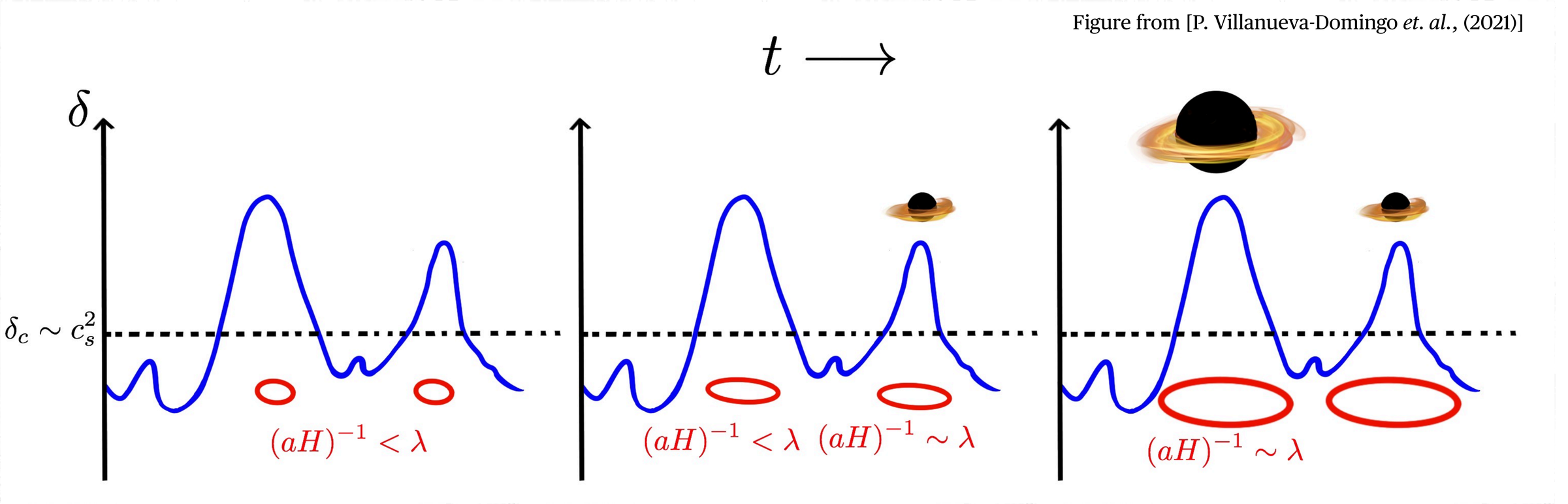


Observational Consequences!

Primordial Black Holes

PBHs form through the collapse of *large overdensities*

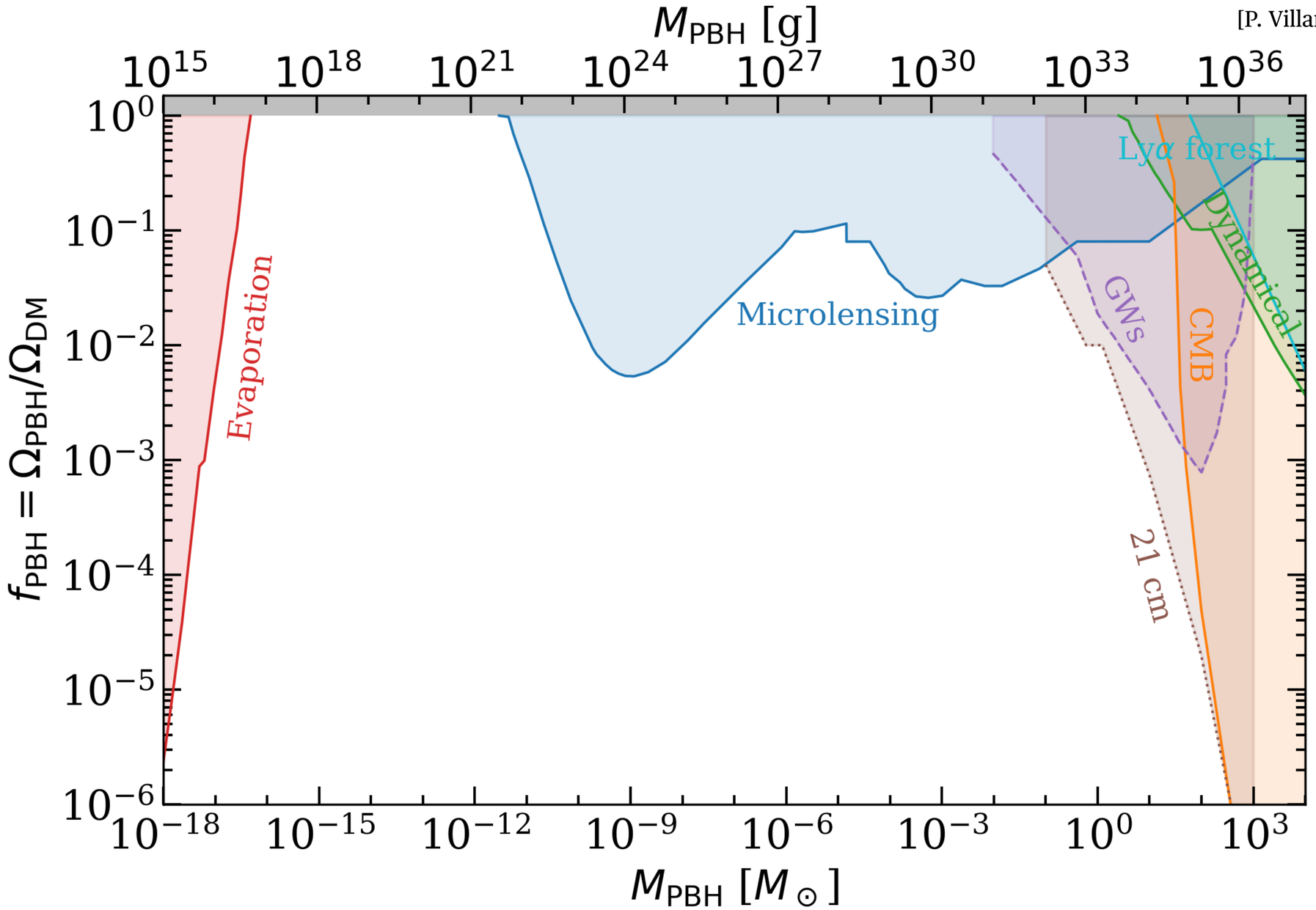
Figure from [P. Villanueva-Domingo *et. al.*, (2021)]



$$\delta_c \sim \mathcal{O}(1) \quad \longleftrightarrow \quad \mathcal{P}_{\mathcal{R}} \sim \mathcal{O}(10^{-2})$$

Primordial Black Holes - Constraints

[P. Villanueva-Domingo *et. al.*, (2021)]



Second Order Gravitational Waves

PBH production can be associated with *stochastic gravitational waves!*

[J.R. Espinosa, D. Racco, A. Riotto, (2018)]
[K. Kohri, T. Terada, (2018)]...

$$\Omega_{\rm GW}(\eta_0, k) = c_g \frac{\Omega_{r,0}}{6} \int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2 - (1+v^2-u^2)^2}{4uv} \right)^2 \overline{\mathcal{I}^2(v,u)} \mathcal{P}_\mathcal{R}(kv) \mathcal{P}_\mathcal{R}(ku)$$

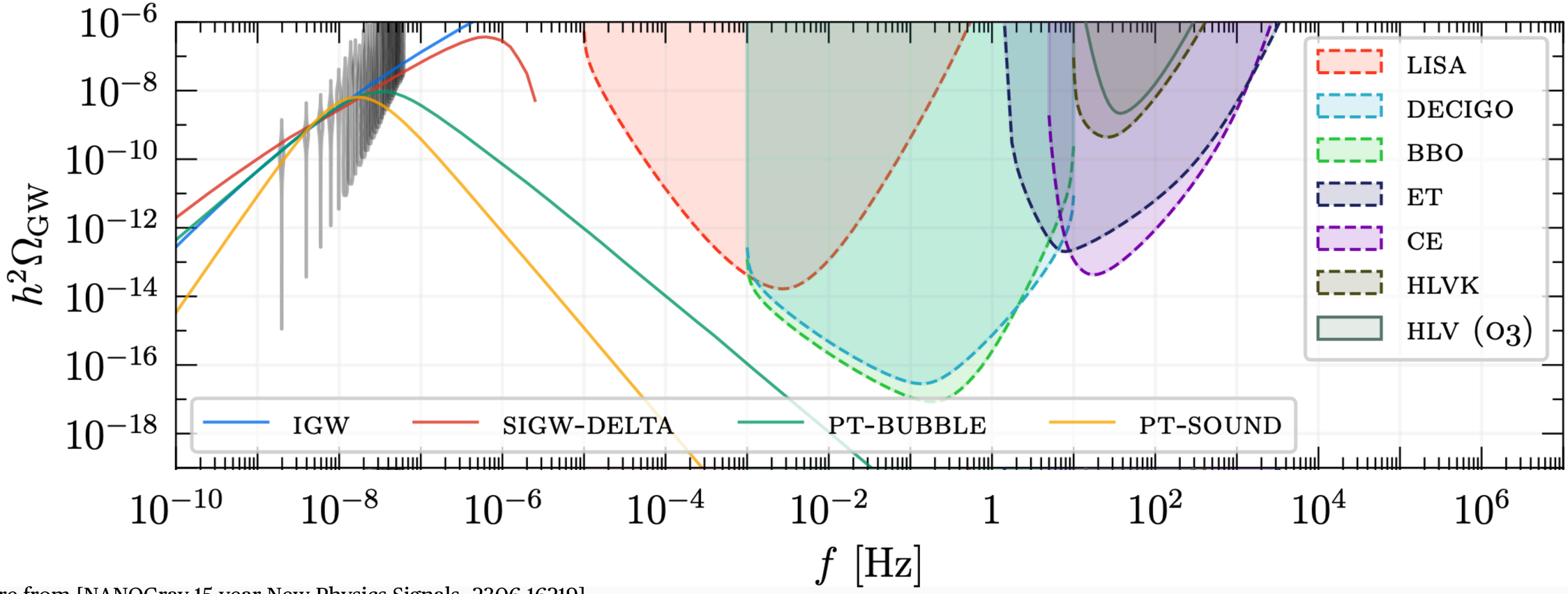


Figure from [NANOGrav 15-year New-Physics Signals, 2306.16219]

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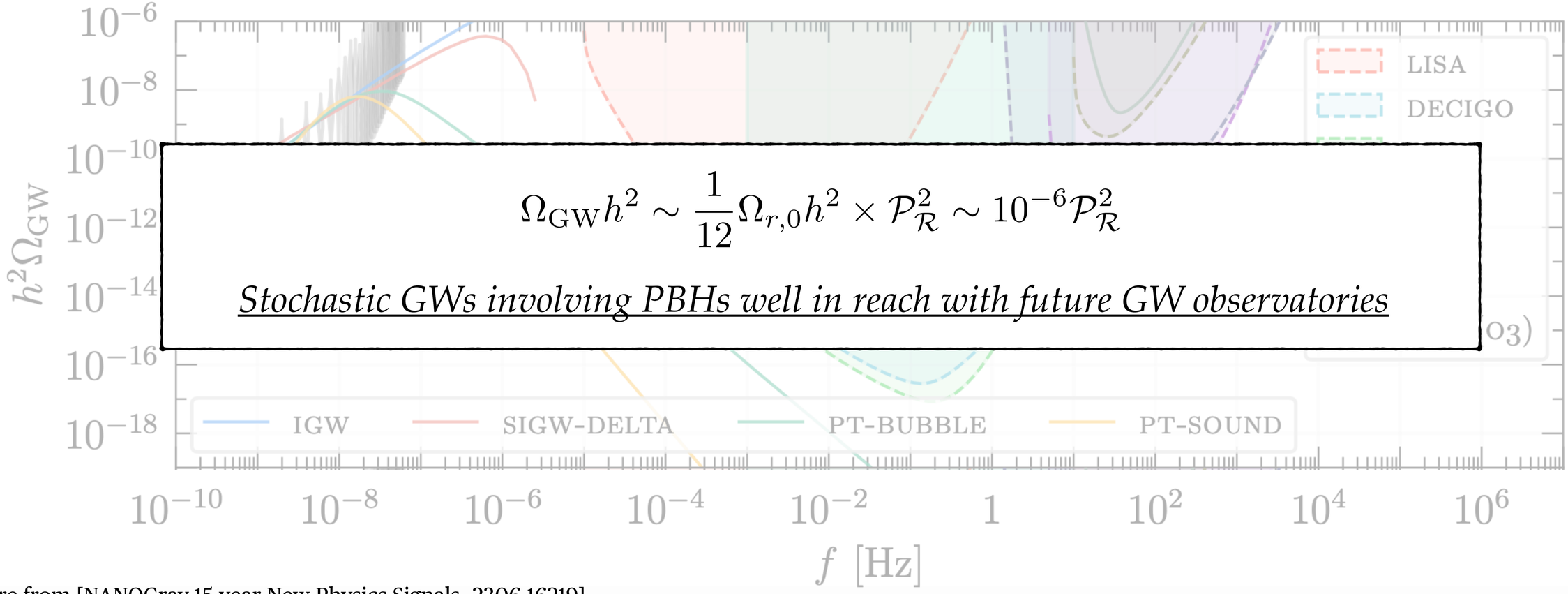

$$\Omega_{\rm GW} h^2 \sim \frac{1}{12} \Omega_{r,0} h^2 \times \mathcal{P}_\mathcal{R}^2 \sim 10^{-6} \mathcal{P}_\mathcal{R}^2$$

Stochastic GWs involving PBHs well in reach with future GW observatories

Figure from [NANOGrav 15-year New-Physics Signals, 2306.16219]

Higgs-R^2 Inflation

Question) What can be our inflaton? —> SM Higgs?

Considering dim-4 operators, R^2 present!

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

non-minimal coupling

scalar d.o.f

Higgs

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Higgs

$$U(s,h) \equiv e^{-2\sqrt{\frac{2}{3}}\frac{s}{M_P}}\left\{\frac{3}{4}M_P^2M^2\left(e^{\sqrt{\frac{2}{3}}\frac{s}{M_P}} - 1 - \frac{\xi h^2}{M_P^2}\right)^2 + \frac{\lambda_{\text{eff}}(\mu)}{4}h^4\right\}$$

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(1) Near-inflection point

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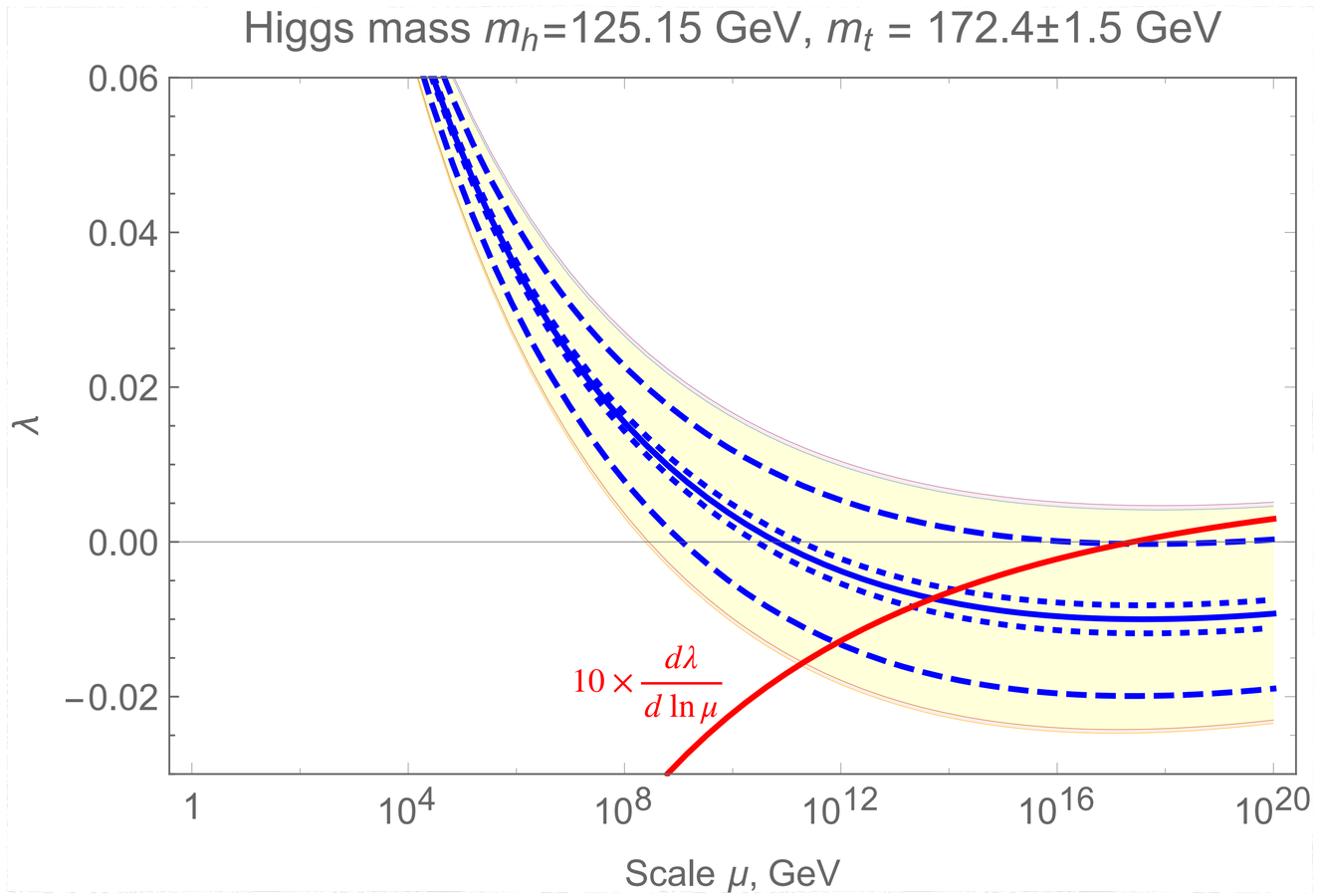
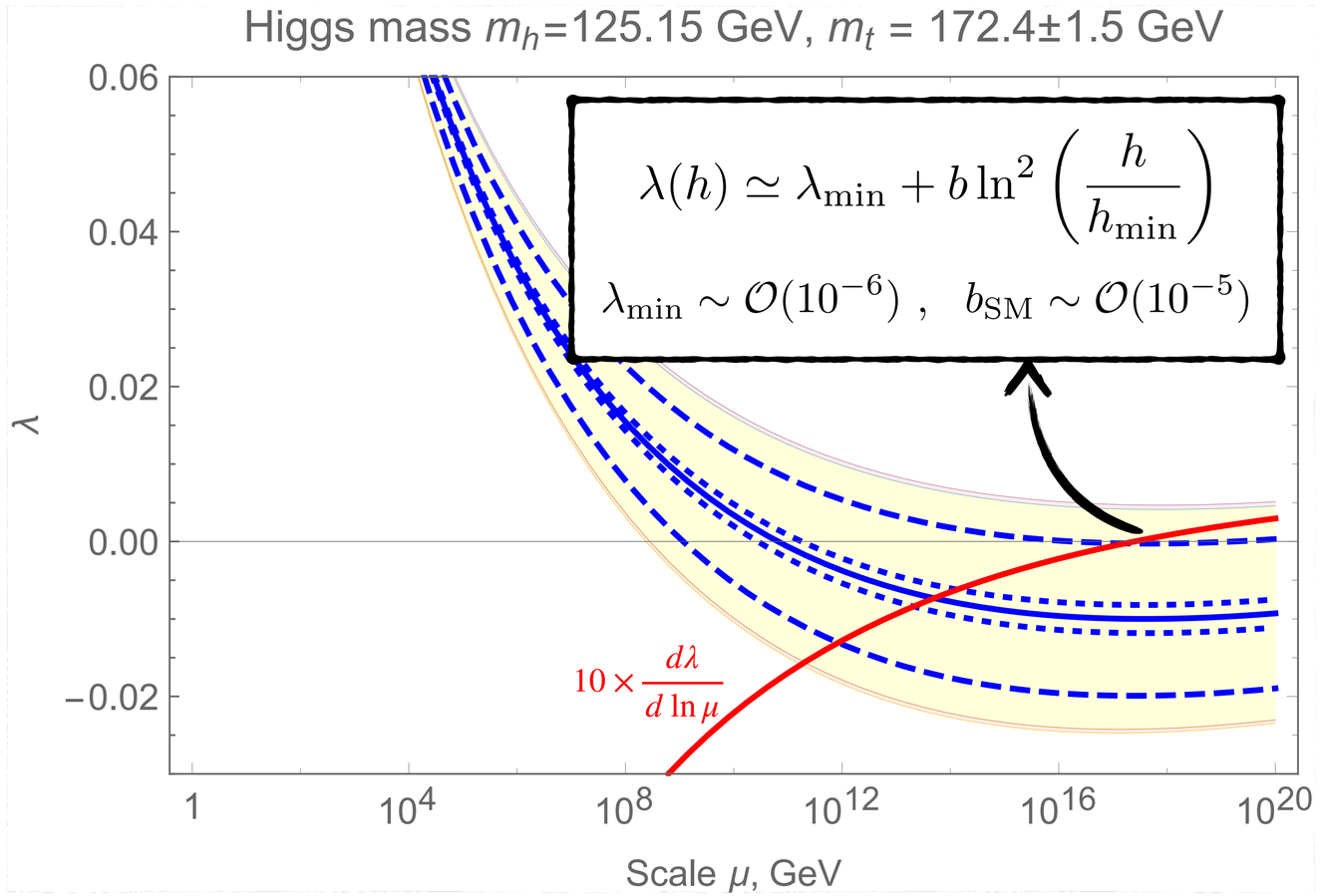
(1) Near-inflection point

