Primordial Black Holes & Gravitational Waves in Higgs-R^2 Inflation

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arXiv:1912.12032 [hep-ph]
arXiv21xx.xxxxx [hep-xx]

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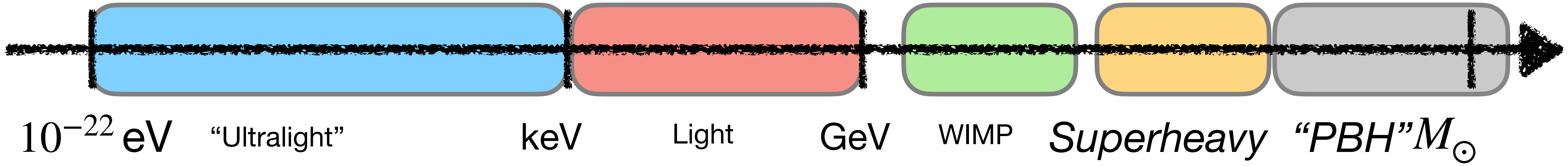
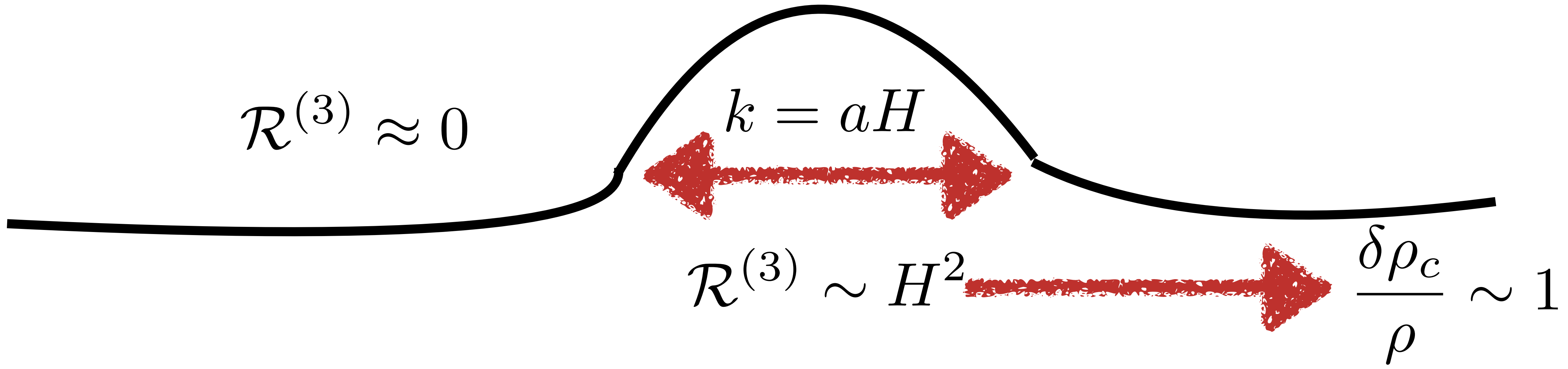
Primordial Black Holes



PBHs still a viable candidate for DM, has many other impact in our cosmology.



$$\frac{1}{3} = w_{\rm RD} \simeq \frac{\delta\rho_c}{\rho} \lesssim \frac{\delta\rho}{\rho} \lesssim 1$$

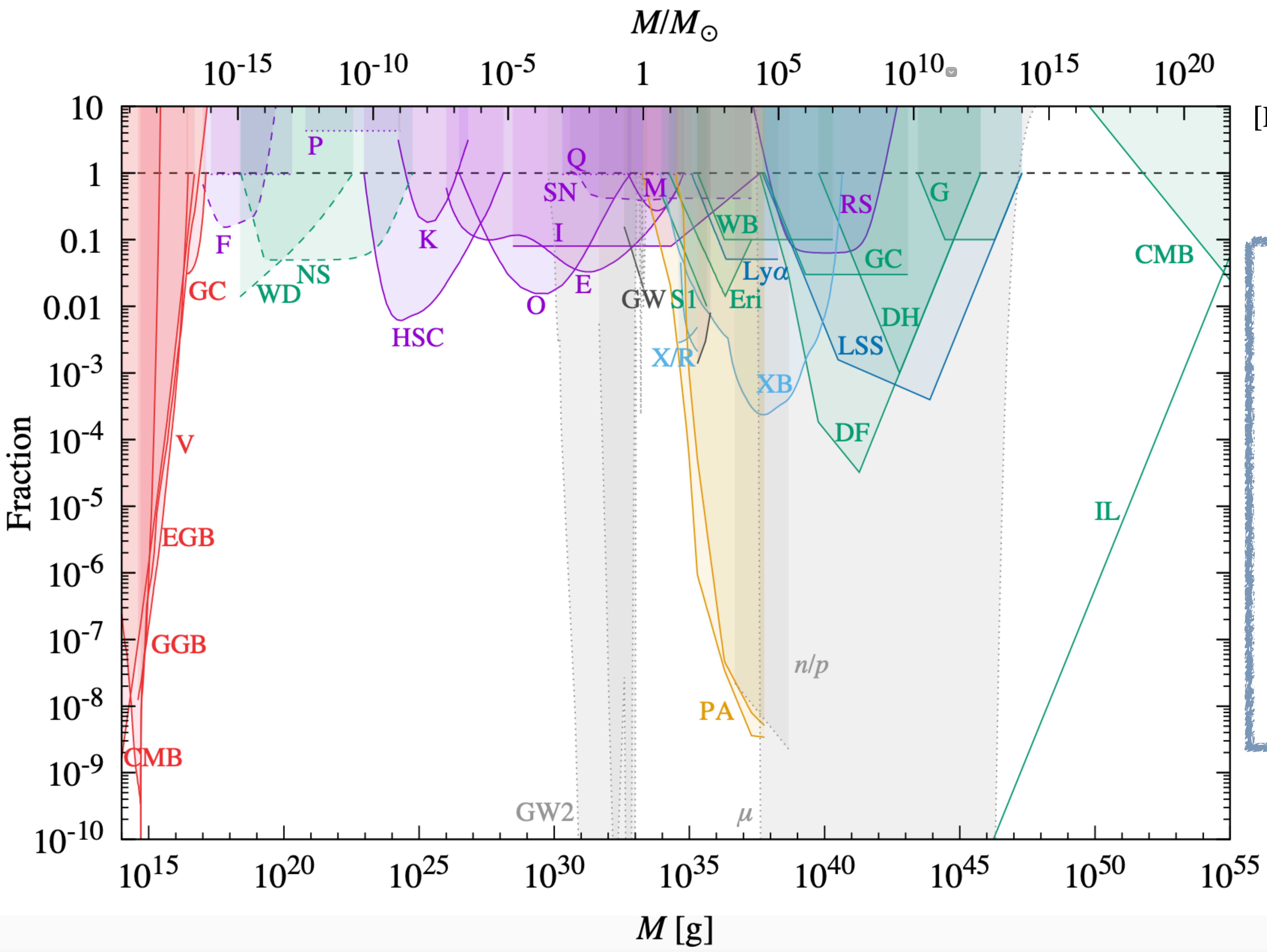
[T. Harada, C.M. Yoo, K. Kohri, arXiv:1309.4201]

PBHs form through the collapse of *<u>large over-densities in the density perturbation</u>*

$$k \leftrightarrow M_{\rm PBH} \to \mathcal{P}_{\mathcal{R}}\left(k\right) \to \mathcal{P}_{\delta}\left(k\right) \to \beta\left(M\right) \to \Omega_{\rm PBH}$$

$$\frac{M_{\rm PBH}}{M_\odot} \sim \left(\frac{k_*}{3.3 \times 10^6 {\rm Mpc}^{-1}}\right)^{-2} \sim \left(\frac{f_*}{5.0 \times 10^{-9} {\rm Hz}}\right)^{-2}$$

Current Status of PBH Constraints



[B. Carr et.al, 2002.12778]

Allowed PBH dark matter mass window : $\left(10^{-16}, 10^{-12}\right) M_{\odot}$

Recent NANOGrav results may indicate PBH DM.

[Z. Arzoumanian et. al.(NANOGrav), 2009.04496]
[V. De Lica, G. Franciolini, A. Riotto, 2009.08268]
[K. Kohri, T. Terada, 2009.11853]
[G. Domènech, S. Phi, 2010.03976]

PBH DM well suitable for interest!

