Primordial Black Holes and Gravitational Waves from the Tachyonic Instability in Higgs-R^2 Inflation

"The Inflaton that Could"



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

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Introduction -Primordial Black Holes

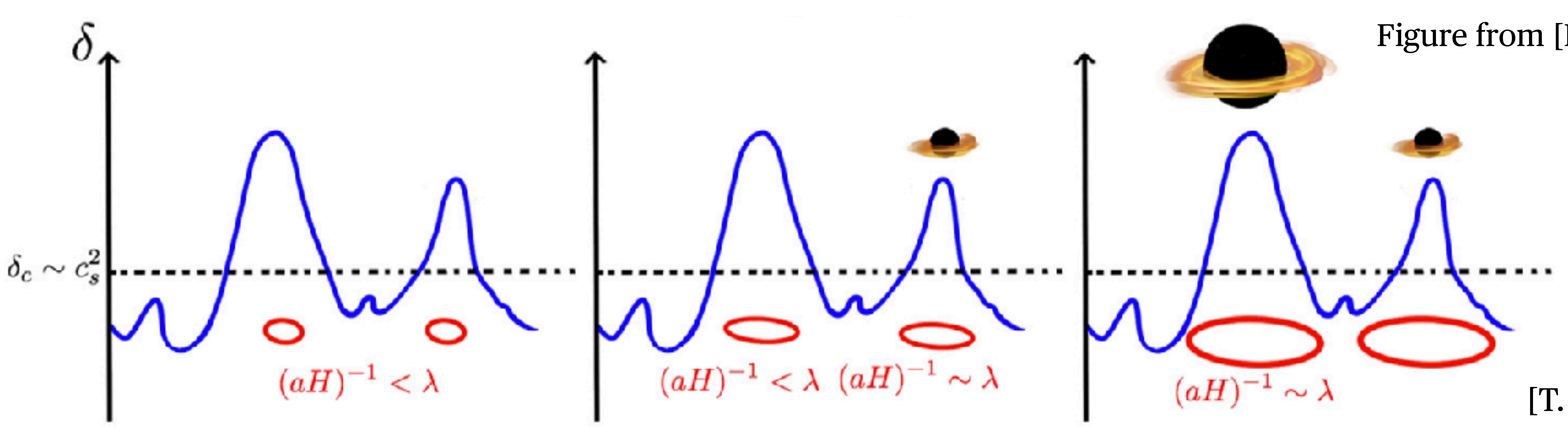


Figure from [P. Villanueva-Domingo *et. al.*, Front.Astron.Space Sci. 8 (2021) 87]

δ_c

$$0.4 \simeq \frac{\delta\rho_c}{\rho} \lesssim \frac{\delta\rho}{\rho} \lesssim 1$$

[T. Harada, C.M. Yoo, K. Kohri, *Phys.Rev.D* 88, 8, 084051 (2013)]

PBHs form through the collapse of *large over-densities in the density perturbation*

$$k \leftrightarrow M_{\rm PBH} \rightarrow \mathcal{P}_{\mathcal{R}}\left(k\right) \rightarrow \mathcal{P}_{\delta}\left(k\right) \rightarrow \beta\left(M\right) = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}} \qquad \frac{M_{\rm PBH}}{M_\odot} \sim \left(\frac{k_*}{3.3 \times 10^6 {\rm Mpc}^{-1}}\right)^{-2} \sim \left(\frac{f_*}{5.0 \times 10^{-9}{\rm Hz}}\right)^{-2}$$

Many mechanisms to produce PBHs —> Inflation is appealing!

Inflation, phase transition, reheating, etc etc..

Introduction -Primordial Black Holes

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

$$\beta \sim \frac{\sigma}{\sqrt{2\pi}\delta_c} e^{-\delta_c^2/(2\sigma^2)} \sim e^{-\delta_c^2/\mathcal{P}_\mathcal{R}} \leftarrow \left.\frac{\rho_{\rm PBH}}{\rho_{\rm tot}}\right|_{\rm form}$$

$$\sigma^2(R) = \int_0^\infty W^2(kR)\mathcal{P}_\delta(k) d\ln k$$

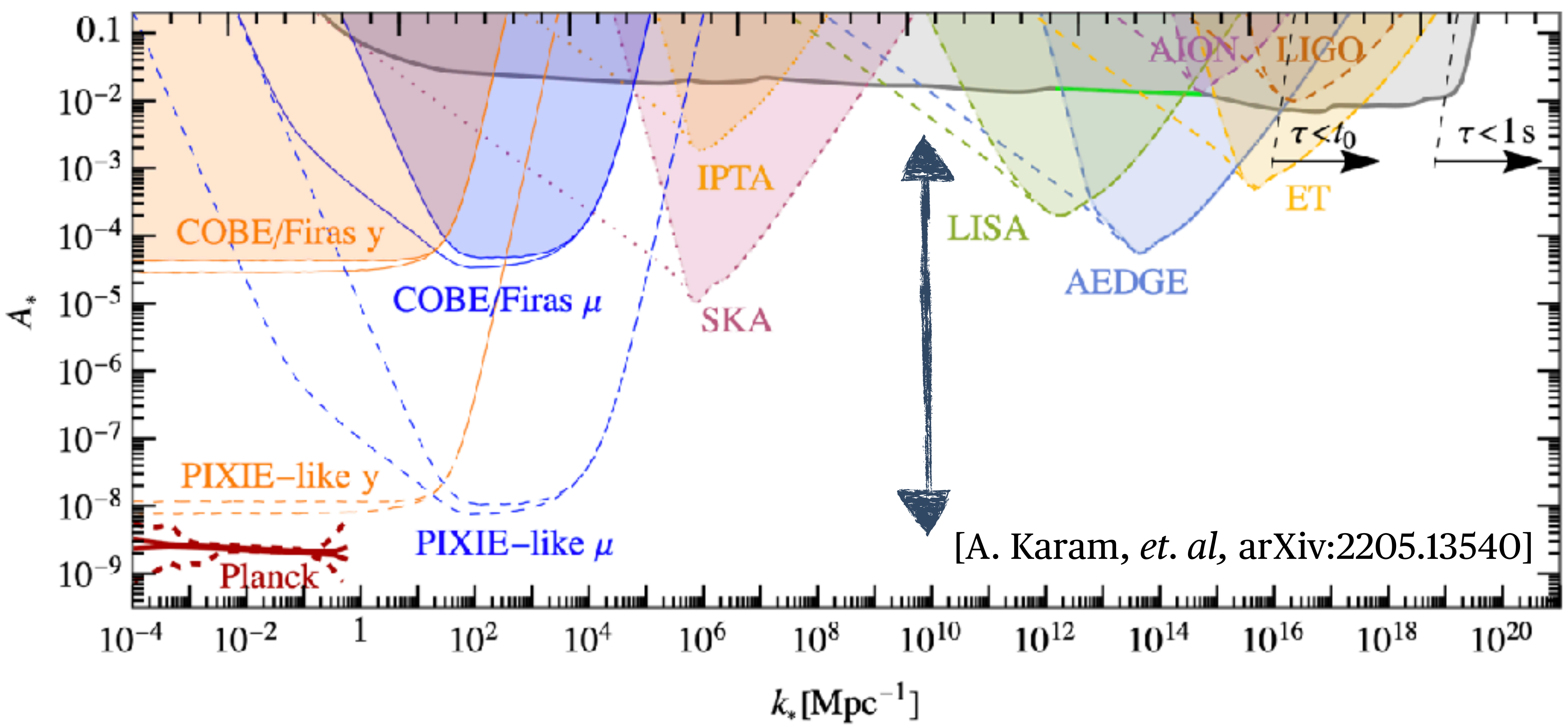
Variance, Naive! $\sigma^2 \sim \mathcal{P}_\mathcal{R}$ *Exponential dependence*

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

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

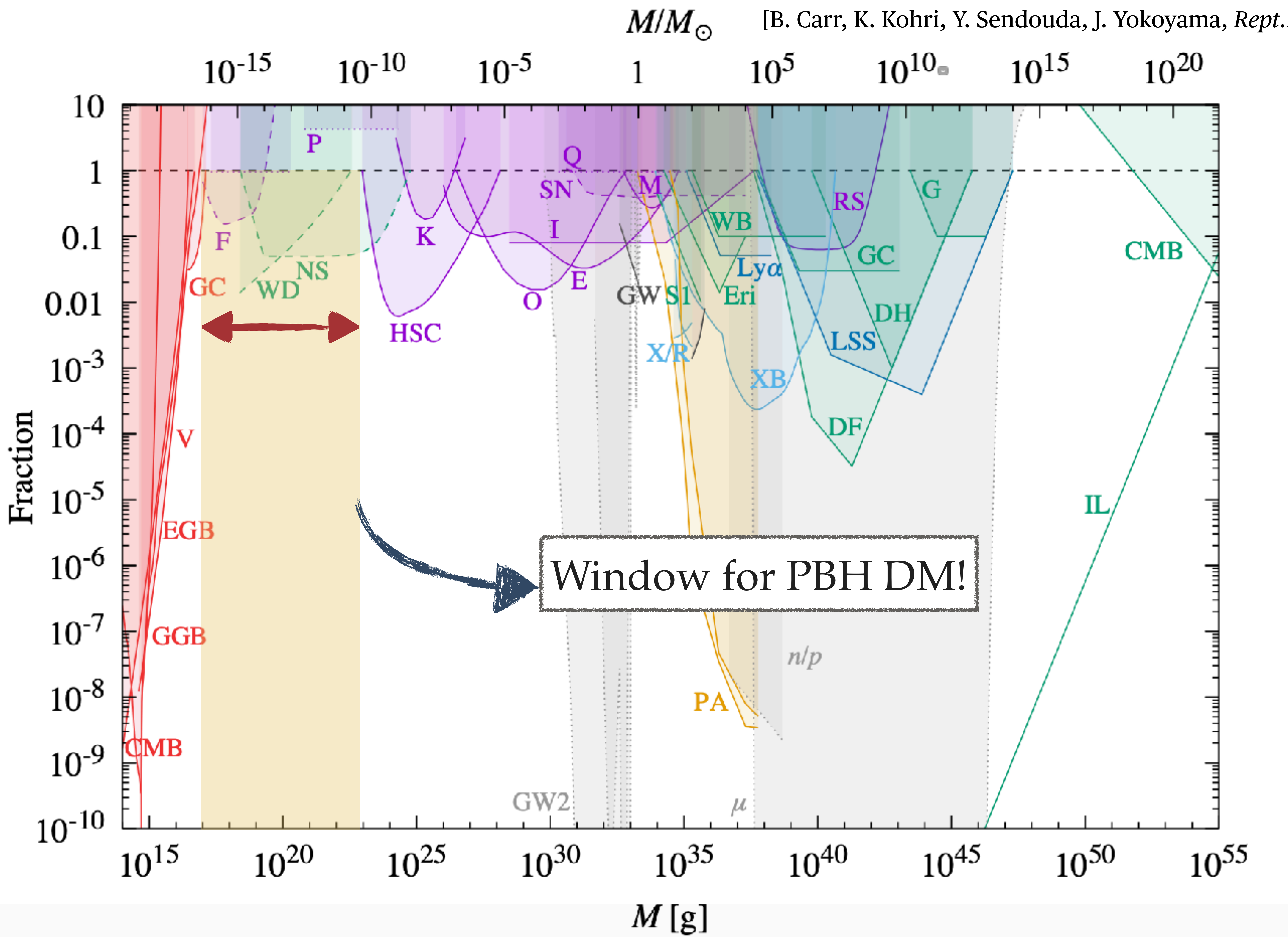
Take $f_{\rm PBH} \sim \mathcal{O}(1) \to \beta(M) \sim 10^{-8}$ then

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



Introduction - Primordial Black Holes

[B. Carr, K. Kohri, Y. Sendouda, J. Yokoyama, *Rept.Prog.Phys.* 84, 11, 116902 (2021)]



Introduction - Second Order GWs

Scalar and tensor perturbations couple at "second order metric perturbations".

[K. Kohri, T. Terada, Phys. Rev. D **97**, 123532 (2018)]

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

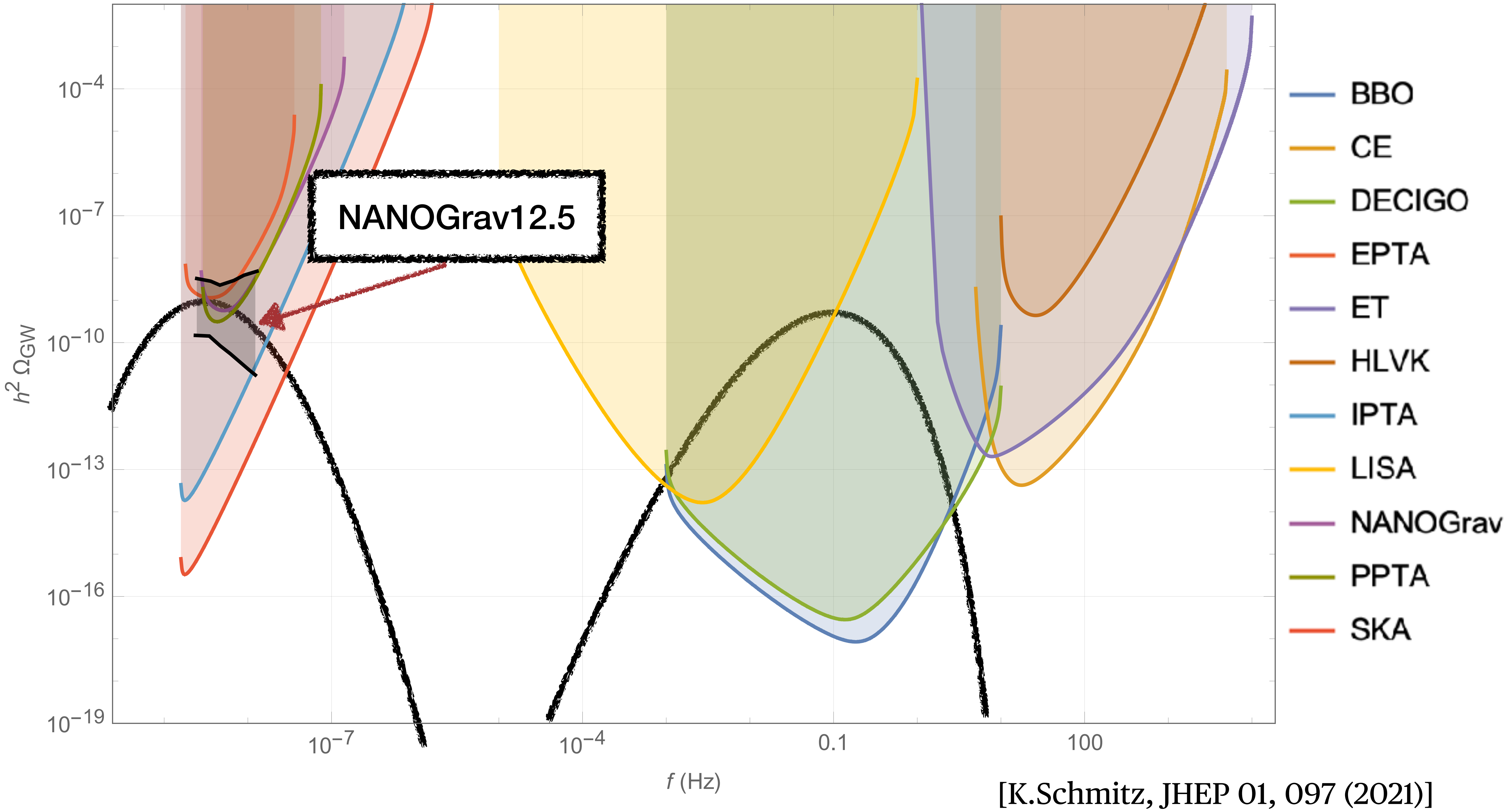
$$\Omega_{\mathrm{GW}} h^2 \sim \frac{1}{12} \Omega_{r,0} h^2 \times \mathcal{P}_{\mathcal{R}}^2 \sim 10^{-6} \mathcal{P}_{\mathcal{R}}^2$$

DECIGO, SKA : $\mathcal{P}_{\mathcal{R}} \sim 10^{-5}$

LISA, CE, ET : $\mathcal{P}_{\mathcal{R}} \sim 10^{-4}$

NANOGrav12.5: $\mathcal{P}_{\mathcal{R}} \sim 10^{-2}$

Future GW observatories well involved in probing the small scale.



[K.Schmitz, JHEP 01, 097 (2021)]
[Z. Arzoumanian et al , Astrophys.J.Lett. 905, 2, L34 (2020)]

Higgs-R^2 Inflation

Q1) What can be our inflaton?

Considering dim-4 operators, R^2 present as well!

[Y. Ema, *Phys.Lett.B* 770 (2017) 403-411]
[Y-C. Wang, T. Wang, *Phys.Rev.D* 96 (2017) 12, 123506]
[M.He, A. A. Starobinsky, J. Yokoyama, *JCAP* 05 (2018) 064]

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

non minimal coupling — R^2 term — Higgs

Conformal transformation into Einstein frame

$$S_E = \int d^4x \sqrt{-g} \left[\frac{M_P^2}{2} R - \frac{1}{2} g^{\mu\nu} \nabla_\mu s \nabla_\nu s - \frac{1}{2} e^{-\sqrt{\frac{2}{3}} \frac{s}{M_P}} g^{\mu\nu} \nabla_\mu h \nabla_\nu h - U(s,h) \right]$$

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

Higgs-R^2 Inflation

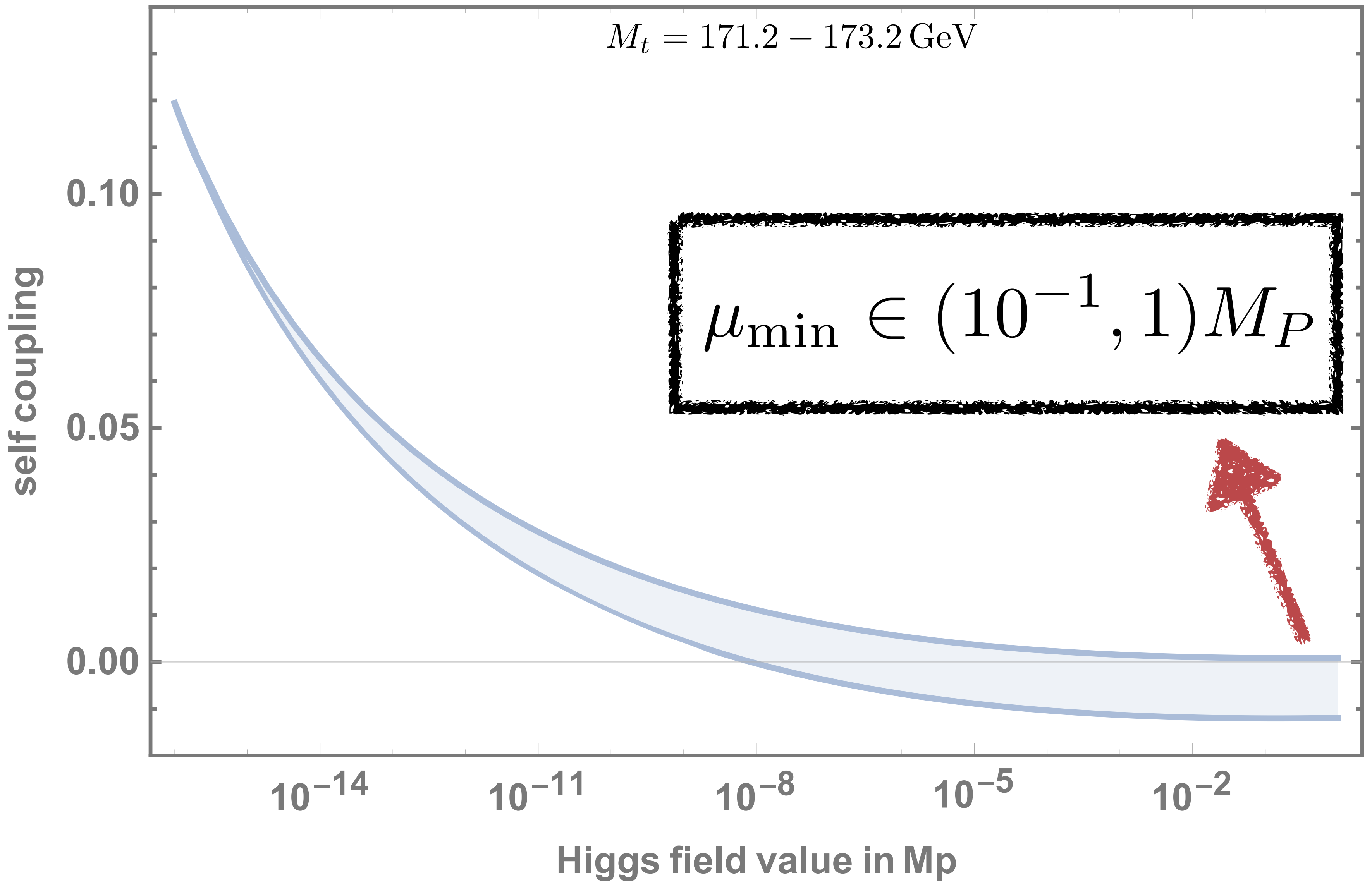
Q1) What can be our inflaton? —> Higgs + R^2

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

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

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

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



Choosing $\mu = h$

$$\lambda(\mu)|_{\mu=h} = \lambda_m + b \ln^2 (|h|/h_m)$$

$$\beta_2^{SM} \simeq 0.5$$

$$b = \frac{\beta_2}{(16\pi^2)^2}$$

Critical values where $\lambda_m \sim \mathcal{O}(10^{-6})$ possible

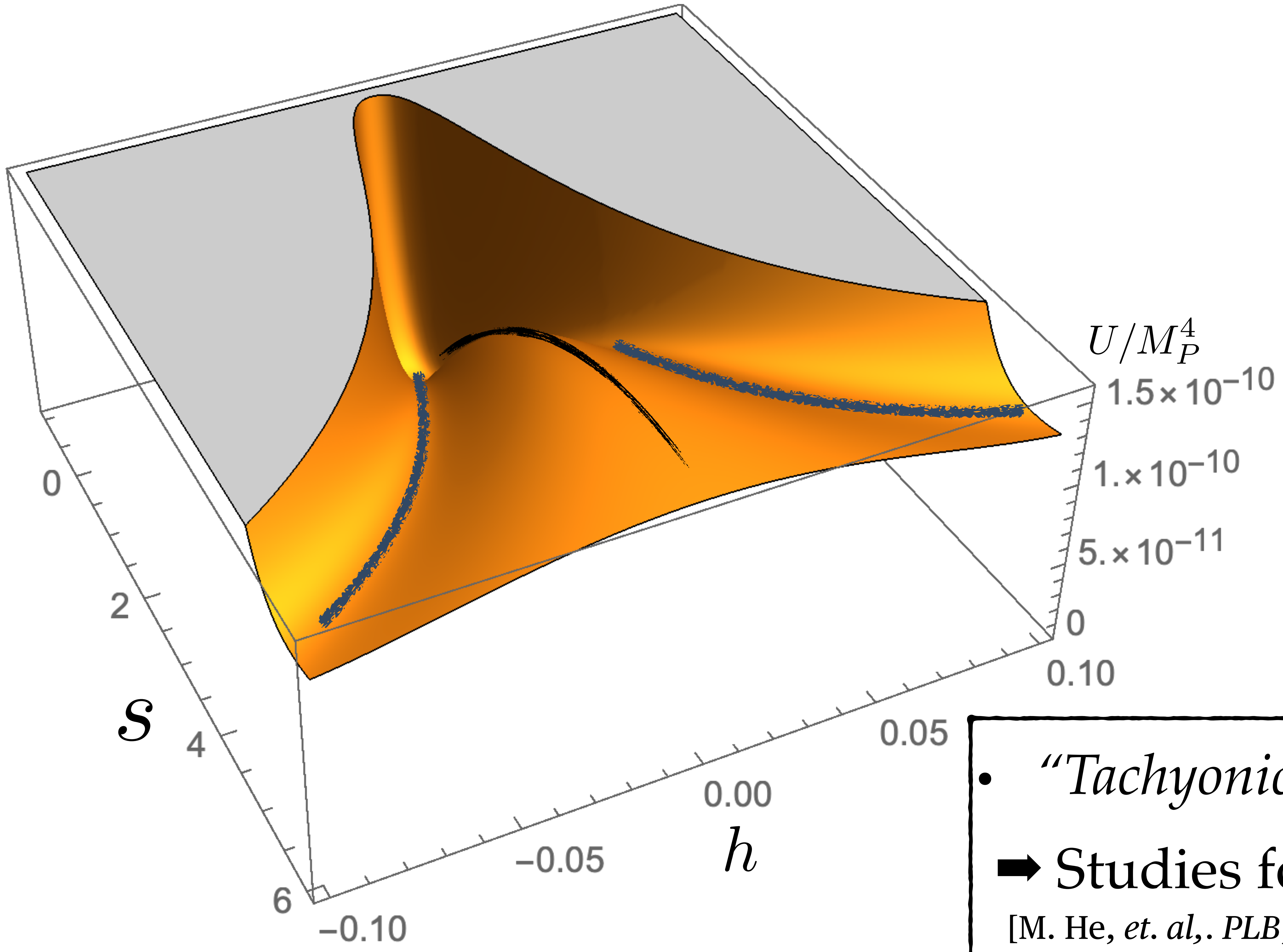
Single-field case : "Critical Higgs inflation"

[Y. Hamada, H. Kawai, K-y. Oda, S.C. Park *Phys.Rev.Lett.* 112 (2014) 24]

[F. Bezrukov, M. Shaposhnikov *Phys.Lett.B* 734 (2014) 249-254]

Higgs-R^2 Inflation

- Shape of the potential? Focus on constant λ for simplicity



- *"Valley"* structure, trajectory (initially) follows,

$$\frac{\partial U(s,h)}{\partial h} = 0 \qquad h_{\rm v}^2 = \frac{e^{\sqrt{\frac{2}{3}}\frac{s}{M_P}} - 1}{\frac{\xi}{M_P^2} + \frac{\lambda}{3\xi M^2}} \text{ for } \phi > 0$$

➡ Isocurvature mass heavier than the Hubble scale, suppression in perturbations.