(2) Tachyonic hill

Higgs-R^2 Inflation, SM Higgs Running



Higgs-R^2 Inflation, SM Higgs Running



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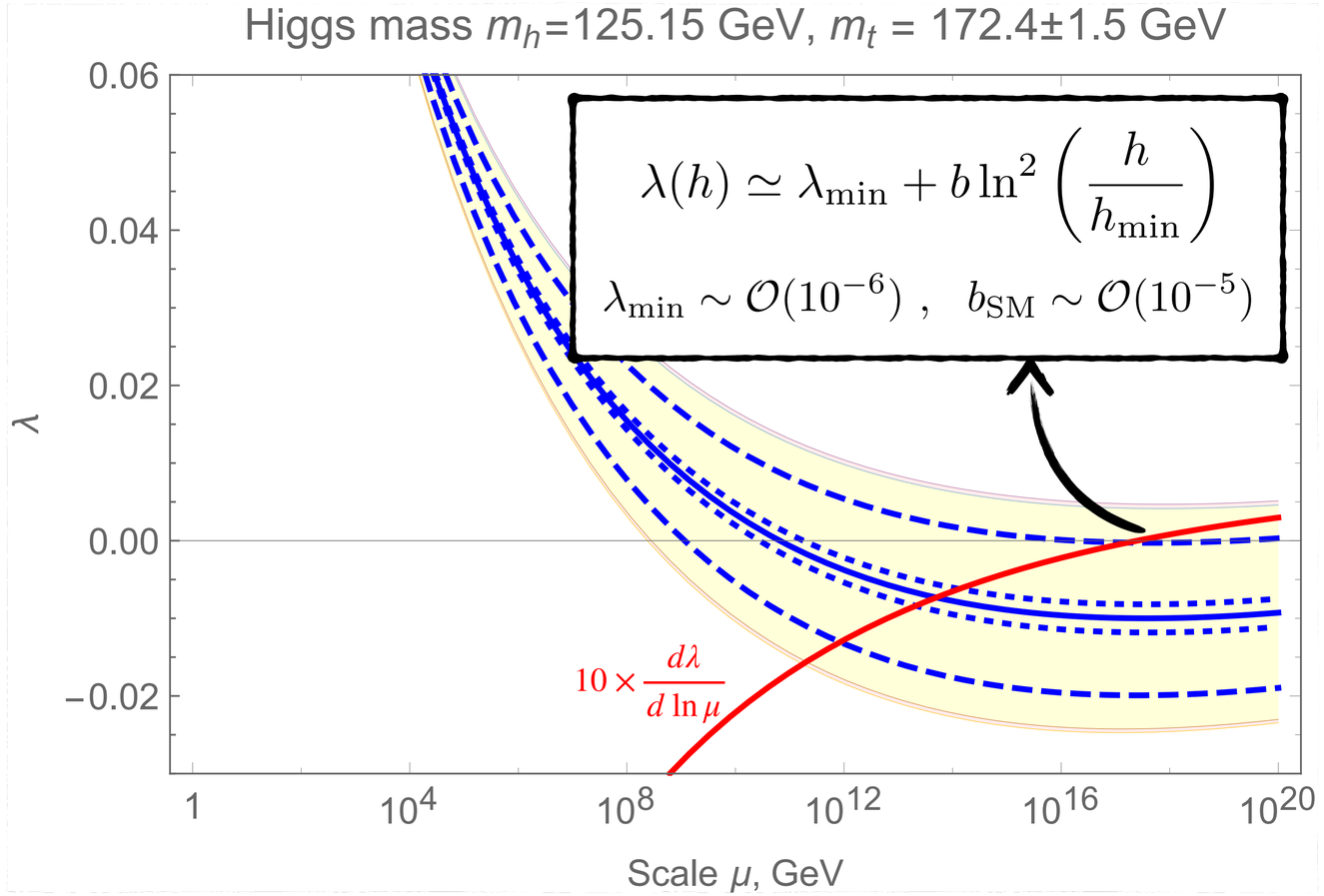
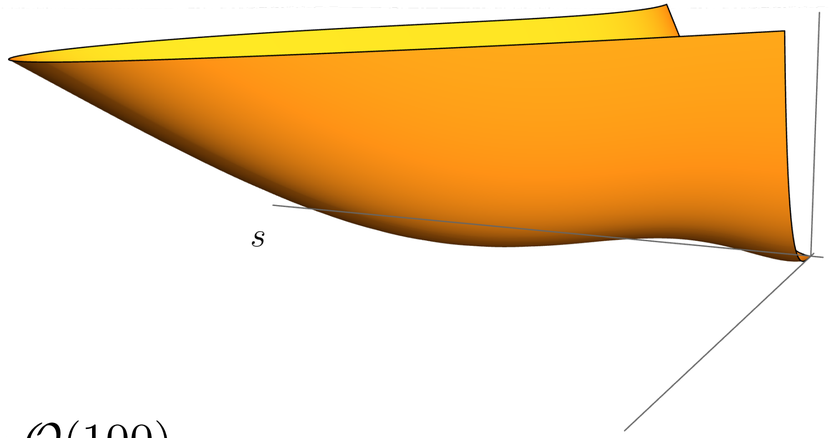
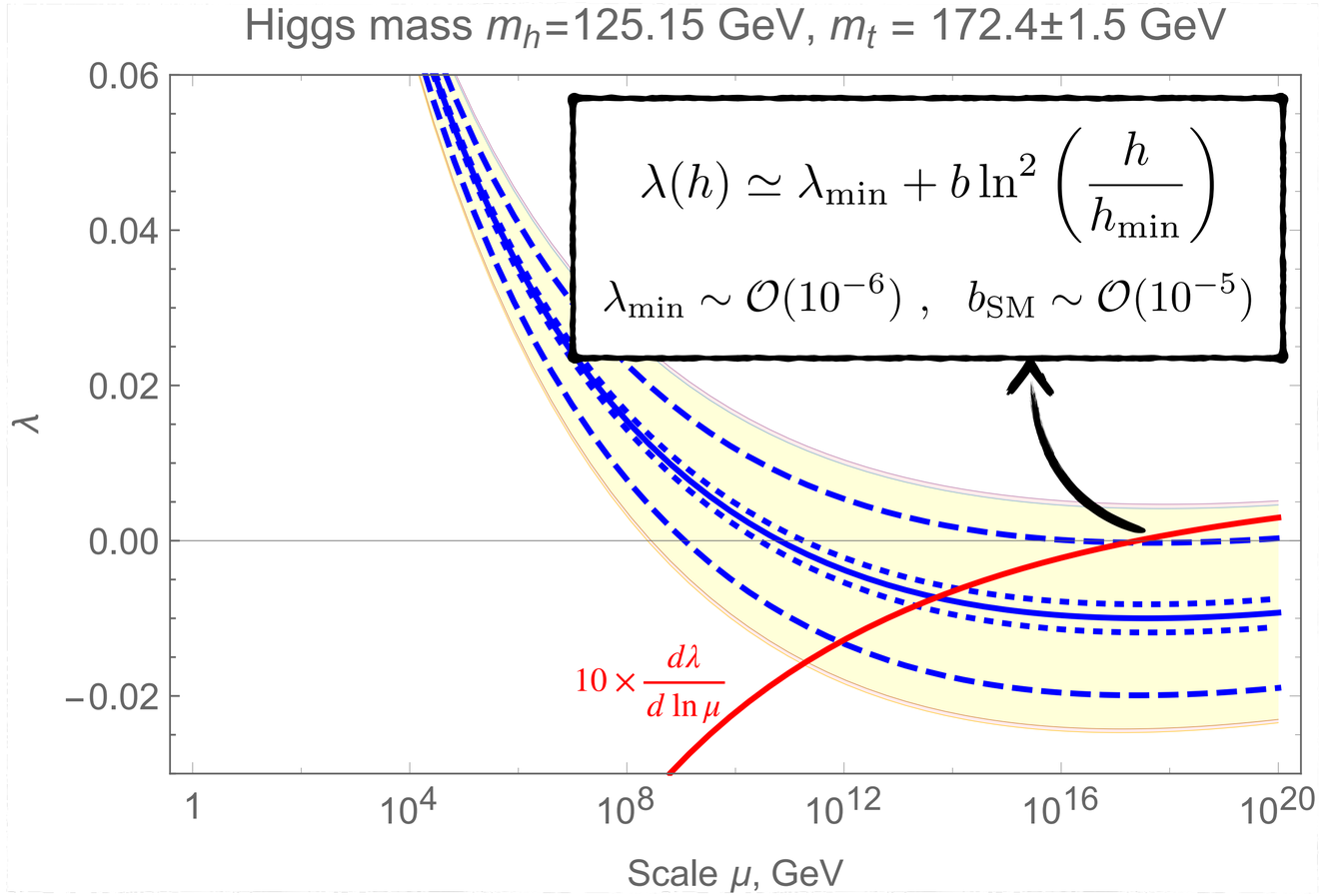
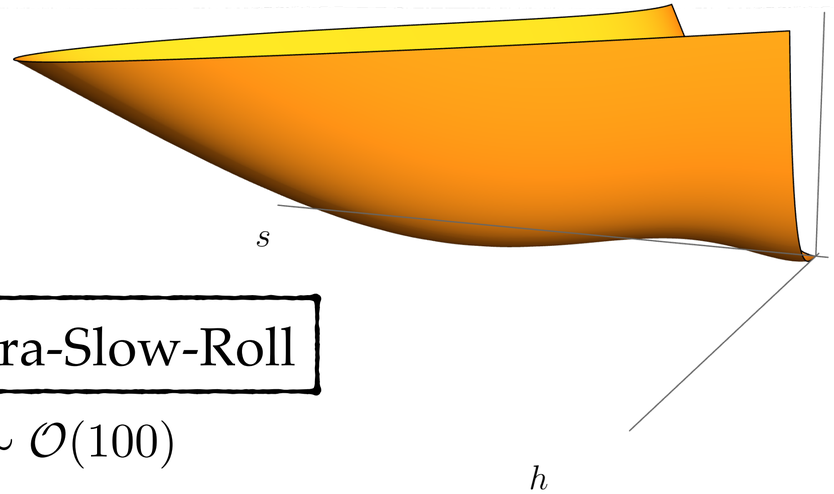




$\xi \sim \mathcal{O}(100)$

Higgs-R^2 Inflation, SM Higgs Running





Ultra-Slow-Roll

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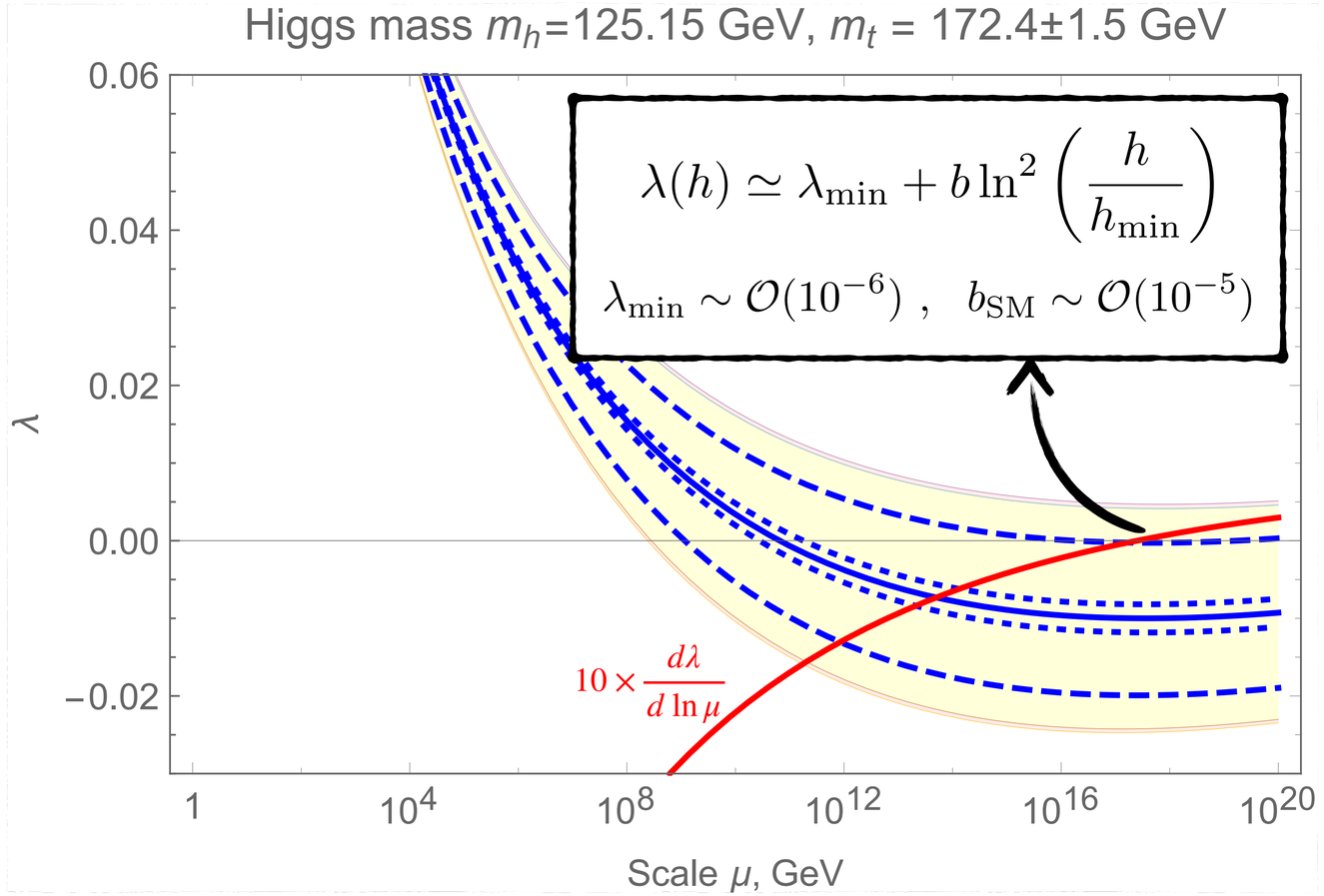
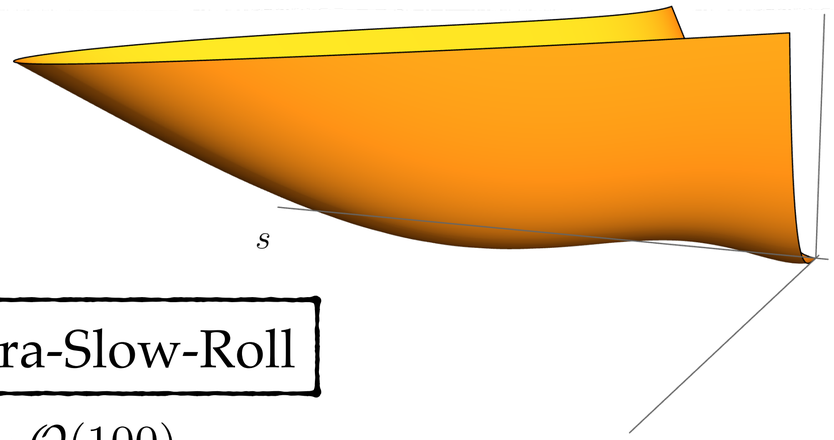
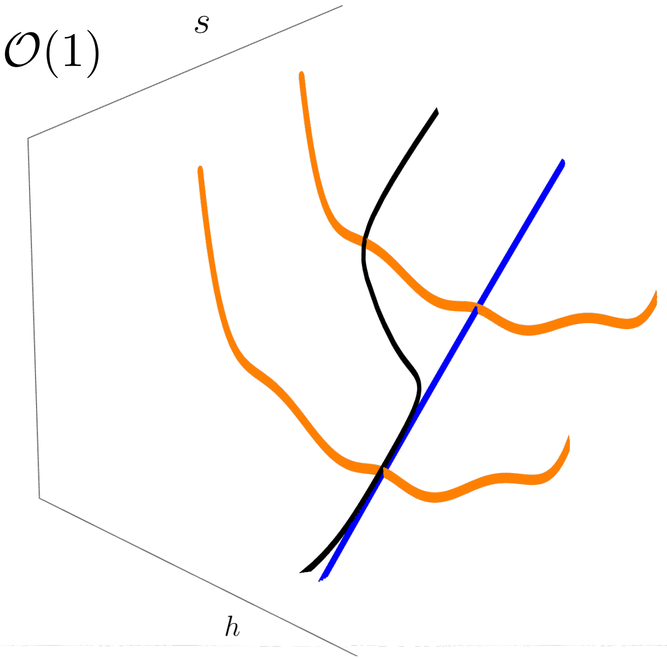




