Tachyonic Production of Primordial Black Holes and Gravitational Waves in Higgs-R^2 Inflation

"The Inflaton that Could"

Dhong Yeon Cheong (Yonsei University)

(in collab. with Kazunori Kohri, Seong Chan Park)

DYC, K.Kohri, S.C.Park, arXiv 2205.14813

LIO International Conference and STAR Workshop 2022 on "Fundamental Forces from Colliders to Gravitational Waves", June. 23rd, 2022

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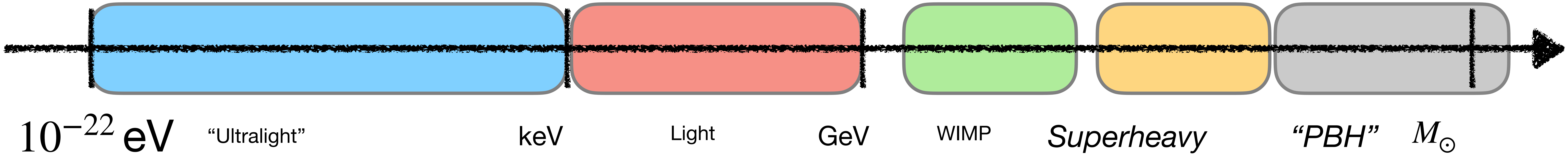
Introduction - Dark Matter



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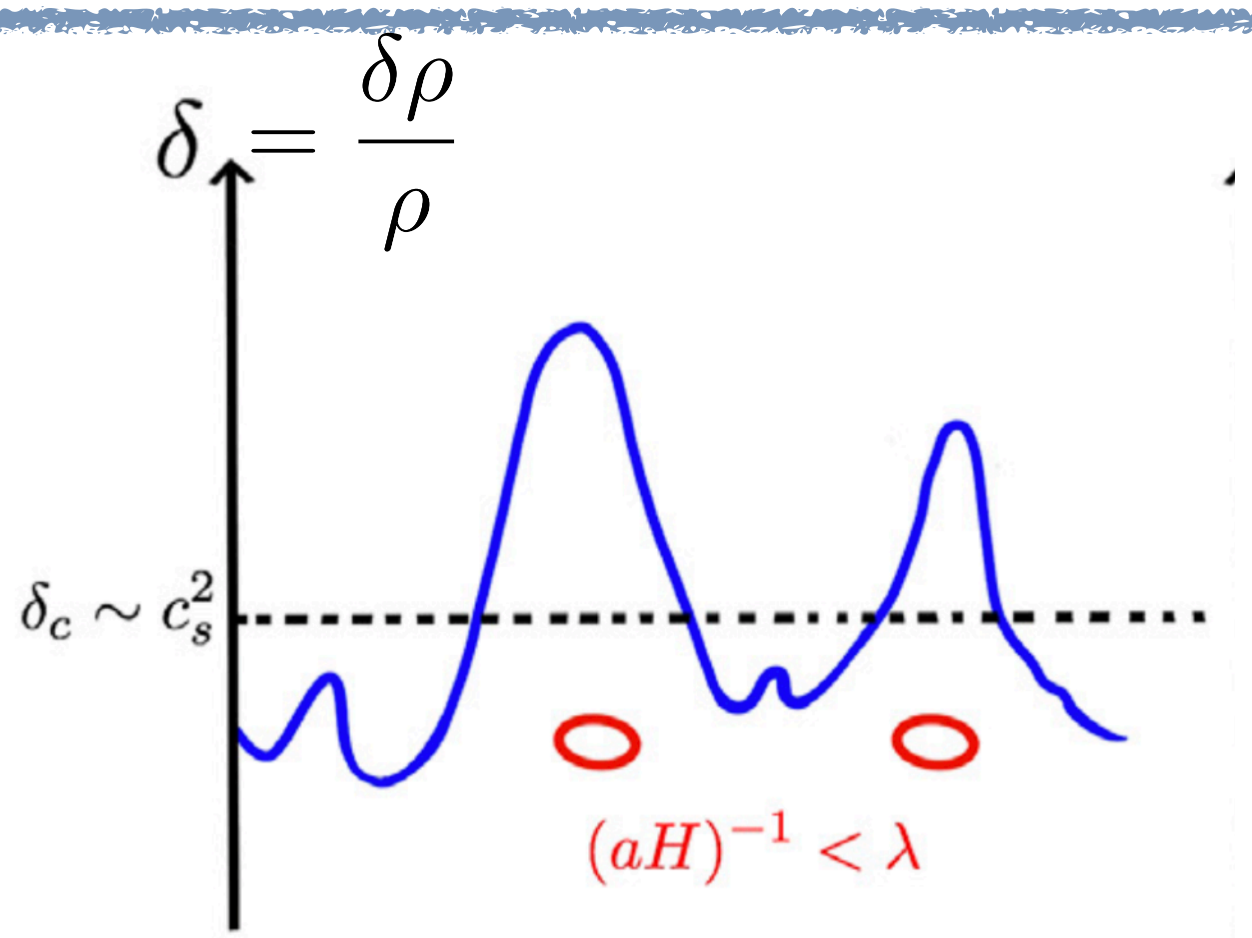

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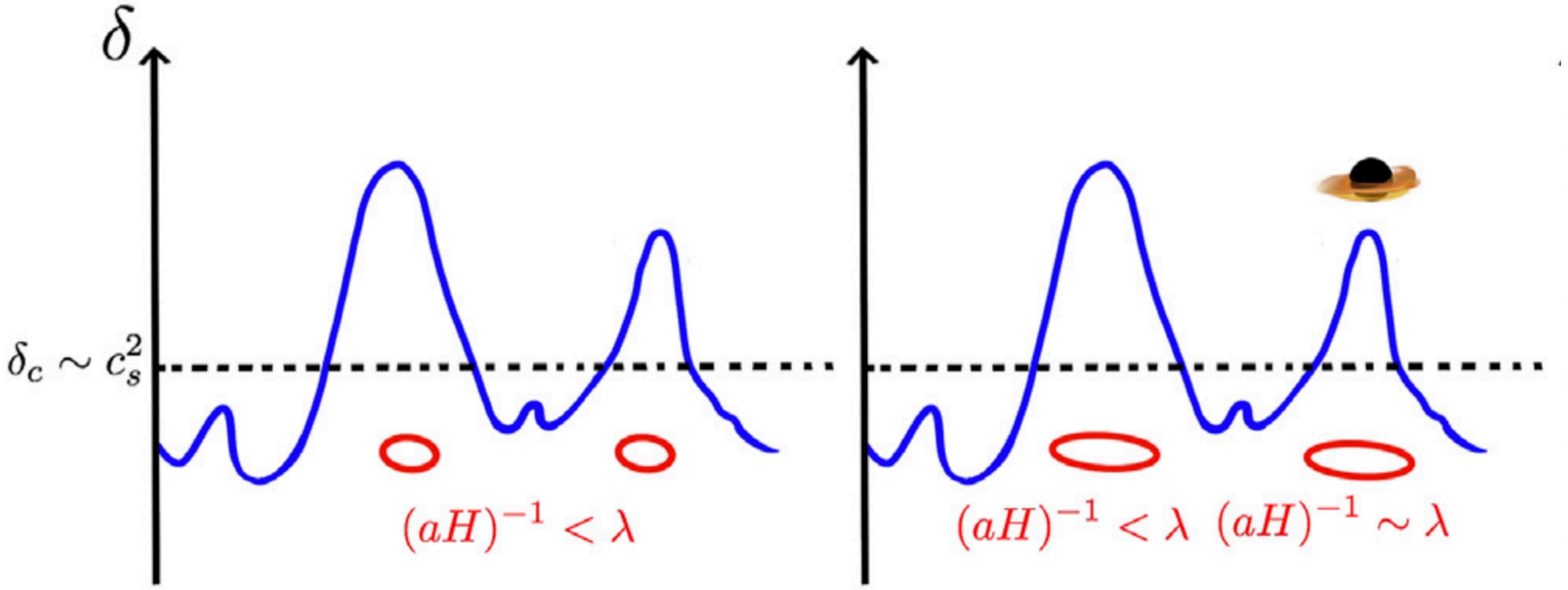

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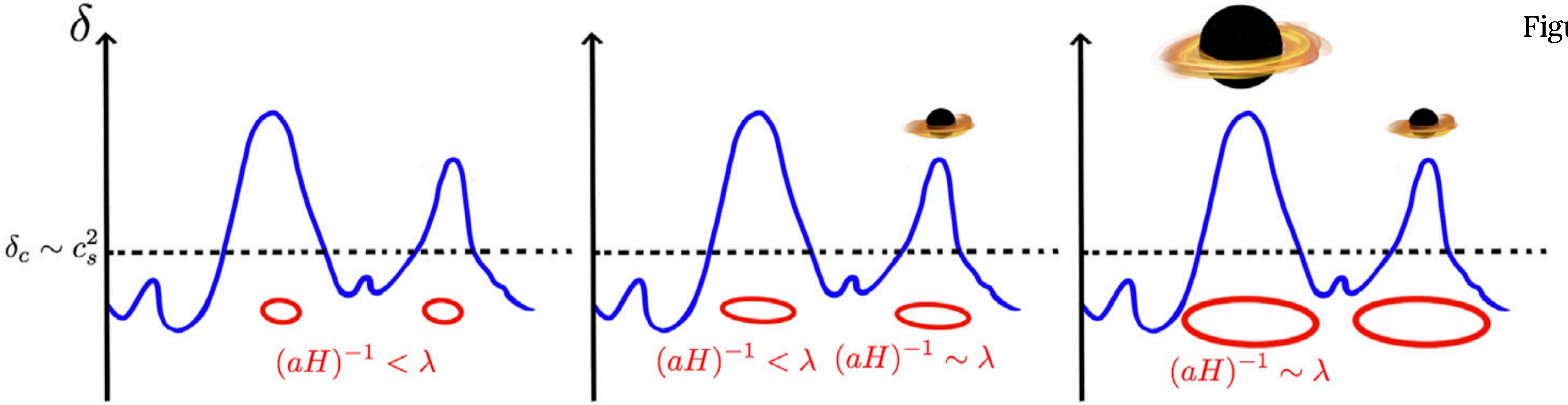

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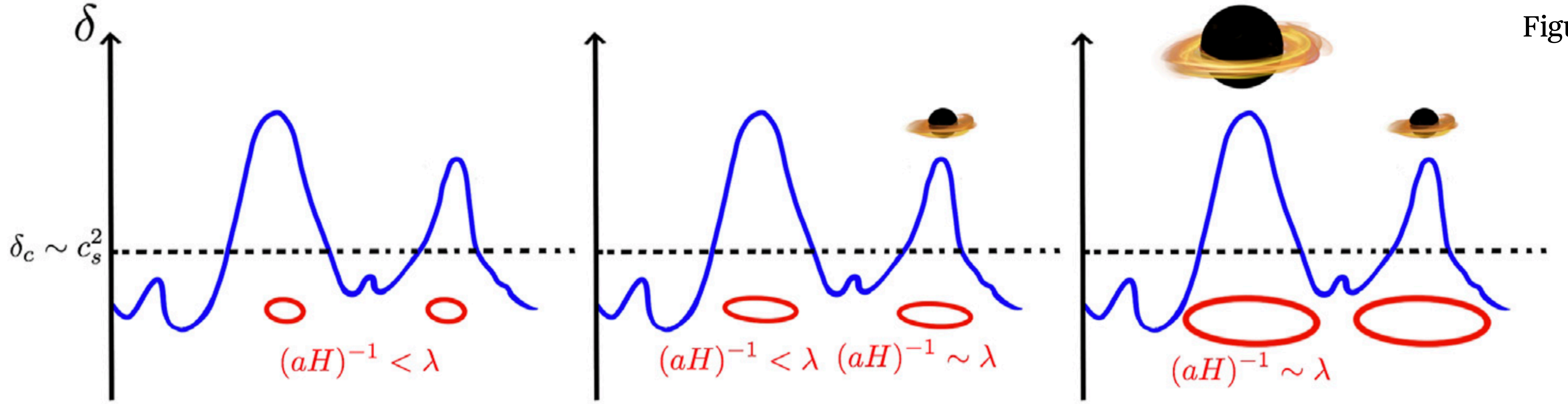

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PBHs form through the collapse of *large over-densities in the density perturbation*

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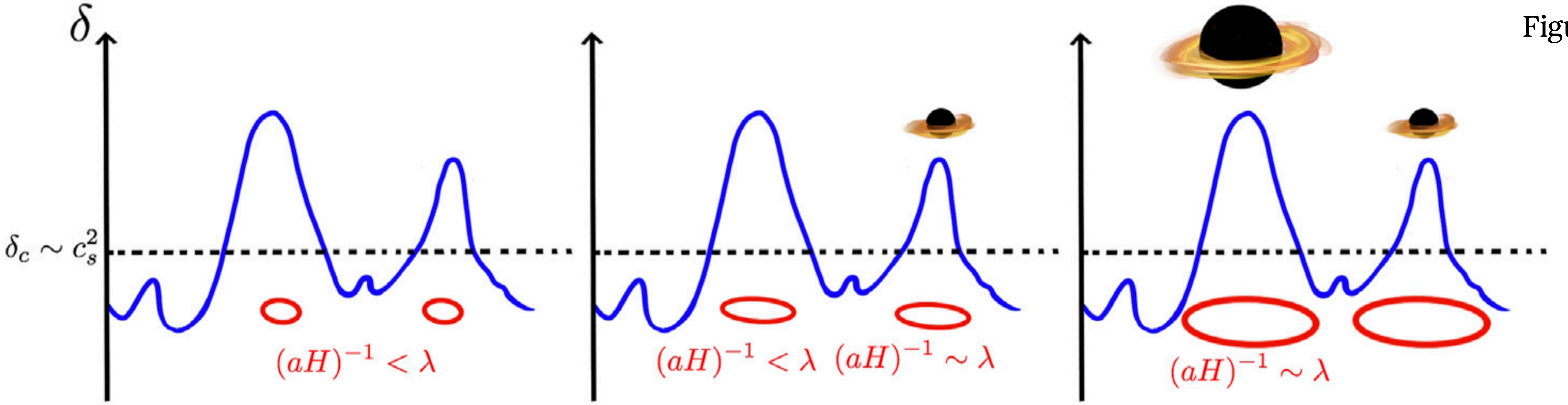

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k

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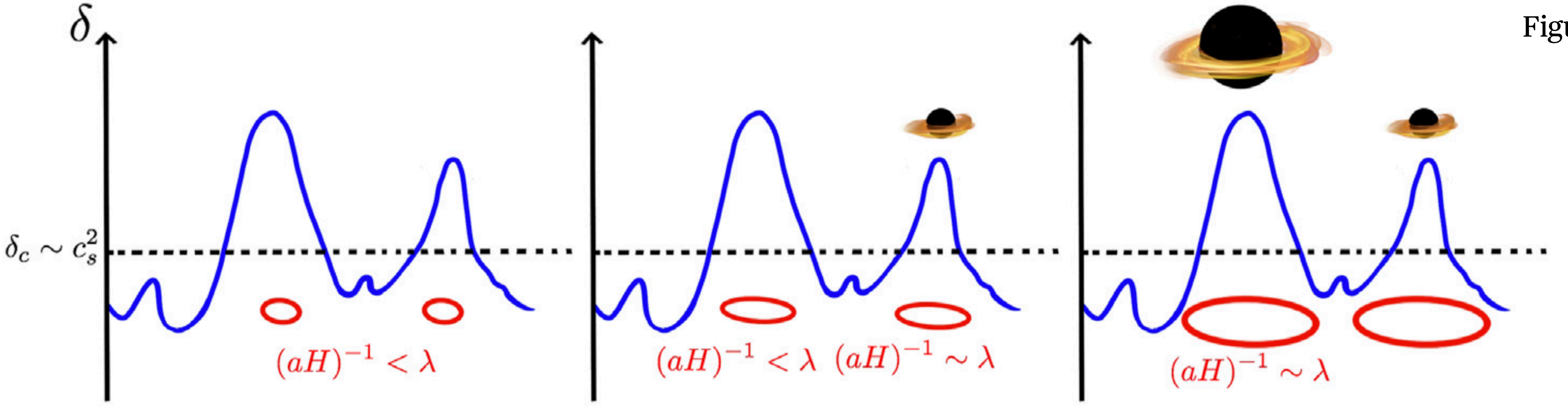

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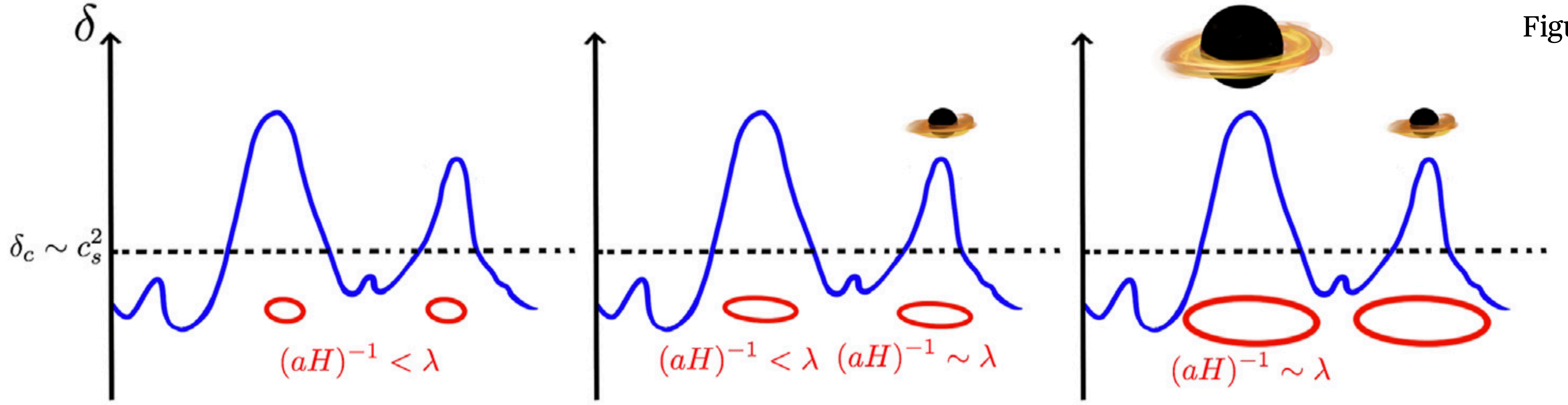

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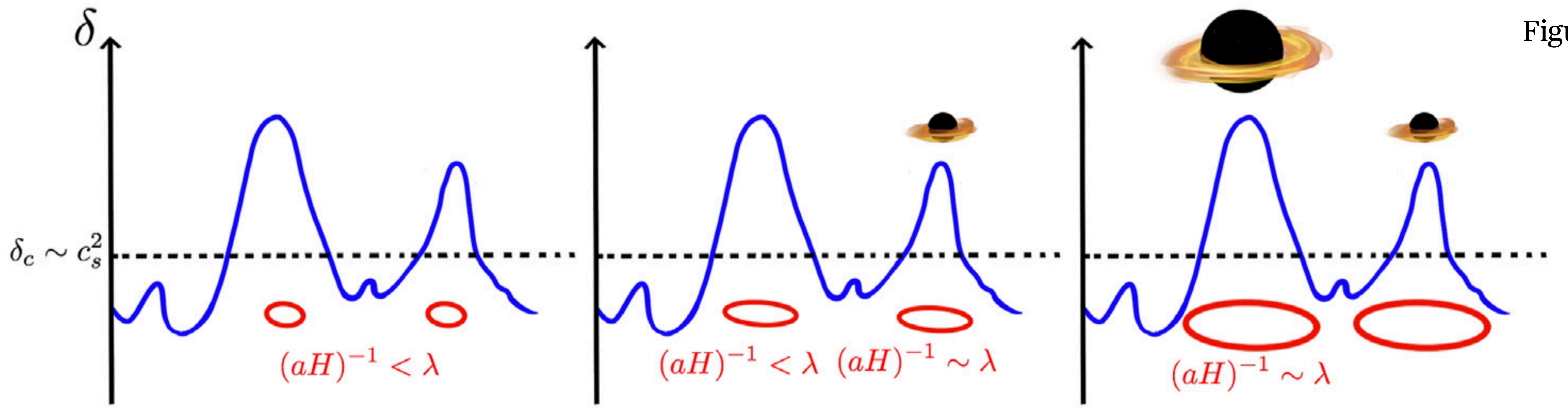

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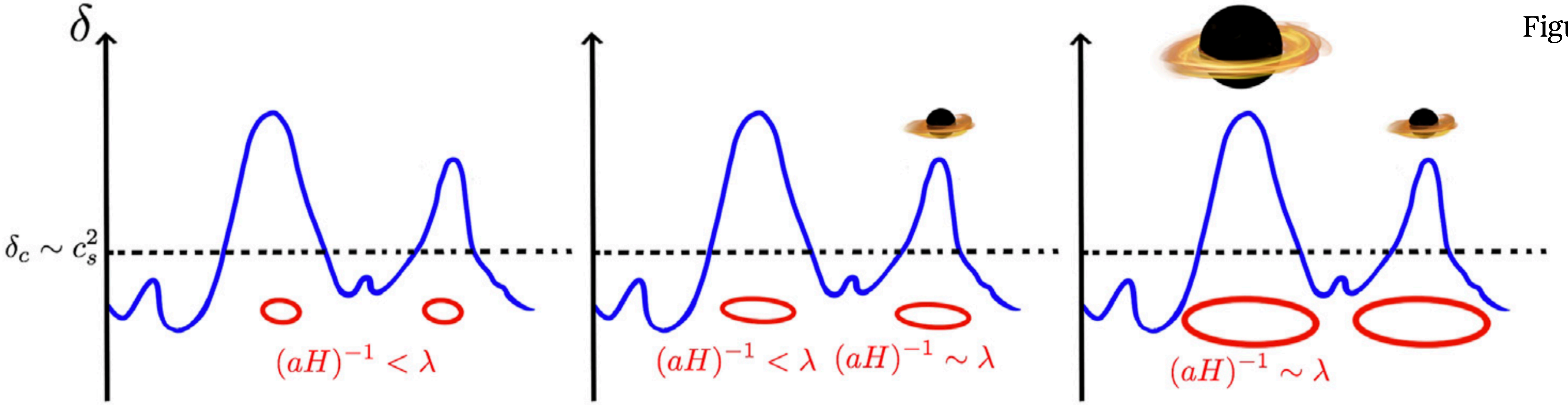

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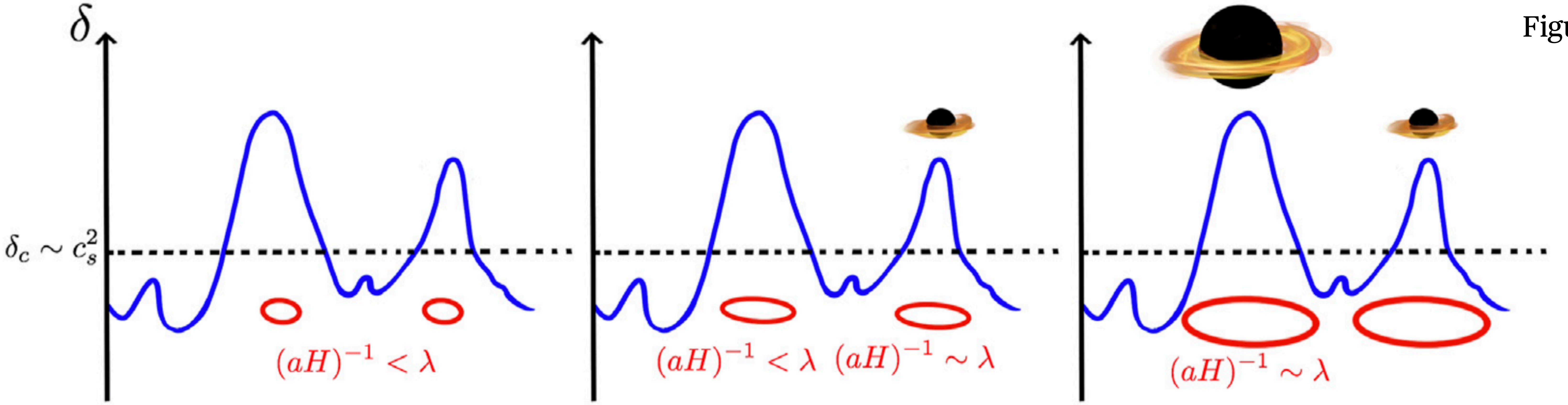

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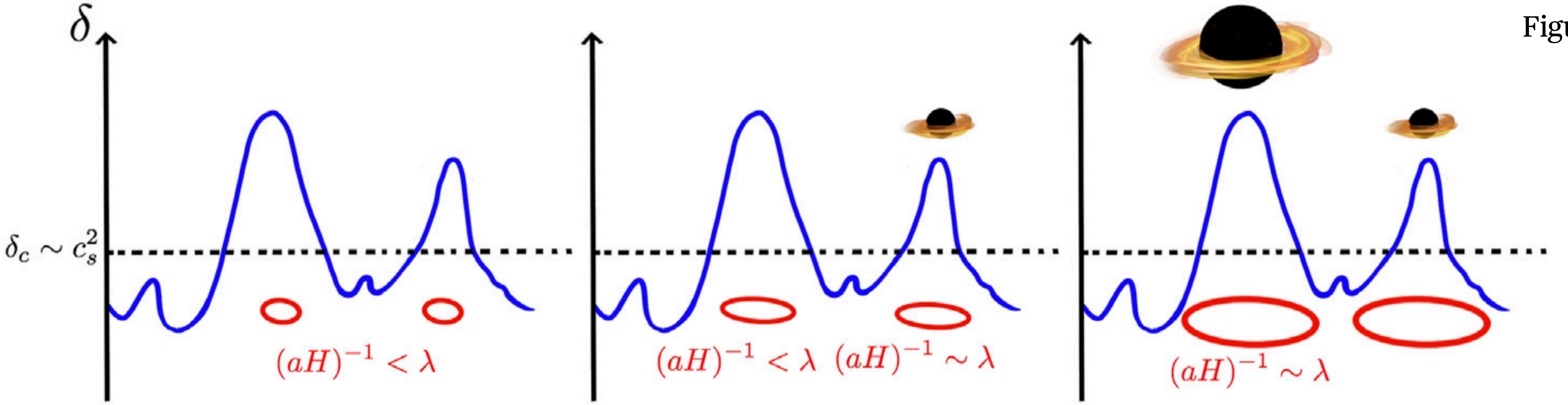

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Many mechanisms to produce large density perturbations —> Inflation is appealing!

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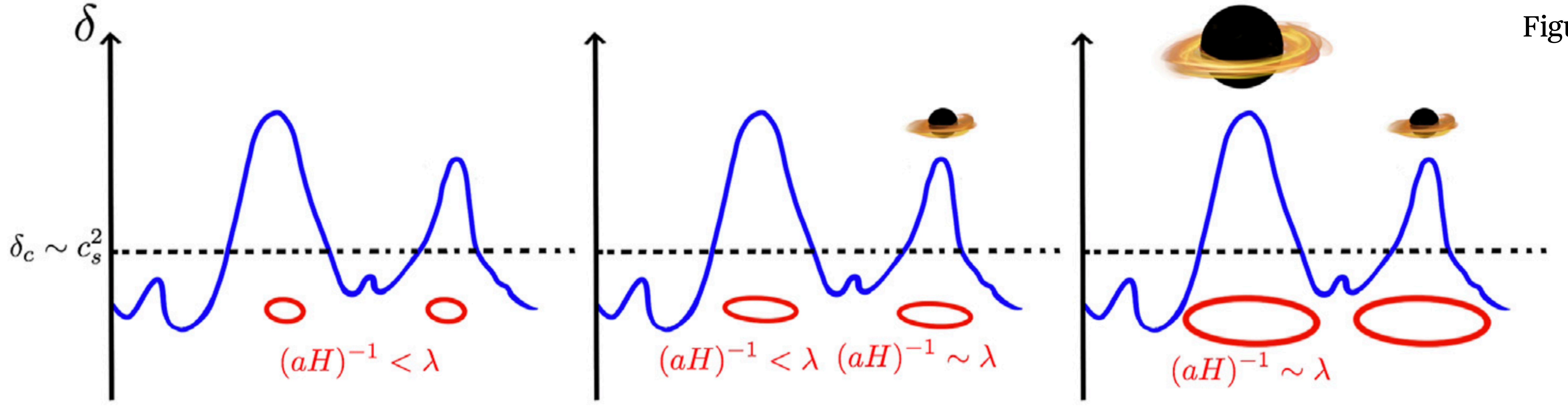

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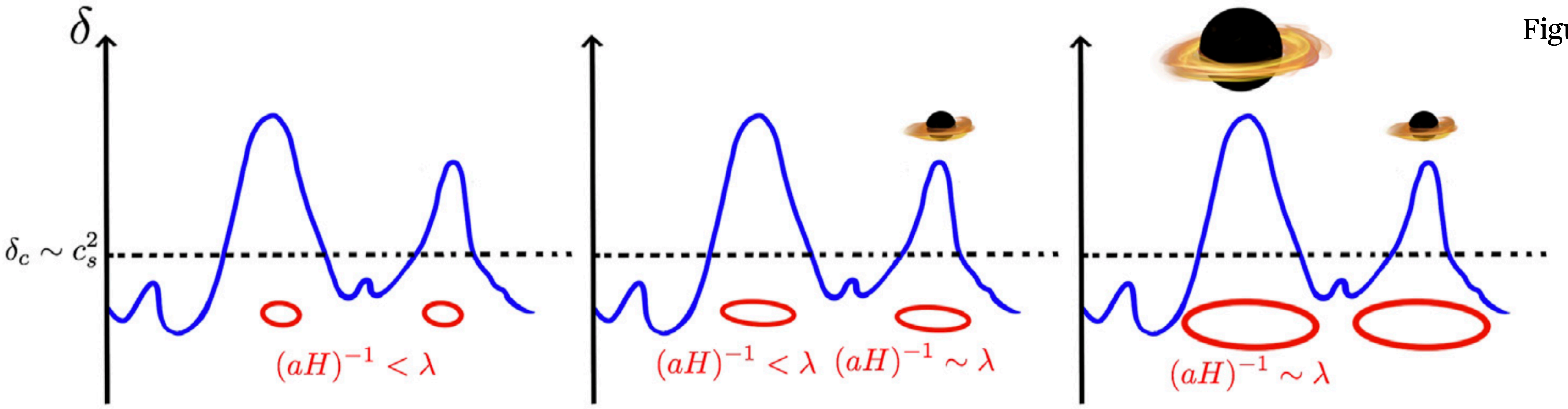

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Inflation, phase transition, cosmic strings, reheating..

Introduction -Primordial Black Holes

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

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

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

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

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

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

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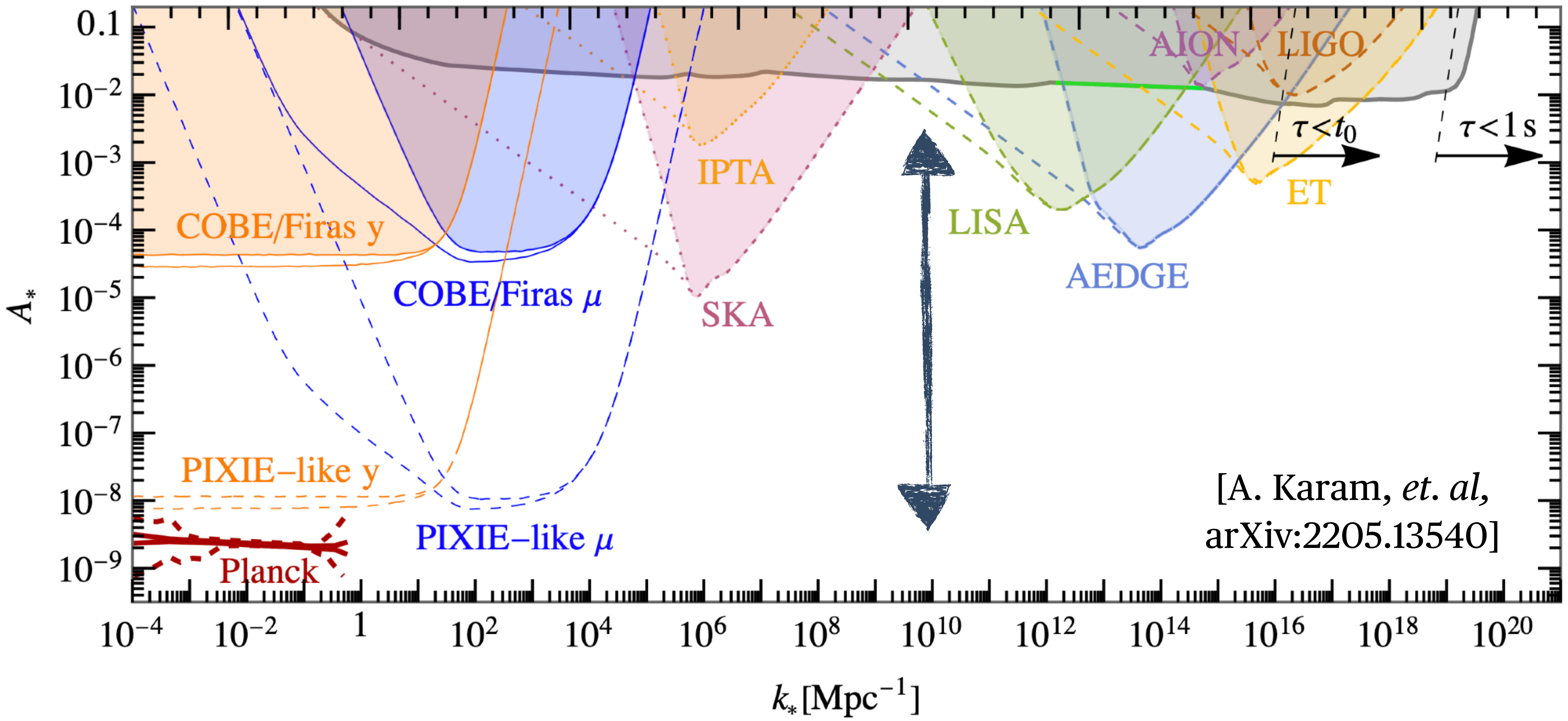

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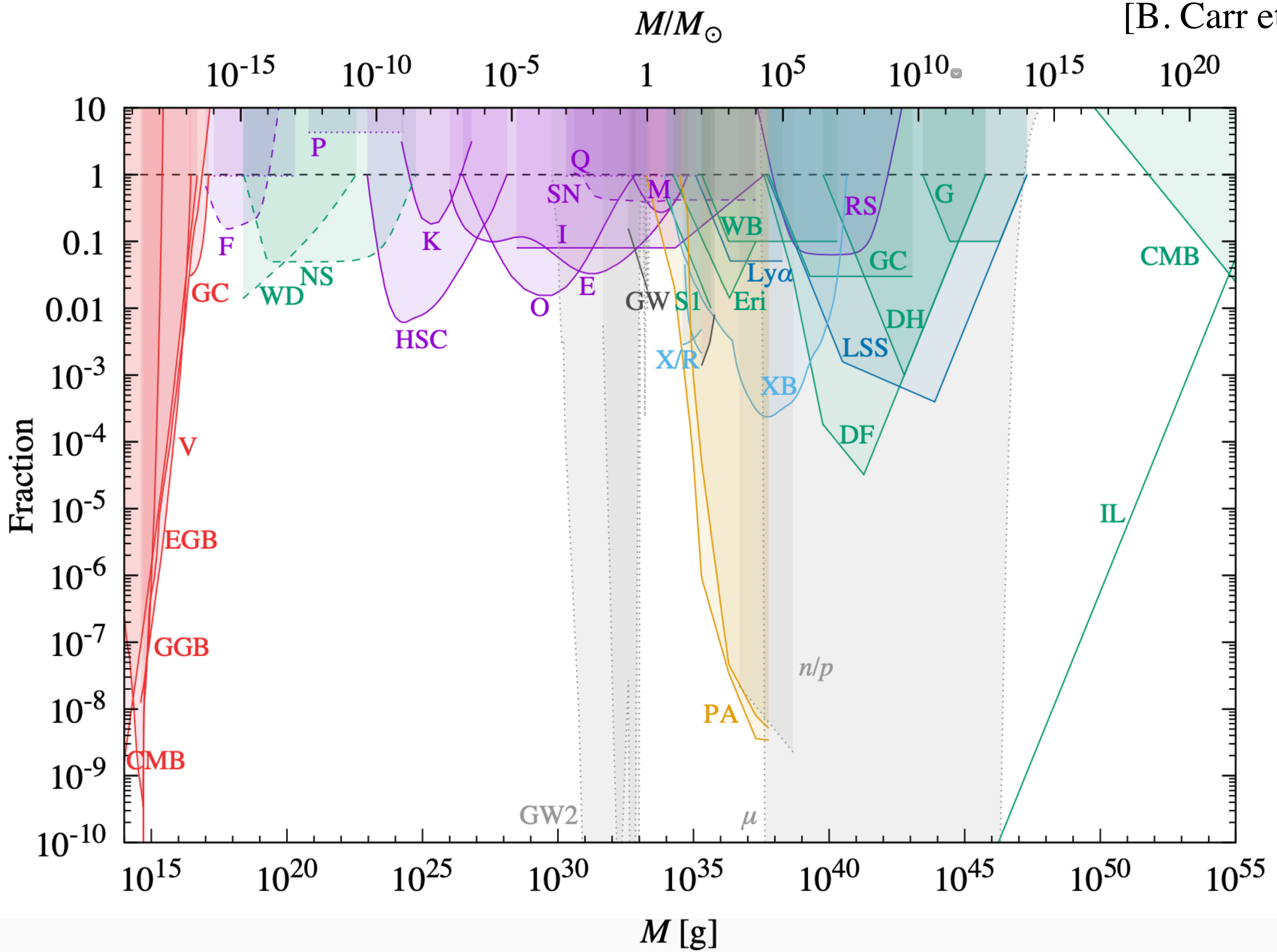

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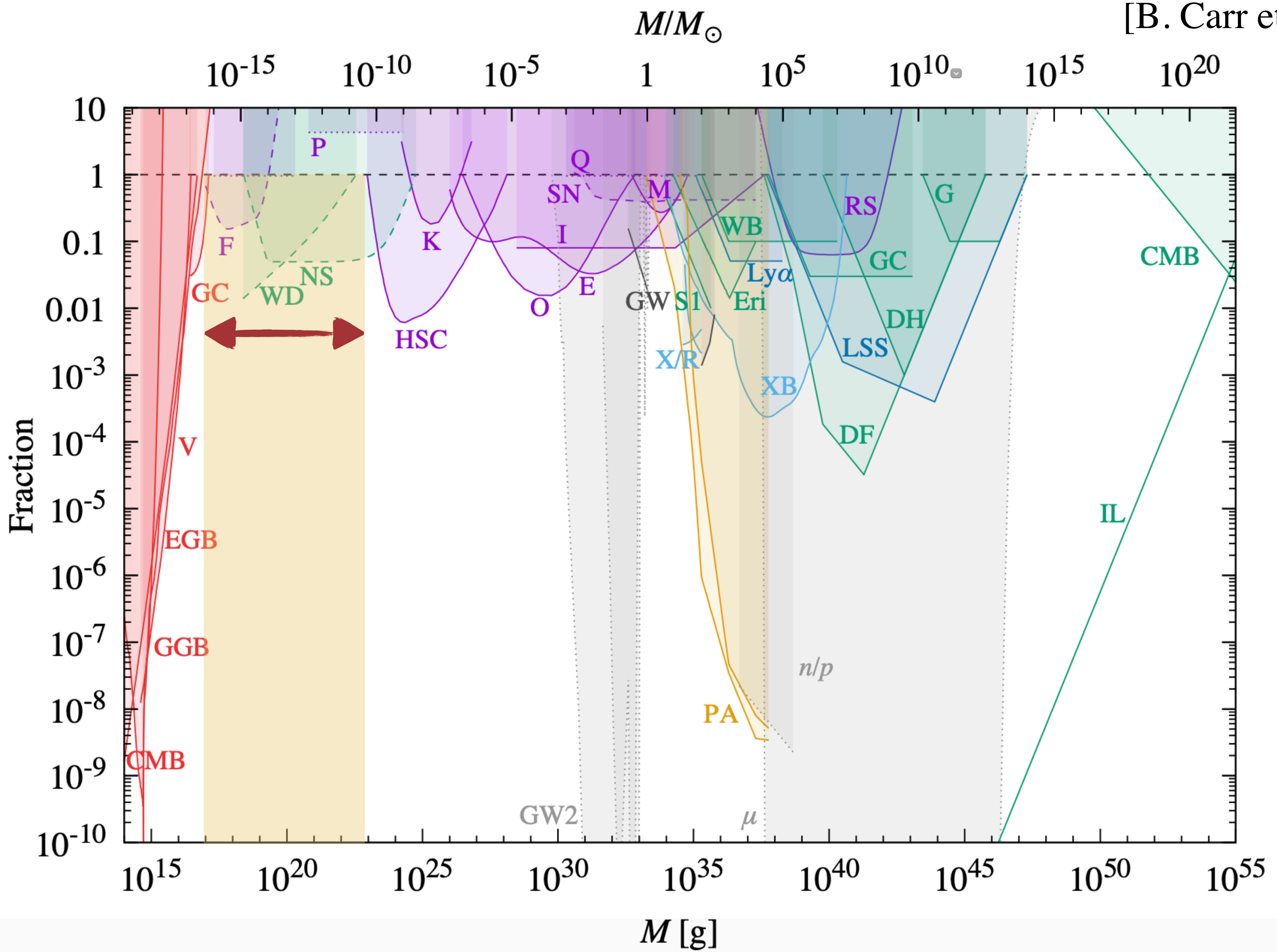

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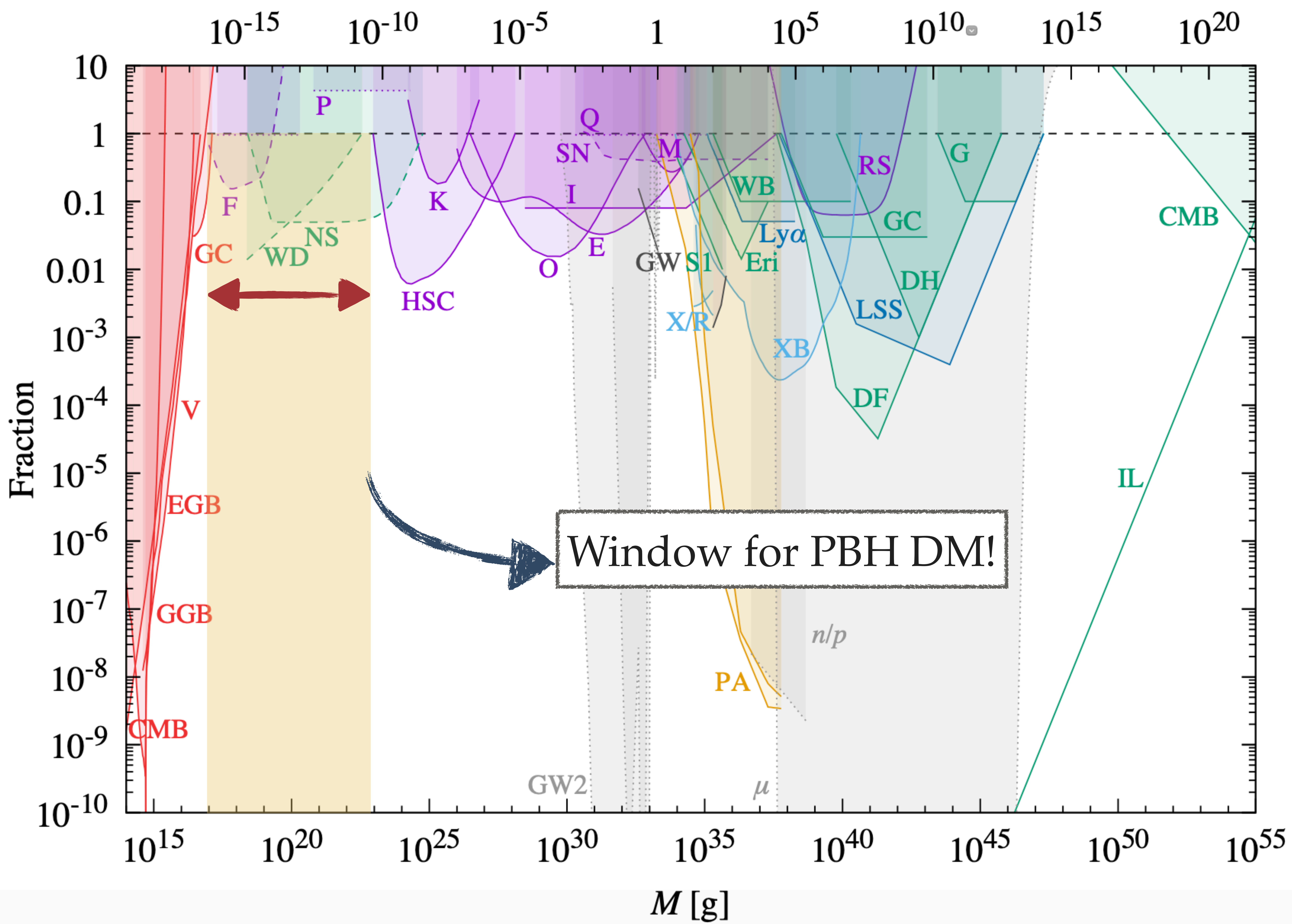

Introduction - Second Order GWs

Scalar and tensor perturbations couple at “second order metric perturbations”.