Second Order Gravitational Waves

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

$$\Omega_{\rm GW}(\eta_0,k) = c_g \frac{\Omega_{r,0}}{72}\int_{-\frac{1}{\sqrt{3}}}^{\frac{1}{\sqrt{3}}} dd \int_{\frac{1}{\sqrt{3}}}^{\infty} ds \left[\frac{(d^2-1/3)(s^2-1/3)}{s^2-d^2}\right] \mathcal{P}_\zeta\left(\frac{k\sqrt{3}}{2}(s+d)\right)\mathcal{P}_\zeta\left(\frac{k\sqrt{3}}{2}(s-d)\right)\left[\mathcal{I}_c^2(x(d,s),y(d,s)) + \mathcal{I}_s^2(x(d,s),y(d,s))\right]$$

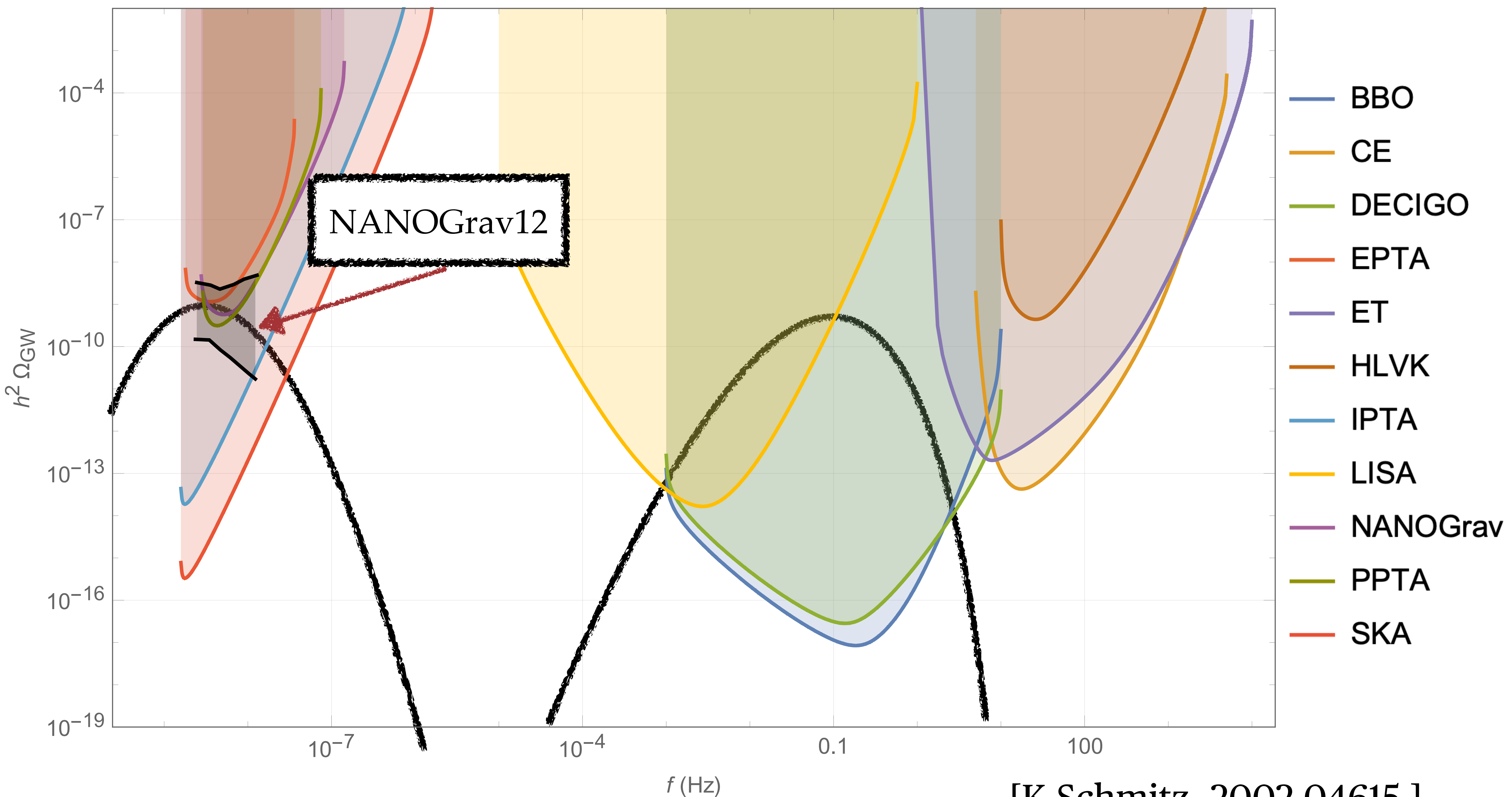
$$\Omega_{\rm GW}h^2 \sim \frac{1}{12}\Omega_{r,0}h^2 \times \mathcal{P}_\mathcal{R}^2 \sim 10^{-6}\mathcal{P}_\mathcal{R}^2$$

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

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

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

Future GW observatories well involved in probing the small scale.

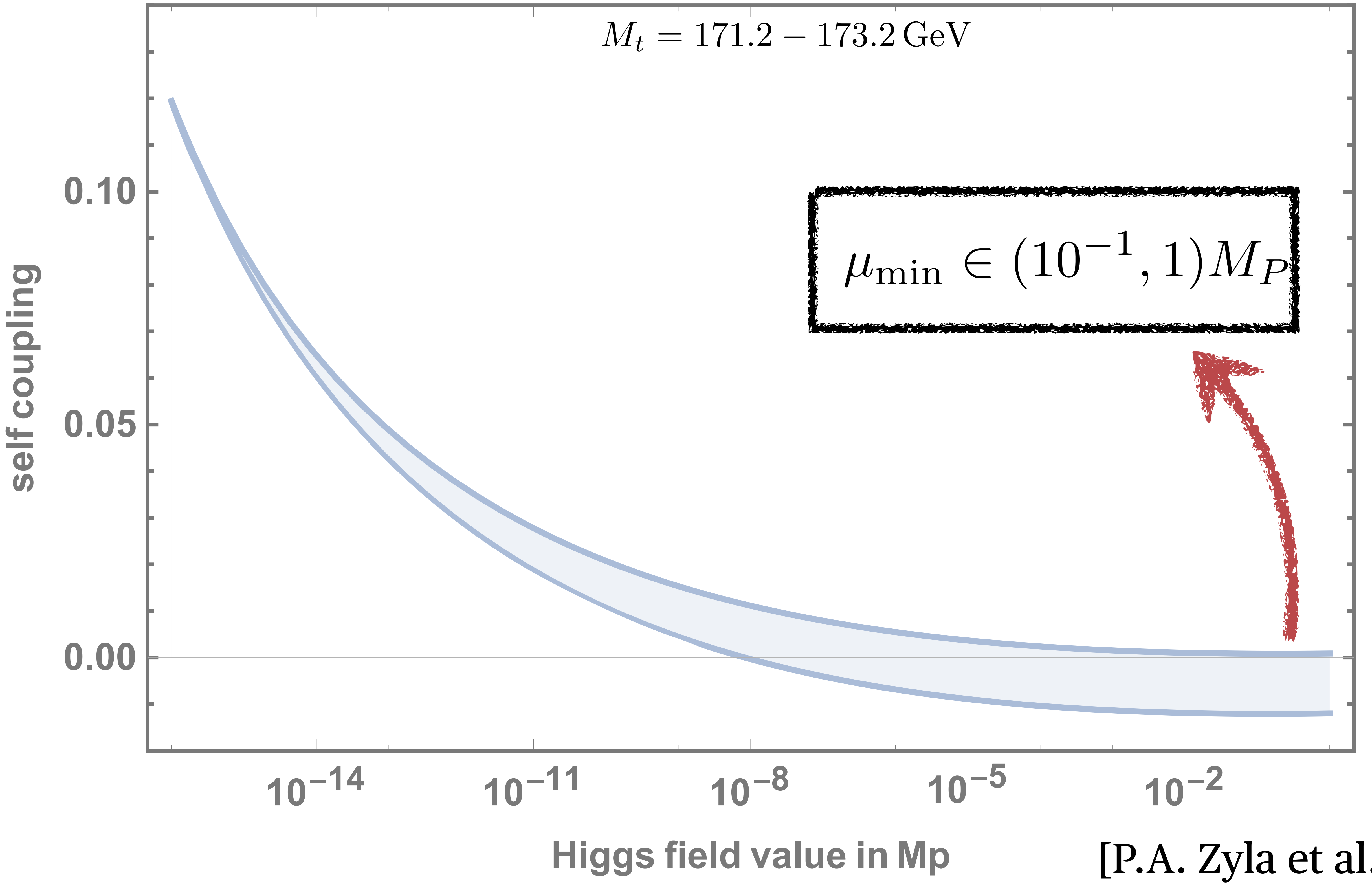


[K.Schmitz, 2002.04615]
[Z. Arzoumanian et al , 2009.04496]