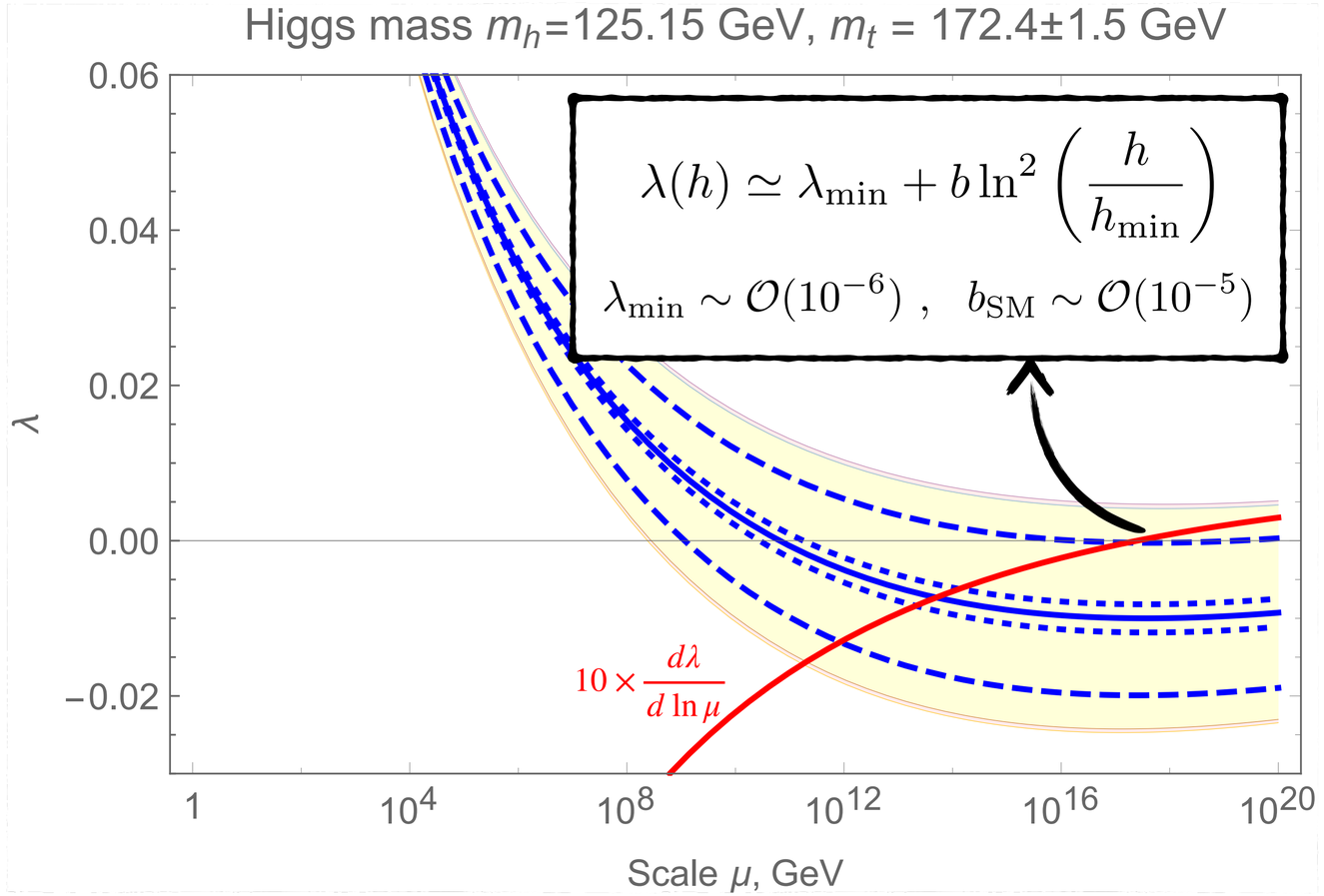
Ultra-Slow-Roll

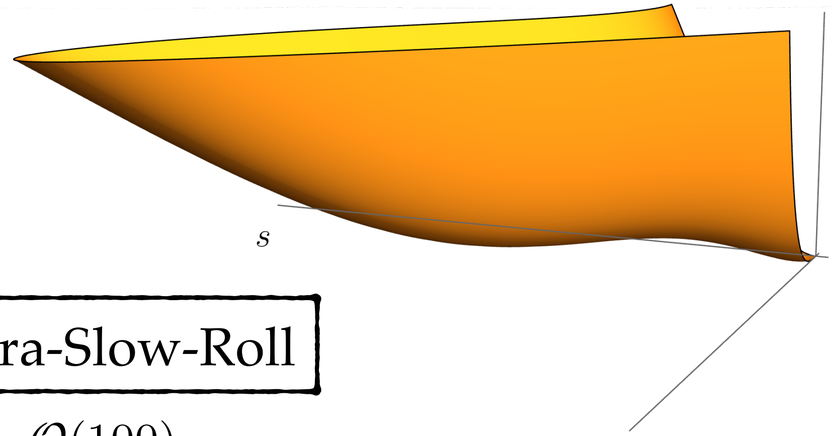
$\xi \sim \mathcal{O}(100)$

$\xi \sim \mathcal{O}(1)$



Higgs-R^2 Inflation, SM Higgs Running





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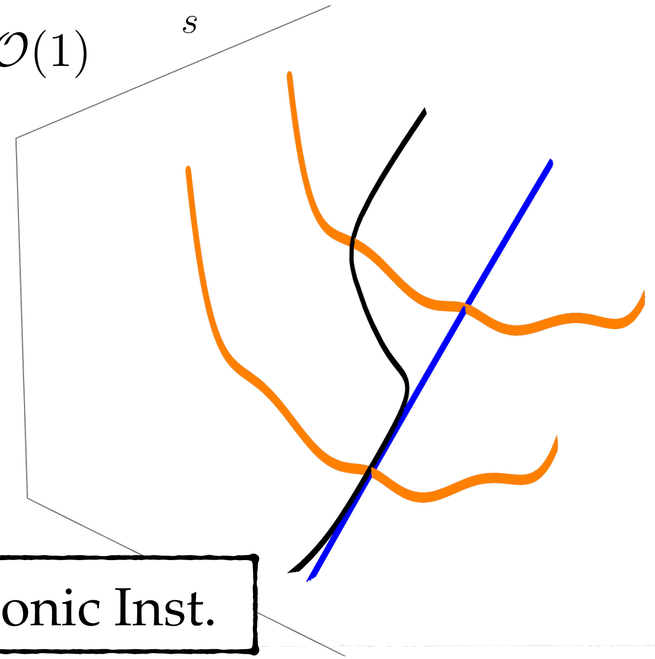
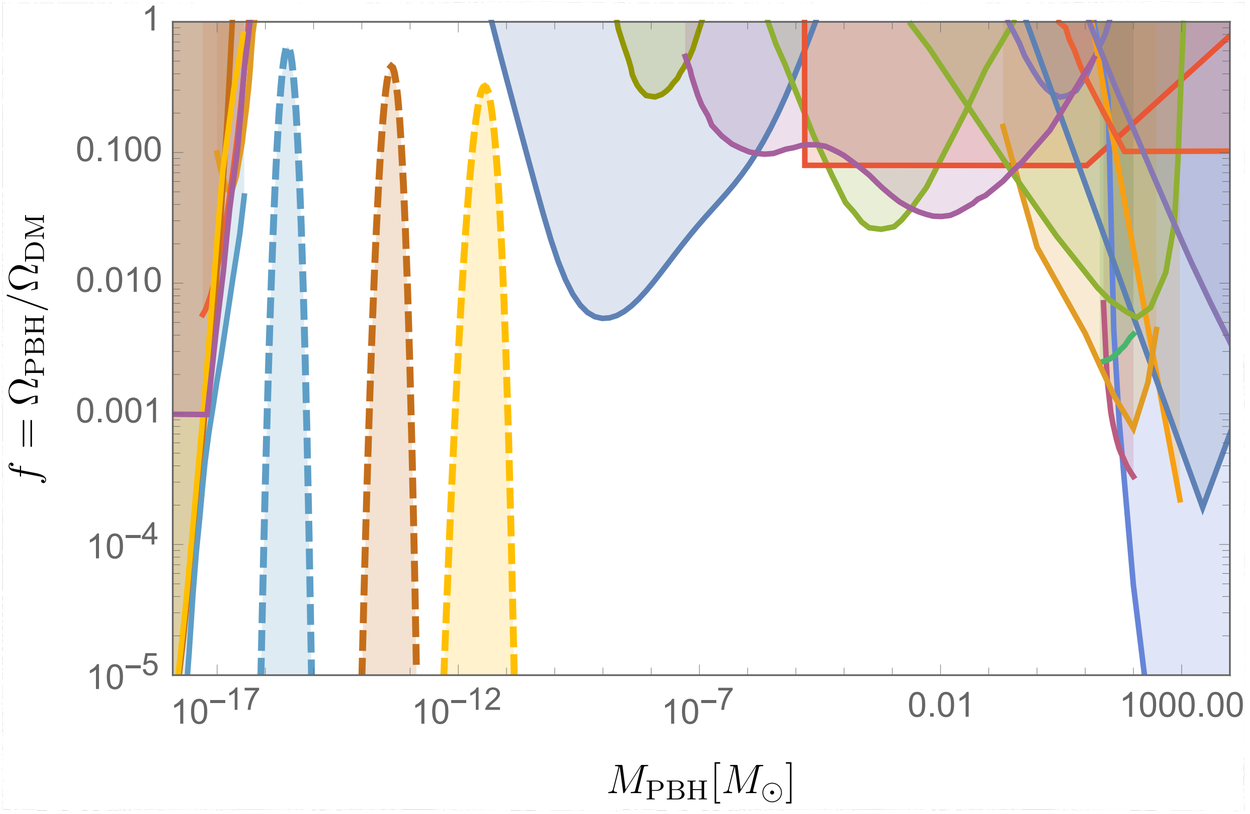
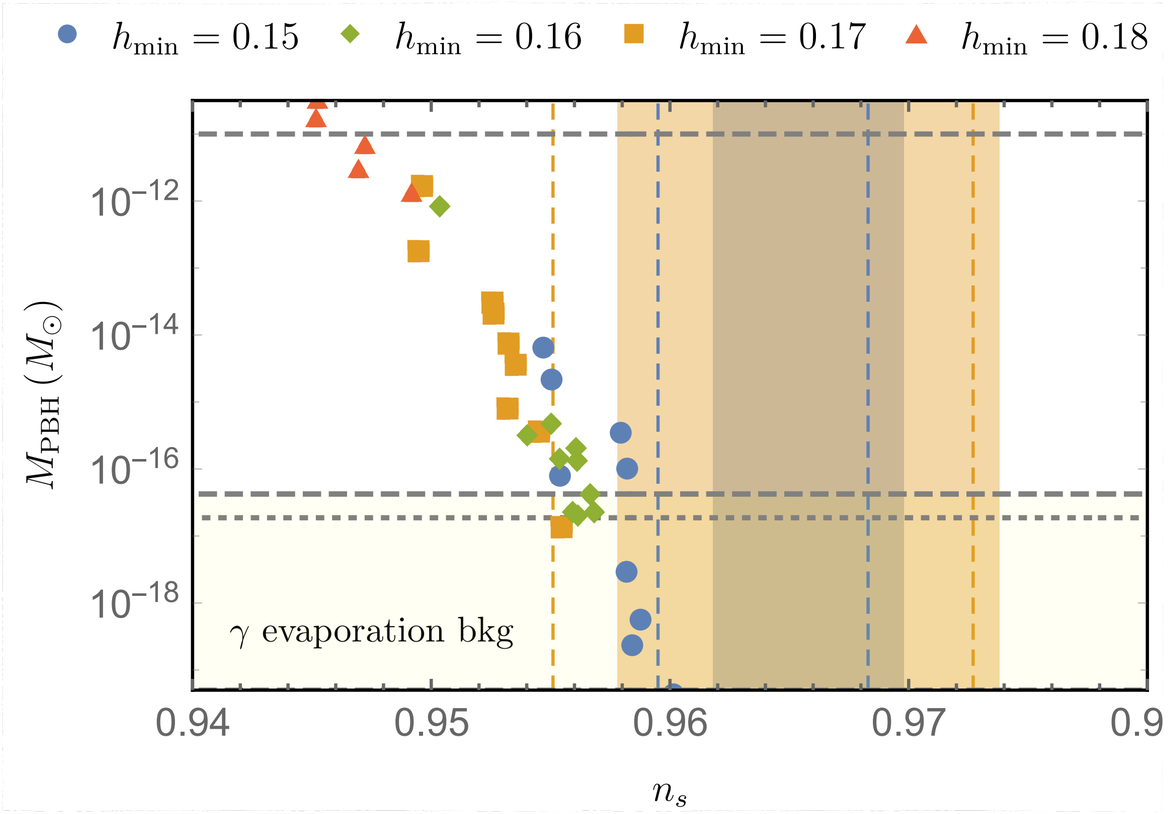


Tachyonic Inst.

Higgs-R^2 Inflation - Ultra Slow-Roll

[DYC, S.M. Lee, S.C. Park, JCAP 01 (2021), 032]





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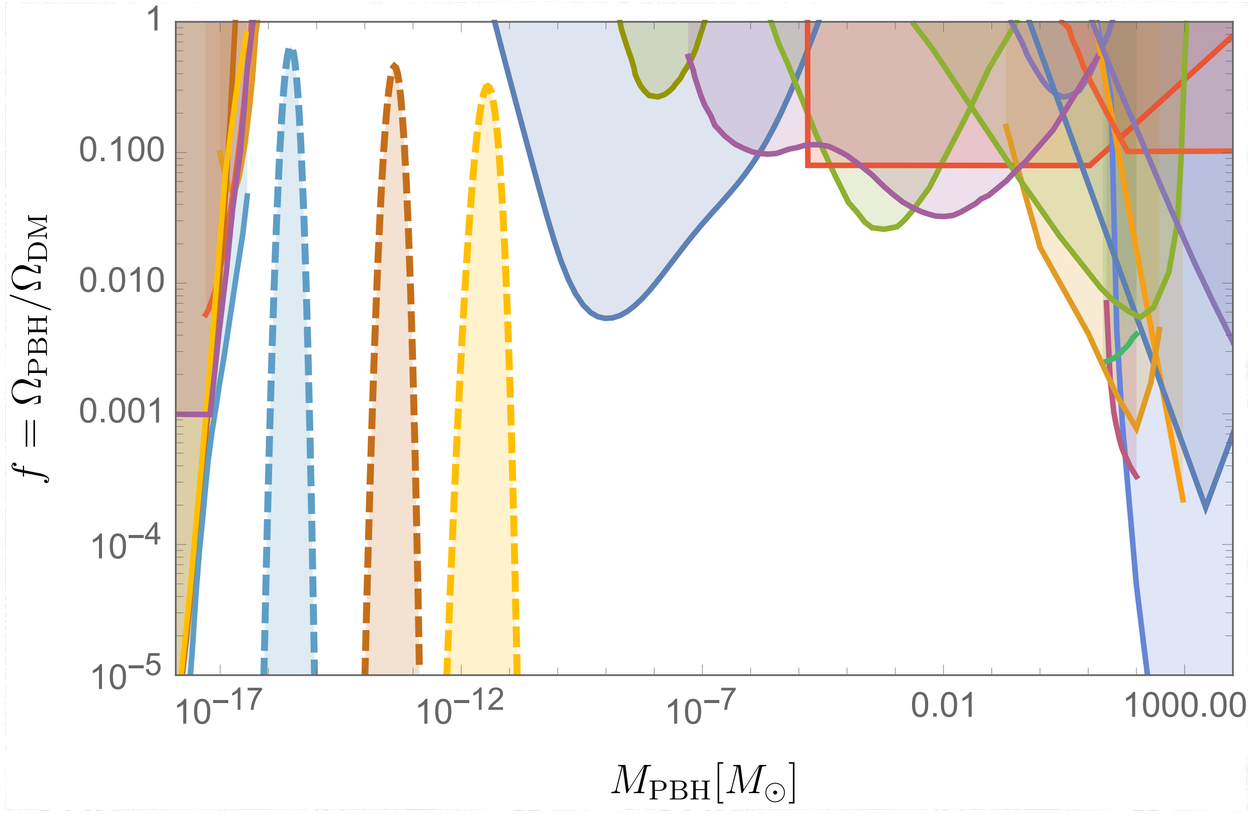
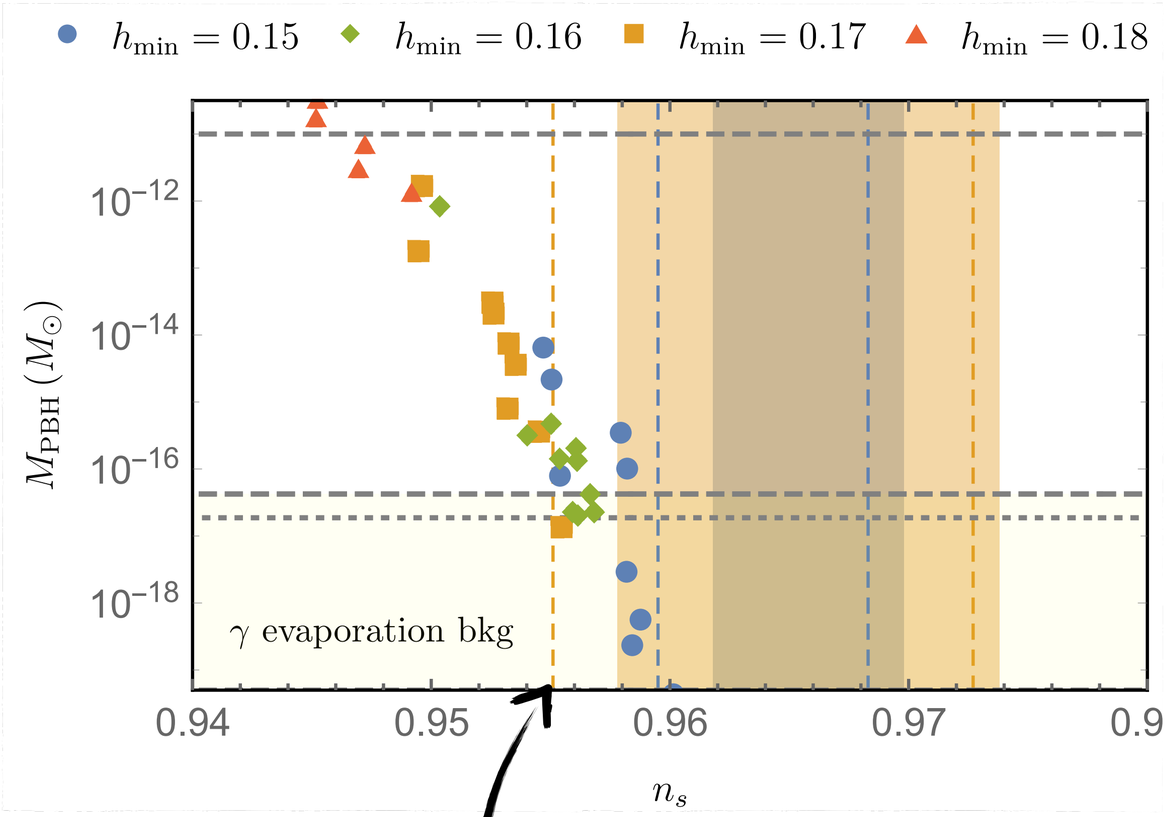


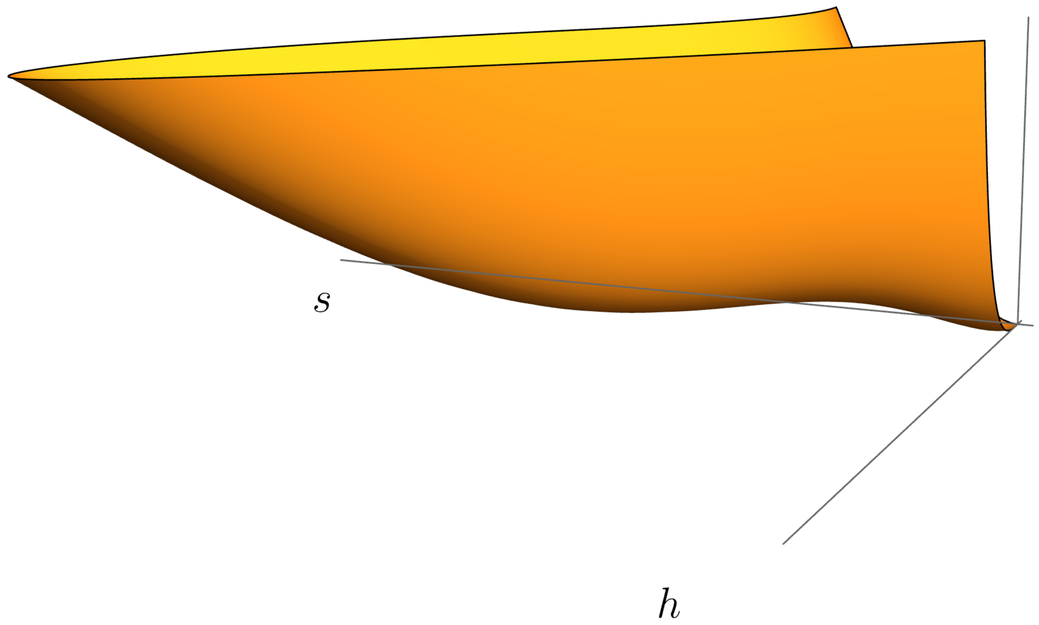


Tension with CMB!

Sensitive to higher order terms e.g. ~R^3

Higgs-R^2 Inflation / USR vs Tachyonic Instability?