➡ Flat plateau induced in the large s limit.

➡ Running of λ can induce a USR phase.

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

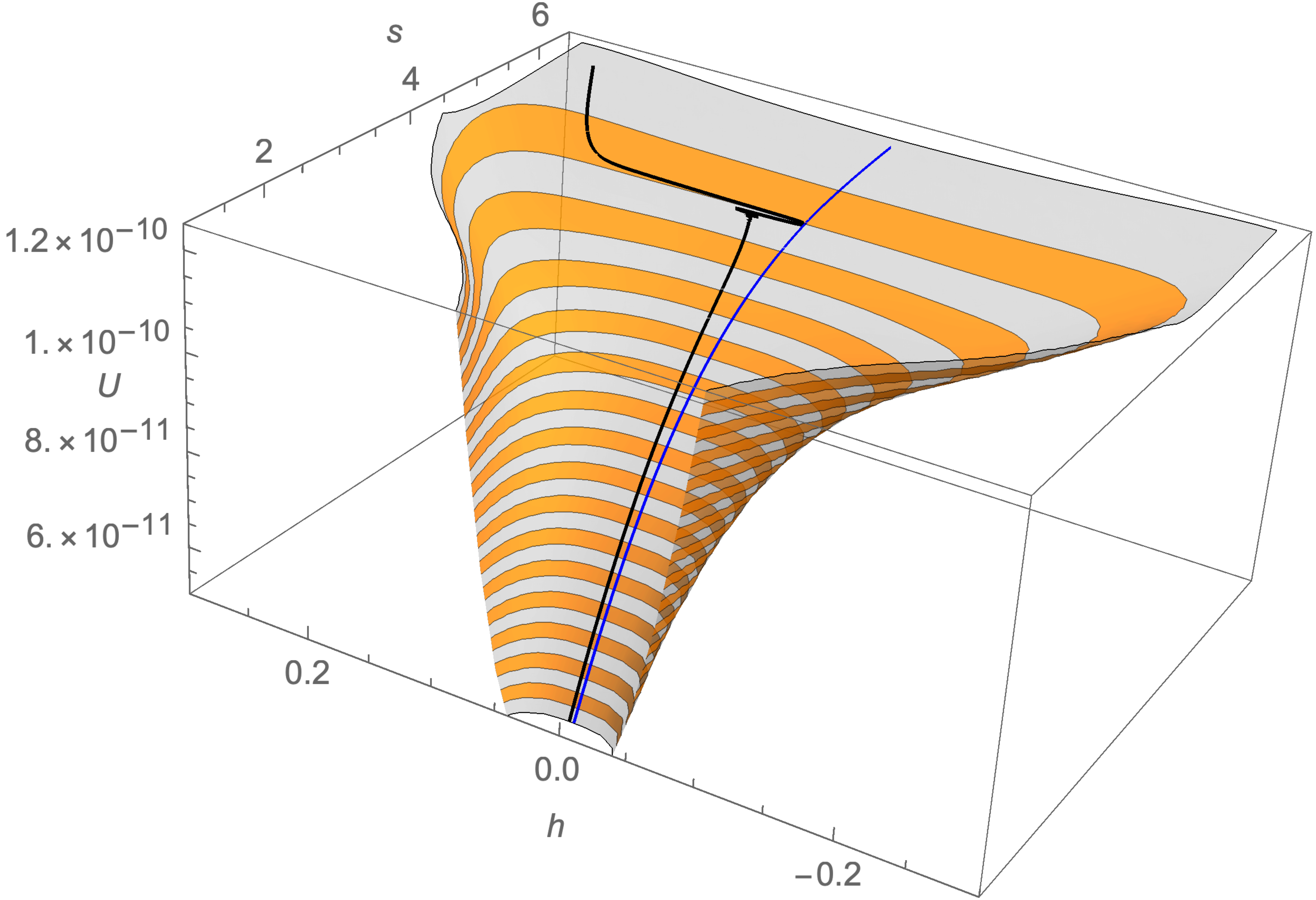
- *"Tachyonic hill"* at $h = 0$ for $s > 0$

➡ Studies focused on a "tachyonic instability" during (p)reheating

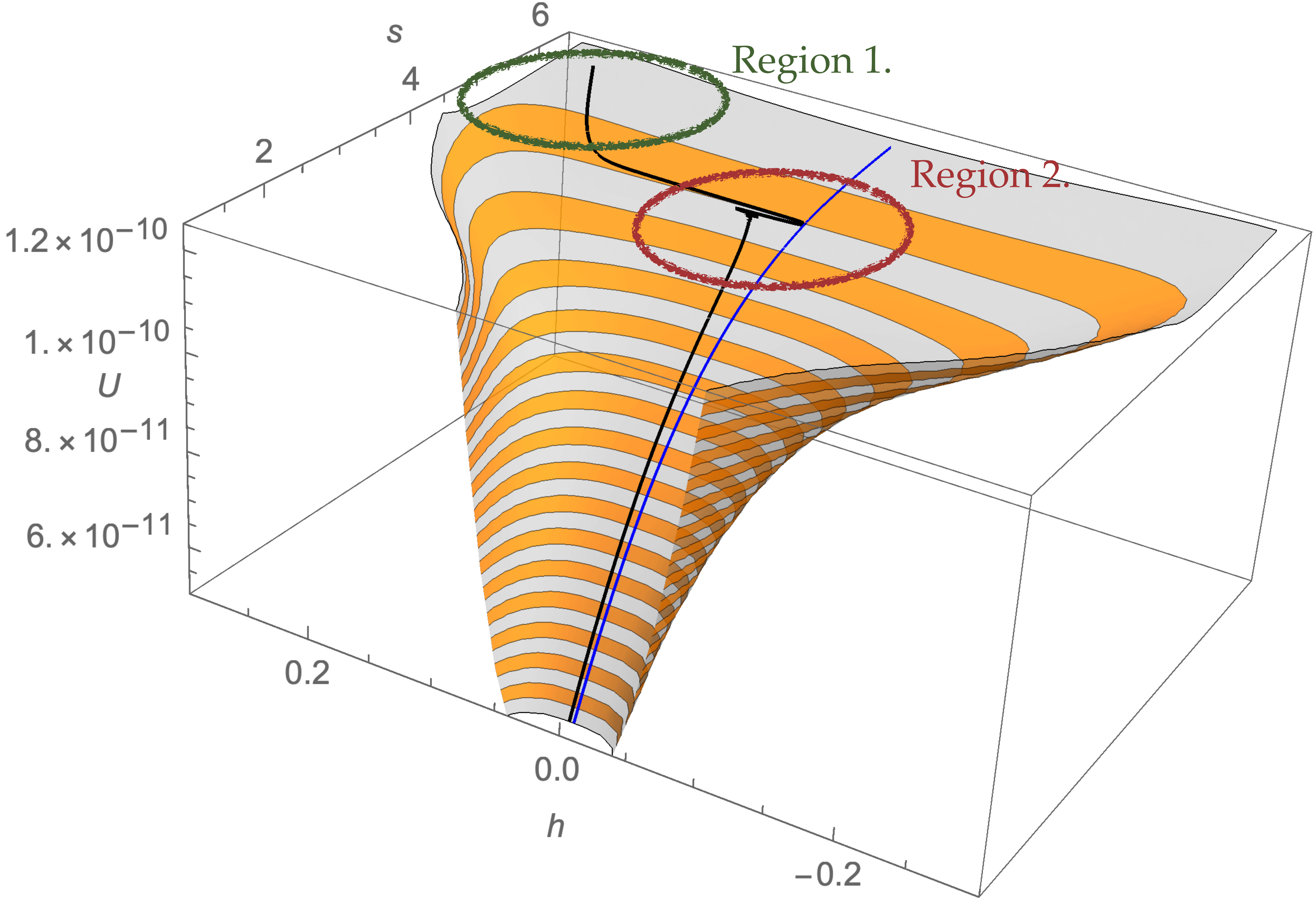
[M. He, *et. al*,. *PLB*, *791*, 36-42 (2019).] [F. Bezrukov, *et. al*,. *PLB*, *795*, 657-665 (2019).]
[M. He, *et. al*, *JCAP* 01 (2021) 066.] [F. Bezrukov, *et. al*, *JCAP* 12 (2020) 028.] [S. Aoki *et. al*, *JHEP* 05 (2022) 121]

➡ Instability "during inflation" induced by λ-running —> exponential growth of perturb.

Higgs-R^2 Inflation, Trajectory



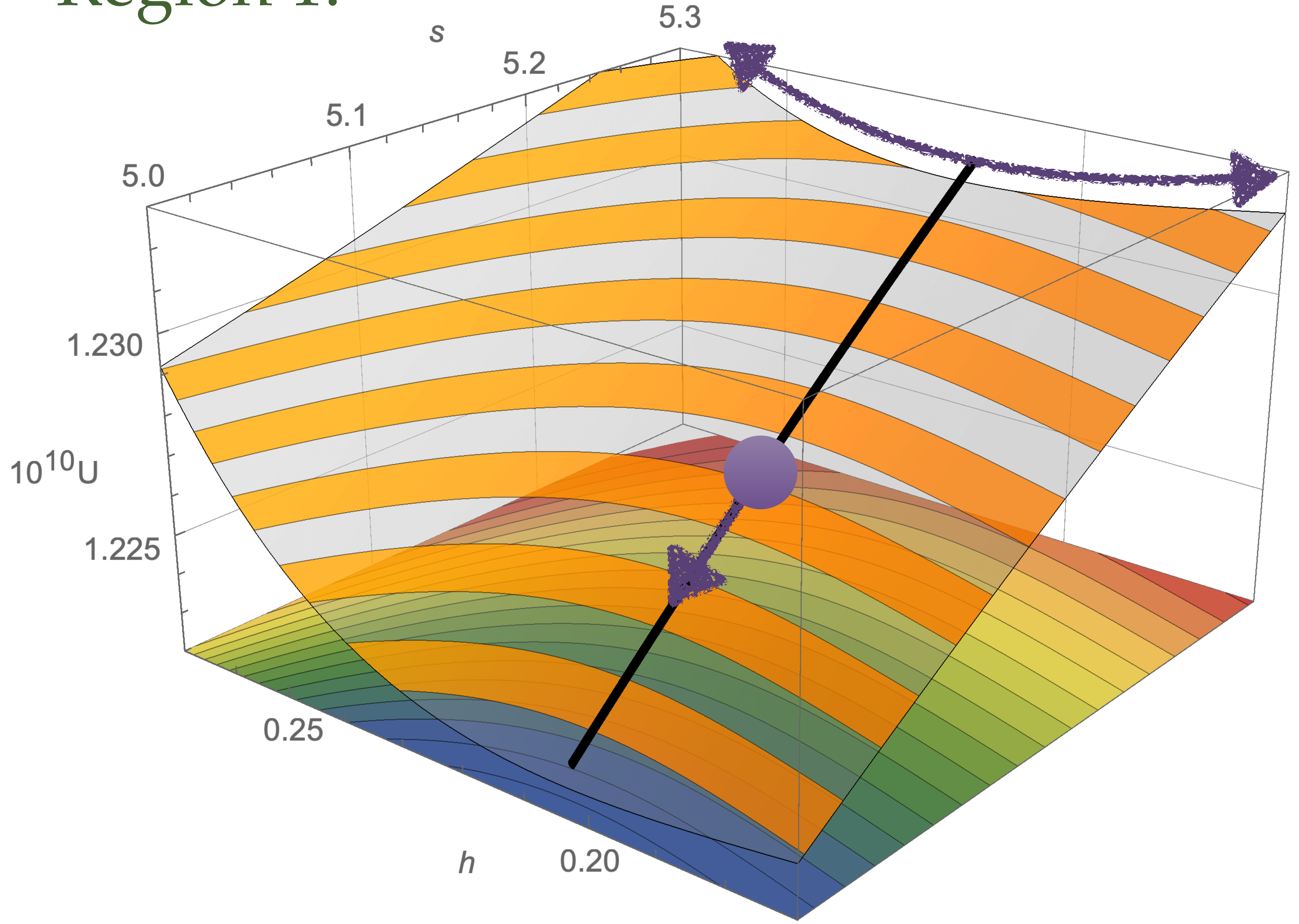
Higgs-R^2 Inflation, Trajectory



Higgs-R^2 Inflation, Trajectory

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

Region 1.



- *"Valley"* structure persists, exhibits an *"attractor"* behavior.
- *Isocurvature perturbations suppressed*
- CMB observables resemble the predictions of an *"effective single-field"* setup.
- "Slightly larger" n_s, r compared to constant λ.

$$n_s \approx 1 - \frac{2}{N_{\rm inf}} - \frac{9}{2N_{\rm inf}^2} + \frac{2M^2\xi^2\, b}{\lambda_m\,(\lambda_m + 3M^2\xi^2)} + \dots \quad r \approx \frac{12}{N_{\rm inf}^2} + \frac{24M^2\xi^2\, b}{\lambda_m(\lambda_m + 3M^2\xi^2)N_{\rm inf}} \ln\left(\frac{4M^2\xi N_{\rm inf}}{(\lambda_m + 3M^2\xi^2)\, h_m^2}\right) + \dots$$

Higgs-R^2 Inflation, Trajectory

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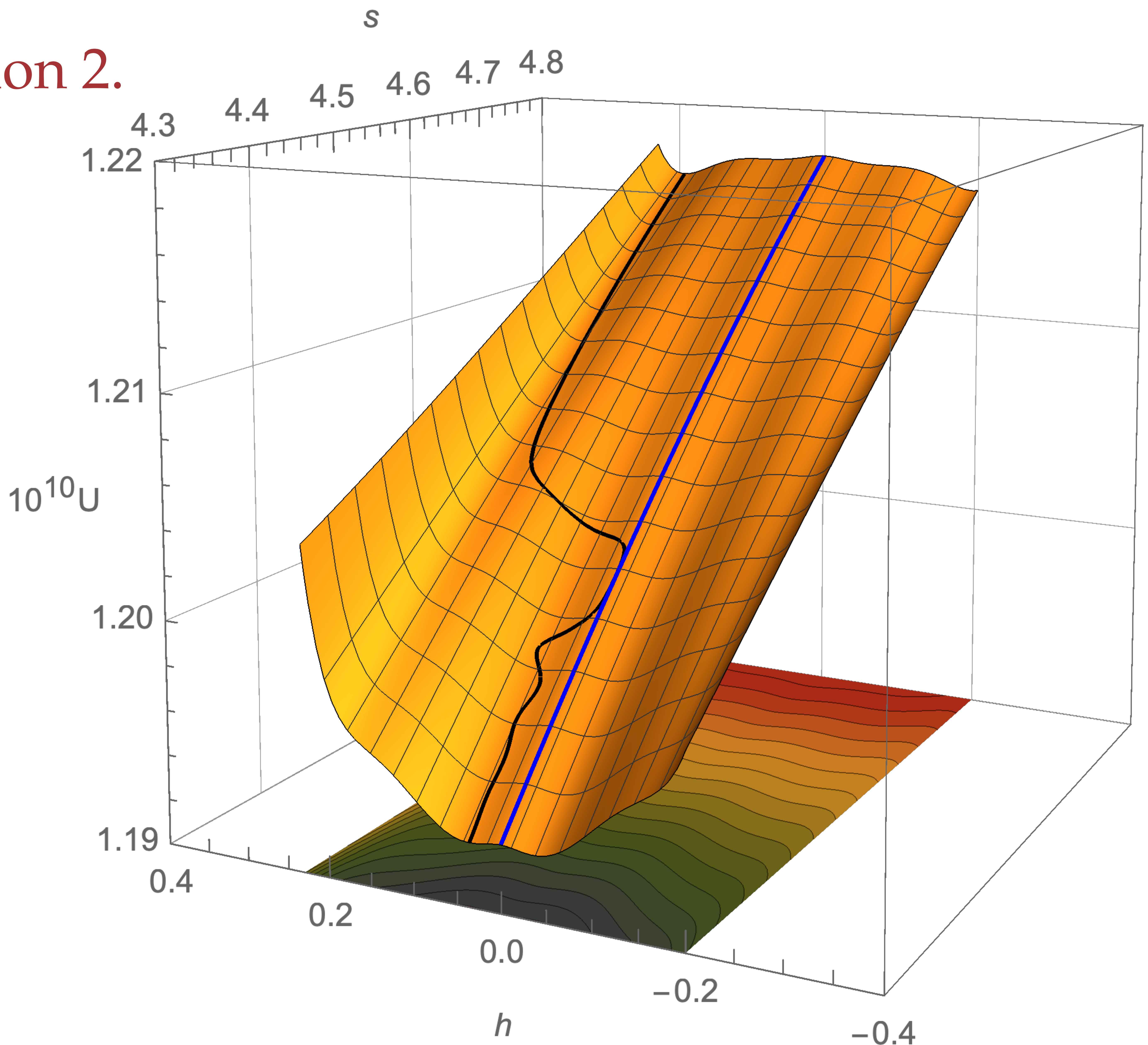
Region 2.



Higgs-R^2 Inflation, Trajectory

Region 2.

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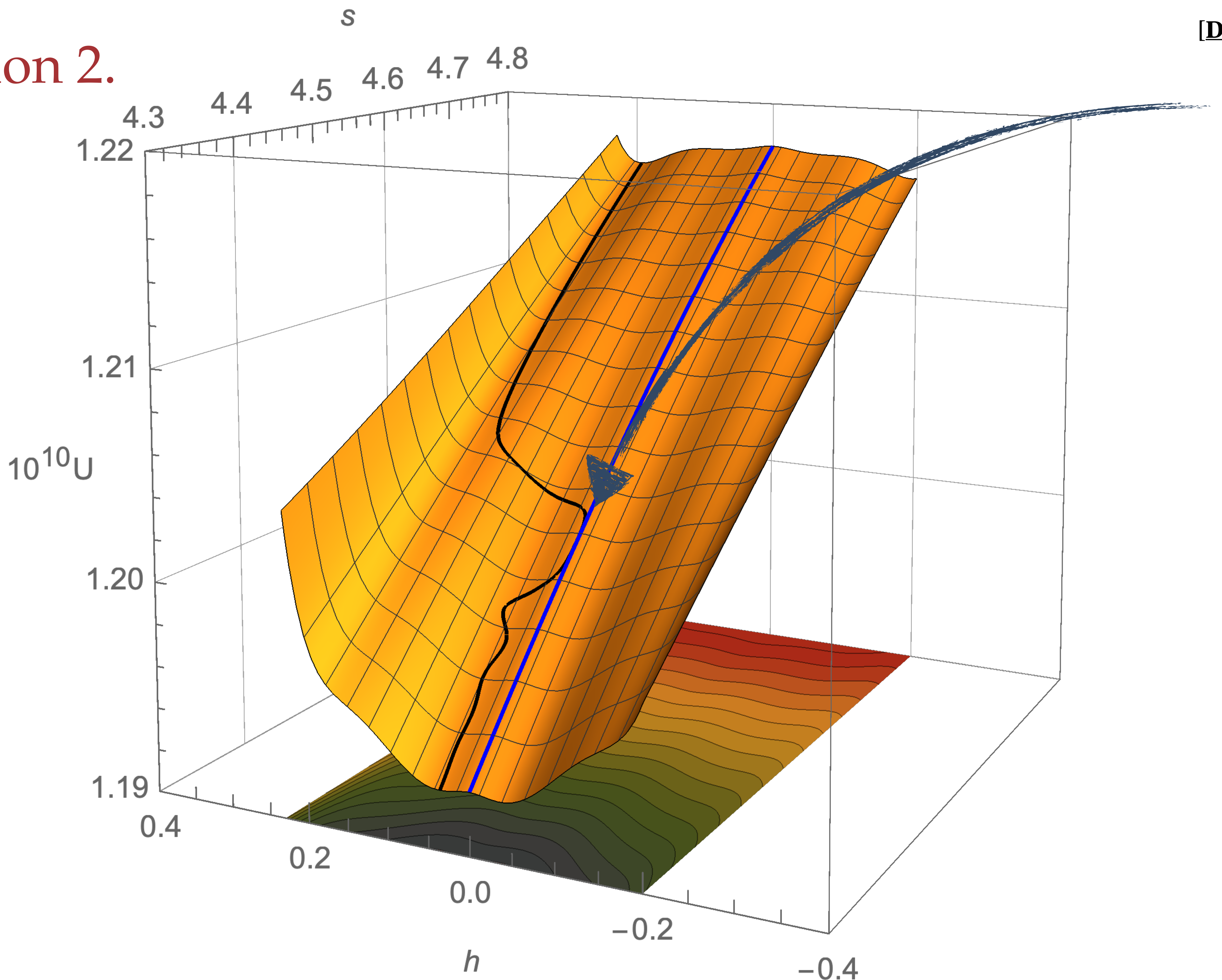
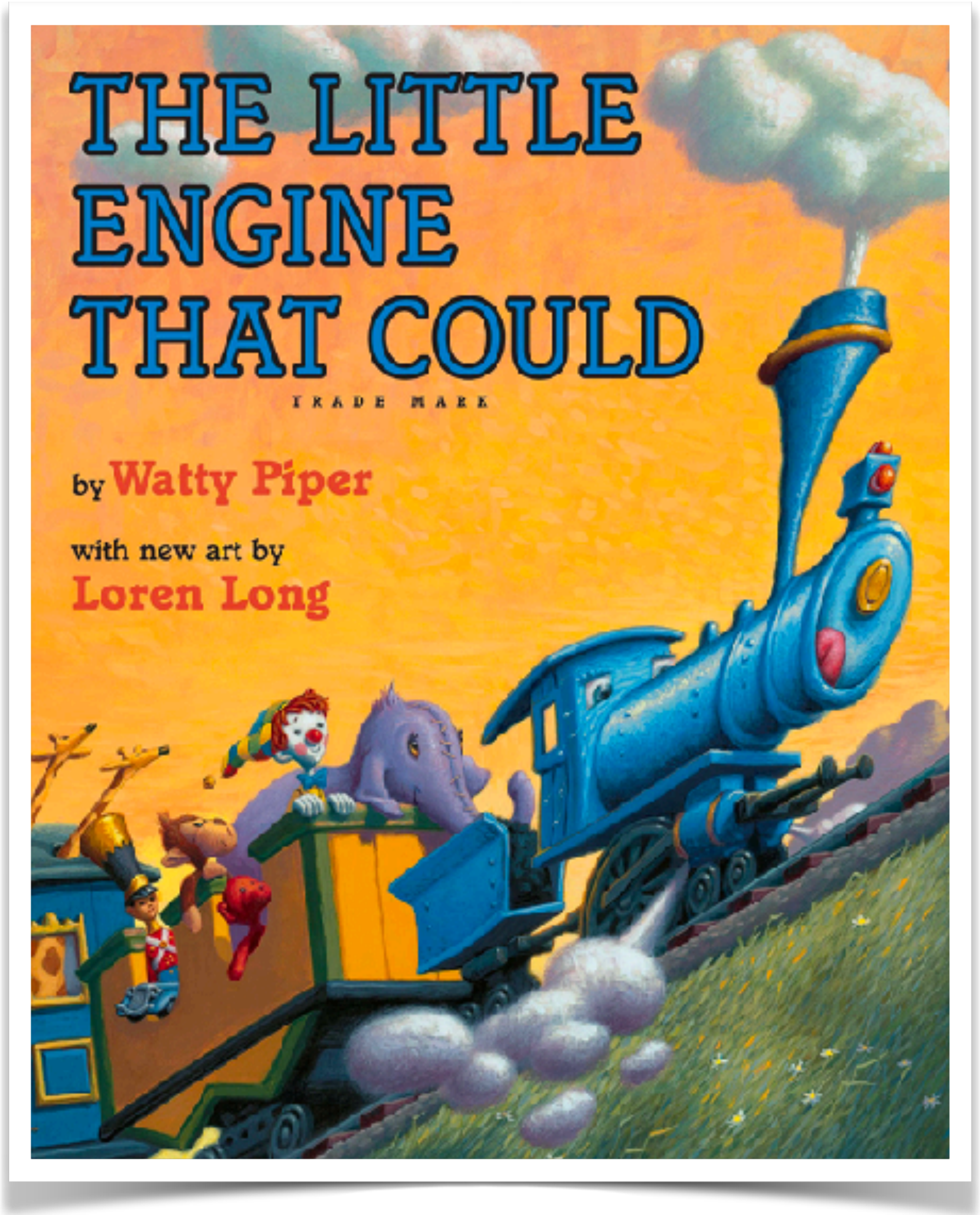


Inflaton *"approaching"* the $h = 0$ hill.



