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Primordial Gravitational Waves induced by Gauss-Bonnet Inflation

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based on: arXiv:1807.04424 with Seoktae Koh and Bum-Hoon Lee

Contents:

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  - ***the spectral tilt of the curvature perturbation:***

$$n_s = 0.9653 \pm 0.0041 \quad (68\,\%\ \textbf{CL, Planck TT,TE,EE+lowE+lensing+BK14})$$

  - ***upper limit on the tensor-to-scalar ratio:***

$$r_{0.002} < 0.064 \quad (95\,\%\ \textbf{CL, Planck TT,TE,EE+lowE+lensing+BK14})\,.$$

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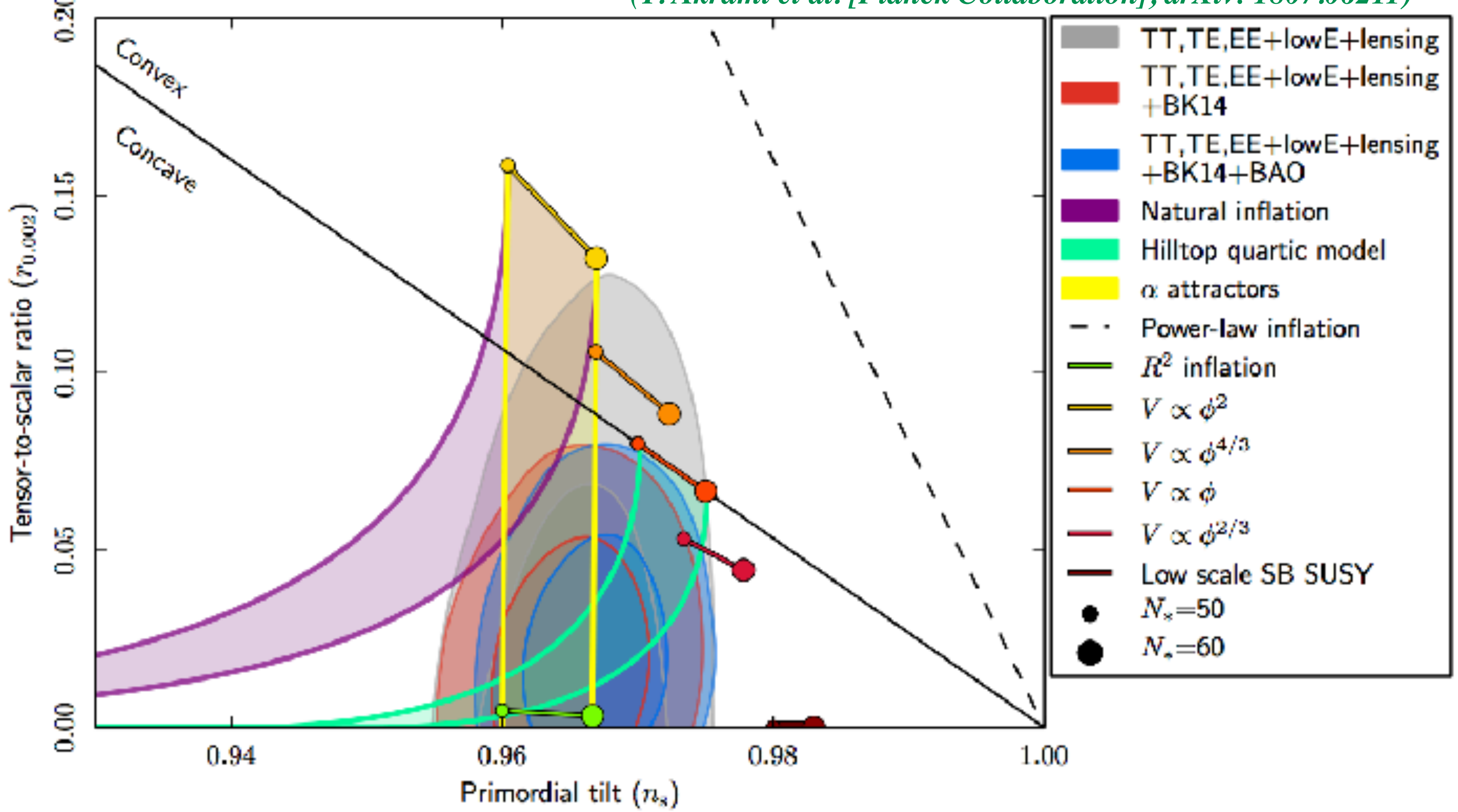

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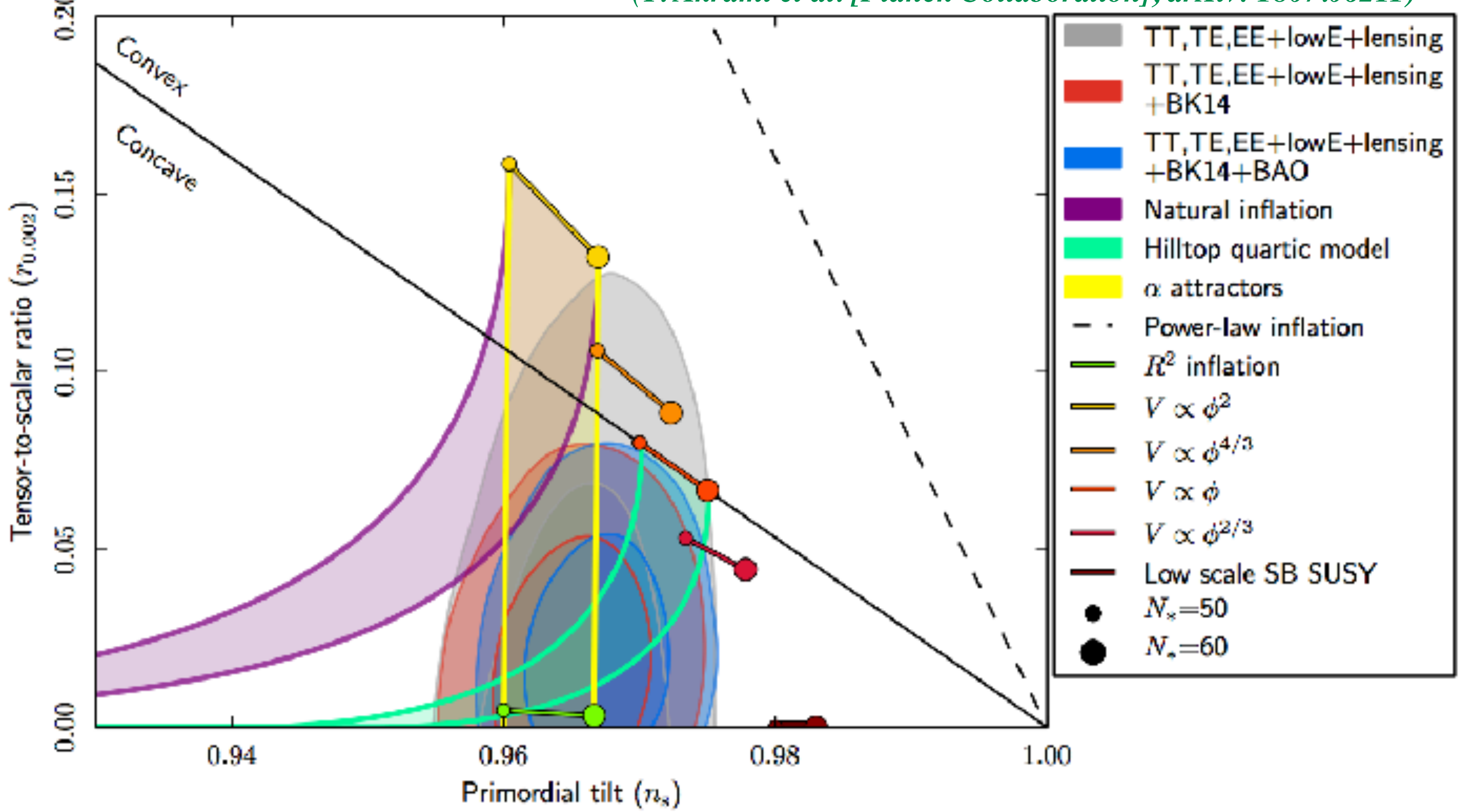