Ultra-Slow-Roll $\xi \sim \mathcal{O}(100)$



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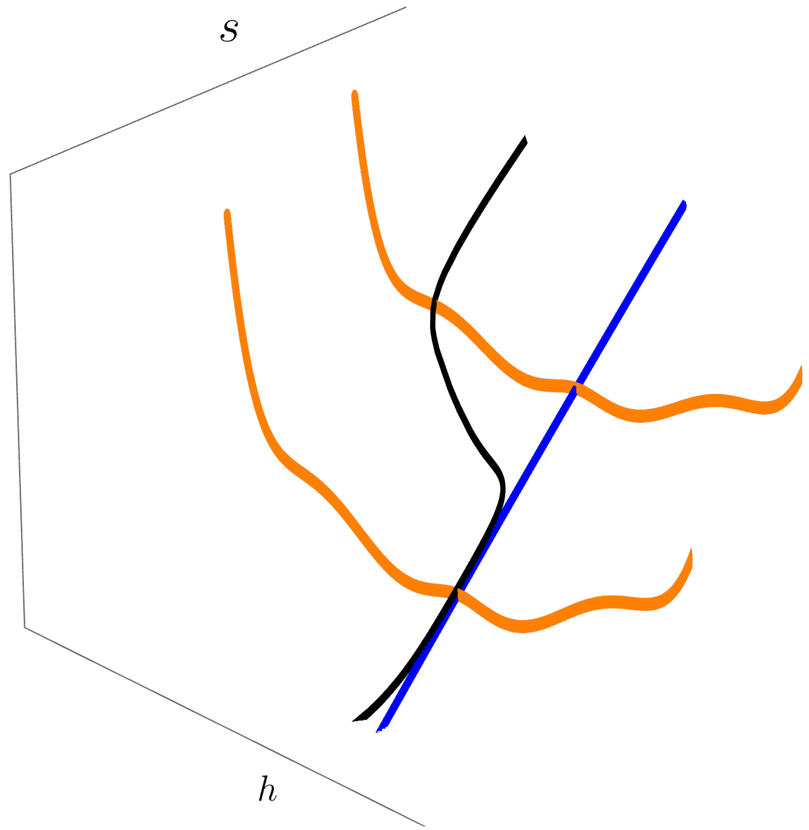

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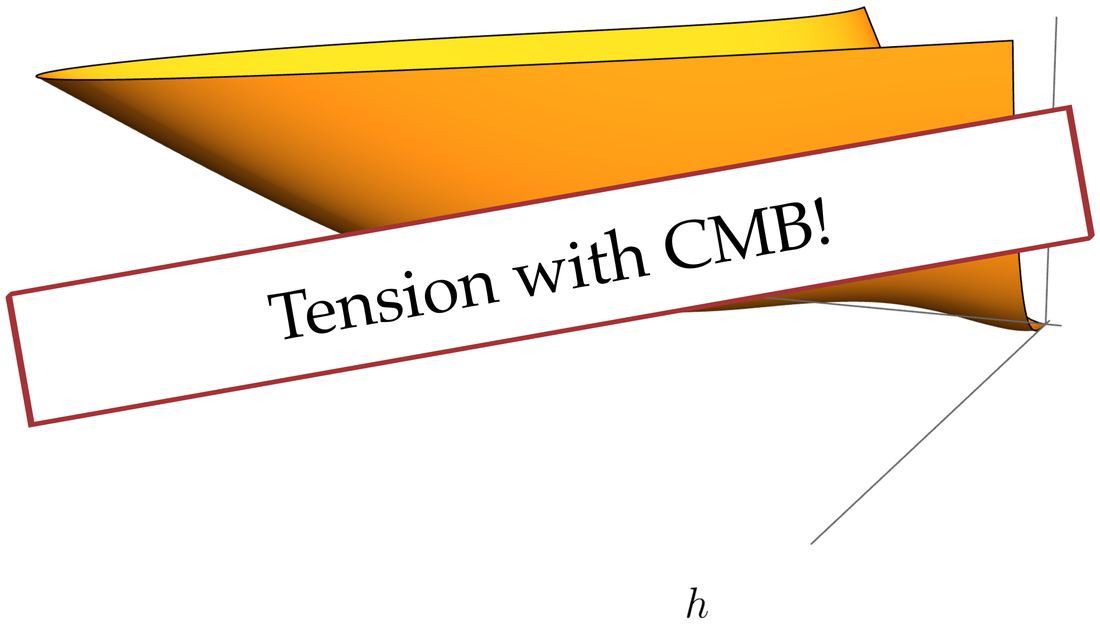

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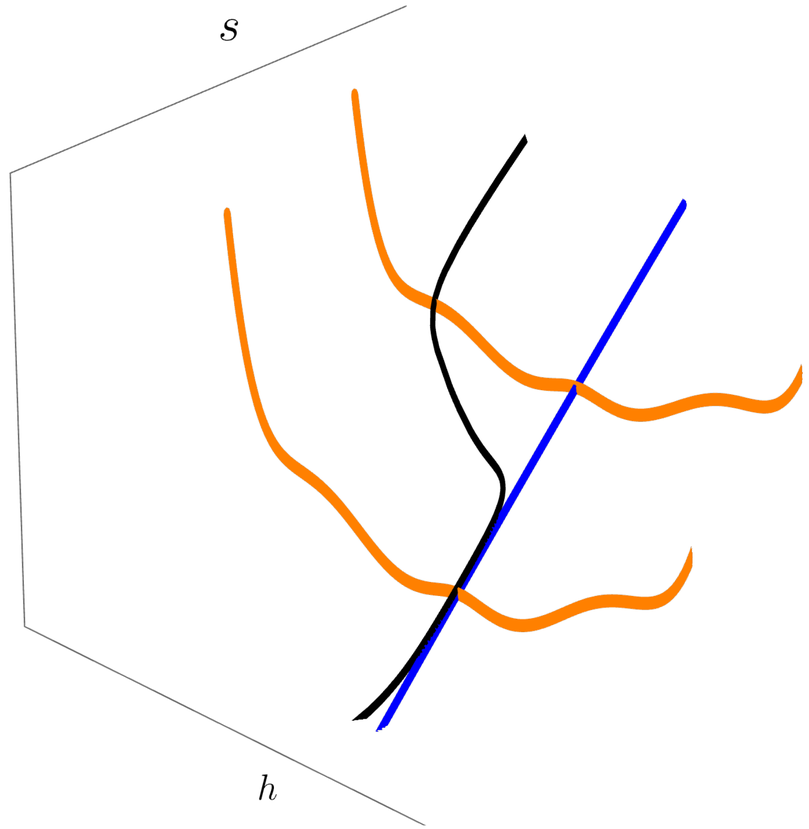

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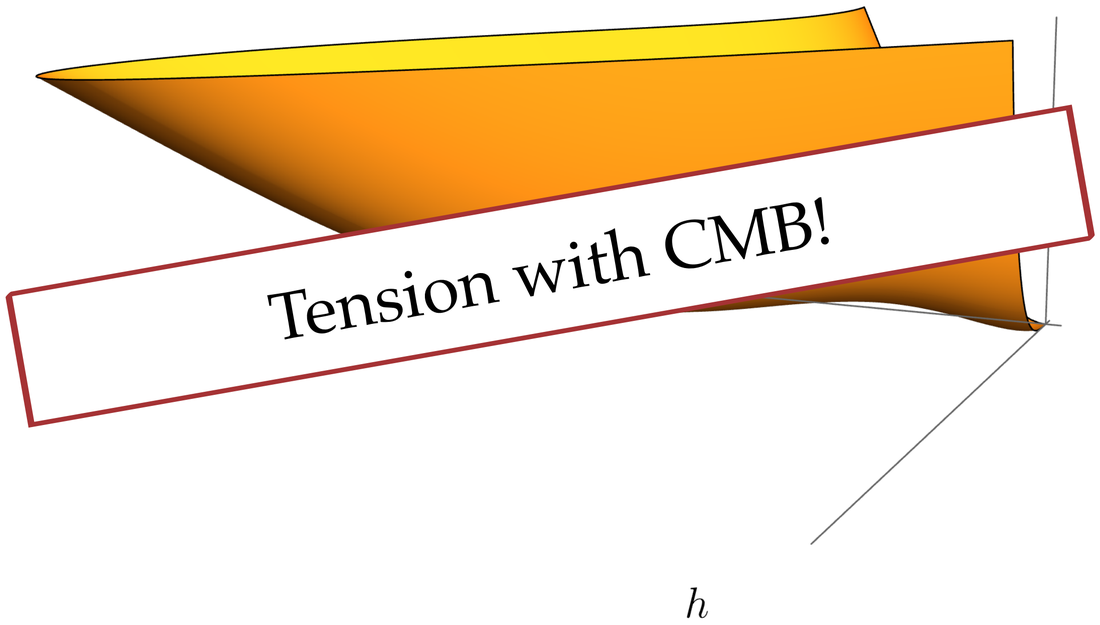

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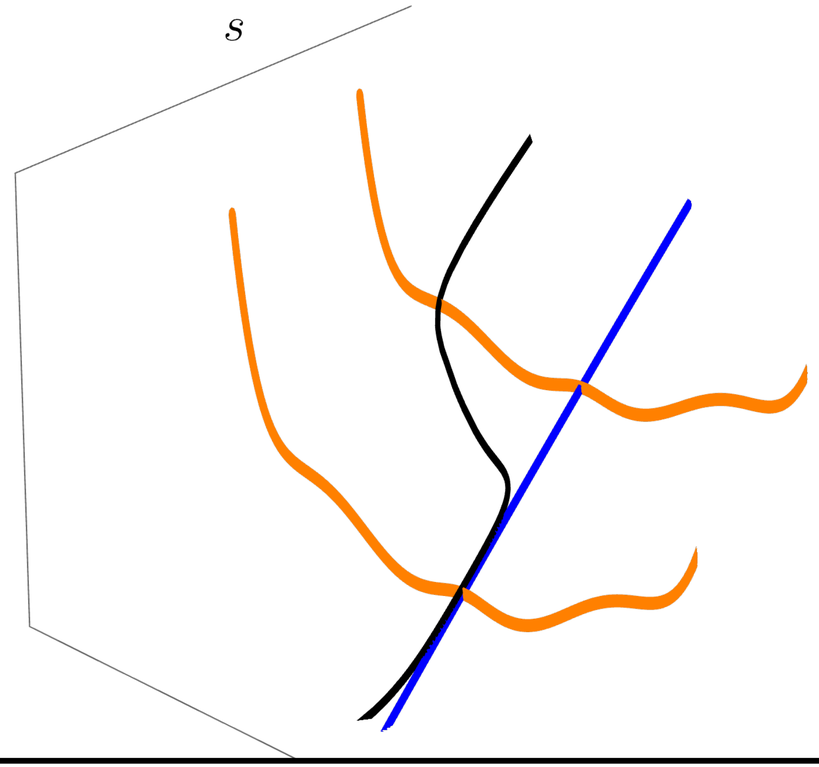
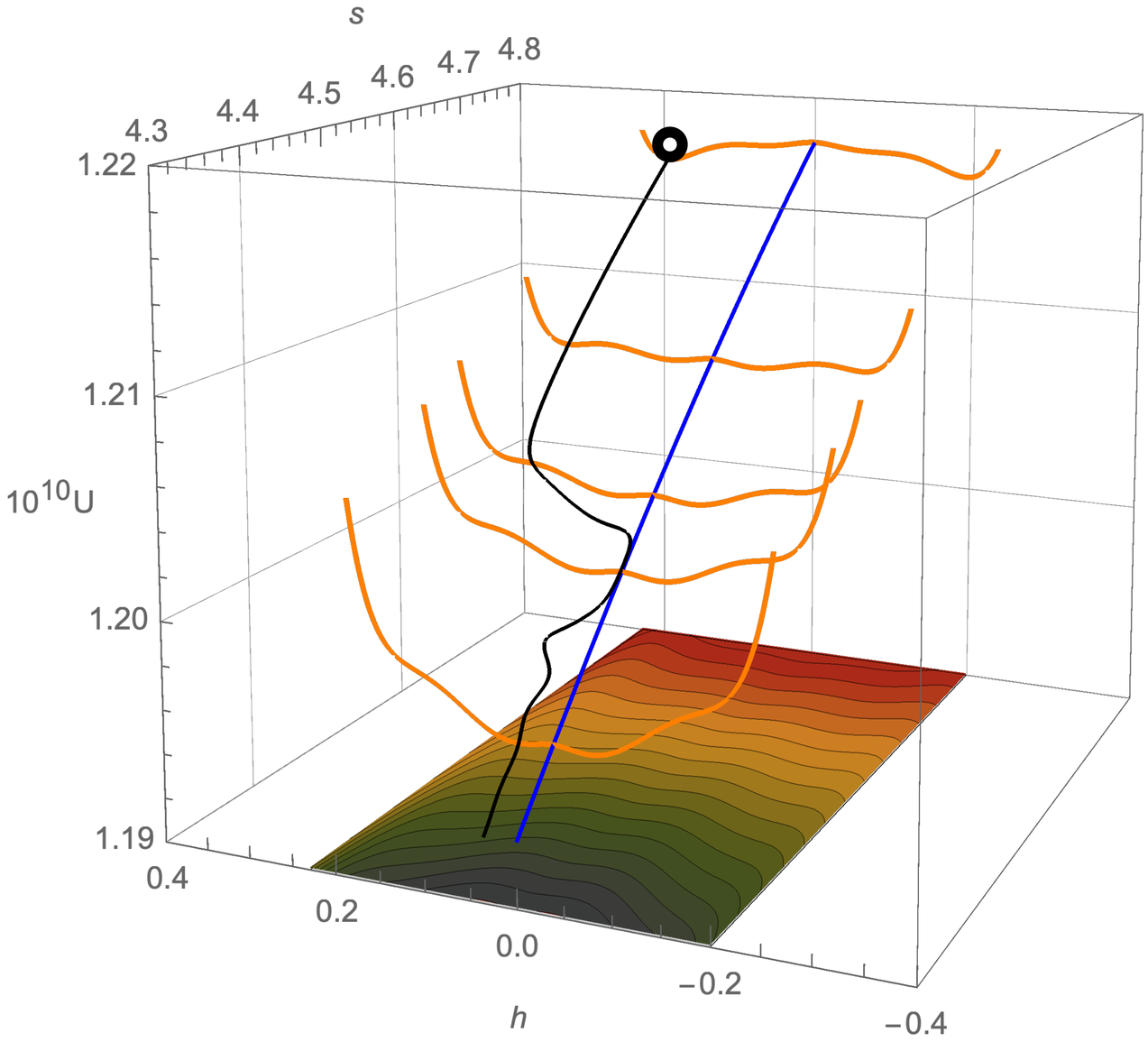
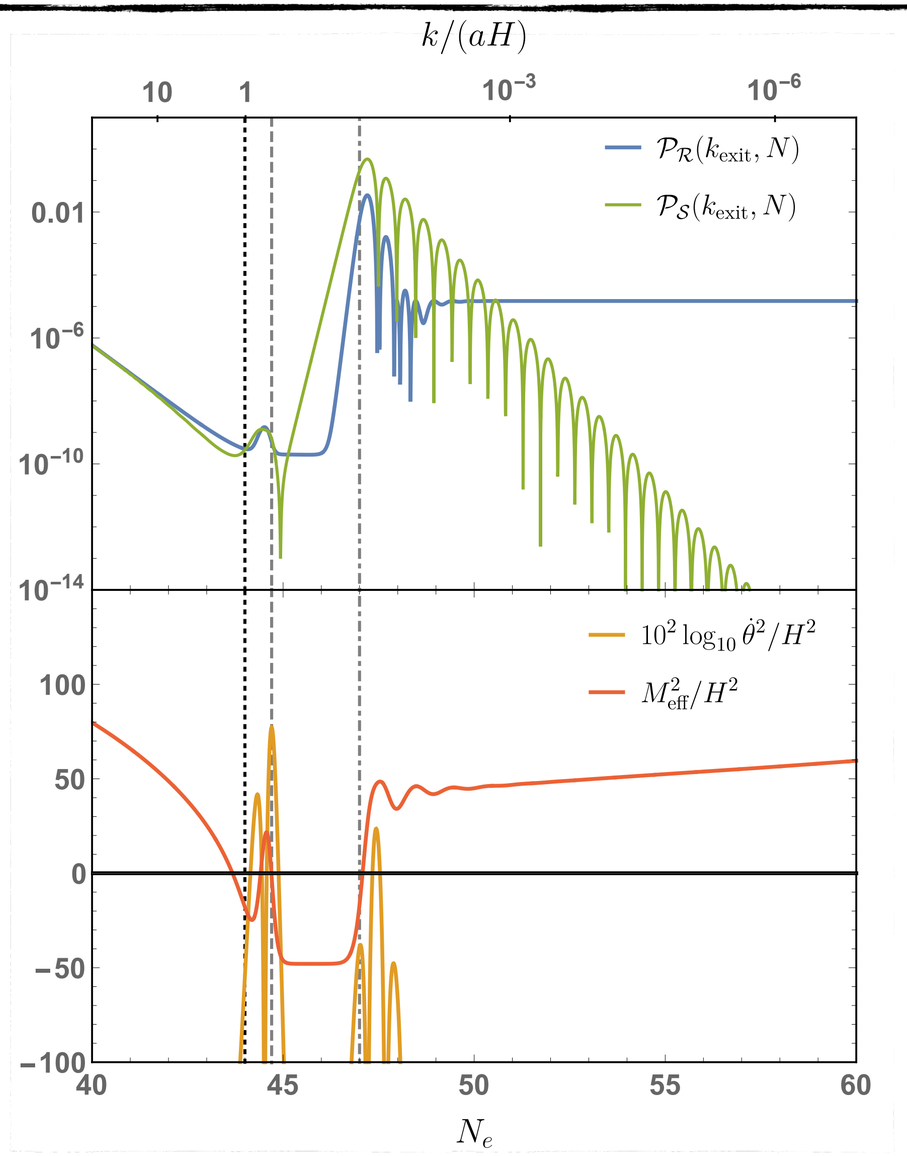


Multi-field effect / Exponential Growth

Higgs-R^2 Inflation, Tachyonic Instability

[**DYC**, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015]





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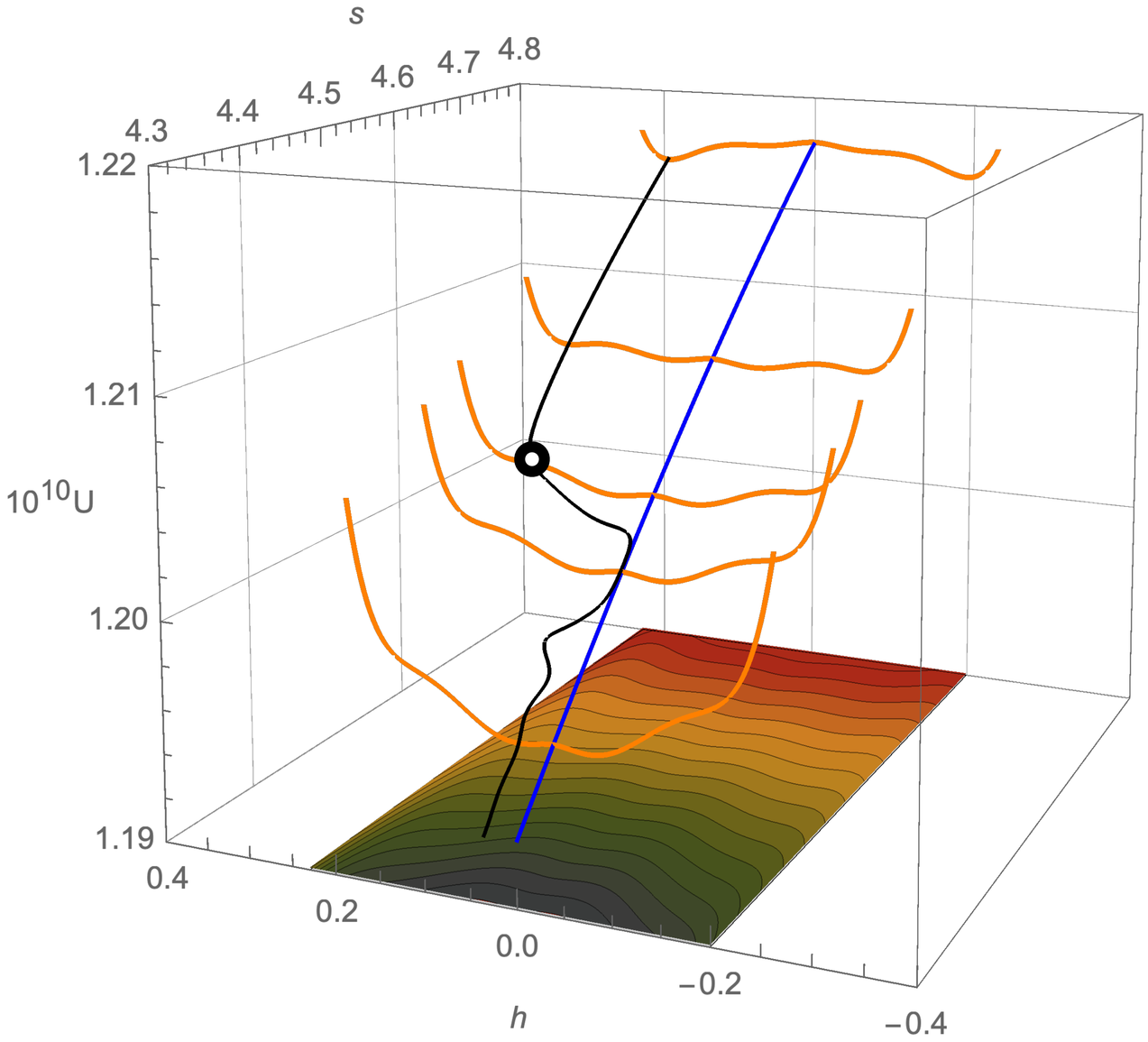