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

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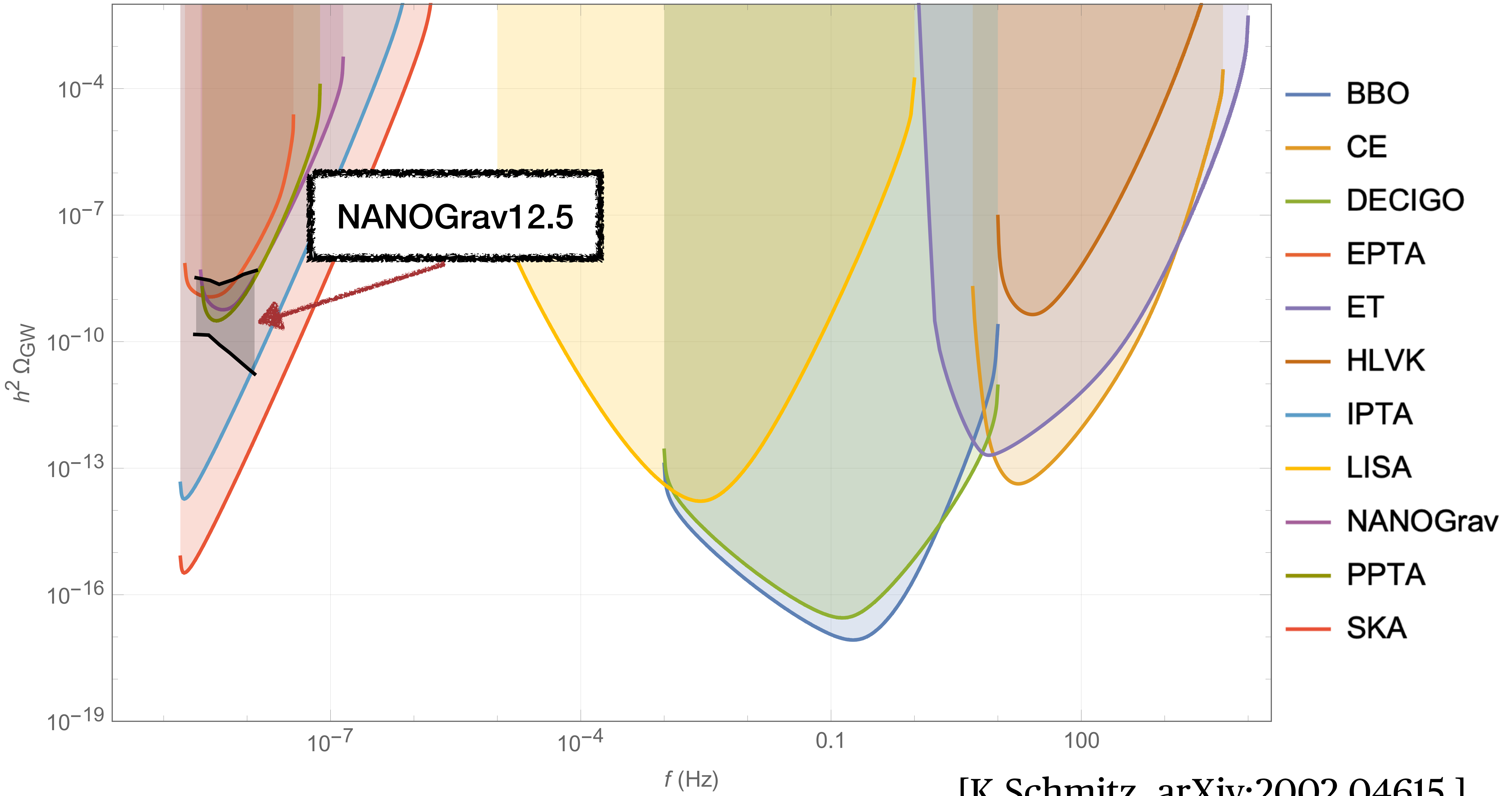
DECIGO, SKA : $\mathcal{P}_\mathcal{R} \sim 10^{-5}$

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, arXiv:2002.04615]
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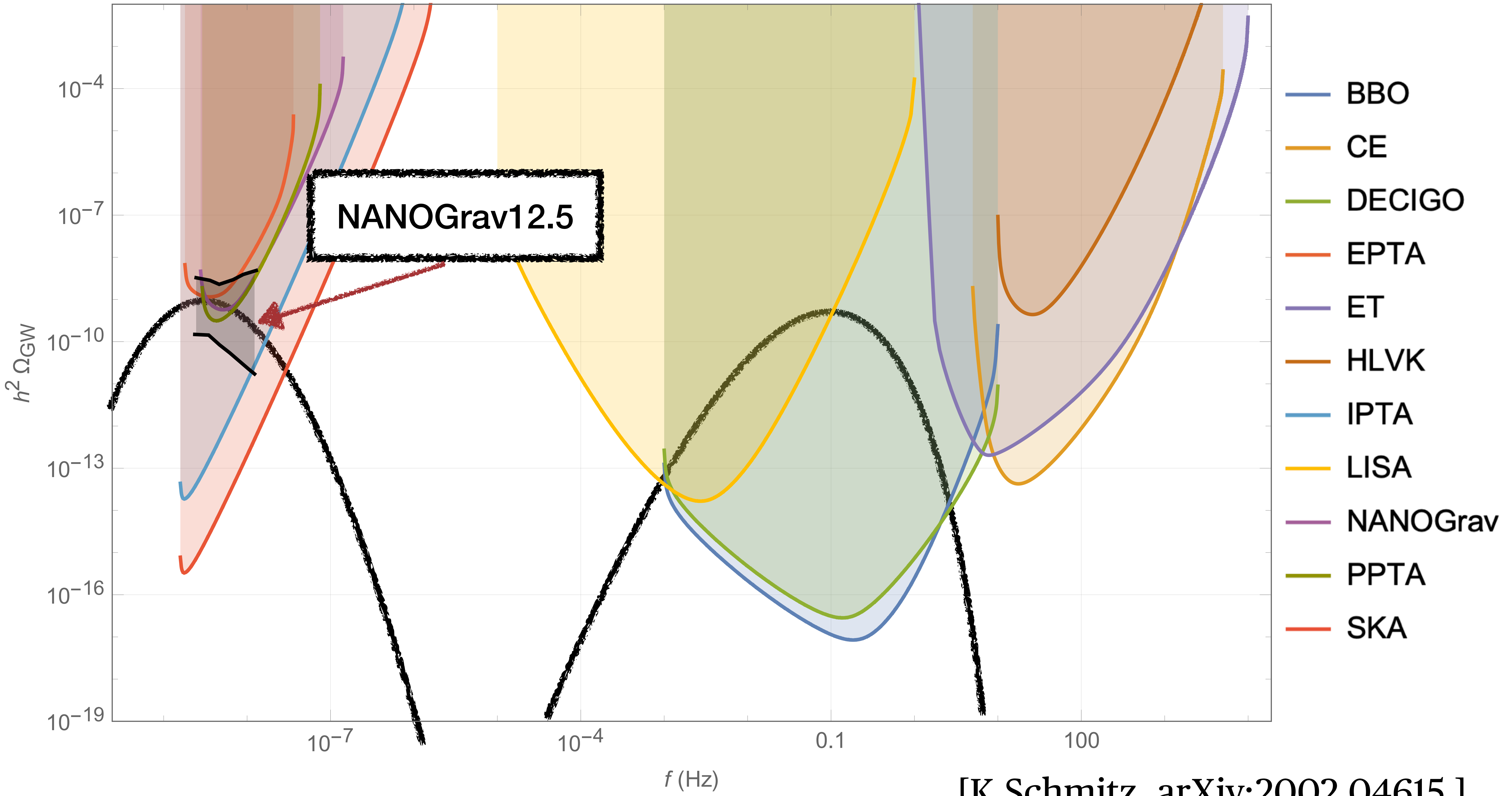

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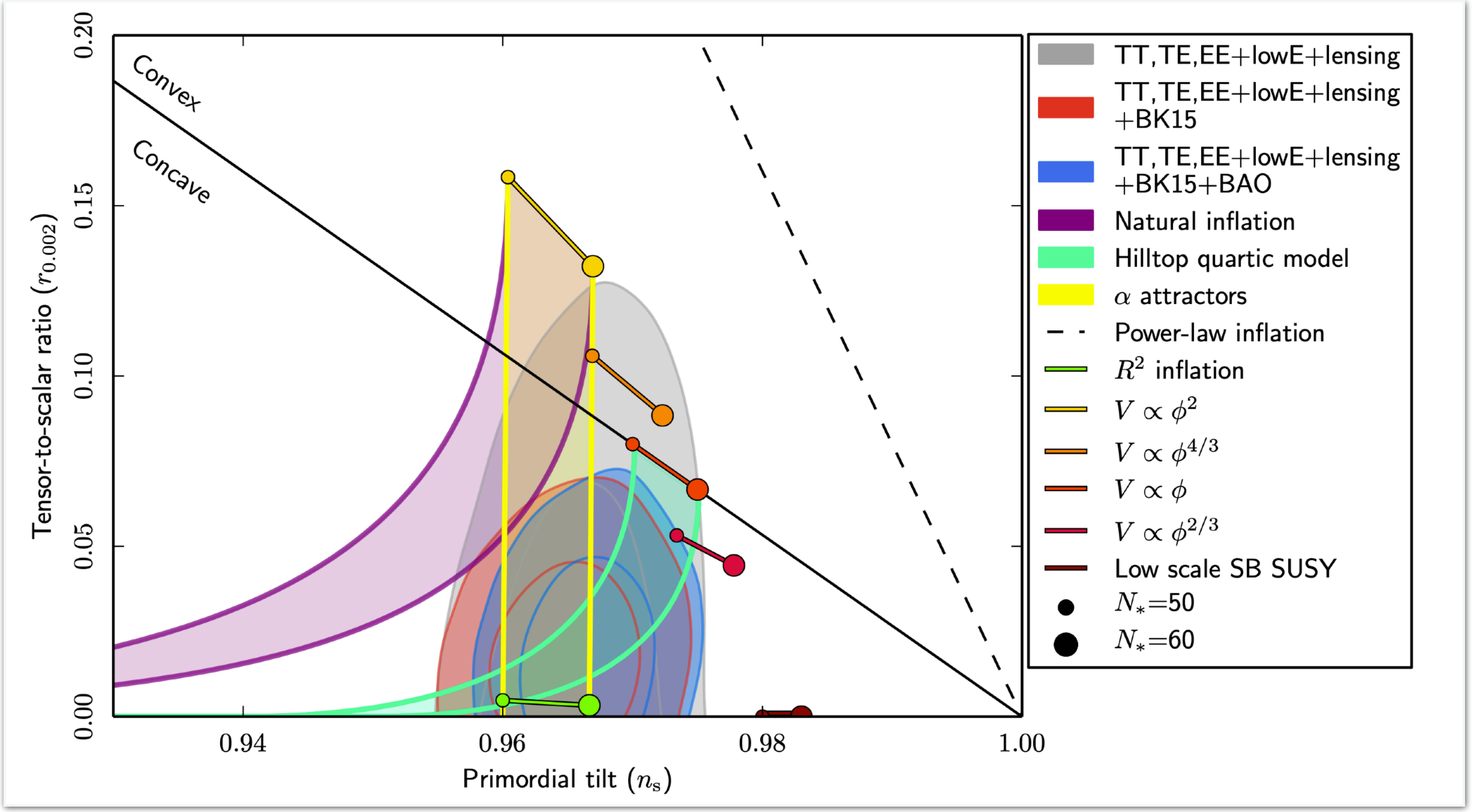
Introduction

Inflation paradigm very successful! CMB observations attempt constraining inflationary models.

[Planck Collaboration., arXiv:1807.06211]



Characterized by *slow-roll parameters*

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}^2}{2H^2}$$

$$\eta \equiv -\frac{\ddot{\phi}}{\dot{\phi}H}$$

$$n_s \simeq 1 - 6\epsilon + 2\eta$$

Q1) What can be our inflaton?

Q2) Phenomenology induced by inflation in smaller scales?

Introduction

Q1) What can be our inflaton?

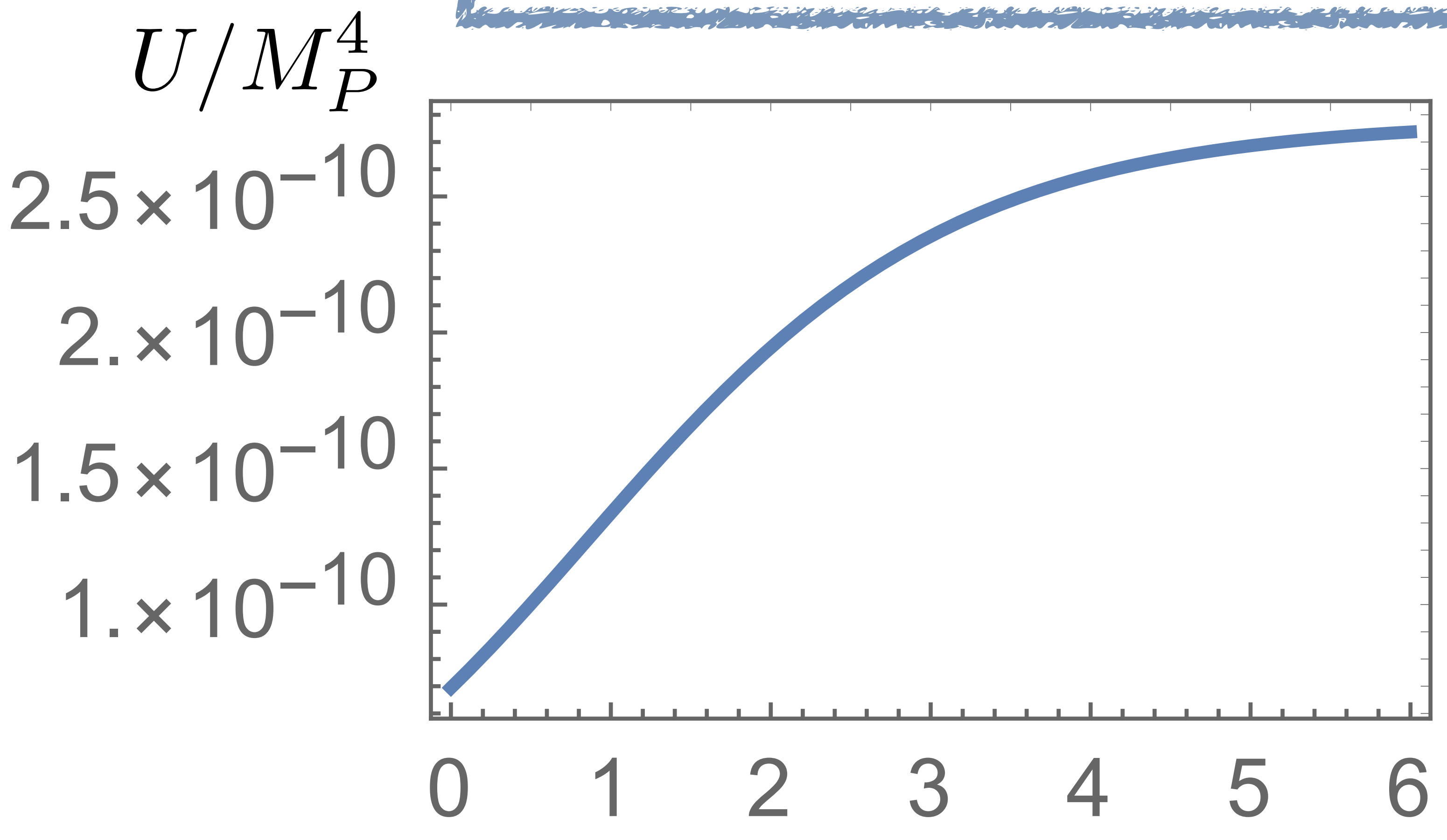
[F. Bezrukov, M. Shaposhnikov, 0710.3755]

—> Sole scalar particle in our Standard Model, the Higgs (with a non-minimal coupling to gravity)

$$S_J = \int d^4x\sqrt{-g_J}\left[\frac{1}{2}\left(M_P^2+\xi h_J^\dagger h_J\right)R_J - \frac{1}{2}\left|\partial_\mu h_J\right|^2 - V\left(h_J\right)\right]$$

$$g_{\mu\nu} = \Omega(h_J)^2 g_{J\mu\nu} \qquad \Omega(h_J)^2 = 1+\frac{\xi h_J^2}{M_P^2}$$

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_P^2 R - \frac{1}{2}\left|\partial_\mu h\right|^2 - U(h)\right] \qquad U(h)\simeq\frac{\lambda M_P^4}{4\xi^2}\left(1+e^{-\sqrt{\frac{2}{3}}\frac{h}{M_P}}\right)^{-2}$$



- Theoretical issues reside? : $\frac{\lambda}{\xi^2}\sim 10^{-10}$

  —> $\lambda \ll 1$ achievable when considering SM running

- Naive cutoff scale appears at $\Lambda\sim\frac{M_P}{\xi}$ for $\xi\sim\mathcal{O}(10^3)$

  —> Issues in the (p)reheating era, unitarity problem?

Introduction

Q1) What can be our inflaton?

[Y. Ema, Phys. Lett. B770:403-411, 2017]
[Y-C. Wang, T. Wang, Phys. Rev. D96(12):123506, 2017]
[M.He, A. A. Starobinsky, J. Yokoyama, JCAP, 1805(05):064, 2018]

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

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

non minimal coupling — R^2 term — Higgs

Conformal transformation into Einstein frame

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

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

Introduction

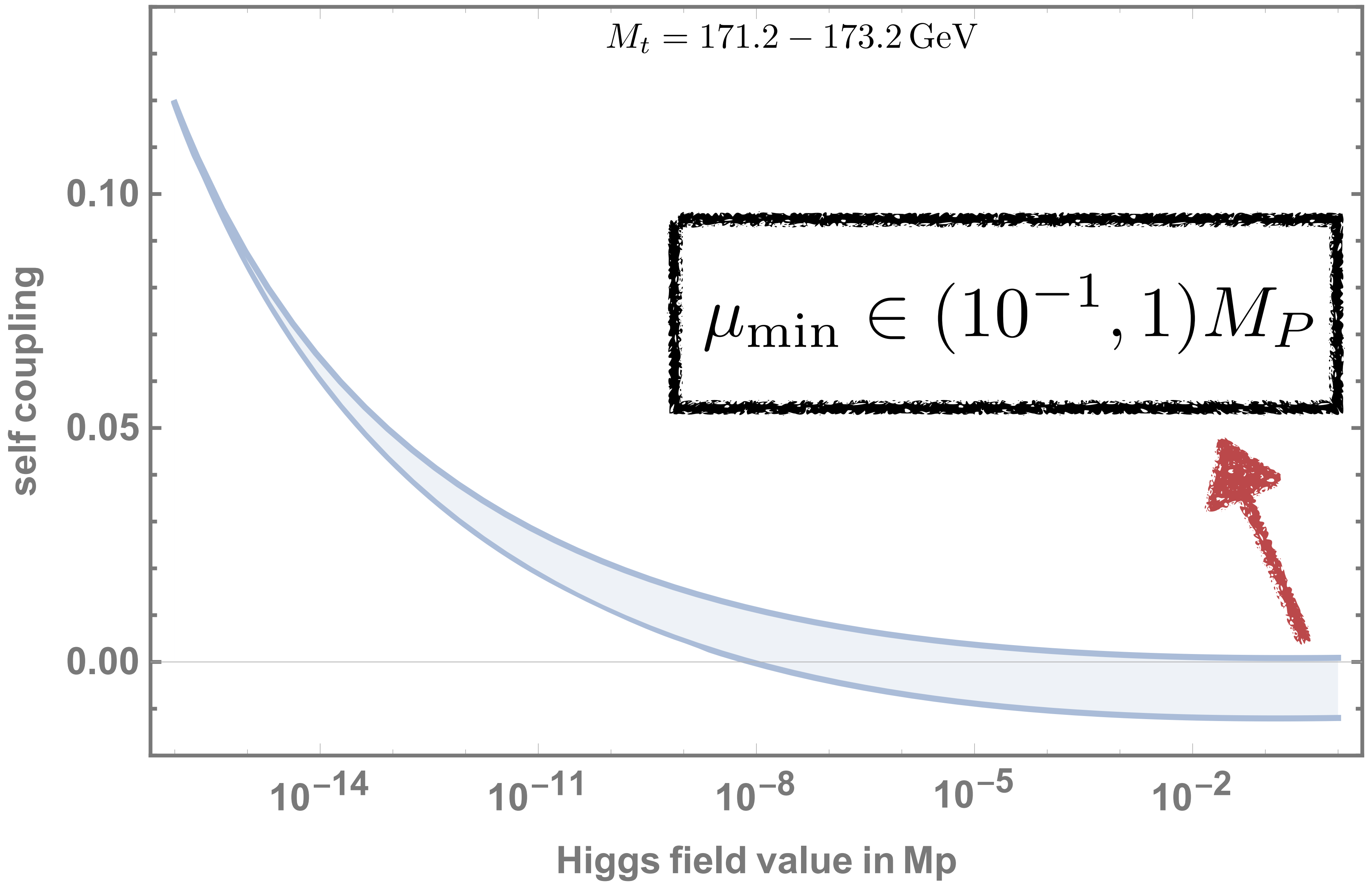
Q1) What can be our inflaton? —> Higgs + R^2

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

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

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

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



Choosing $\mu \simeq \sqrt{h^2}$

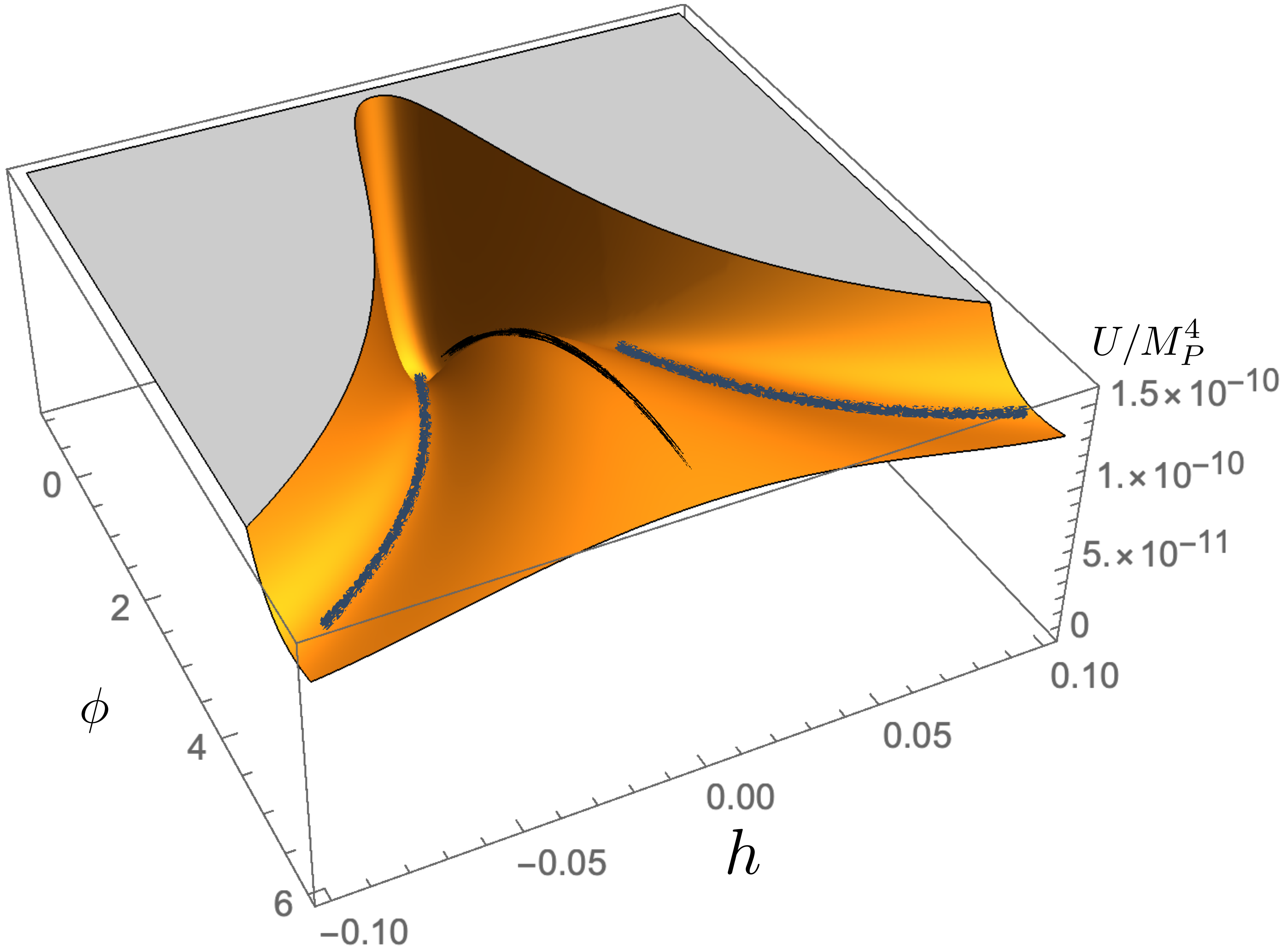
$$\lambda(\mu)|_{\mu=h} = \lambda_m + \frac{\beta_2^{\rm SM}}{(16\pi^2)^2} \ln^2\left(\sqrt{\frac{h^2}{h_m^2}} \right) = \lambda_m + b \ln^2\left(\sqrt{\frac{h^2}{h_m^2}} \right)$$

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

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

Higgs-R^2 Inflation

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



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

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

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

➡ Flat plateau induced in the large s limit.

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

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

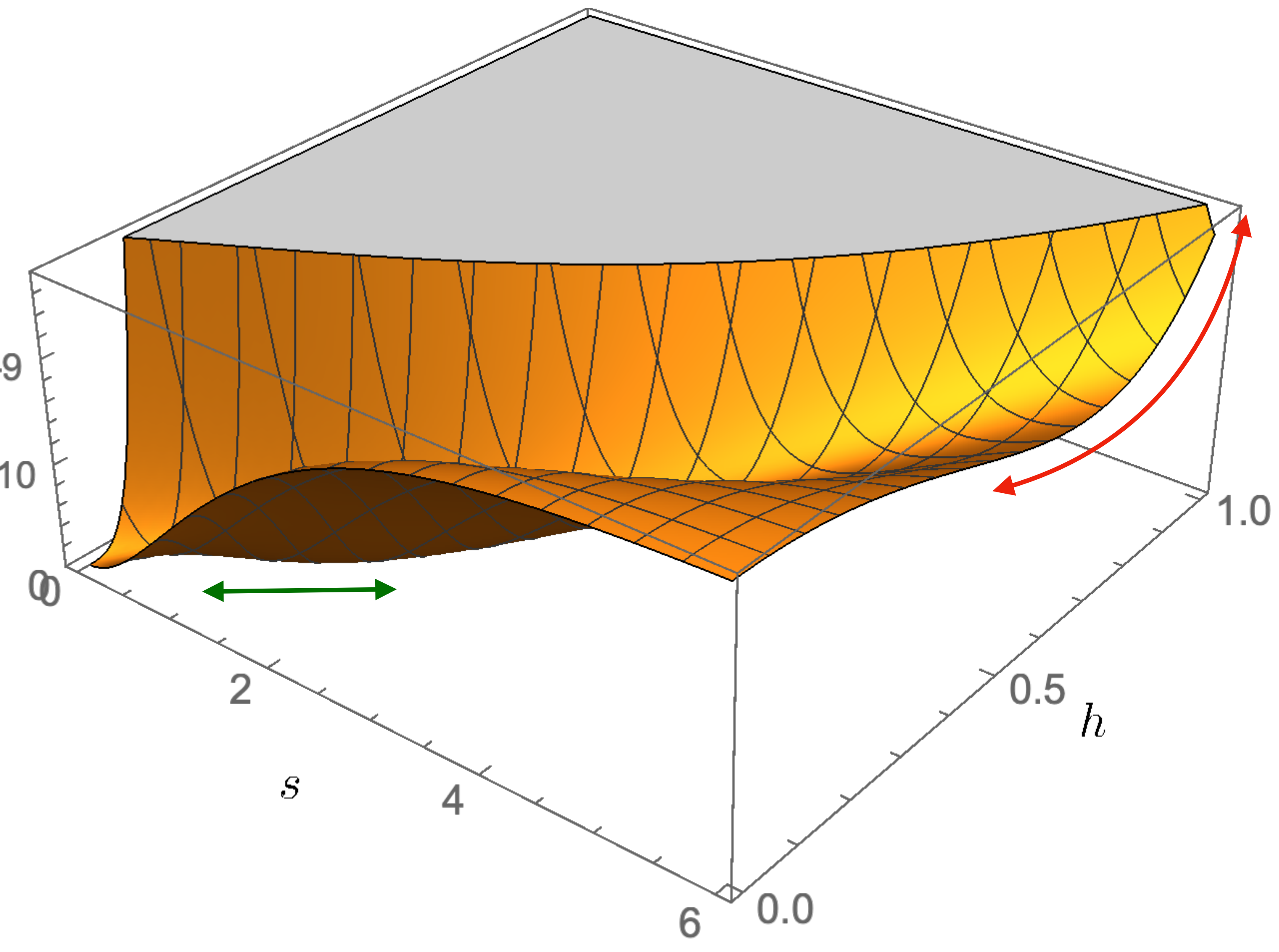
- Previous studies focused on inflationary dynamics *inside the valley, but rich phenomena also on the hill.*

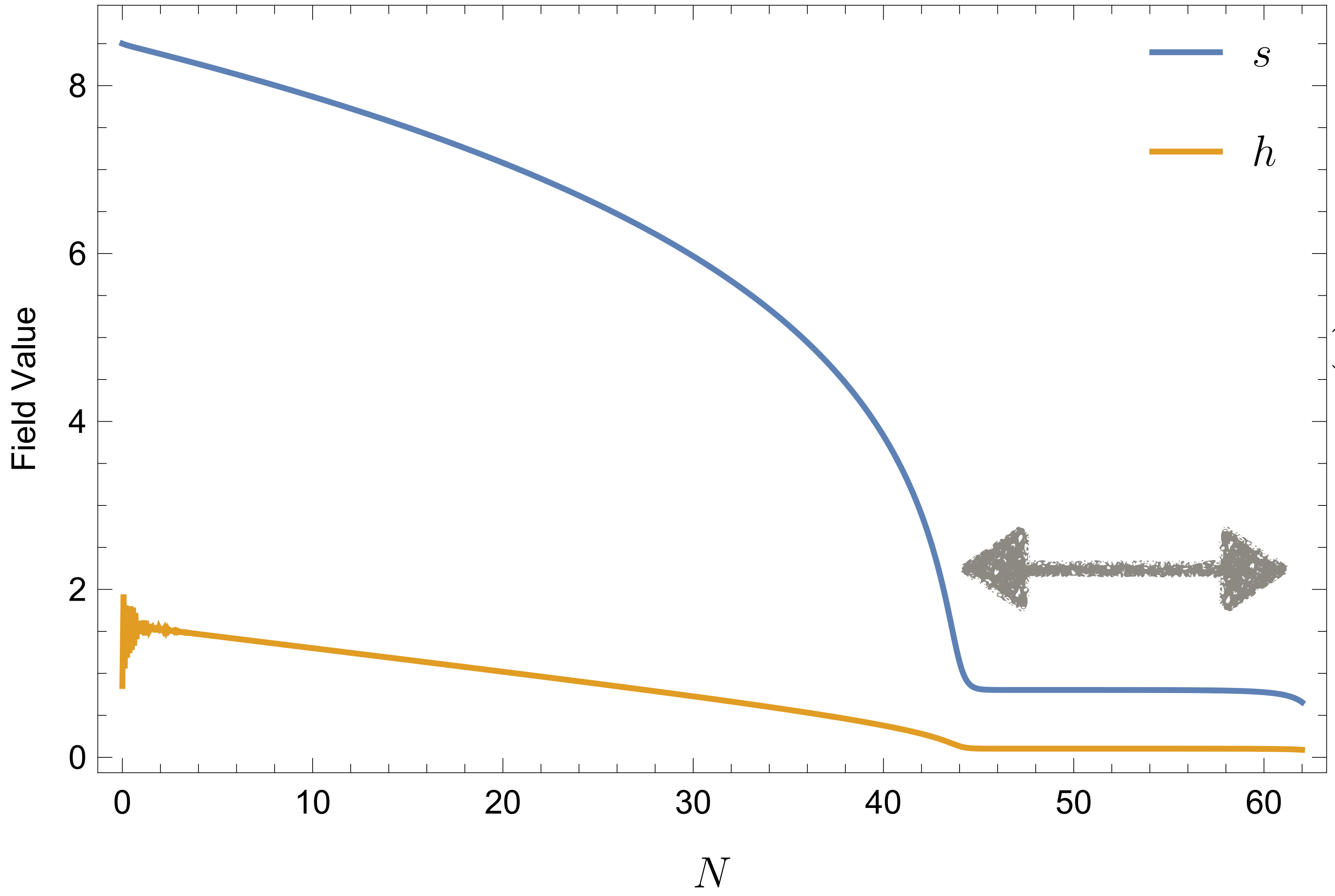
[M. He, *et. al*,. *PLB*, *791*, 36-42 (2019).]
[F. Bezrukov, *et. al*,. *PLB*, *795*, 657-665 (2019).]
[M. He, *et. al*, *JCAP* 01 (2021) 066.]
[F. Bezrukov, C. Shepherd *JCAP* 12 (2020) 028.]
[S. Aoki *et. al*, arXiv:2202.13063], and many more

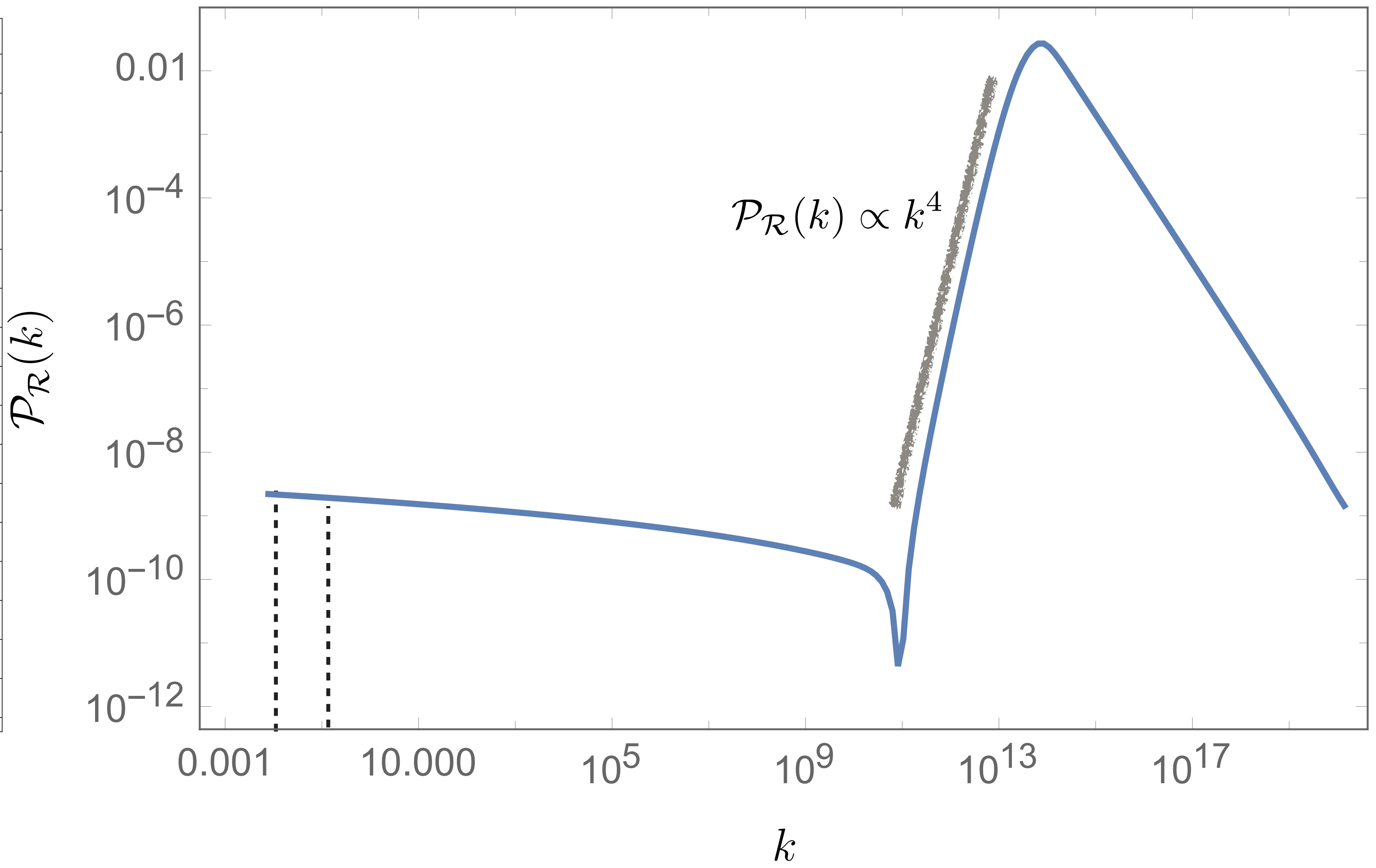
Higgs-R^2 Inflation - Ultra Slow-Roll

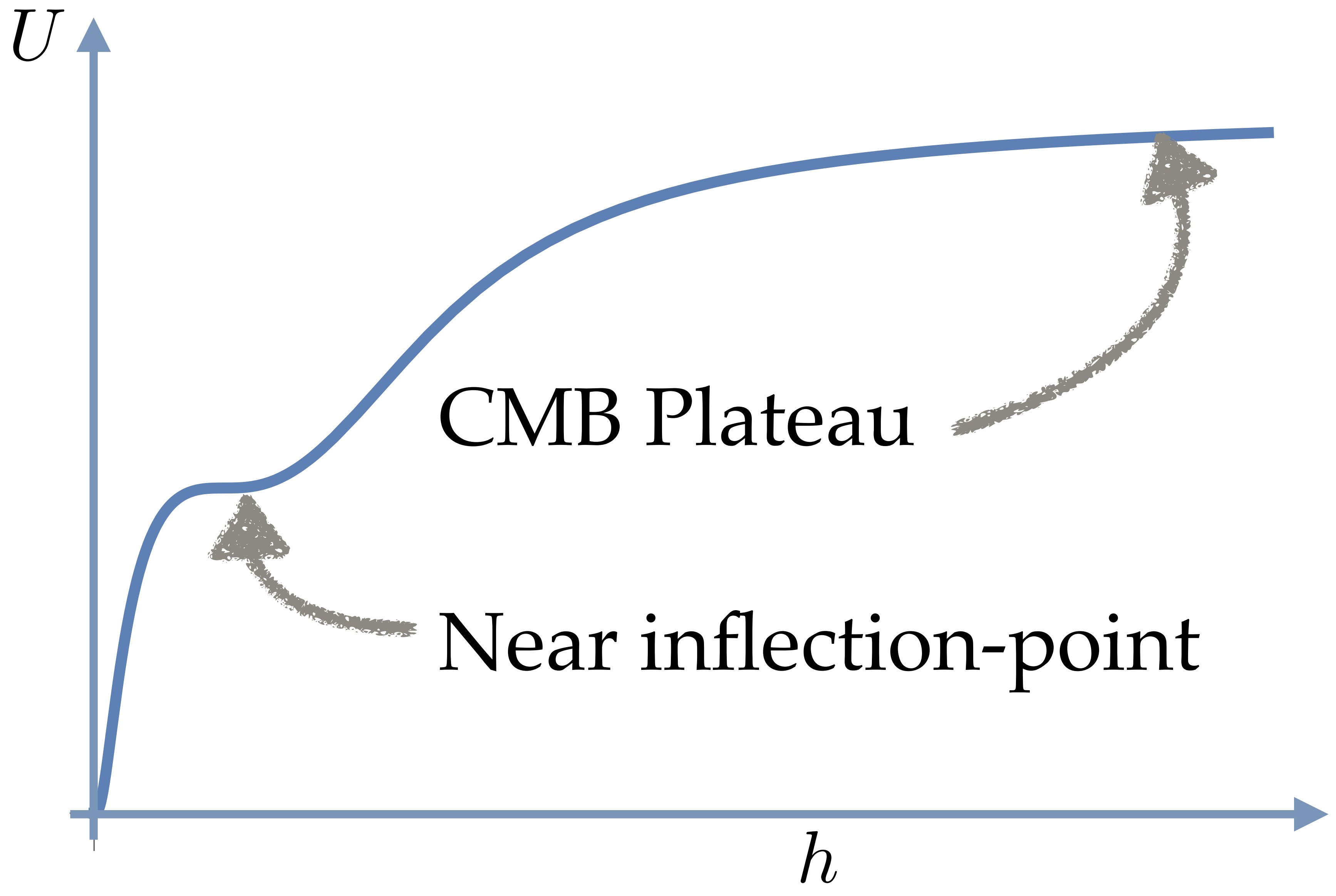
[DYC, S.M. Lee, S.C. Park, JCAP 01 (2021), 032]