- ***Among hundreds of inflation models that are consistent with the observational data, extended models of inflation seem to be more promising!***

- ***The simplest scenario of inflation is based upon a single field, which is minimally coupled to a gravity, with a flat potential;***

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right],$$

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- ***We consider high order [quantum] corrections to Ricci-scalar, so-called the Gauss-Bonnet term:***

$$\boxed{R^2_{\rm GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2}$$

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- ***In the early universe, approaching the Planck era, it is quite natural to consider corrections like this.***
- ***Thus, the action becomes,***

$$S=\int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-V(\phi)\boxed{-\frac{1}{2}\xi(\phi)R^2_{\rm GB}}\right],$$

- ***Here, it is worth noting that*** $\xi(\phi) \neq const\,.$

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{2} \xi(\phi) R^2_{\rm GB} \right],$$

- ***The background EoM in flat FRW universe:*** $ds^2 = -dt^2 + a^2 \left(dr^2 + r^2 d\Omega^2 \right),$

$$H^2 = \frac{\kappa^2}{3} \left(\frac{1}{2} \dot{\phi}^2 + V + 12 \dot{\xi} H^3 \right),$$

$$\dot{H} = -\frac{\kappa^2}{2} \left[\dot{\phi}^2 - 4 \ddot{\xi} H^2 - 4 \dot{\xi} H \left(2\dot{H} - H^2 \right) \right],$$

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi + 12 \xi_\phi H^2 \left(\dot{H} + H^2 \right) = 0\,,$$

Thus, we are interested in understanding the effects of this additional term

- ***to the inflationary observables***
- ***to the primordial GW spectra***

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- **The observable quantities for GB inflation models are derived in our previous work [PRD 90, 063527 (2014)] as,**

$$\mathscr{P}_S(k) = \mathscr{P}_S(k_*)\left(\frac{k}{k_*}\right)^{n_S - 1}, \qquad \mathscr{P}_T(k) = \mathscr{P}_T(k_*)\left(\frac{k}{k_*}\right)^{n_T}$$

$$n_S - 1 \simeq -2\epsilon - \frac{2\epsilon(2\epsilon+\eta) - \delta_1(\delta_2 - \epsilon)}{2\epsilon - \delta_1}, \qquad n_T \simeq -2\epsilon, \qquad r \simeq 8(2\epsilon - \delta_1),$$

where $\epsilon \equiv -\frac{\dot{H}}{H^2}, \quad \eta \equiv \frac{\ddot{H}}{H\dot{H}}, \quad \zeta \equiv \frac{\dddot{H}}{H^2\dot{H}}, \quad \delta_1 \equiv 4\kappa^2\dot{\xi}H, \quad \delta_2 \equiv \frac{\ddot{\xi}}{\dot{\xi}H}, \quad \delta_3 = \frac{\dddot{\xi}}{\dot{\xi}H^2}.$

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$$\epsilon = \frac{1}{2\kappa^2}\frac{V_\phi}{V}\left(\frac{V_\phi}{V} + \frac{4}{3}\kappa^4\xi_\phi V\right)$$

- ***Conditions for the potential and the coupling functions:***

$$\begin{cases} \xi_\phi > -\frac{3}{4\kappa^4}\frac{V_\phi}{V^2}, & \text{for} \quad V_\phi > 0, \\ \xi_\phi < -\frac{3}{4\kappa^4}\frac{V_\phi}{V^2}, & \text{for} \quad V_\phi < 0\,. \end{cases}$$

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- ***Selected models for each category:***

Model-I:

$$V(\phi) = \frac{V_0}{\kappa^4}(\kappa\phi)^n\,, \quad \xi(\phi) = \xi_0(\kappa\phi)^{-n}\,,$$

Model-II:

$$V(\phi) = \frac{1}{\kappa^4}\left[\tanh\left(\kappa\phi\right) + \sqrt{\mu}\,\mathrm{sech}\left(\kappa\phi\right)\right]^2\,, \quad \xi(\phi) = \frac{3\left[\sinh^2(\kappa\phi) - \frac{1}{\sqrt{\mu}}\sinh(\kappa\phi)\right]}{4\left[\sqrt{\mu} + \sinh\left(\kappa\phi\right)\right]^2}\,,$$

S. Koh, B. H. Lee, and GT, PRD 95, 123509 (2017)

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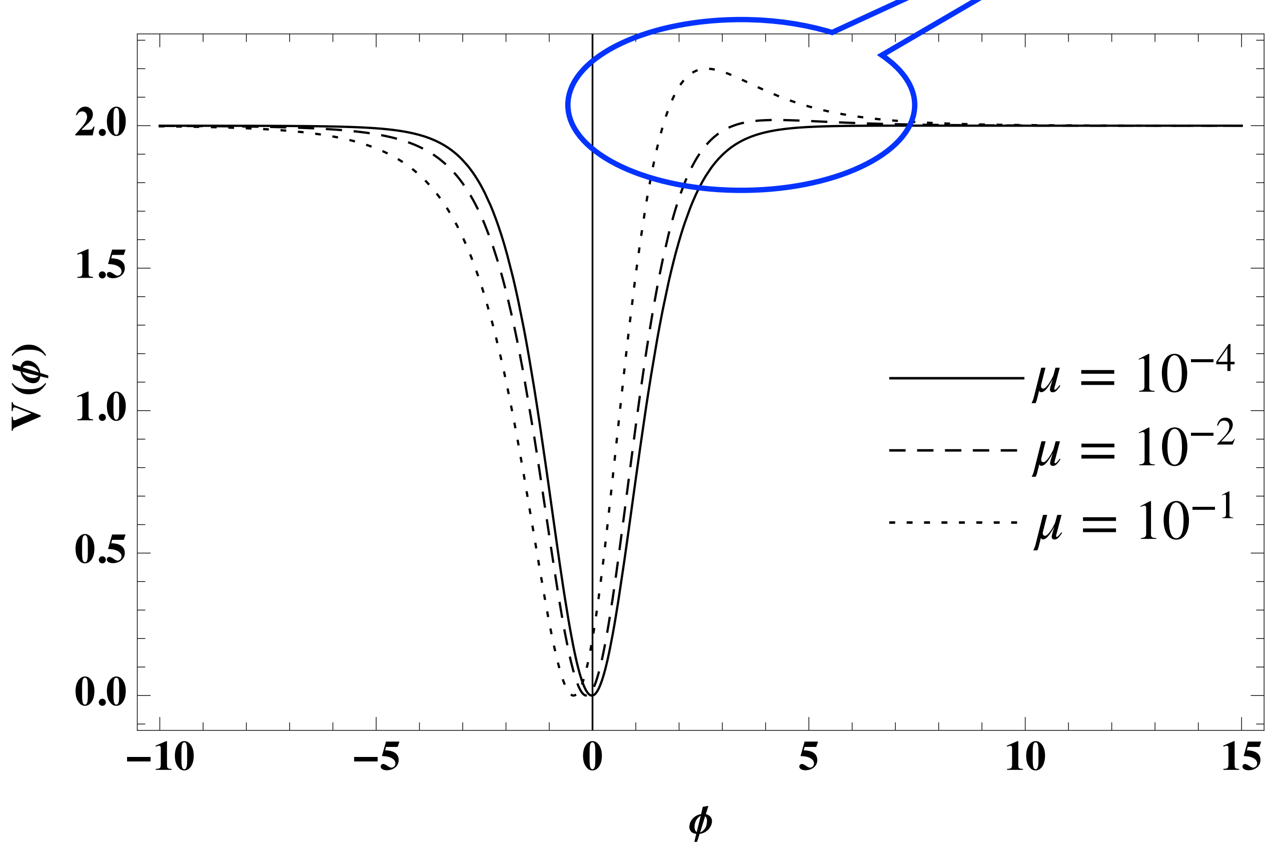