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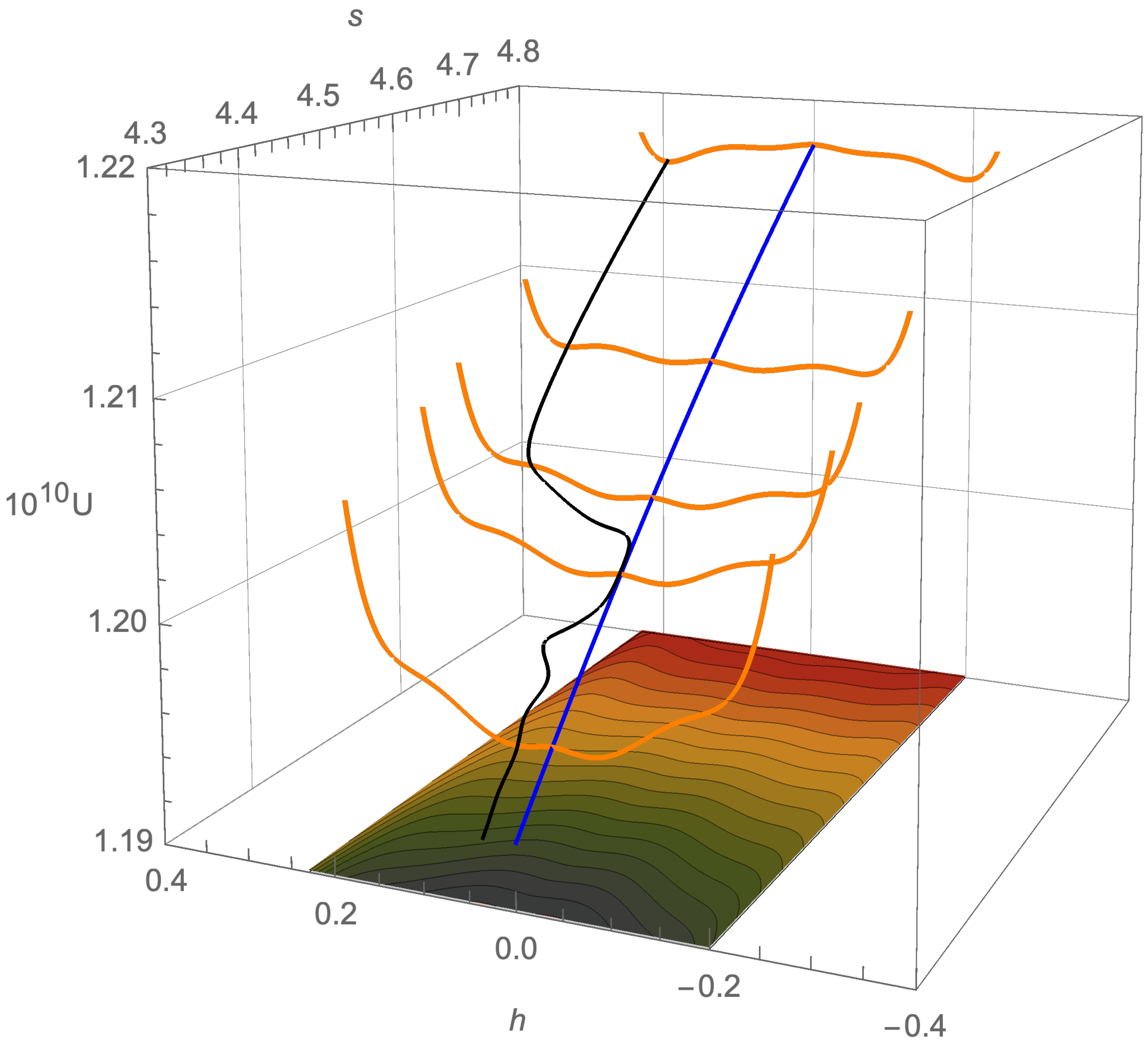

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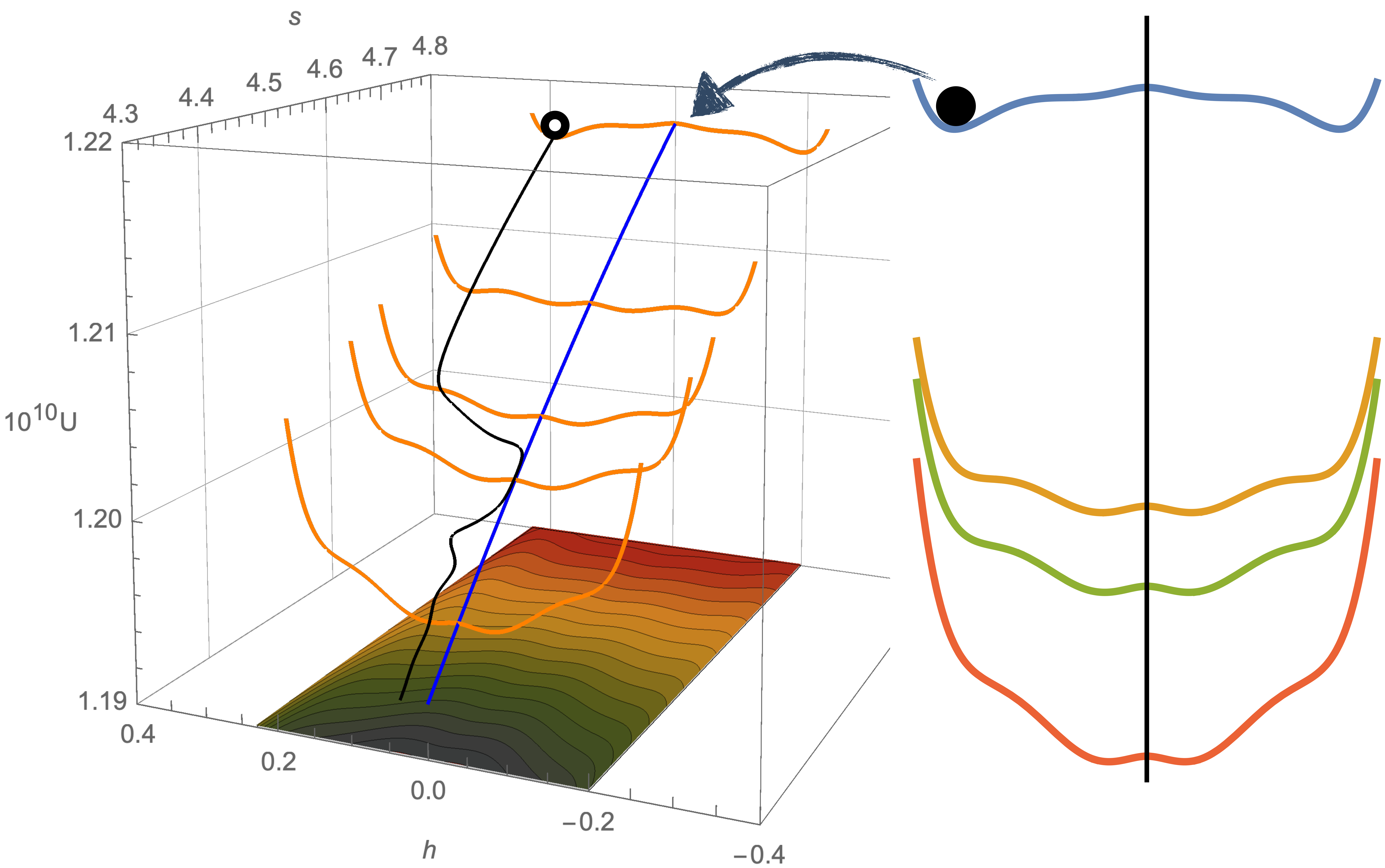

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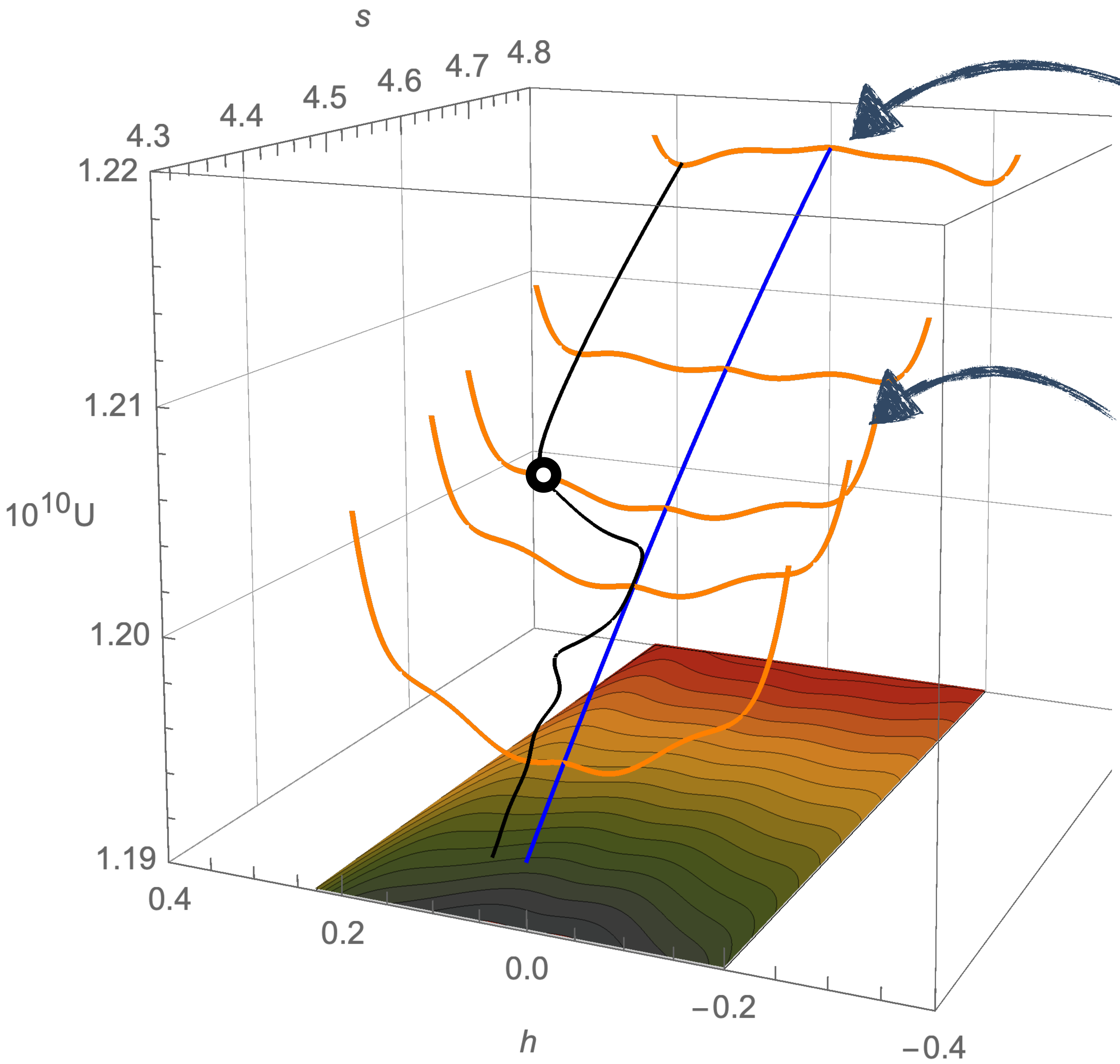

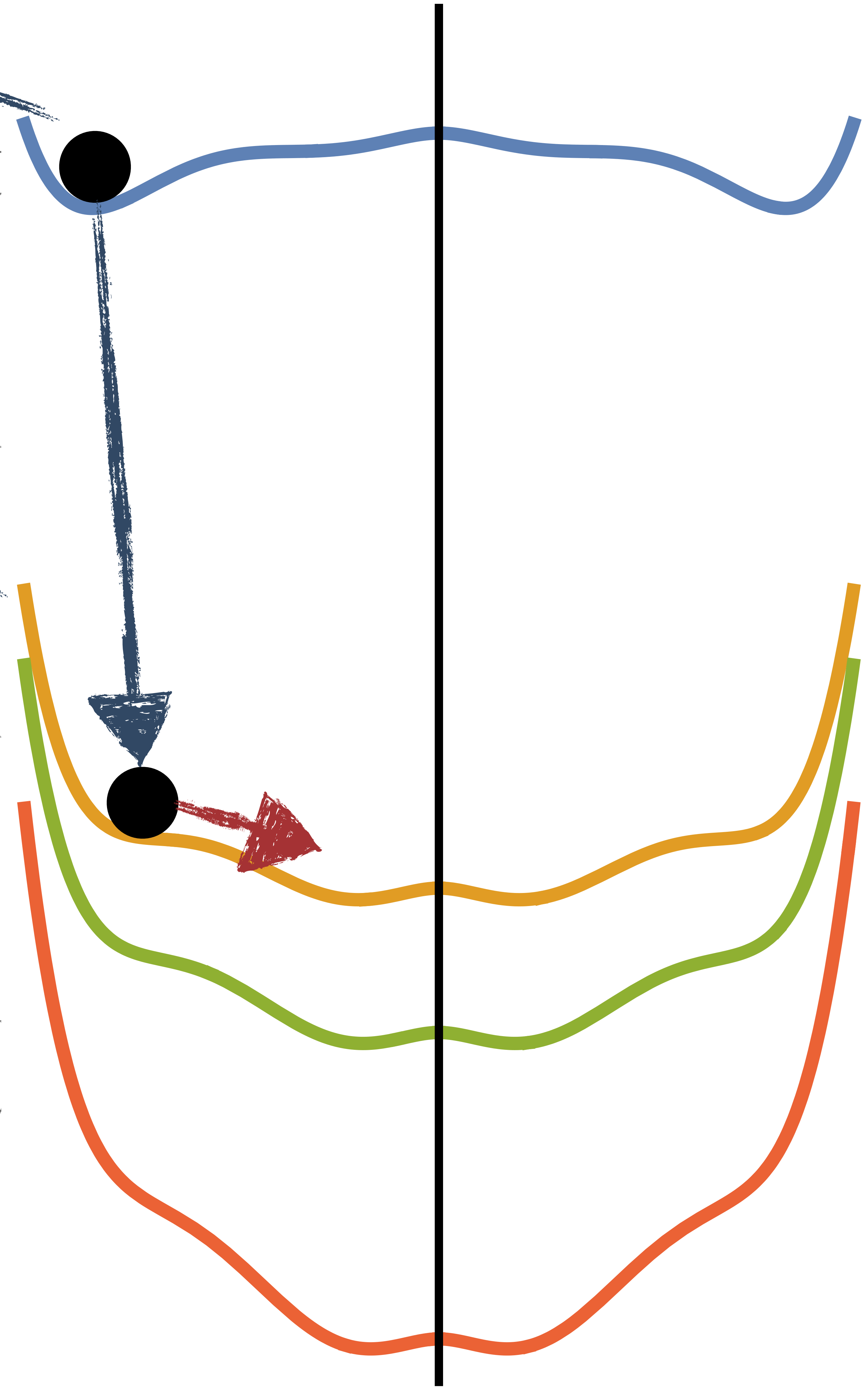

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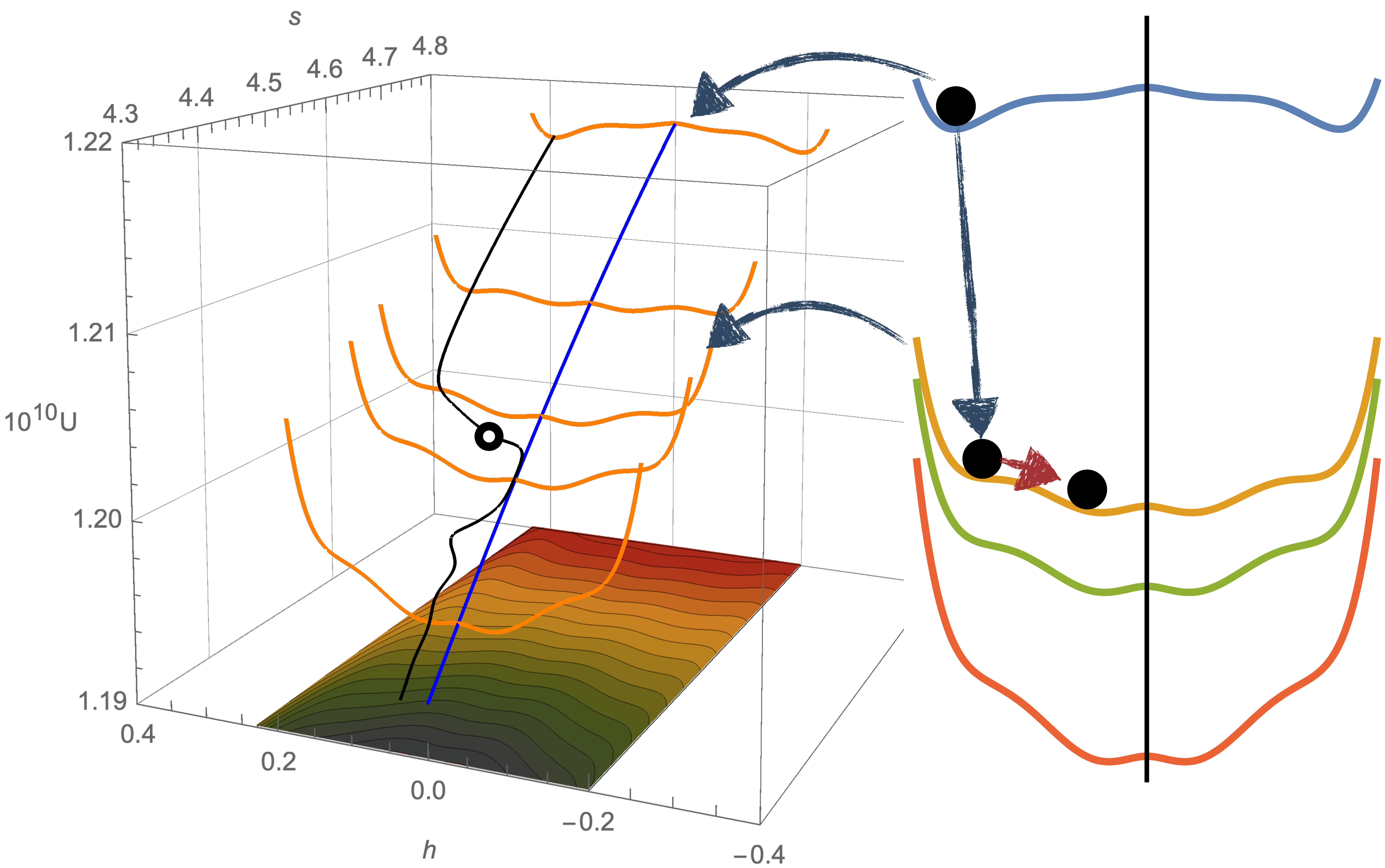

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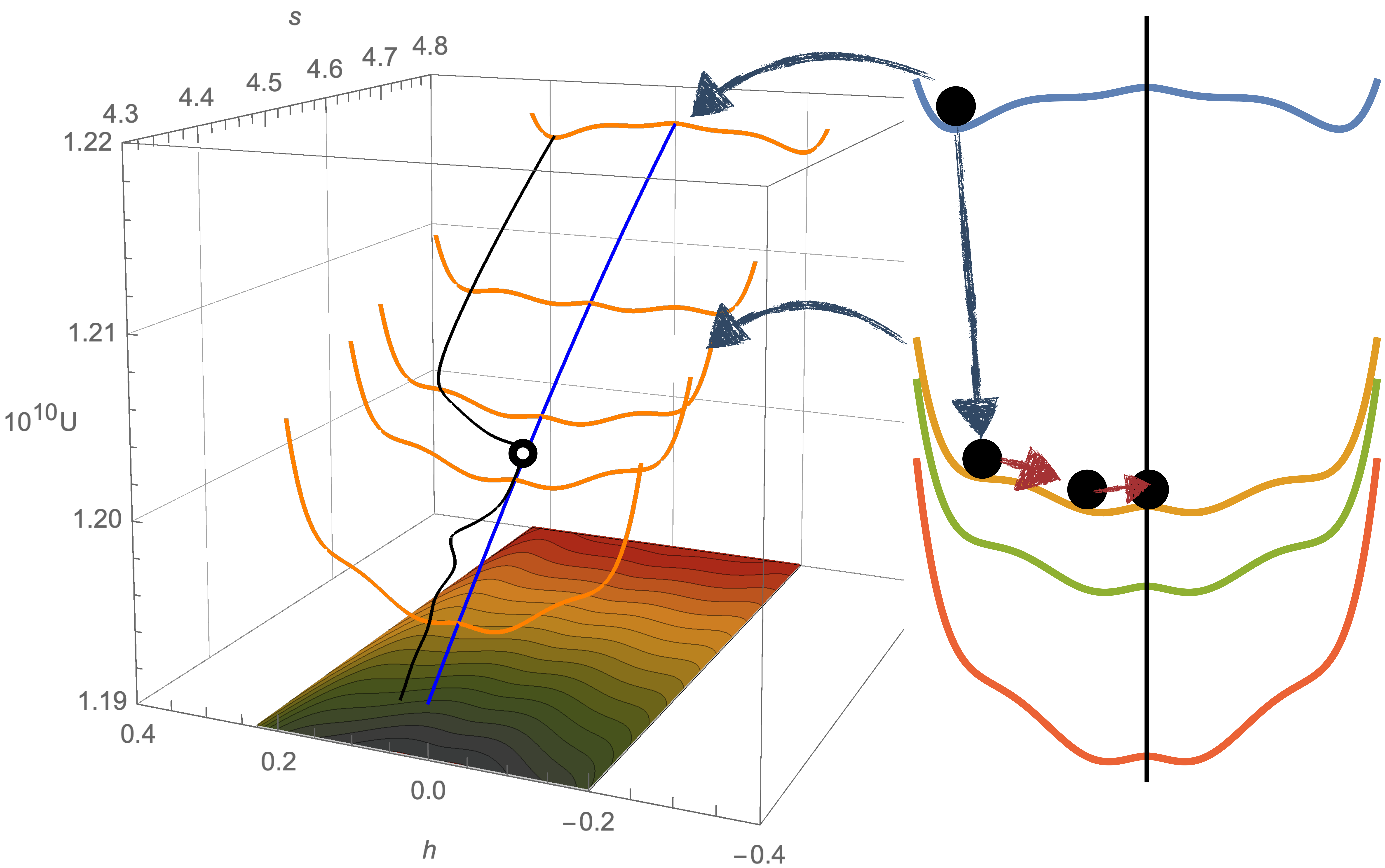

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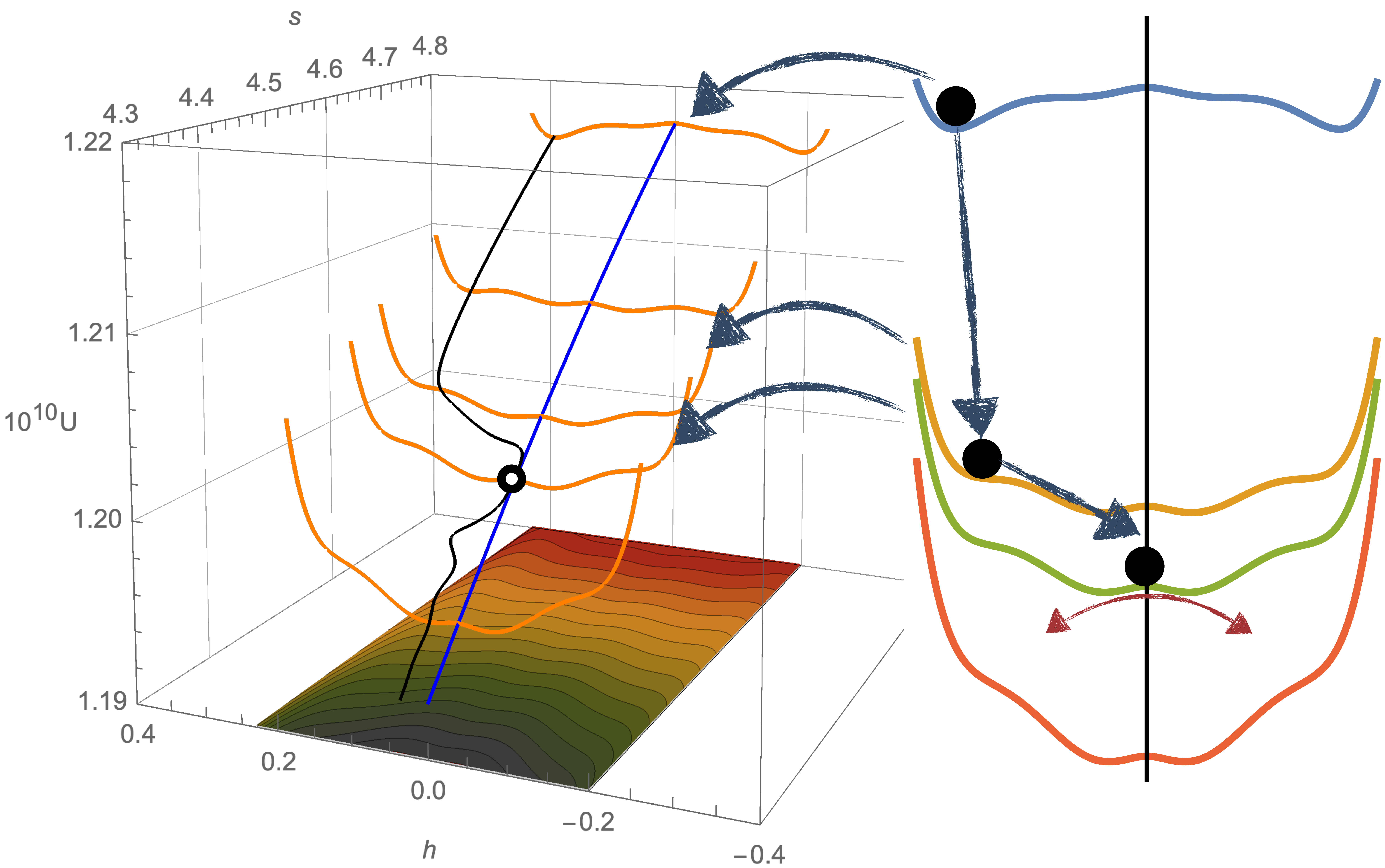