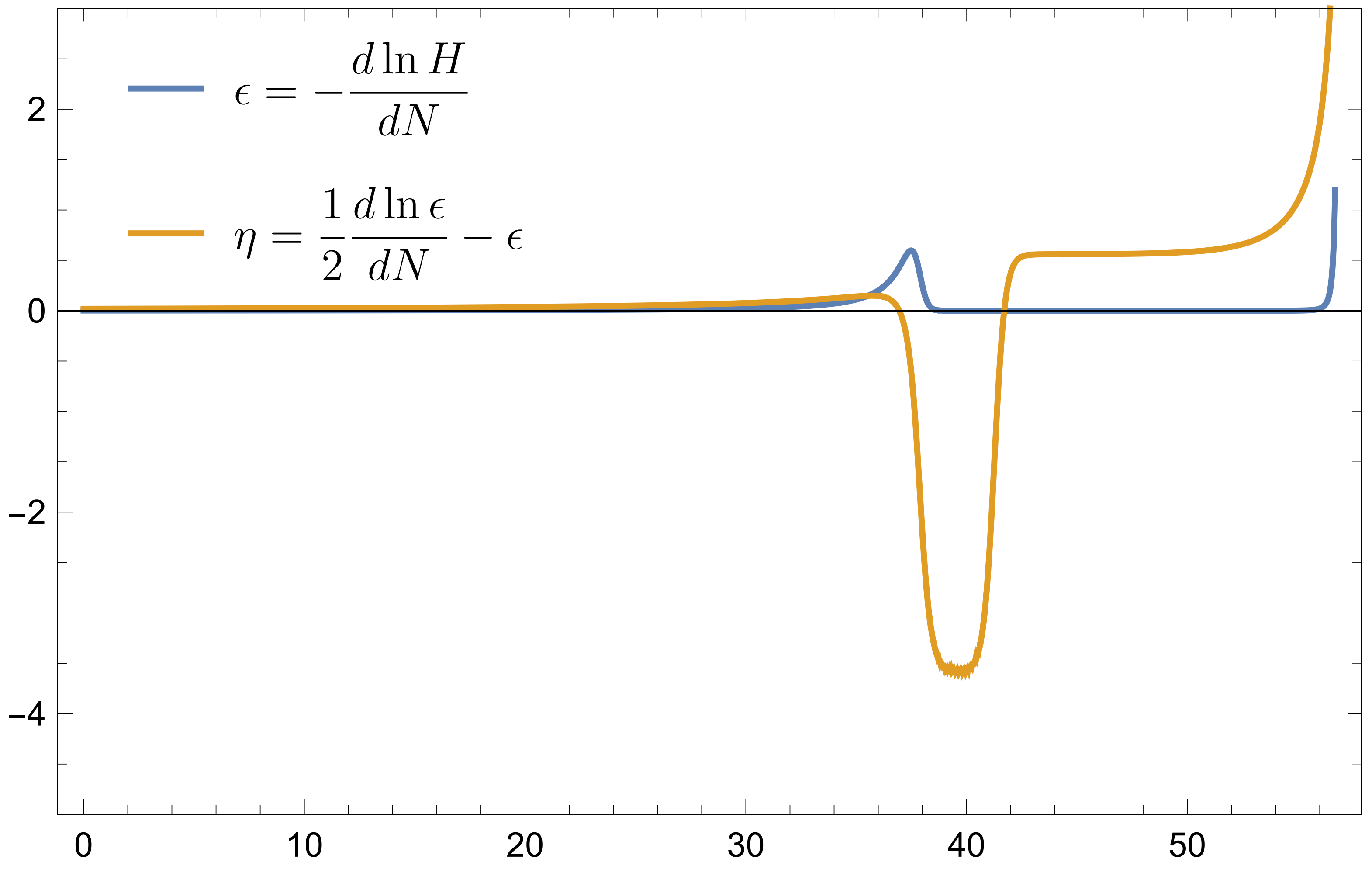
$$M = 4.2 \times 10^{-5} M_P \quad \xi = 79 \quad h_{\rm min} = 0.15 M_P \quad b = 2 \times 10^{-5} \quad \lambda_{\rm min} = 4.11087 \times 10^{-6}$$











- USR phase induced by $\lambda(h)$. Inflaton *always* rolls down the well defined valley
- $\eta > 3$, Growth in the curvature perturbation
- Growth proportional to $\propto k^4$

Higgs-R^2 Inflation - Ultra Slow-Roll

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

$$\mathcal{P}_{\mathcal{R}}(k) \propto \frac{H^2}{\epsilon} e^{(4\eta - 6)Ht}$$

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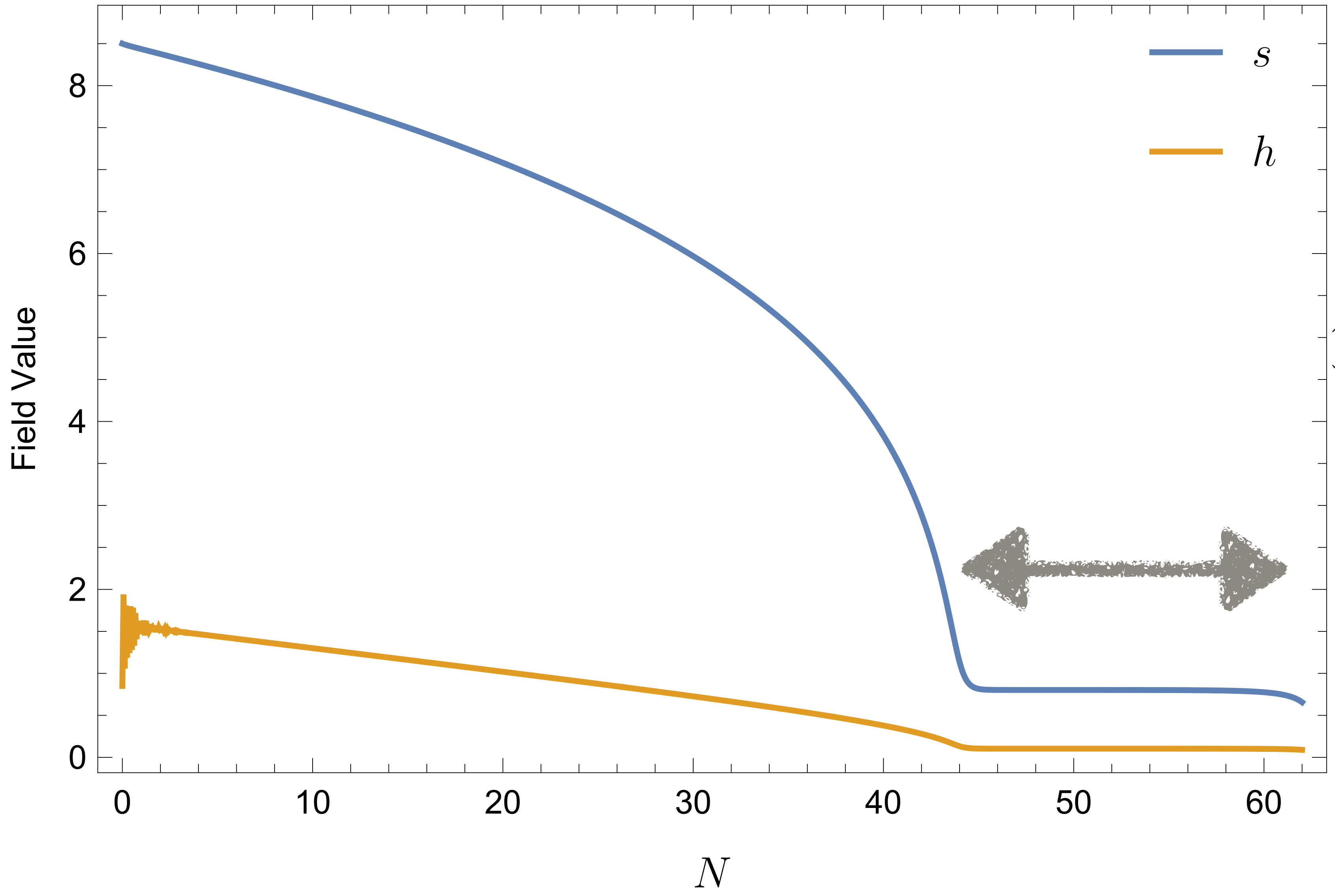

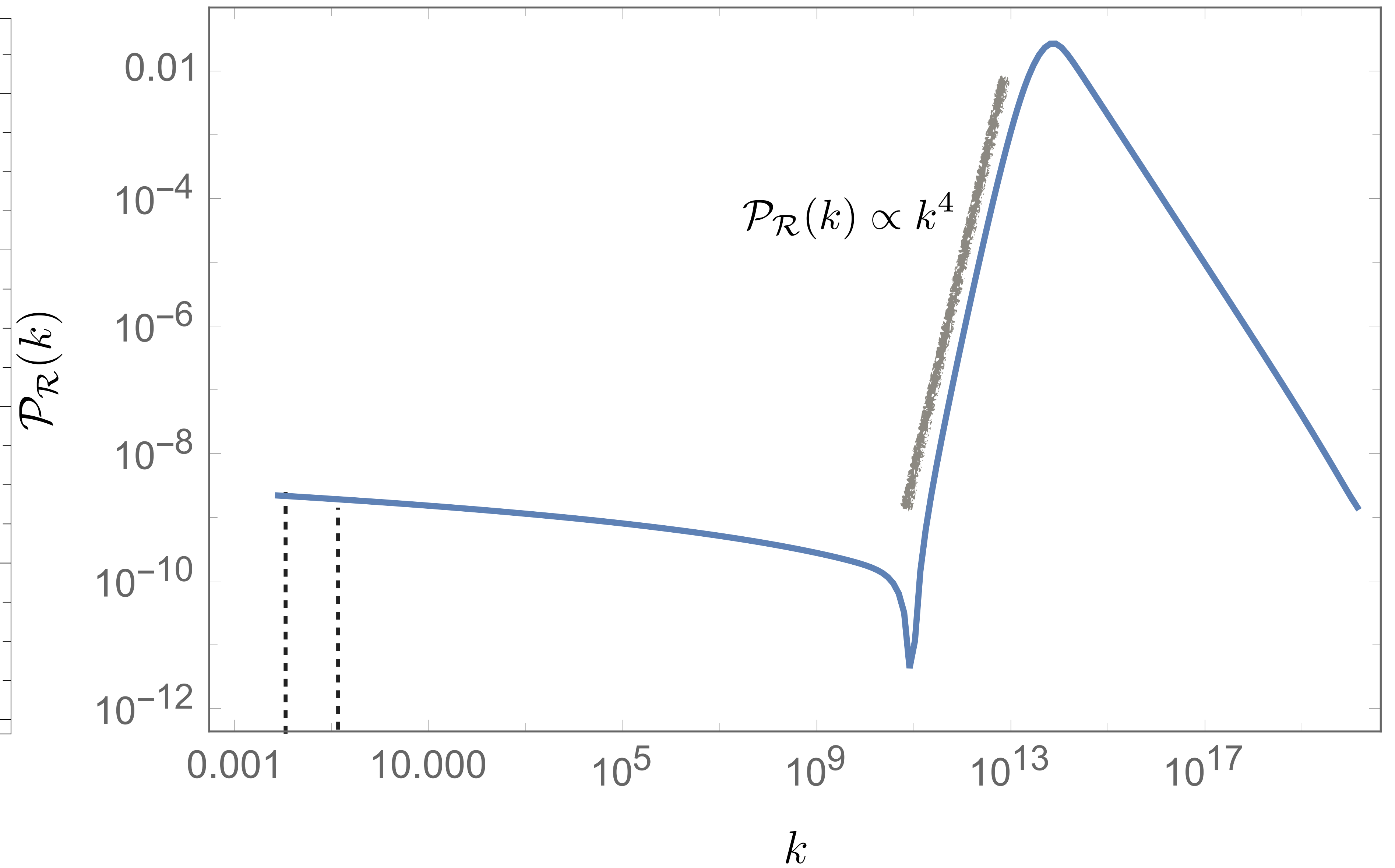

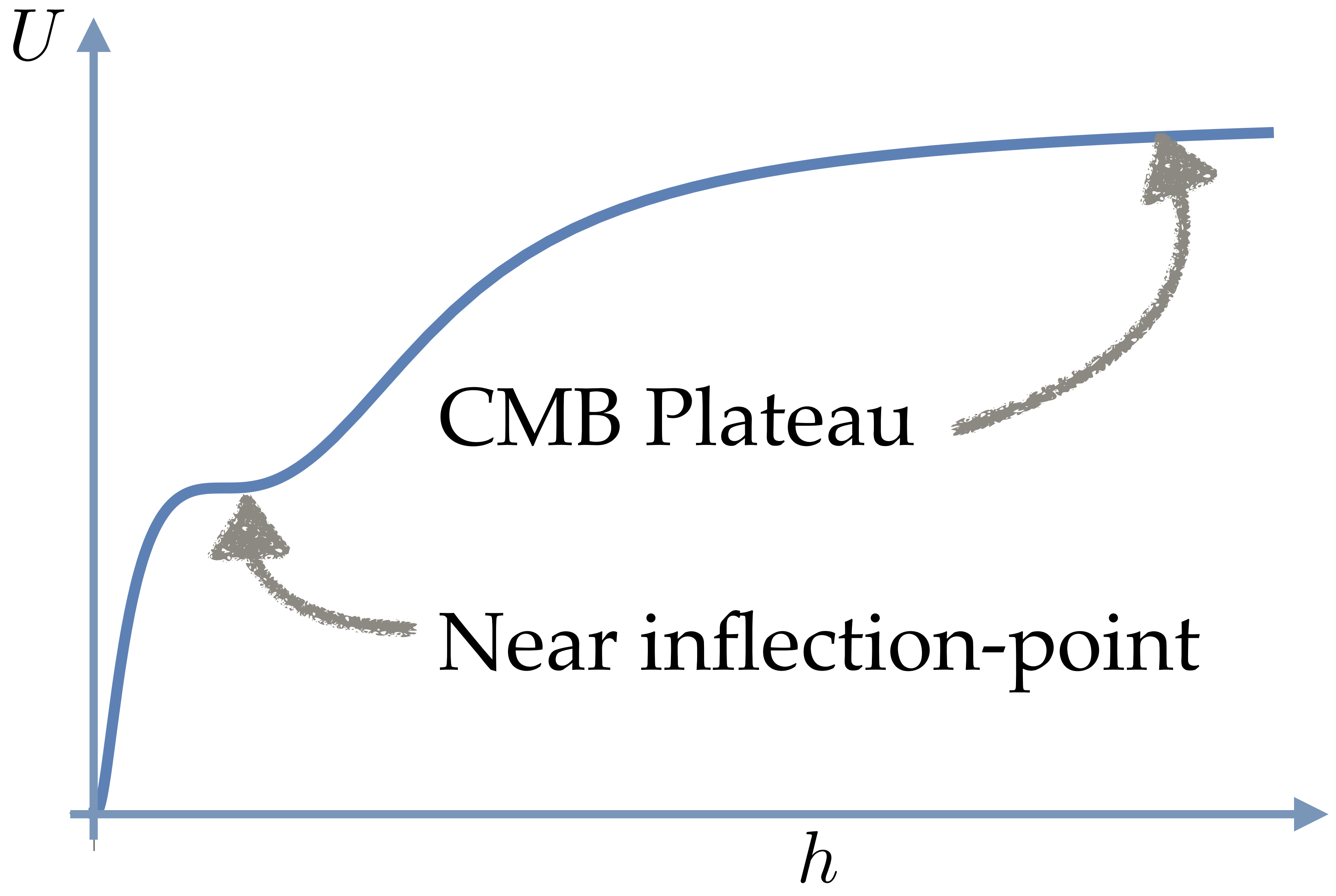

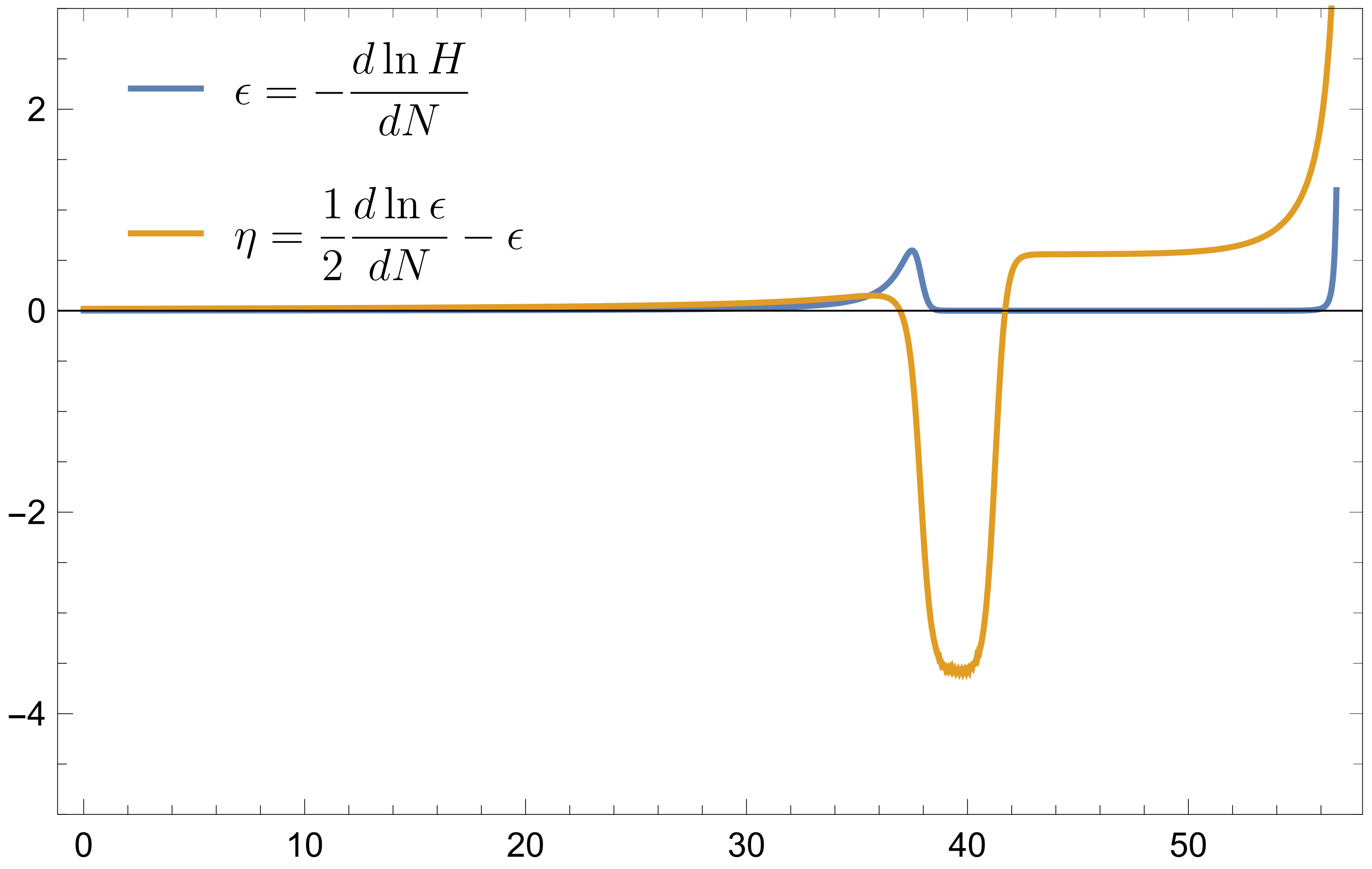

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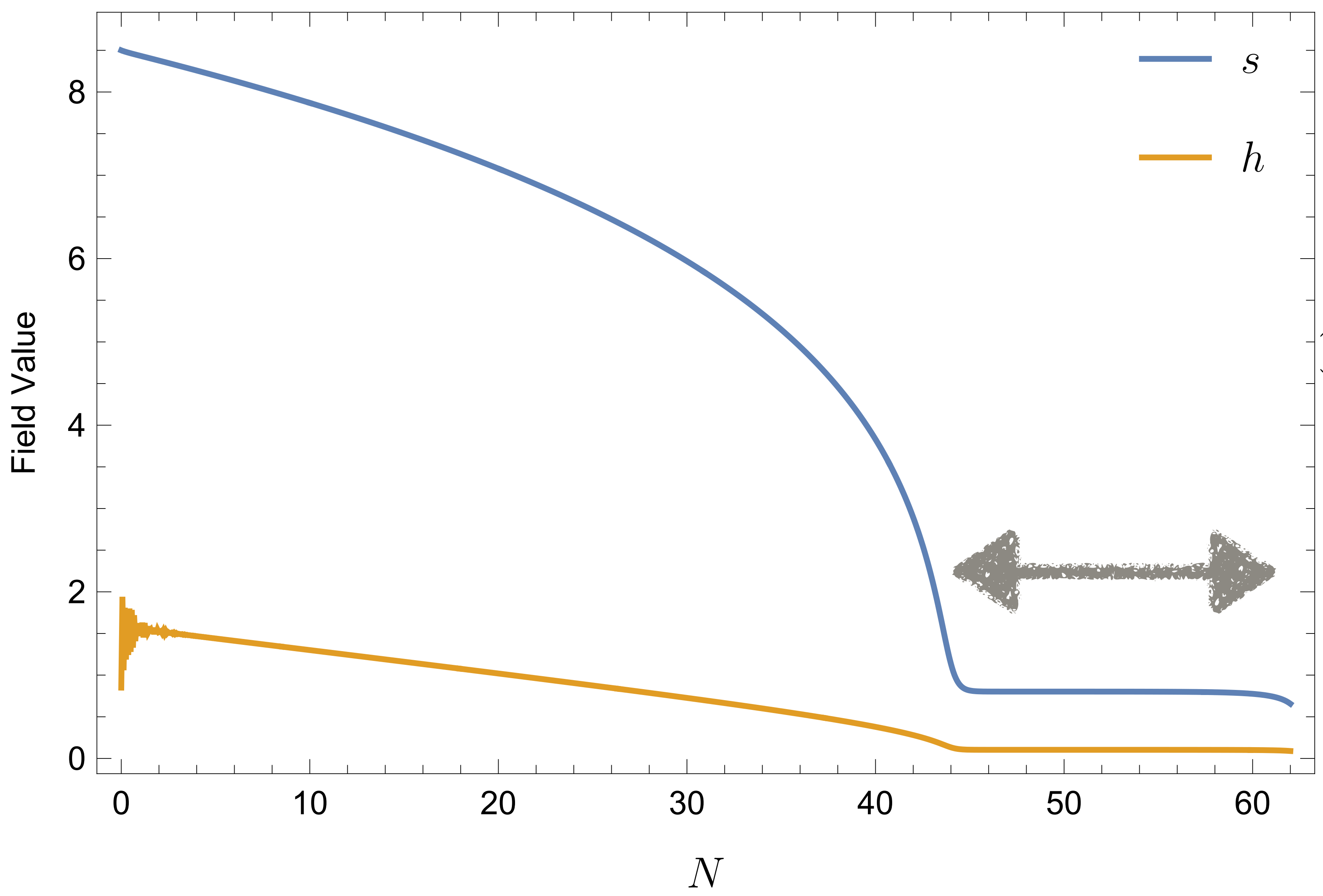