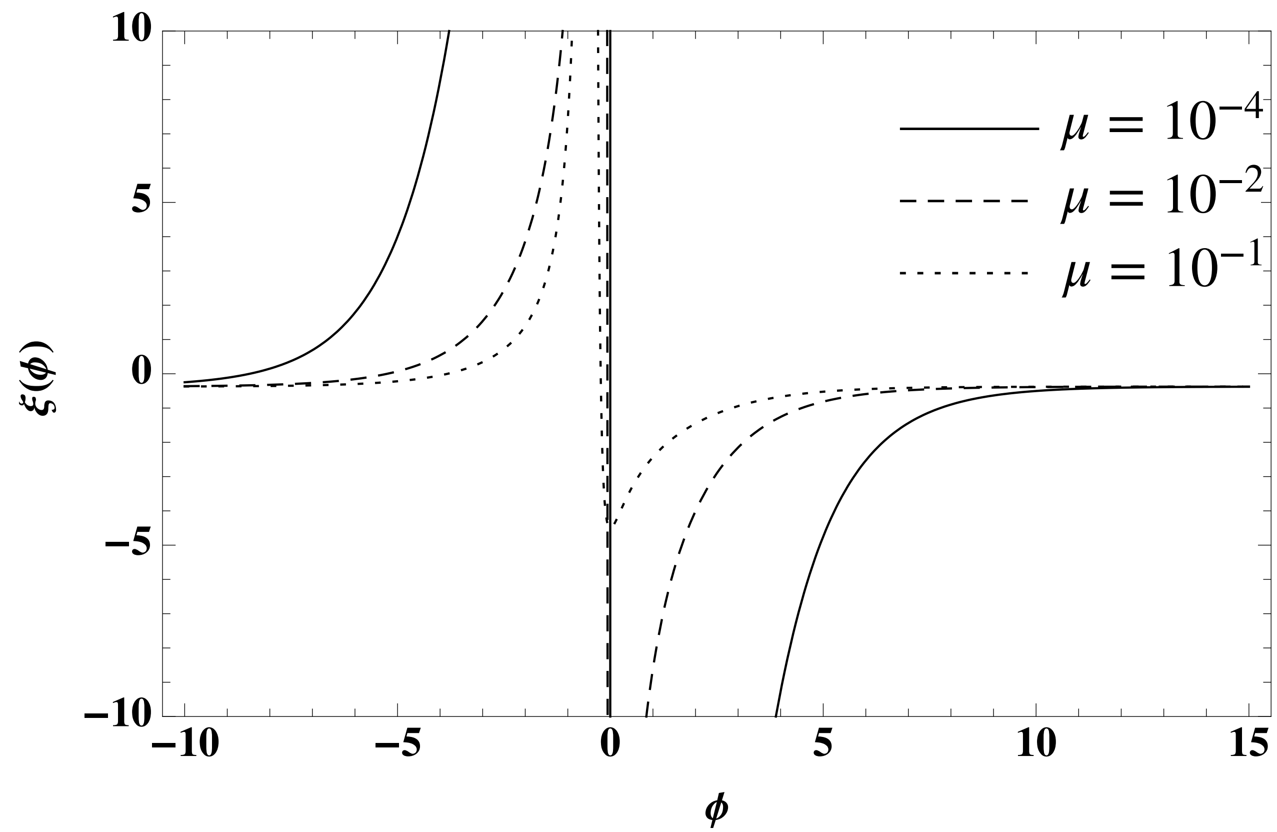

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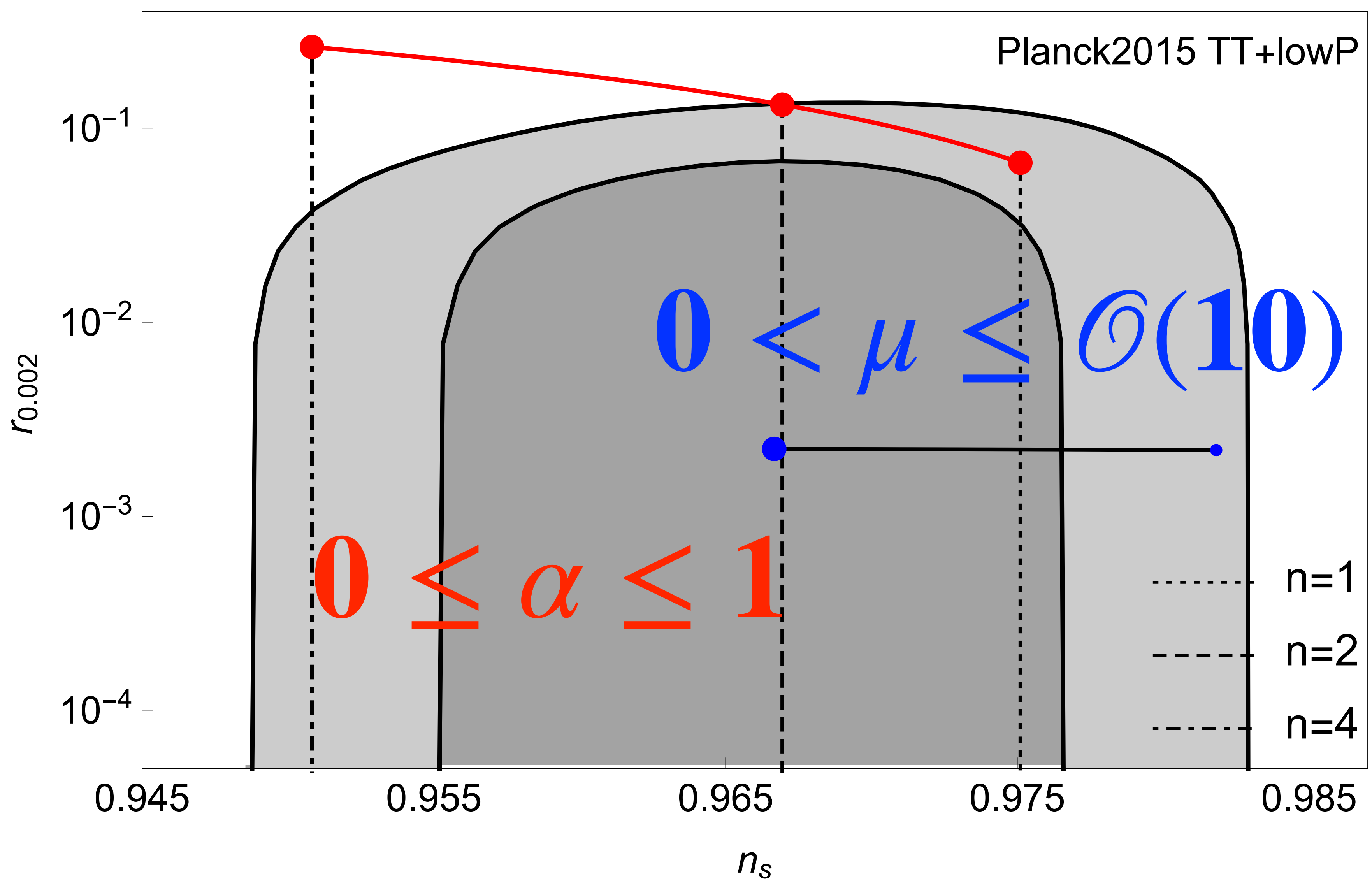

- ***These models predict the inflationary tensor power spectrum to have both*** $n_T < 0$, ***and*** $n_T > 0$.

Primordial GW spectrum

- ***The pGWs are described by the tensor part of the pert. metric***

$$ds^2 = a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j\right],$$

- ***The strength of GW is characterized by their energy spectrum***

$$\boxed{\Omega_{GW}(k) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{GW}}{d\ln k},}$$

$$\rho_{GW} = \frac{M_p^2}{4} \int d\ln k \left(\frac{k}{a}\right)^2 \frac{k^3}{\pi^2} \sum_{\lambda} \langle h^{\dagger}_{\lambda,\,k} h_{\lambda,\,k}\rangle.$$

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$$\Downarrow$$

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$$P_T \equiv \frac{k^3}{\pi^2} \sum_\lambda \langle h^\dagger_{\lambda,k} h_{\lambda,k}\rangle = \mathcal{T}^2(k)\mathcal{P}_T(k).$$

$$\mathcal{P}_T(k) = \mathcal{P}_T(k_*)\left(\frac{k}{k_*}\right)^{n_T + \frac{\alpha_T}{2}\ln(k/k_*)},$$