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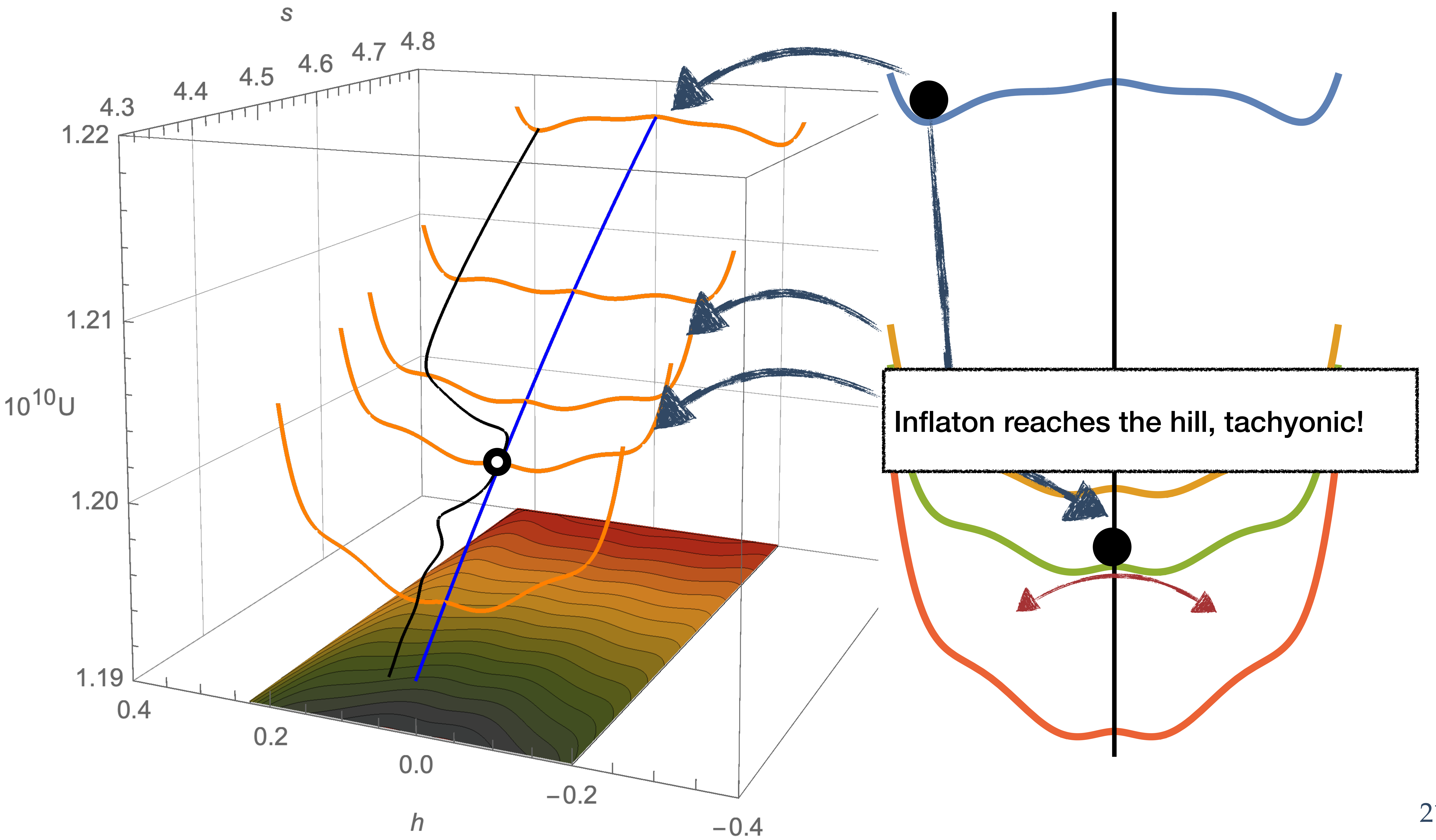

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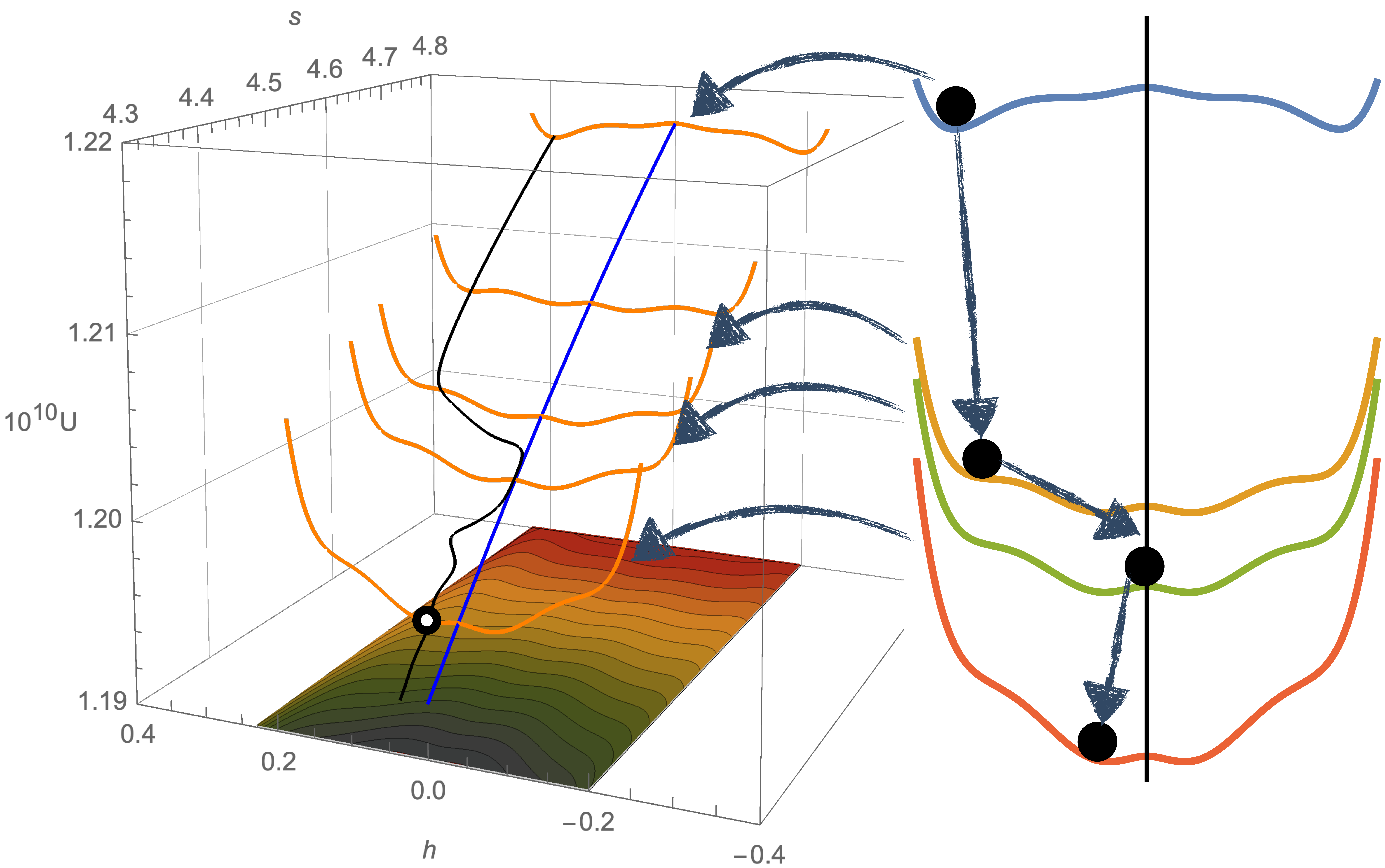


Higgs-R^2 Inflation, Perturbations

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

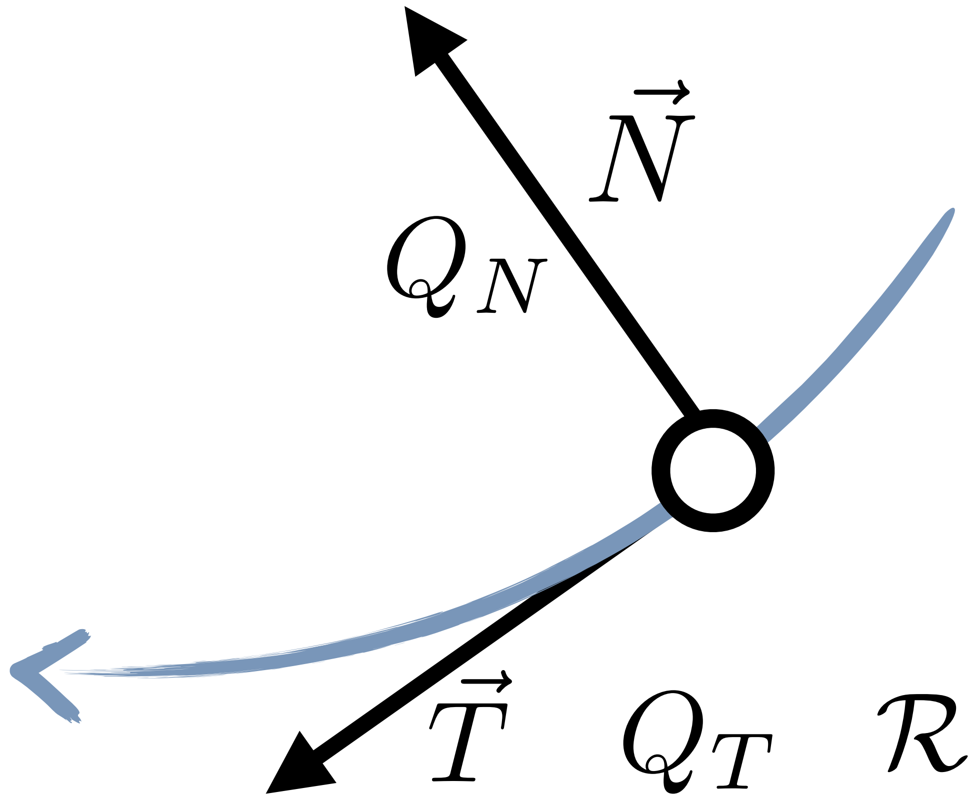
$$\ddot{\mathcal{R}} + (3 + 2\epsilon - 2\eta_\parallel) H\dot{\mathcal{R}} + \frac{k^2}{a^2}\mathcal{R} = -2\frac{H^2}{\dot{\phi}_0}\eta_\perp \left[\dot{Q}_N + \left(3 - \eta_\parallel + \frac{\dot{\eta}_\perp}{H\eta_\perp}\right) HQ_N\right]$$

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

[S. Cespedes et. al, JCAP 05 (2012) 008]
[A. Achucarro et. al, Phys. Rev. D86 (2012) 121301]
[S. Groot Nibbelink and B.J.W. van Tent , Class. Quant. Grav. 19 (2002) 613]
and many more…

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

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



$\mathcal{R} = \frac{H}{\dot{\phi}_0}Q_T$

- $M_{\rm eff}^2 < 0$ leads to *tachyonic growth of Q_N*, then gets *sourced to $\mathcal{R}$* through *turns in the trajectory.*
- Tachyonic mass at the *"hill"* of the potential at $h = 0$, $M_{\rm eff}^2 \simeq -3M^2\xi\left(1 - e^{-\sqrt{\frac{2}{3}}s}\right)$

Higgs-R^2 Inflation, Perturbations

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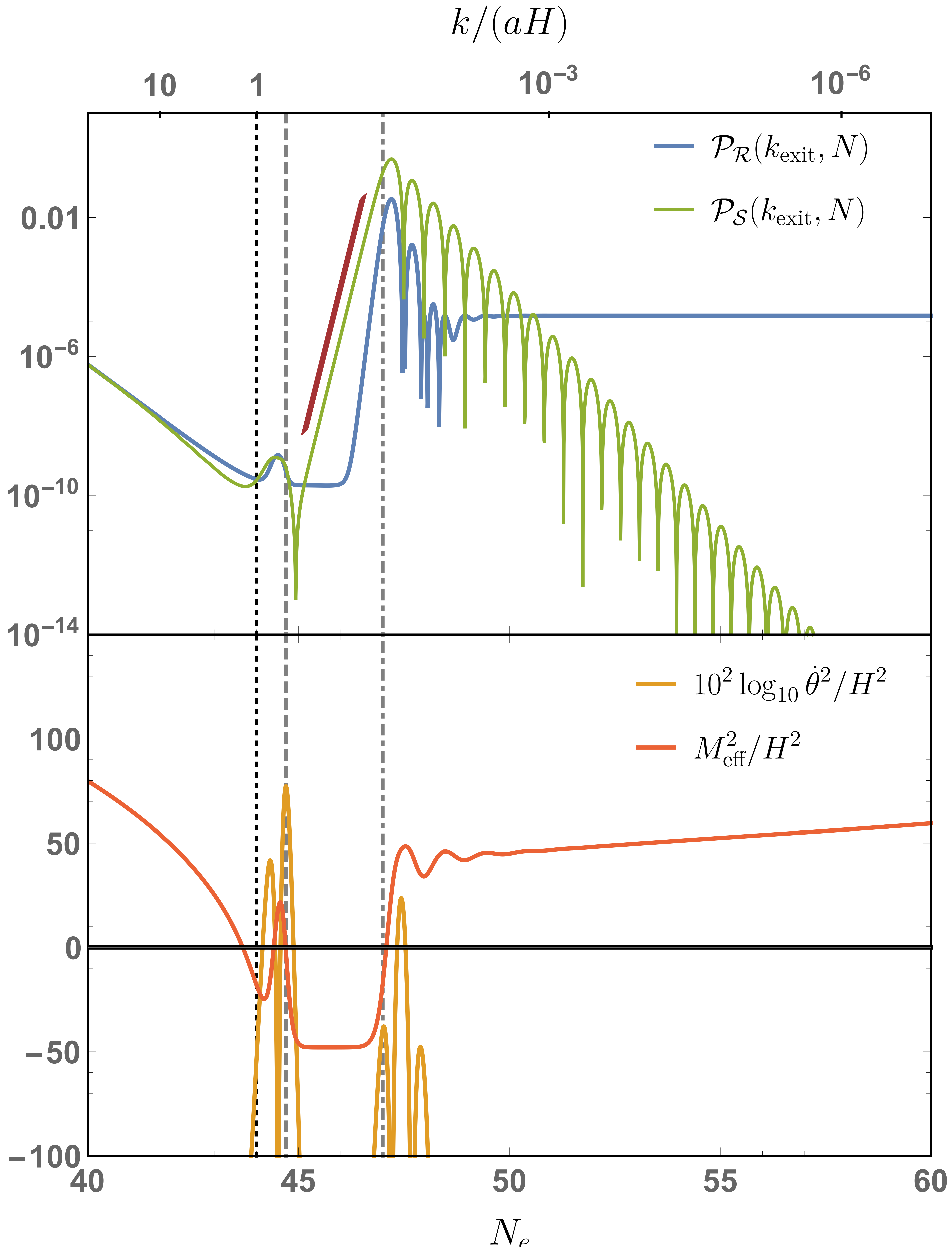

Higgs-R^2 Inflation, Perturbations

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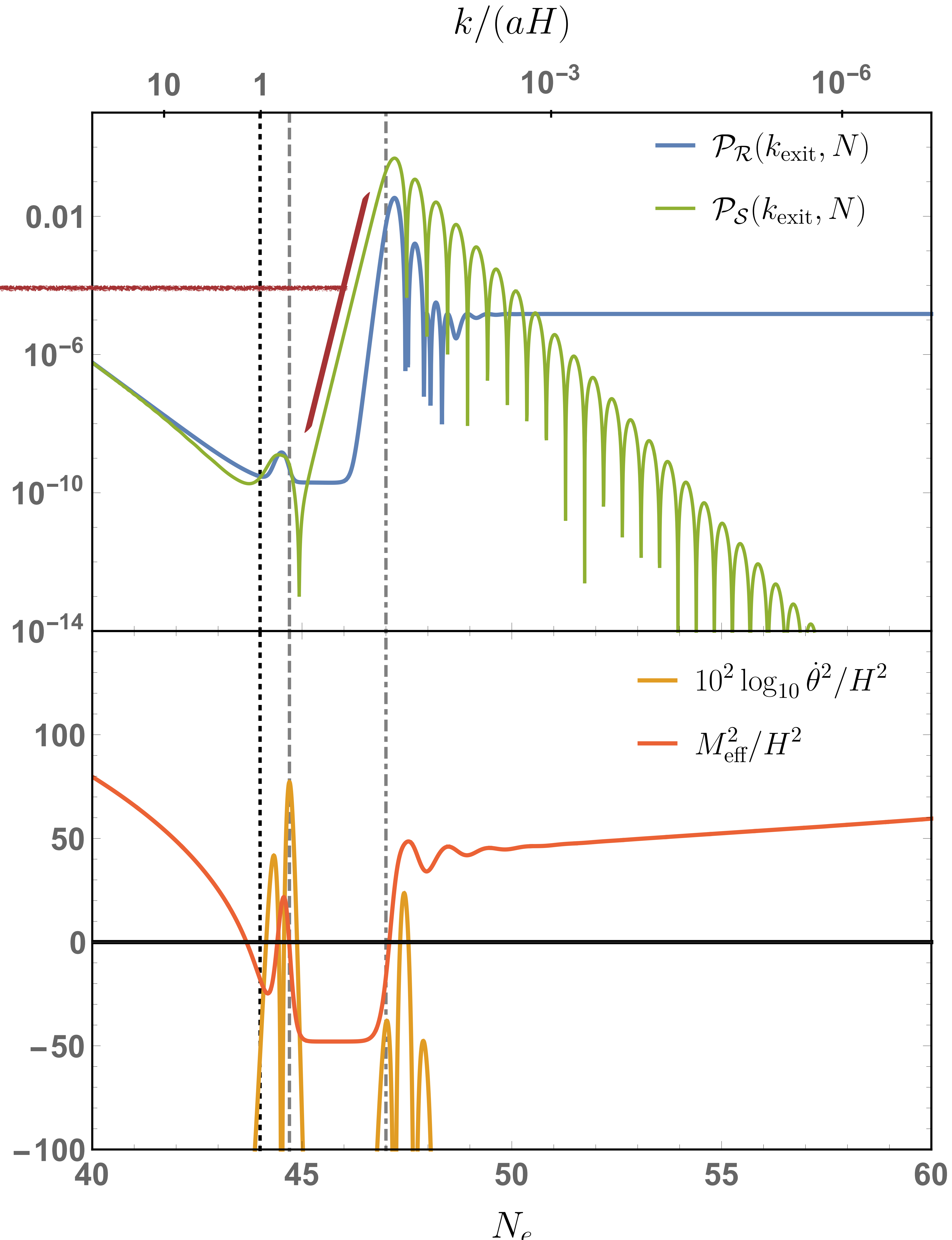
$$\mathcal{P}_{\mathcal{S}} \propto \exp\left[\left(\frac{2|M_{\rm eff}|}{H} - 3\right) N_e\right]$$



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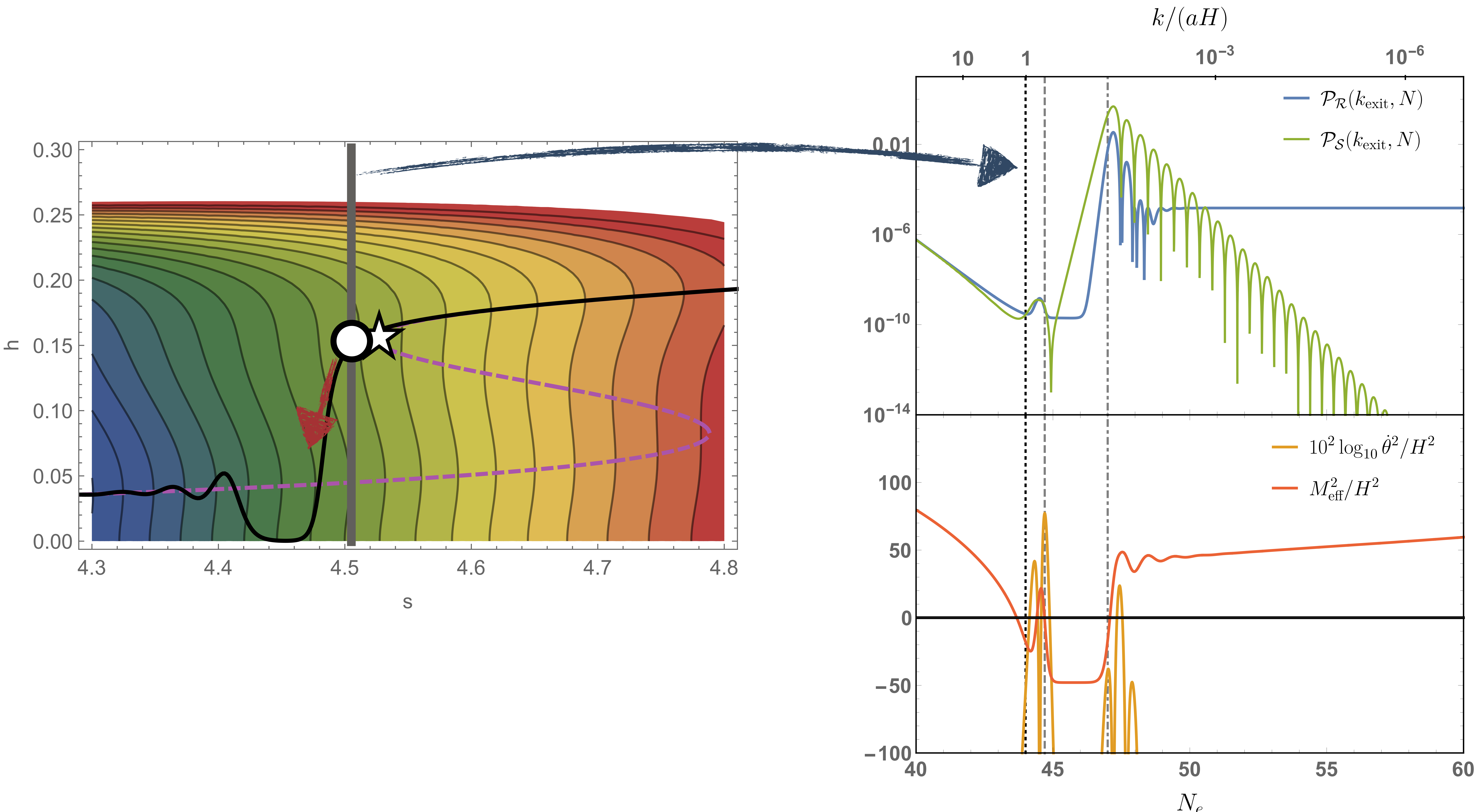

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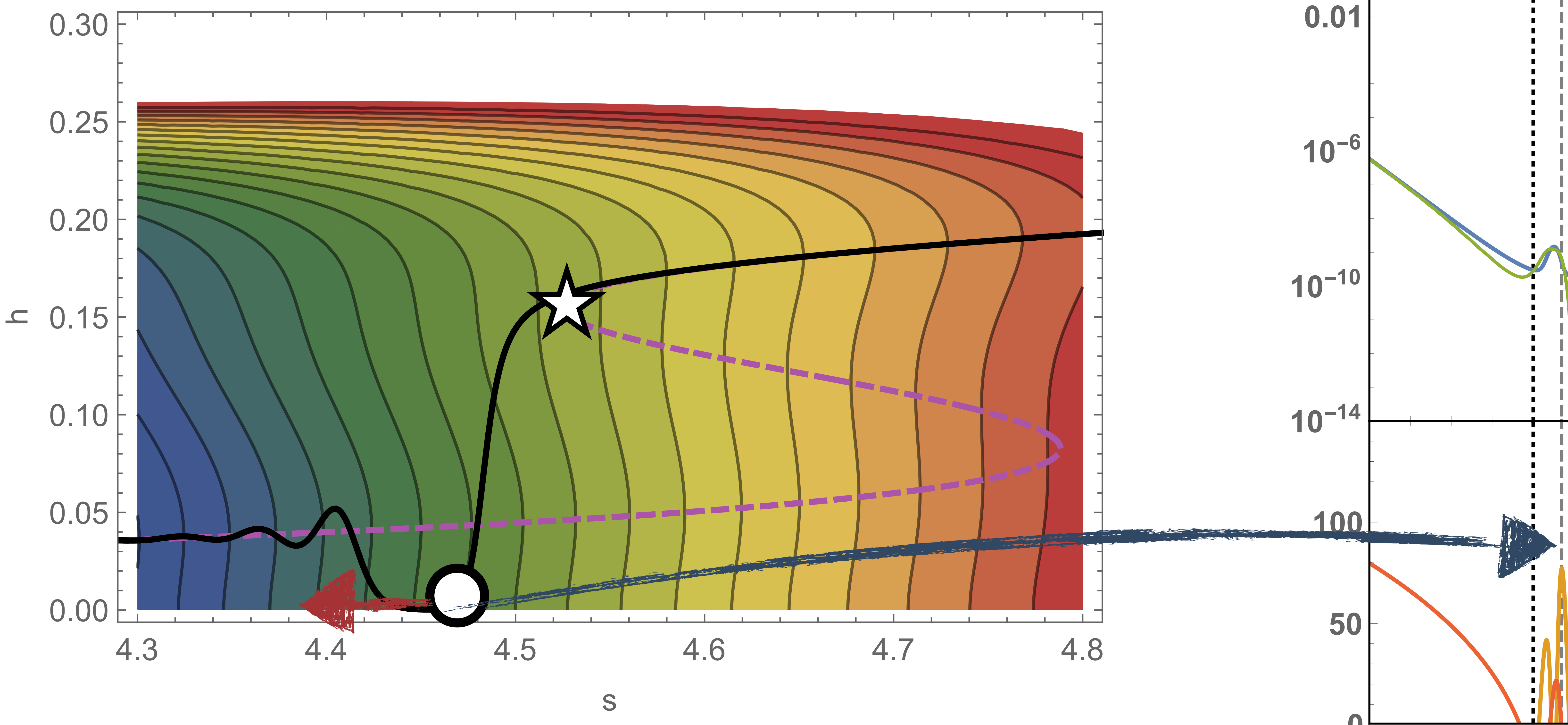