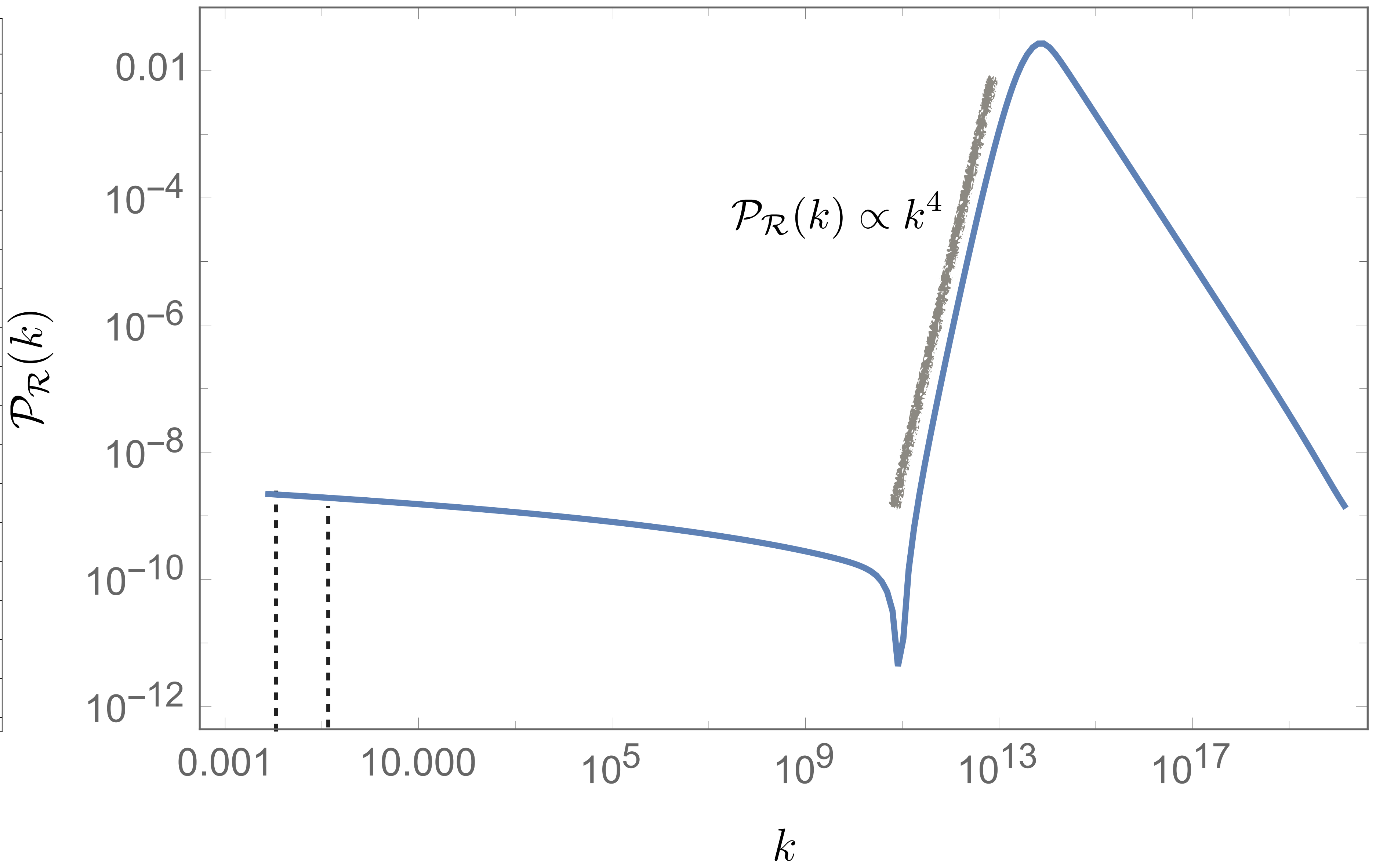

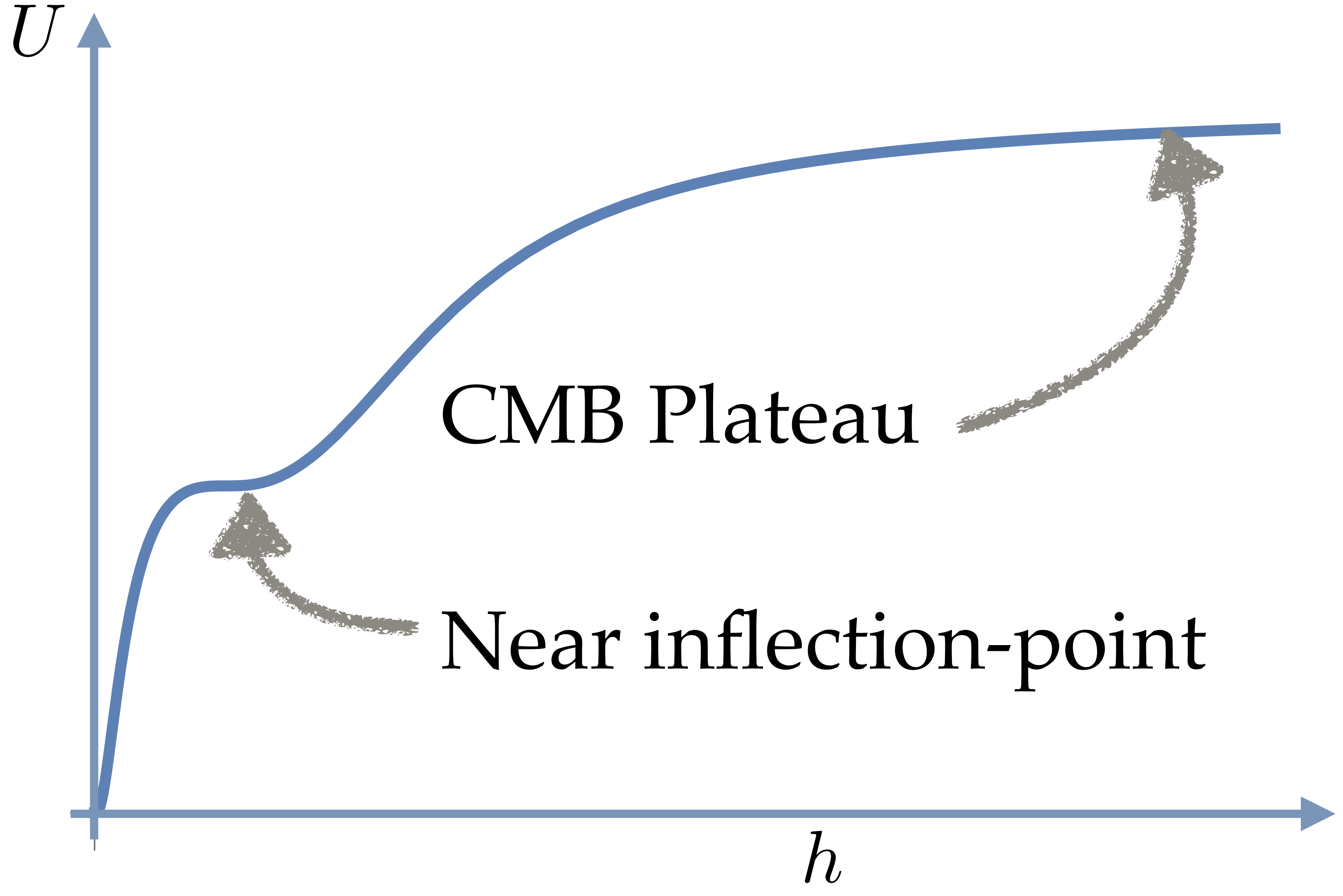

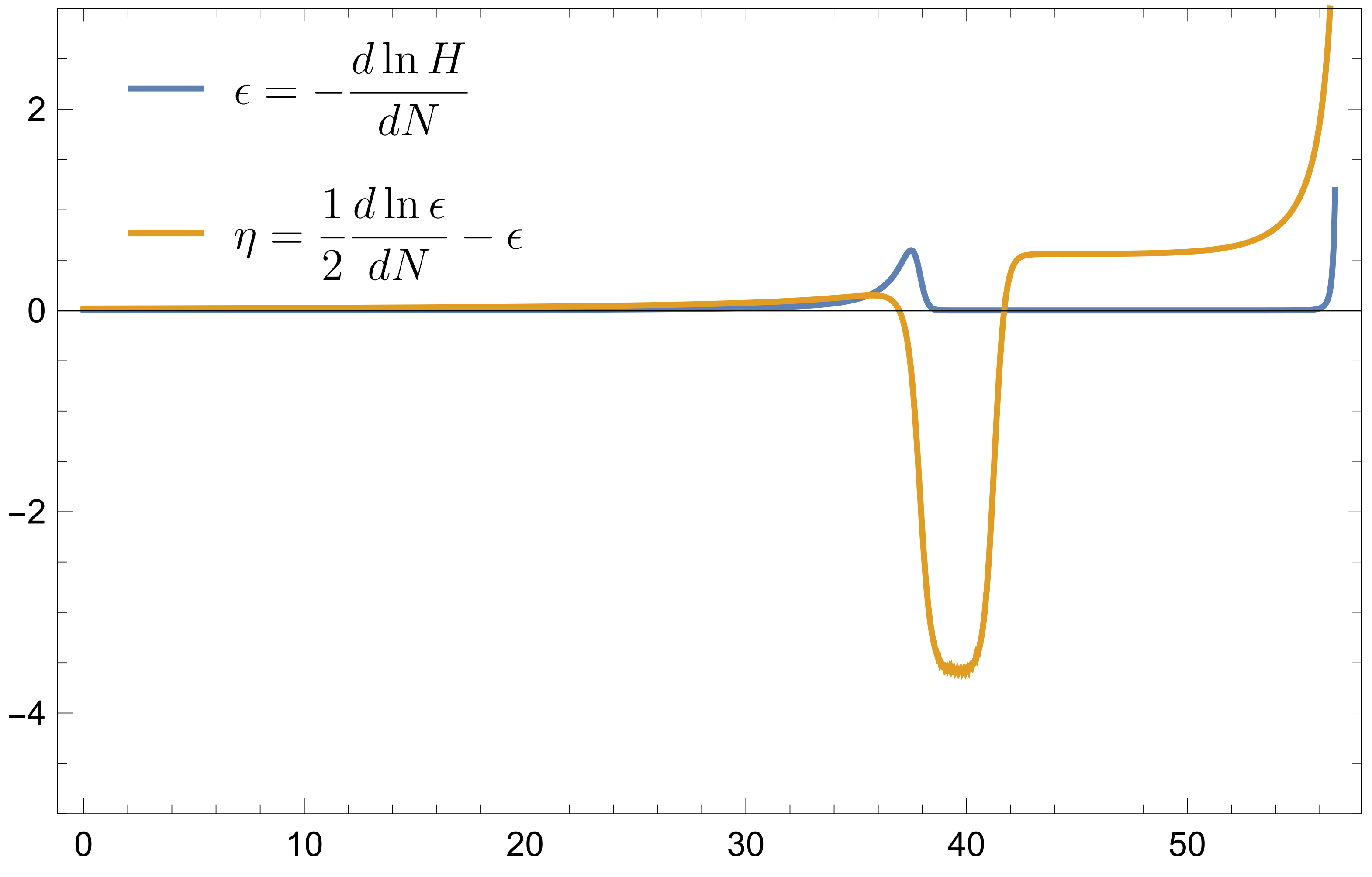

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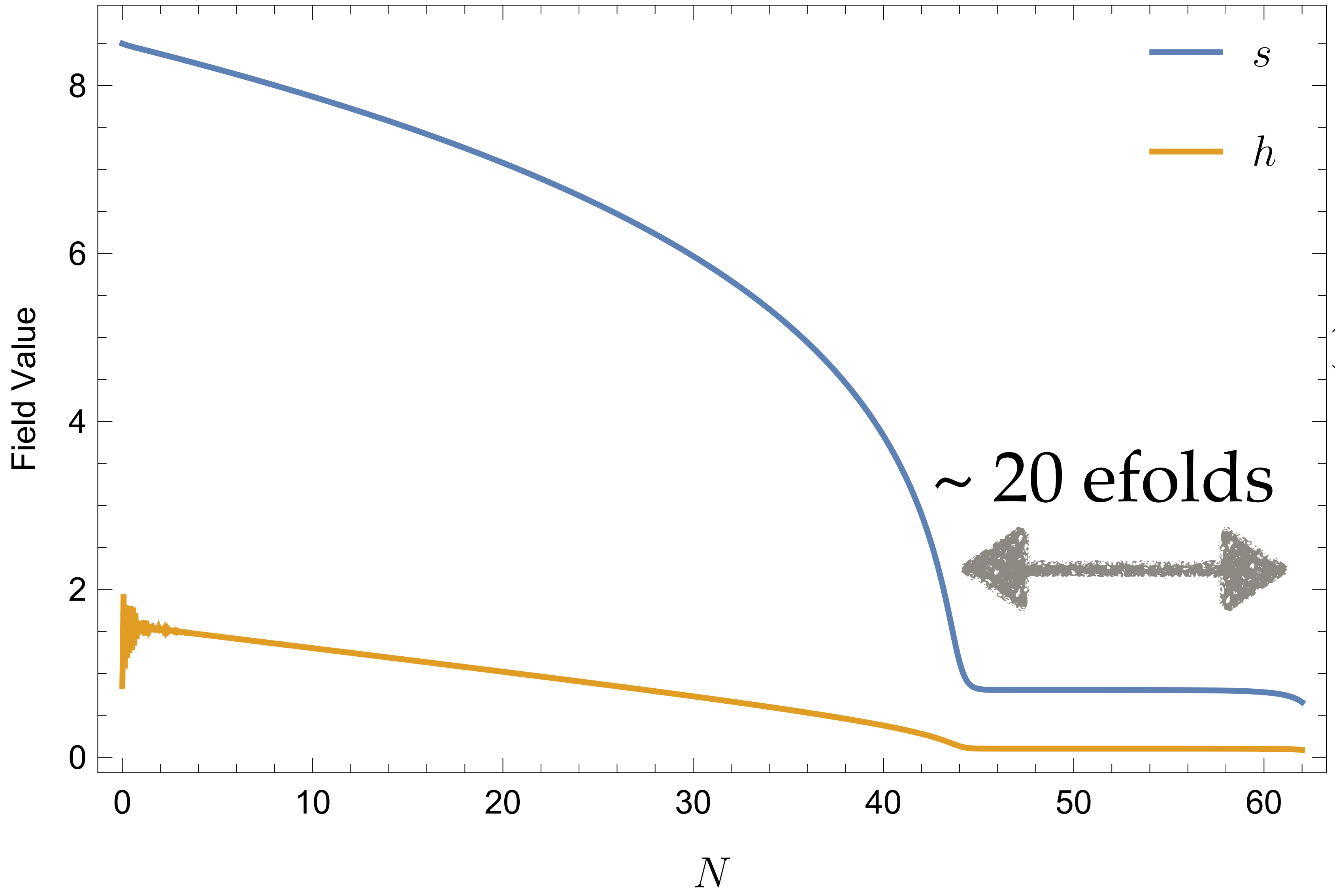
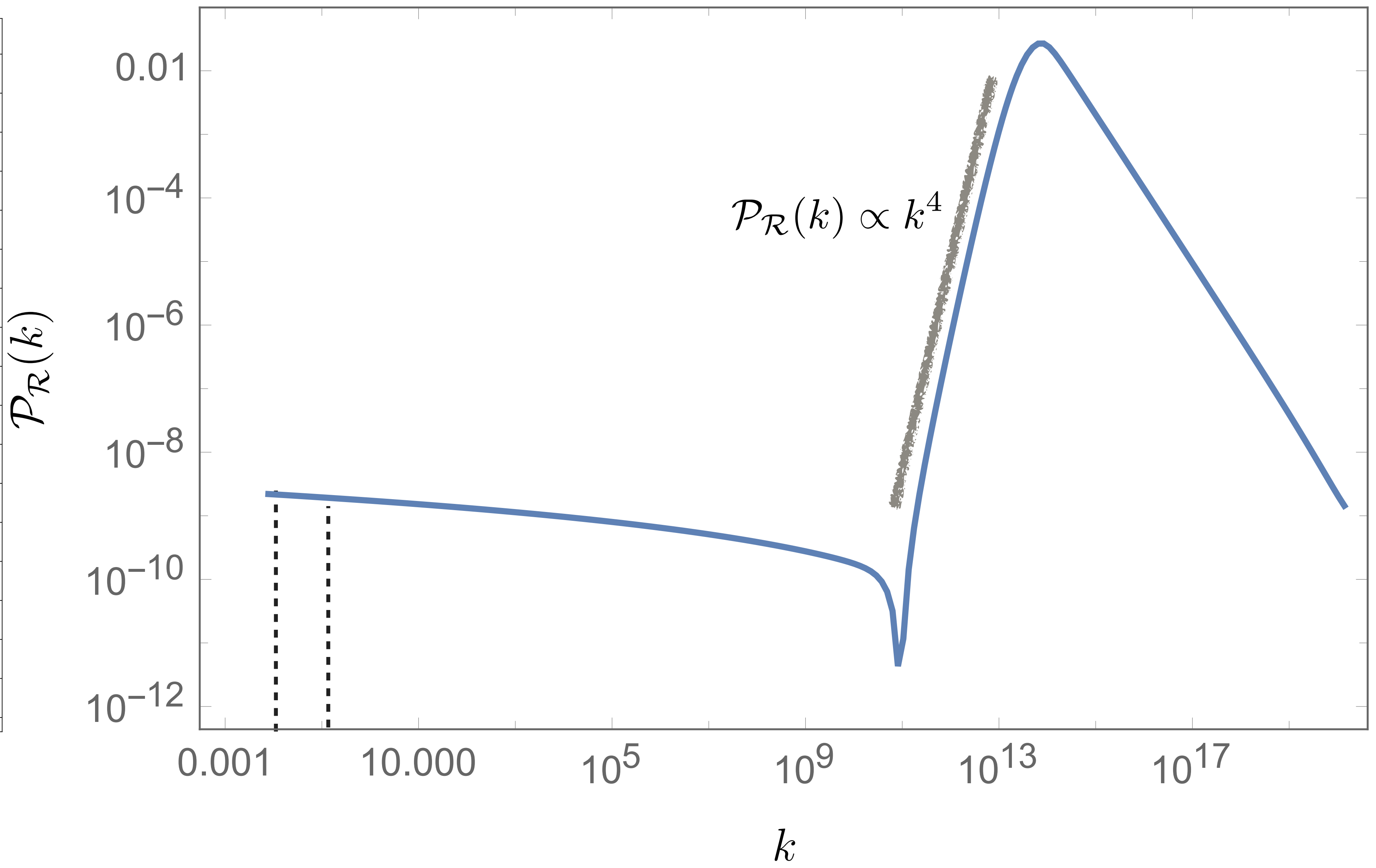
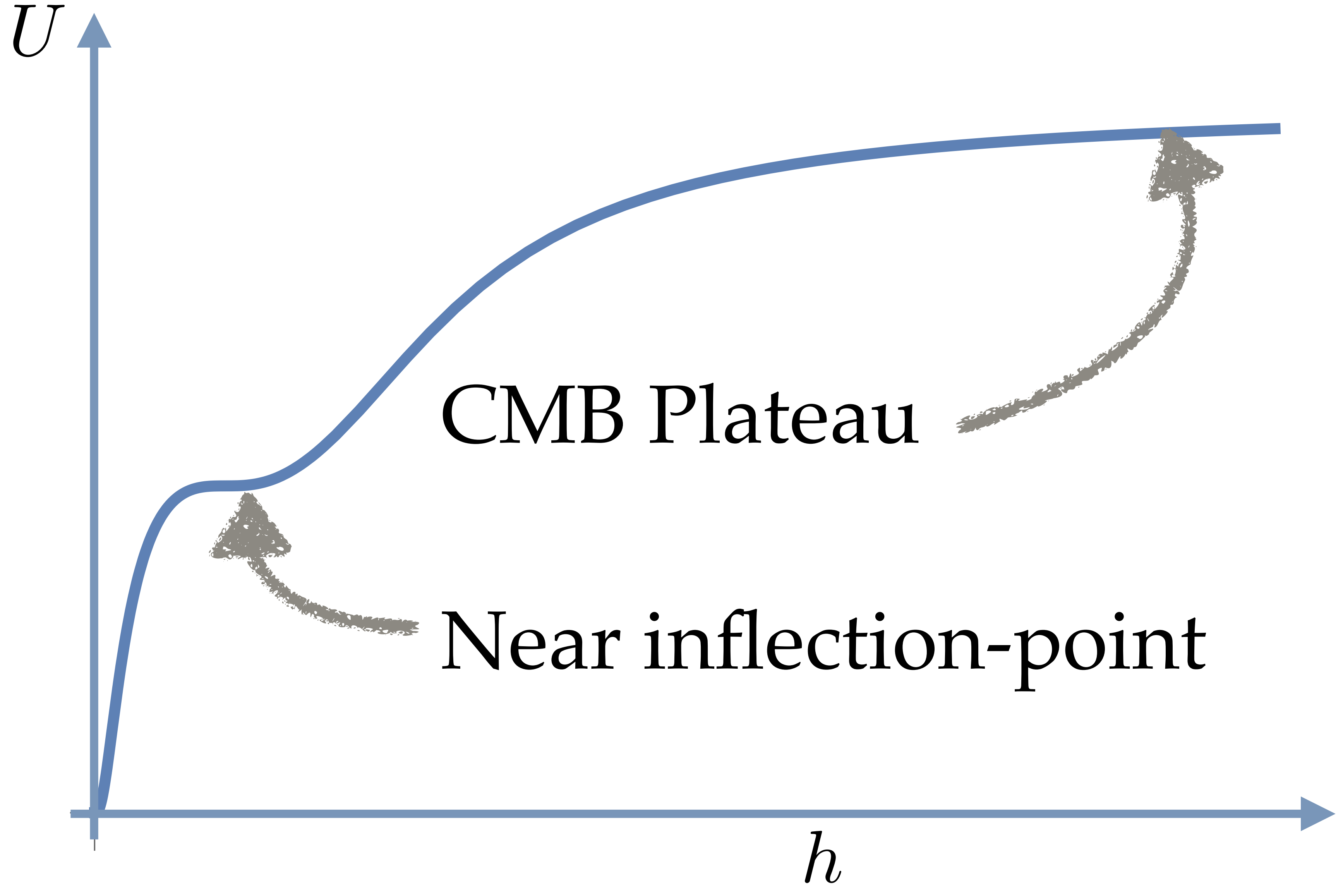
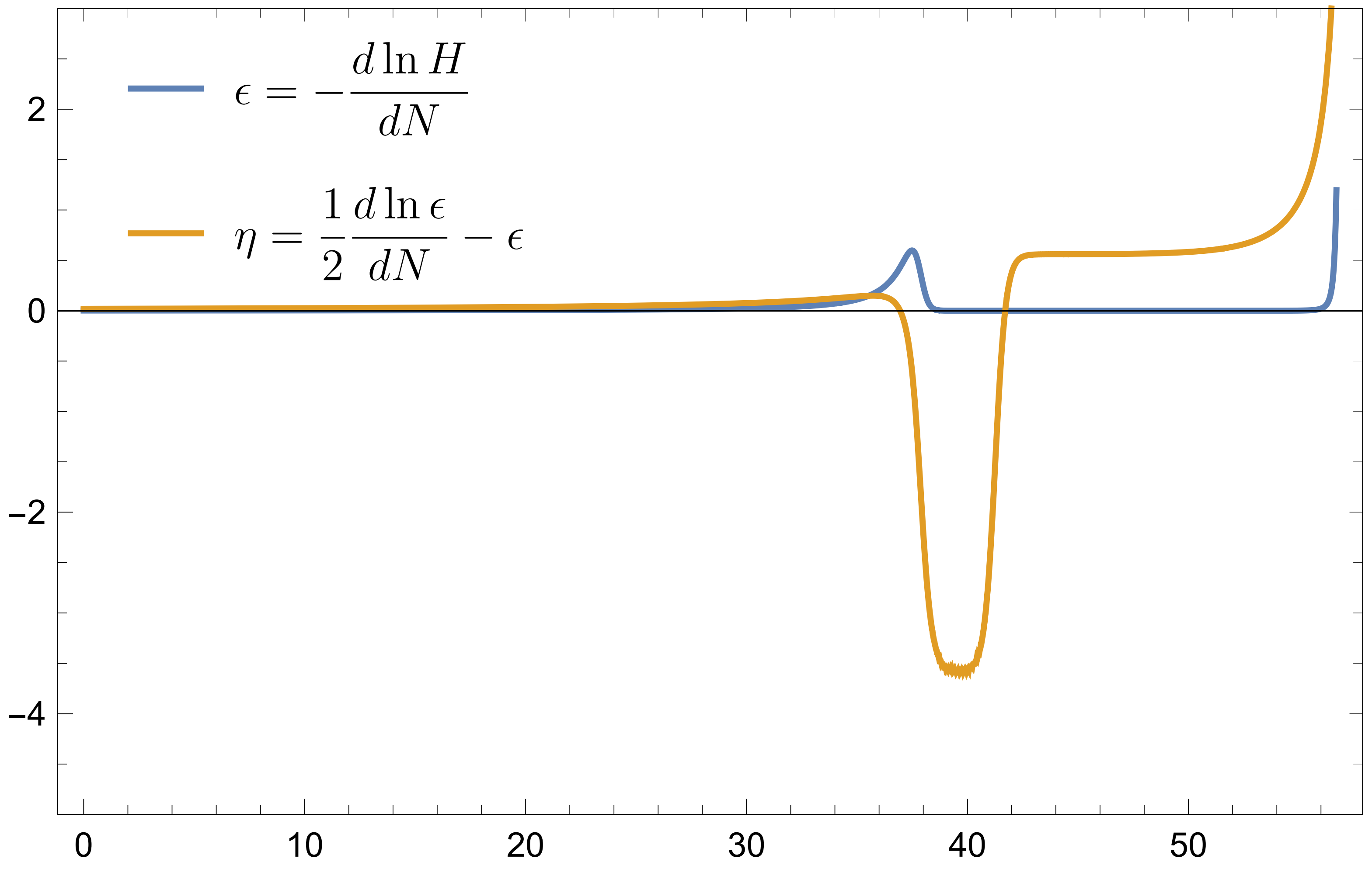
$\epsilon \ll 1$ ⟷ $\dot{\phi} \simeq 0$

$\eta > \frac{3}{2}$ ⟷ $\ddot{\phi} \sim \dot{\phi} \simeq 0$









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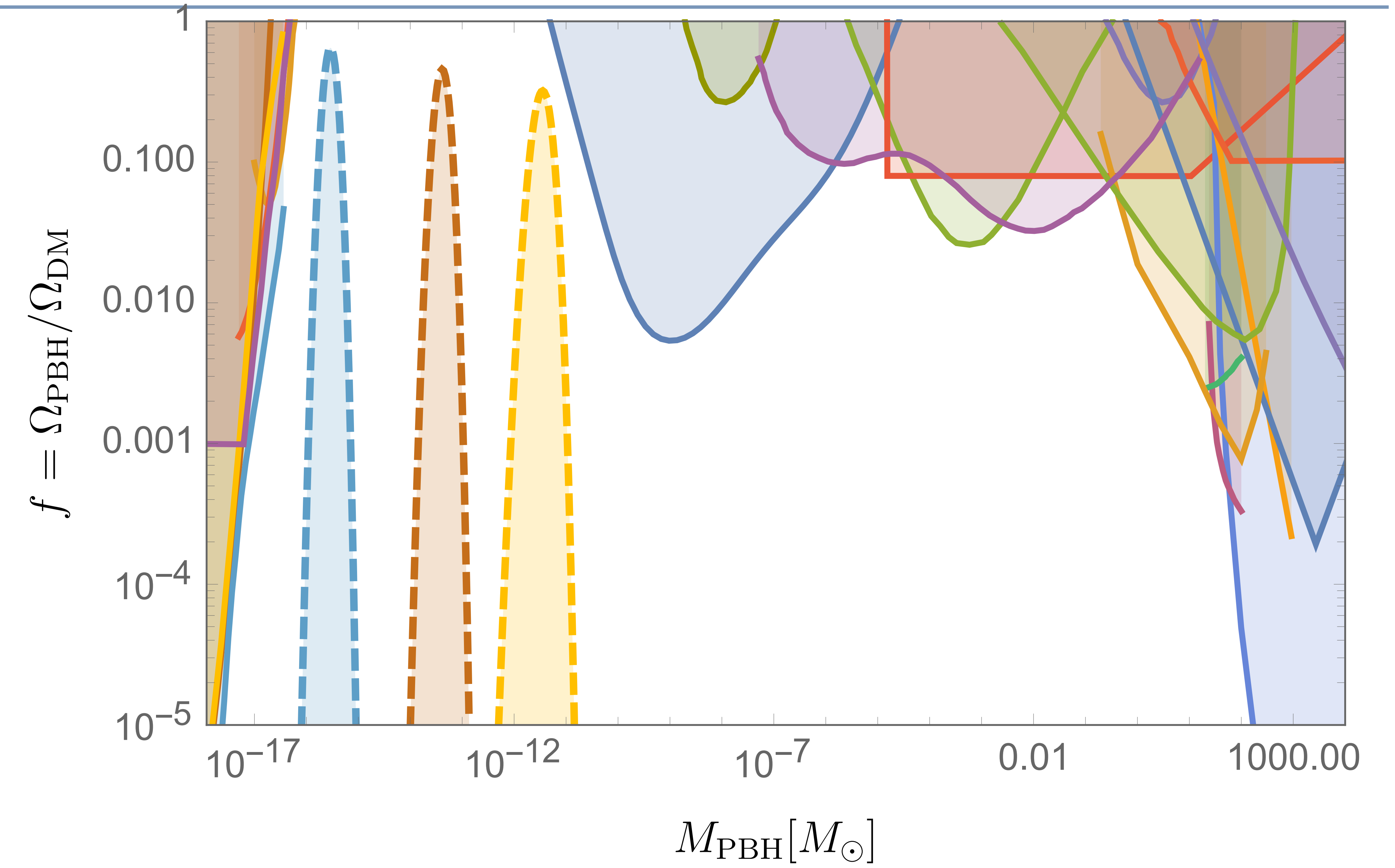
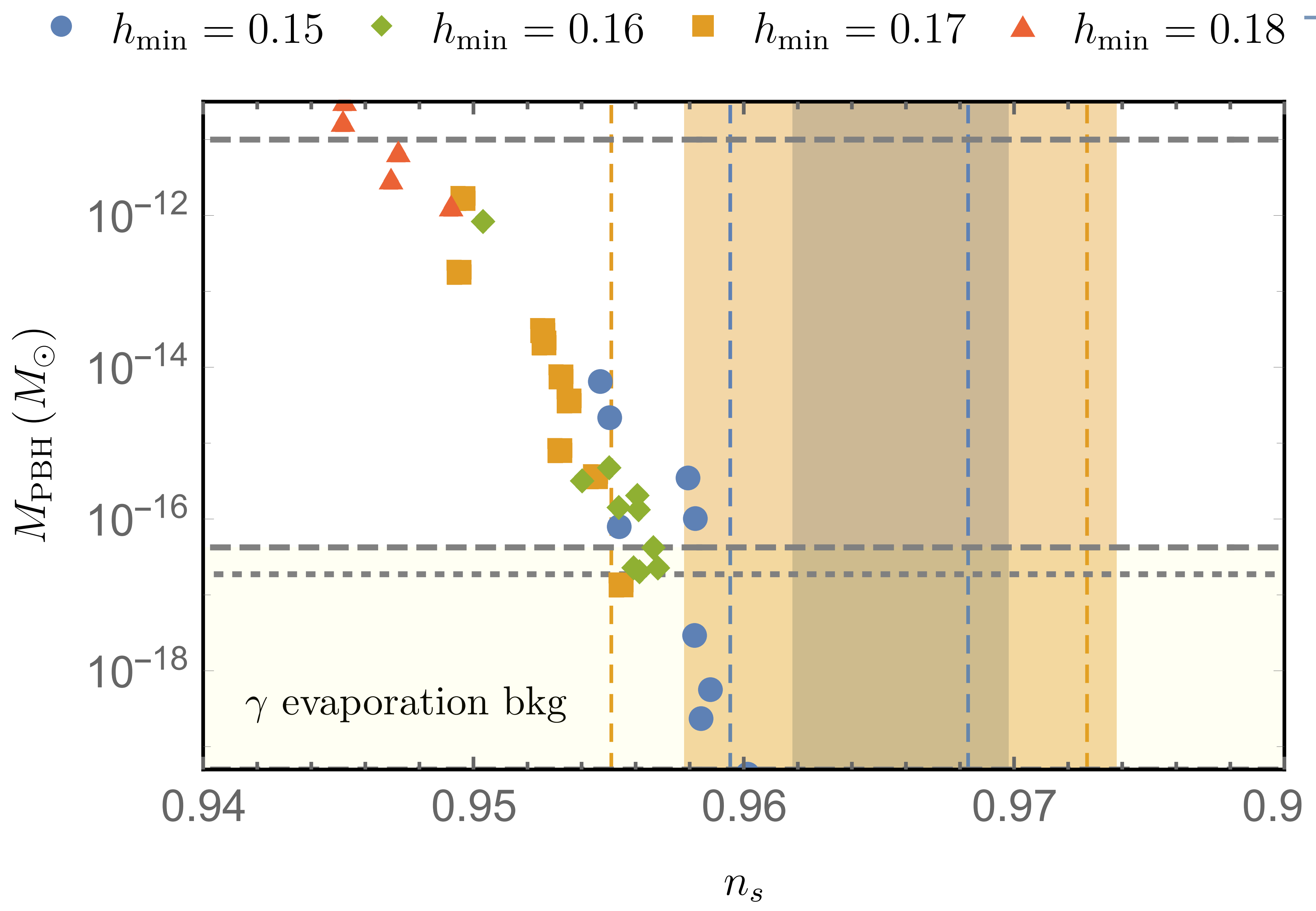
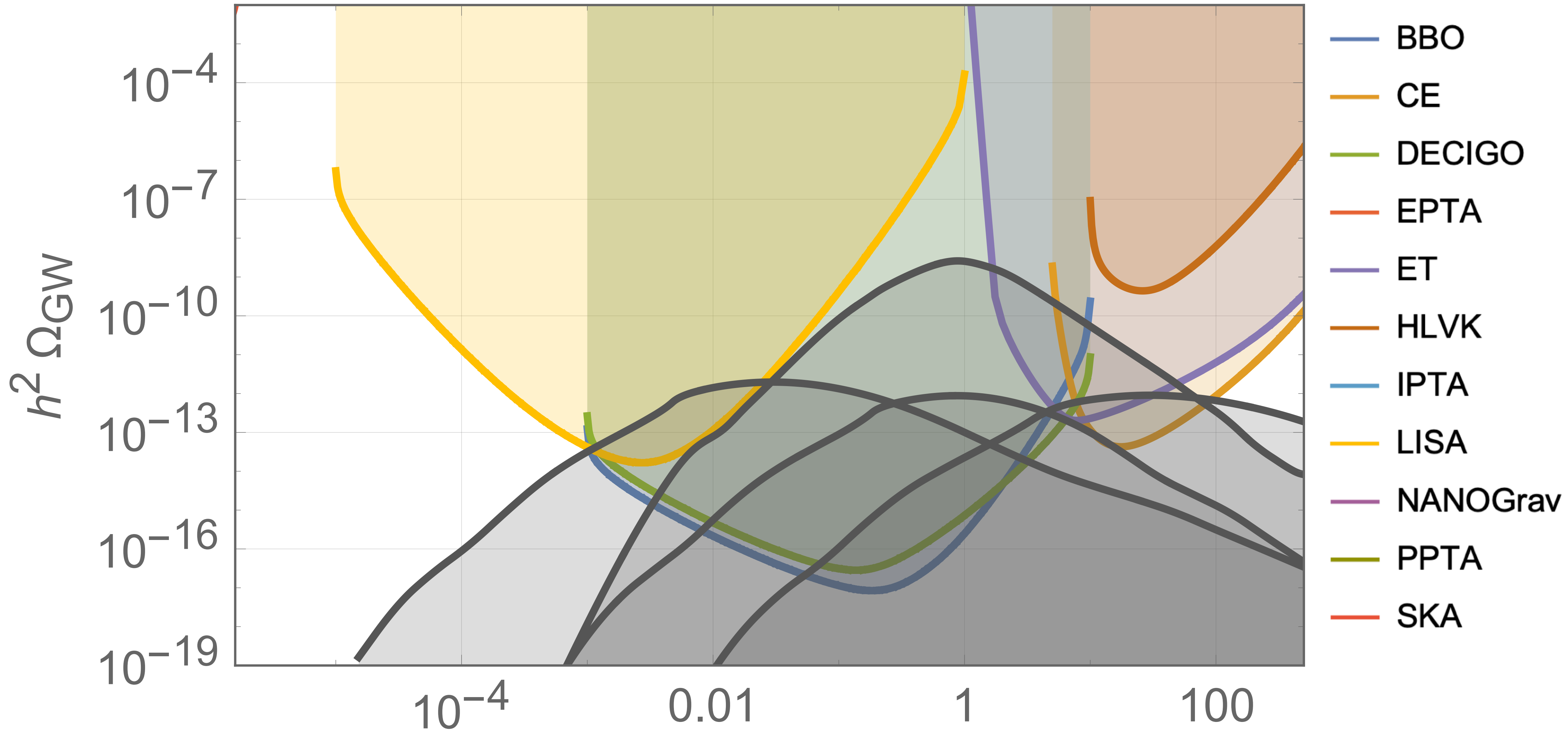




[DYC, S.M. Lee, S.C. Park, JCAP 01 (2021), 032]



- PBHs compatible for a suitable amount of DM.
- Slight tension with CMB due to the prolonged USR.
  → can be resolved with additional R^n

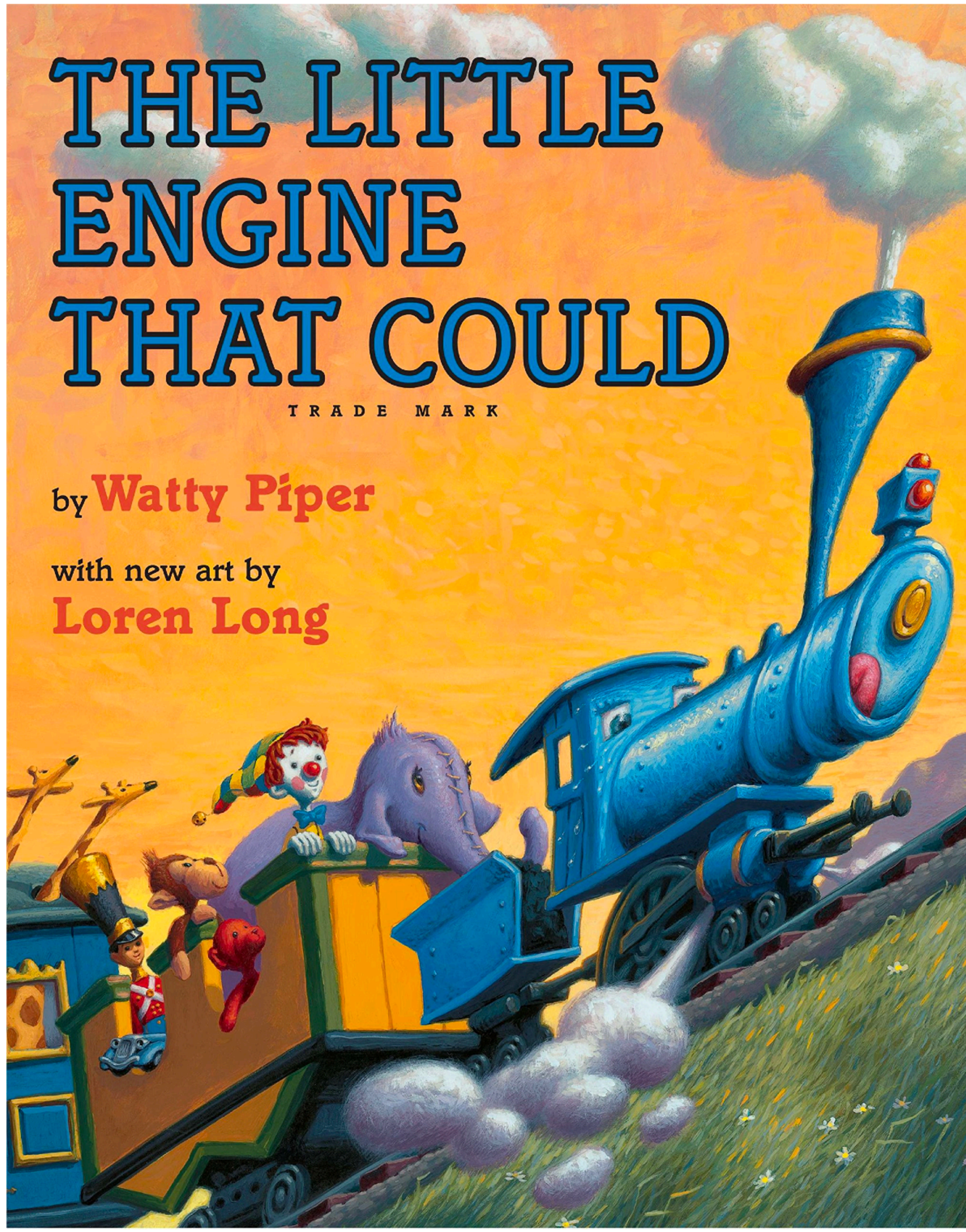
  [DYC, H.M. Lee, S.C. Park, Phys. Lett. B 805 (2020) 135453]
- LISA, DECIGO, CE, ET available to probe wider parameter range compared to PBHs.

So, is this the end of the story?

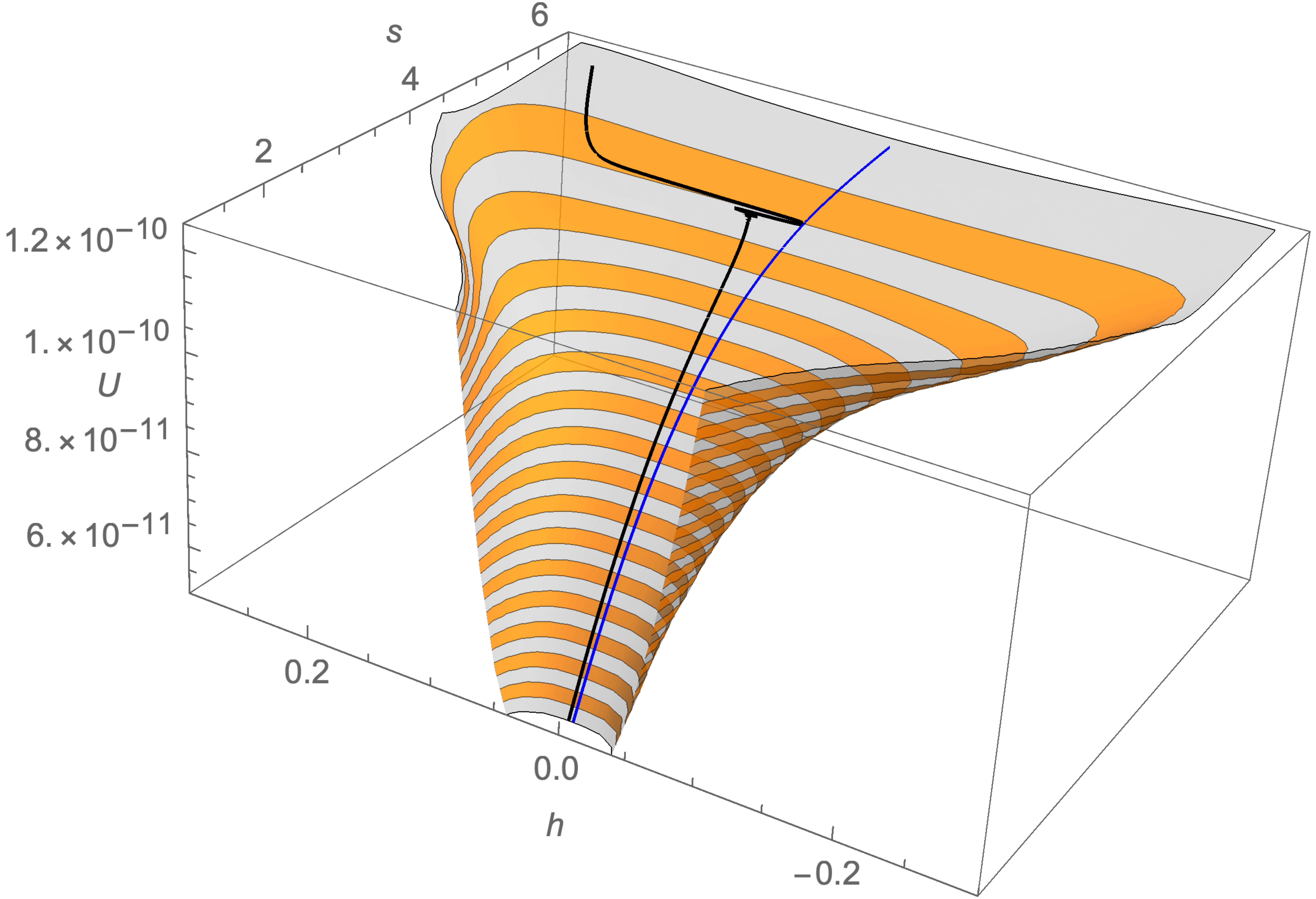
- Apparently, this is not the end of the phenomenology the critical Higgs-R^2 inflation can exhibit.

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

- Inflaton *rides* towards the hill at $h = 0$, leading to *tachyonic perturbation growth!*



Higgs-R^2 Inflation, Trajectory



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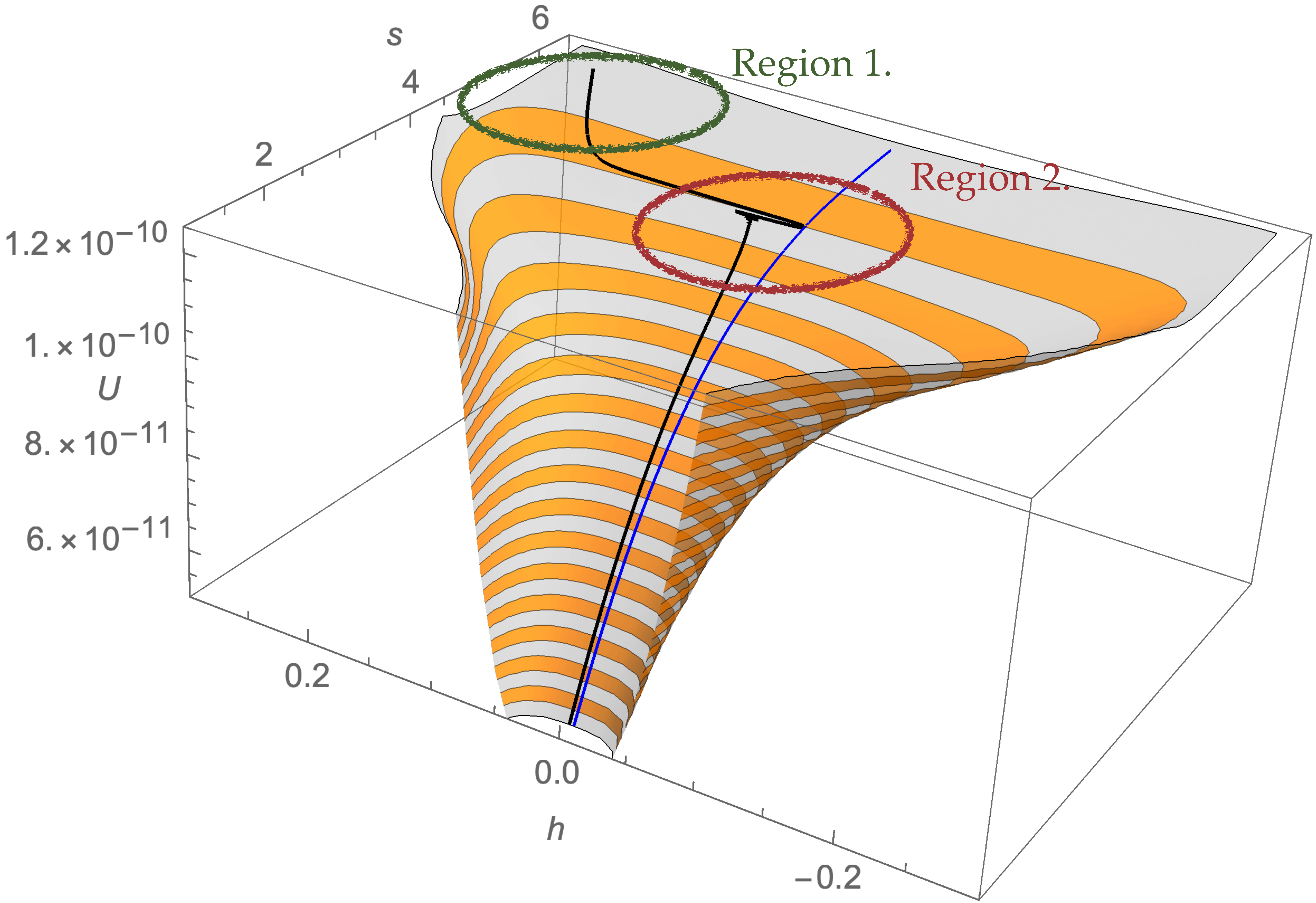
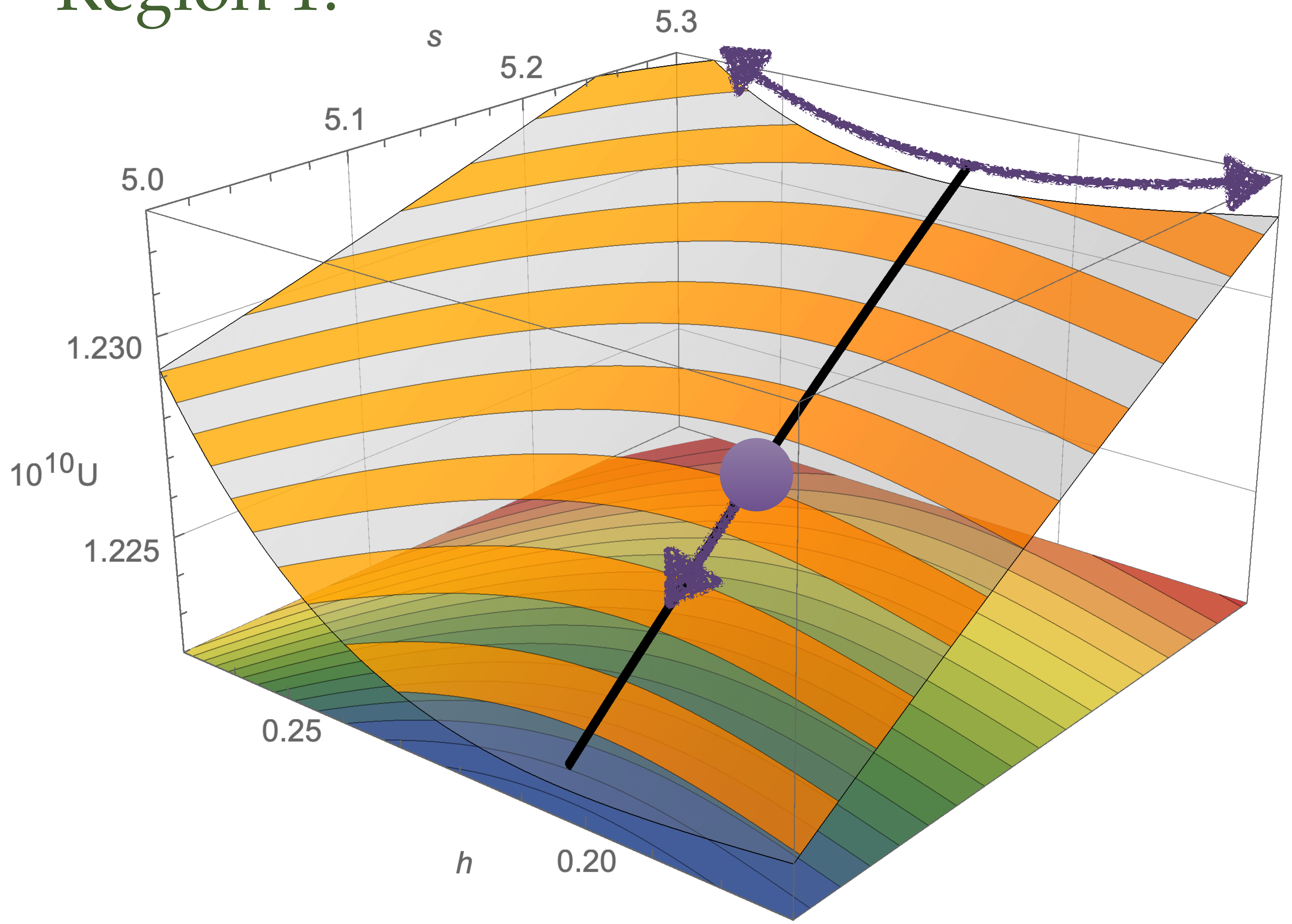


Higgs-R^2 Inflation, Trajectory

[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]

Region 1.



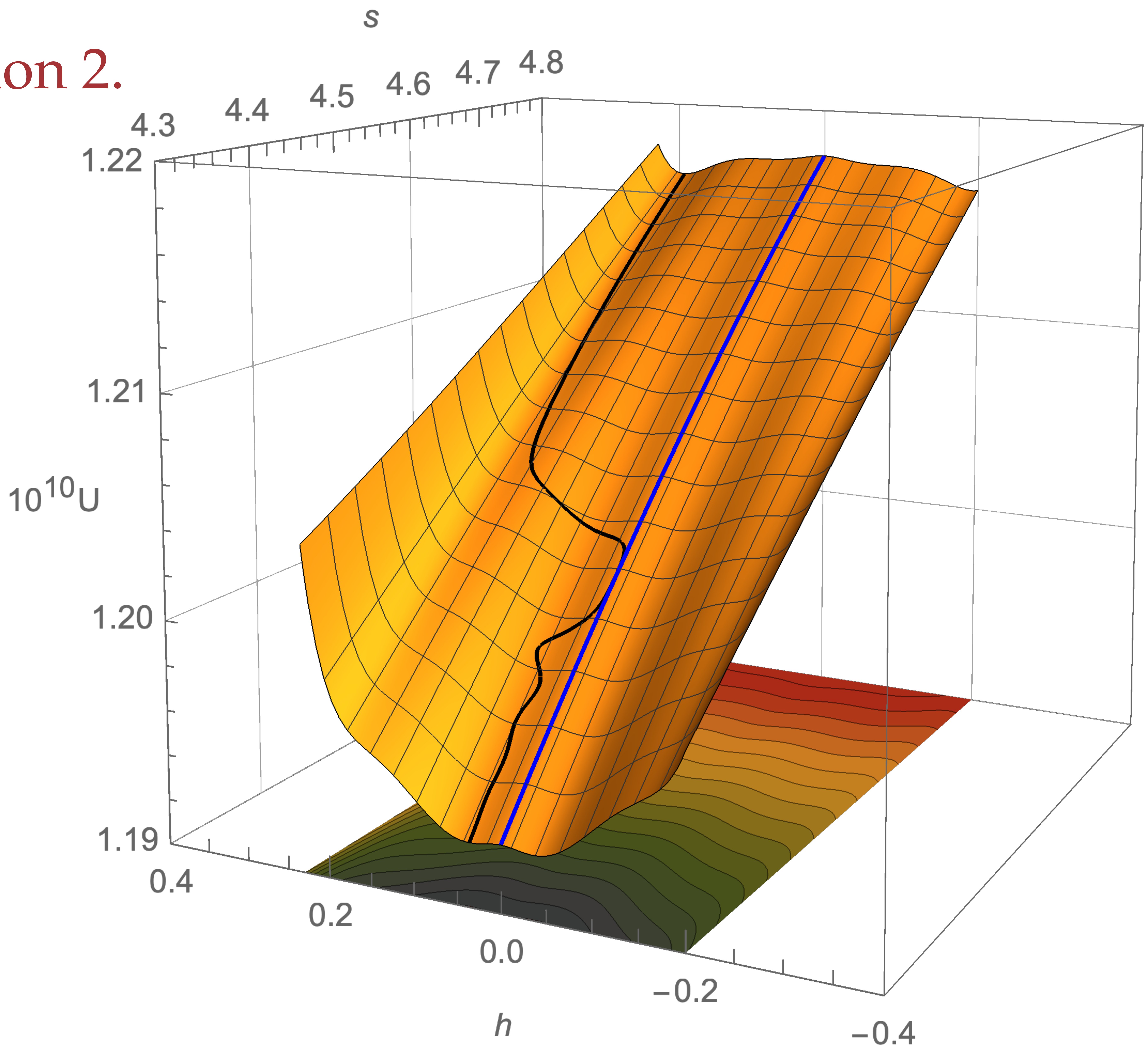
- *"Valley"* structure persists, exhibits an *"attractor"* behavior.
- *Isocurvature perturbations suppressed*
- CMB observables resemble the predictions of an *"effective single-field"* setup.
- "Slightly larger" n_s, r compared to constant λ.

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

Higgs-R^2 Inflation, Trajectory

Region 2.