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$$h''_{\lambda,k} + 2\frac{z'_T}{z_T} h'_{\lambda,k} + k^2 c_T^2 h_{\lambda,k} = 0,$$

$$\Downarrow$$

$$h_0^2\Omega_{GW} = \frac{3h_0^2}{32\pi^2 H_0^2 \tau_0^4 f^2} \Omega_m^2 \mathcal{T}_1^2\left(\frac{f}{f_{\rm eq}}\right) \mathcal{T}_2^2\left(\frac{f}{f_{\rm th}}\right) r\,\mathcal{P}_S\left(\frac{f}{f_*}\right)^{n_T + \frac{\alpha_T}{2}\ln(f/f_*)},$$

- ***Numerical results:***

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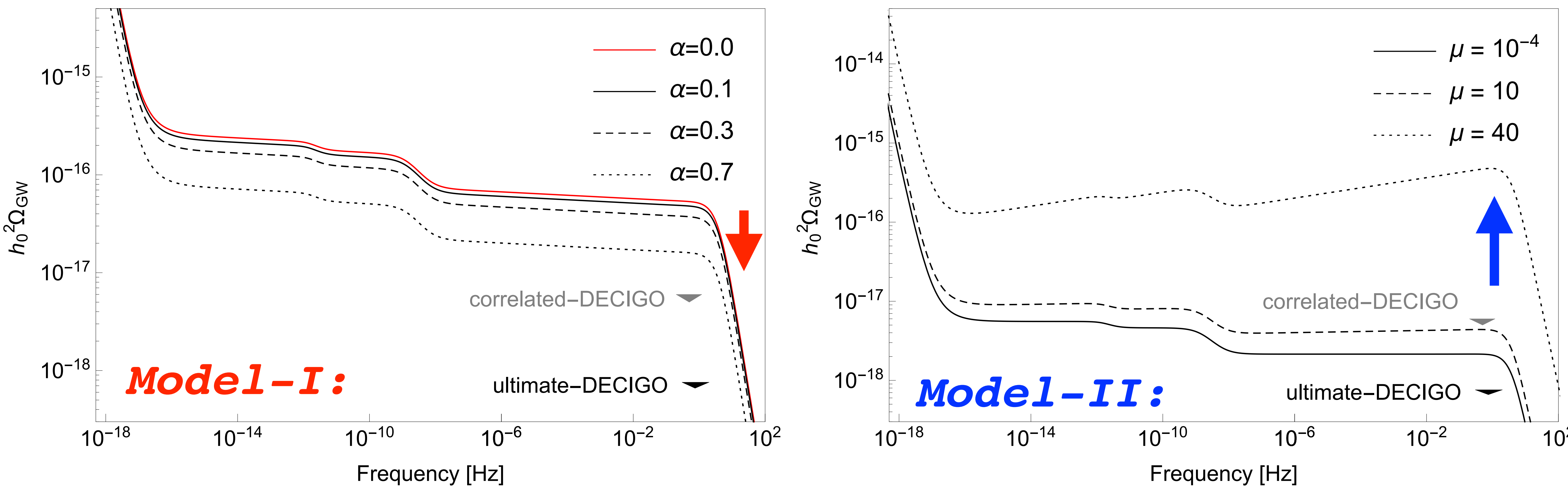
Model-II: $$V(\phi) = \frac{1}{\kappa^4}\left[\tanh(\kappa\phi) + \sqrt{\mu}\,\mathrm{sech}(\kappa\phi)\right]^2, \quad \xi(\phi) = \frac{3\left[\sinh^2(\kappa\phi) - \frac{1}{\sqrt{\mu}}\sinh(\kappa\phi)\right]}{4\left[\sqrt{\mu}+\sinh(\kappa\phi)\right]^2},$$



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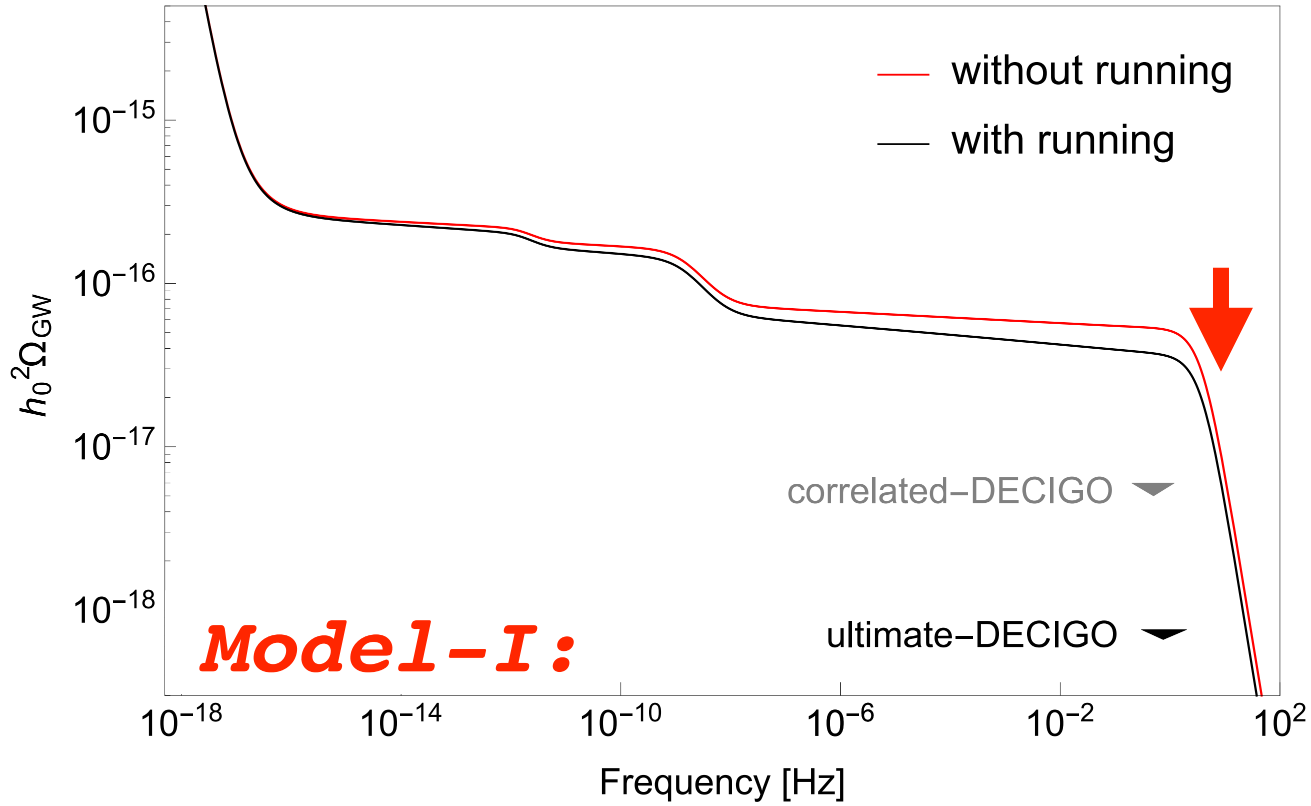