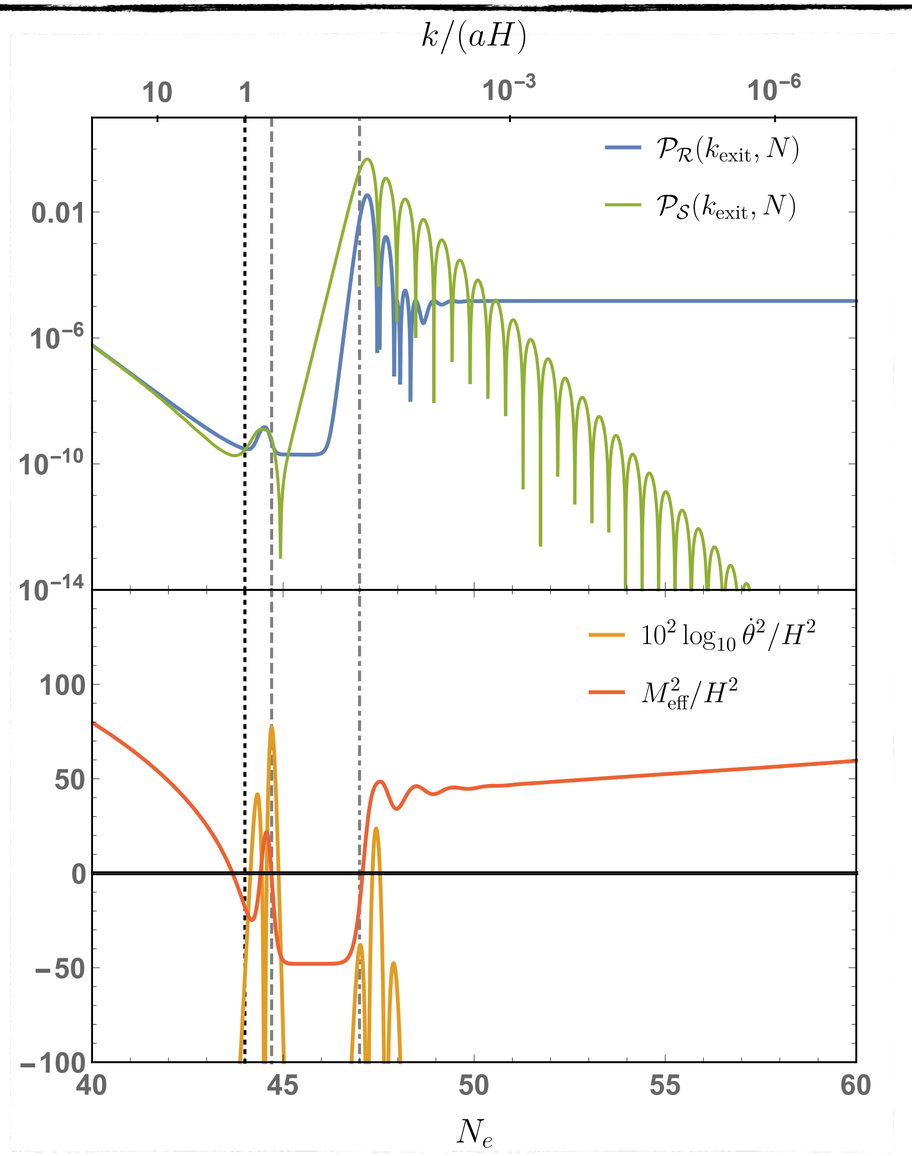

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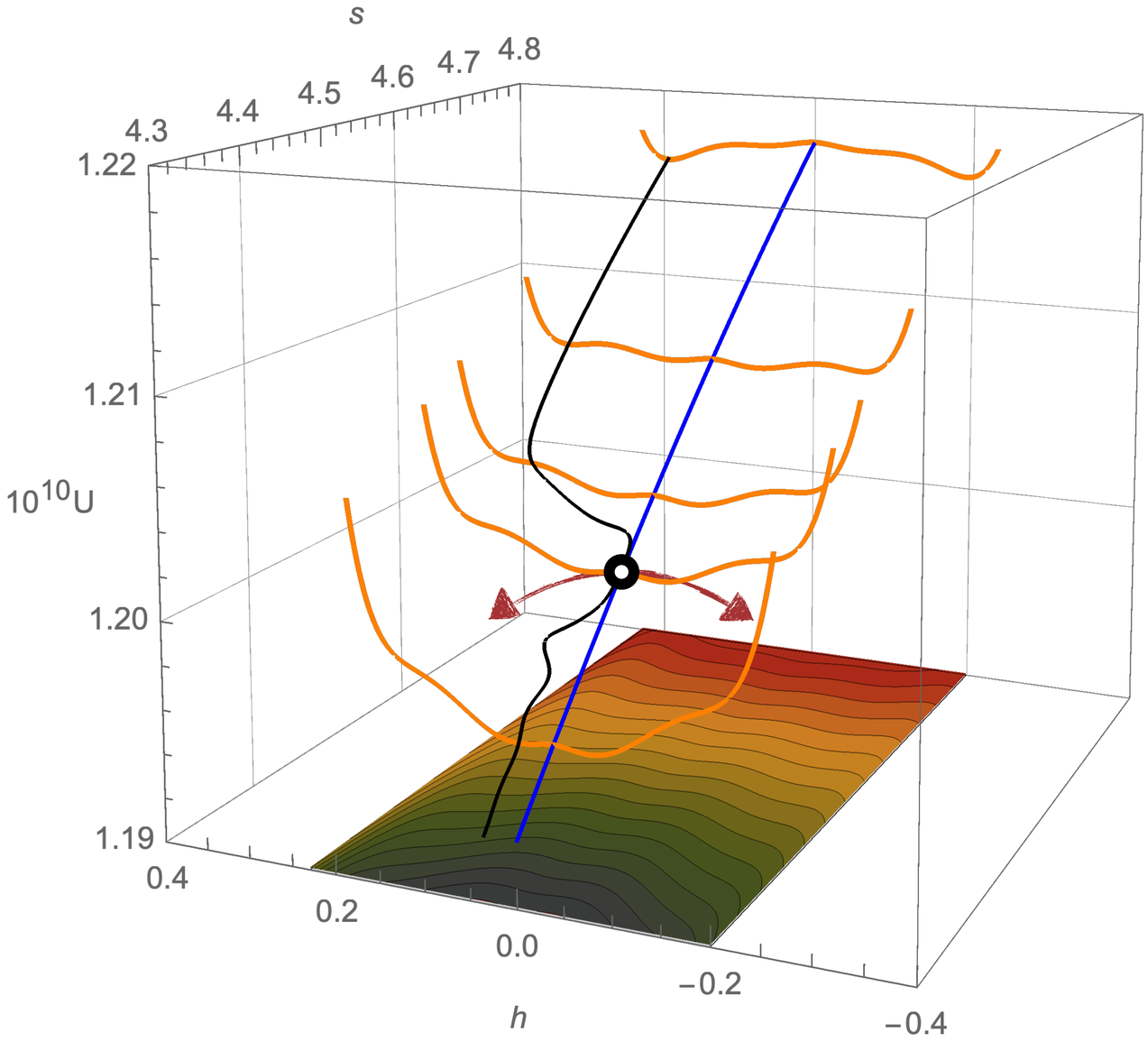
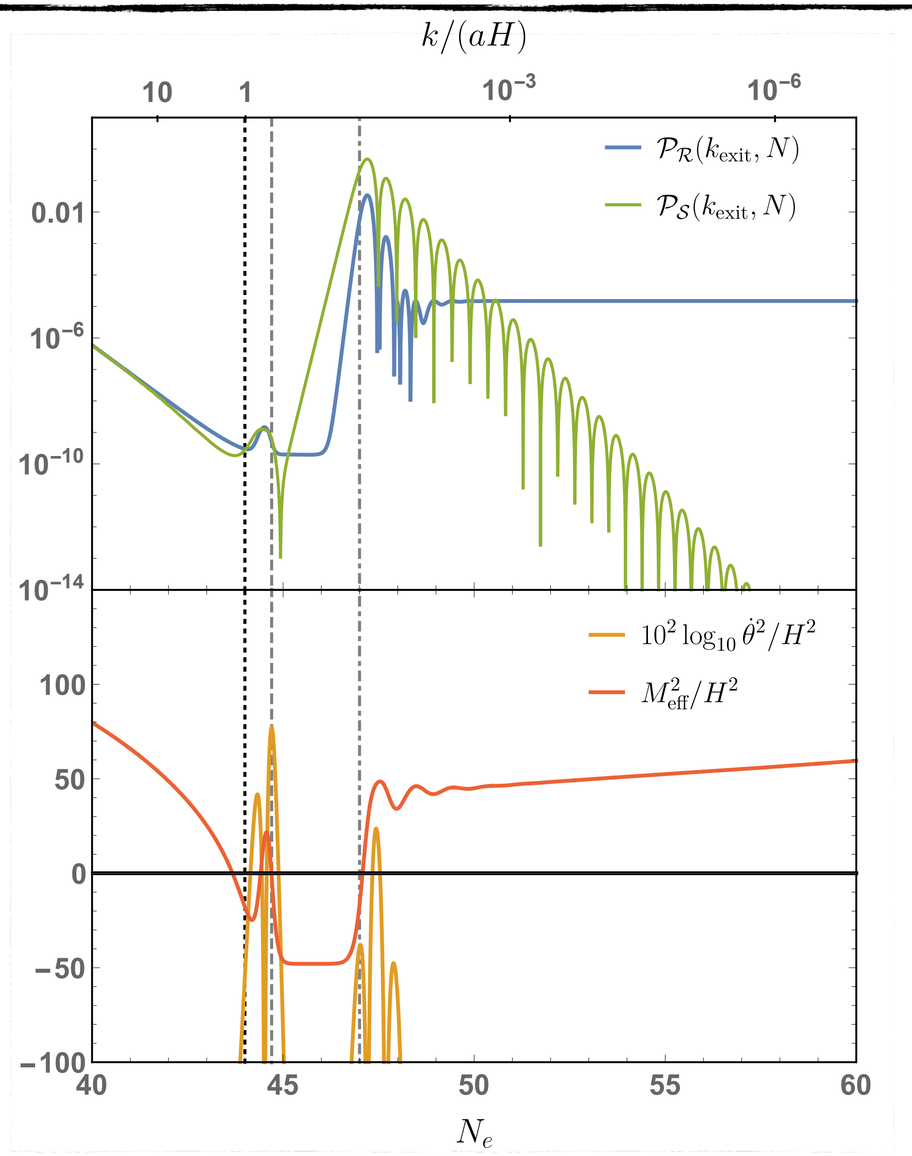


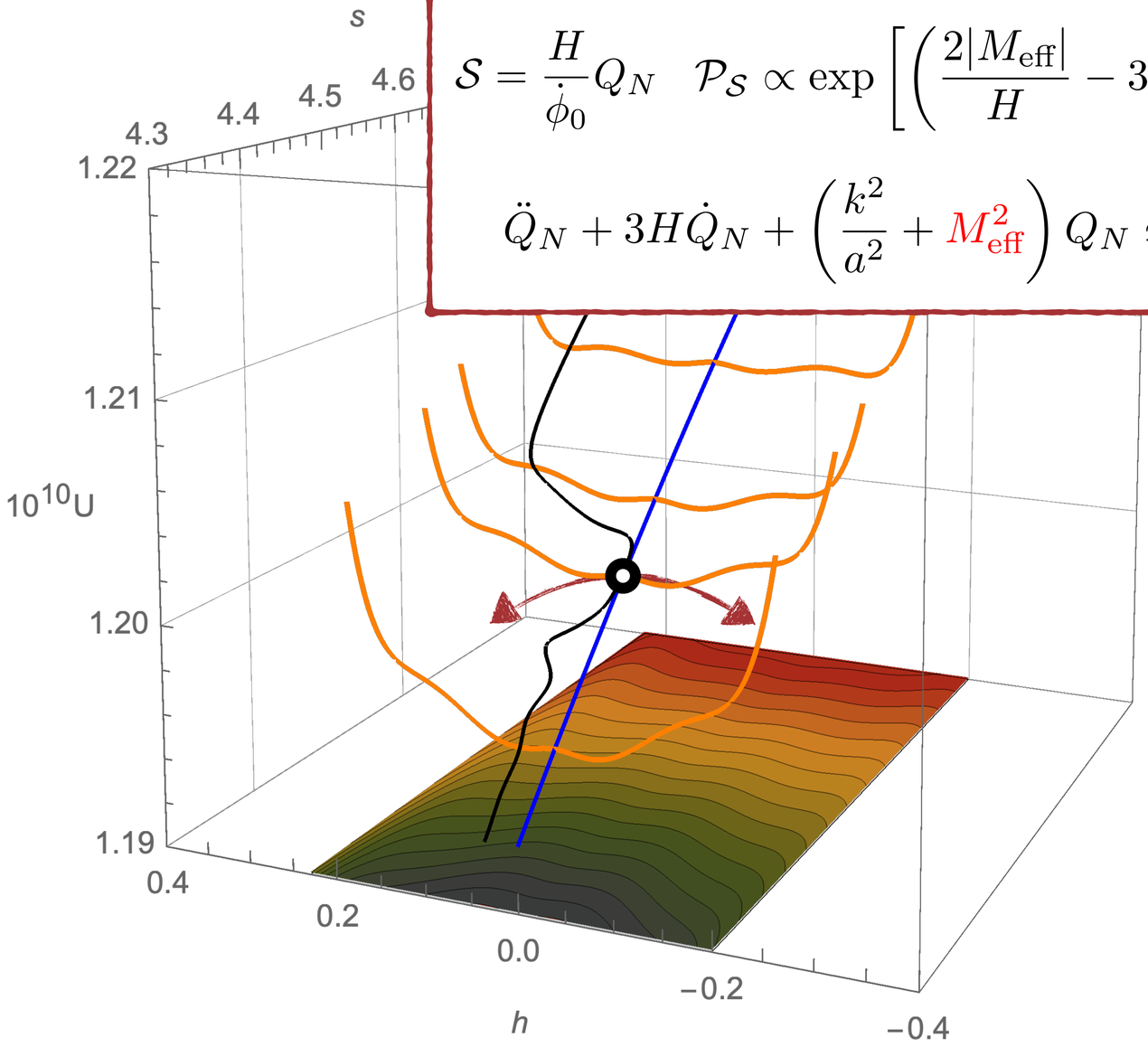


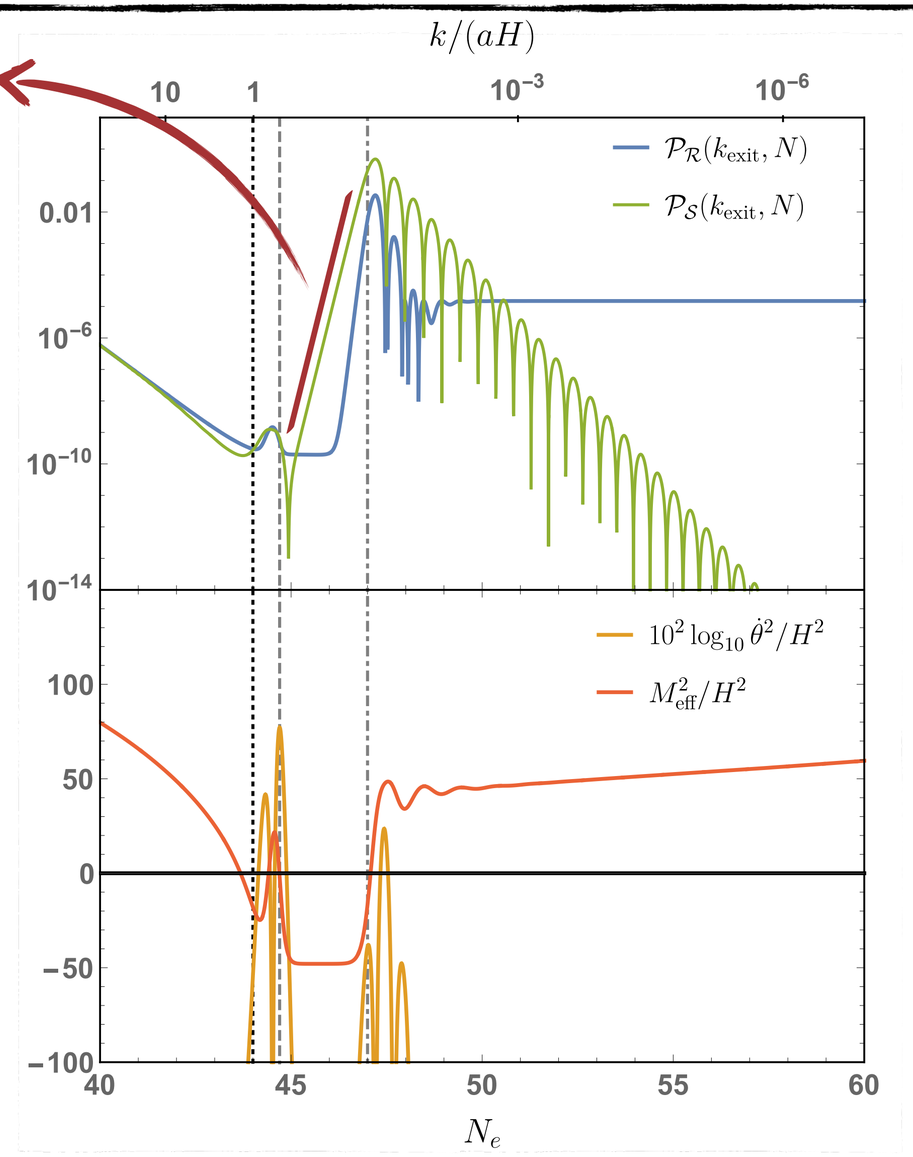
Higgs-R^2 Inflation, Tachyonic Instability

[**DYC**, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015]

$$\mathcal{S} = \frac{H}{\dot{\phi}_0} Q_N \quad \mathcal{P}_\mathcal{S} \propto \exp\left[\left(\frac{2|M_{\rm eff}|}{H} - 3\right) N_e\right]$$

$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M_{\rm eff}^2\right) Q_N \simeq 0$$





Higgs-R^2 Inflation, Tachyonic Instability

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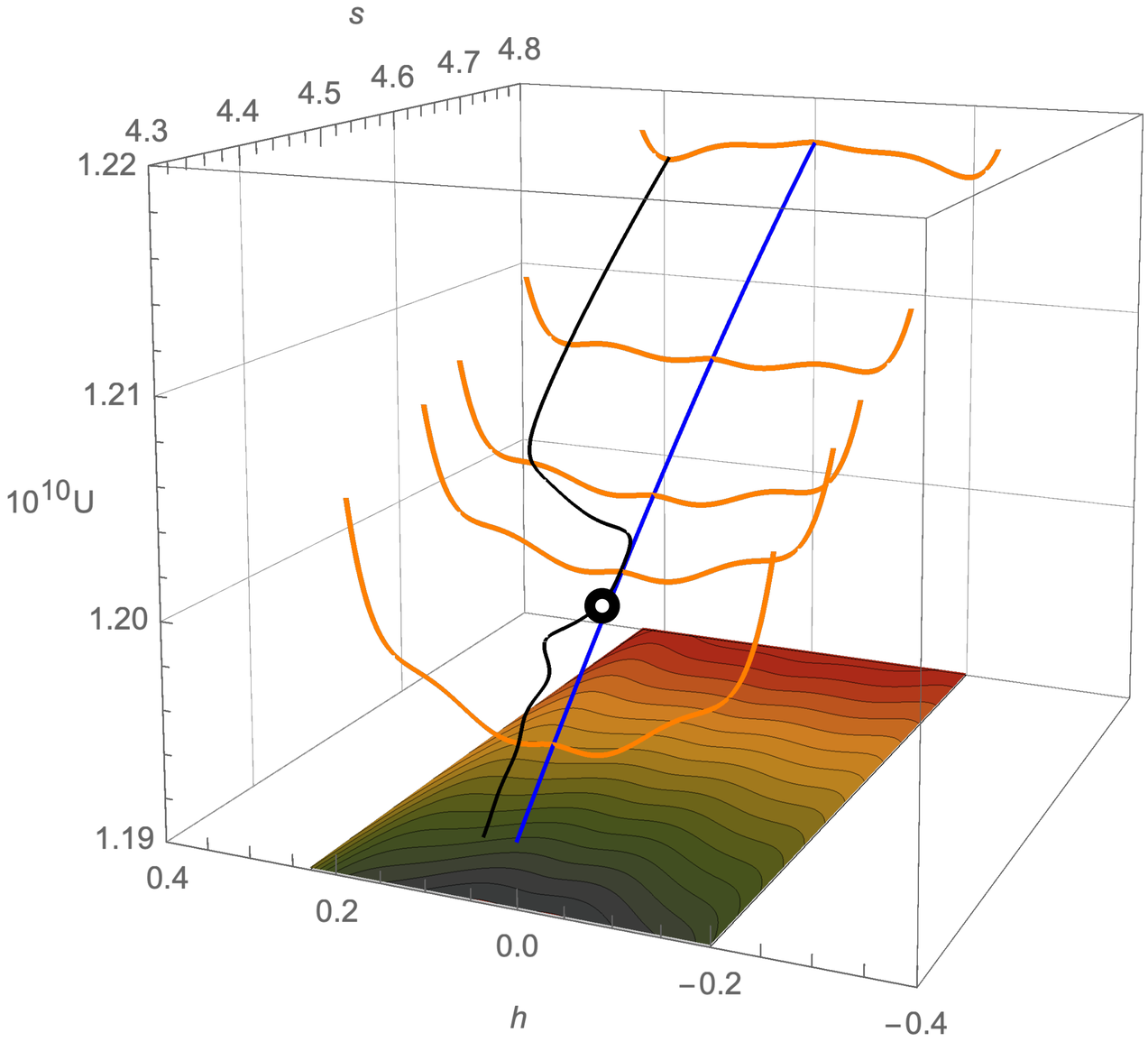