PBH DM in Inflation

Q. Can a “minimal setup” of inflation in the SM framework produce these enhanced curvature perturbations?

- The Standard Model Higgs self coupling λ runs : critical values possible



t-Quark Pole Mass from Cross-Section Measurements

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
172.5±0.7 OUR AVERAGE				
$173.1^{+2.0}_{-2.1}$	[1] AAD	20Q	ATLS	$e + \mu + 1$ or 2 b-jets
$171.1 \pm 0.4 \pm 0.9^{+0.7}_{-0.3}$	[2] AAD	19G	ATLS	$\ell + \not\!\!E_T + \geq 5\, j$ (2b-j)
$173.2 \pm 0.9 \pm 0.8 \pm 1.2$	[3] AABOUD	17BC	ATLS	$e + \mu + \geq 1b$ jets
170.6 ± 2.7	[4] SIRUNYAN	17W	CMS	$\ell + \geq 1$j
$172.8 \pm 1.1^{+3.3}_{-3.1}$	[5] ABAZOV	16F	D0	$\ell\ell$, ℓ+jets channels
$173.8^{+1.7}_{-1.8}$	[6] KHACHATRY...	16AW	CMS	$e + \mu + \not\!\!E_T + \geq 0$j
$173.7^{+2.3}_{-2.1}$	[7] AAD	15BW	ATLS	$\ell + \not\!\!E_T + \geq 5$j (2$b$-tag)
$172.9^{+2.5}_{-2.6}$	[8] AAD	14AY	ATLS	pp at $\sqrt{s} = 7$, 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
170.5 ± 0.8	[9] SIRUNYAN	20BV	CMS	$t\bar{t}$ normalized multi-differential cross sections
$176.7^{+3.0}_{-2.8}$	[10] CHATRCHYAN	14	CMS	pp at $\sqrt{s} = 7$ TeV

[P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 (2020)]

Criticality of the Higgs self coupling : $m_t^{\mathrm{pole}} \lesssim 171.4\mathrm{GeV}$

Higgs-R^2 Inflation

- SM Higgs runs, critical values still valid. Can this near critical behavior induce observable GWs or PBHs?

- "Minimal" critical Higgs inflation insufficient by itself, either a large ξ running or PBHs remnants are necessary.

  [J.M. Ezquiaga, J. García-Bellido, E.R. Morales, 1705.04861]
  [F. Bezrukov, M. Pauly, J. Rubio, 1706.05007]
  [S. Räsänen, E. Tomberg, 1810.12608]

- Which extensions can alleviate these tensions?

- Single field Higgs inflation "incomplete" by itself!

- Simple UV extension considering the R^2 operator : Higgs-R^2 inflation

- Additional scalar d.o.f. : multi field inflation

(Critical) Higgs-R^2 Inflation

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

non minimal coupling — R^2 term — Higgs effective potential

Conformal transformation into Einstein frame

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

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

$$\lambda_{\rm eff}(\mu)|_{\mu=h} = \lambda_{\rm min} + b\ln\left(\frac{h}{h_{\rm min}}\right)^2$$

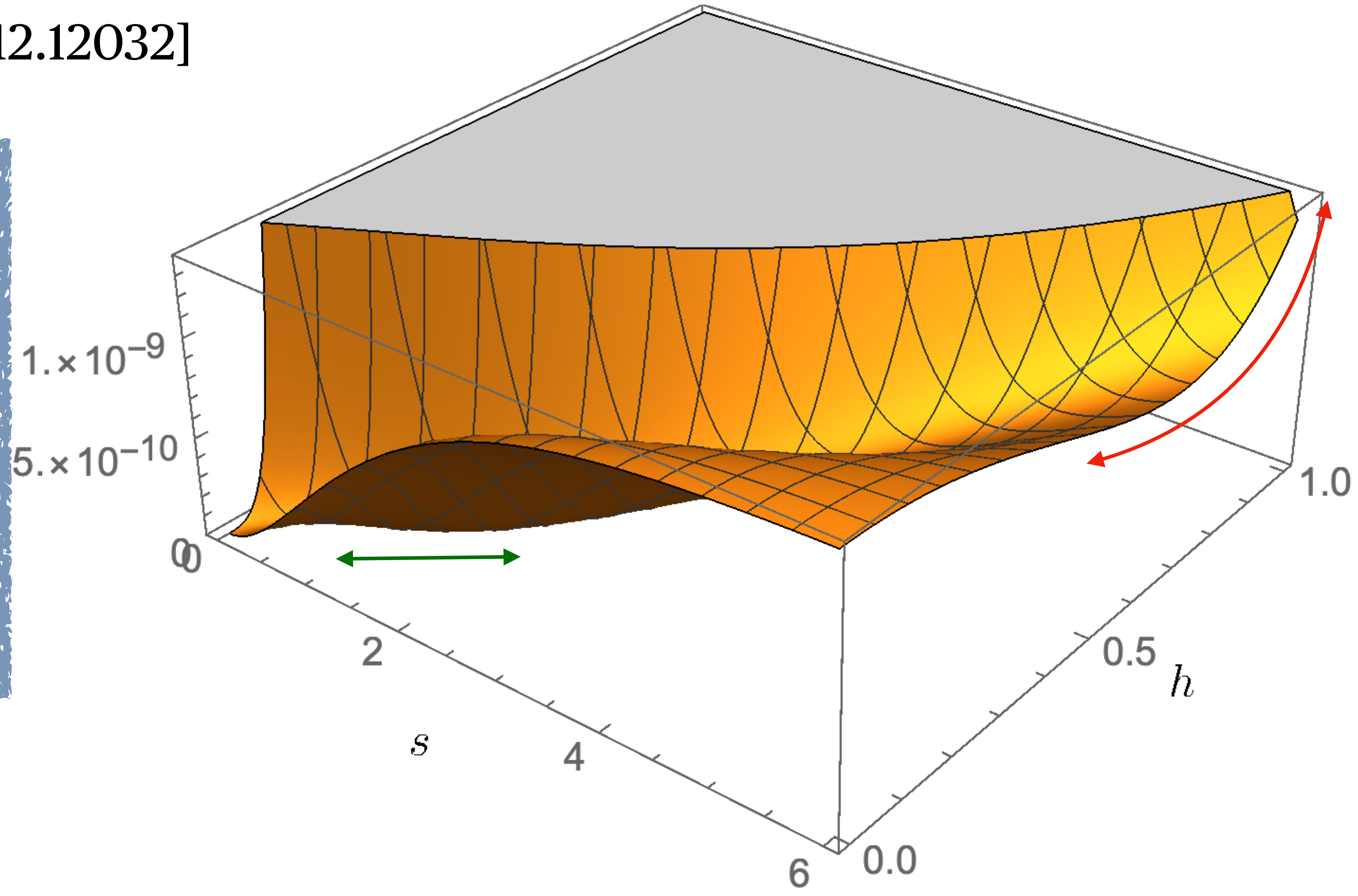
→ Critically flat potential induced!