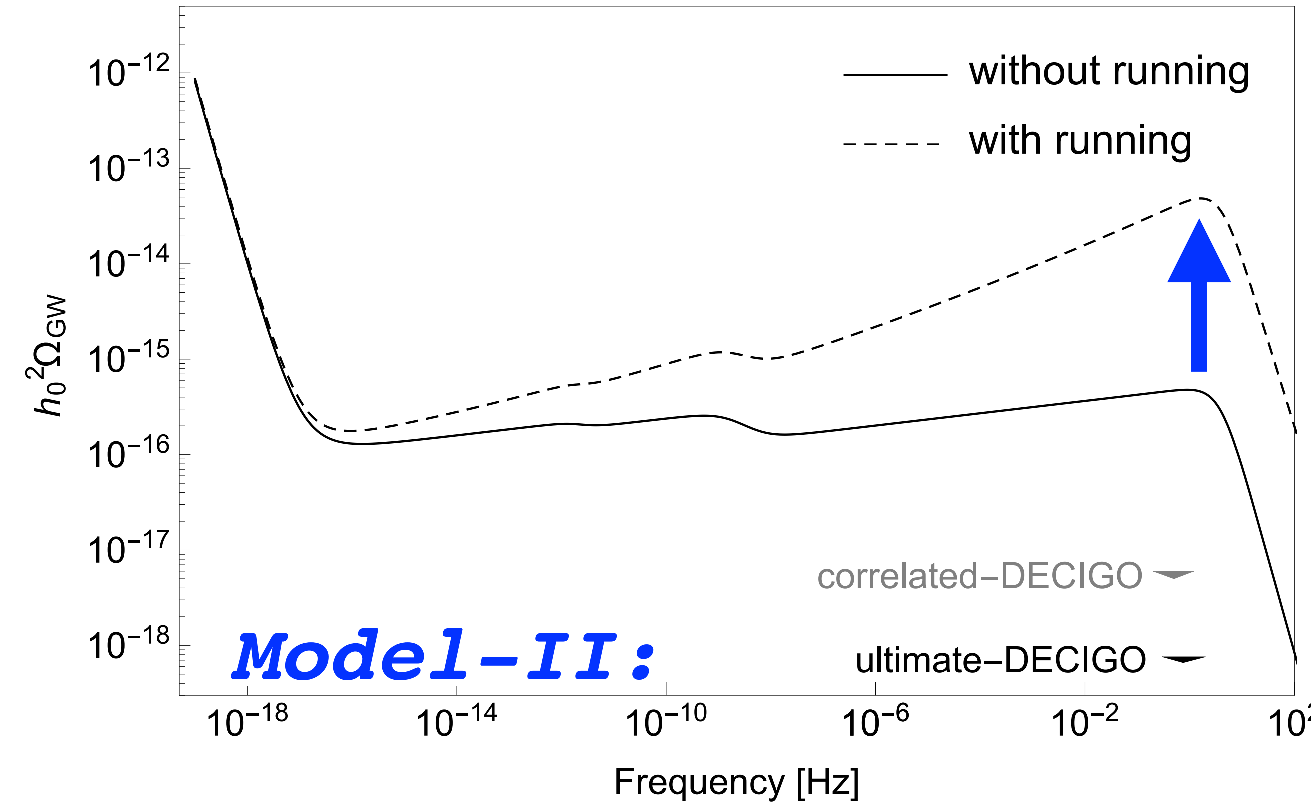

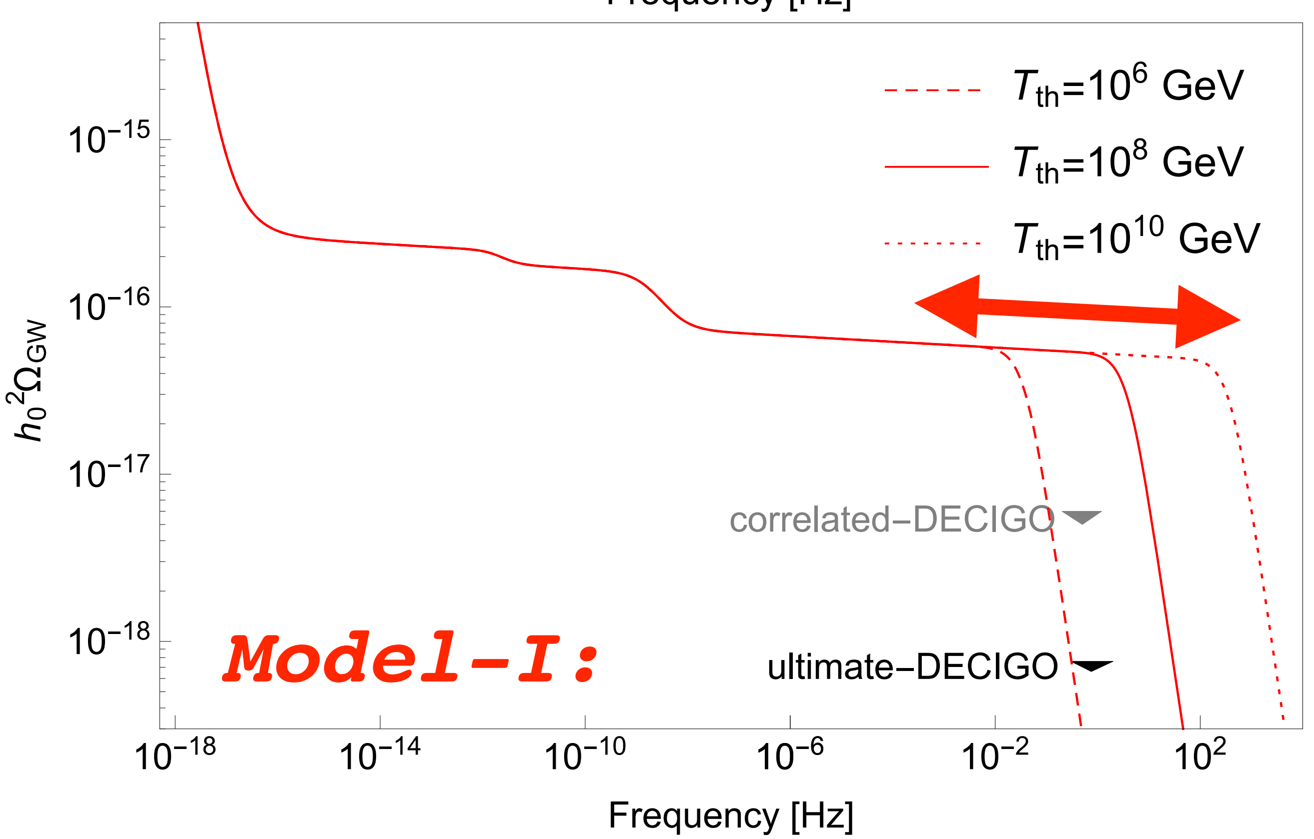

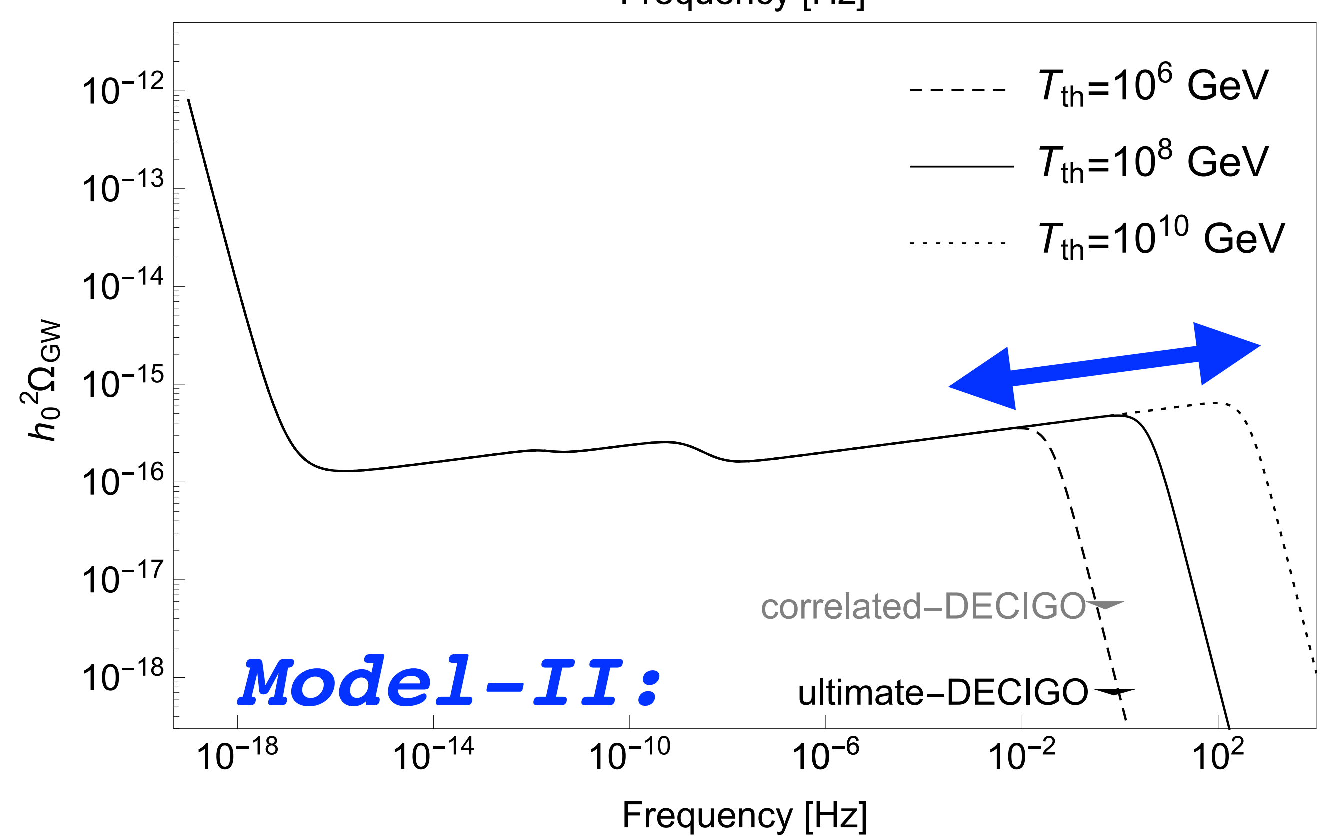

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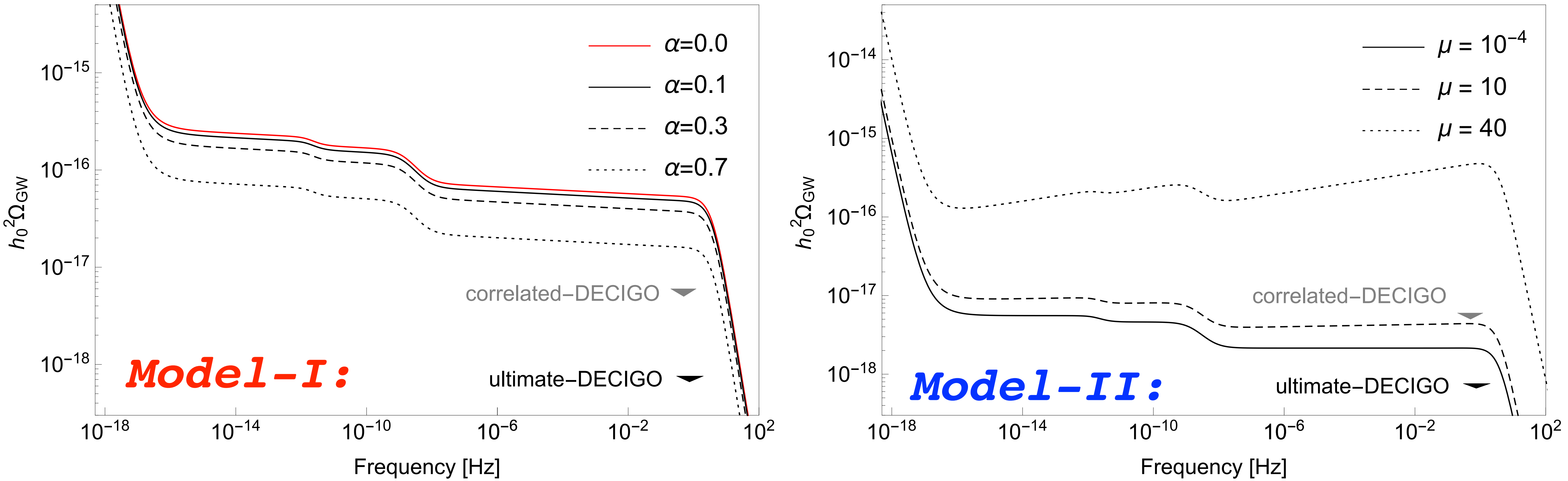

$$\mathcal{T}_1^2\left(\frac{k}{k_{\rm eq}}\right) = 1 + 1.65\left(\frac{k}{k_{\rm eq}}\right) + 1.92\left(\frac{k}{k_{\rm eq}}\right)^2, \qquad \mathcal{T}_2^2\left(\frac{k}{k_{\rm th}}\right) = \left[1+\gamma\left(\frac{k}{k_{\rm th}}\right)^{\frac{3}{2}}+\sigma\left(\frac{k}{k_{\rm th}}\right)^2\right]^{-1},$$

- ***Once the pGWs from inflationary origin are detected:***

$$k_{\rm th} = 1.7\times 10^{13}\,\mathbf{Mpc}^{-1}\left(\frac{g_{*s}(T_{\rm th})}{106.75}\right)^{\frac{1}{6}}\left(\frac{T_{\rm th}}{10^6\,\mathbf{GeV}}\right)$$

Constraints on reheating parameters

- ***By assuming,***
  - ***constant equation-of-state during reheating,*** $\omega_{\text{th}} = const,$
  - ***no entropy production after the end of reheating***

we calculate the duration of reheating and the thermalization temperature at the end of reheating,