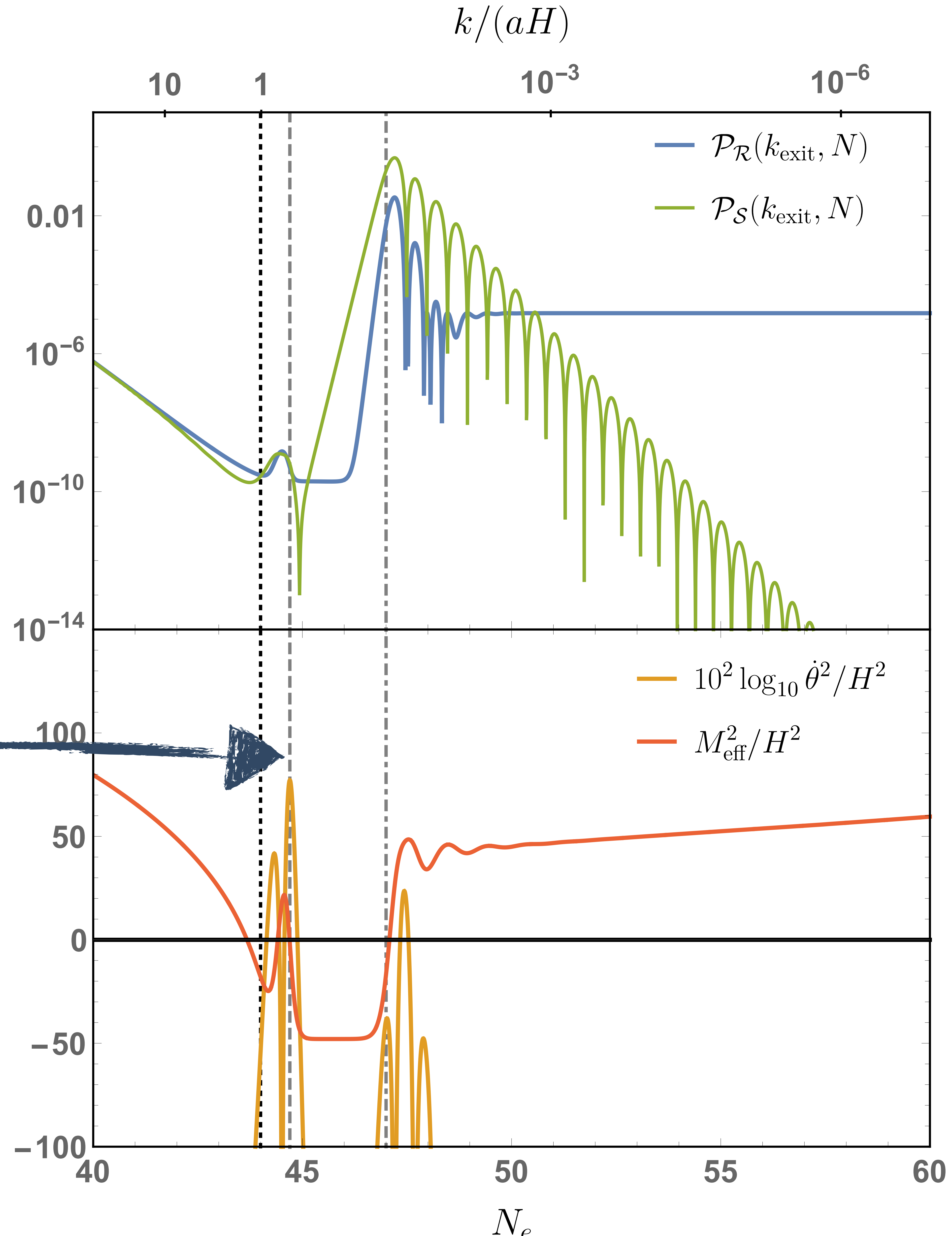

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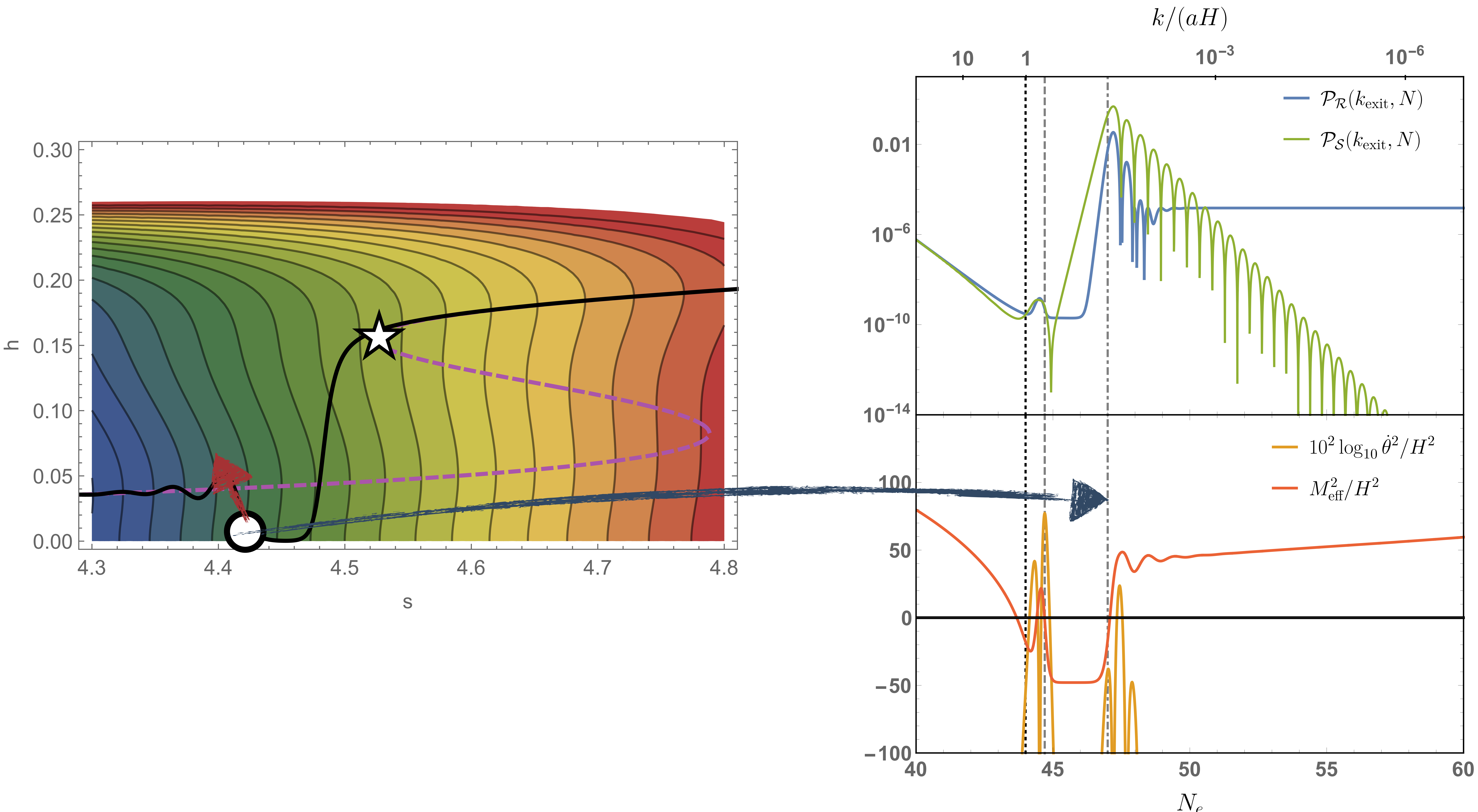

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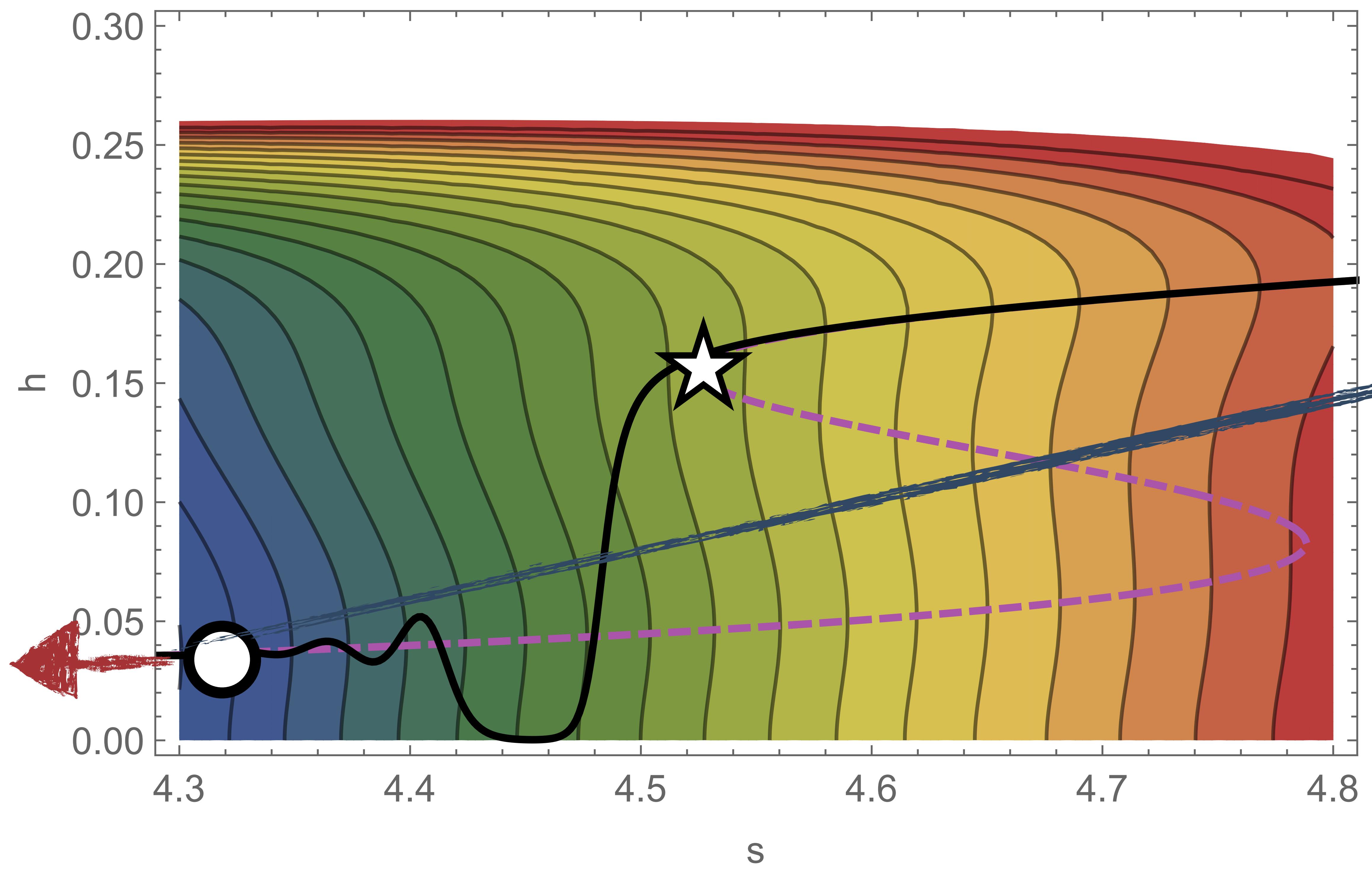

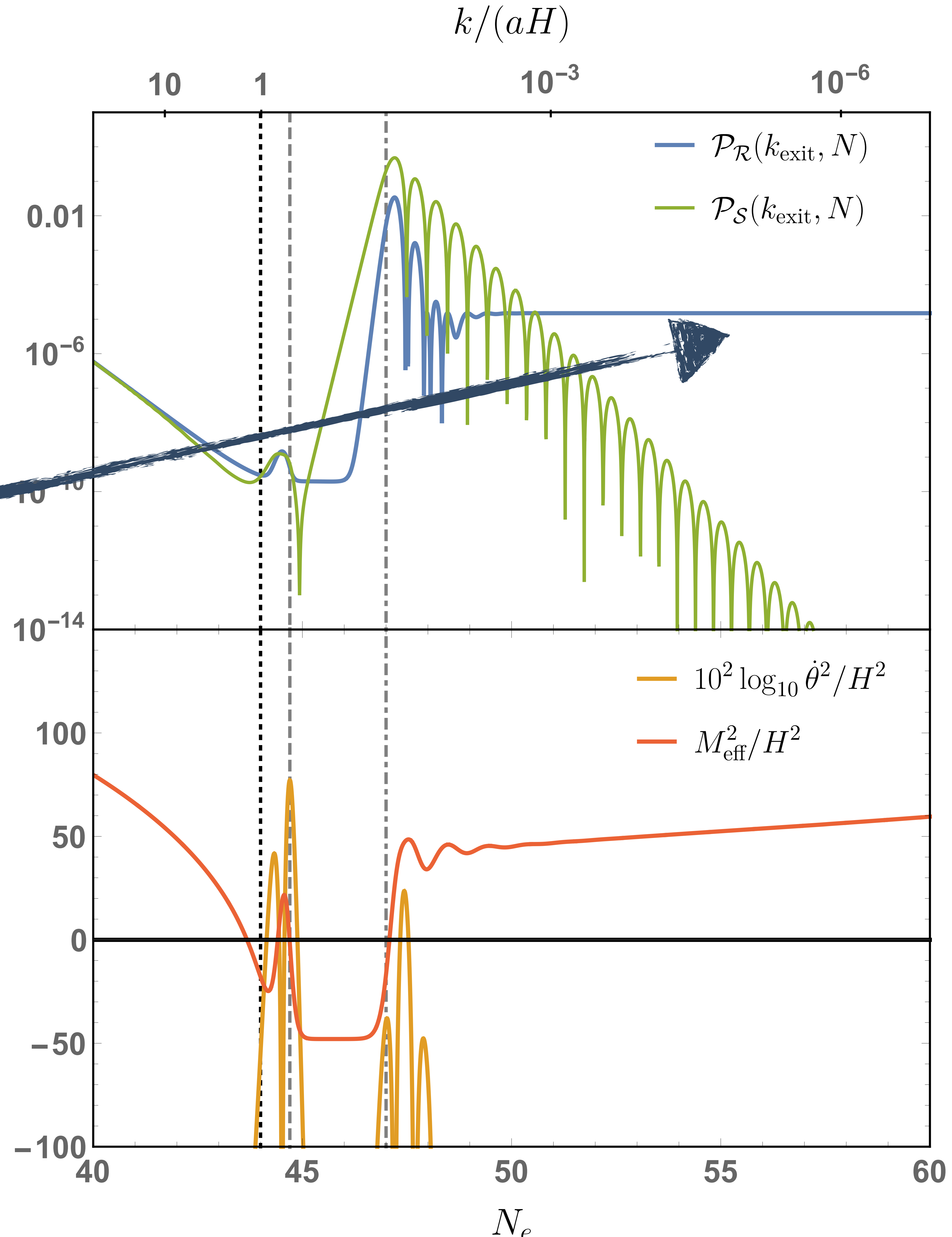

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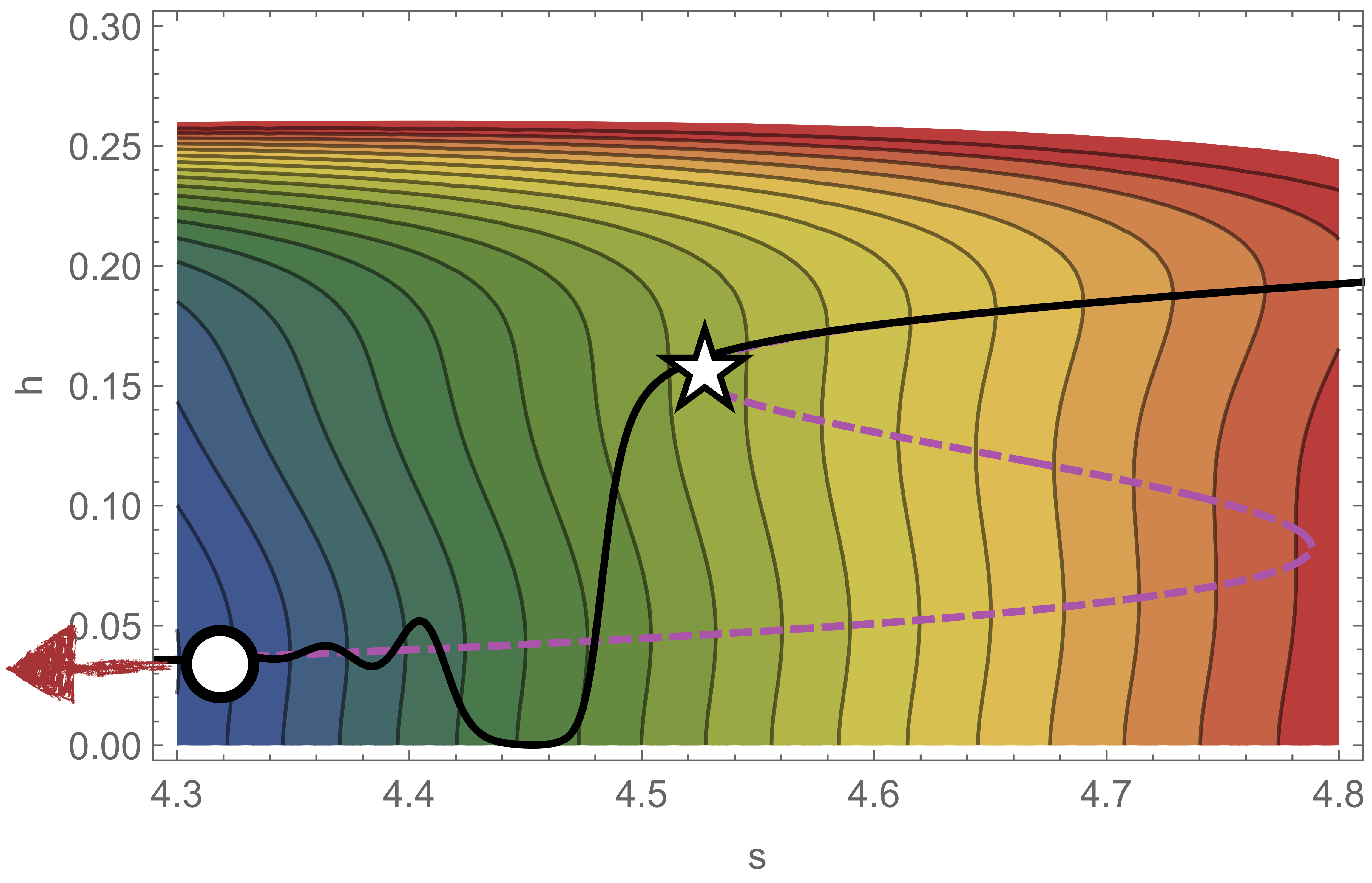

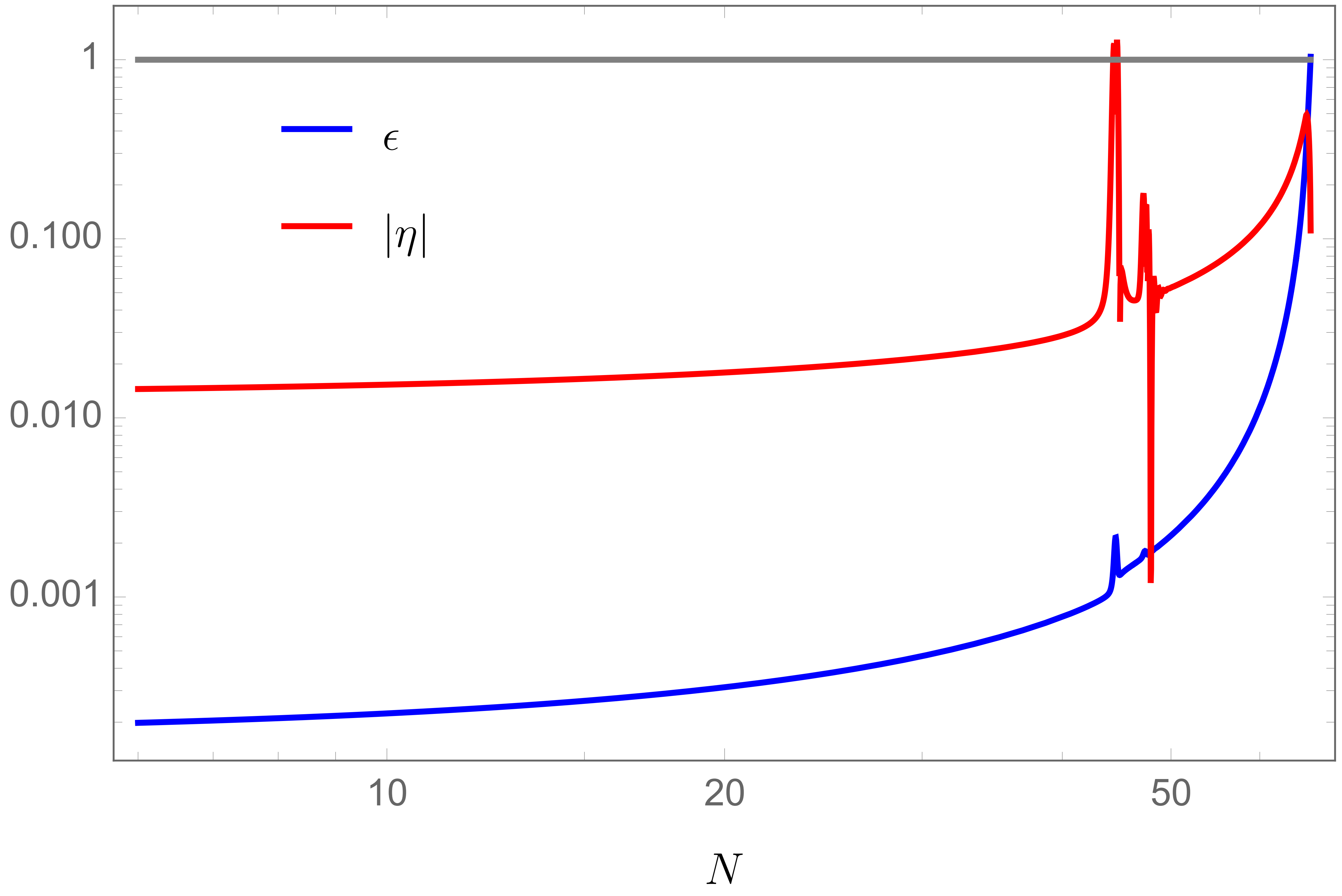

Higgs-R^2 Inflation, Power Spectrum

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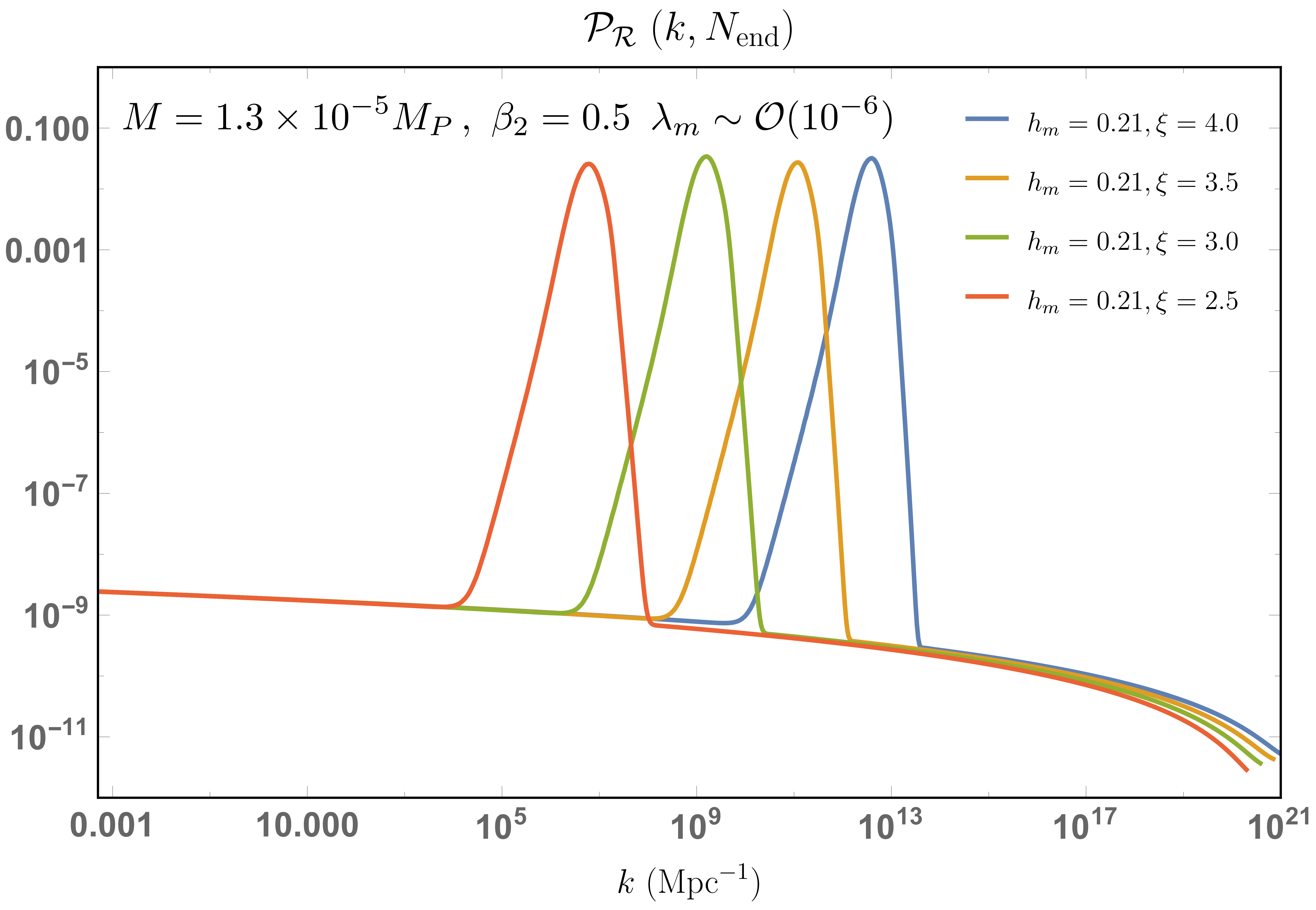