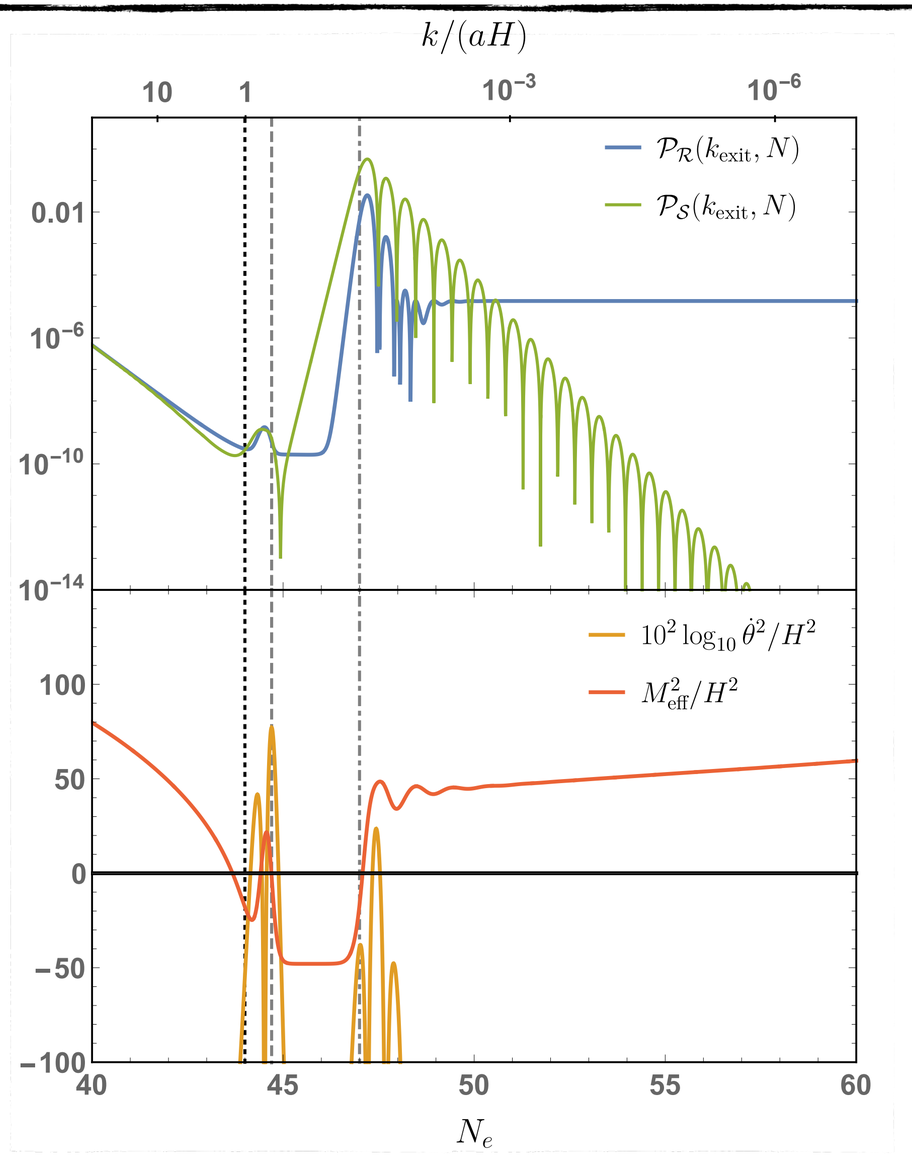

Higgs-R^2 Inflation, Tachyonic Instability

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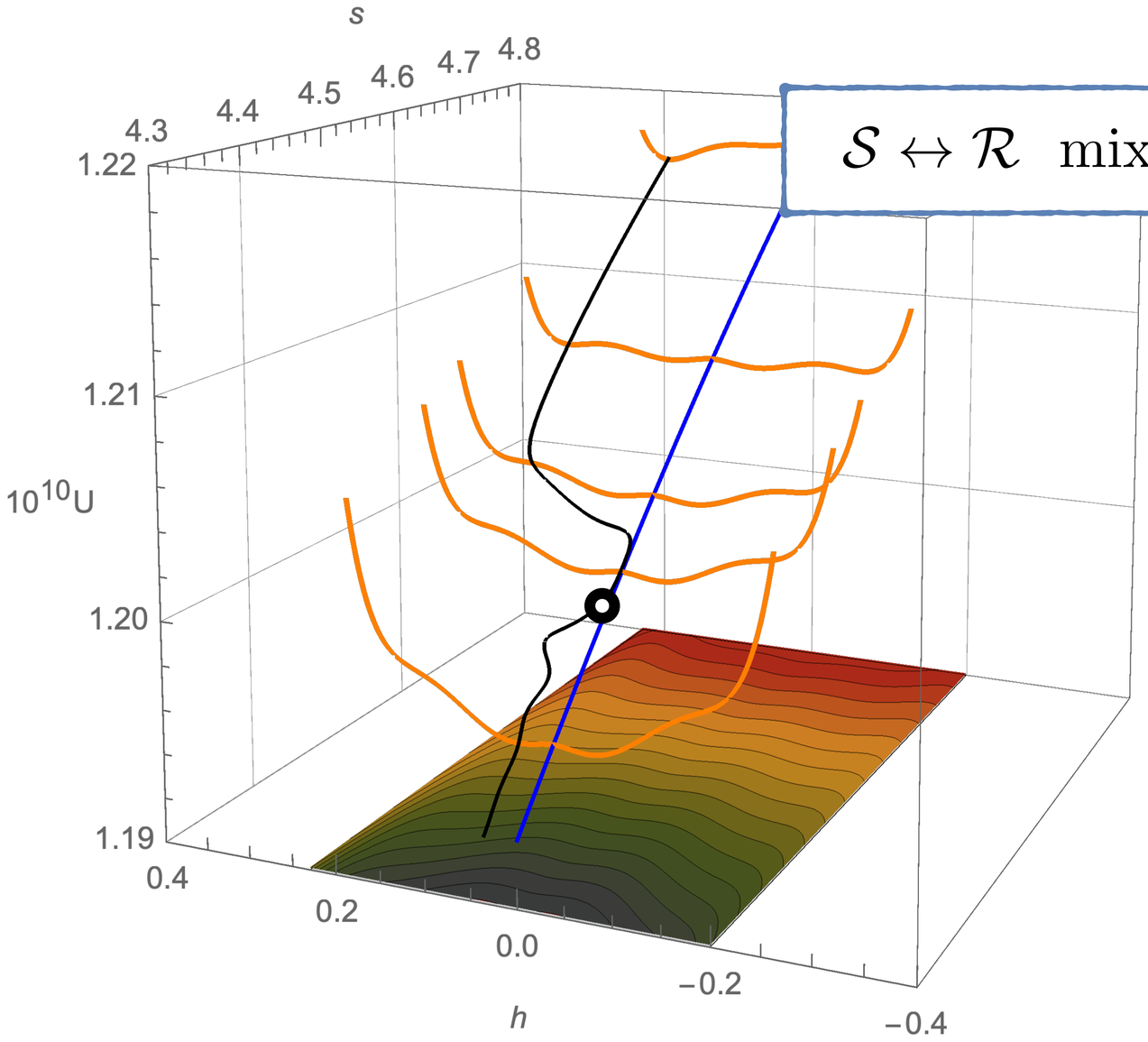
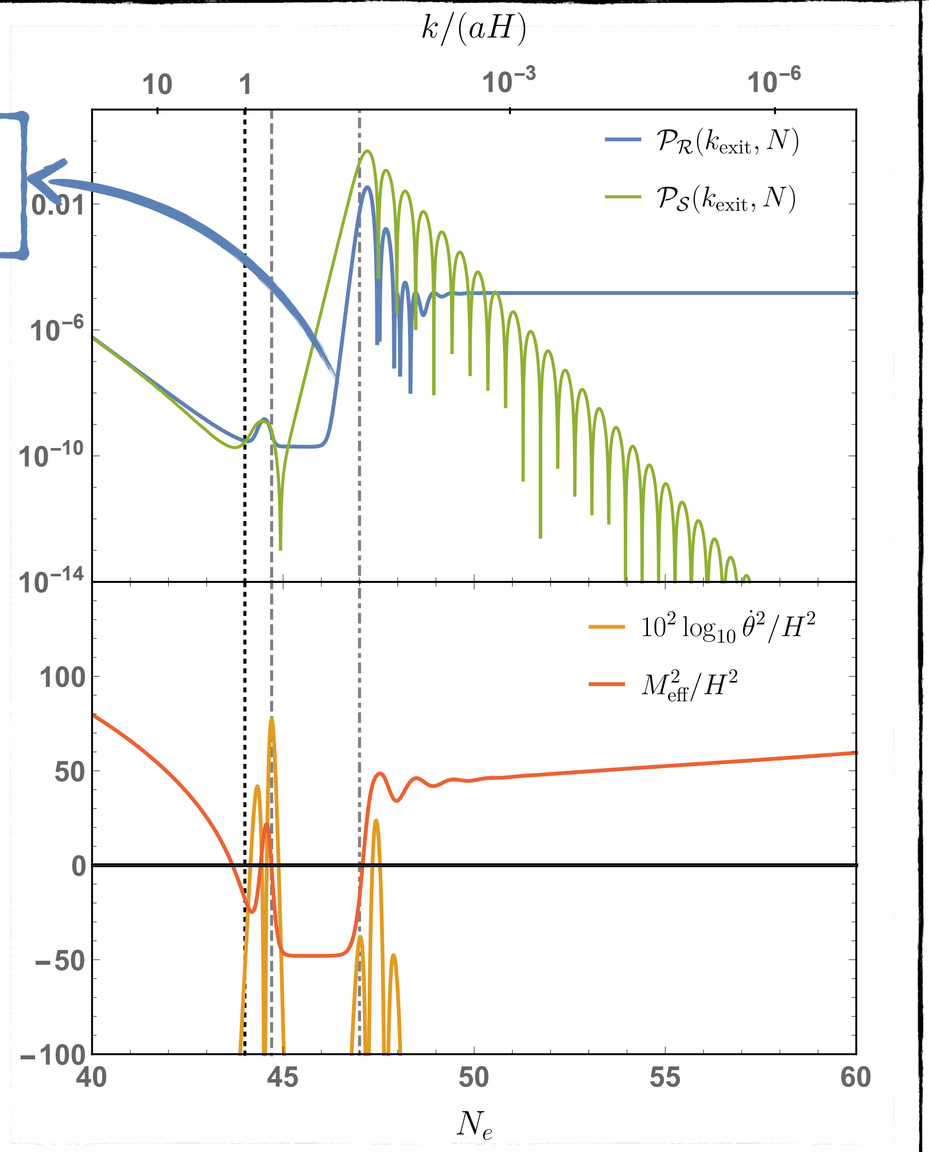
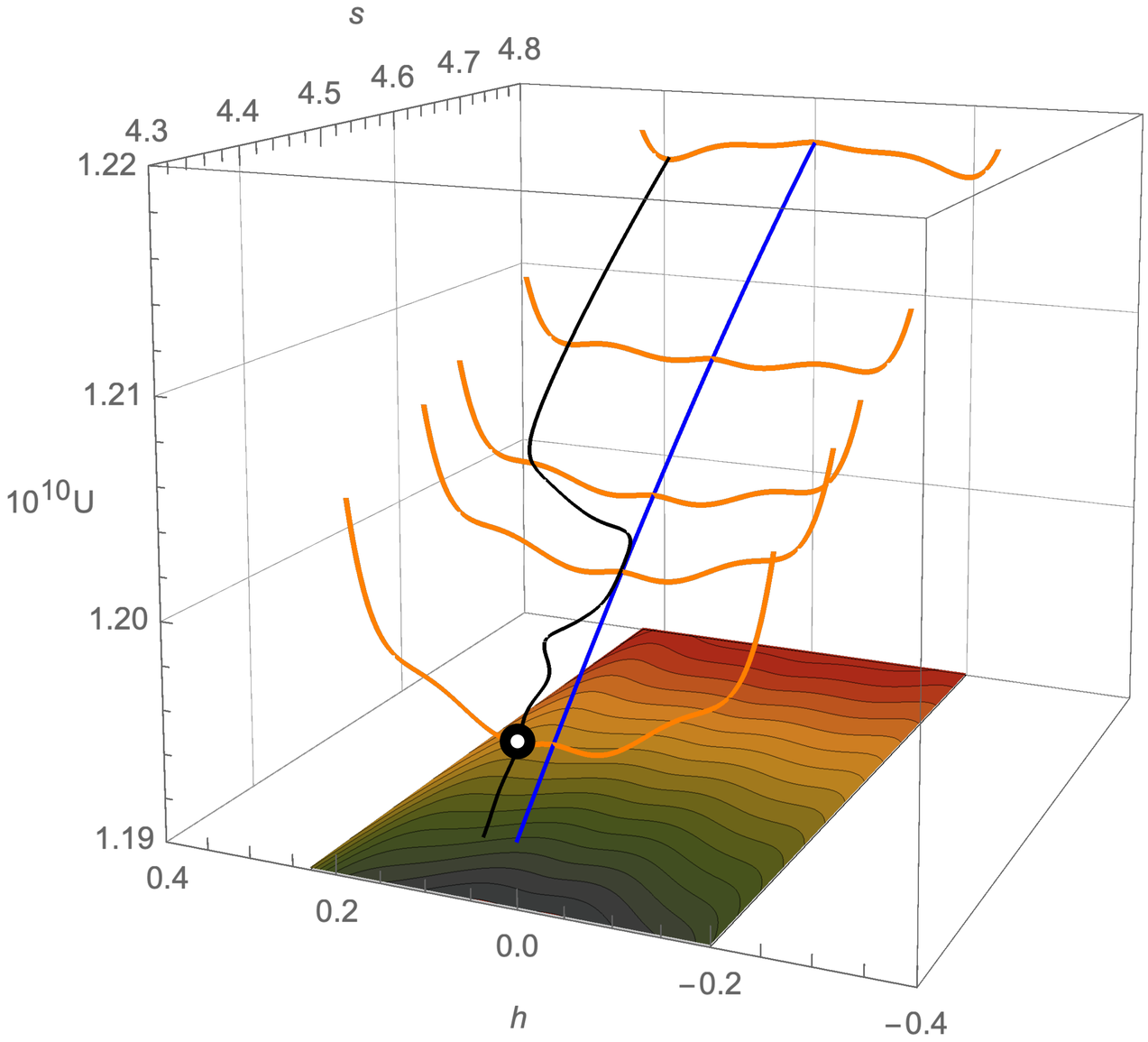


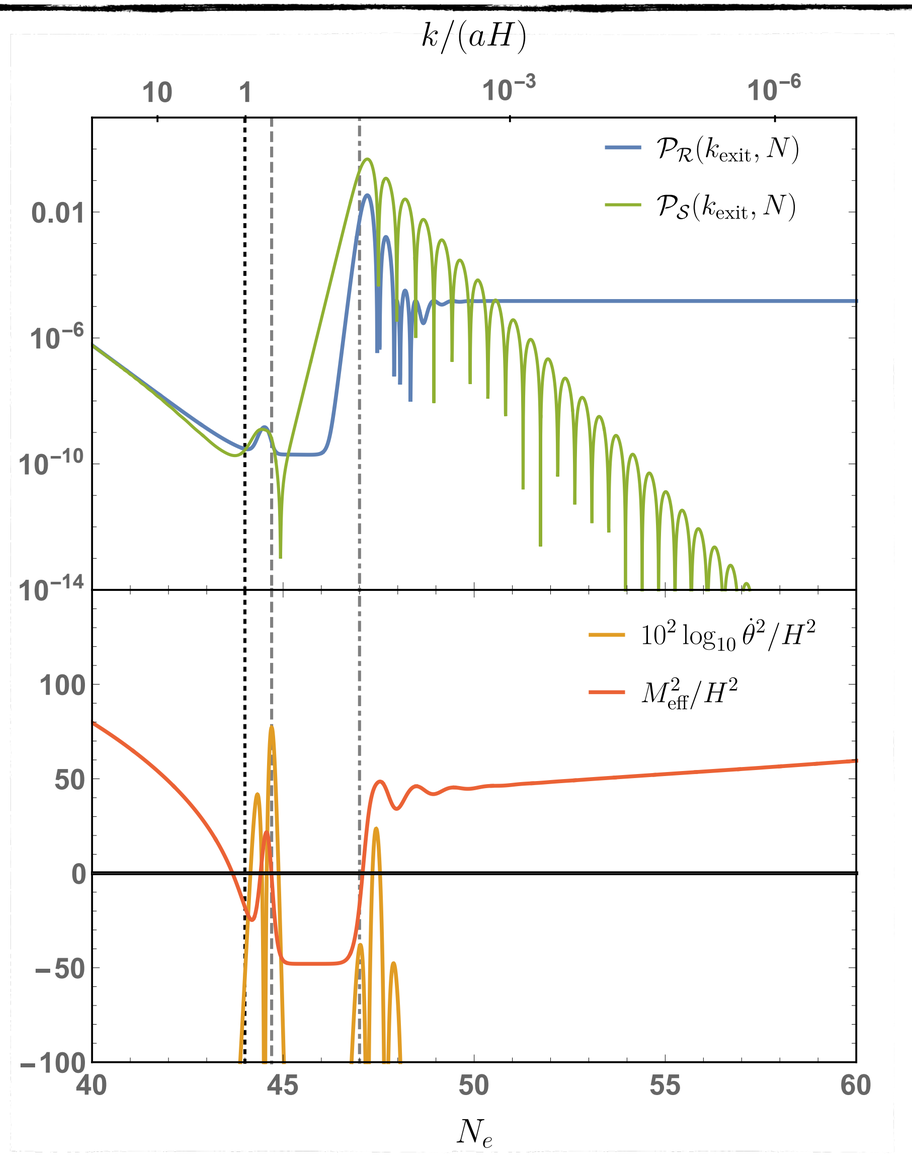
$\mathcal{S} \leftrightarrow \mathcal{R}$ mixing!



Higgs-R^2 Inflation, Tachyonic Instability

[**DYC**, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015]





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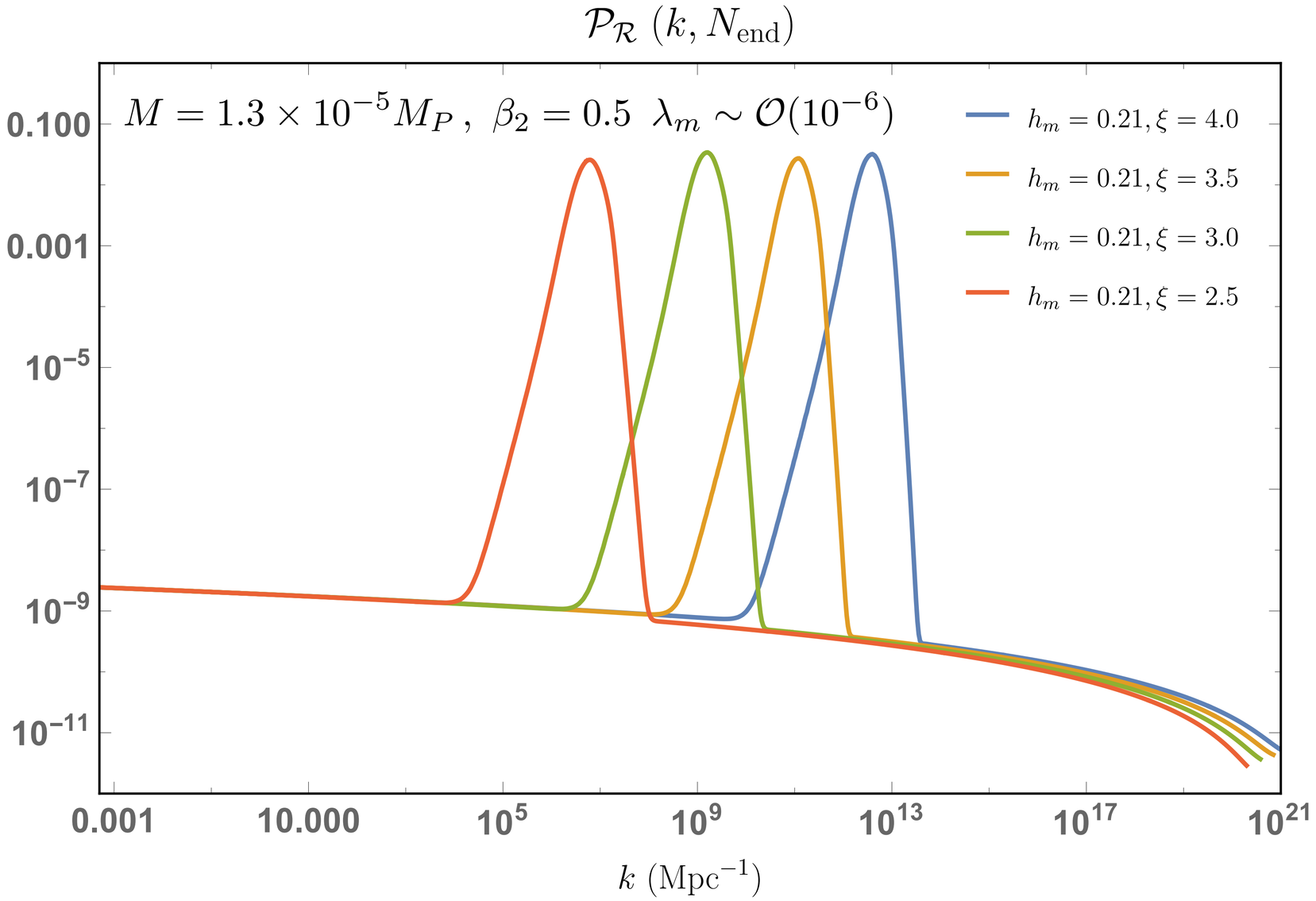