$$N_{\text{th}} = \frac{4}{3\omega_{\text{th}} - 1}\left[\ln\left(\frac{k}{a_0 T_0}\right) + \frac{1}{3}\ln\left(\frac{11 g_{*s}}{43}\right) + \frac{1}{4}\ln\left(\frac{30\lambda_{\text{end}}}{\pi^2 g_*}\right) + \frac{1}{4}\ln\left(\frac{V_{\text{end}}}{H_*^4}\right) + N_*\right].$$

$$T_{\text{th}} = \left(\frac{30\lambda_{\text{end}} V_{\text{end}}}{\pi^2 g_*}\right)^{\frac{1}{4}} e^{-\frac{3}{4}(1+\omega_{\text{th}})N_{\text{th}}}.$$

where $\lambda_{\text{end}} = \left.\frac{6}{6 - 2\epsilon - \delta_1(5 - 2\epsilon + \delta_2)}\right|_{\phi=\phi_{\text{end}}}$

- ***In our numerical study, we consider following models:***

Model-I: $V(\phi) = \frac{V_0}{\kappa^4}(\kappa\phi)^n, \quad \xi(\phi) = \xi_0(\kappa\phi)^{-n},$ ⇨ $\alpha \equiv \frac{4}{3}V_0\xi_0$

Model-II: $V(\phi) = \frac{1}{\kappa^4}\left[\tanh(\kappa\phi) + \sqrt{\mu}\,\text{sech}(\kappa\phi)\right]^2, \quad \xi(\phi) = \frac{3\left[\sinh^2(\kappa\phi) - \frac{1}{\sqrt{\mu}}\sinh(\kappa\phi)\right]}{4\left[\sqrt{\mu} + \sinh(\kappa\phi)\right]^2},$

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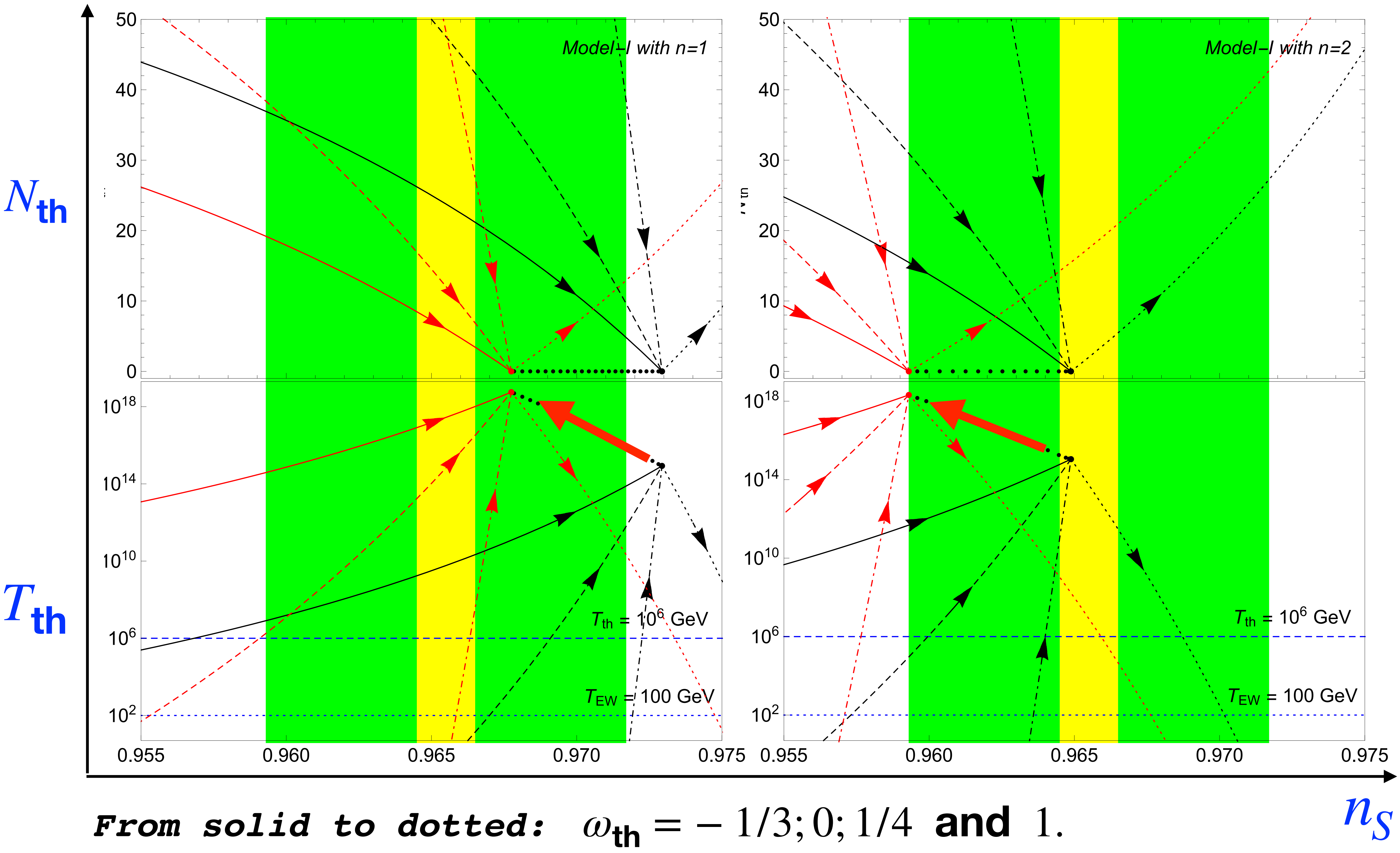