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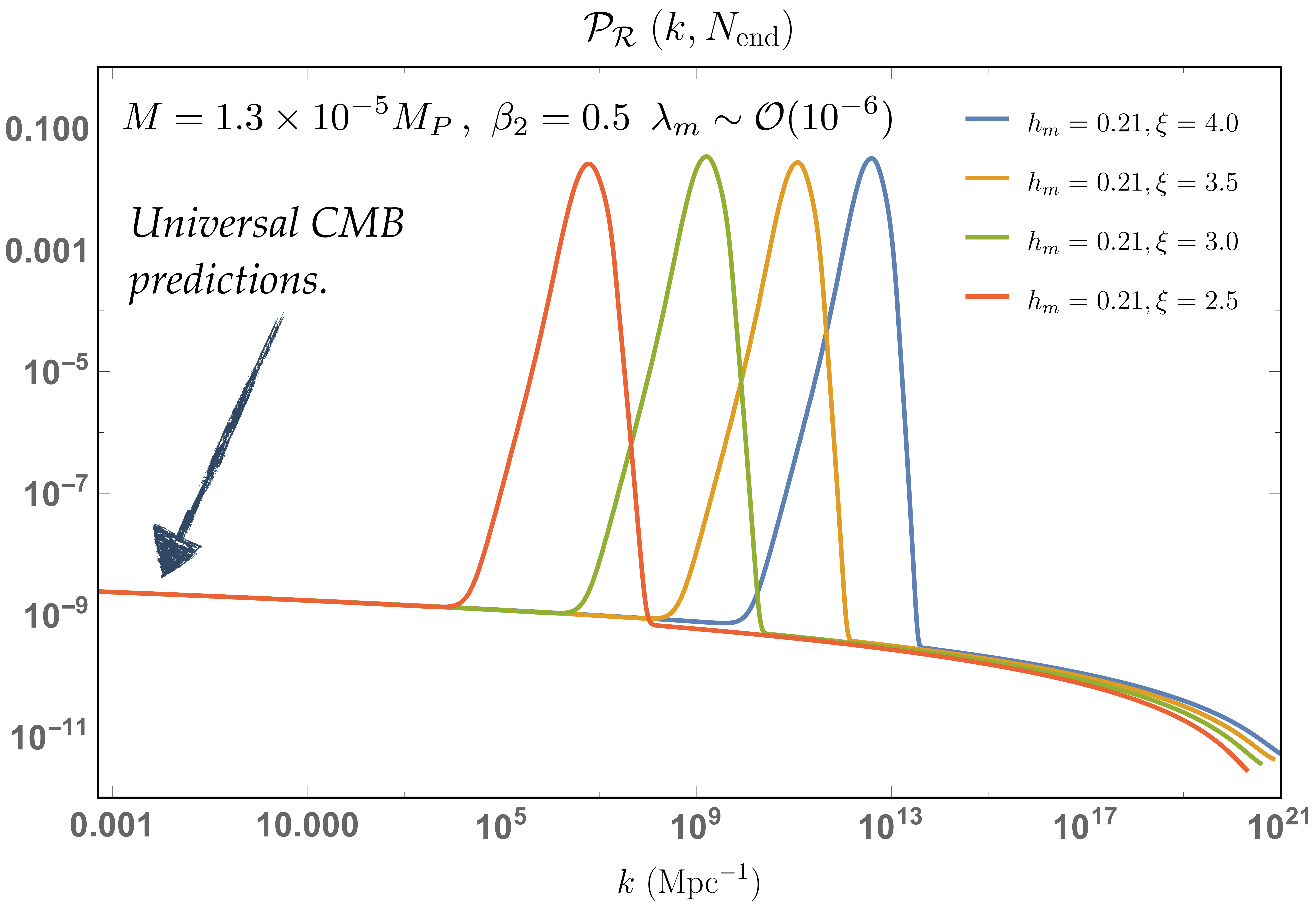

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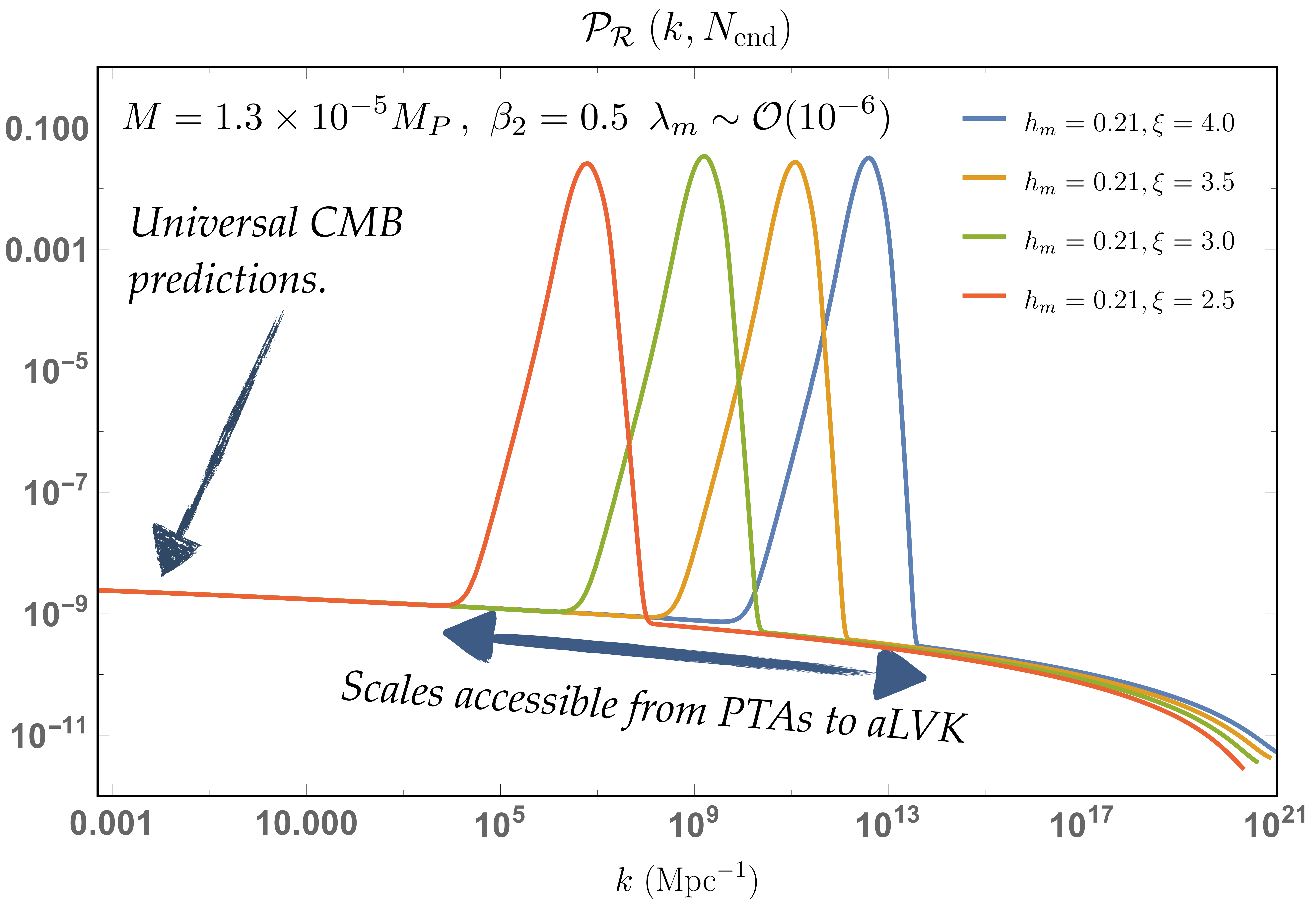
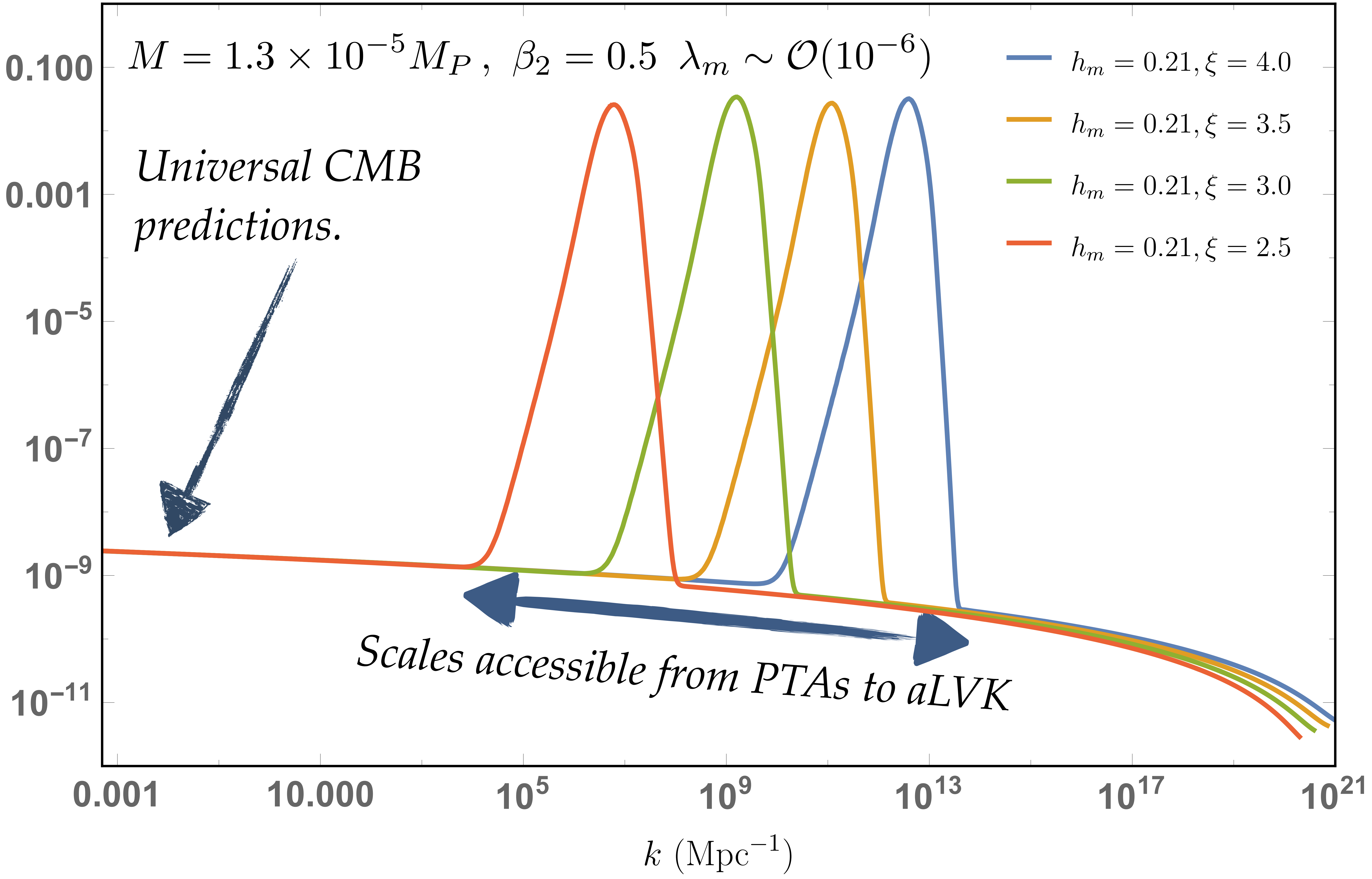


Higgs-R^2 Inflation, Power Spectrum

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



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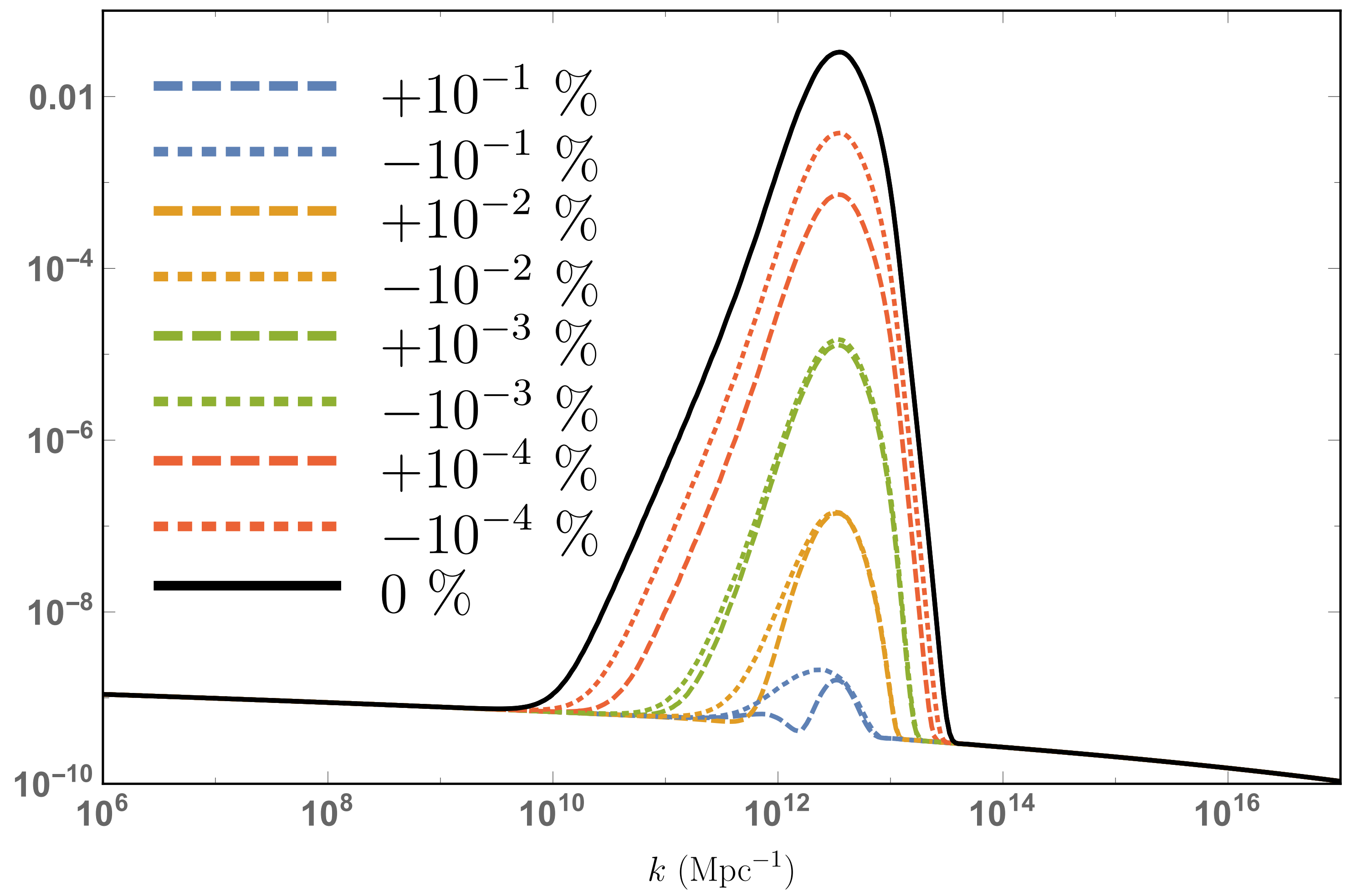

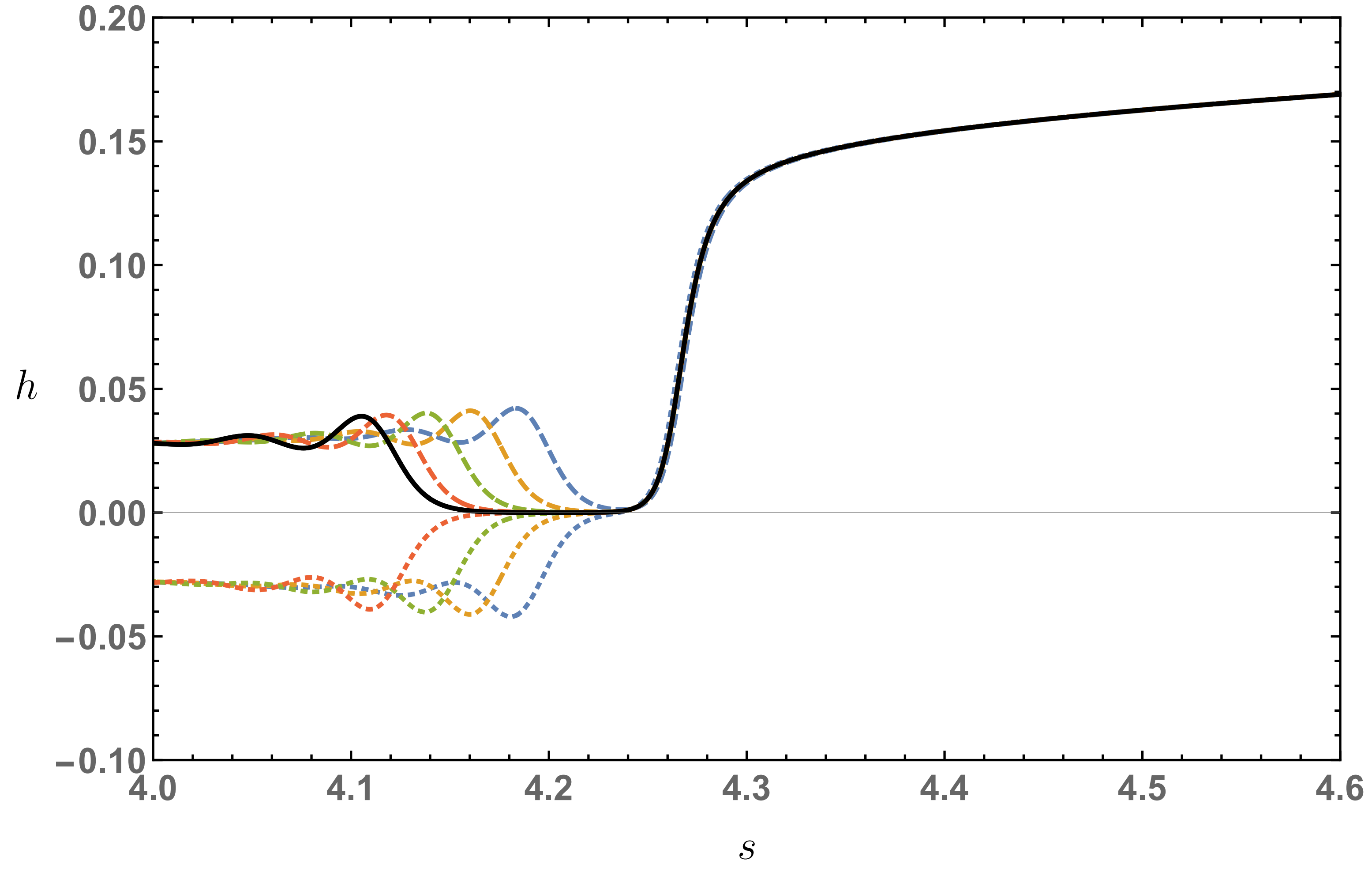

$$\frac{\delta\lambda_m}{\lambda_m} \equiv \frac{\lambda_m^{dev} - \lambda_m}{\lambda_m} \sim 10^{-4}\%$$

Phenomena — Primordial Black Holes

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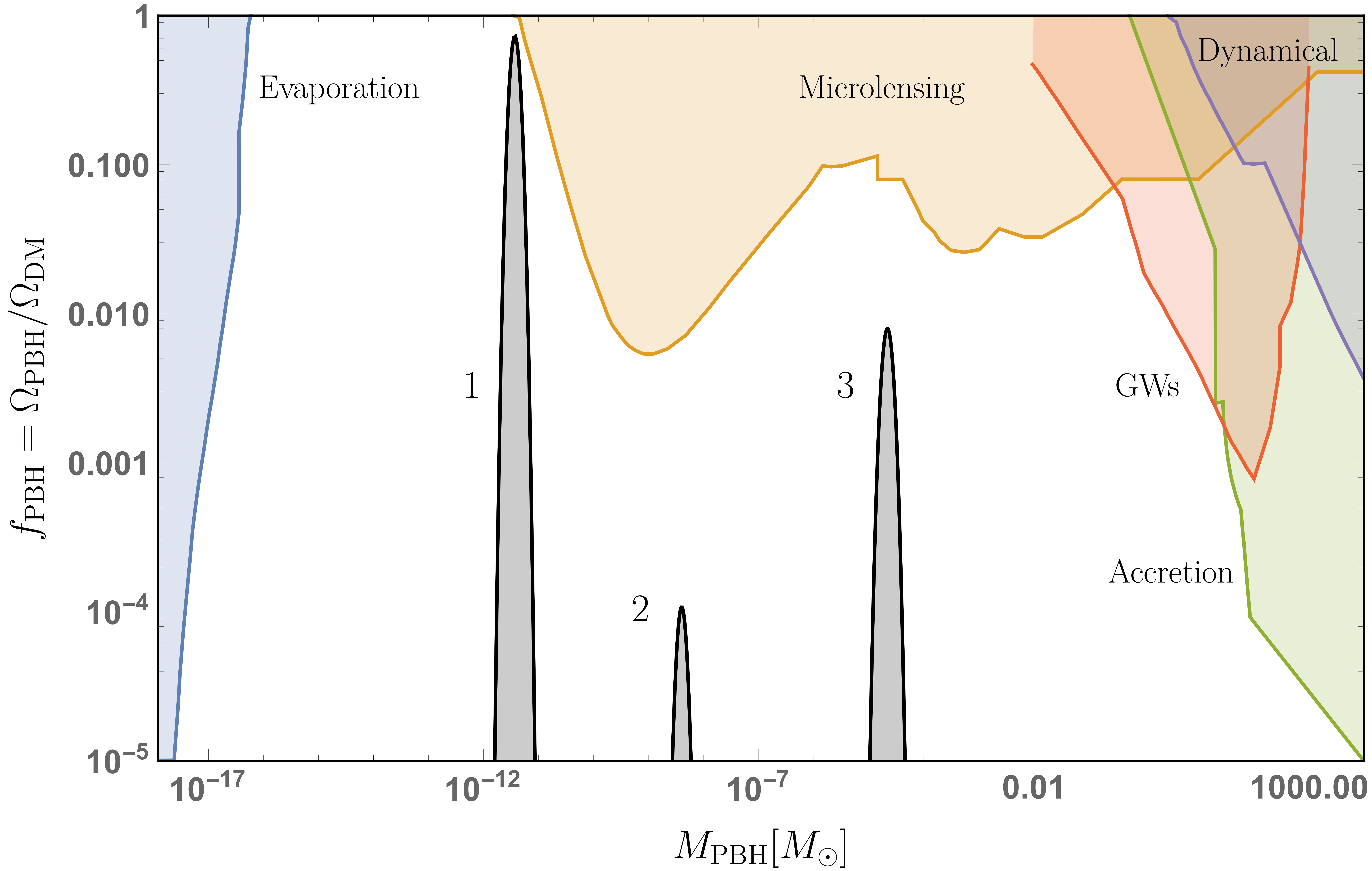
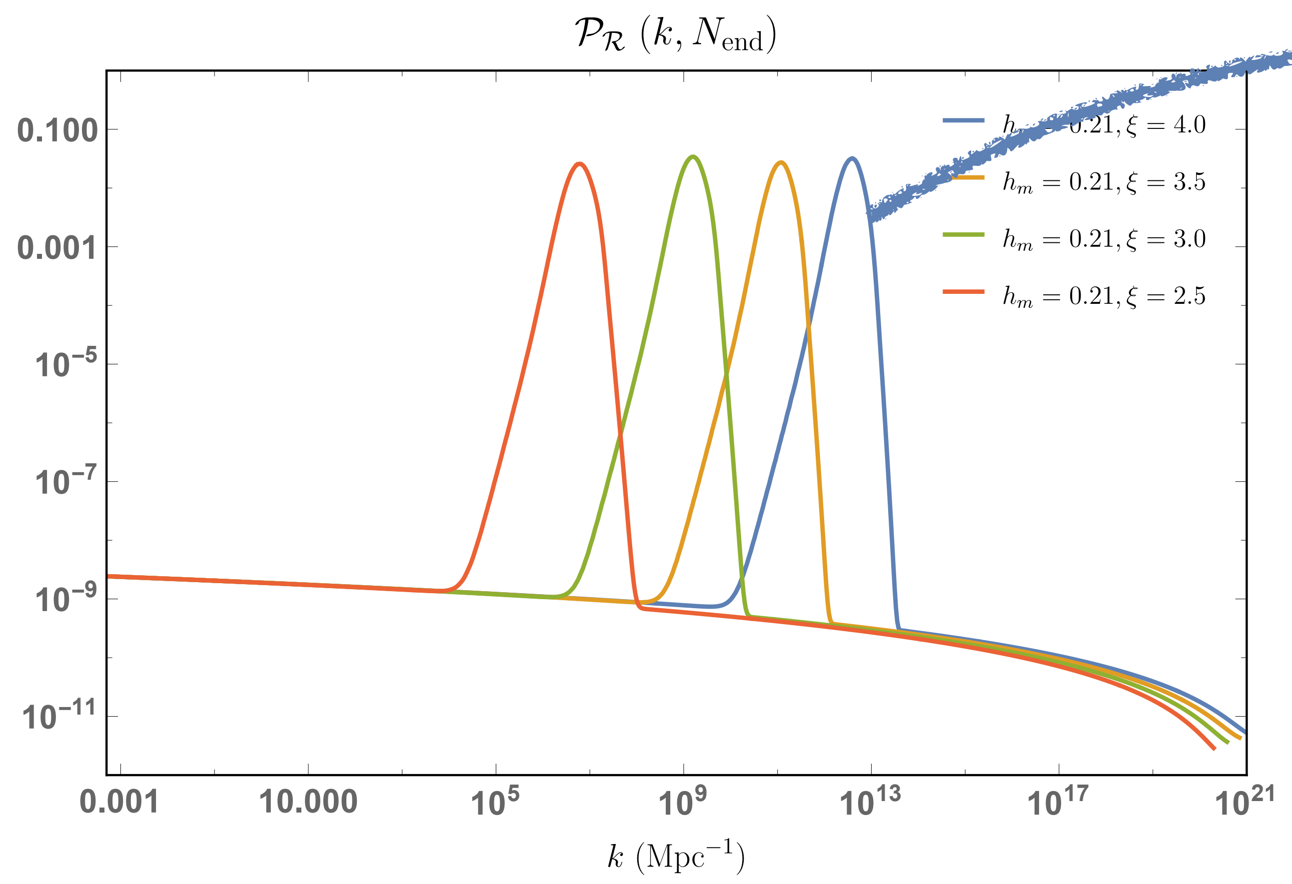