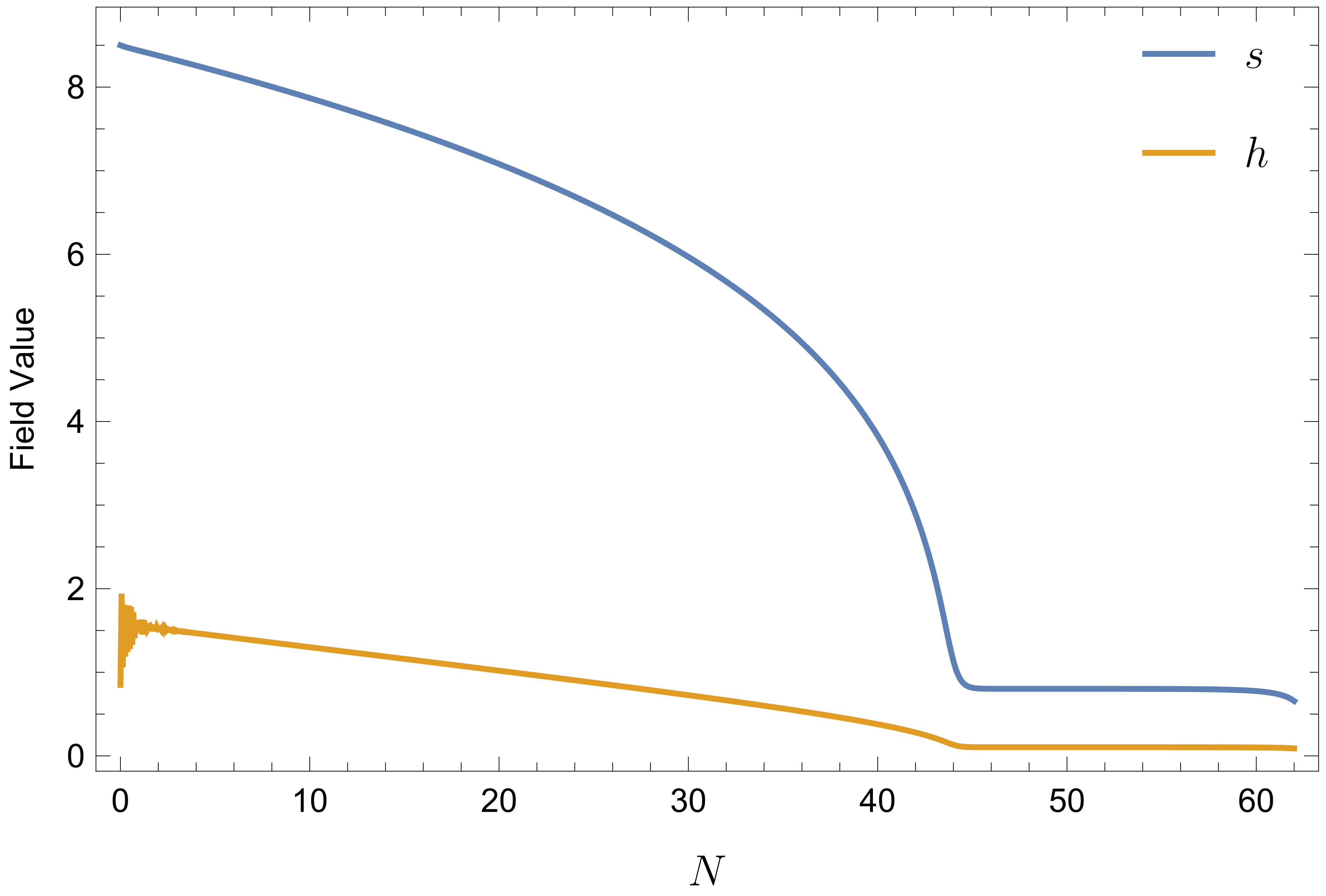
Y. Ema, Phys. Lett. B770:403-411, 2017
Y-C. Wang, T. Wang, Phys. Rev. D96(12):123506, 2017
M.He, A. A. Starobinsky, J. Yokoyama, JCAP, 1805(05):064, 2018
DYC, S.M. Lee, S.C. Park, arXiv: 1912.12032 [hep-ph]

Higgs-R^2 Inflation - Background Dynamics

[DYC, S.M. Lee, S.C. Park, 1912.12032]

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



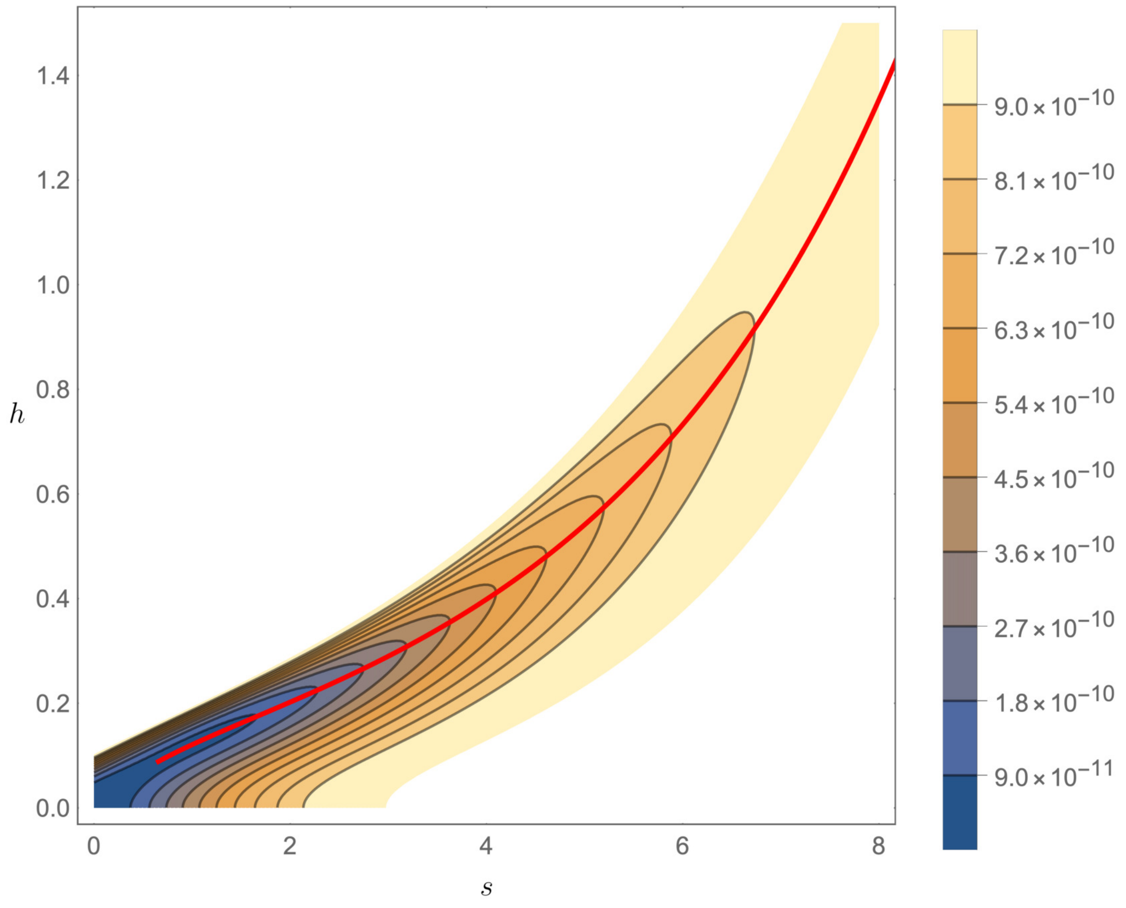


Valley structure : Inflaton rolls along the "minimum" $D_h U = 0$

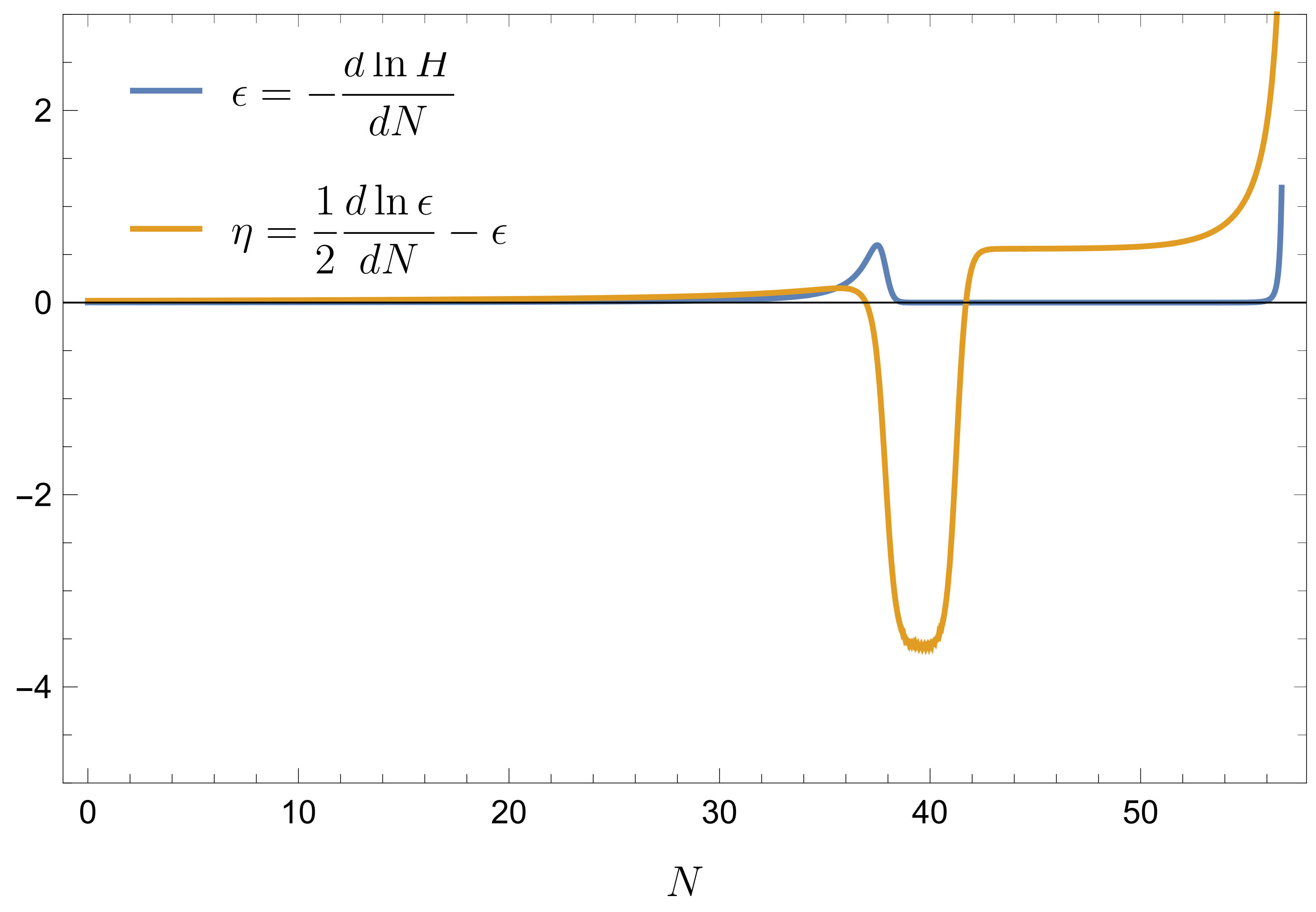
2nd plateau from the saddle point at small scales $\phi \sim 1 M_{\rm Pl}$.