From solid to dotted: $\omega_{\text{th}} = -1/3; 0; 1/4$ **and** $1.$

- ***Numerical results:***

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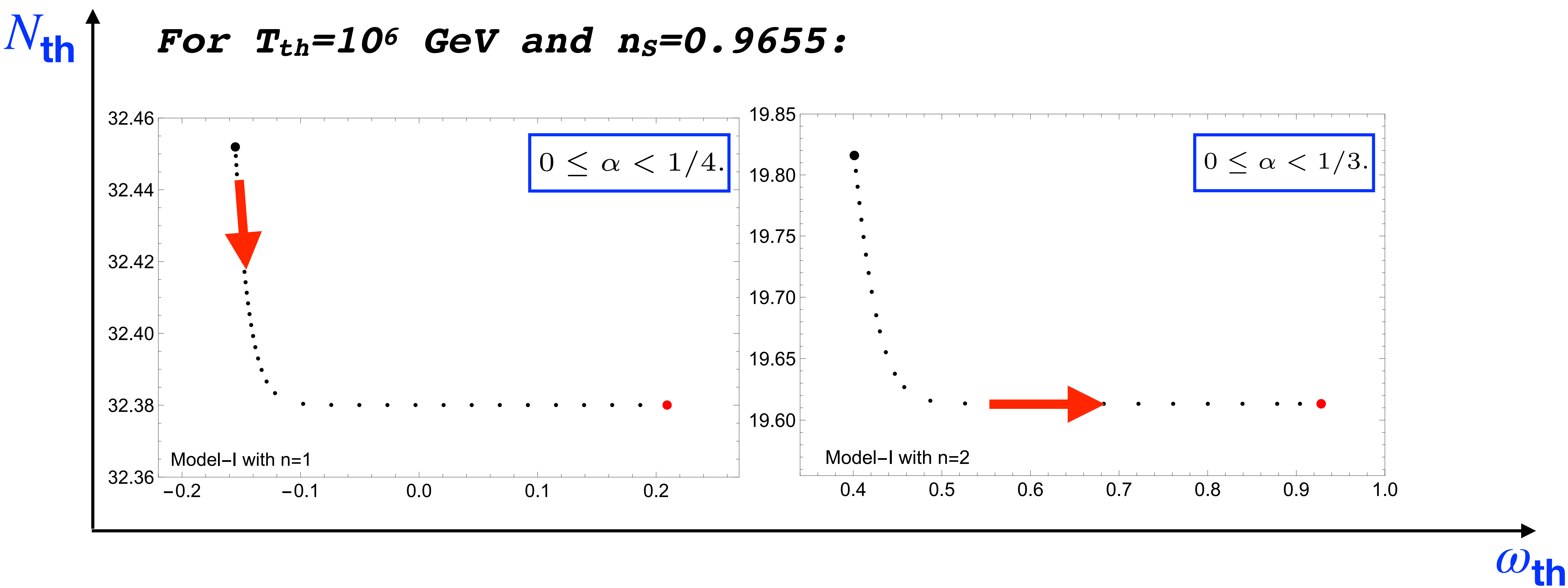
$$N_{\rm th} \;=\; \frac{4}{3\omega_{\rm th}-1}\left[-60.0085 + \frac{1}{4}\ln\left(\frac{3\lambda_{\rm end}}{100\pi^2}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm end}}{H_*^4}\right) + N_*\right]$$

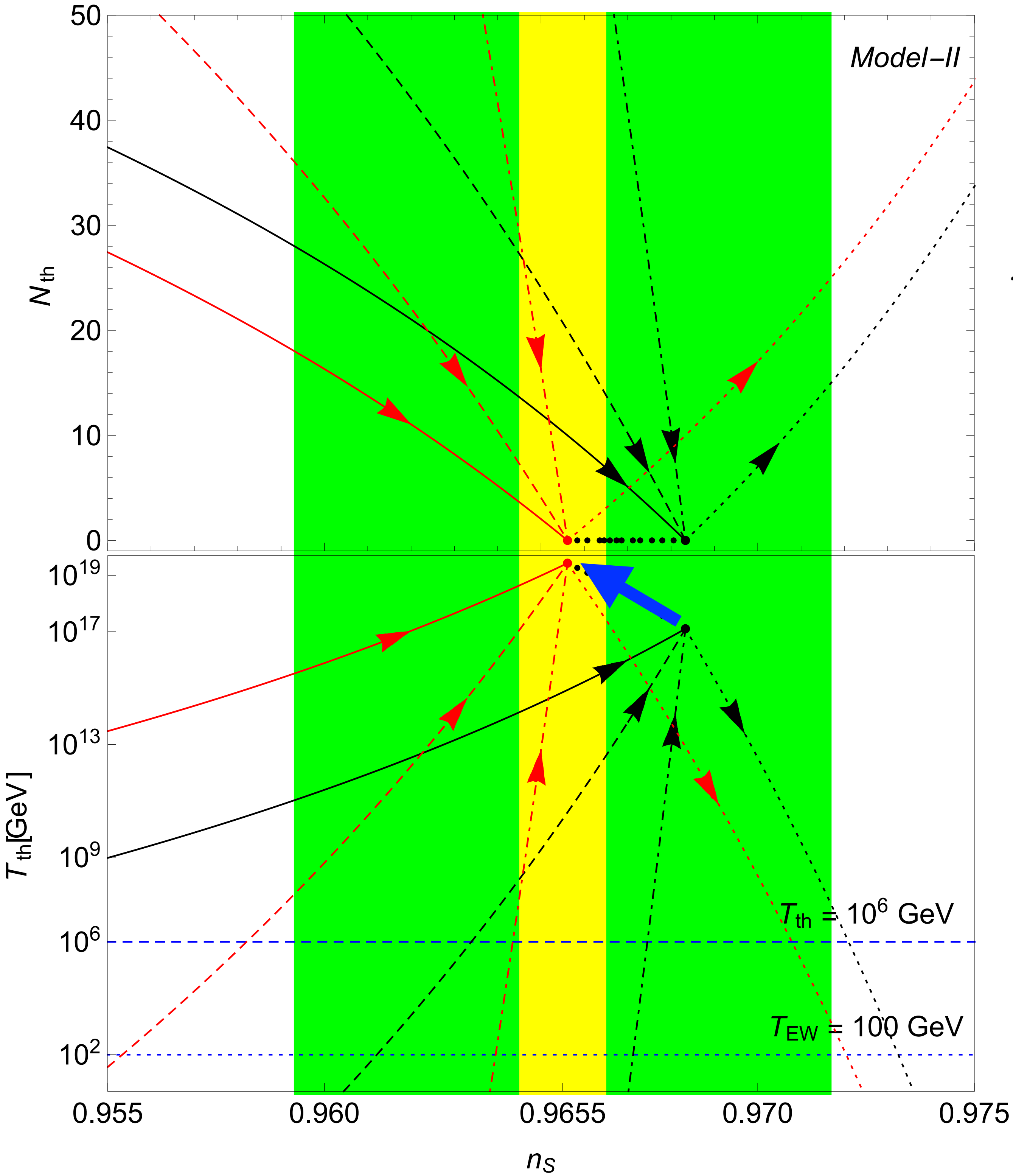
$$\lambda_{\rm end} = \frac{6}{6-2\epsilon-\delta_1(5-2\epsilon+\delta_2)}\bigg|_{\phi=\phi_{\rm end}} > 0; \quad 0 \le \alpha \le 1 \;\Rightarrow\; 0 \le \alpha < \frac{n}{2n+2}.$$