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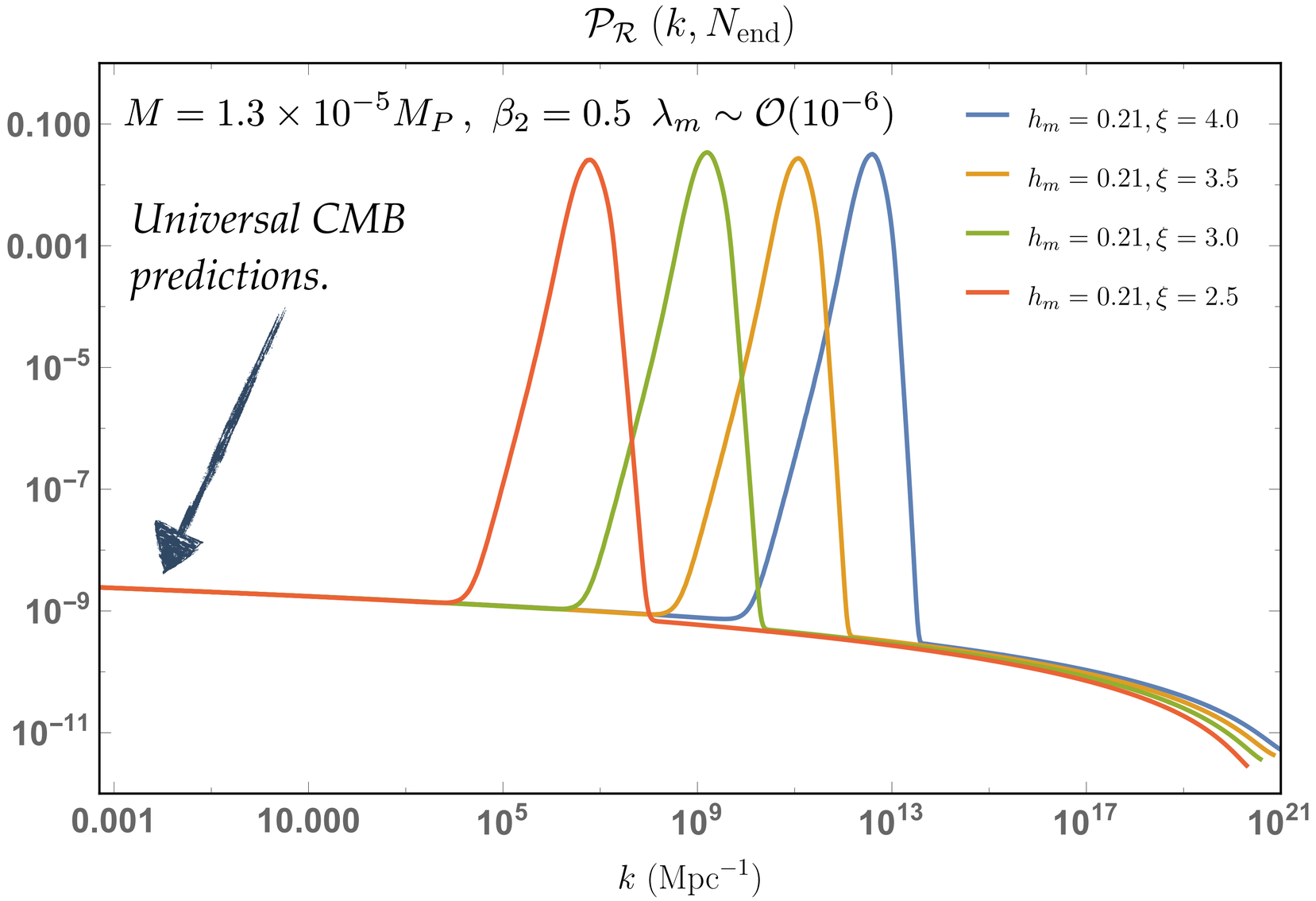

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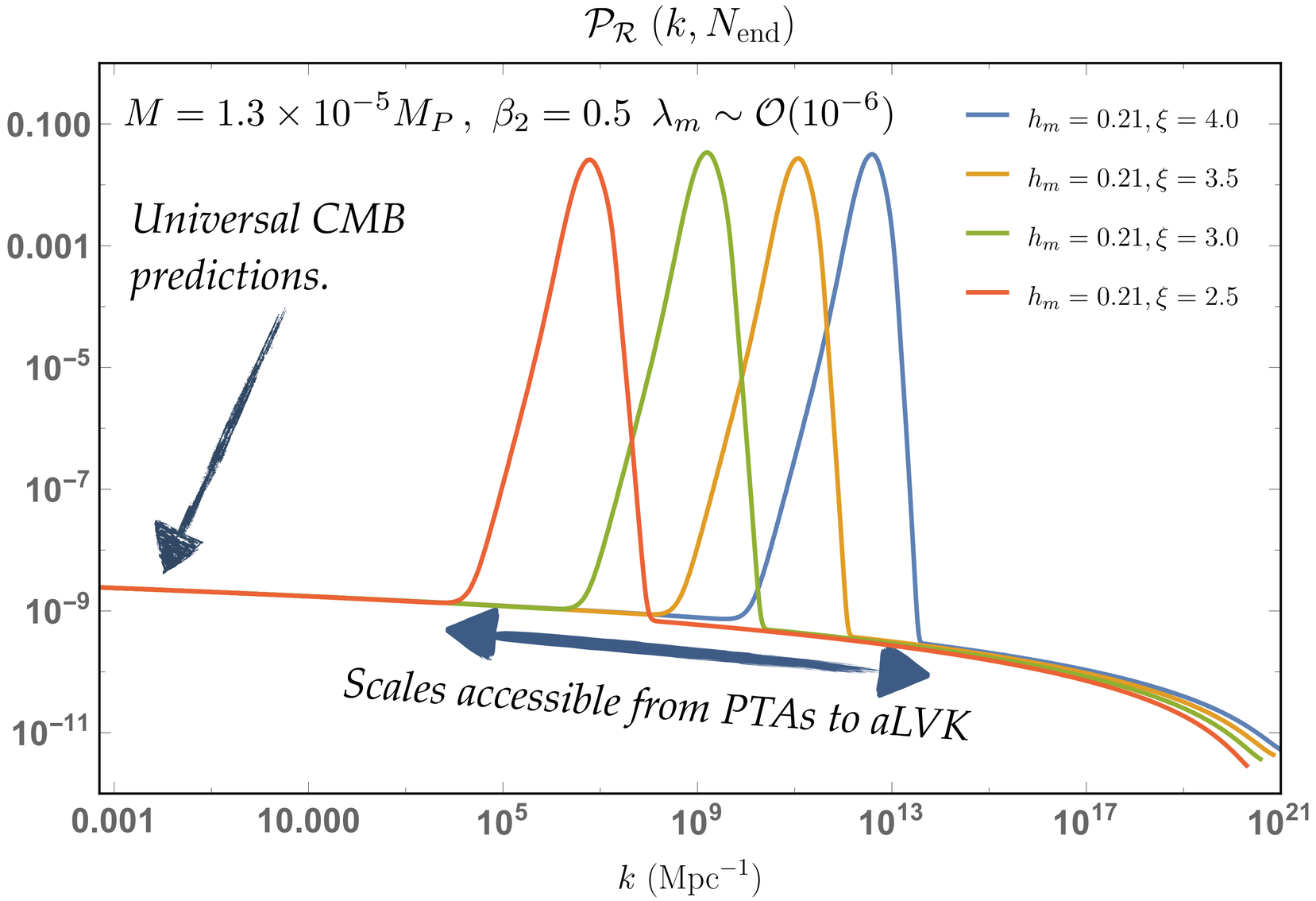

Higgs-R^2 Inflation, Tachyonic Instability

$\mathcal{P}_{\mathcal{R}}\,(k, N_{\rm end})$

$M = 1.3 \times 10^{-5} M_P\,,\ \beta_2 = 0.5\ \ \lambda_m \sim \mathcal{O}(10^{-6})$

Universal CMB predictions.

$h_m = 0.21, \xi = 4.0$

$h_m = 0.21, \xi = 3.5$

$h_m = 0.21, \xi = 3.0$

$h_m = 0.21, \xi = 2.5$

Scales accessible from PTAs to aLVK

0.100 · 0.001 · 10^{-5} · 10^{-7} · 10^{-9} · 10^{-11}

0.001 · 10.000 · 10^{5} · 10^{9} · 10^{13} · 10^{17} · 10^{21}

$k\ (\mathrm{Mpc}^{-1})$

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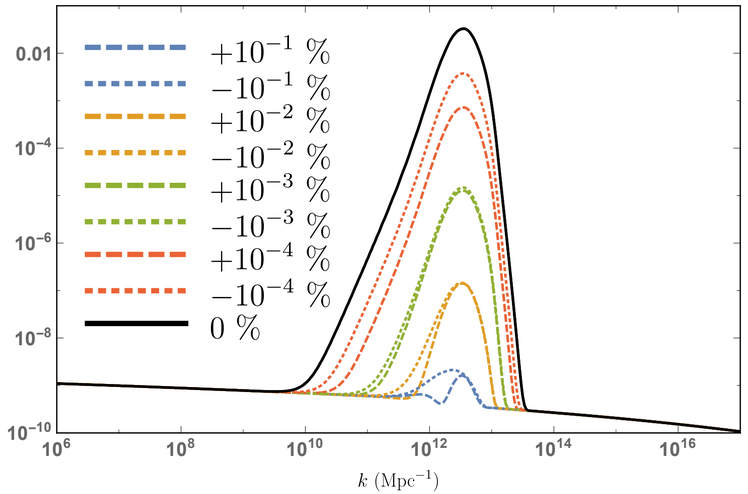
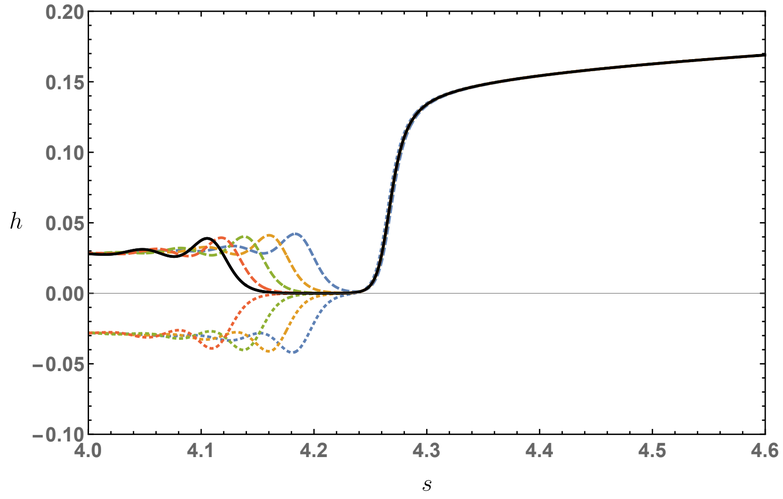
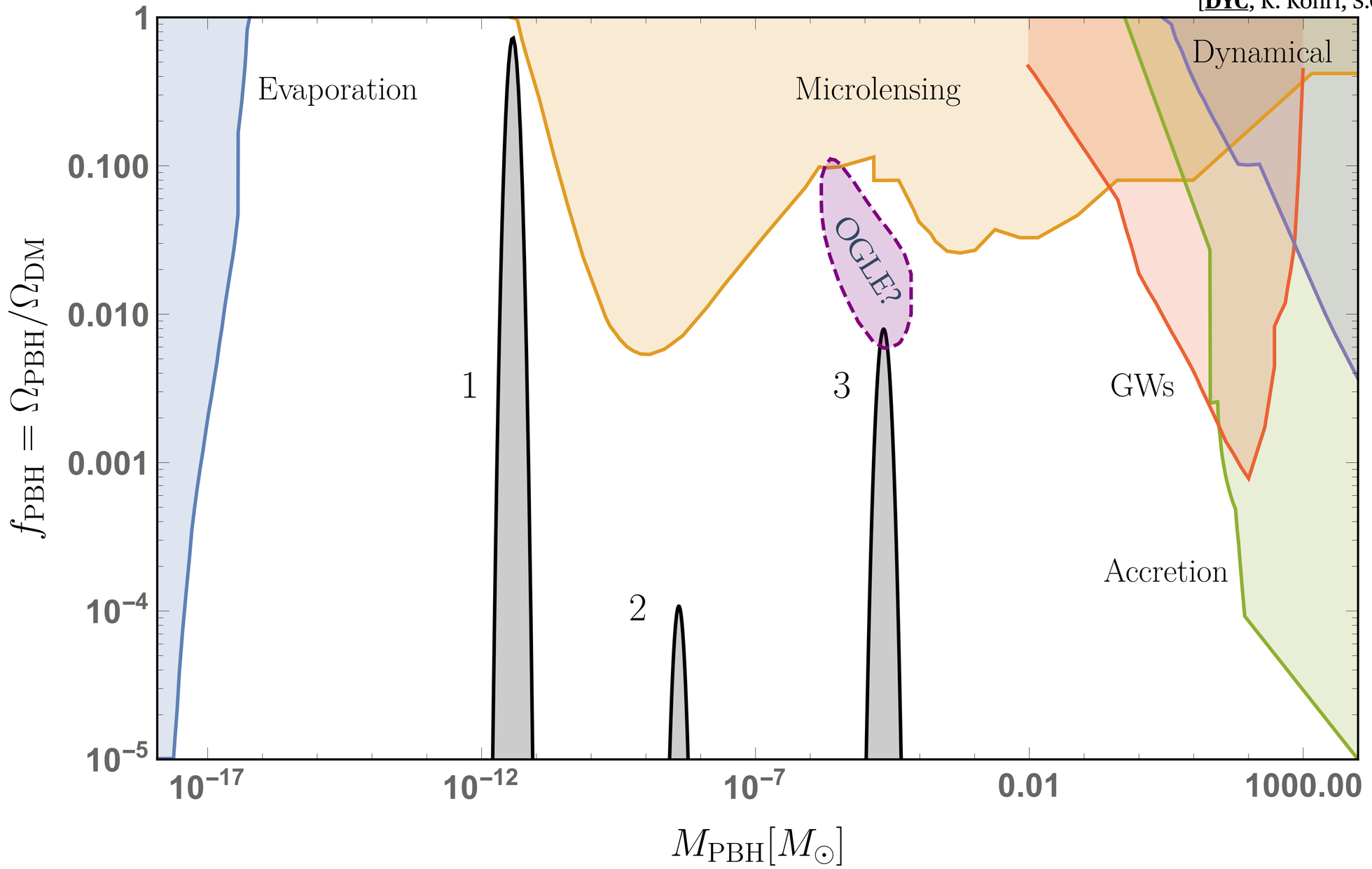




$$\frac{\delta\lambda_m}{\lambda_m} \equiv \frac{\lambda_m^{dev} - \lambda_m}{\lambda_m} \sim 10^{-4}\%$$

Phenomena —Primordial Black Holes

[**DYC**, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015]



Phenomena —Primordial Black Holes

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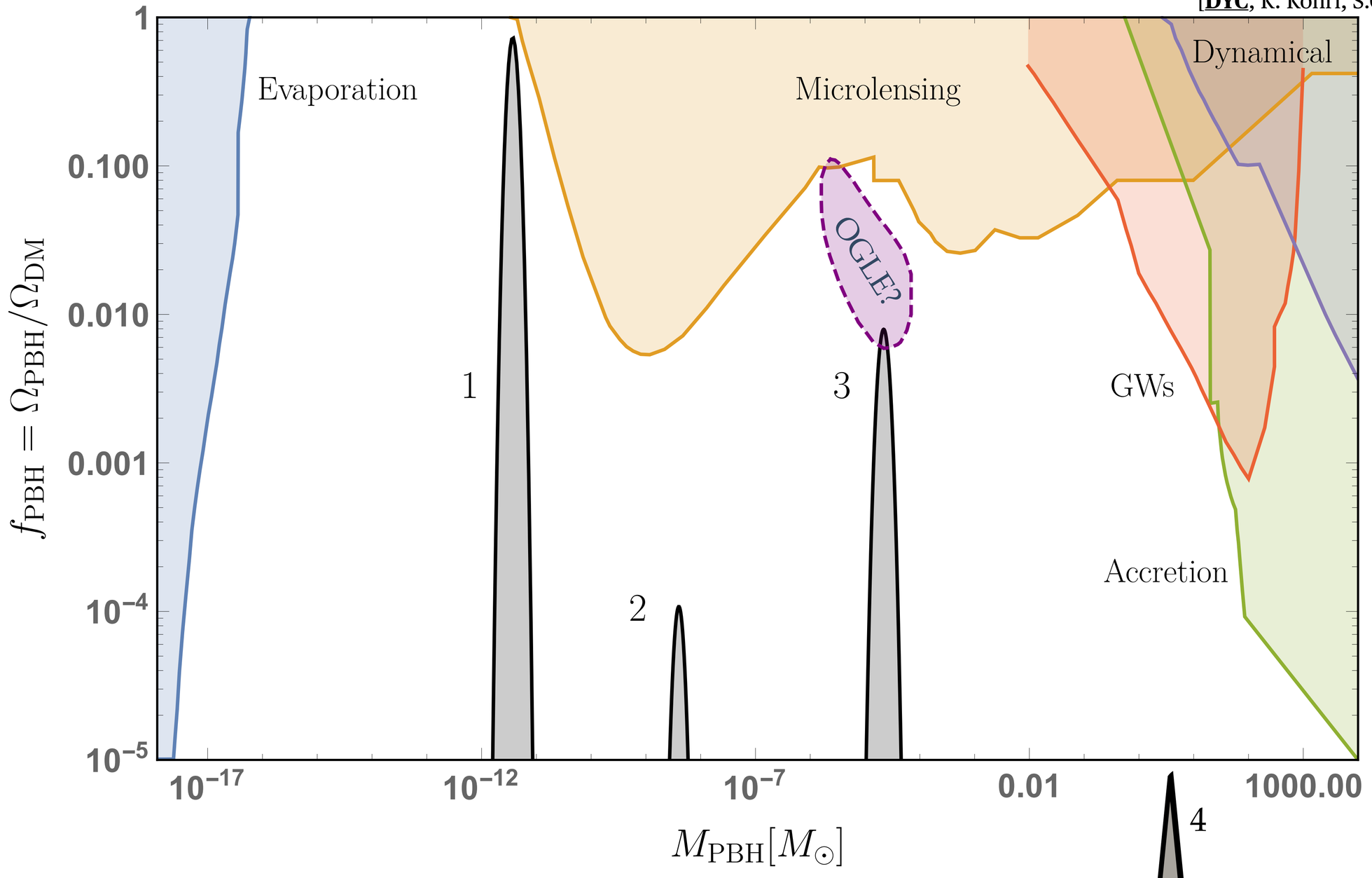
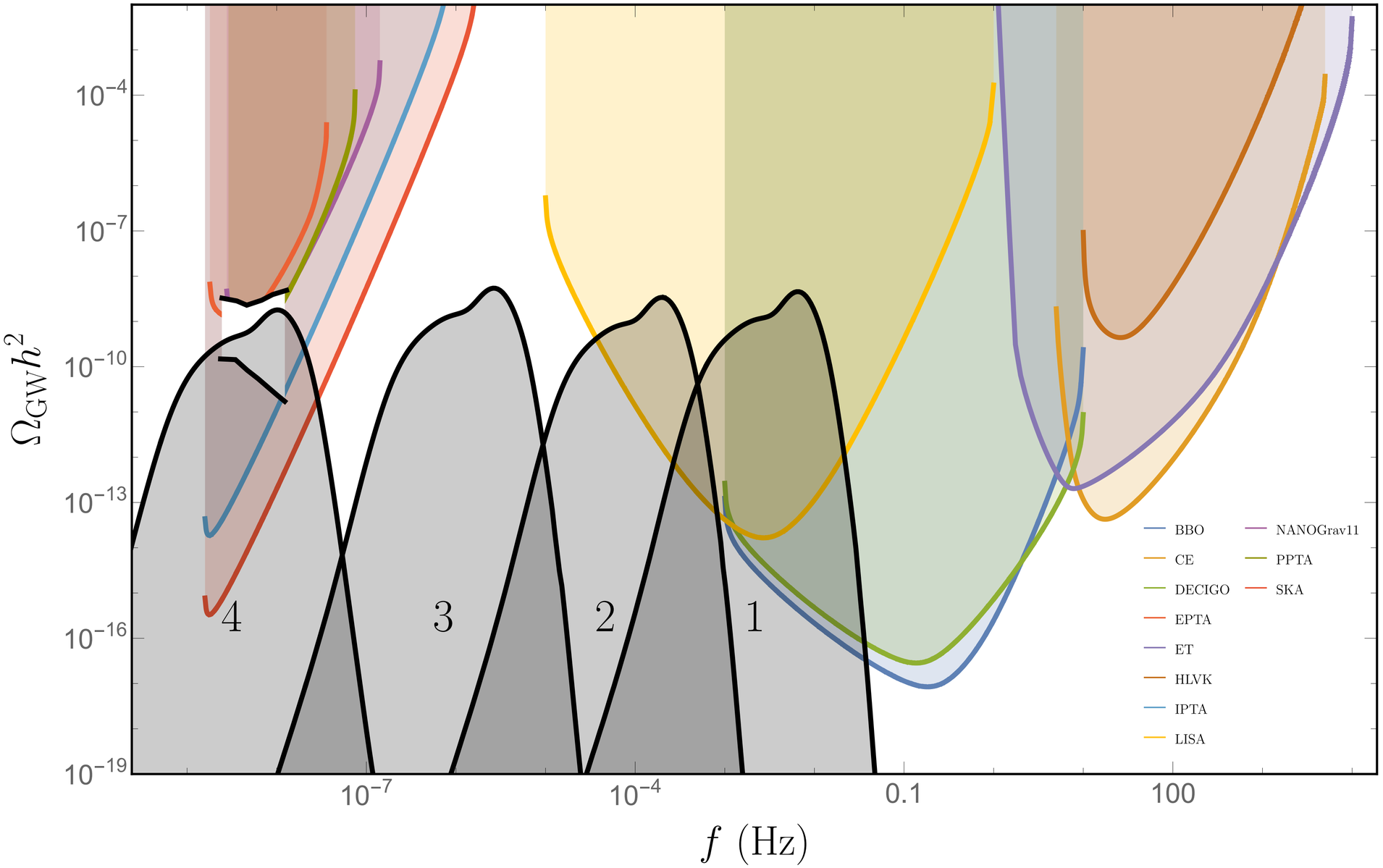