[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]



Higgs-R^2 Inflation, Trajectory

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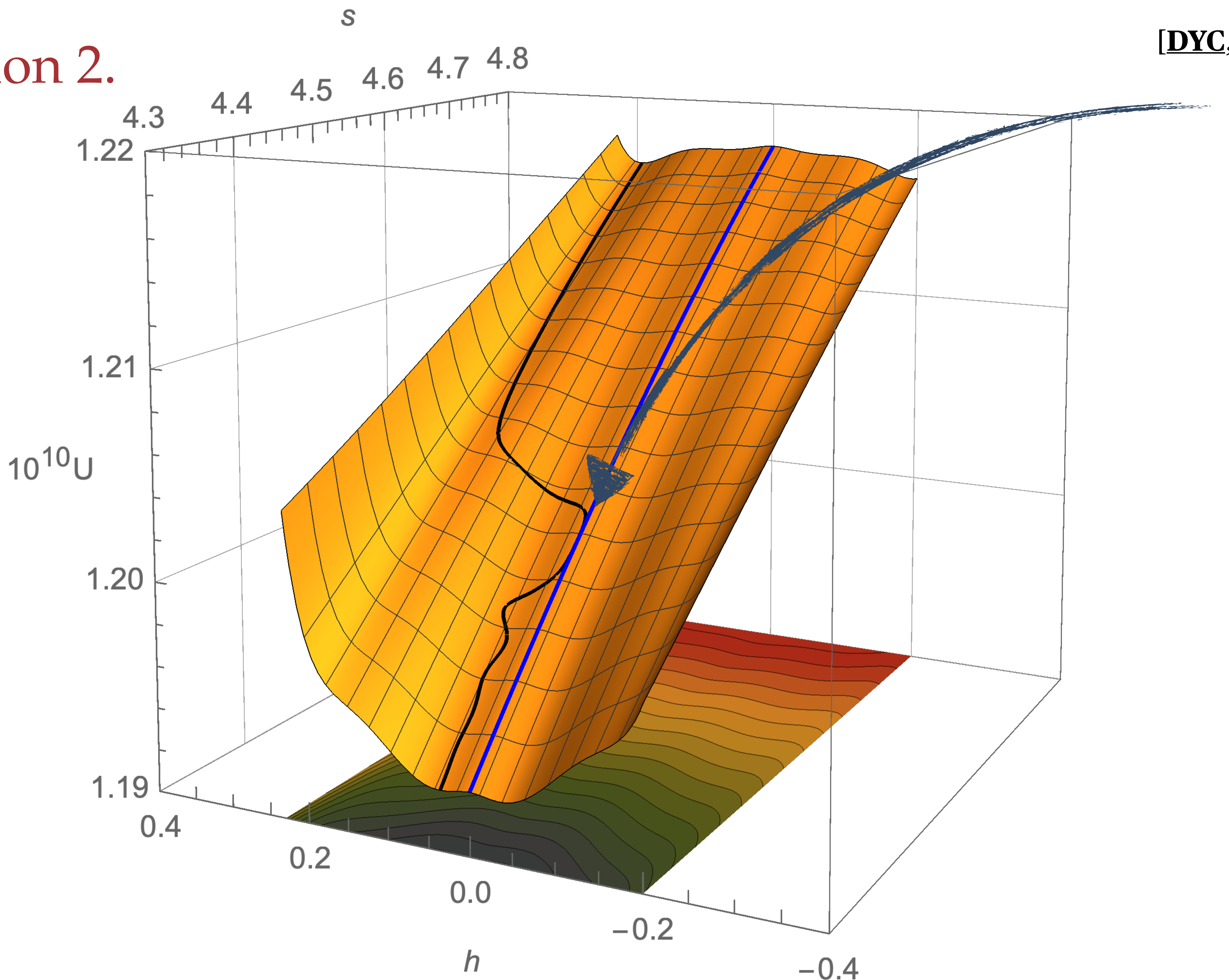
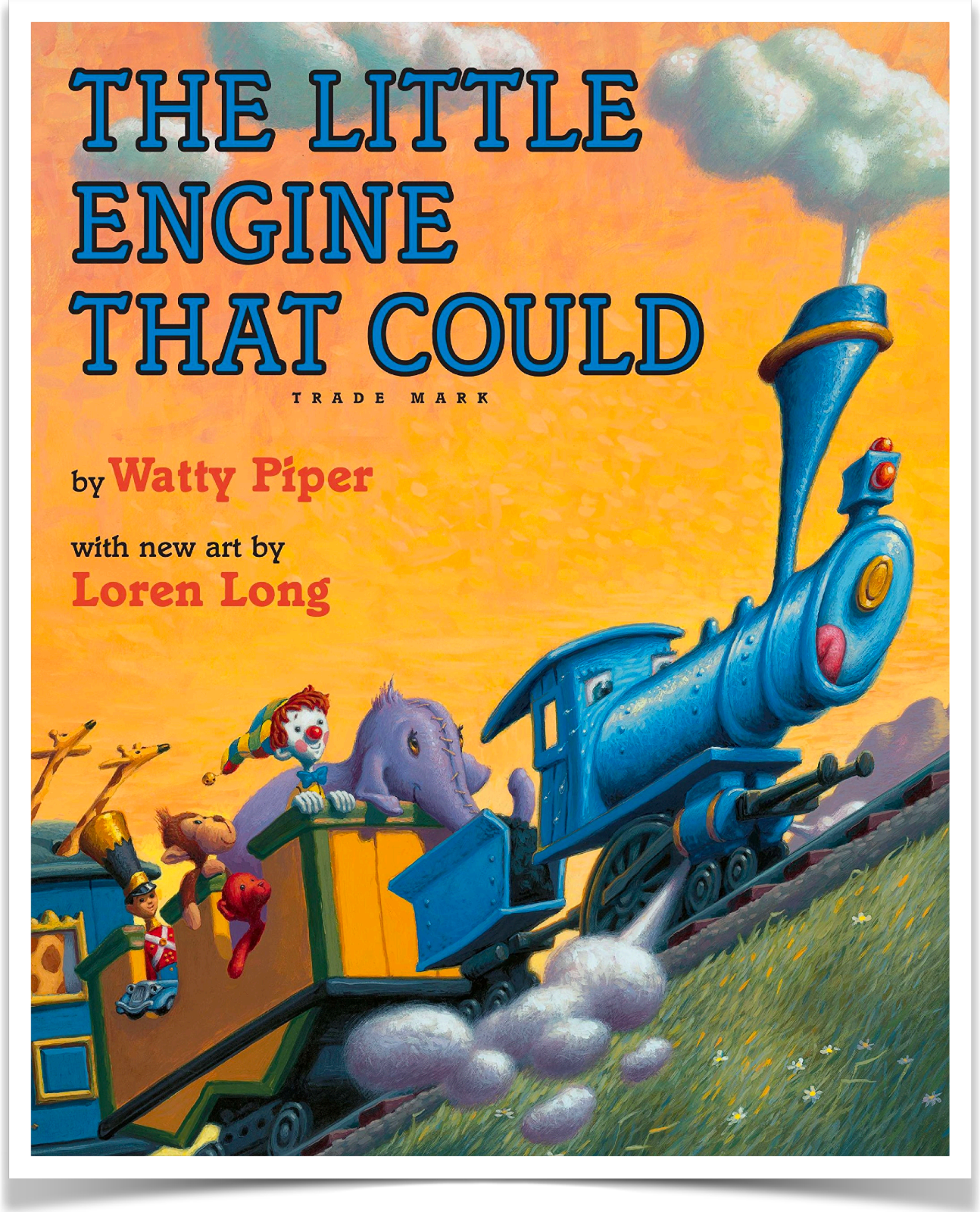
[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]



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



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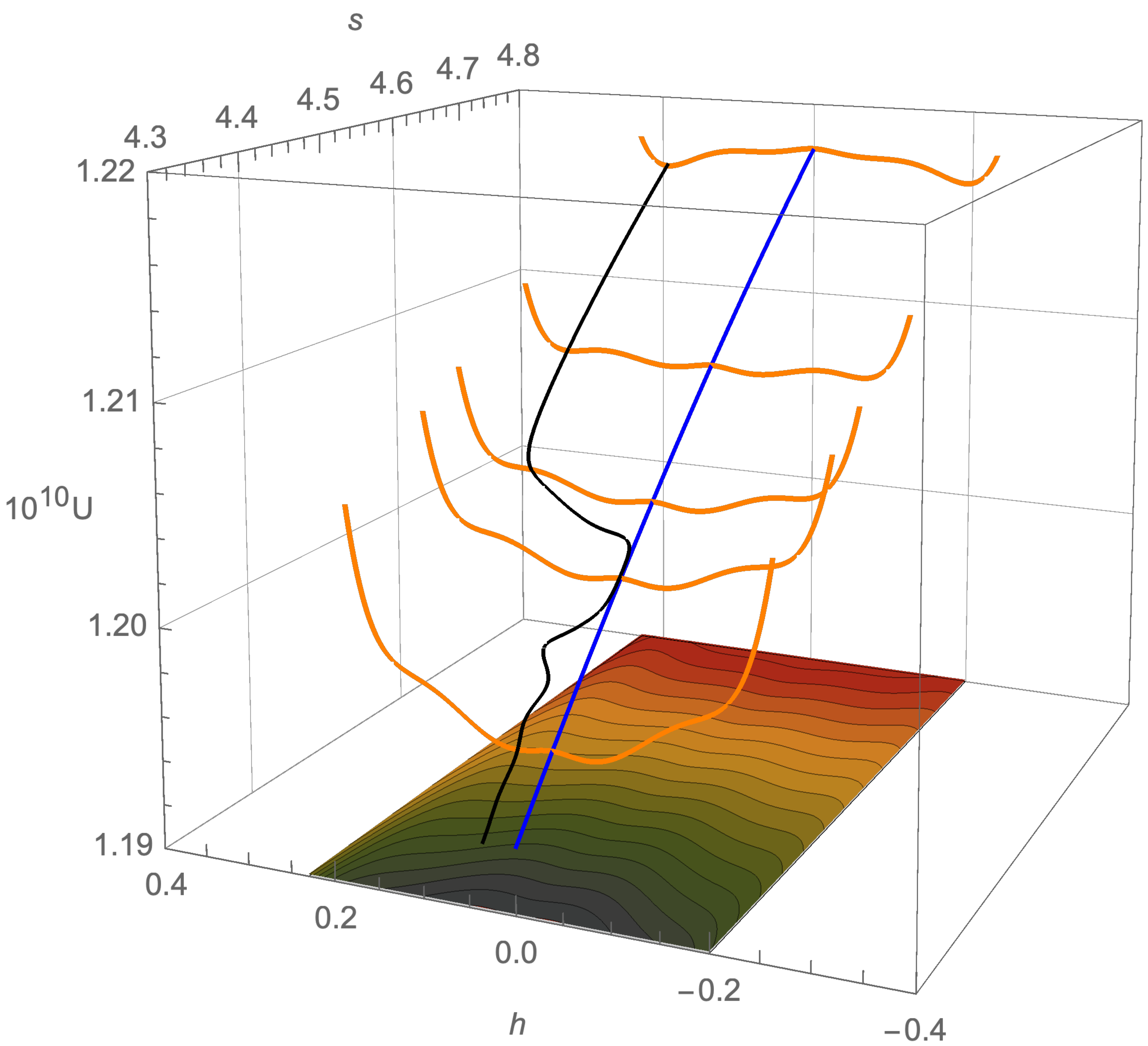

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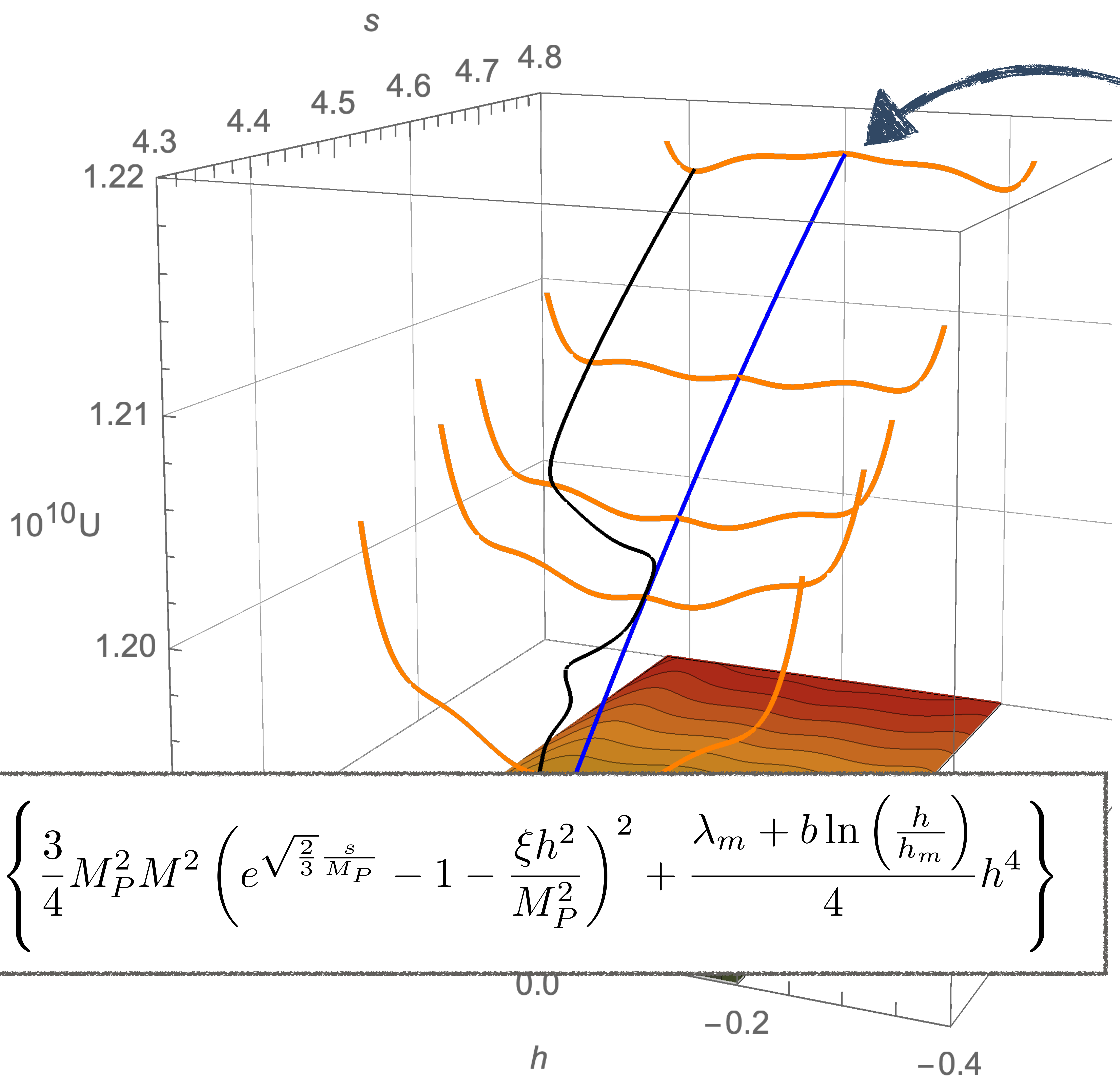

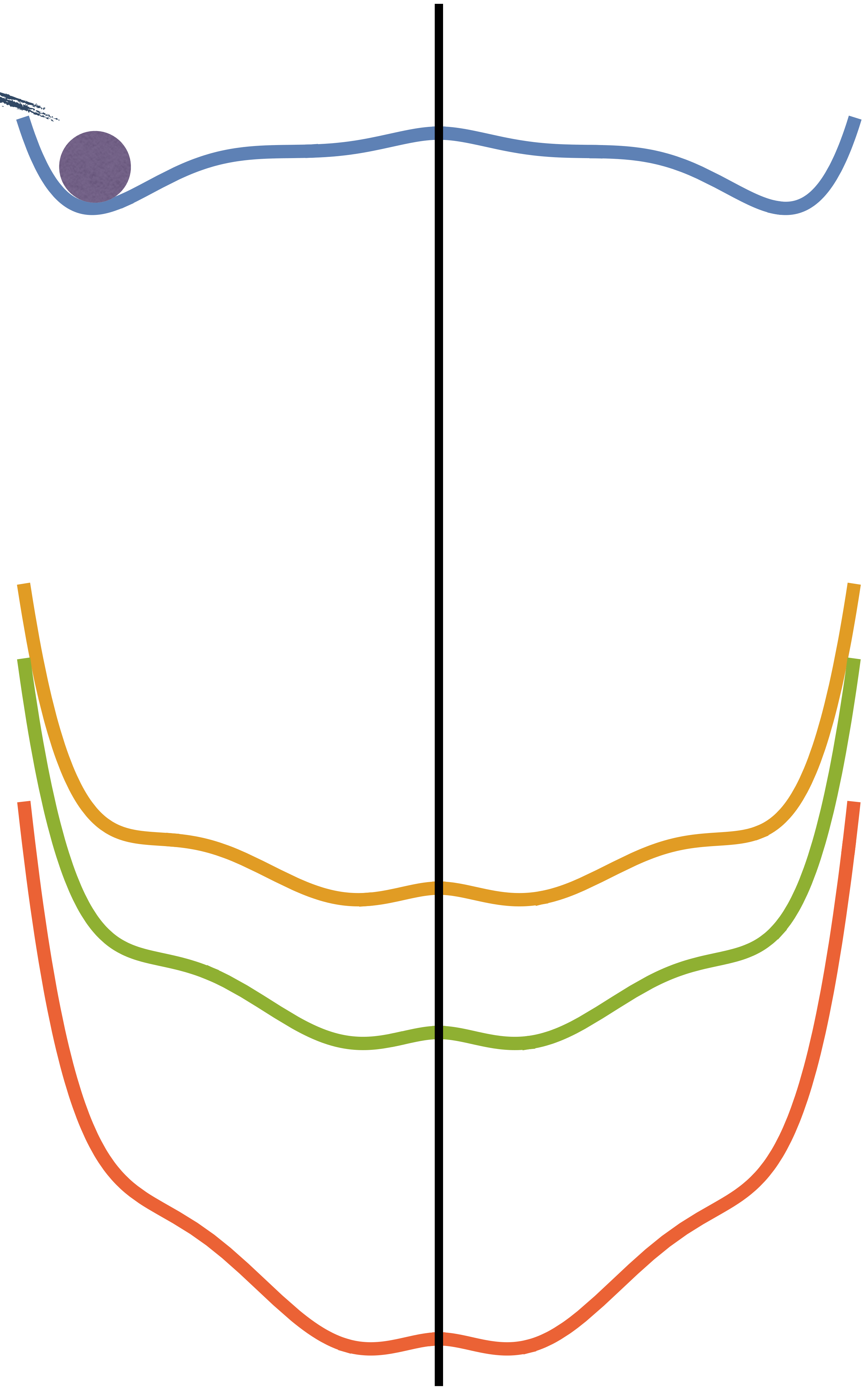

$$U = e^{-2\sqrt{\frac{2}{3}}\frac{s}{M_P}} \left\{ \frac{3}{4} M_P^2 M^2 \left(e^{\sqrt{\frac{2}{3}}\frac{s}{M_P}} - 1 - \frac{\xi h^2}{M_P^2} \right)^2 + \frac{\lambda_m + b \ln\left(\frac{h}{h_m}\right)}{4} h^4 \right\}$$

Higgs-R^2 Inflation, Trajectory

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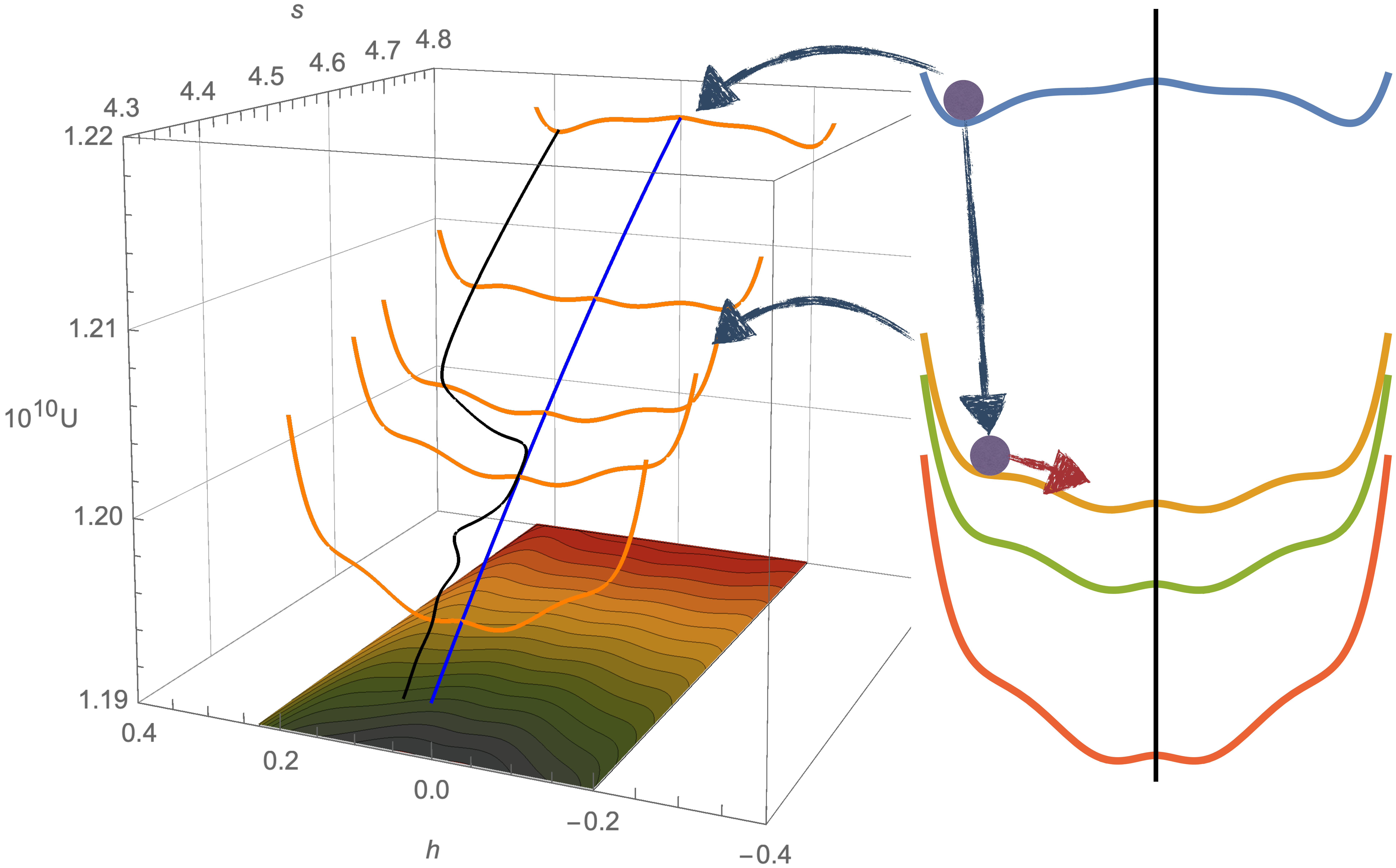

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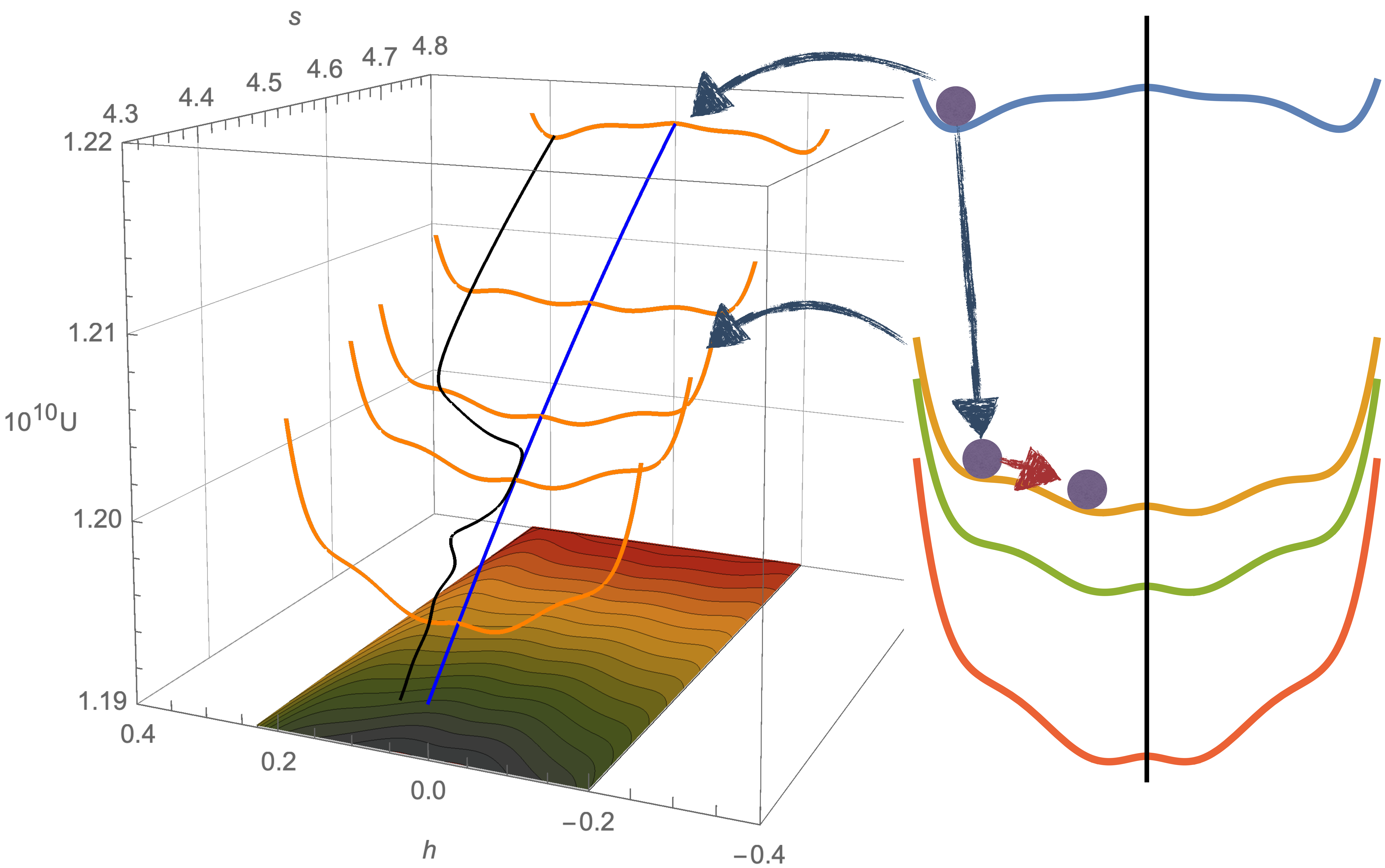

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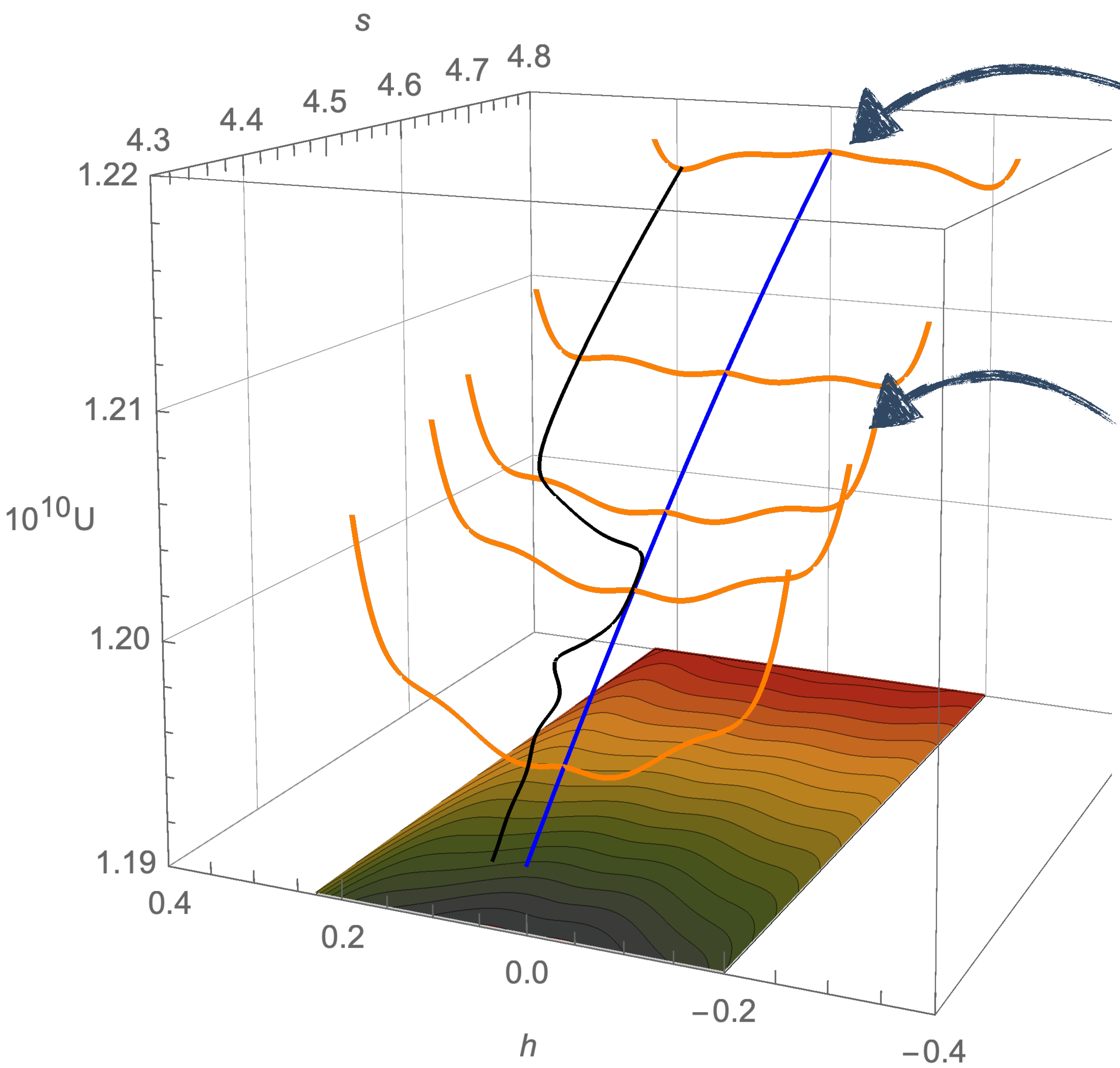

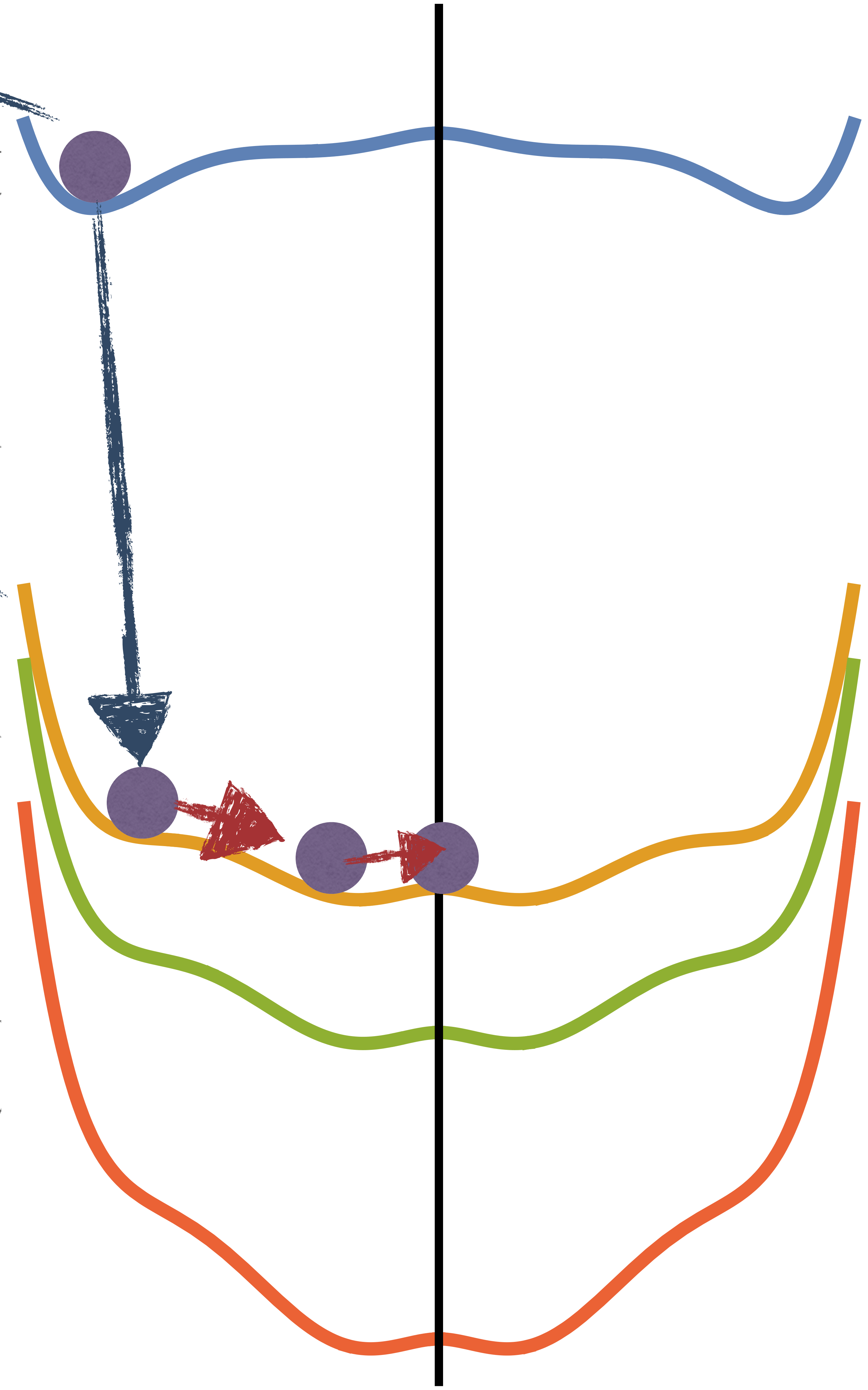

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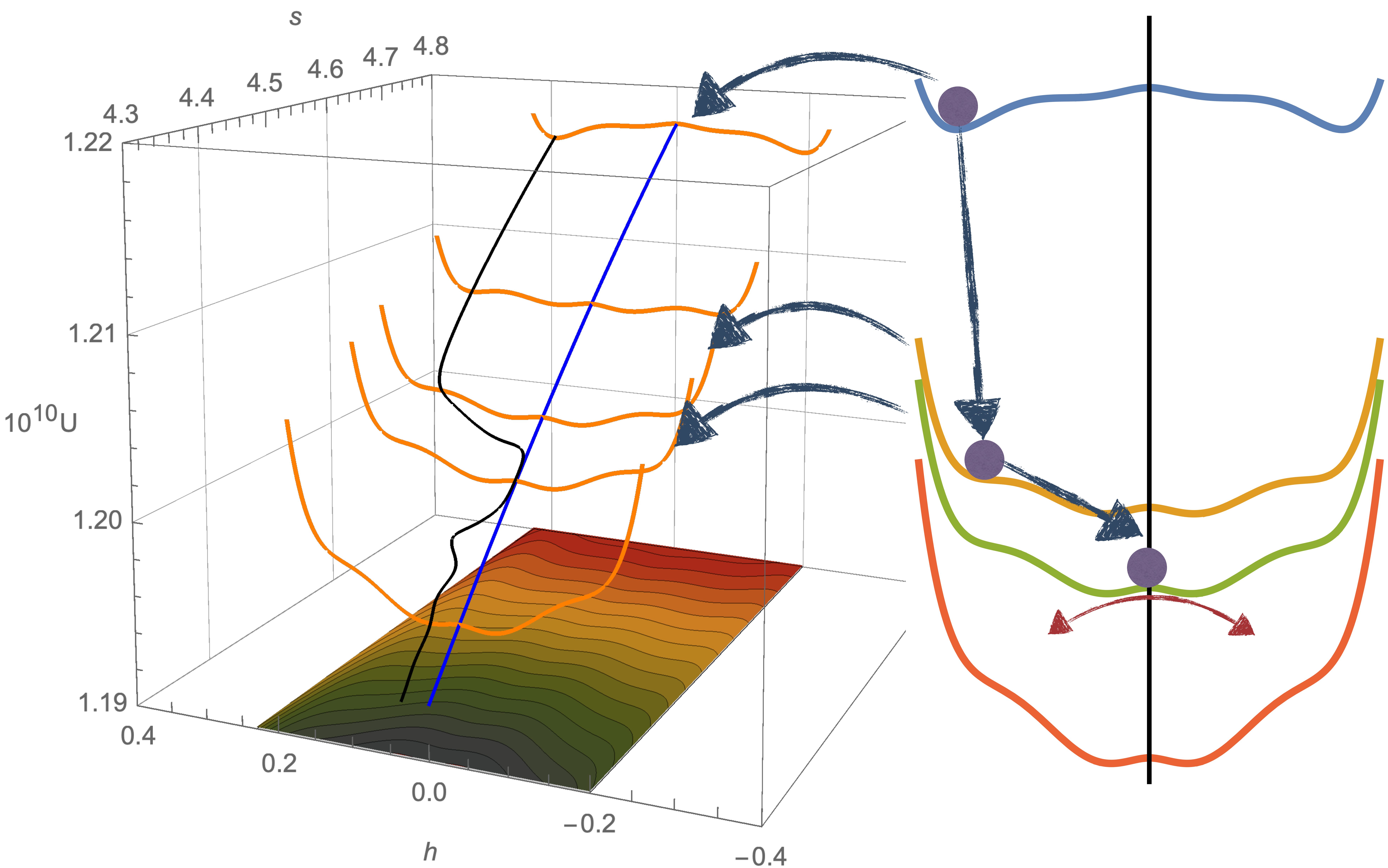

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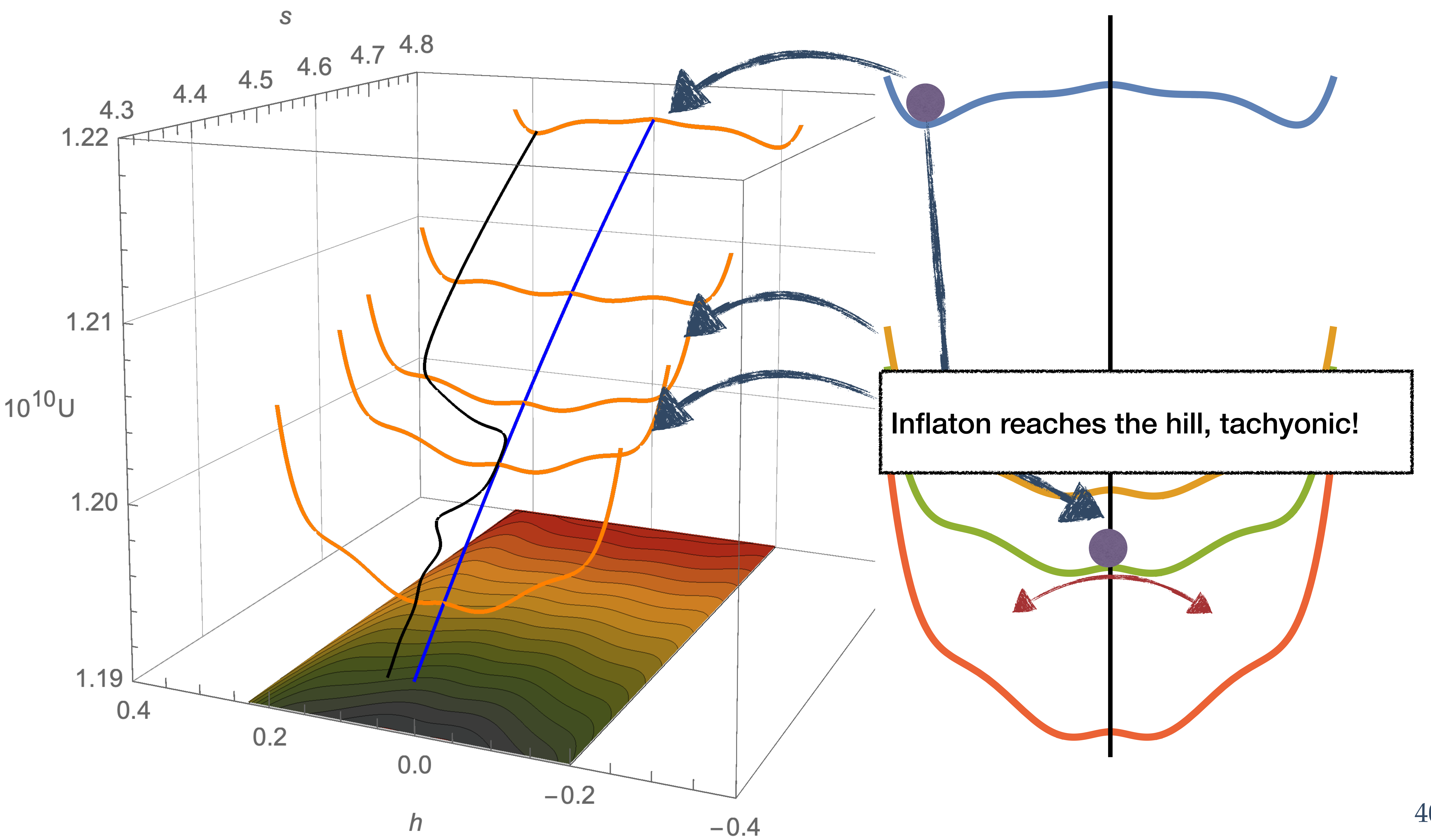

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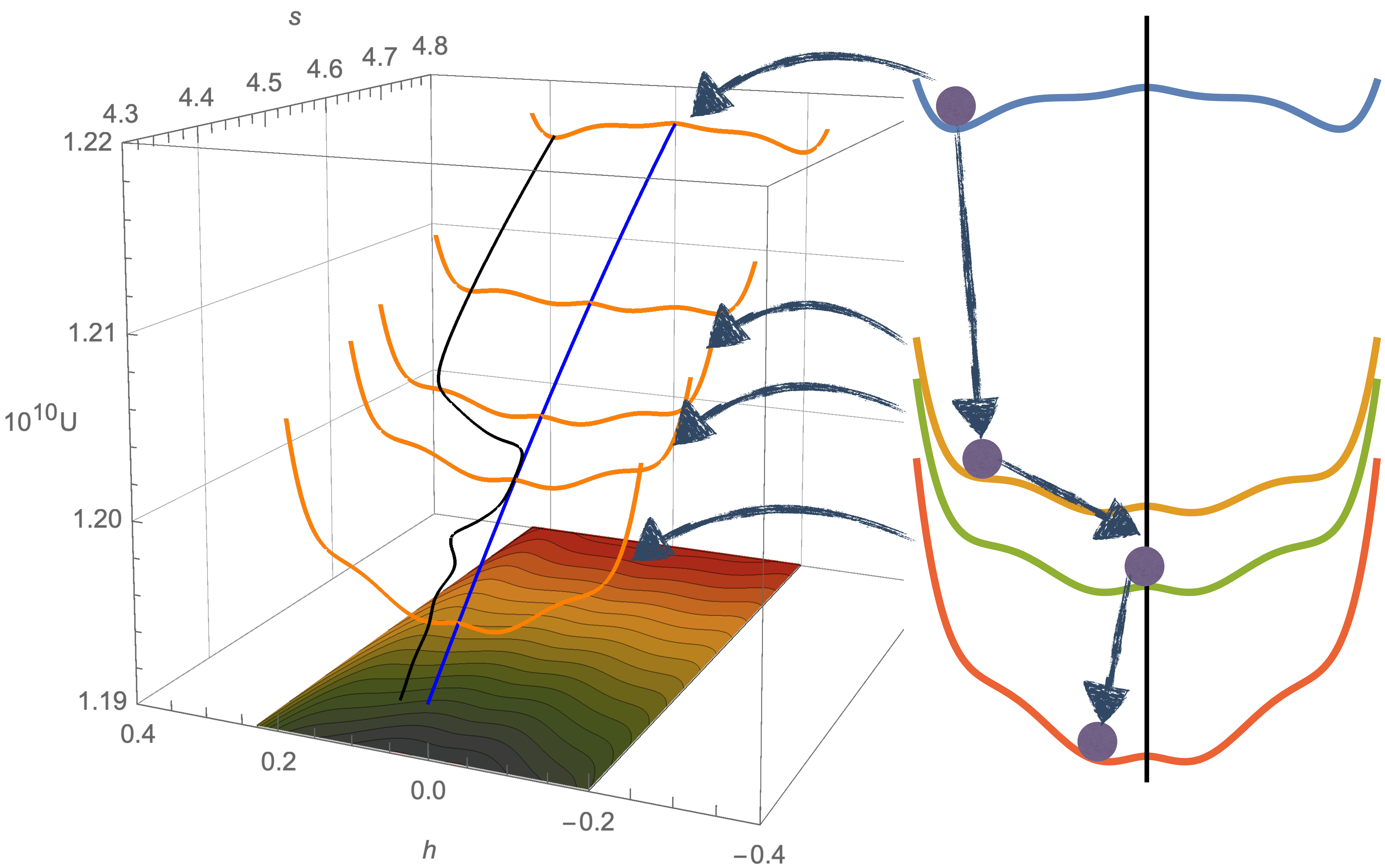

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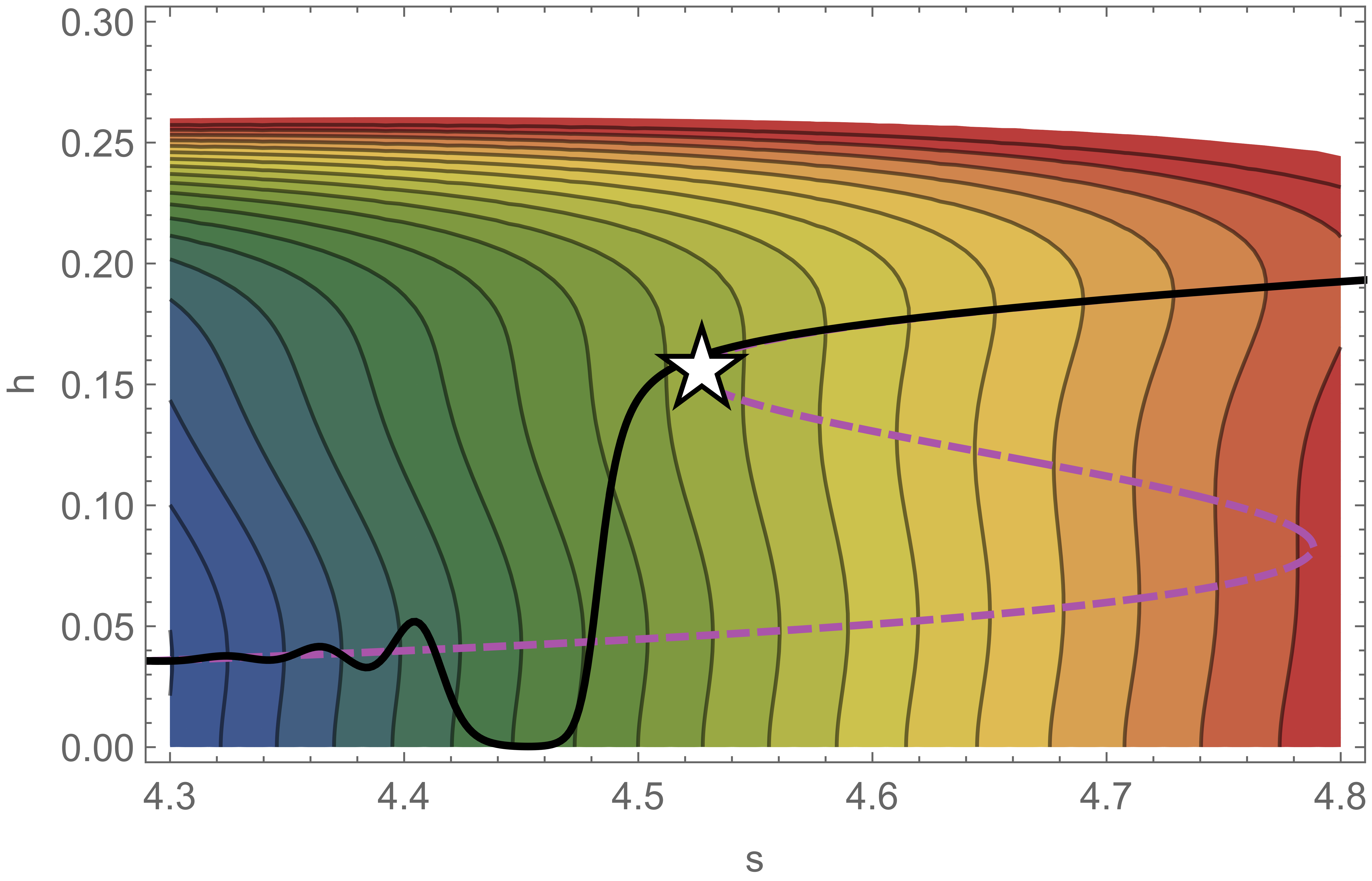


Dashed, Purple : $\frac{\partial U}{\partial h} = 0$

Valley structure departure, second valley emerges at smaller h.

$$\frac{h_{local\ min}}{h_m} = e^{-\frac{3}{4}+\frac{\sqrt{5b^2-16b\lambda_m-48bM^2\xi^2}}{4b}}$$

$$0 \leq \xi < \frac{1}{4\sqrt{3}M}\sqrt{5b-16\lambda_m}\ , \quad \lambda_m < \frac{5b}{16}.$$

Departure induced by the nonzero b, differs from constant λ!