Phenomena — Primordial Black Holes



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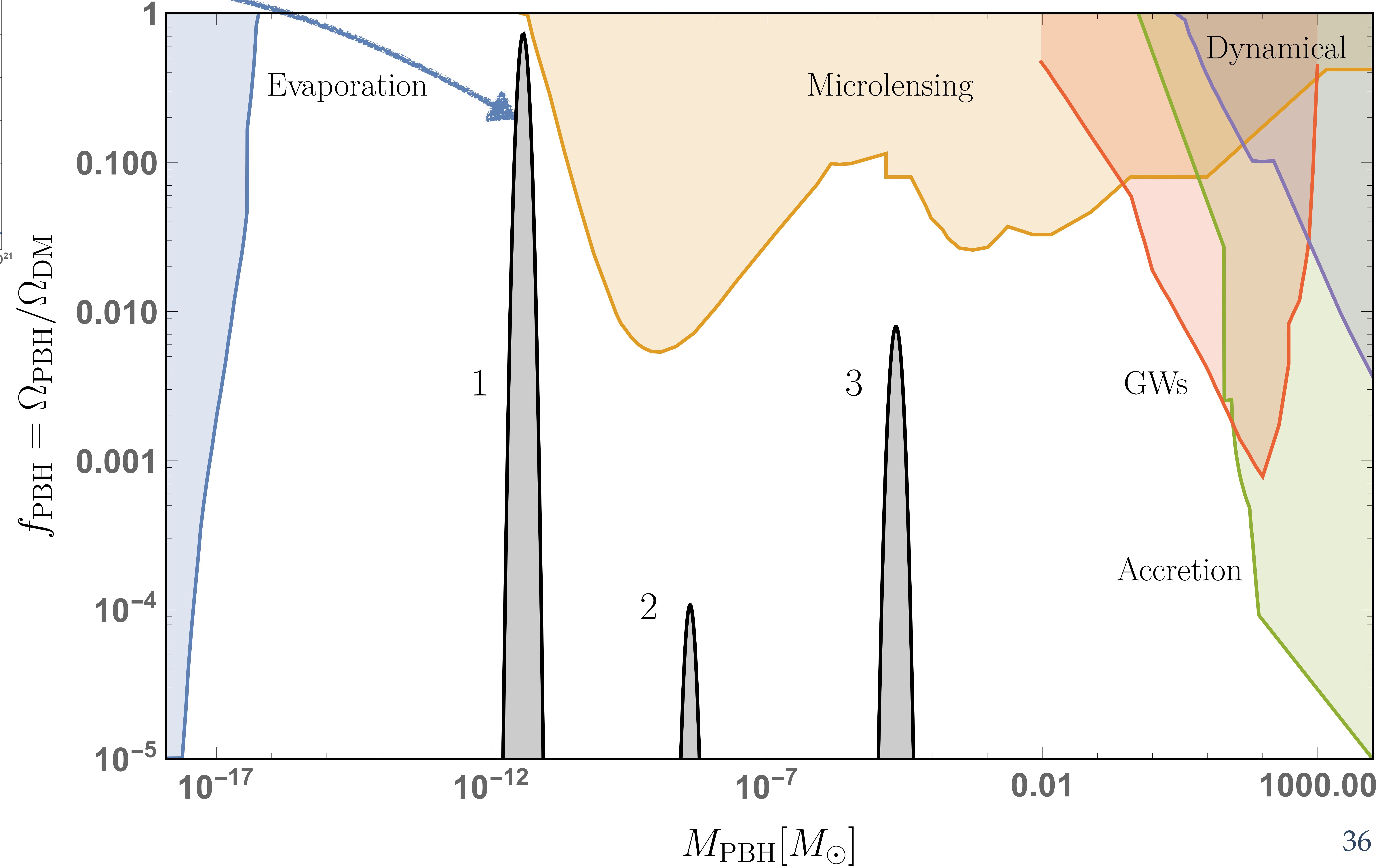

Phenomena — Primordial Black Holes

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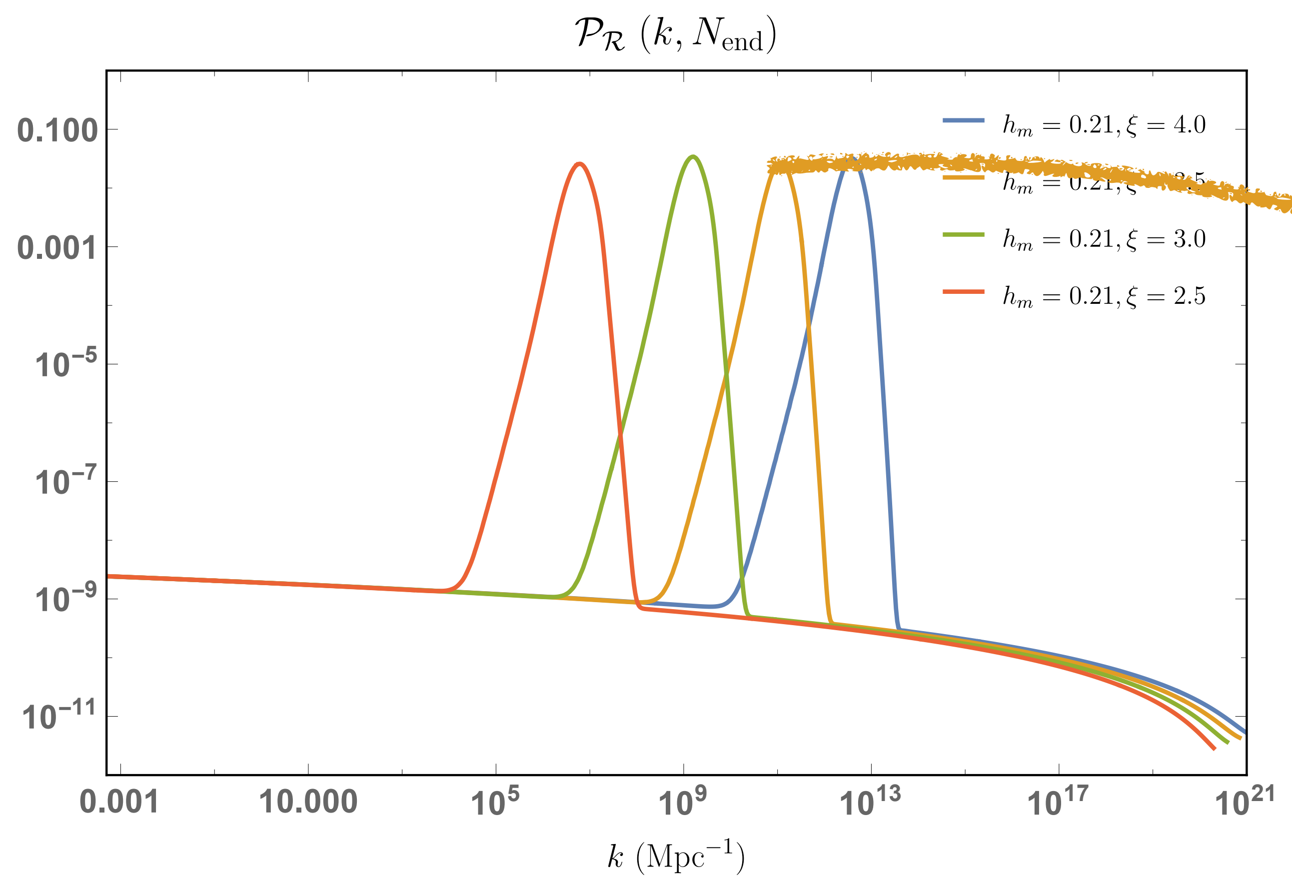

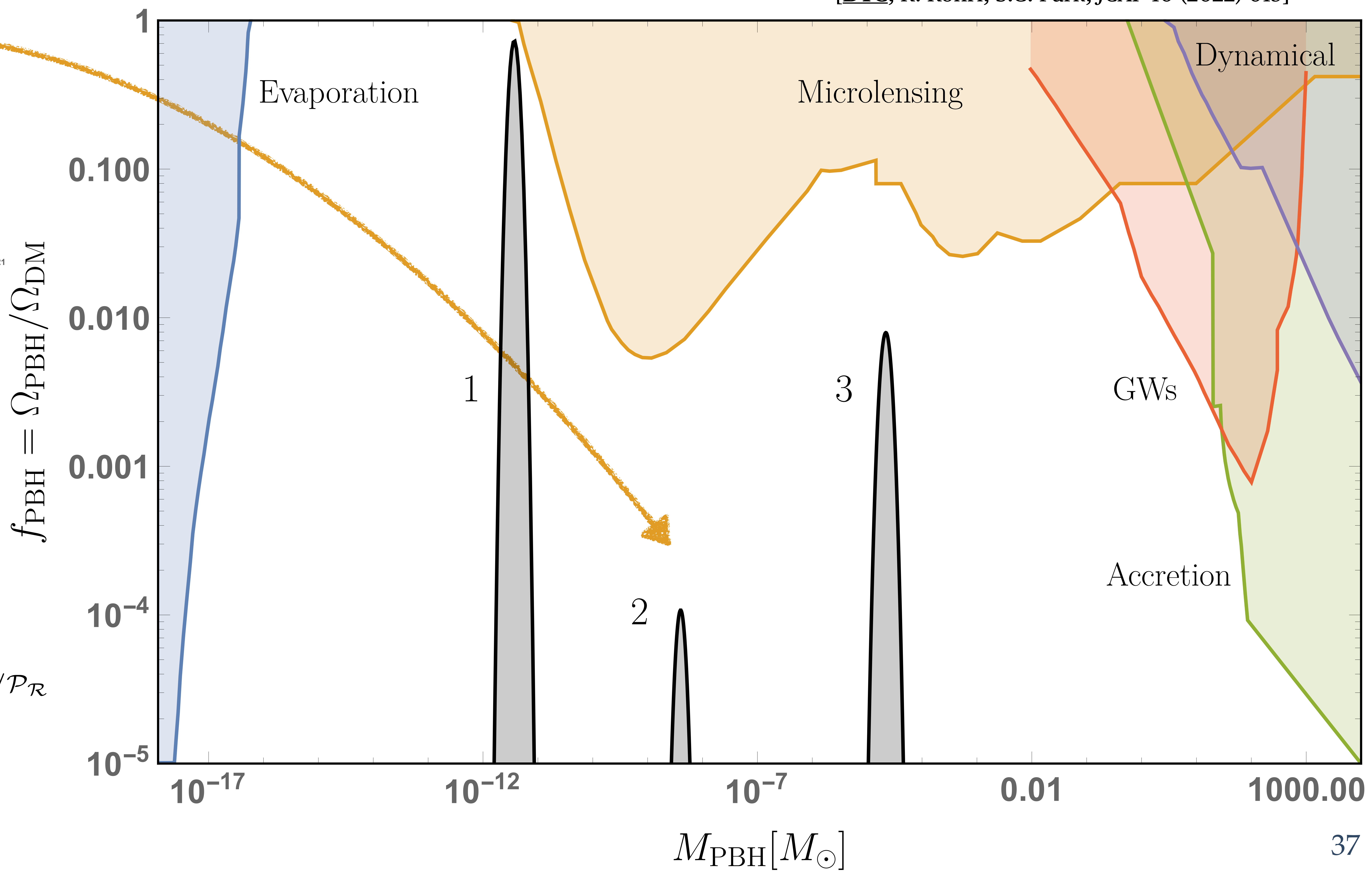

$$\beta \sim \frac{\sigma}{\sqrt{2\pi}\delta_c} e^{-\delta_c^2/(2\sigma^2)} \sim e^{-\delta_c^2/\mathcal{P}_\mathcal{R}}$$

Phenomena — Primordial Black Holes

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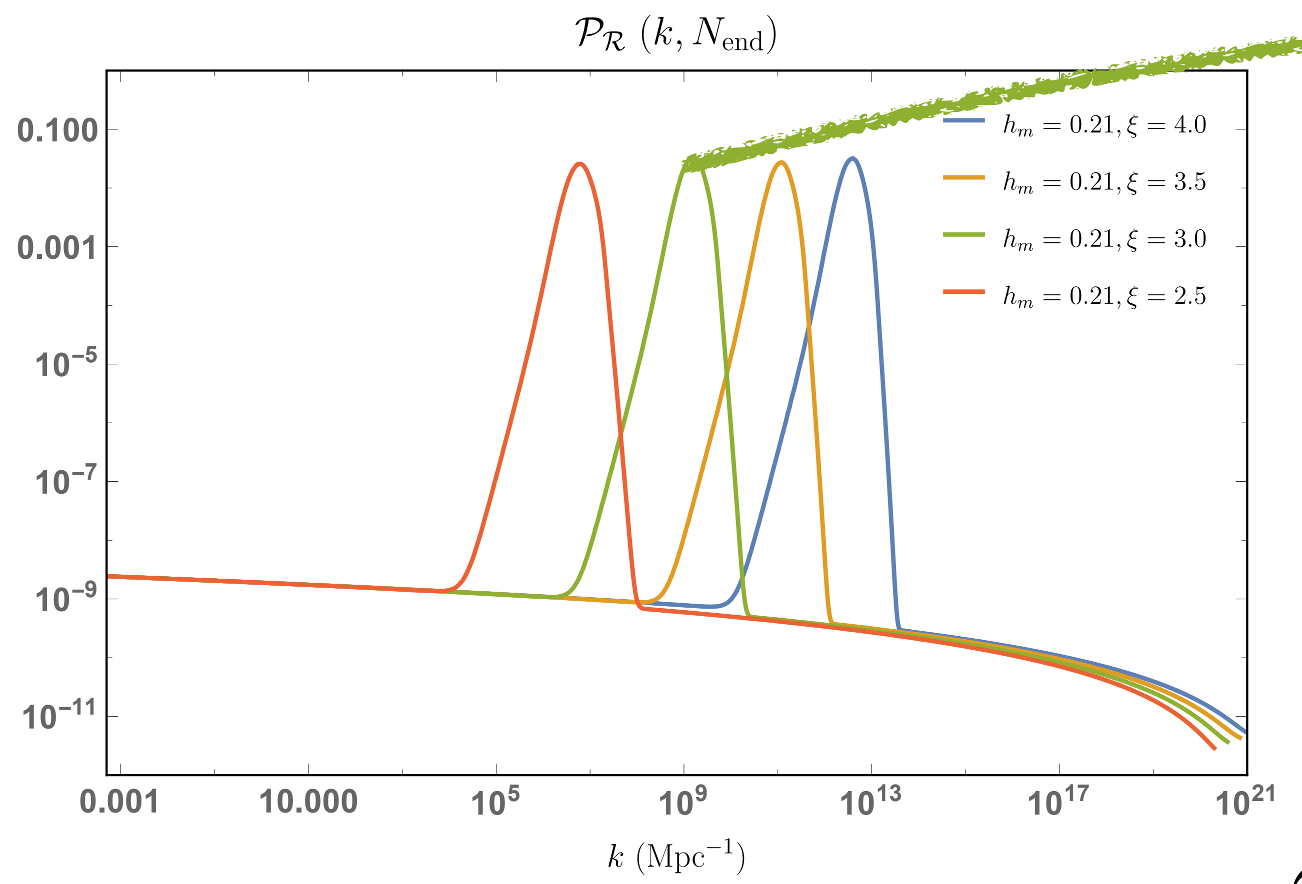
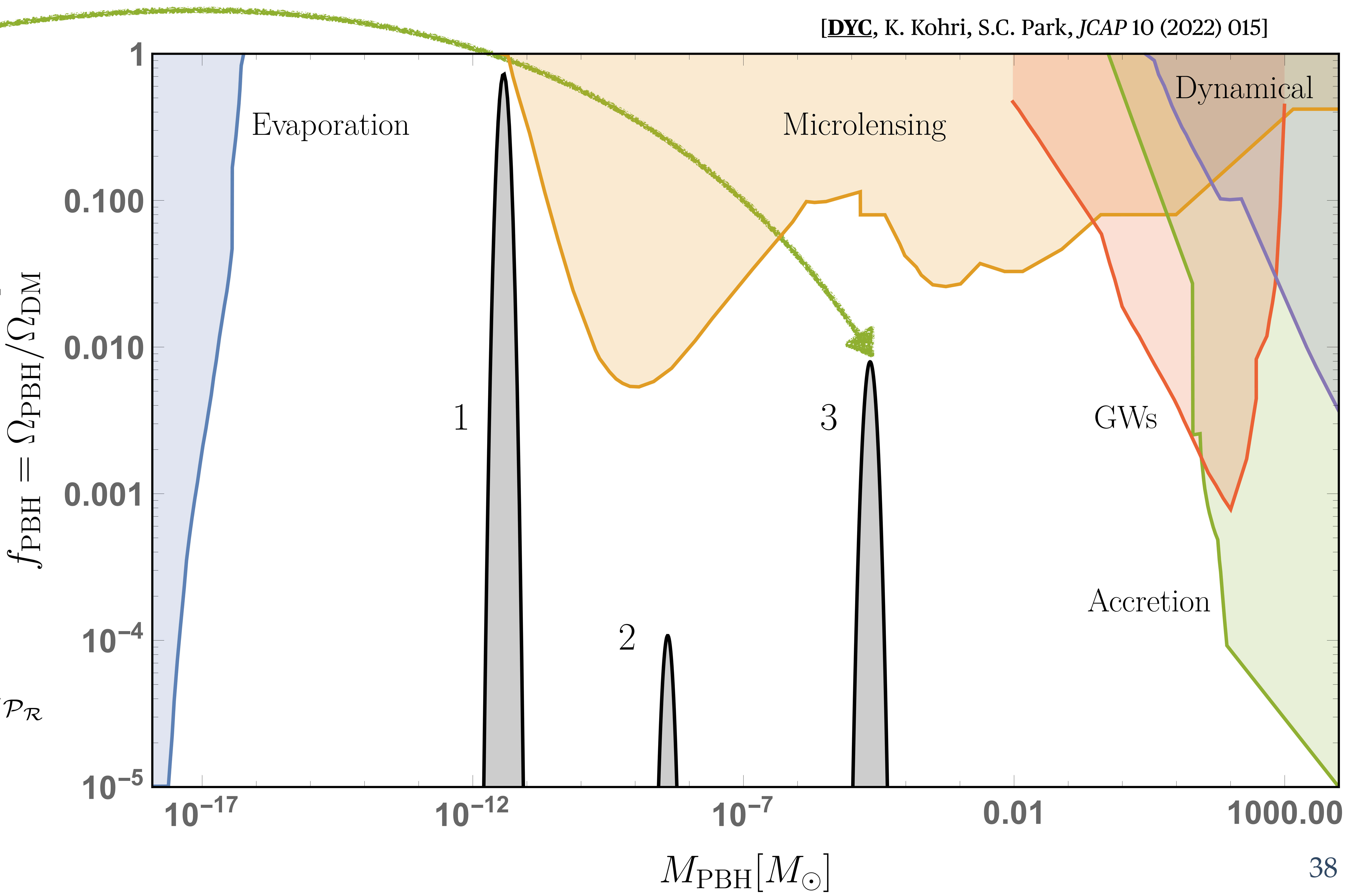
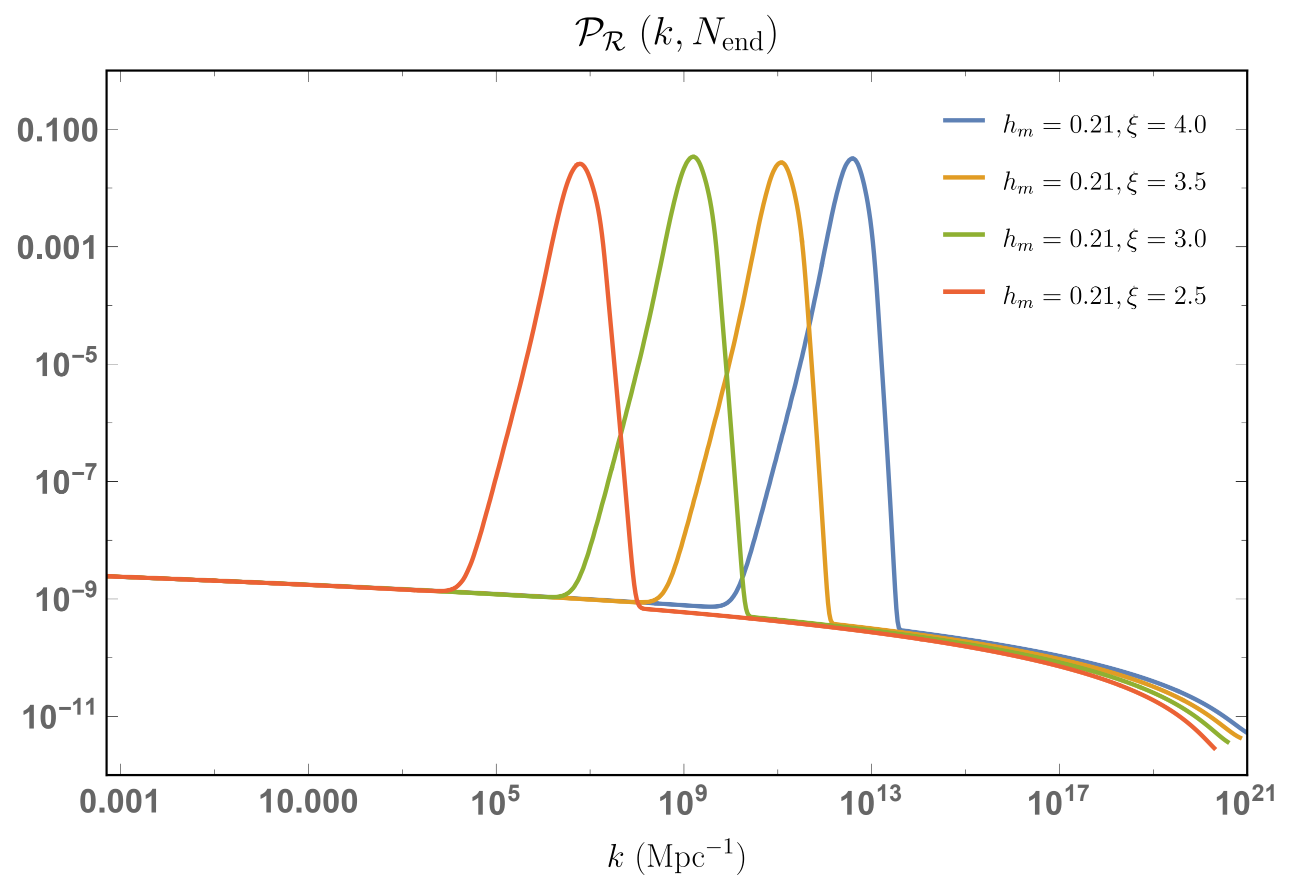




$$\beta \sim \frac{\sigma}{\sqrt{2\pi}\delta_c} e^{-\delta_c^2/(2\sigma^2)} \sim e^{-\delta_c^2/\mathcal{P}_{\mathcal{R}}}$$