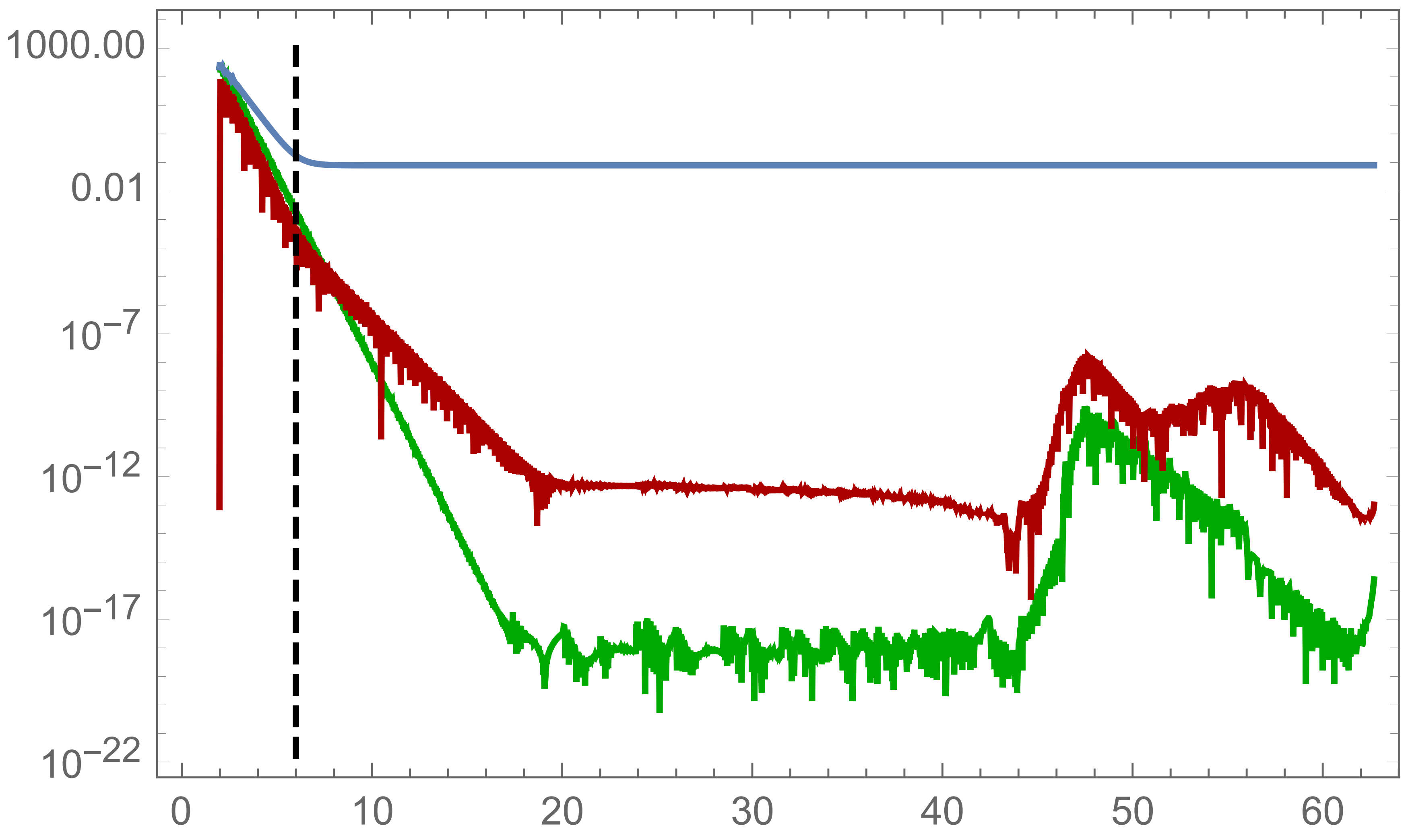
$$\partial U/\partial\phi|_{\phi=\phi^*} = 0\,, \quad \partial U/\partial h|_{h=h^*} = 0 \quad {\rm Hess}\,(U) = \begin{vmatrix} D_\phi\,(\partial_\phi U) & D_\phi\,(\partial_h U) \\ D_h\,(\partial_\phi U) & D_h\,(\partial_h U) \end{vmatrix}_{\phi=\phi^*, h=h^*} = 0$$

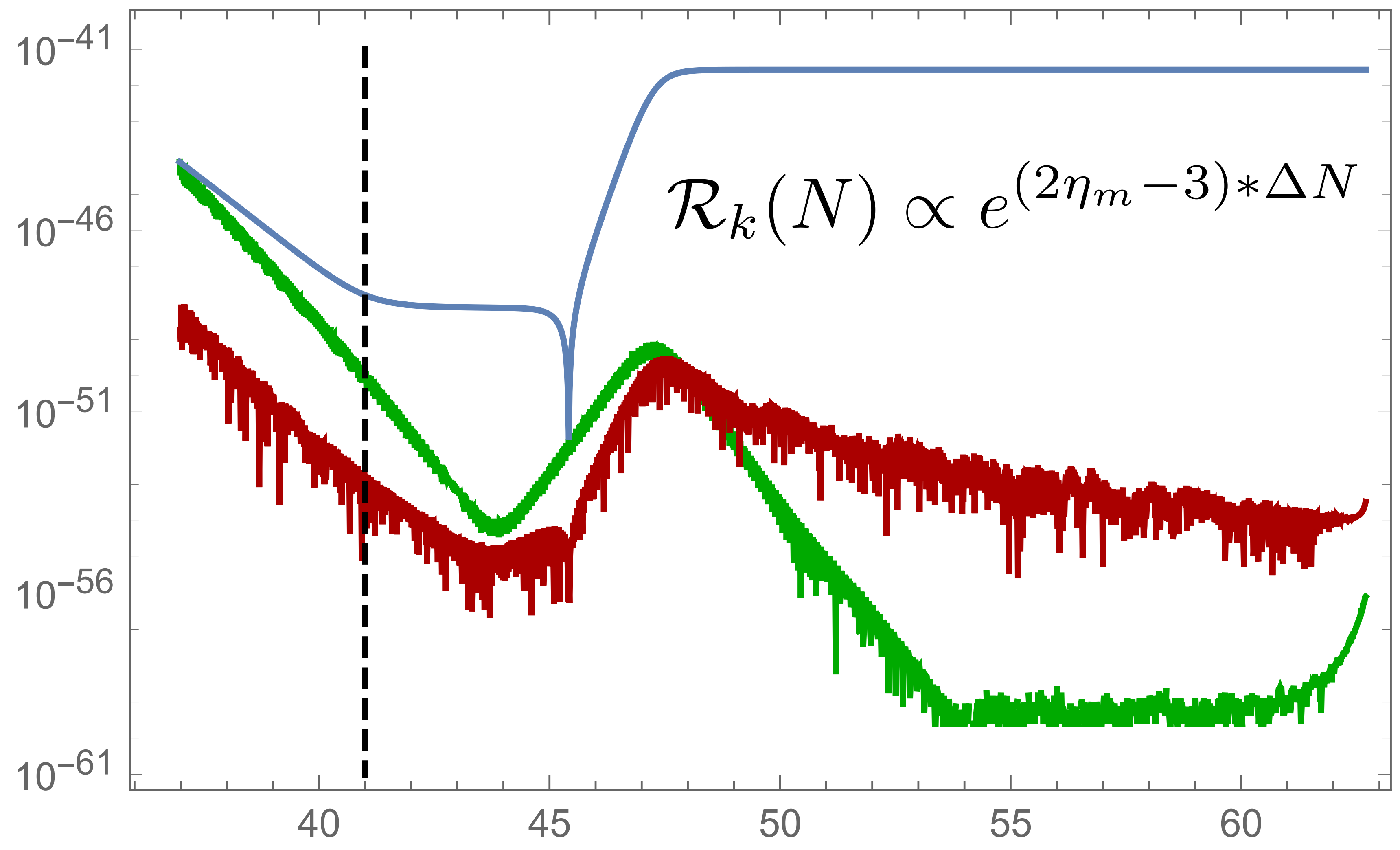
$$\lambda_{\rm min} = -\frac{2b\ln^3\left(\frac{h_0}{h_{\rm min}}\right)}{2\ln\left(\frac{h_0}{h_{\rm min}}\right)+1} - \delta \qquad \xi = \frac{-4\ln\left(\frac{h_0}{h_{\rm min}}\right)-1}{h_0^2\left(2\ln\left(\frac{h_0}{h_{\rm min}}\right)+1\right)}$$