Nonminimal coupling ξ determines position of the hill-reaching.

Higgs-R^2 Inflation, Perturbations

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

with the perturbation equations

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

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

[S. 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...

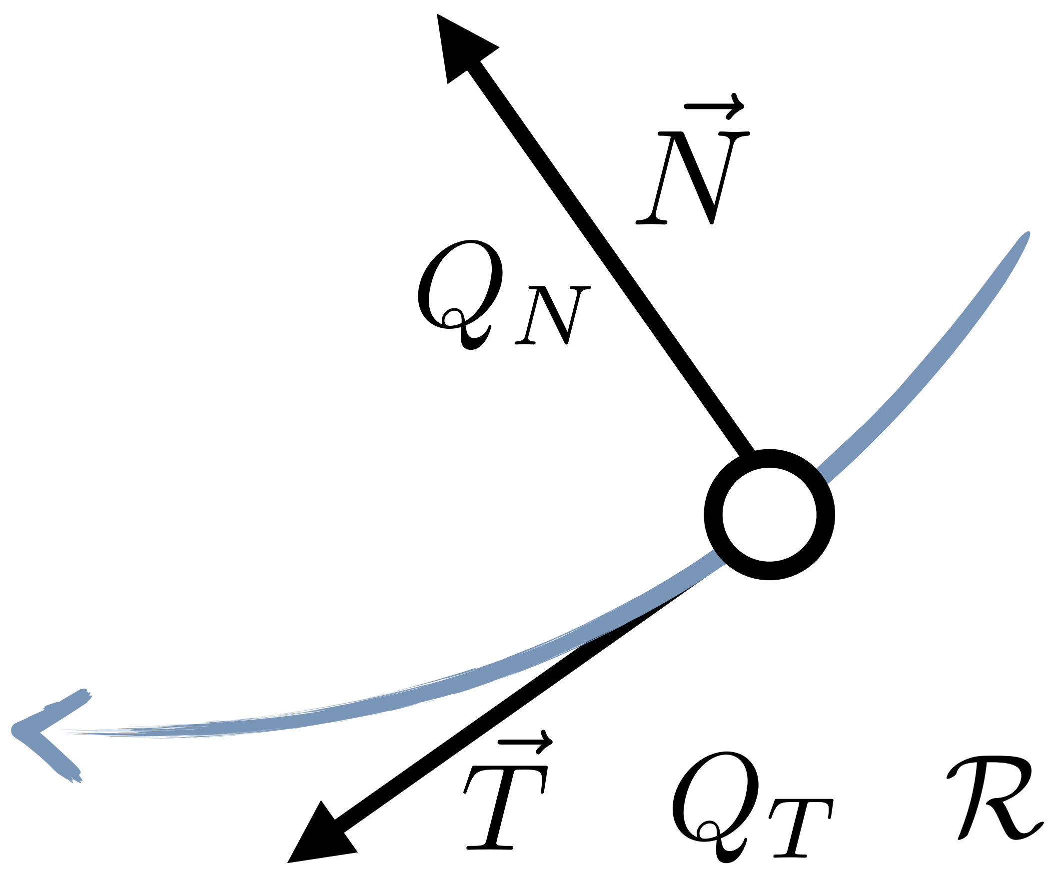
$$\eta_{\|} \equiv -\frac{\ddot{\phi}_0}{\dot{\phi}_0 H}$$

$$\eta_{\perp} \equiv \frac{U_N}{\dot{\phi}_0 H}$$

$$Q^a \equiv \delta\phi^a + \frac{\dot{\phi}^a}{H}\psi$$

$$\dot{\theta} \equiv H\eta_{\perp}$$

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



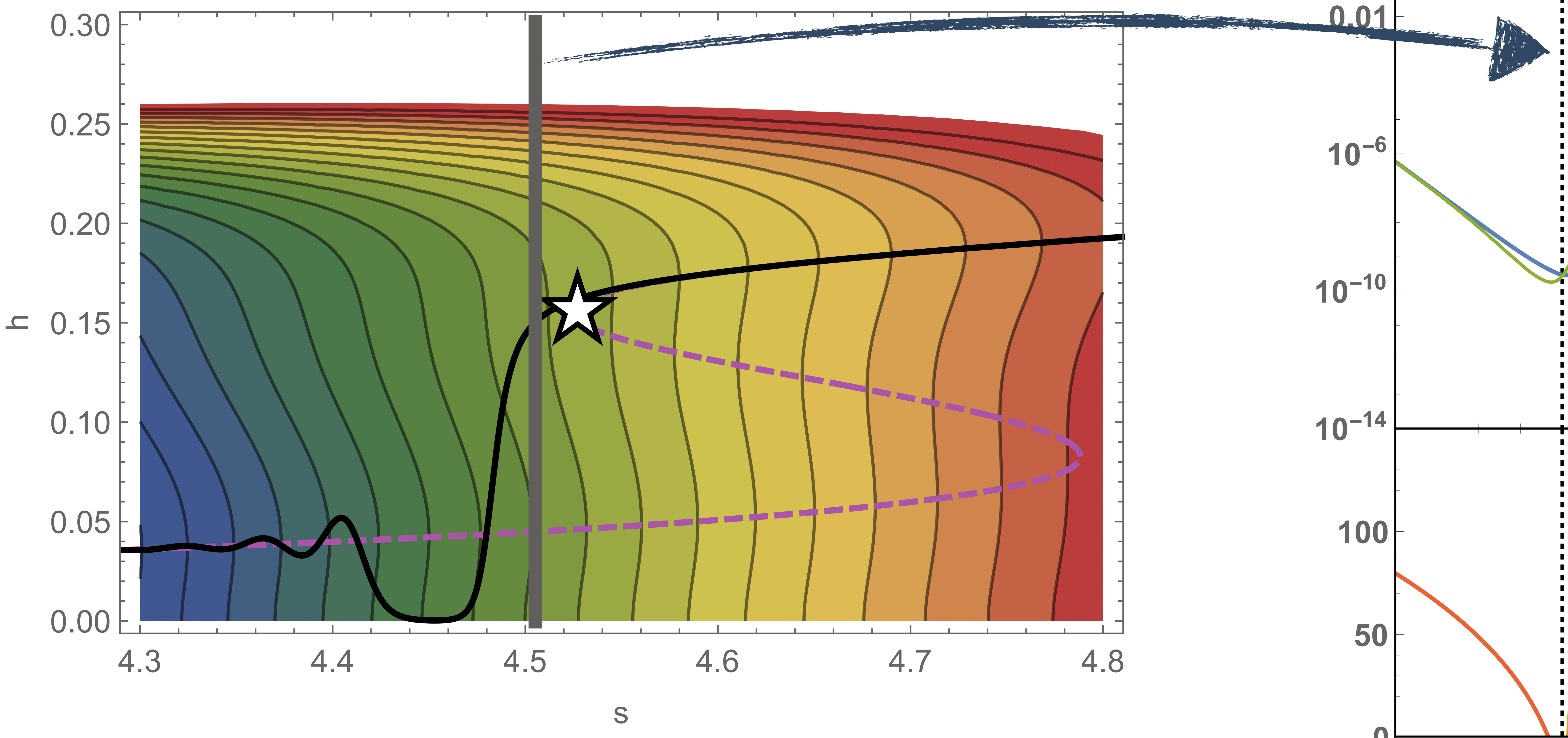
$$\mathcal{R} = \frac{H}{\dot{\phi}_0}Q_T$$

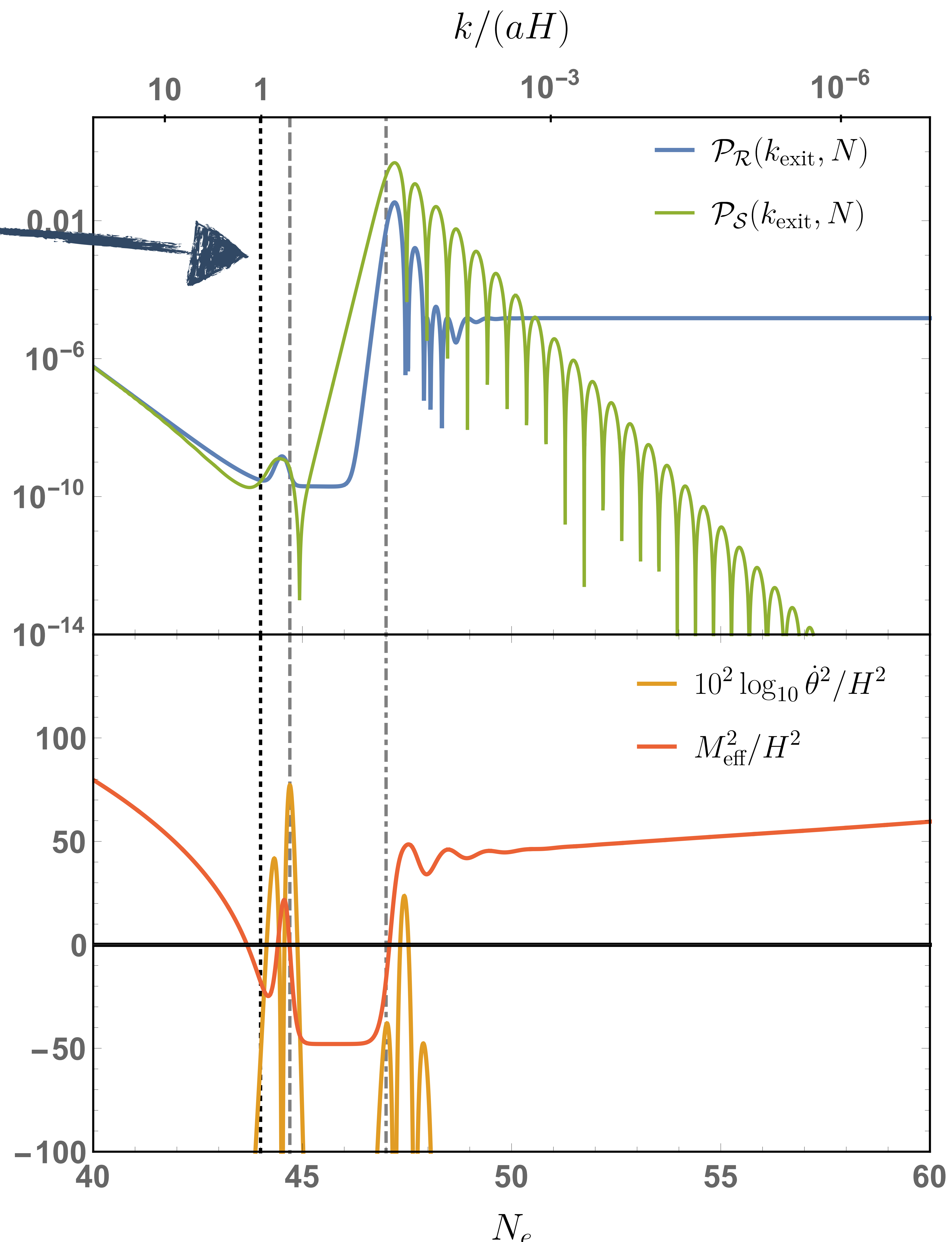
- $M_{\text{eff}}^2 < 0$ leads to *tachyonic growth of Q_N*, then gets *sourced to $\mathcal{R}$* through *turns in the trajectory.*

- Tachyonic mass at the *"hill"* of the potential at $h = 0$, $M_{\text{eff}}^2 \simeq -3M^2\xi\left(1 - e^{-\sqrt{\frac{2}{3}}s}\right)$

Higgs-R^2 Inflation, Perturbations

[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]





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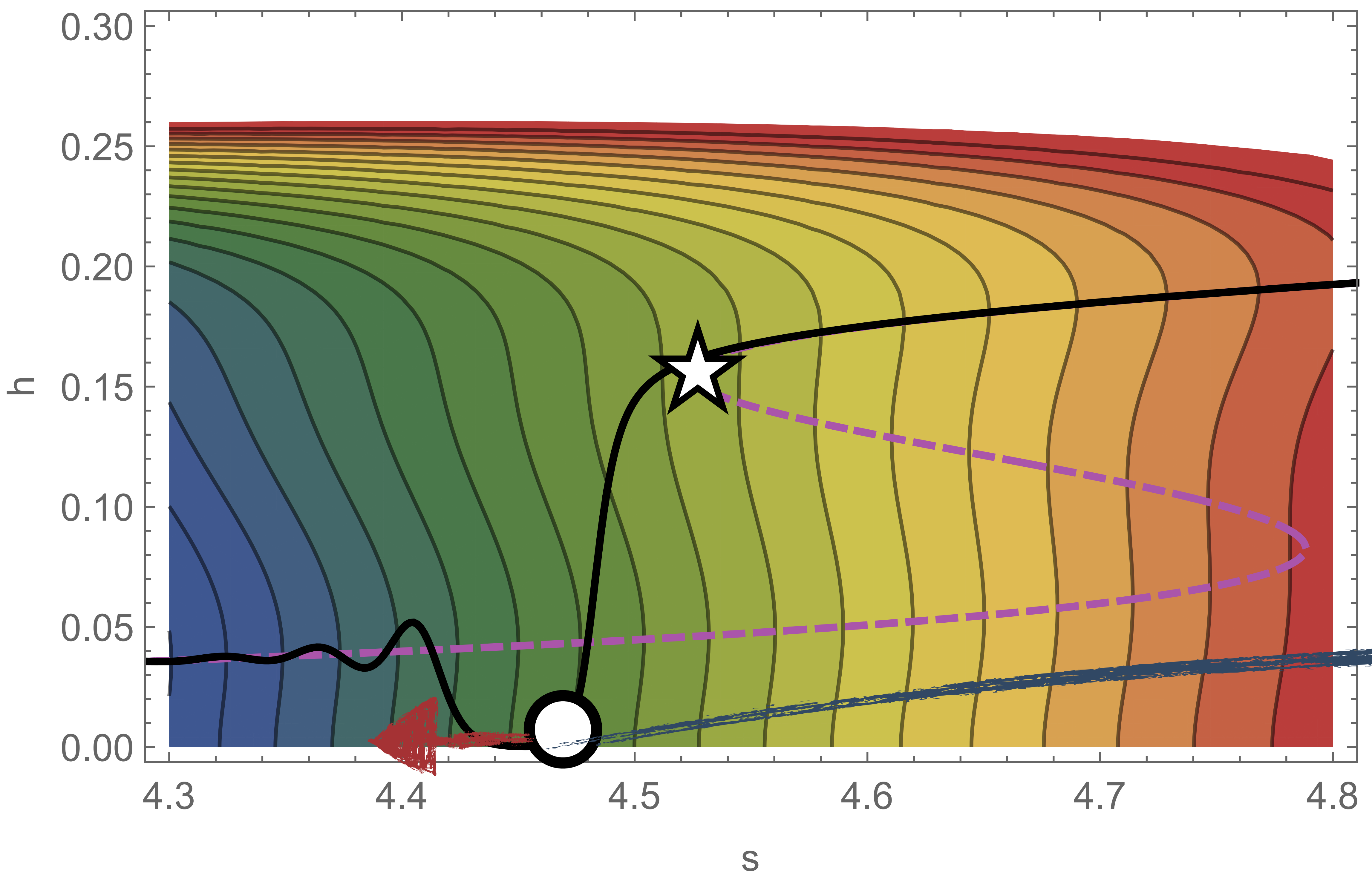

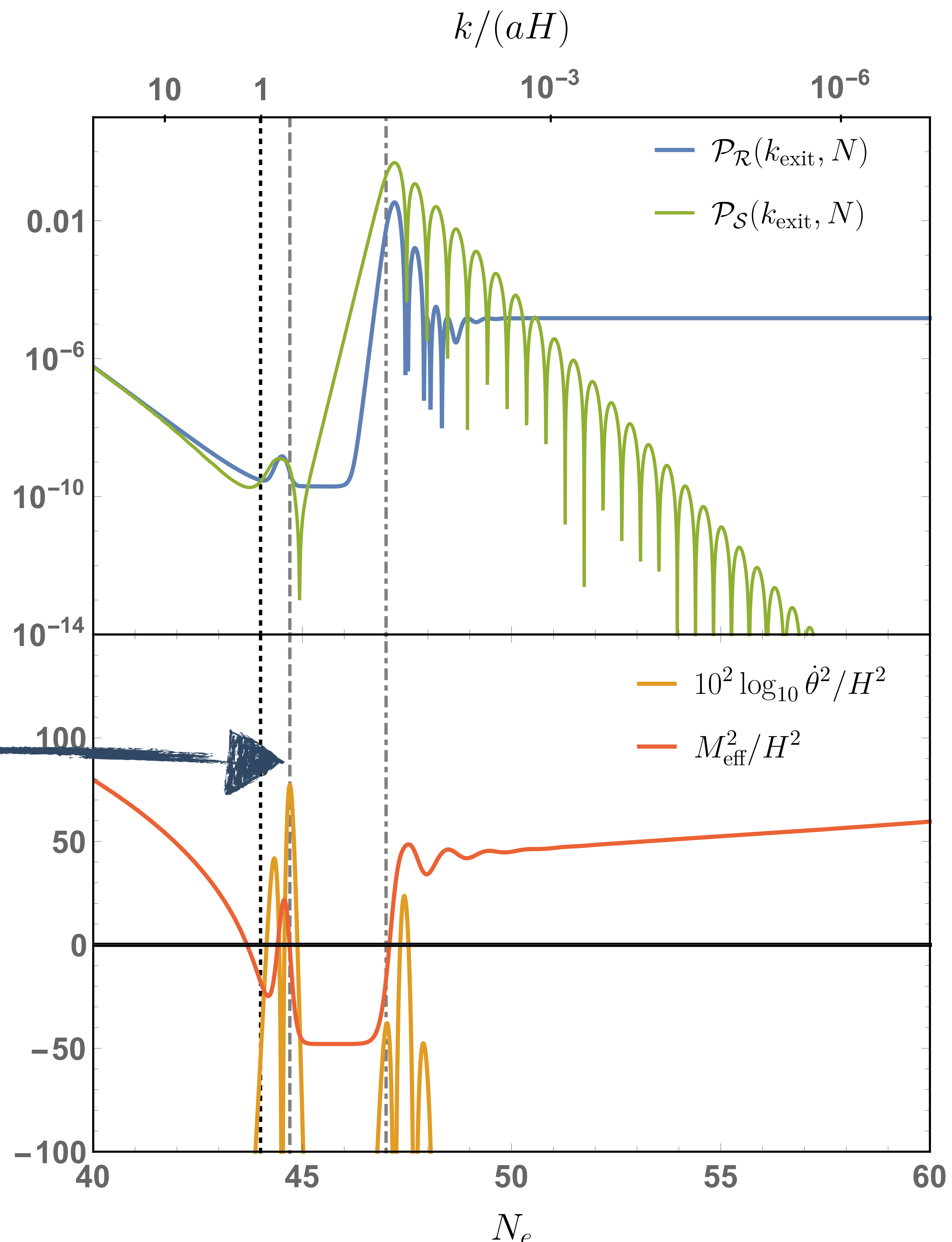

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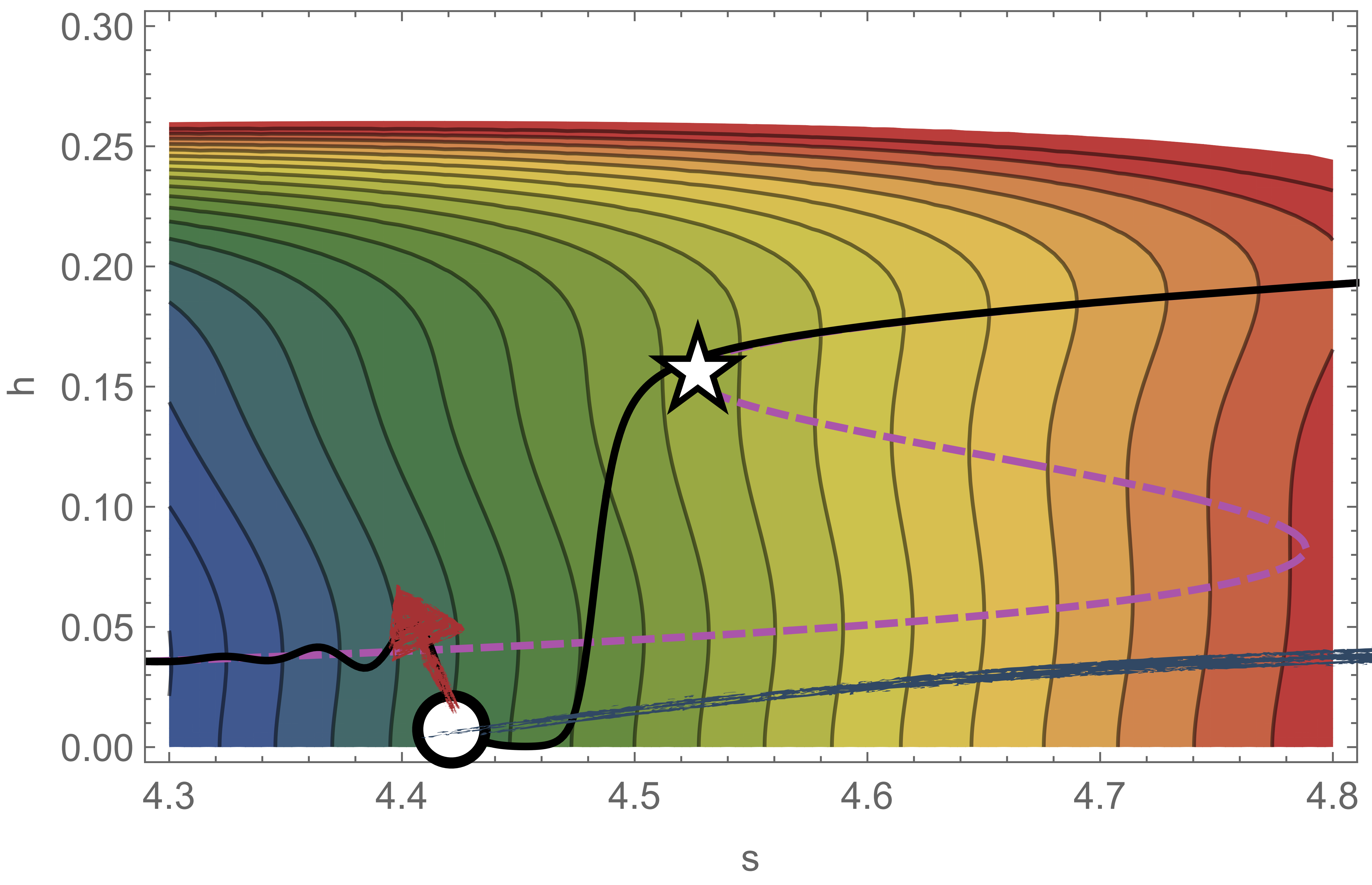

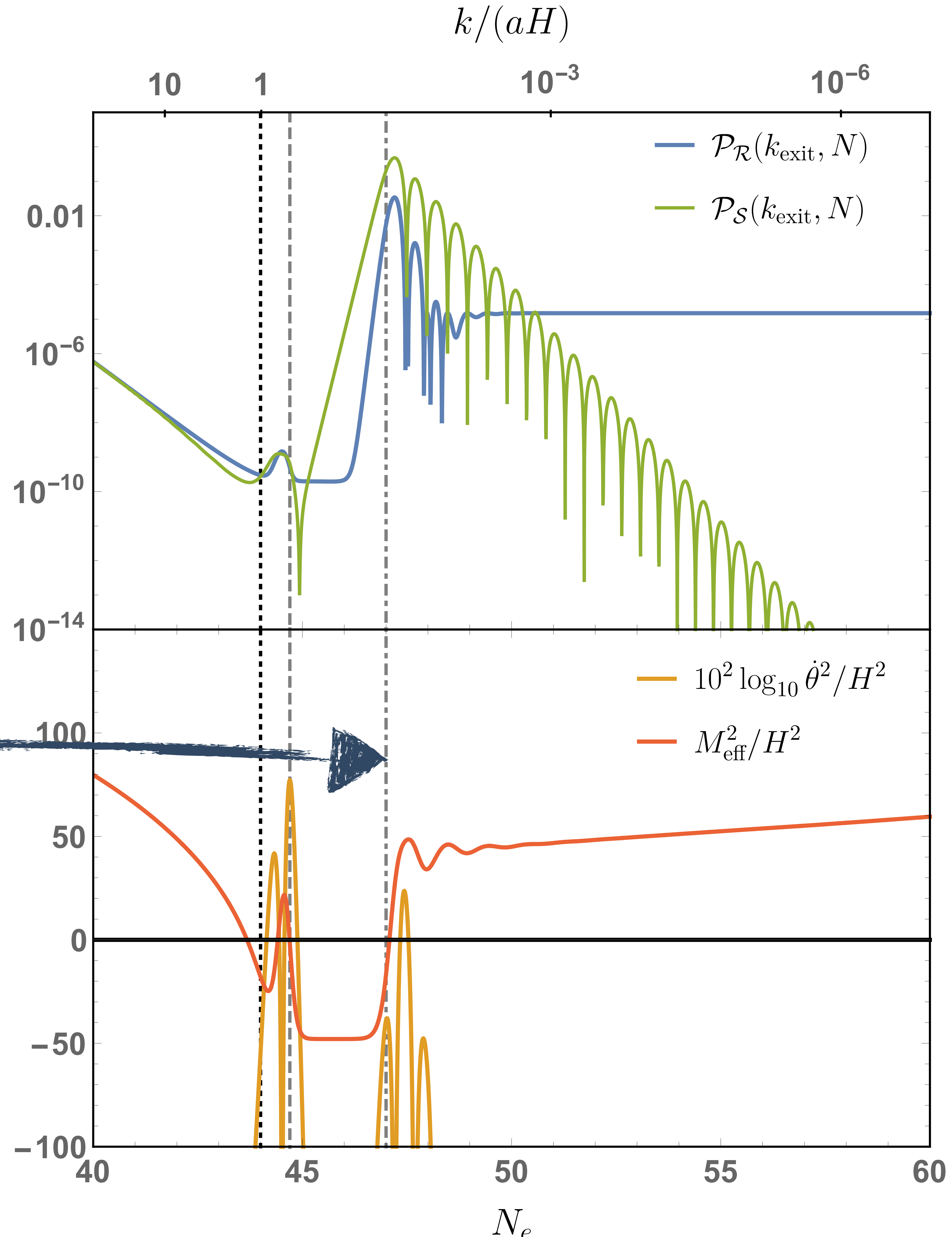

Higgs-R^2 Inflation, Perturbations

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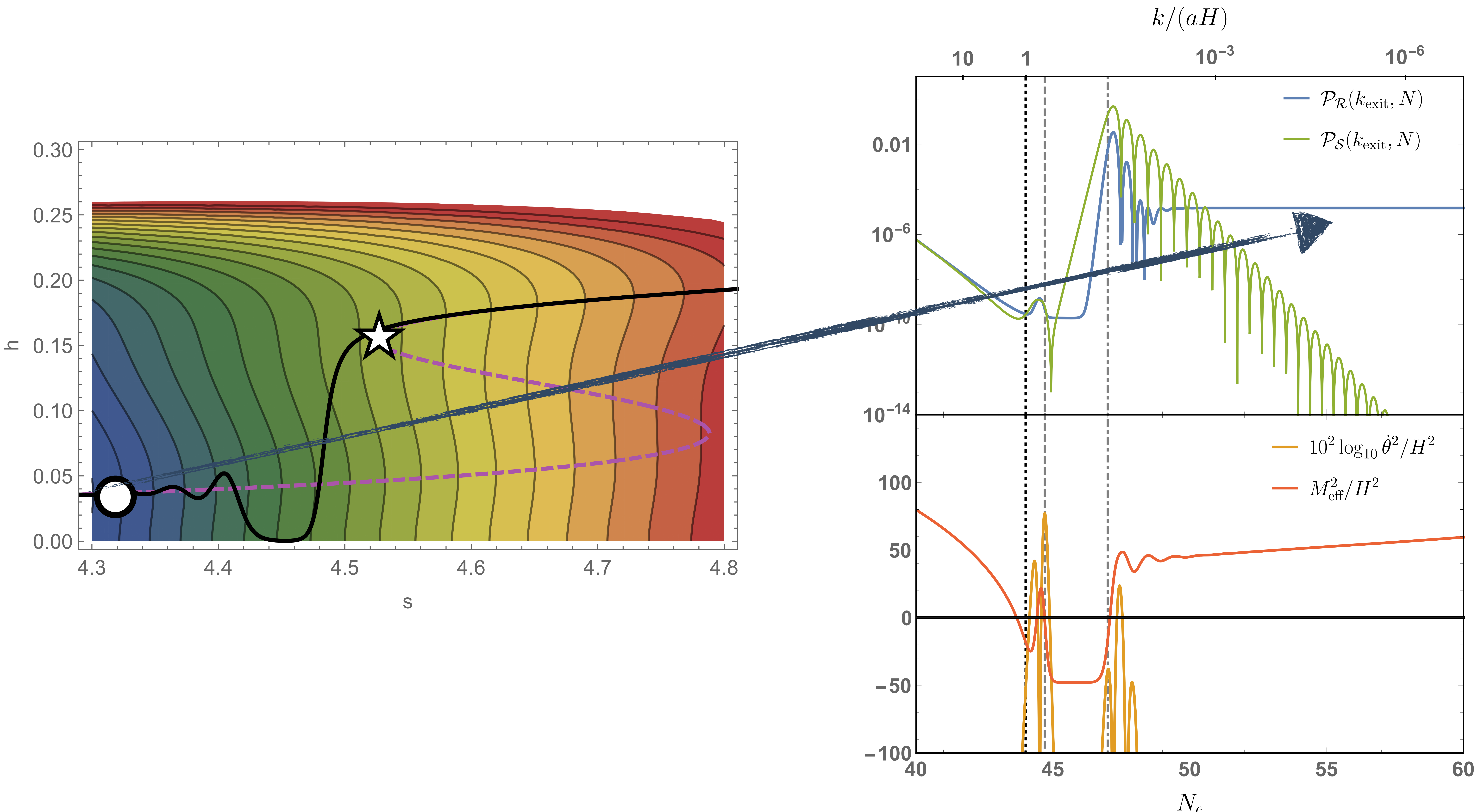
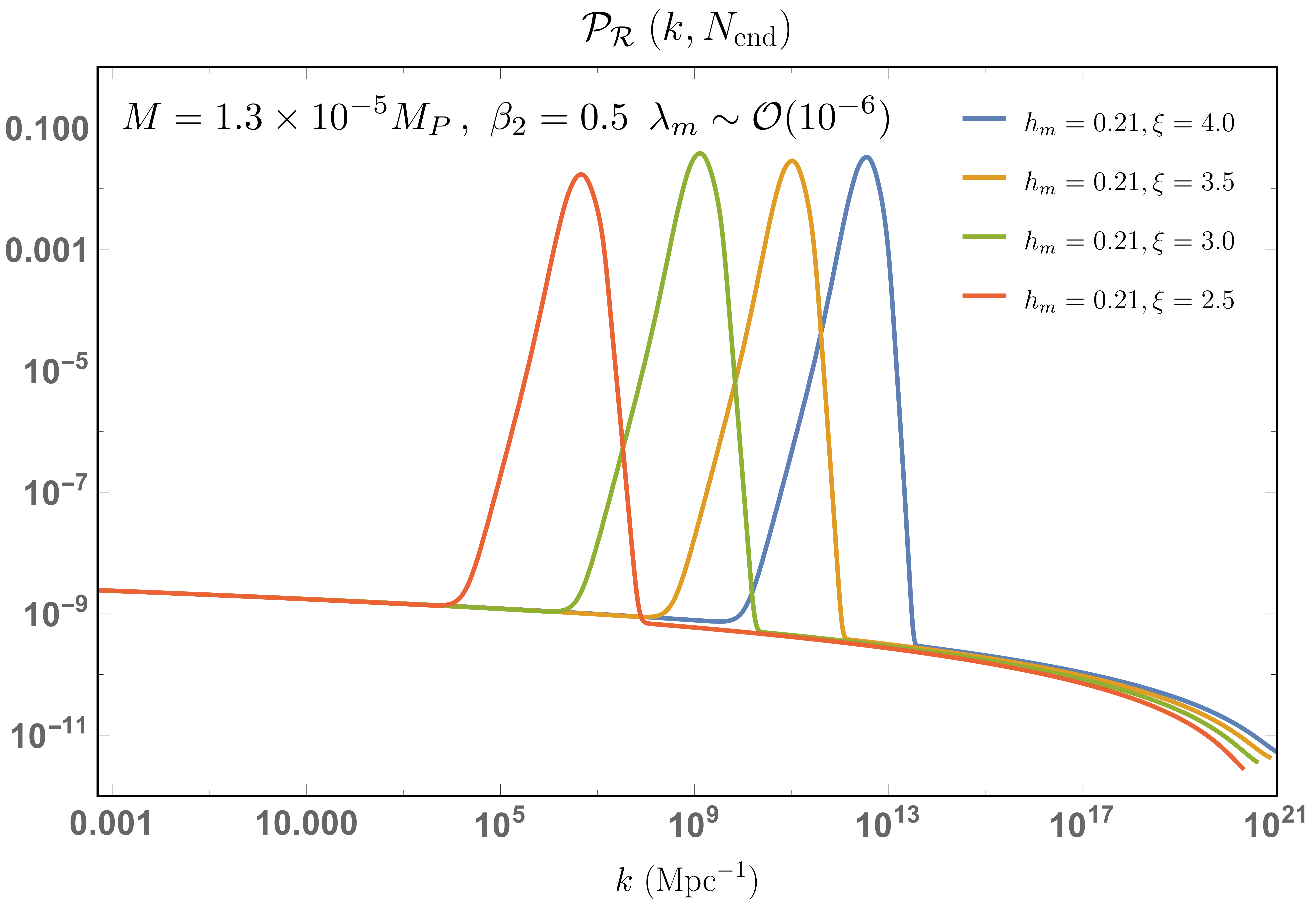


Higgs-R^2 Inflation, Power Spectrum

[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]



Higgs-R^2 Inflation, Power Spectrum

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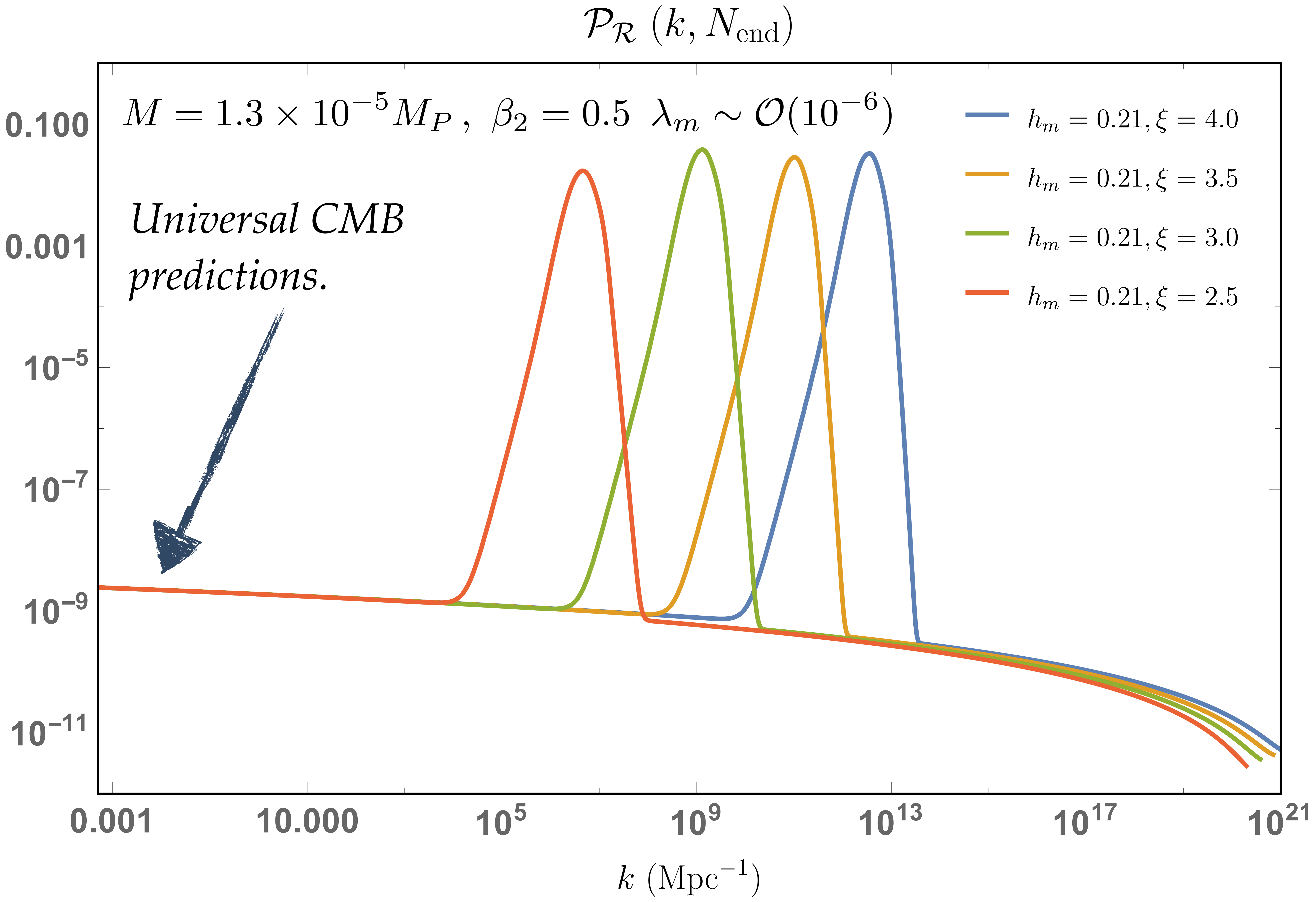