Phenomena — Second order GWs



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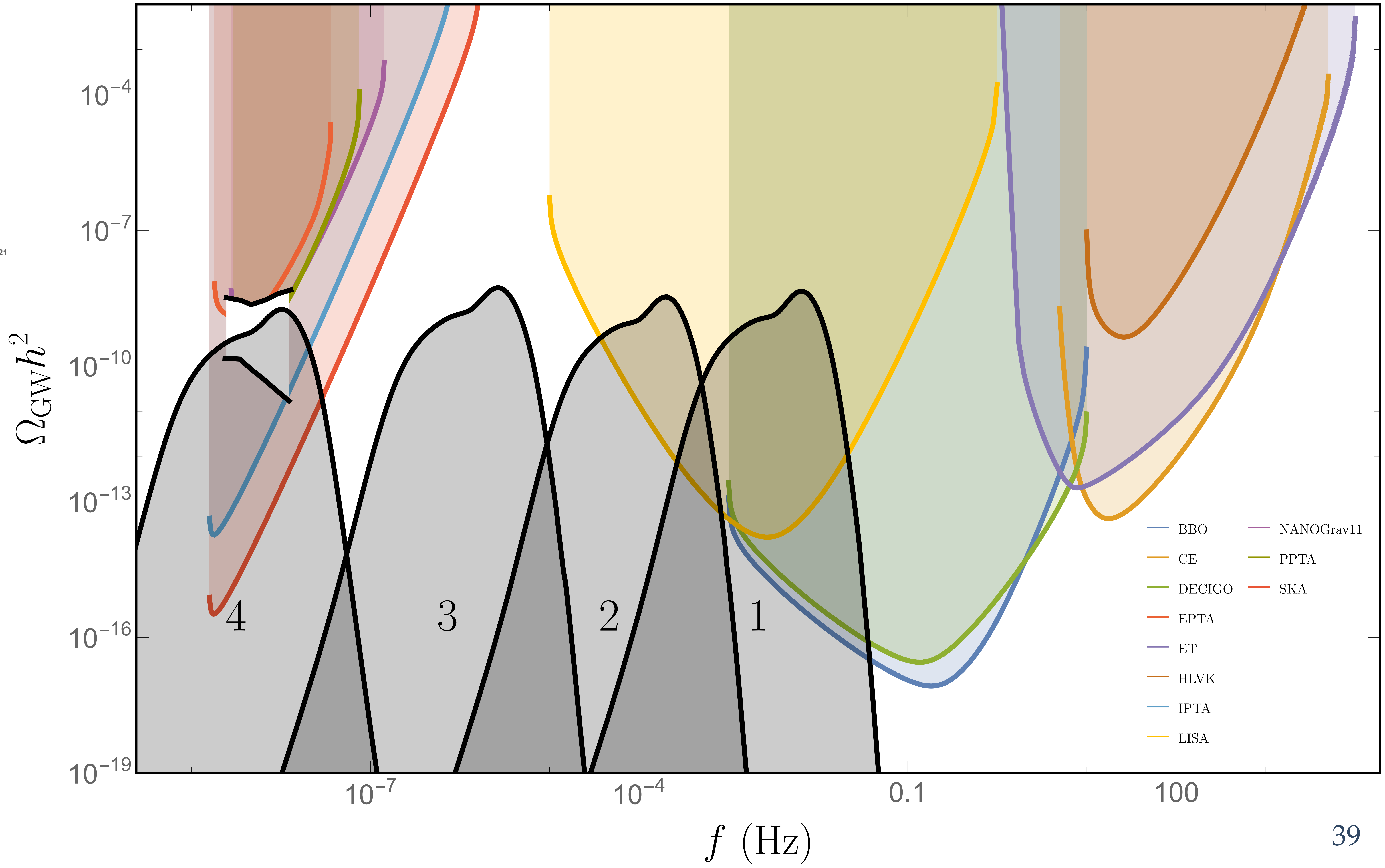
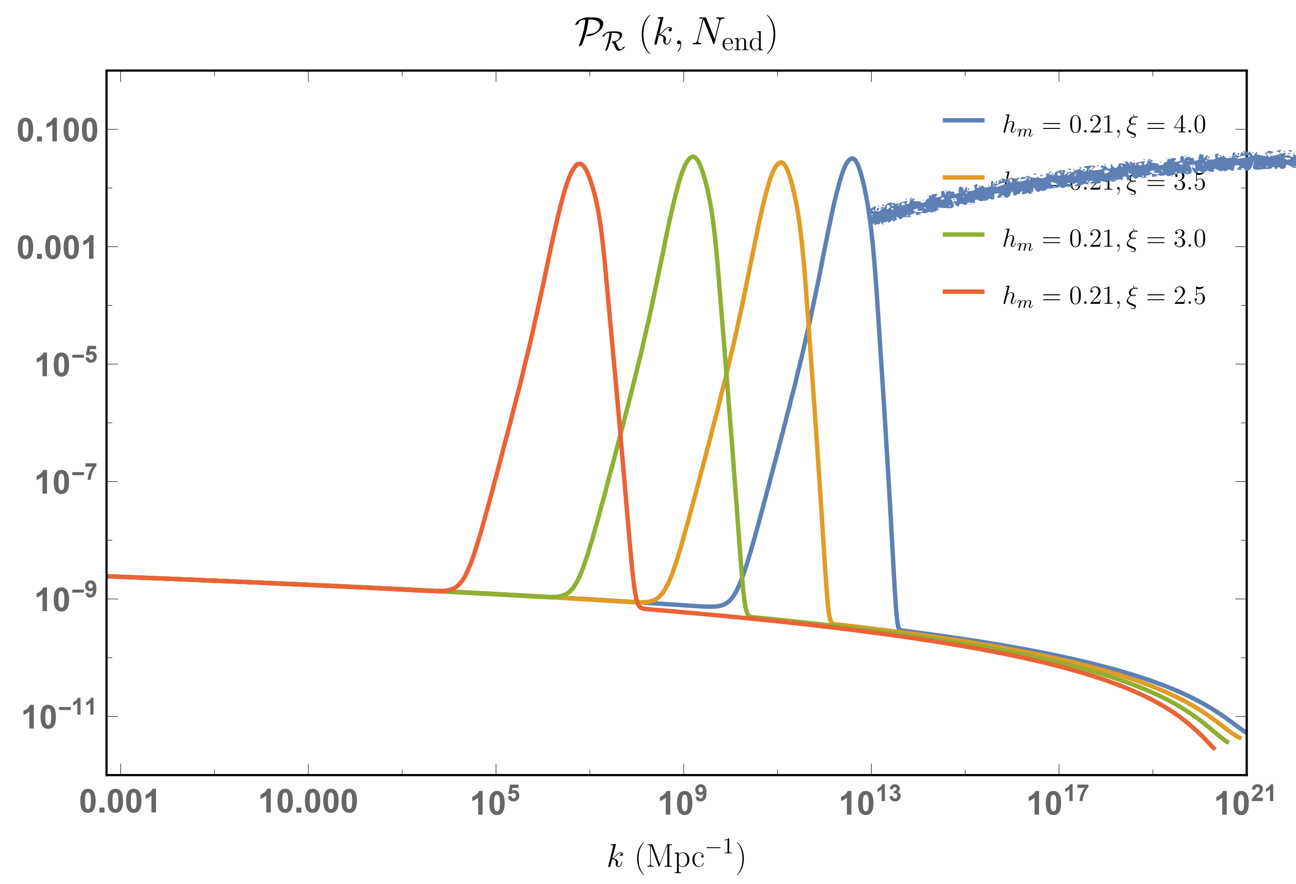


Phenomena — Second order GWs



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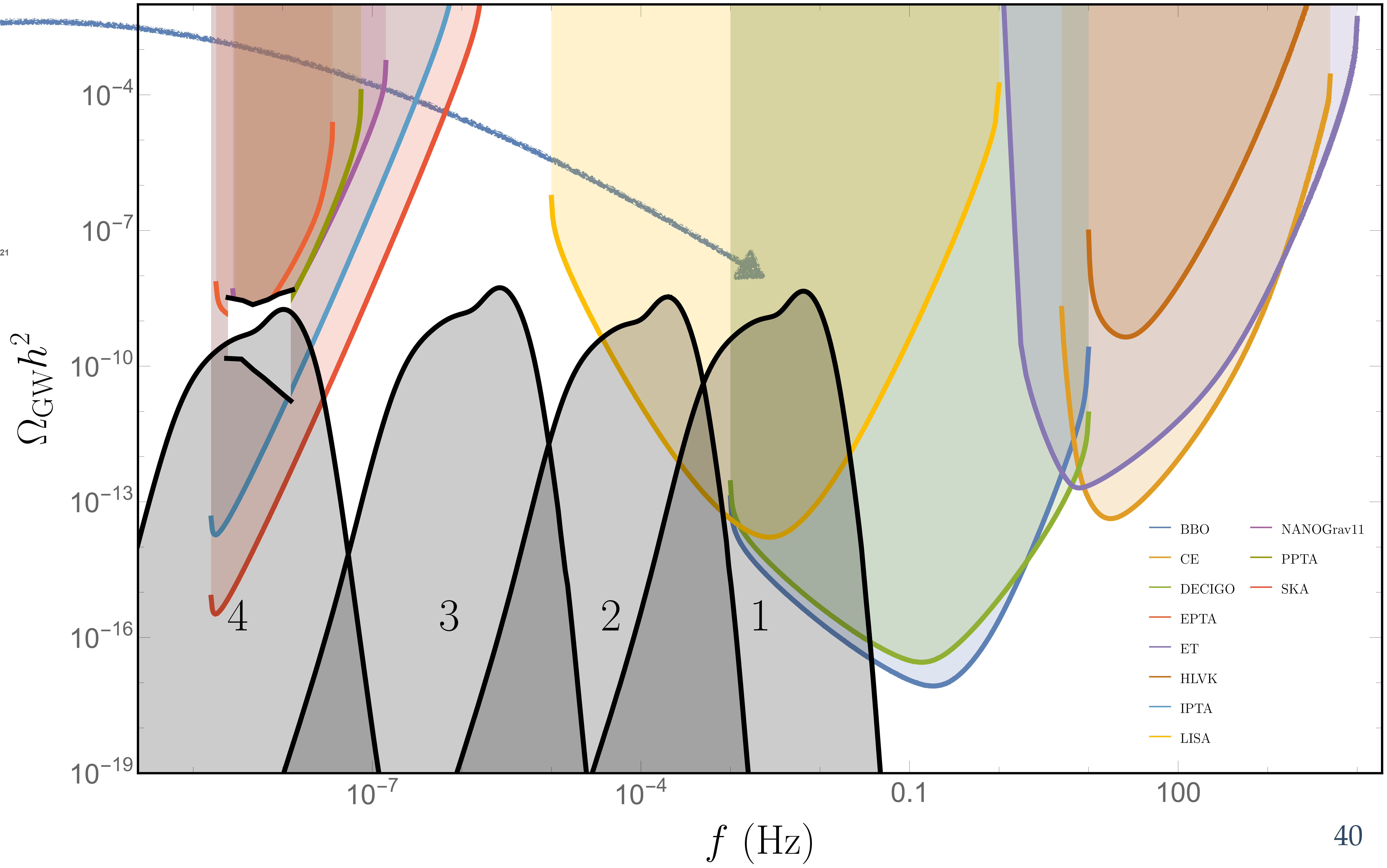

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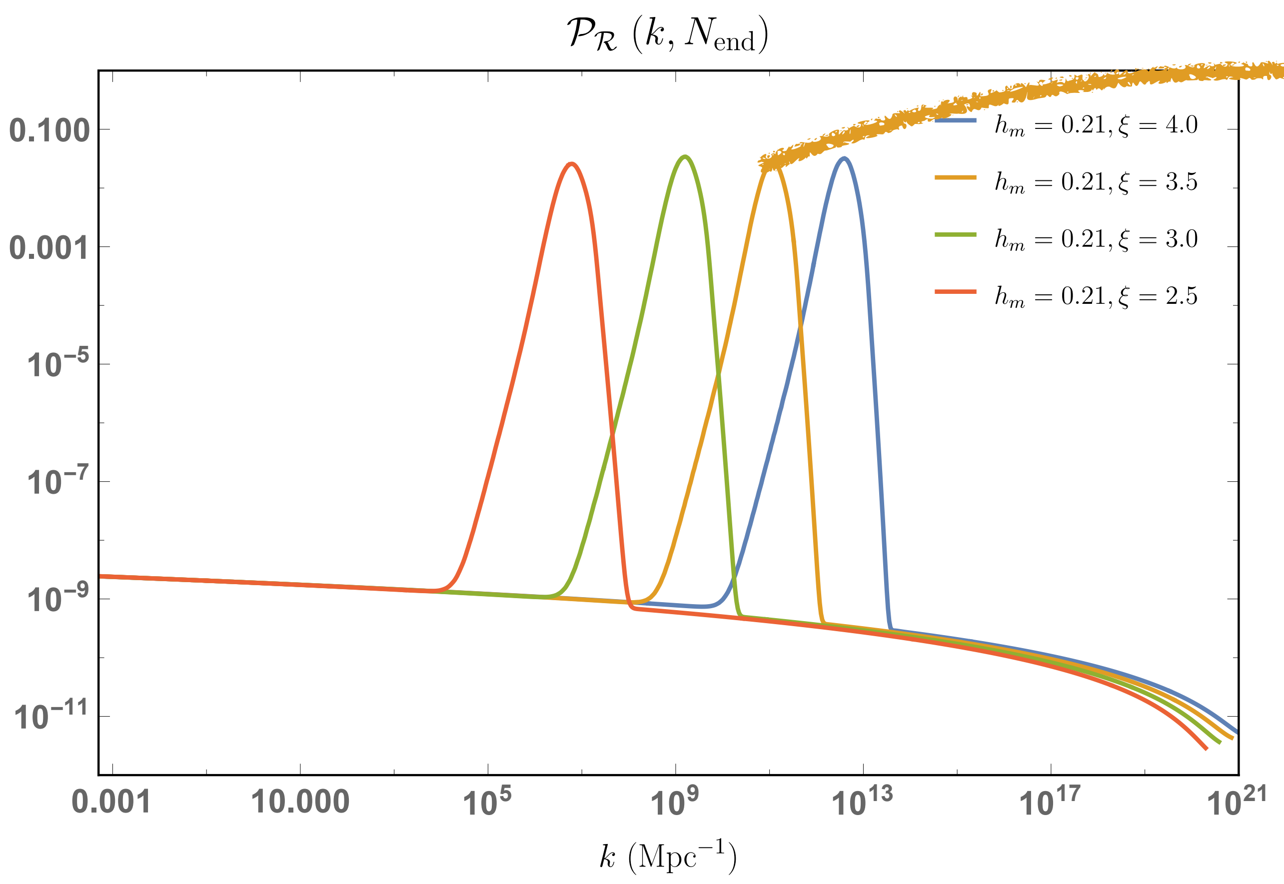

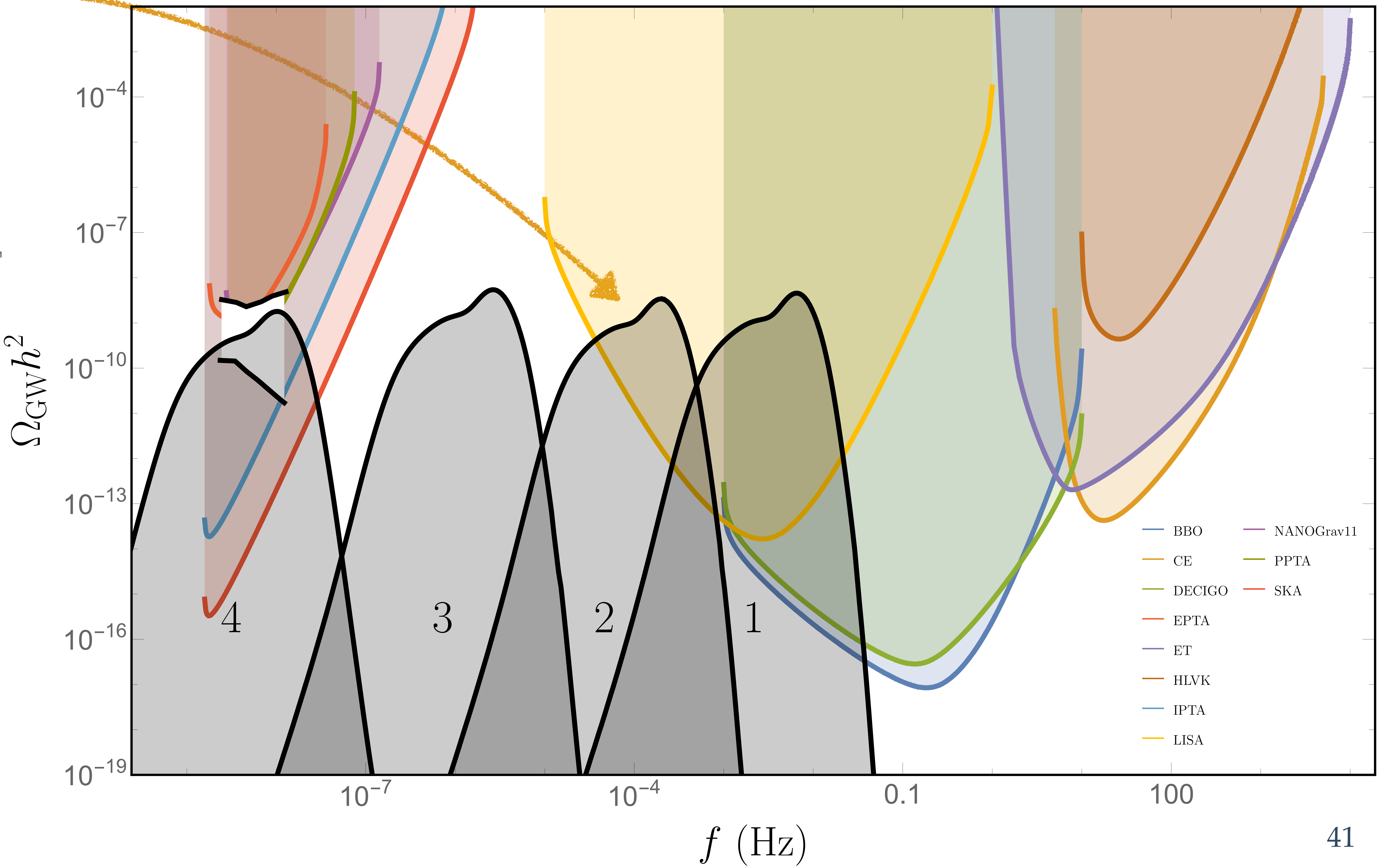

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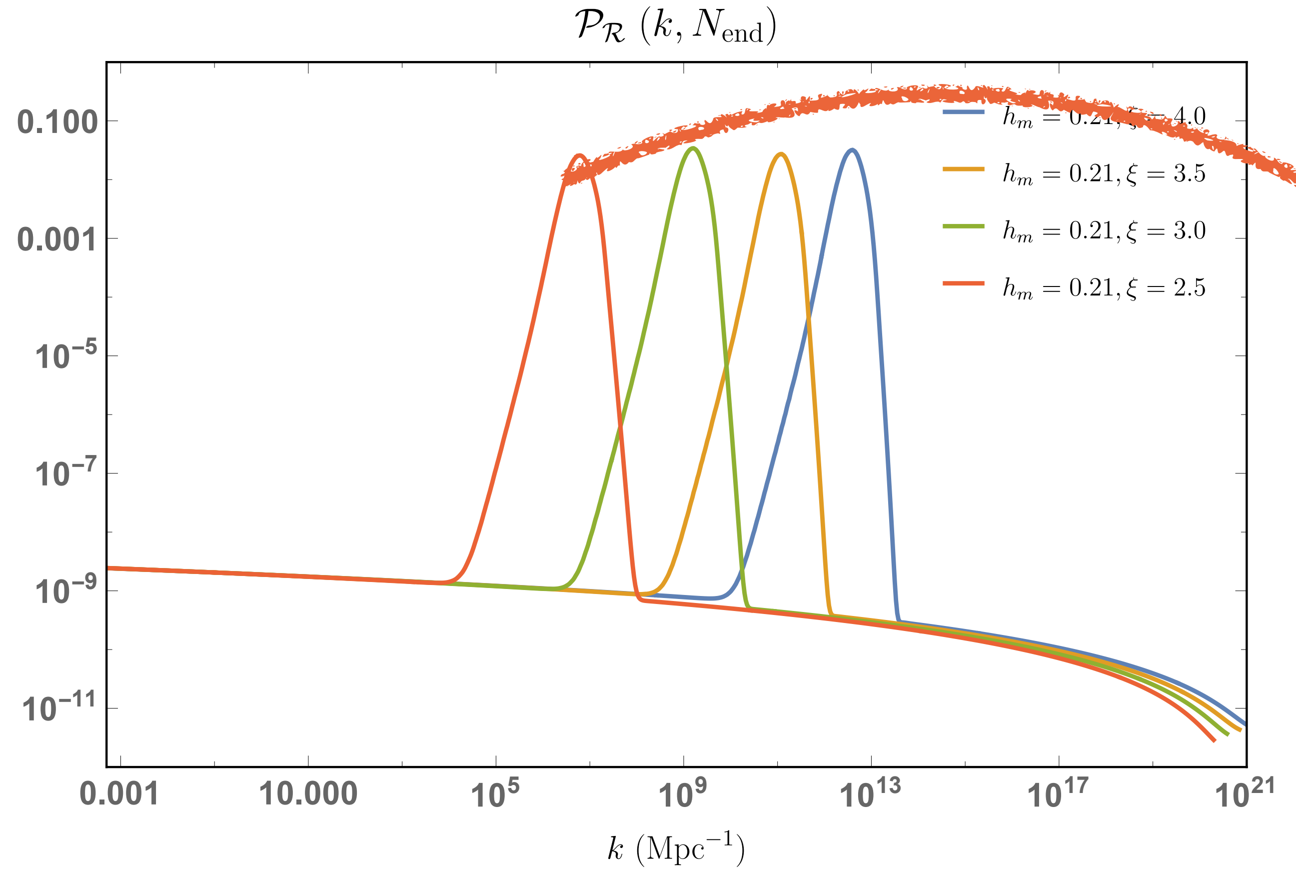

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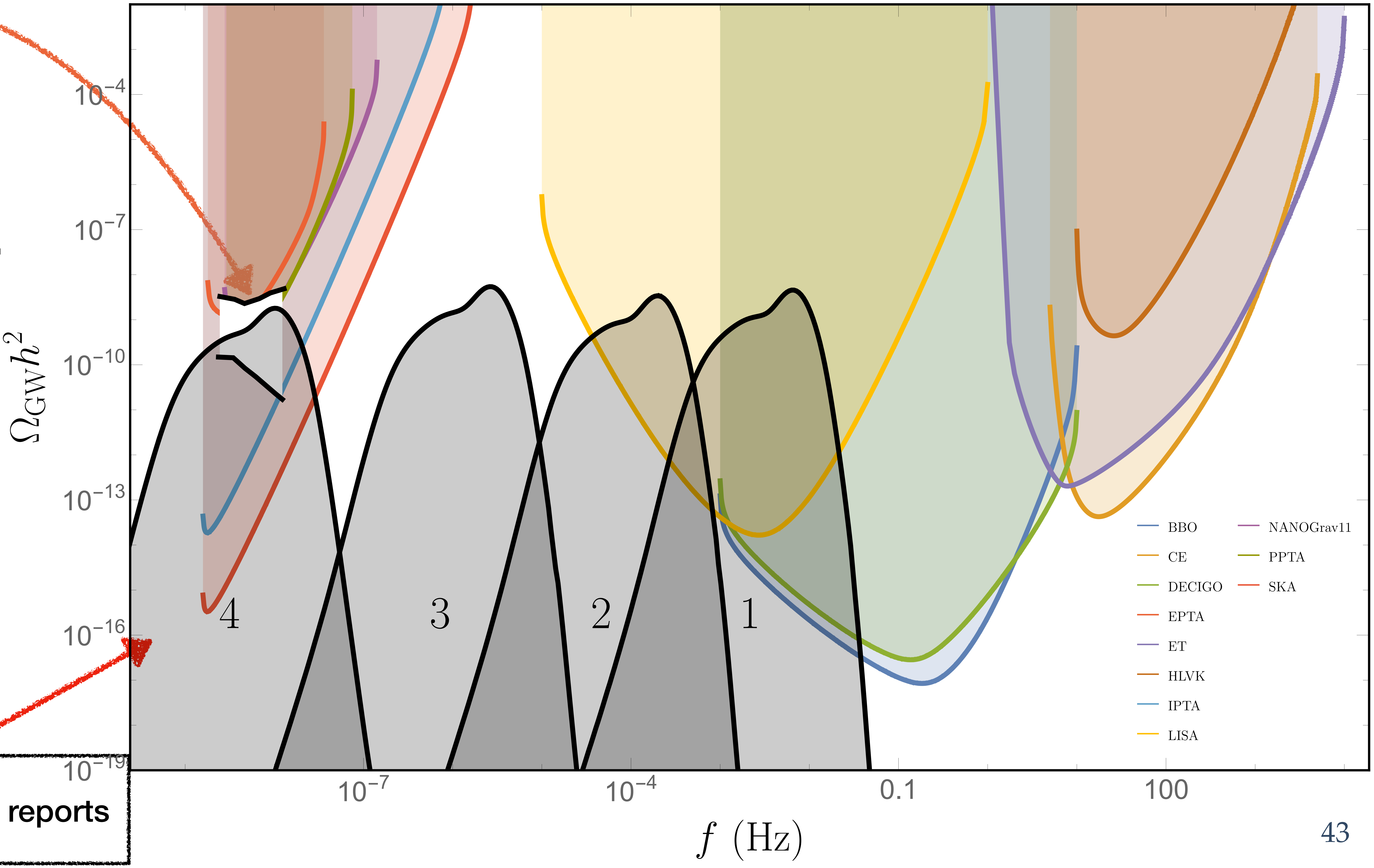

Possible to match NANOGrav reports

Summary & Outlooks

- Primordial Black Holes, an appealing DM candidate, can be produced through large curvature perturbations, that can be associated with second order gravitational waves.
- The Higgs-R^2 model, featuring both a *distinctive valley* and a *noticeable hill*, can exhibit a *tachyonic instability* induced by the *running* λ.
- *Tachyonic instability* can produce a wide range of PBHs/GWs from *LIGO/Virgo to PTA frequencies*.
- Backreaction considerations, non-Gaussianity?
- Further distinguishable features? Direct correlation to collider observables? (m_{top})

"Thank you!"