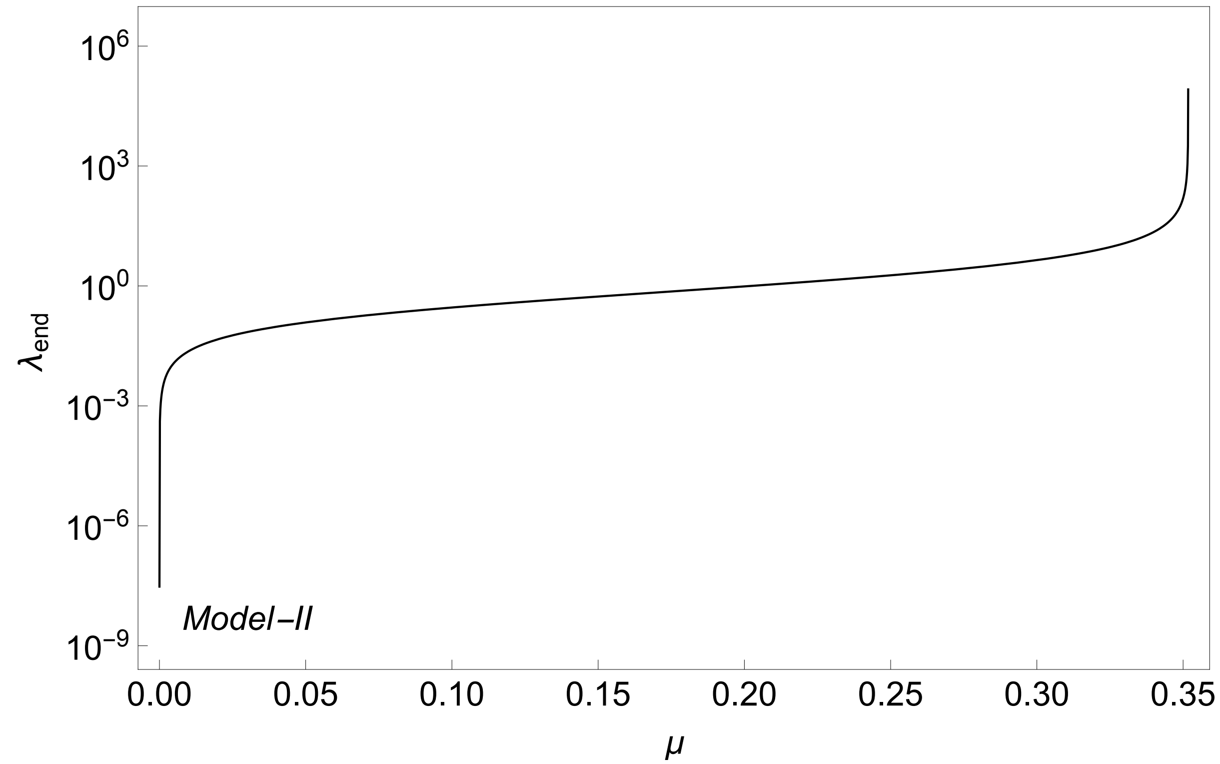
For $T_{th}=10^6$ ***GeV and*** $n_s=0.9655$***:***

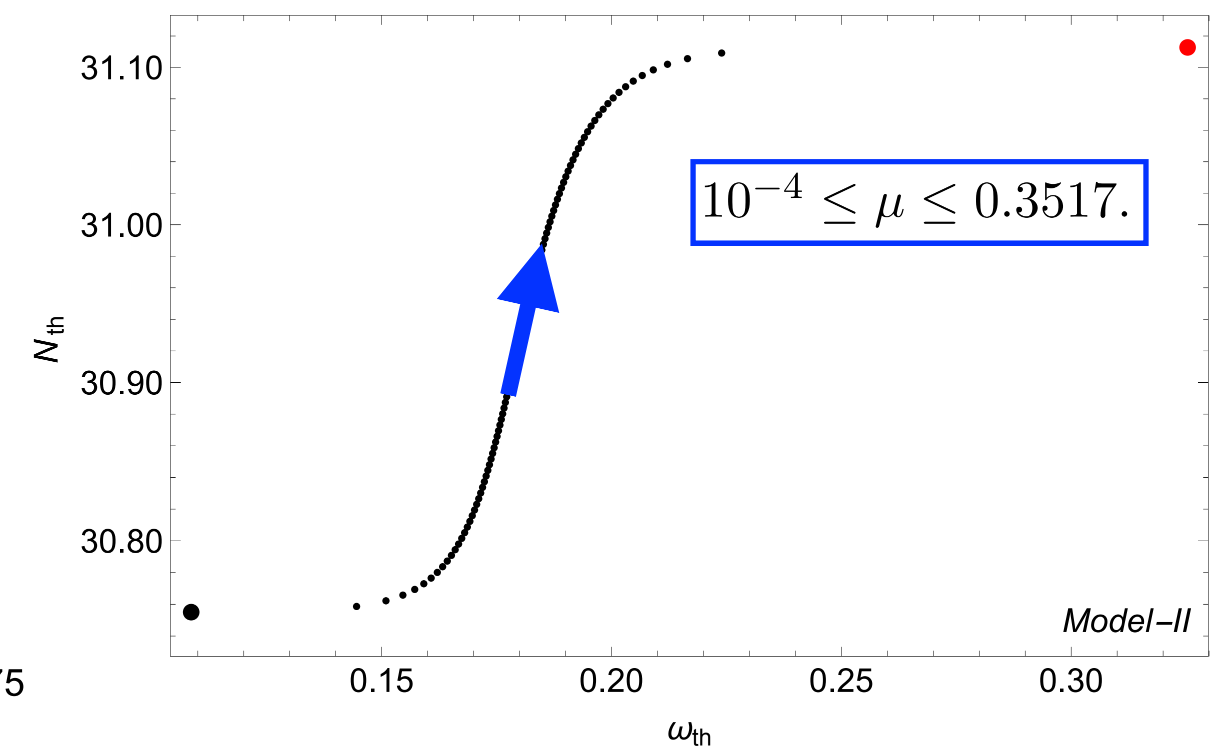


Numerical results:

Model-II: $$V(\phi) = \frac{1}{\kappa^4}\left[\tanh\left(\kappa\phi\right) + \sqrt{\mu}\,\mathrm{sech}\left(\kappa\phi\right)\right]^2\,, \quad \xi(\phi) = \frac{3\left[\sinh^2(\kappa\phi) - \frac{1}{\sqrt{\mu}}\sinh(\kappa\phi)\right]}{4\left[\sqrt{\mu} + \sinh\left(\kappa\phi\right)\right]^2}\,,$$







We are interested in understanding the effects of this additional term

- *to the inflationary observables*
- *to the primordial GW spectra*

SUMMARY:

- ***Inflationary models with a Gauss-Bonnet term are consistent with observational data,***
- ***These models predict both red- and blue-tilted inflationary tensor power spectrum,***
- ***Primordial GW spectrum suppresses (enhances) for $n_T<0$ ($n_T>0$),***
- ***Once pGWs are detected (DECIGO), T_{th} can be determined hence the other parameter of reheating including N_{th} and ω_{th} can also be determined.***
- ***T_{th} significantly increases in the presence of the GB term***
- ***Moreover, reheating can be used as an additional constraint to inflationary models!***

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THANK YOU FOR YOUR KIND ATTENTION!