Higgs-R^2 Inflation - Inflationary Dynamics



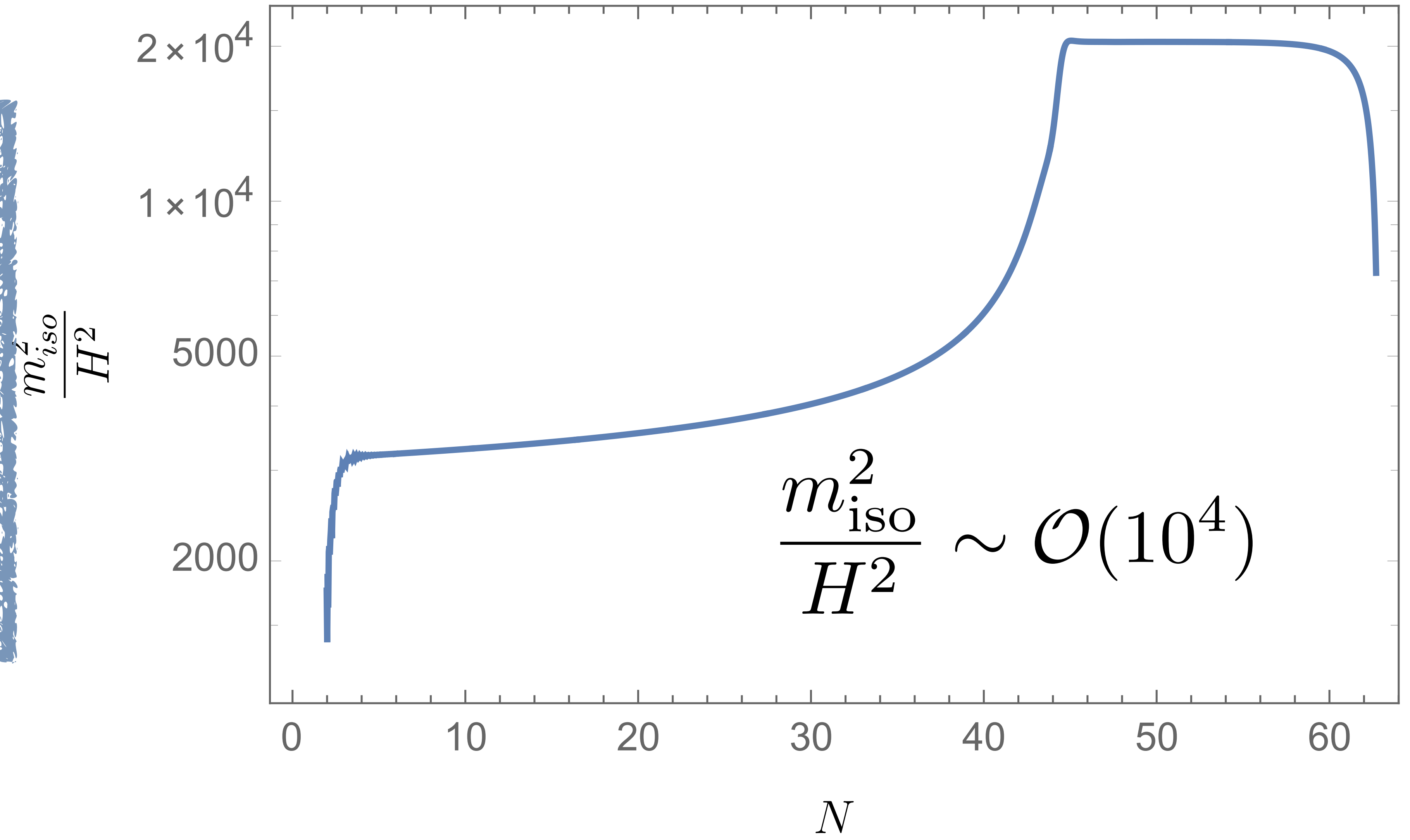


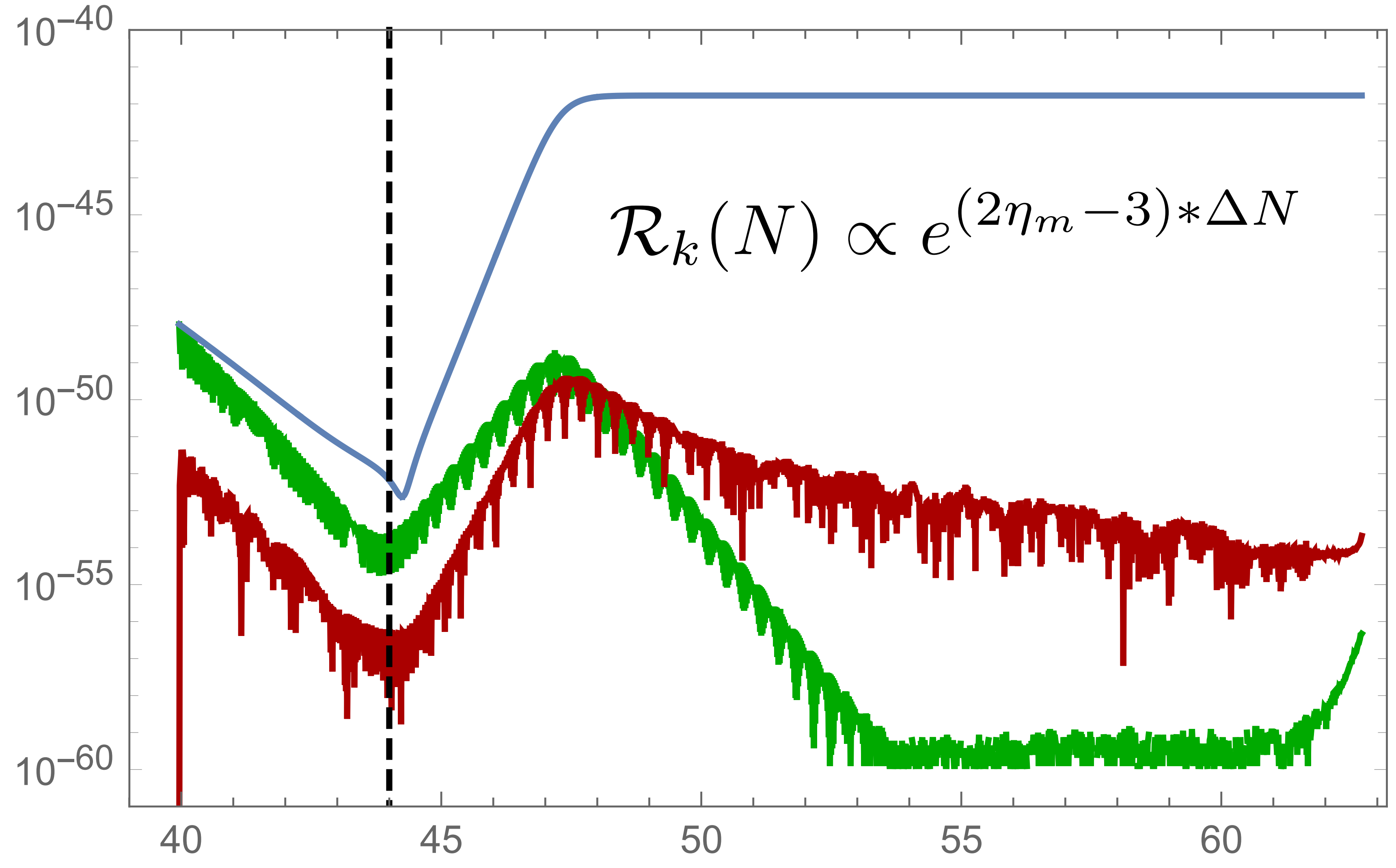


USR phase induced by $\lambda(h)$

Growing mode in $\mathcal{R}_k$

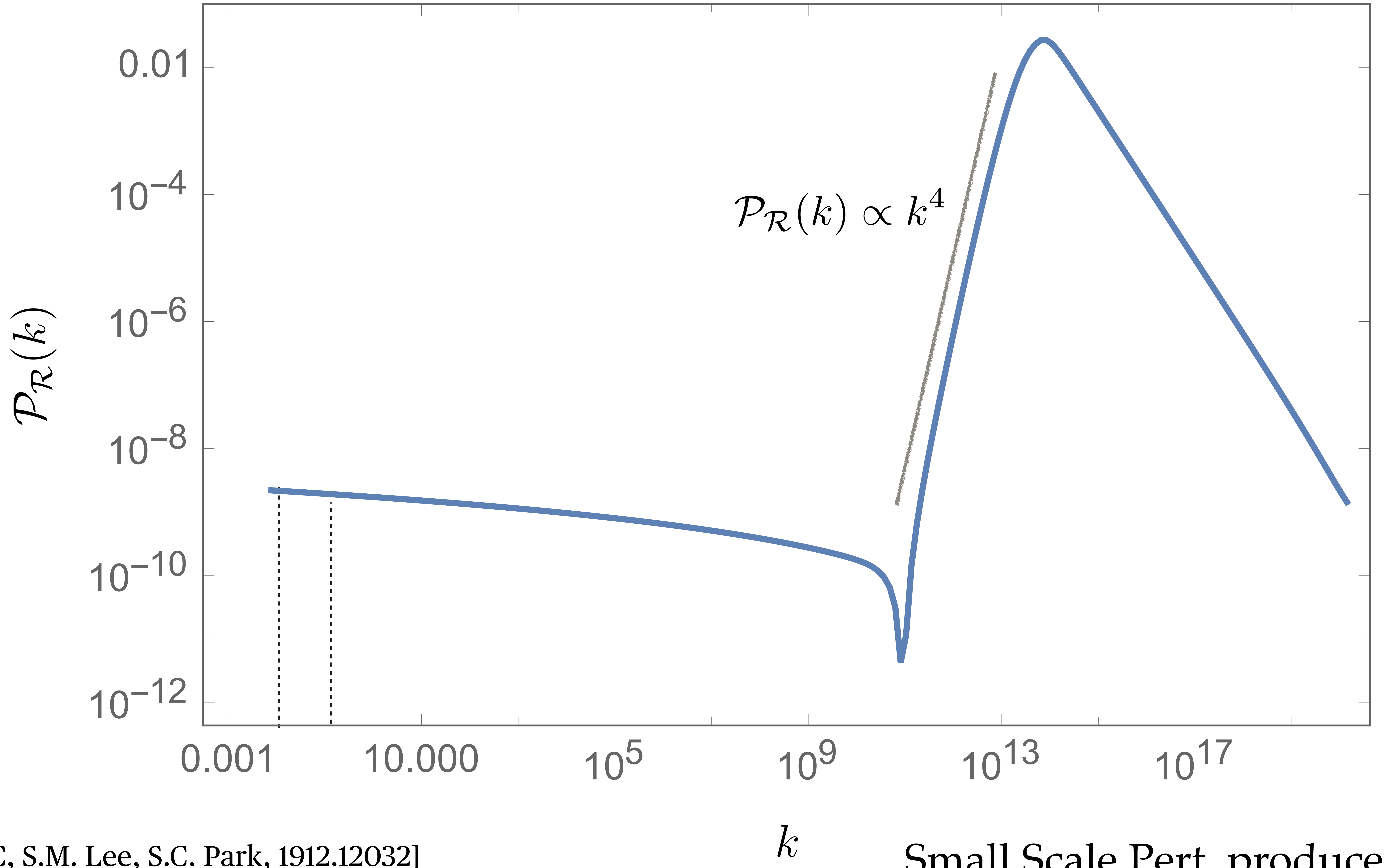
$$\eta_m \sim 3.5 \gg 1$$





[DYC, S.M. Lee, S.C. Park, 1912.12032]