Phenomena —Second order GWs

[**DYC**, K. Kohri, S.C. Park, *JCAP* 10 (2022) 015]



Summary

Higgs-R^2 inflation + SM Higgs Running

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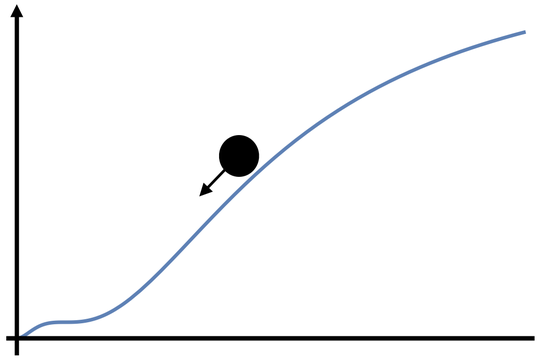
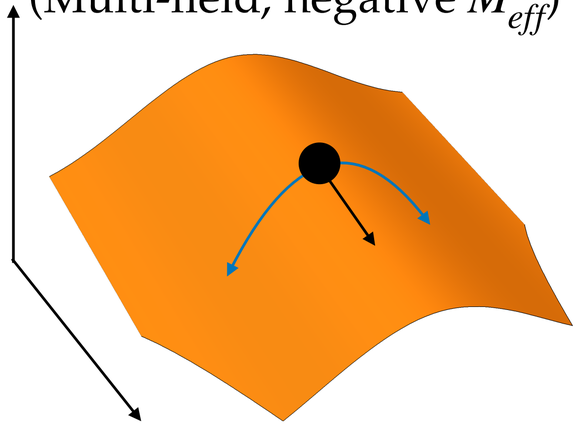
Higgs-R^2 inflation + SM Higgs Running

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



2. Tachyonic instability
(Multi-field, negative M^2_{eff})



Summary

Higgs-R^2 inflation + SM Higgs Running

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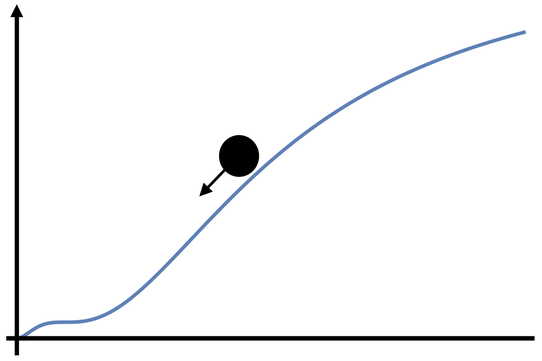

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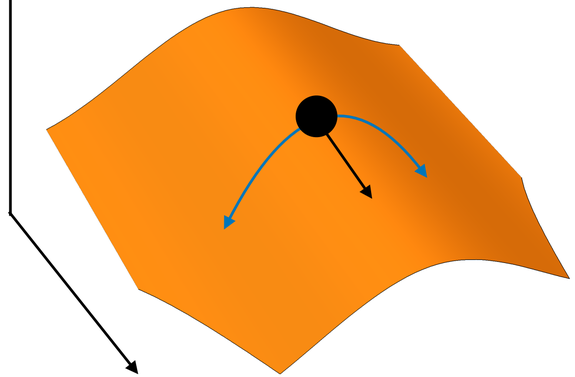
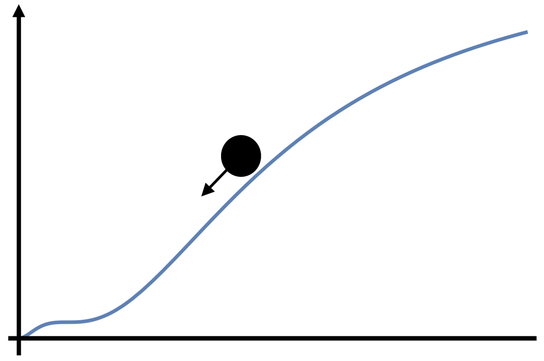


PBH & SGWB Production - SM consistency!

Summary

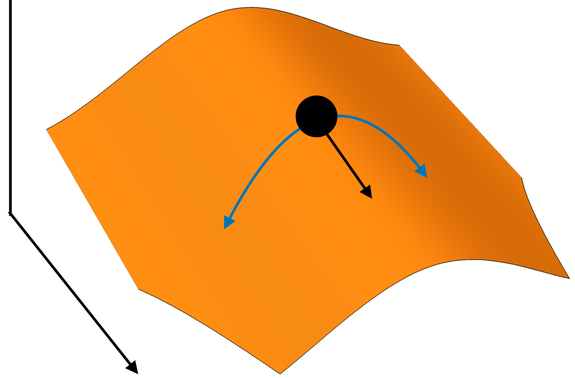
Higgs-R^2 inflation + SM Higgs Running

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



Possible Signatures of the Higgs in the Early Universe!

2. Tachyonic instability
(Multi-field, negative M^2_{eff})



PBH & SGWB Production - SM consistency!

Backup slides.

Introduction - Primordial Black Holes

Then, how large should the density perturbations / curvature perturbations be?

$$\beta \sim \frac{\sigma}{\sqrt{2\pi}\delta_c} e^{-\delta_c^2/(2\sigma^2)} \sim e^{-\delta_c^2/\mathcal{P}_\mathcal{R}}$$

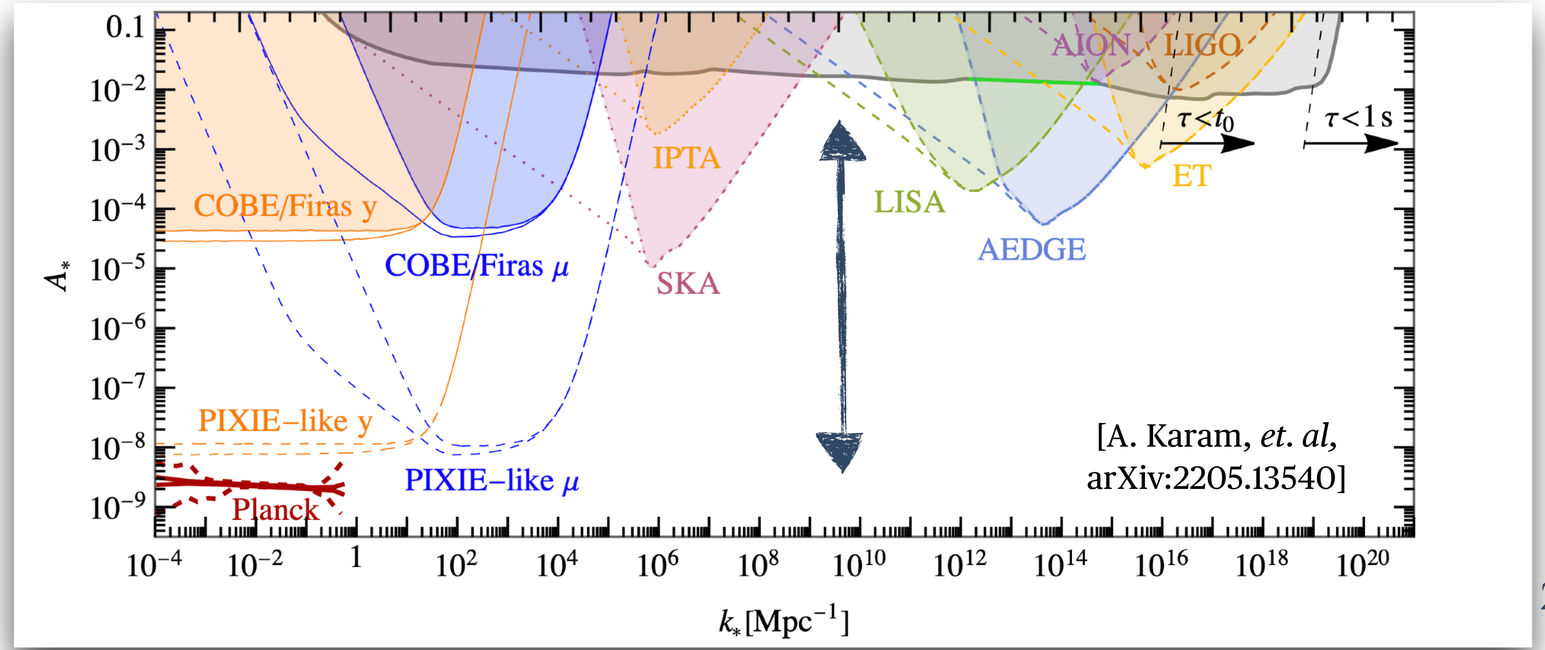
Naive! $\sigma^2 \sim \mathcal{P}_\mathcal{R}$ *Exponential dependence*

$$f_{\rm PBH} \equiv \frac{\rho_{\rm PBH}}{\rho_{\rm DM}} = \left(\frac{a_{\rm eq}}{a_{\rm form}}\right)\beta(M)$$

For solar-mass black holes, $a_{\rm eq}/a_{\rm form} \sim 10^8$ in RD

Take $f_{\rm PBH} \sim \mathcal{O}(1) \to \beta(M) \sim 10^{-8}$ then

$$\mathcal{P}_\mathcal{R} \sim \mathcal{O}(10^{-2})$$



Higgs-R^2 Inflation, Perturbations

Second order perturbation with $\phi^a(t,\vec{x}) = \phi_0^a(t) + \delta\phi^a(t,\vec{x}),\ ds^2 = -(1+2\psi)dt^2 + a(t)^2(1-2\psi)\delta_{ij}dx^i dx^j.$

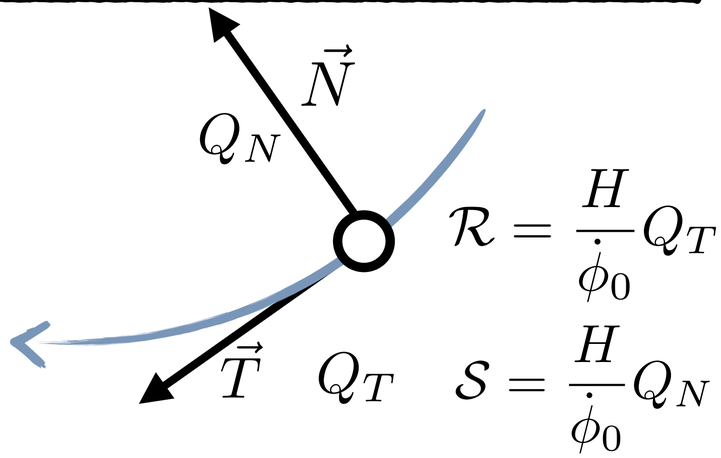
$$\ddot{\mathcal{R}} + \left(3 + 2\epsilon - 2\eta_{\parallel}\right) H\dot{\mathcal{R}} + \frac{k^2}{a^2}\mathcal{R} = -2\frac{H^2}{\dot{\phi}_0}\eta_{\perp}\left[\dot{Q}_N + \left(3 - \eta_{\parallel} + \frac{\dot{\eta}_{\perp}}{H\eta_{\perp}}\right) HQ_N\right]$$

$$\ddot{Q}_N + 3H\dot{Q}_N + \left(\frac{k^2}{a^2} + M_{\text{eff}}^2\right) Q_N = 2\dot{\phi}_0\eta_{\perp}\dot{\mathcal{R}}.$$

[S. Groot Nibbelink, B.J.W. van Tent,(2002)] ,[S. Cespedes et. al, (2012)] [A. Achucarro et. al, (2012)] ...

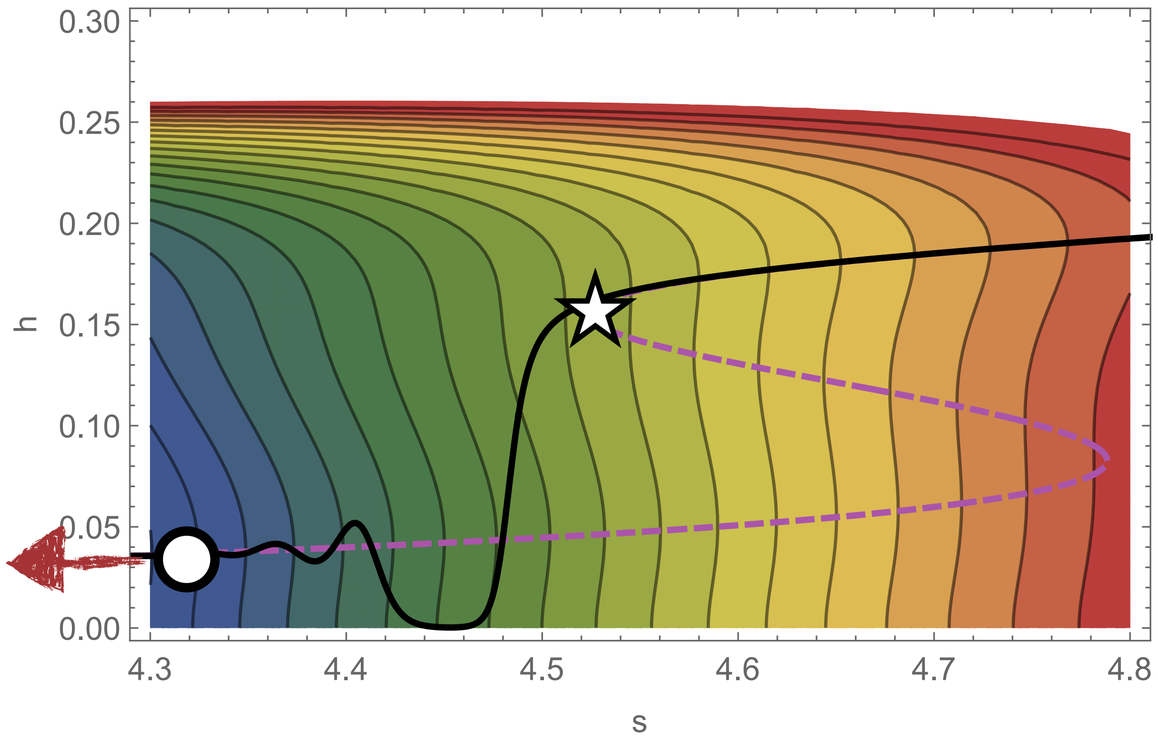
$\eta_{\parallel} \equiv -\frac{\ddot{\phi}_0}{\dot{\phi}_0 H}$ $\eta_{\perp} \equiv \frac{U_N}{\dot{\phi}_0 H}$ $Q^a \equiv \delta\phi^a + \frac{\dot{\phi}^a}{H}\psi$ $\dot{\theta} \equiv H\eta_{\perp}$

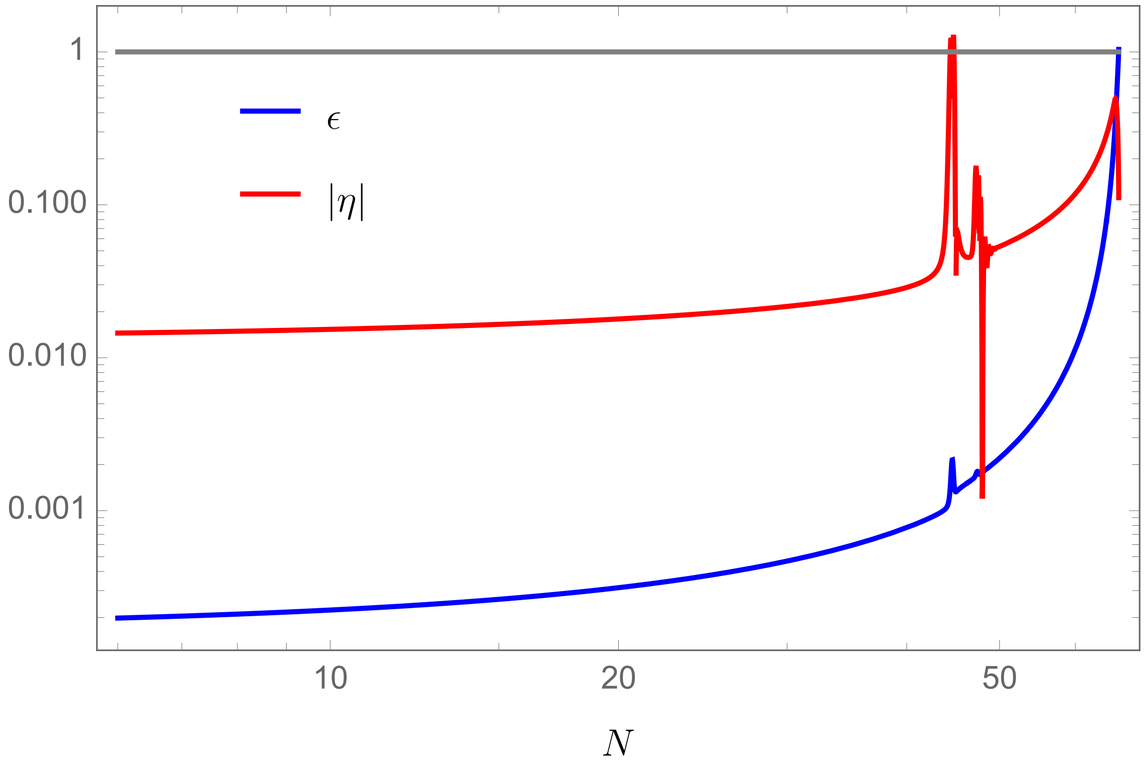
$$M_{\text{eff}}^2 = U_{NN} + H^2\epsilon\mathbb{R} - \dot{\theta}^2.$$



- $M_{\text{eff}}^2 < 0$ leads to *tachyonic growth of* Q_N, then gets *sourced to* $\mathcal{R}$ through *turns in the trajectory.*

Higgs-R^2 Inflation, Slow-Roll Parameters





Higgs-R^2 Inflation / Scalaron

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

Auxiliary field χ

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

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

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

Notice "non-canonical field space metric"

Multi-field / $(h, R) \to (h, s)$ system.

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

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

$(s,h) \simeq (0,0)$

$$\simeq \frac{\lambda}{4}h^4 + \frac{3\xi^2M^2}{4M_P^2}h^4 + \frac{1}{2}M^2s^2 + \ldots - \frac{\lambda}{\sqrt{6}M_P}sh^4 - \frac{M^2}{6\sqrt{6}M_P^3}s^5 + \left(\frac{\lambda}{3M_P^2} + \frac{\xi^2M^2}{M_P^4}\right)h^4s^2 + \ldots.$$

$$\Lambda \sim \mathcal{O}\left(\frac{M_P^2}{\xi^2M^2}\right)M_P > M_P$$ Theory unitarized through the scalaron!