Higgs-R^2 Inflation, Power Spectrum

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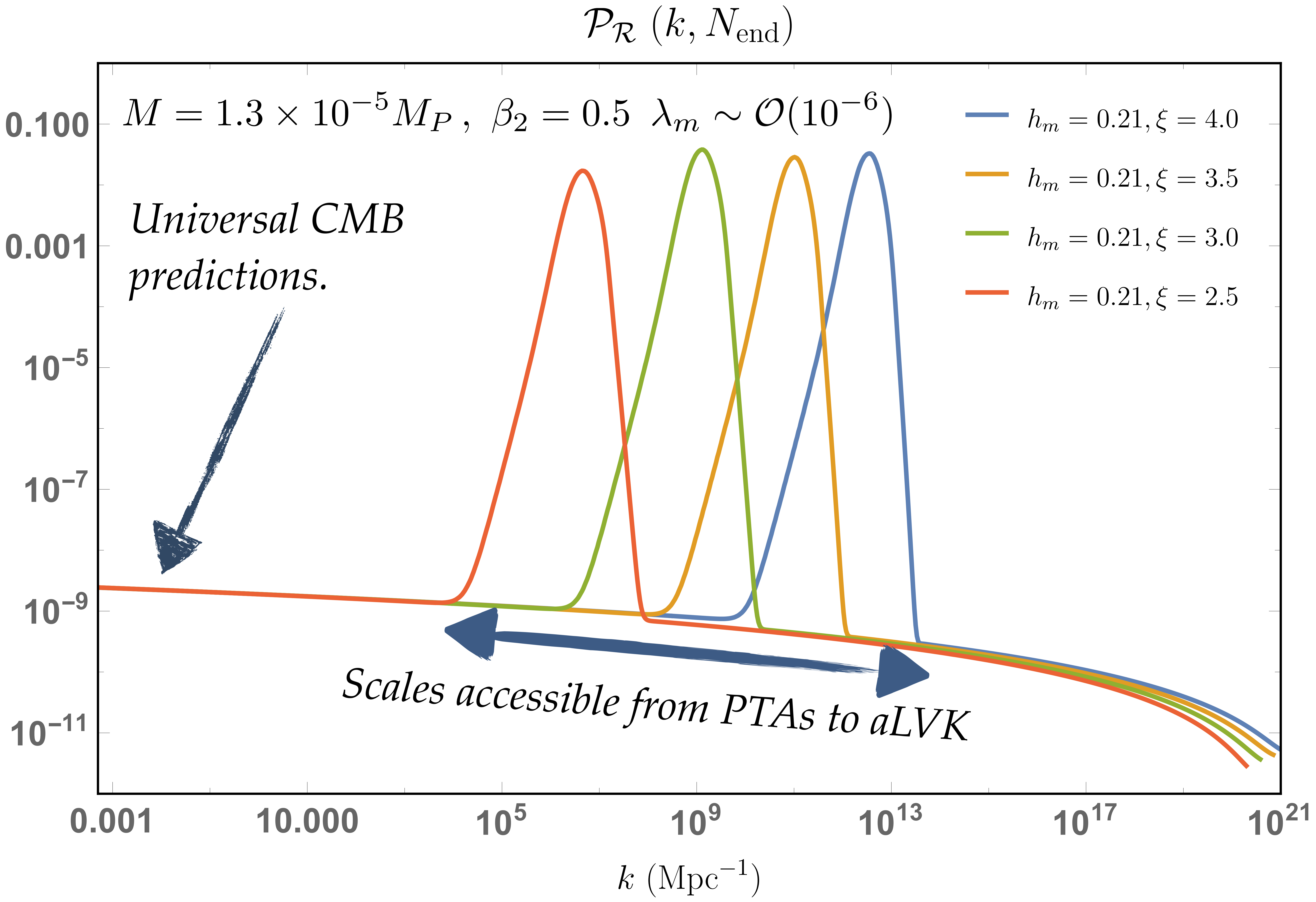
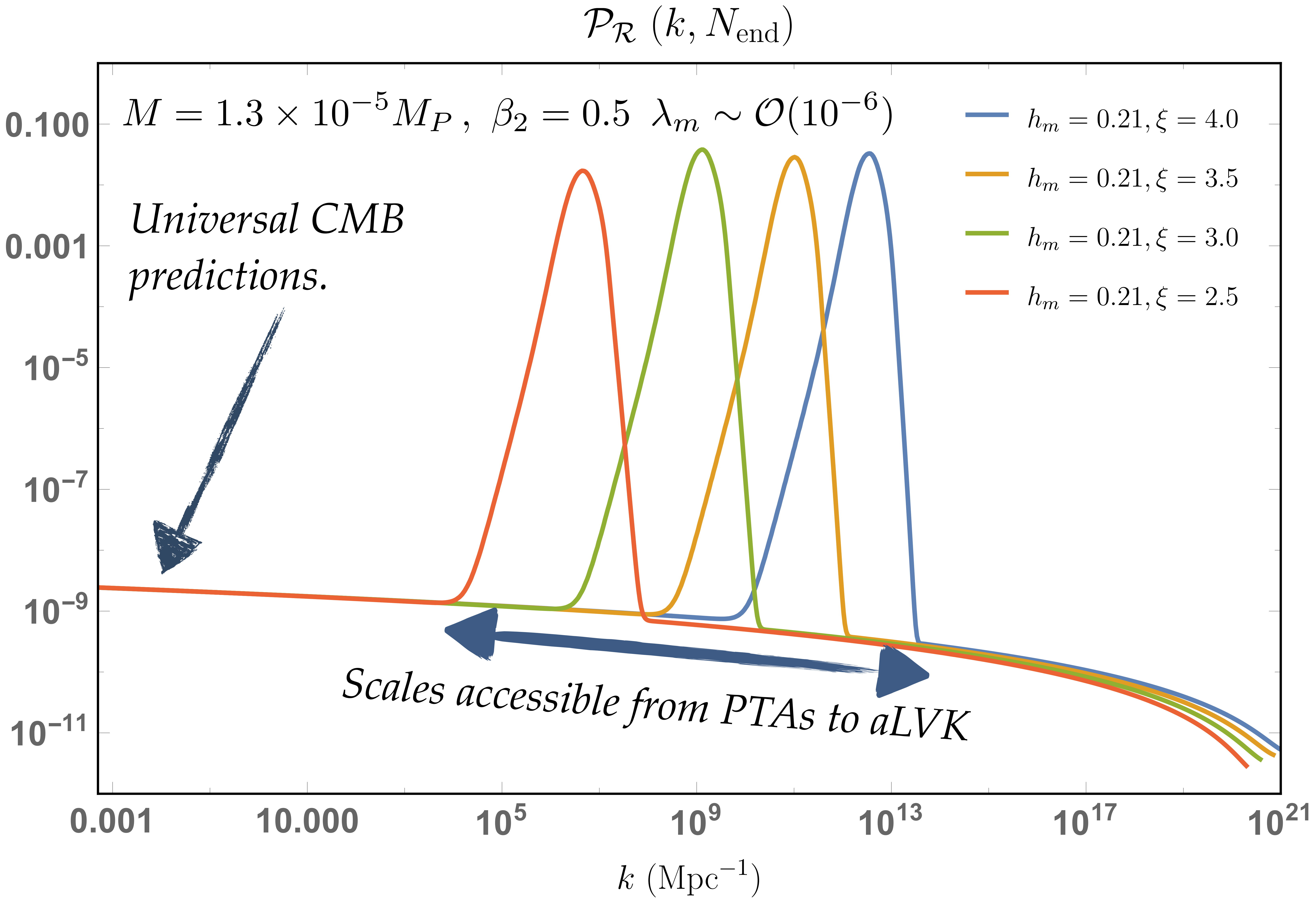


Higgs-R^2 Inflation, Power Spectrum



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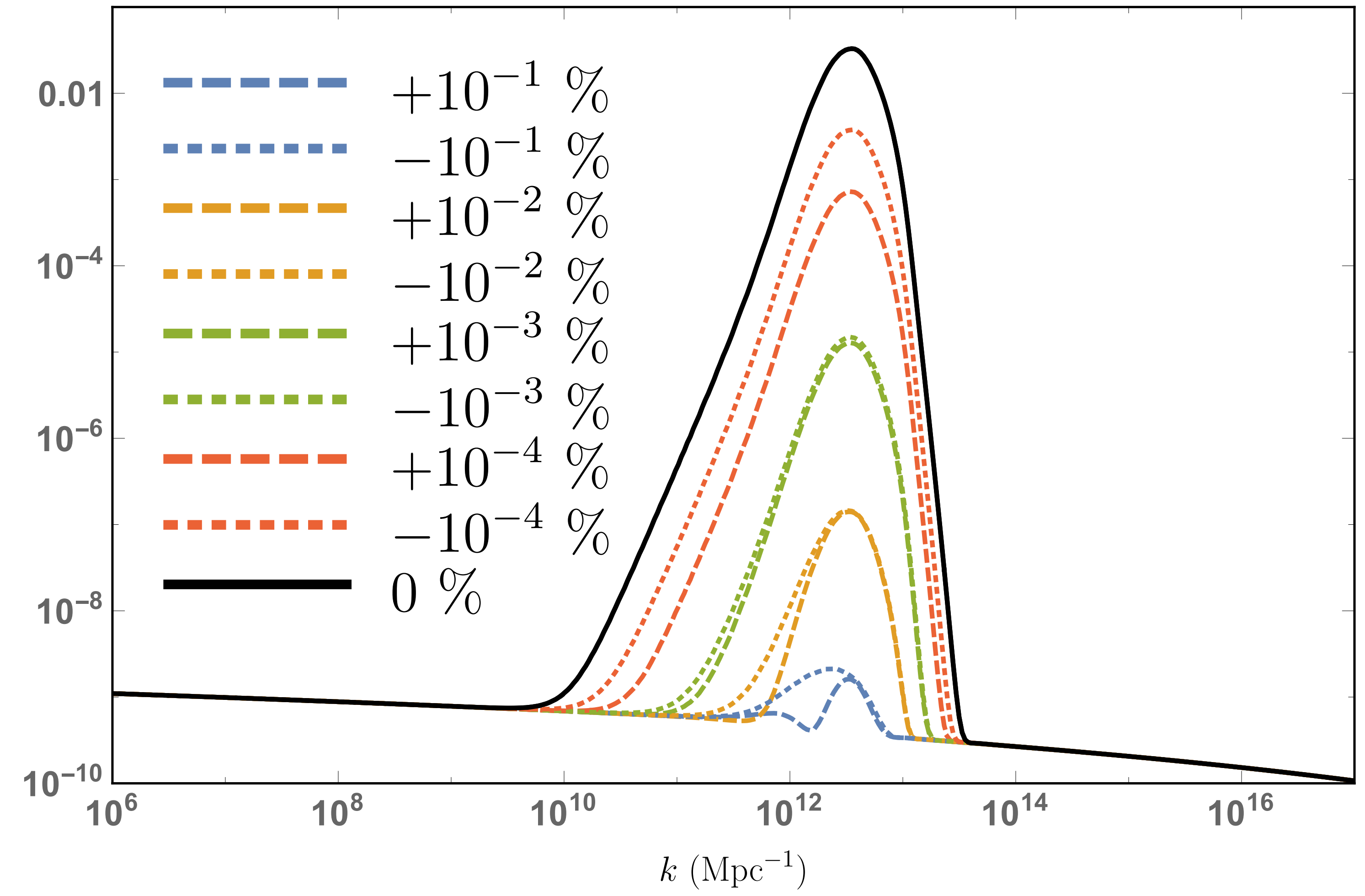
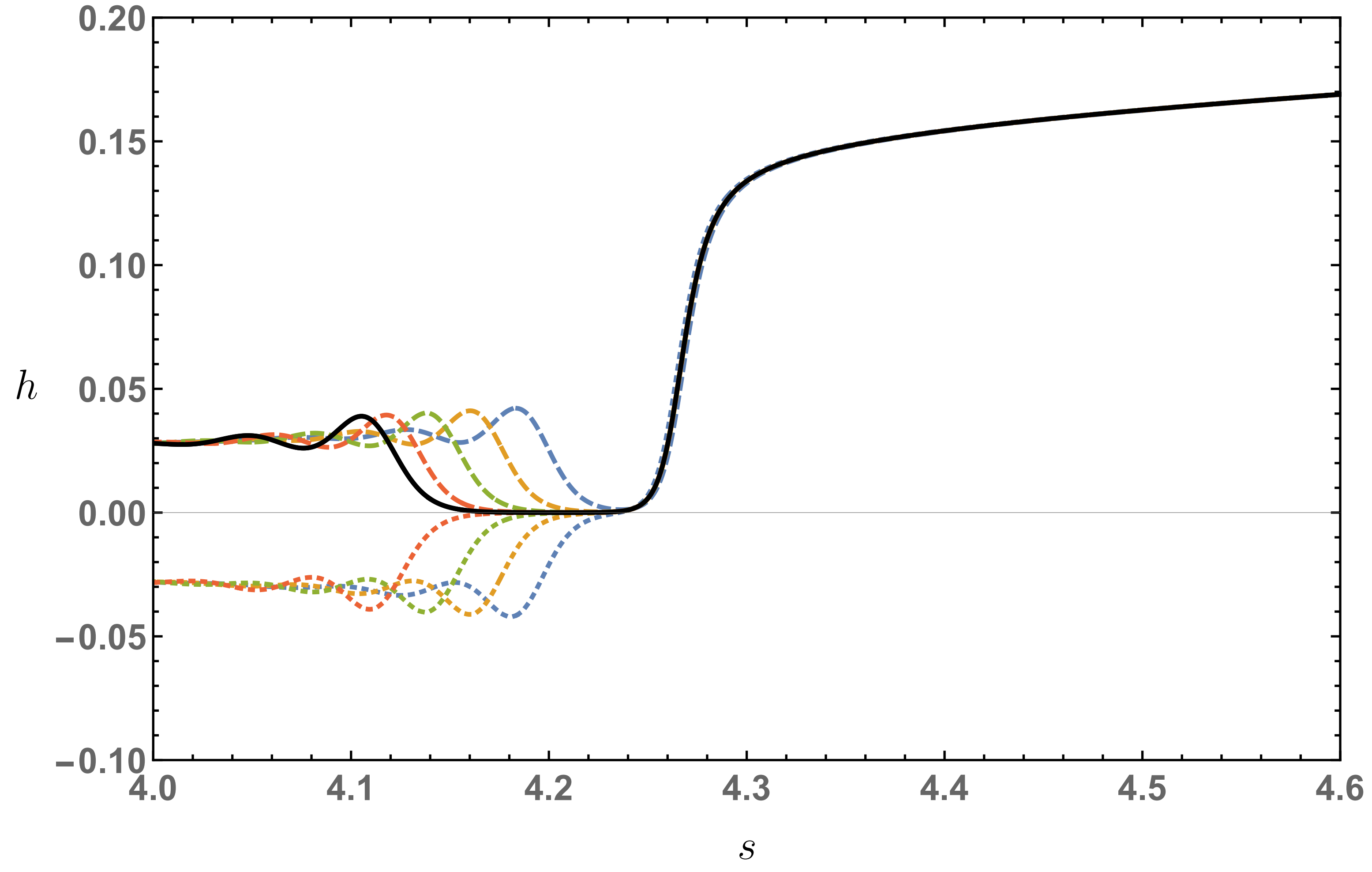
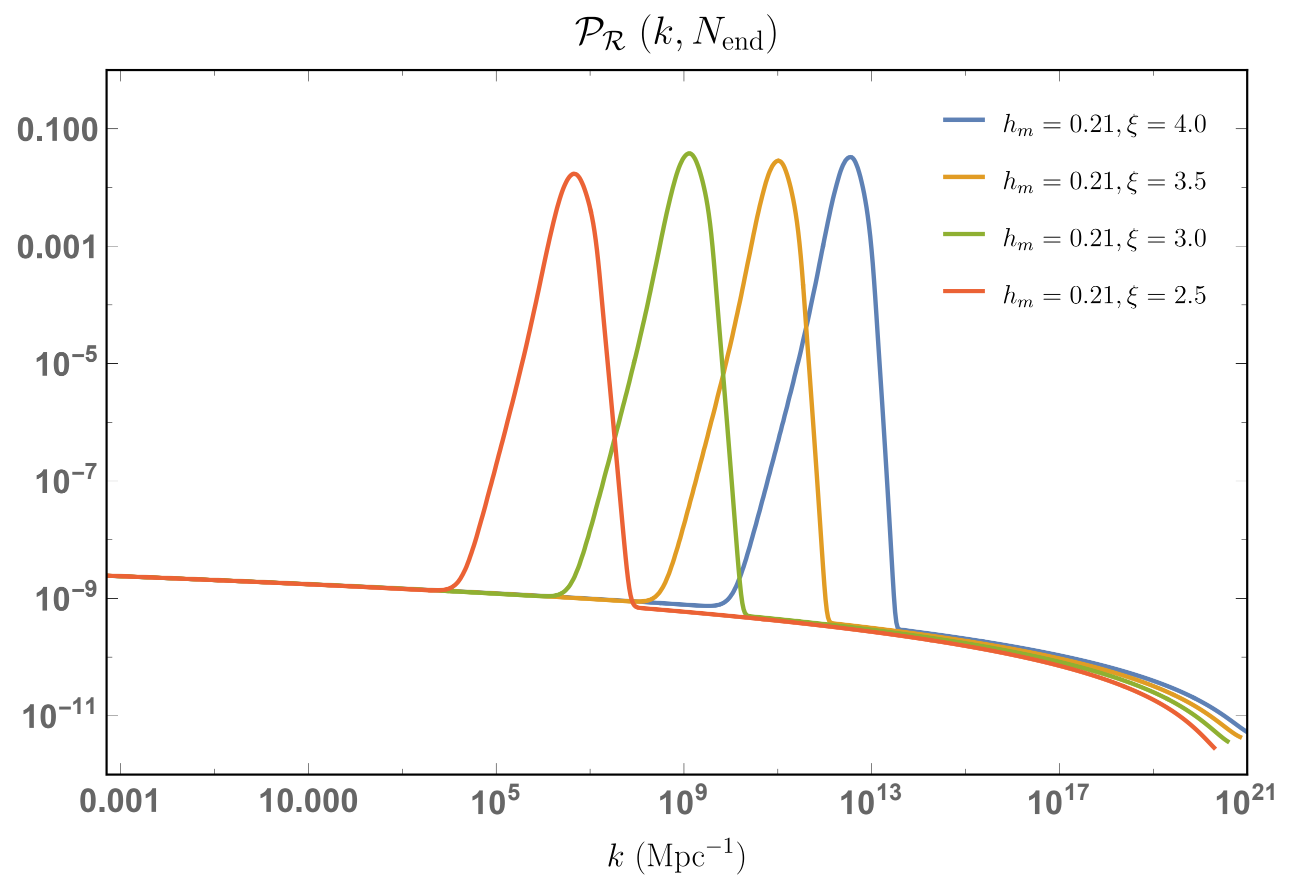




$$\frac{\delta\lambda_m}{\lambda_m} \equiv \frac{\lambda_m^{dev} - \lambda_m}{\lambda_m} \sim 10^{-4}\%$$

Phenomena —Primordial Black Holes



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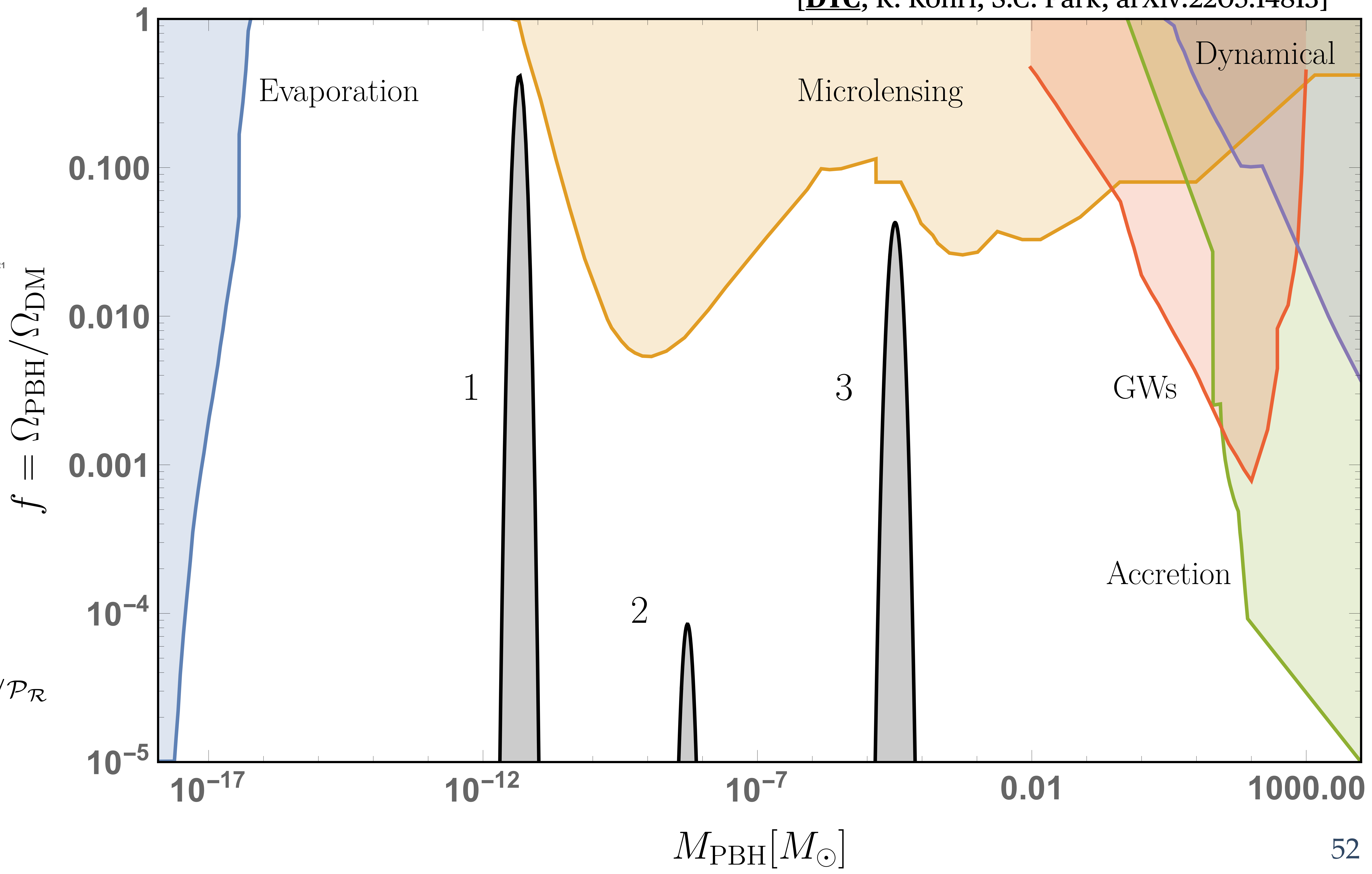
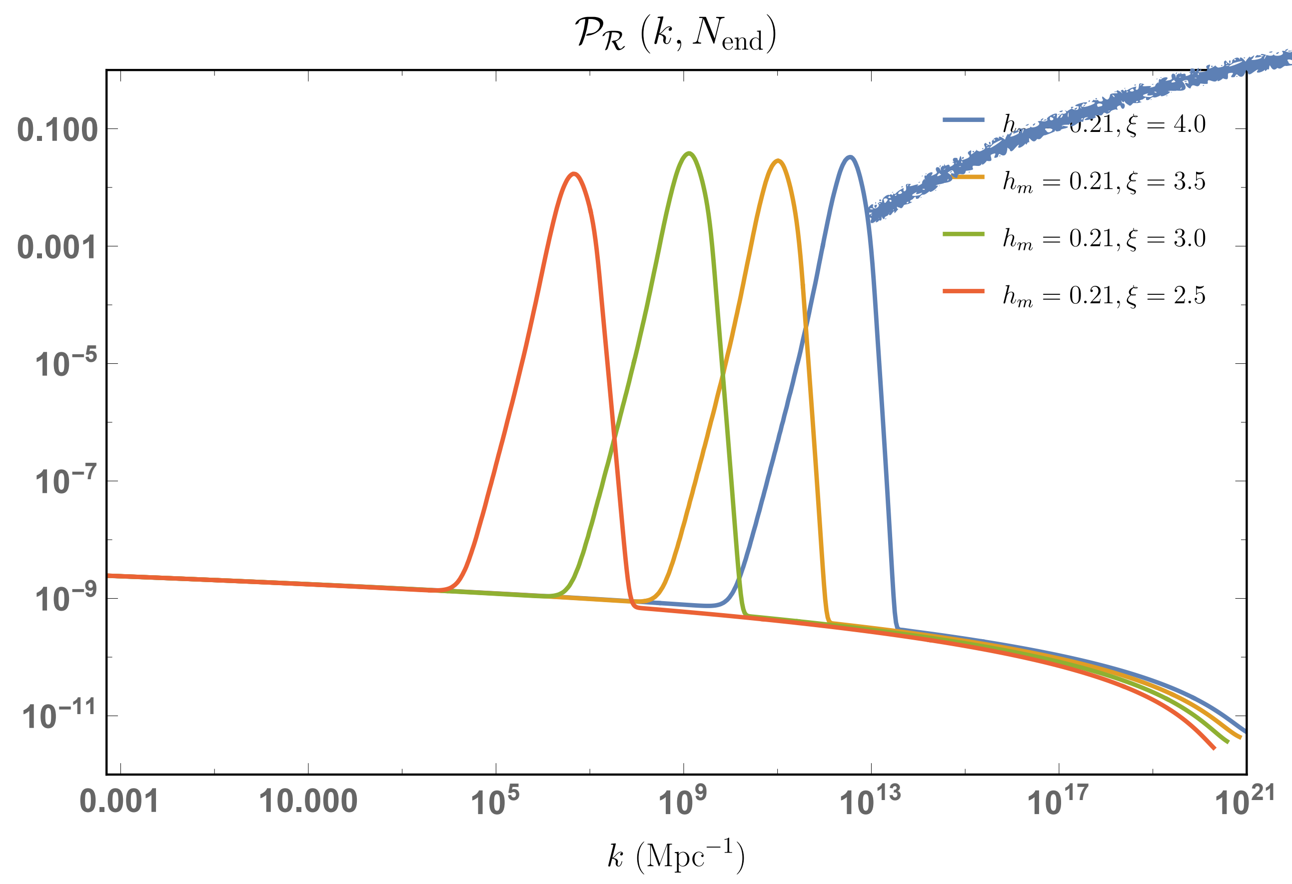


$$\beta \sim \frac{\sigma}{\sqrt{2\pi}\delta_c} e^{-\delta_c^2/(2\sigma^2)} \sim e^{-\delta_c^2/\mathcal{P}_\mathcal{R}}$$

Phenomena — Primordial Black Holes



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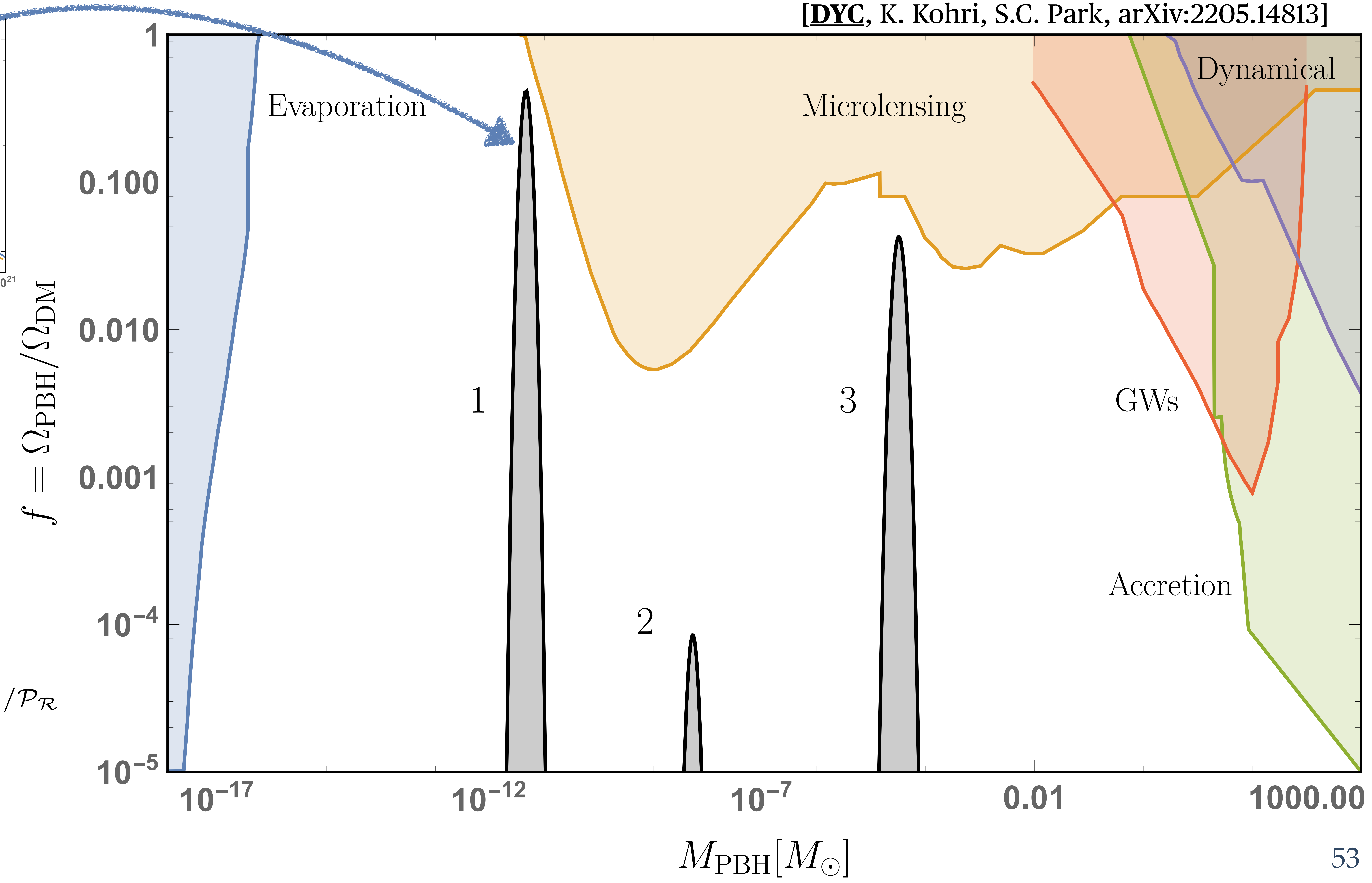

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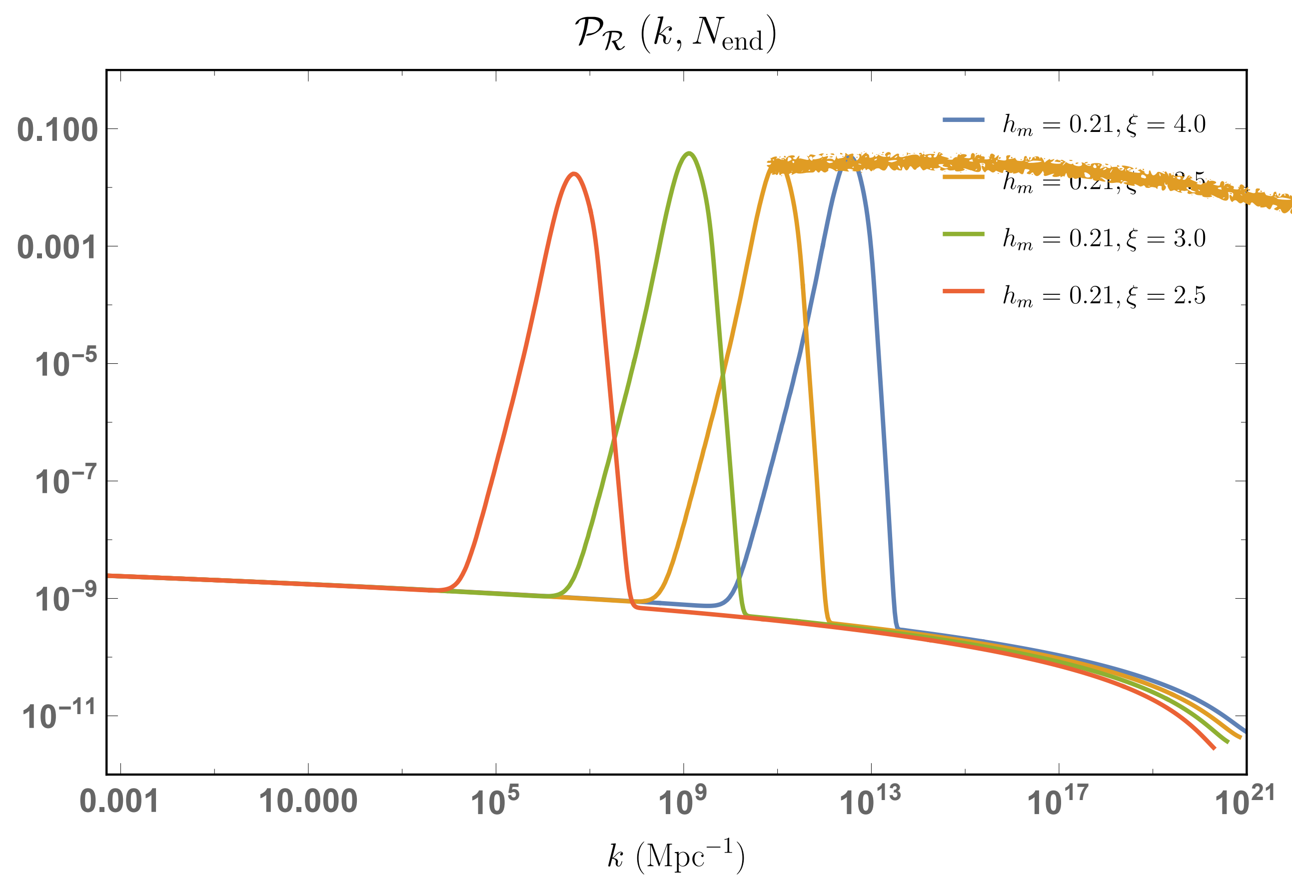

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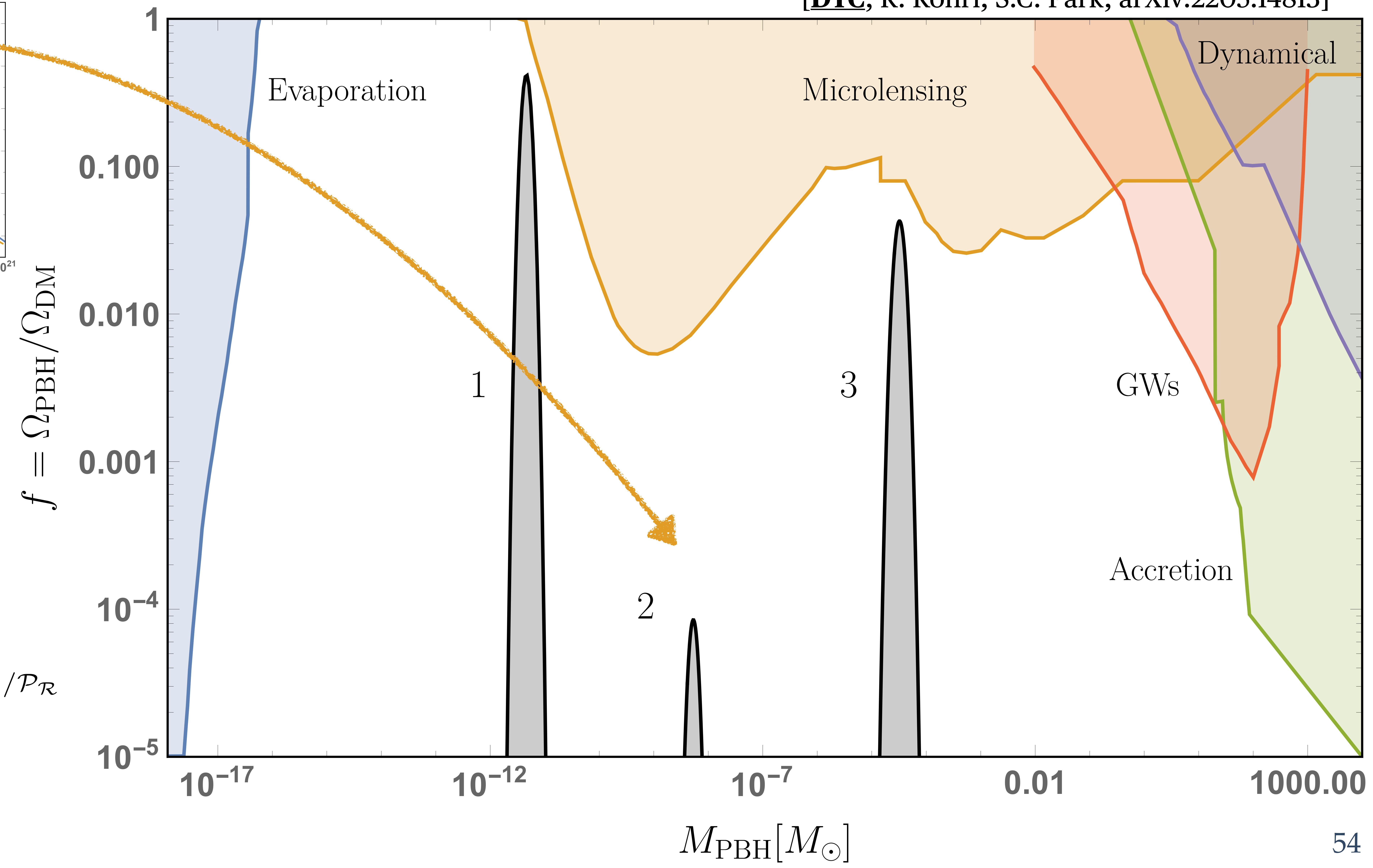

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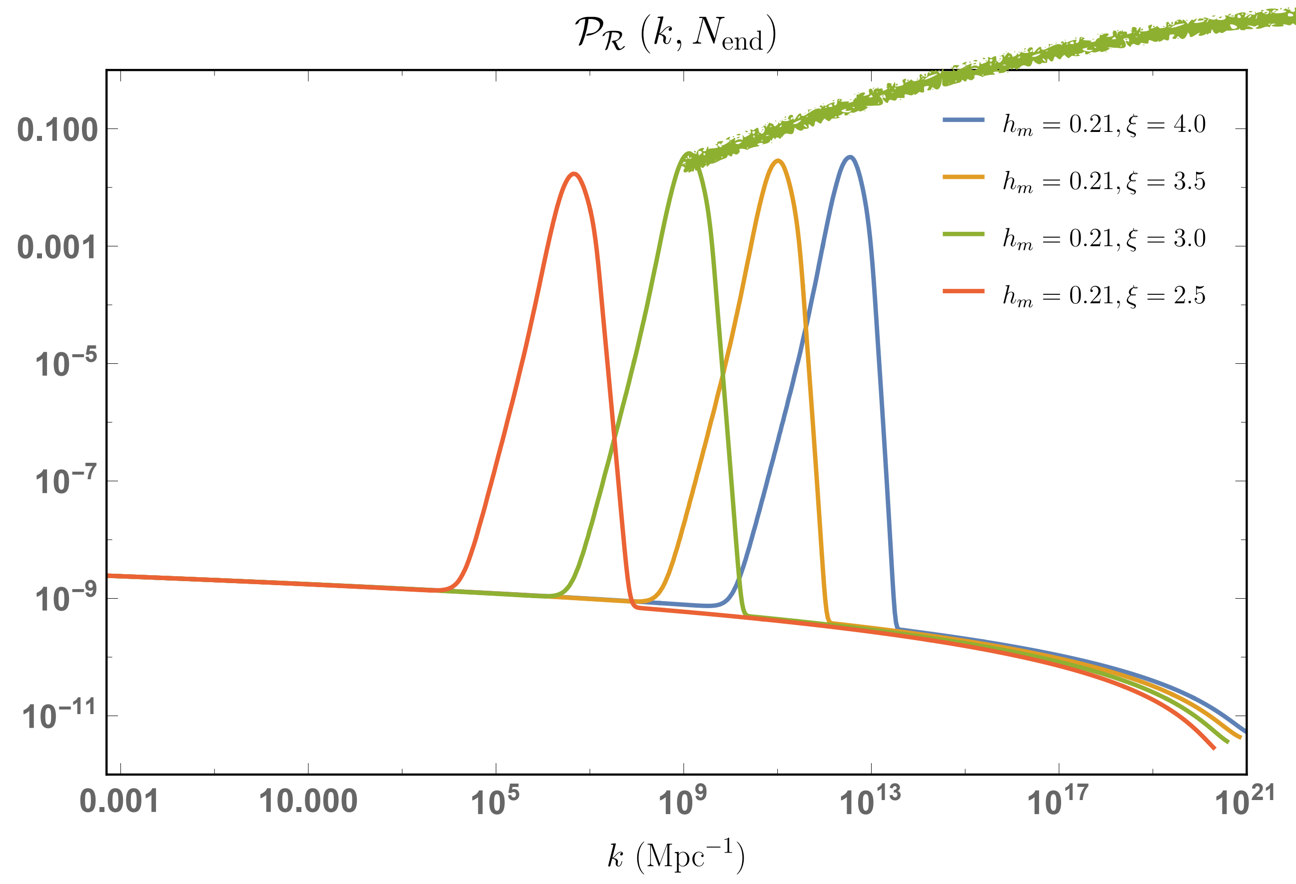