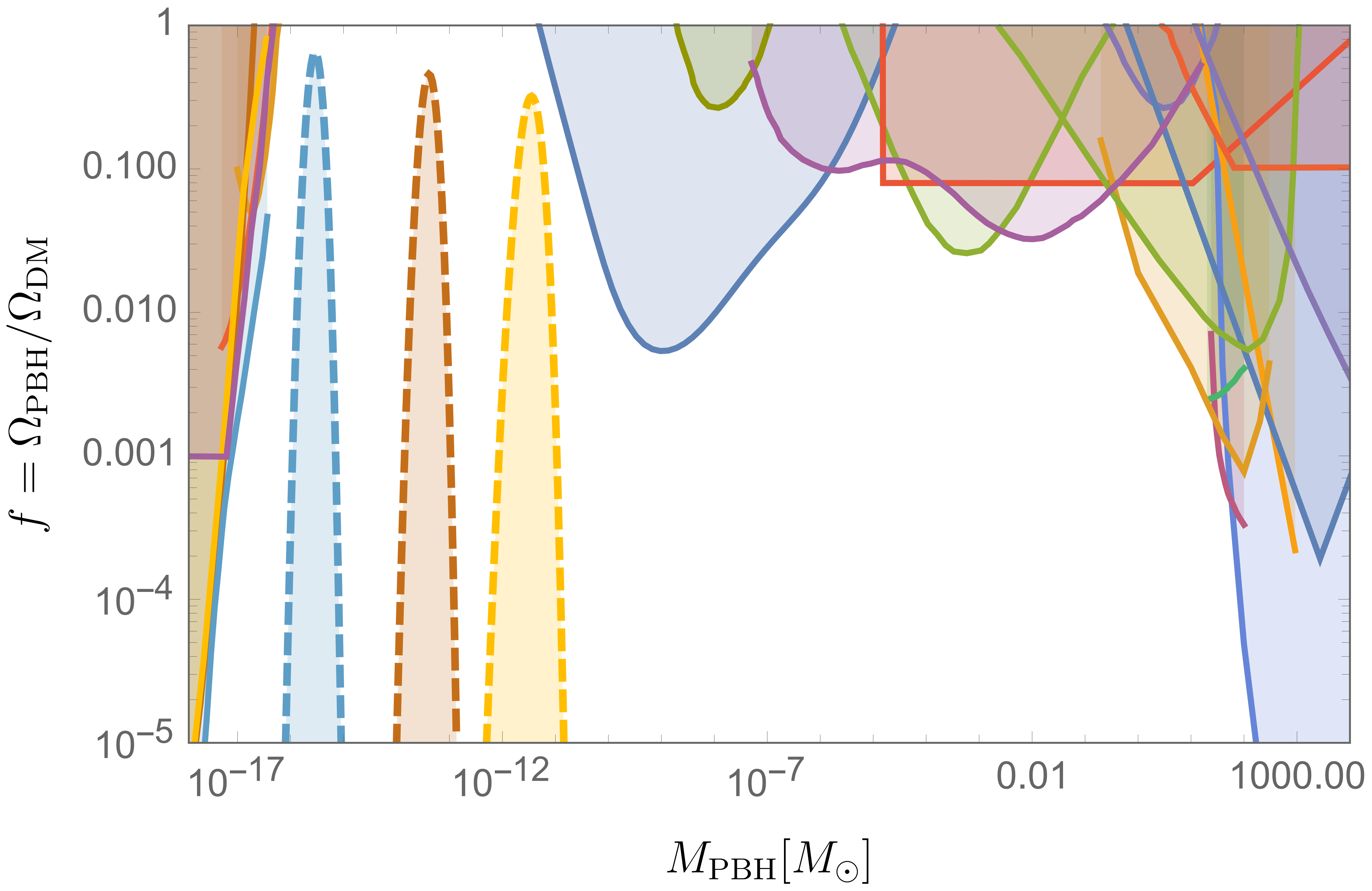
Higgs-R^2 Inflation - Power Spectrum

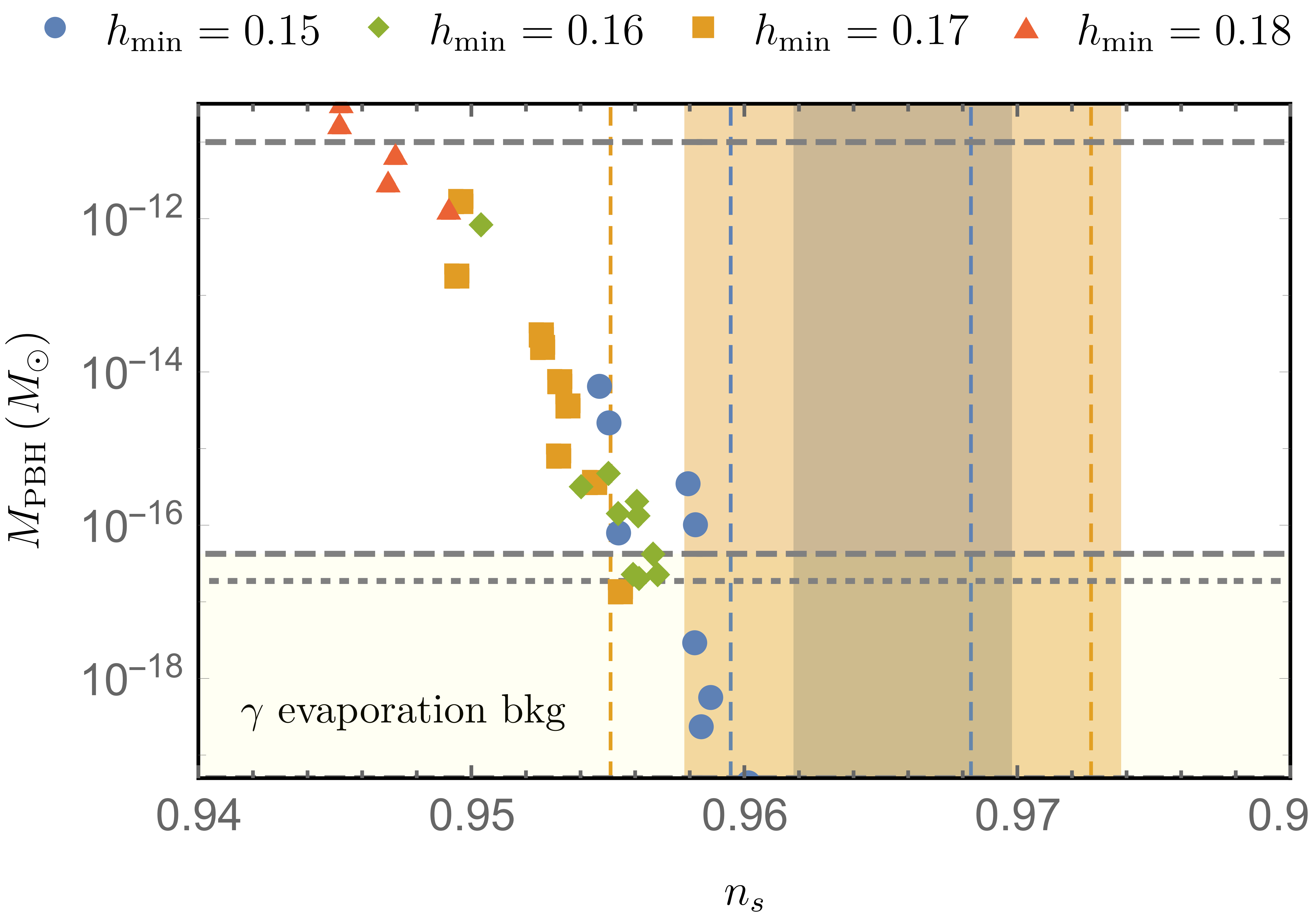


[DYC, S.M. Lee, S.C. Park, 1912.12032]

Small Scale Pert. produce PBHs and GWs

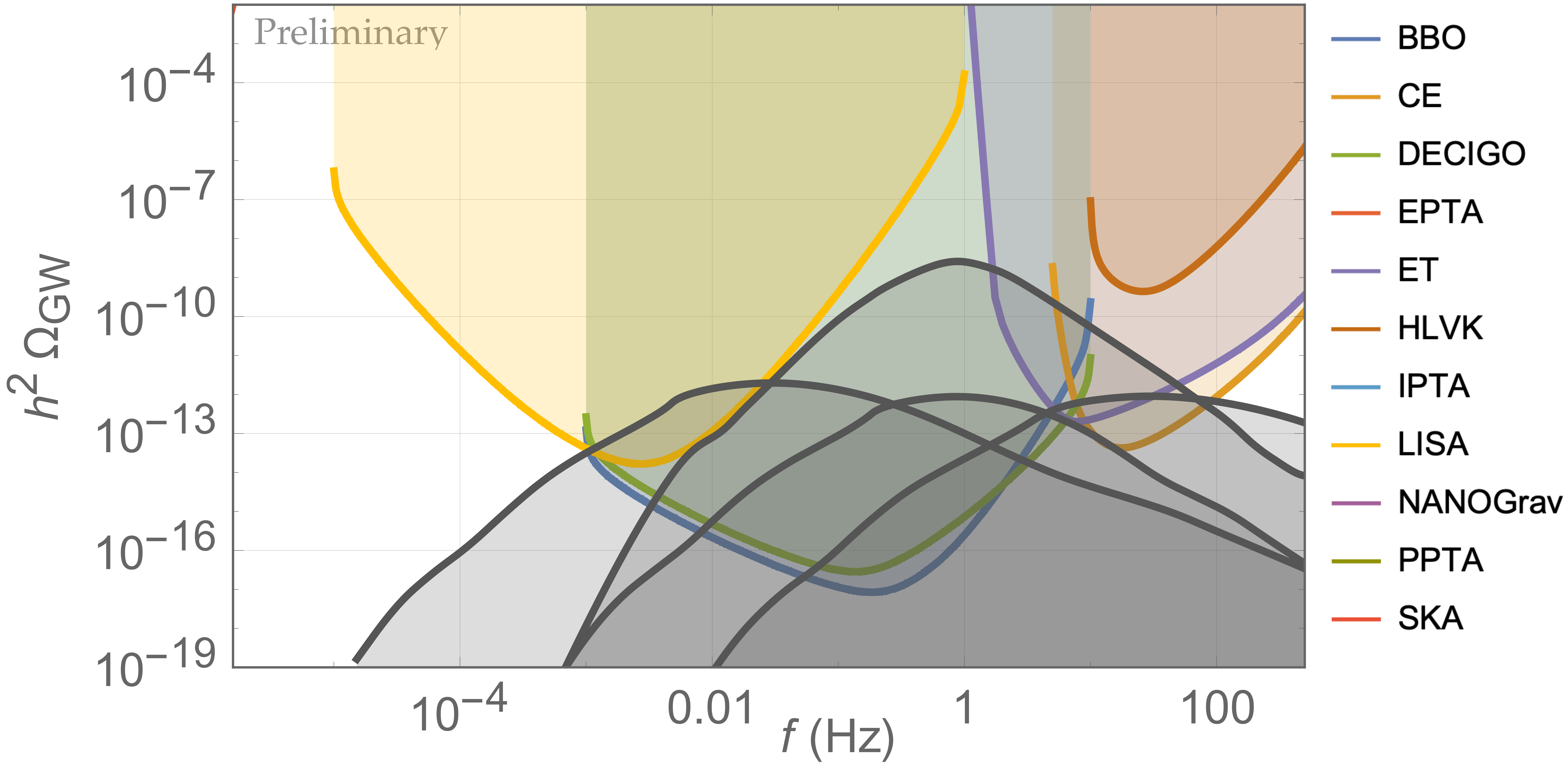
Higgs-R^2 Inflation - PBH abundance





[DYC, S.M. Lee, S.C. Park, 1912.12032]

Higgs-R^2 Inflation - Gravitational Waves



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

Conclusions & Outlooks

- Primordial Black Holes, still an appealing DM candidate, can be produced through large curvature perturbations.
- Secondary gravitational waves associated with the large curvature perturbations are expected to be probed at gravitational wave observatories.
- The Higgs-R^2 model, being a minimal UV extension to Higgs inflation, can give a significant PBH abundance within the mass range $M_{\rm PBH} \in (10^{-16}, 10^{-15}) M_\odot$
- Future gravitational wave observatories will be able to constrain more ranges of the model regardless of PBH formation, hints for low energy particle physics details?
- Focused on effective single field USR, parameter space limited, end of story? Is there a multi field trajectory that exhibits small scale phenomena?

“Thank you!”