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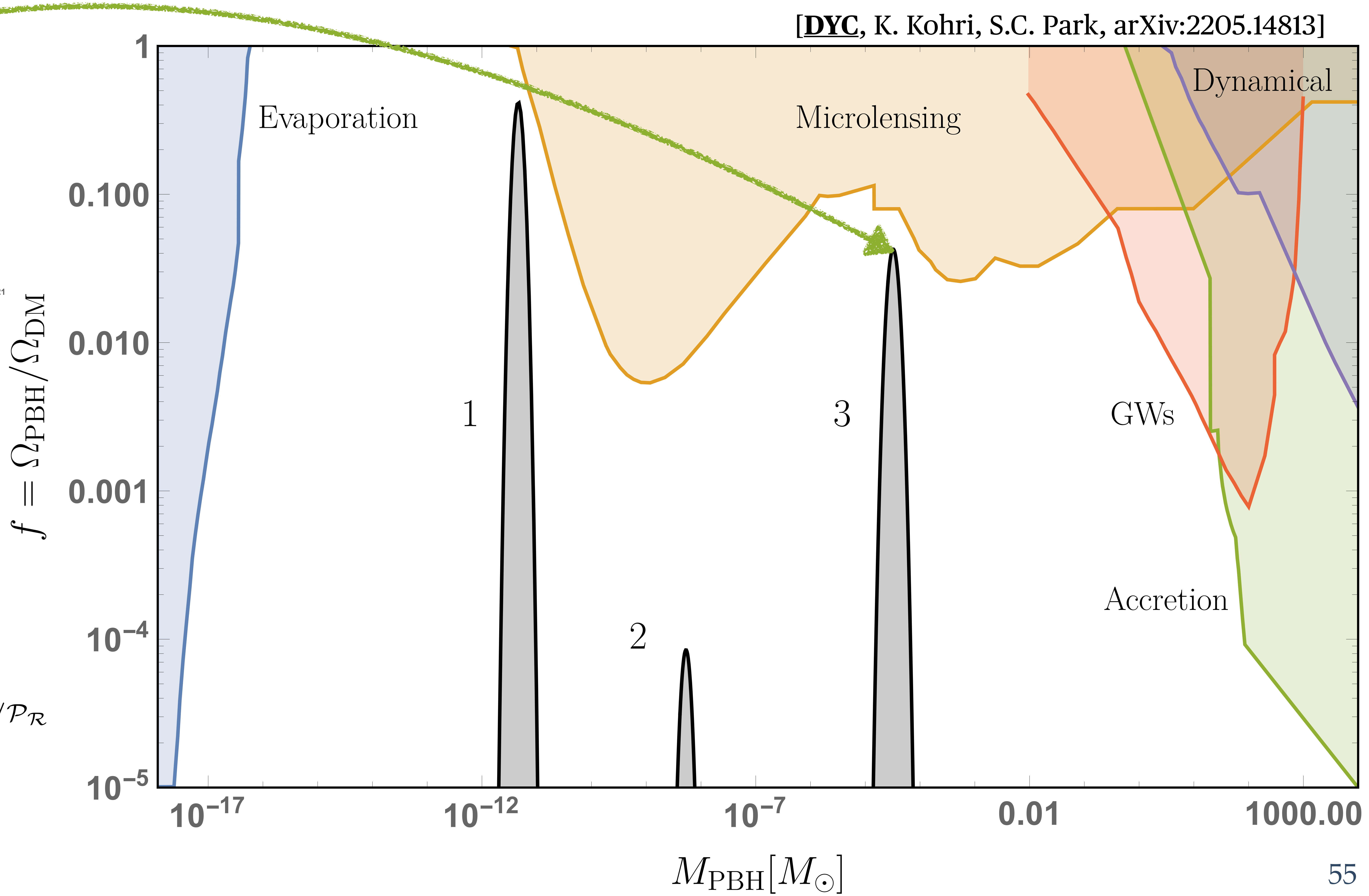

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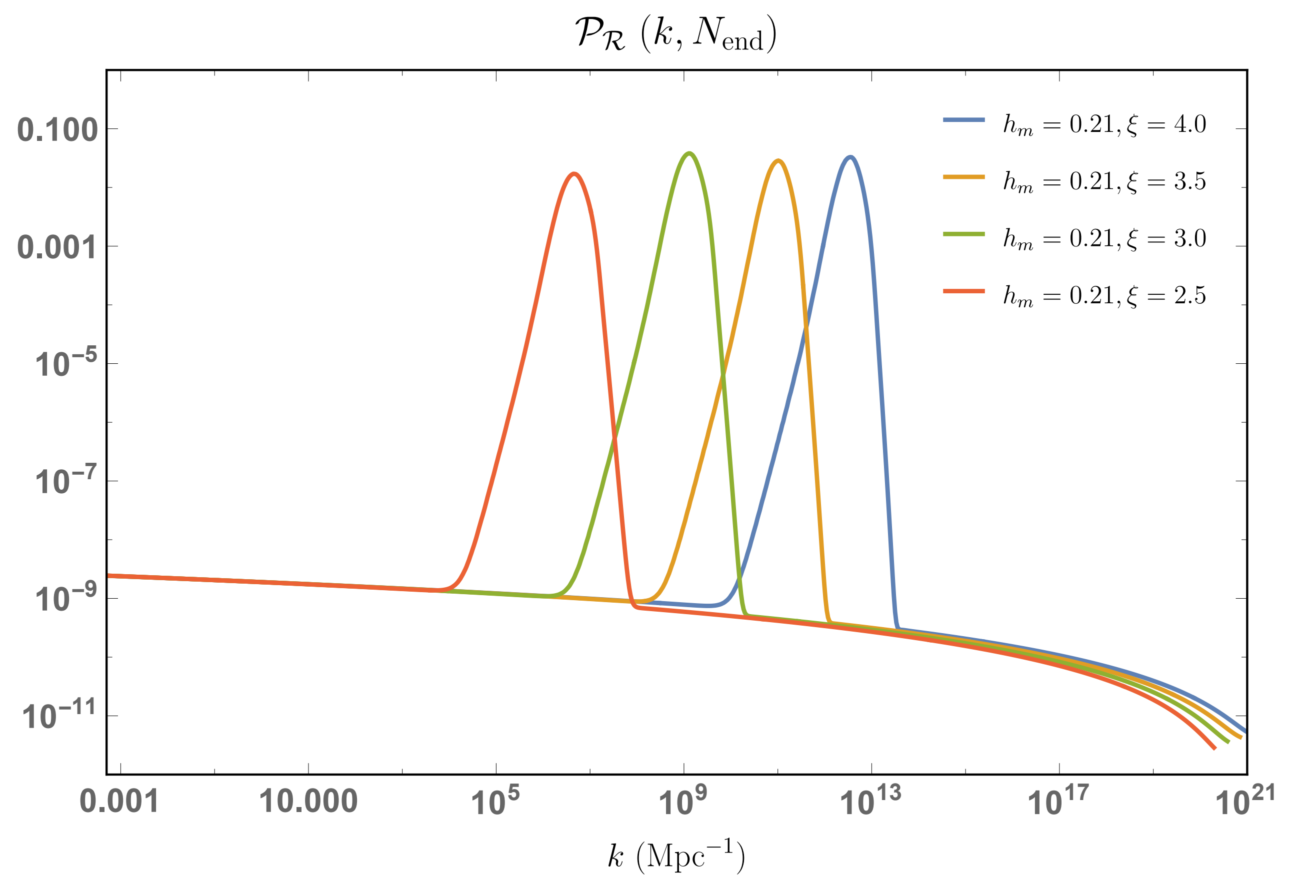
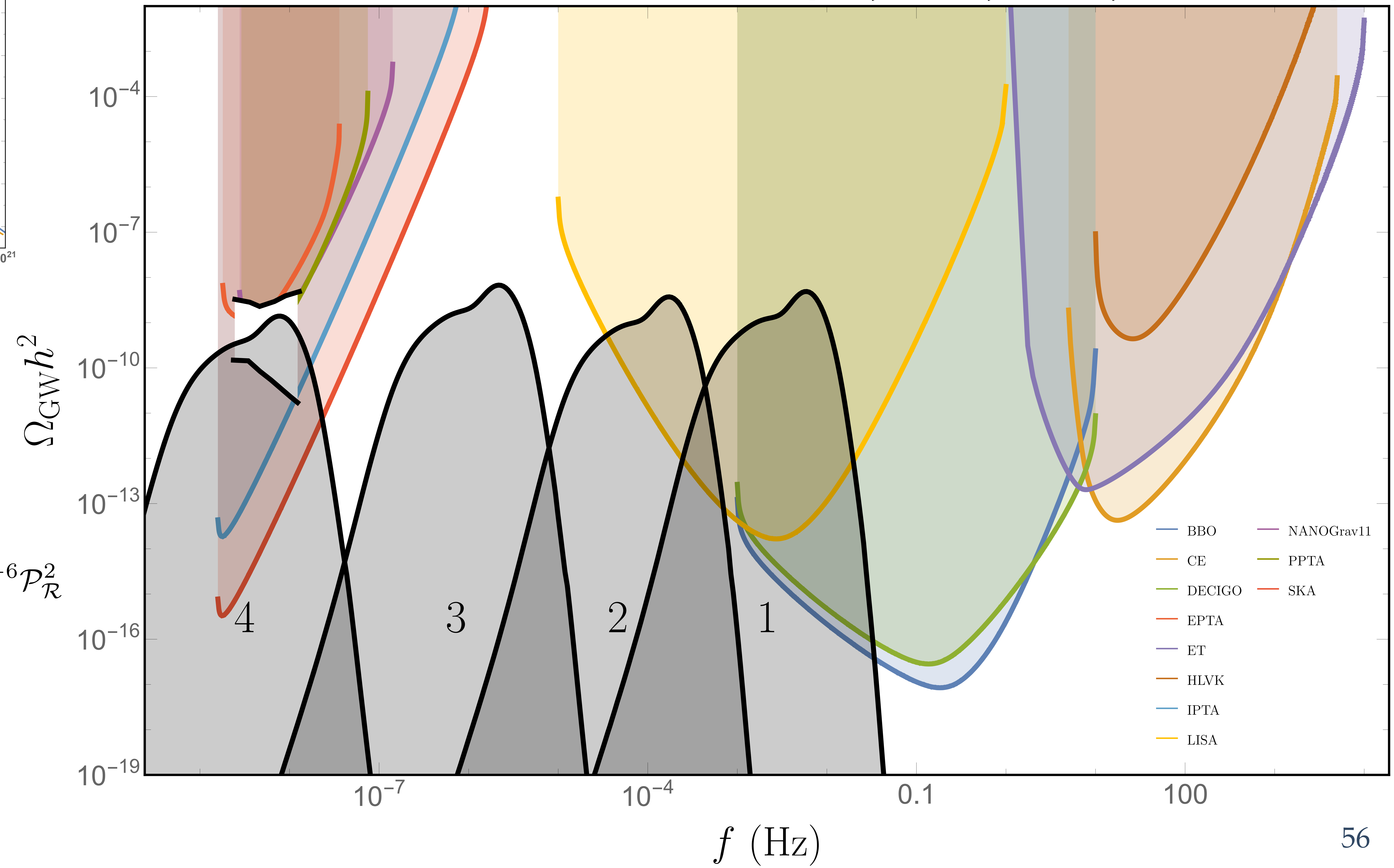
Phenomena —Second order GWs



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

[**DYC**, K. Kohri, S.C. Park, arXiv:2205.14813]



Phenomena —Second order GWs

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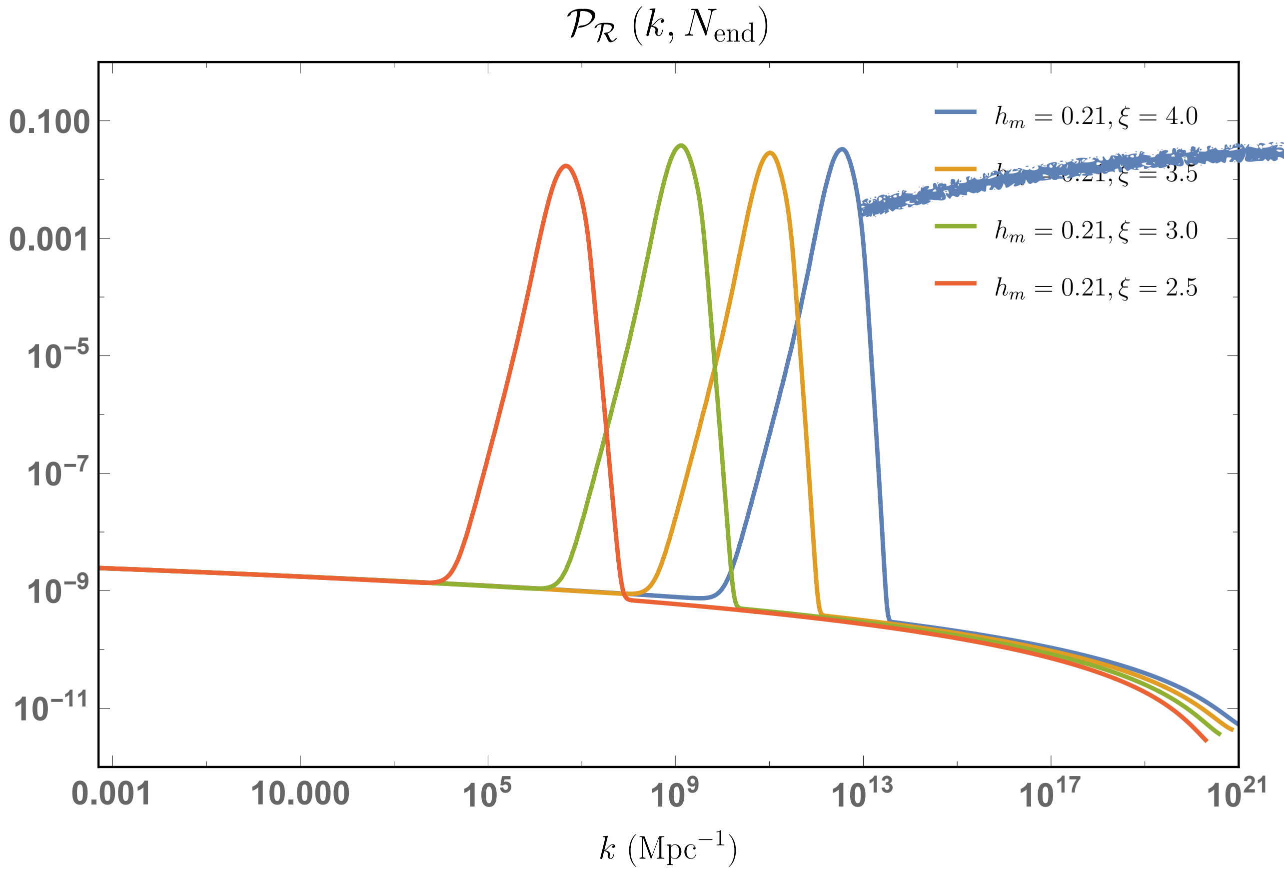

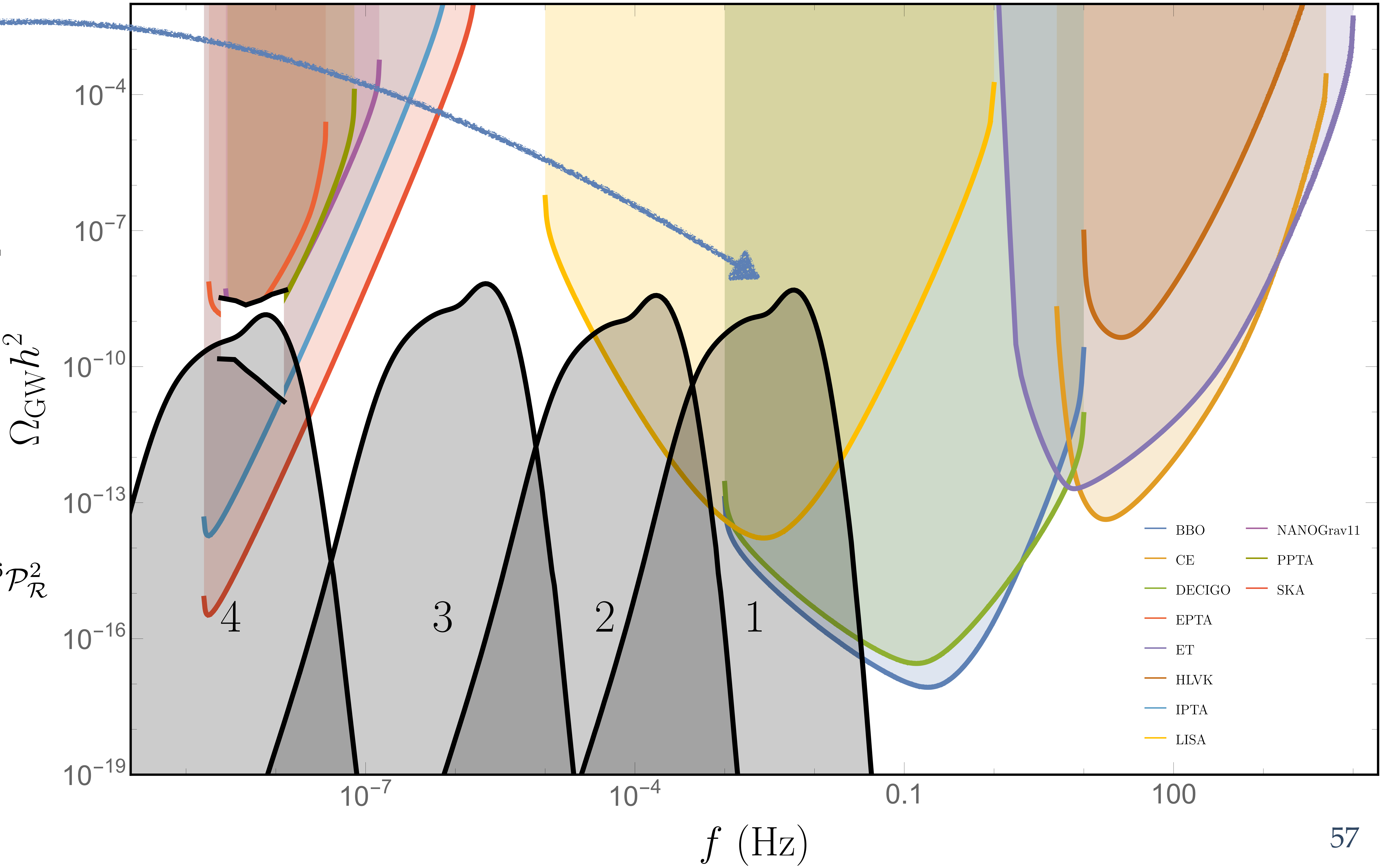

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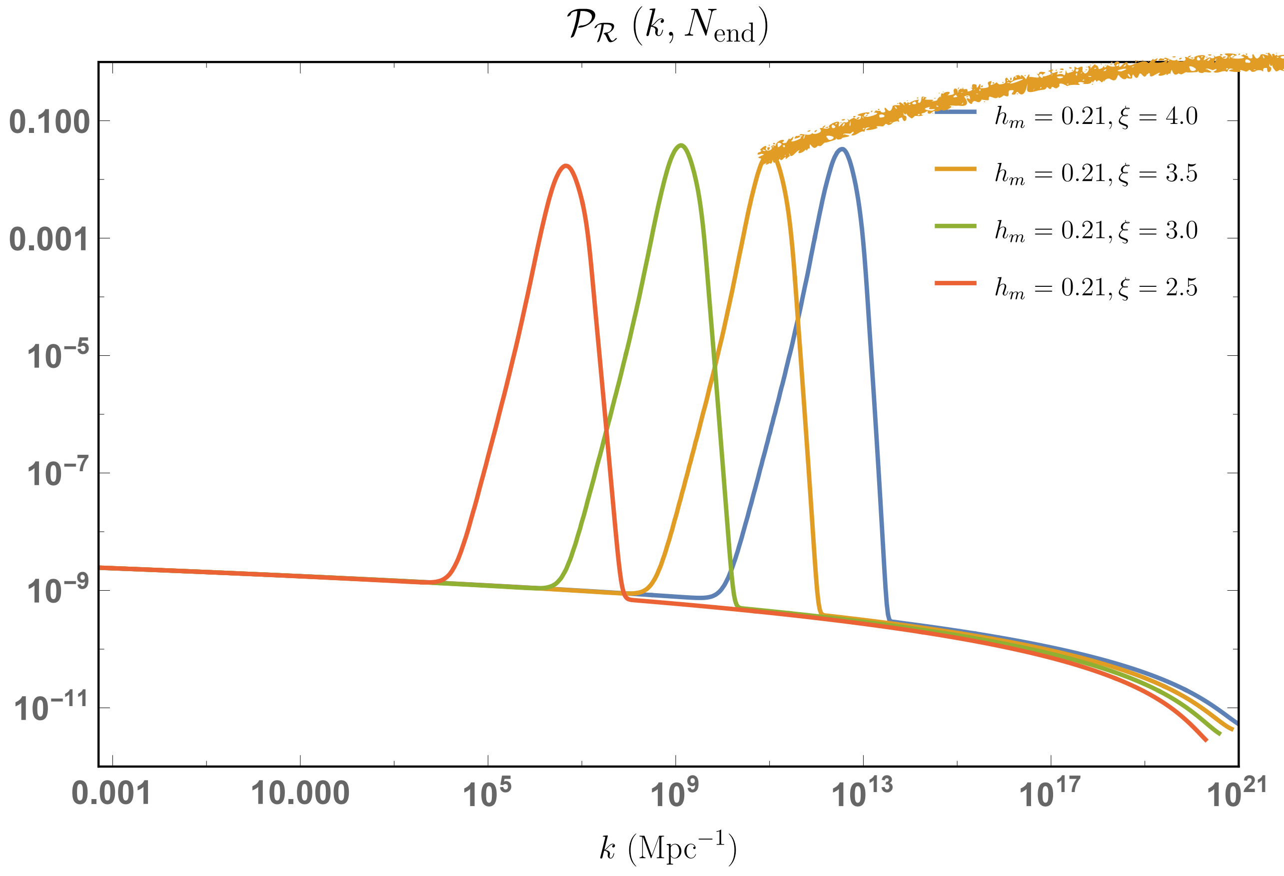

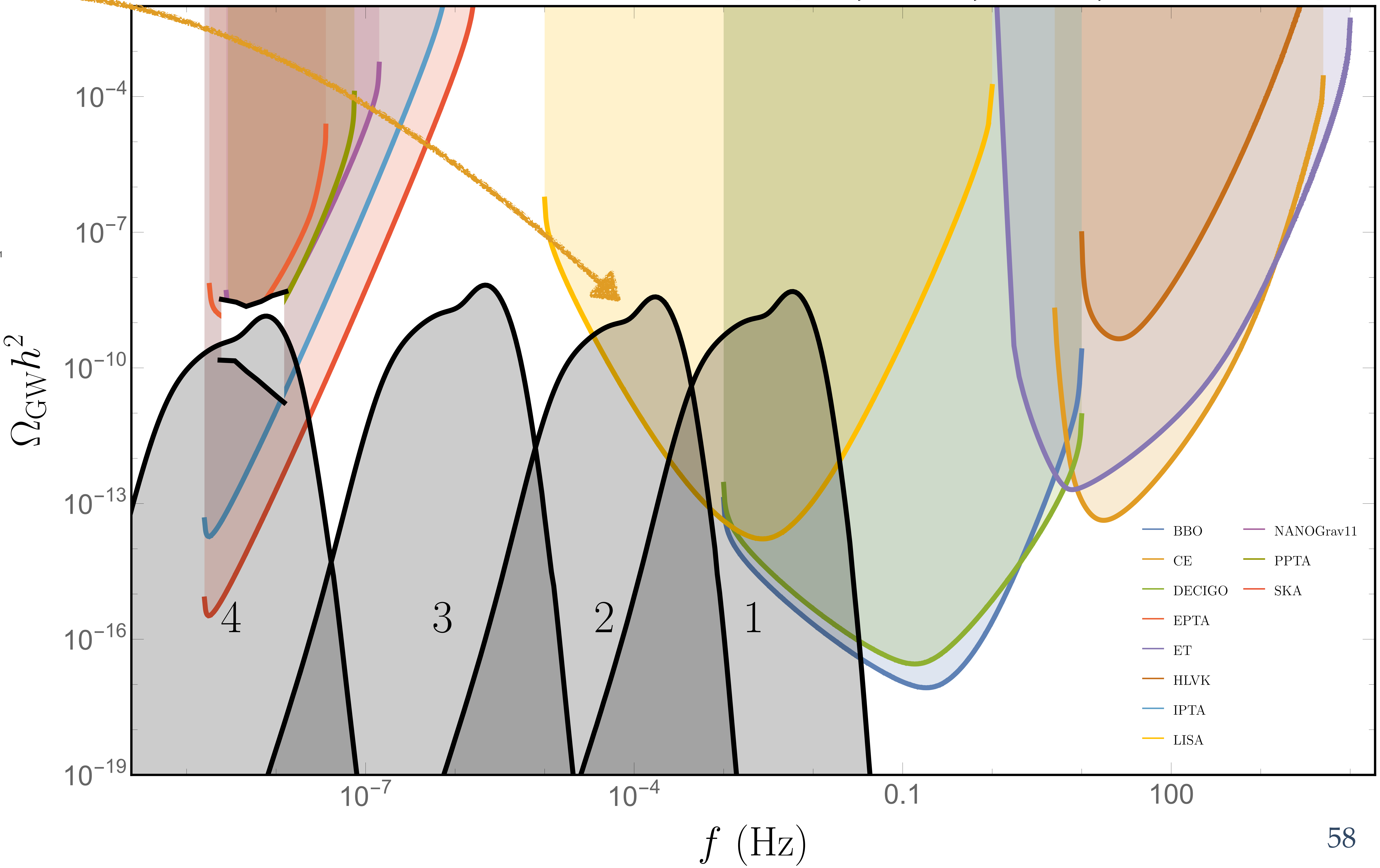

Phenomena —Second order GWs

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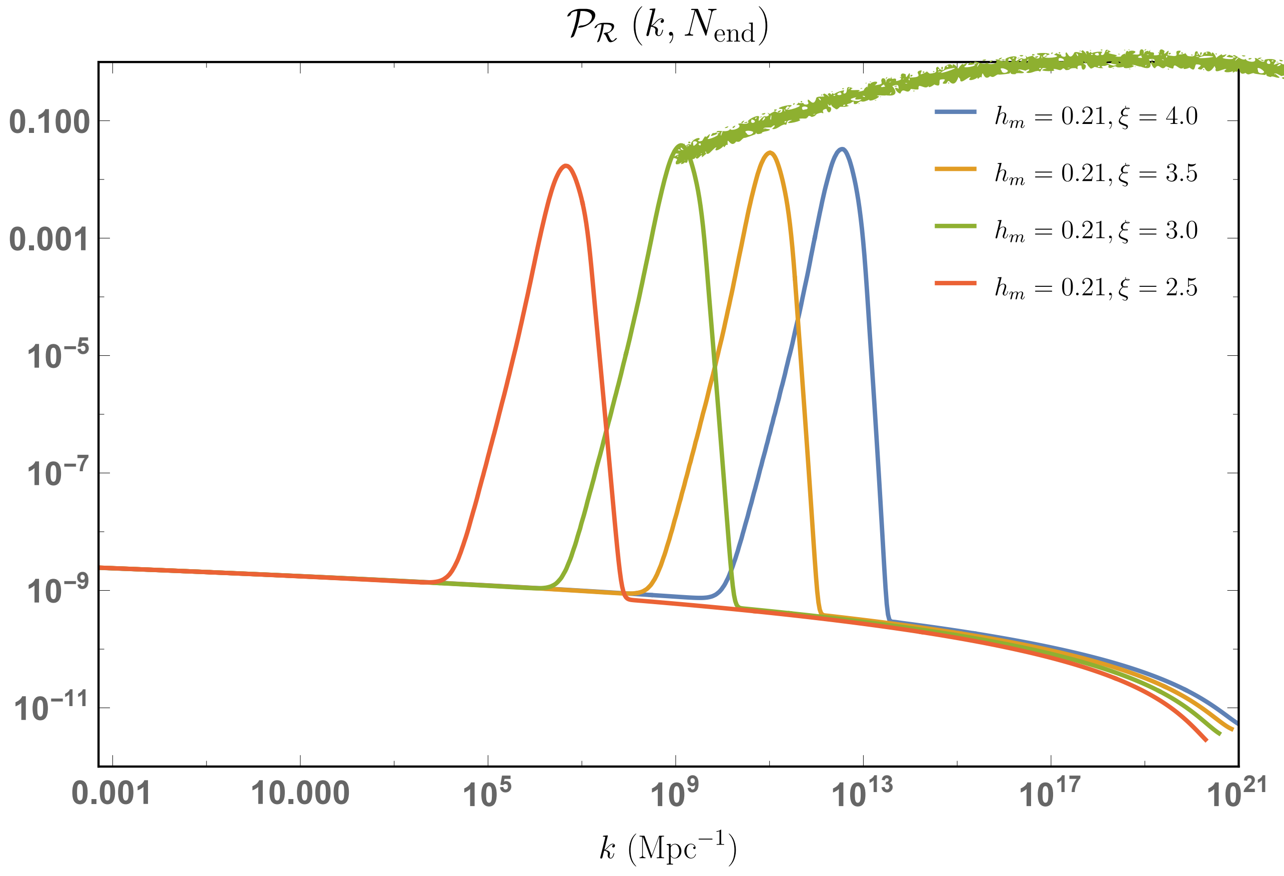

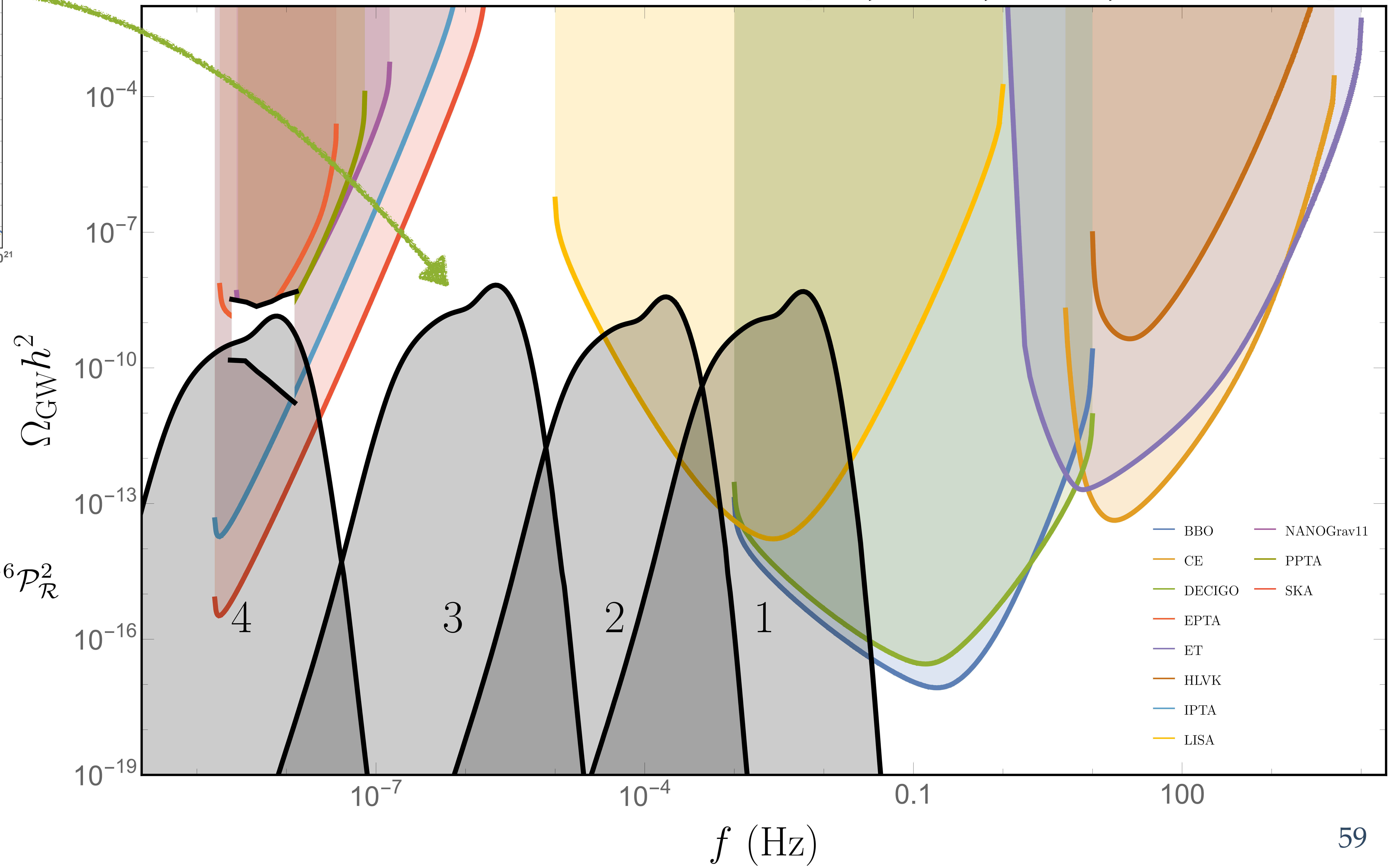

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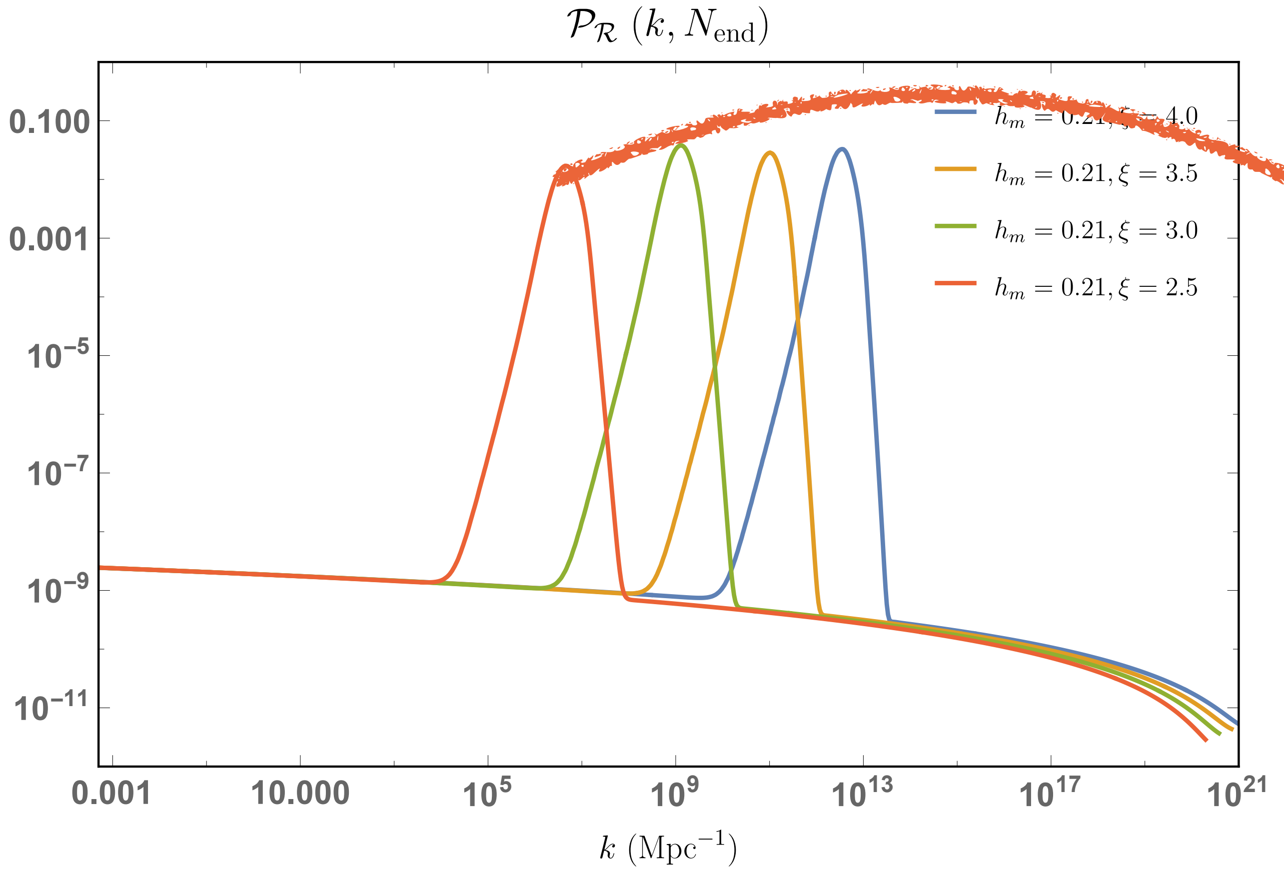

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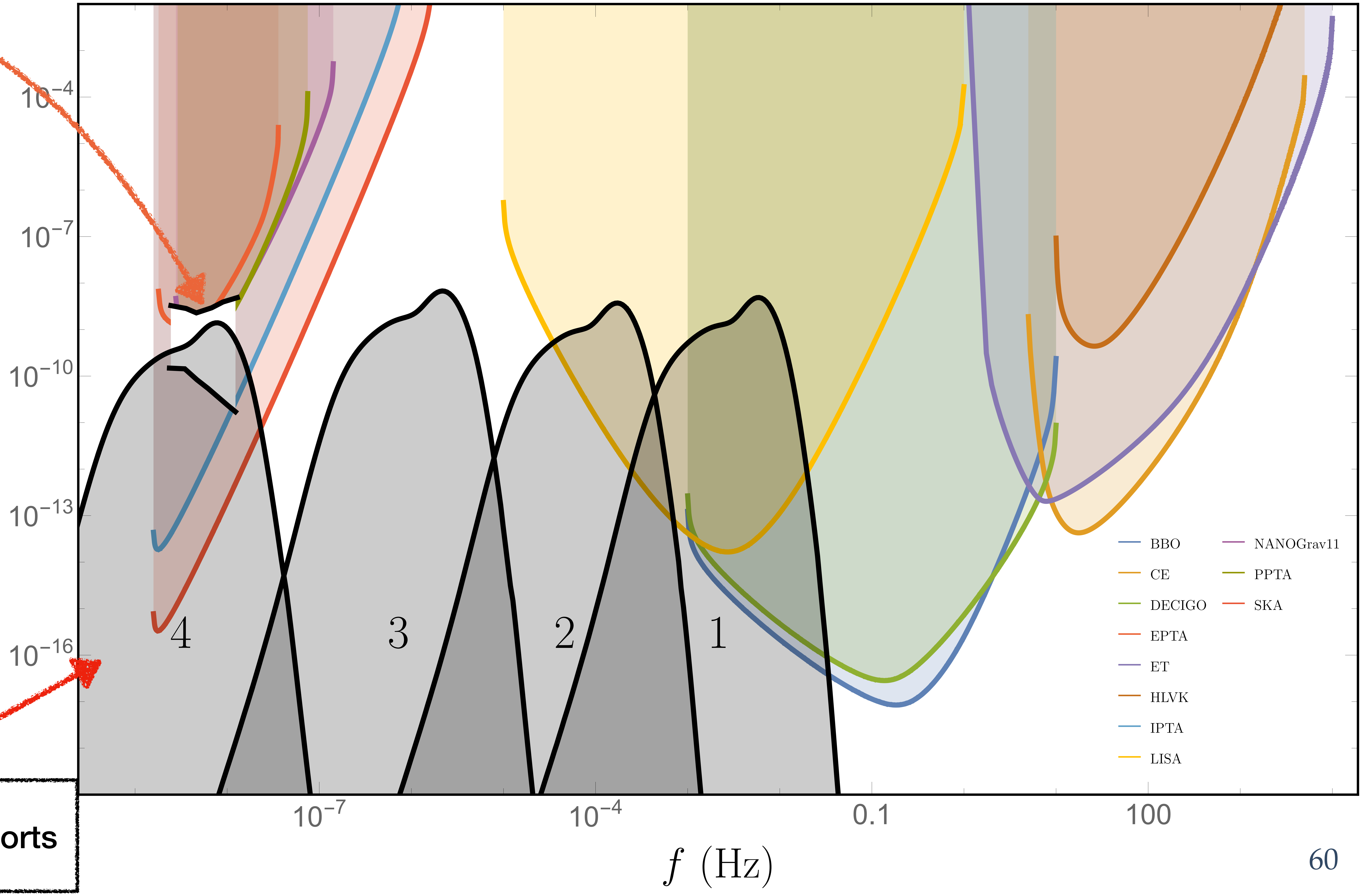

$$\Omega_{\rm GW} h^2 \sim \frac{1}{12}\Omega_{r,0} h^2 \times \mathcal{P}_{\mathcal{R}}^2 \sim 10^{-6}\mathcal{P}_{\mathcal{R}}^2$$

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 near inflection point USR phase and/or a tachyonic instability induced by the running λ.

- Apart from USR induced PBHs/GWs, that limit a significant PBH abundance within the mass range $M_{\rm PBH} \in (10^{-16}, 10^{-15}) M_\odot$, the *tachyonic instability* can produce a wide range of PBHs/GWs from *LIGO/Virgo to PTA frequencies*.

- Further distinguishable features? Direct correlation to collider observables? (m_{top})

“Thank you!”