Particle production during inflation and the Swampland Distance Conjecture

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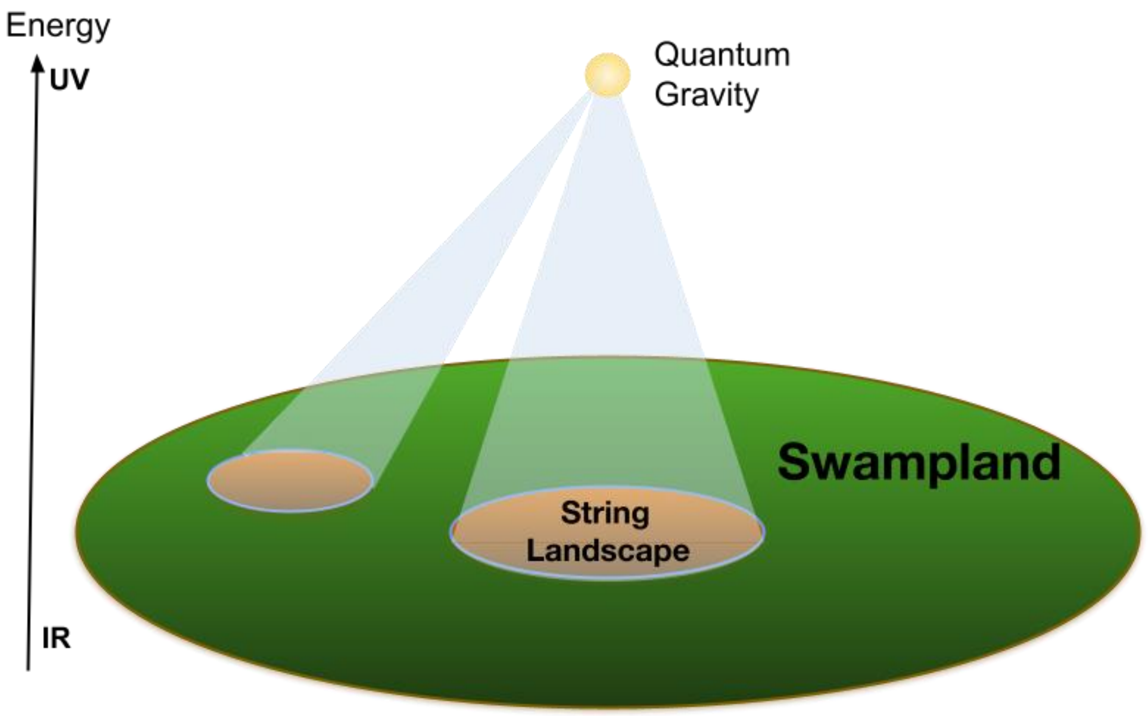
Introduction

- This project is about the **Swampland program**, a novel approach which aims to obtain quantum gravity constraints for EFTs at energies lower than the Planck scale.

- In particular we studied the consequences of applying some of the Swampland Conjectures on the cosmological EFT of Inflation.



Inflation

- We can use **scalar driven inflation** as a toy model:

$$S = \int dx^4 \sqrt{-g}\,[\partial_\mu\phi\partial^\mu\phi - V(\phi)]$$

- We can read the energy density and pressure from the energy momentum tensor:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad P_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \qquad a(t) \simeq e^{Ht}$$

- Using the **Friedmann equations** we find the e.o.m. for ϕ

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Curvature perturbations

- The Inflaton inevitably presents **quantum fluctuations**, even if the background solution is homogenous $\phi_0(t)$, the fluctuations present spatial dependence $\delta\phi(t, \mathbf{x})$.

- These fluctuations then act as sources for **metric perturbations** $\delta g_{\mu\nu}$.

- These can be categorized as **scalar**, **vector** and **tensor** perturbations:
  - **Scalar**: Are produced during inflation, can be observed in **the temperature fluctuations in the CMB**.
  - **Vector**: Not produced during inflation, would nevertheless **decay shortly**.
  - **Tensor**: Primordial GW's produced during inflation, affect the **polarization of the CMB.**

Curvature perturbations

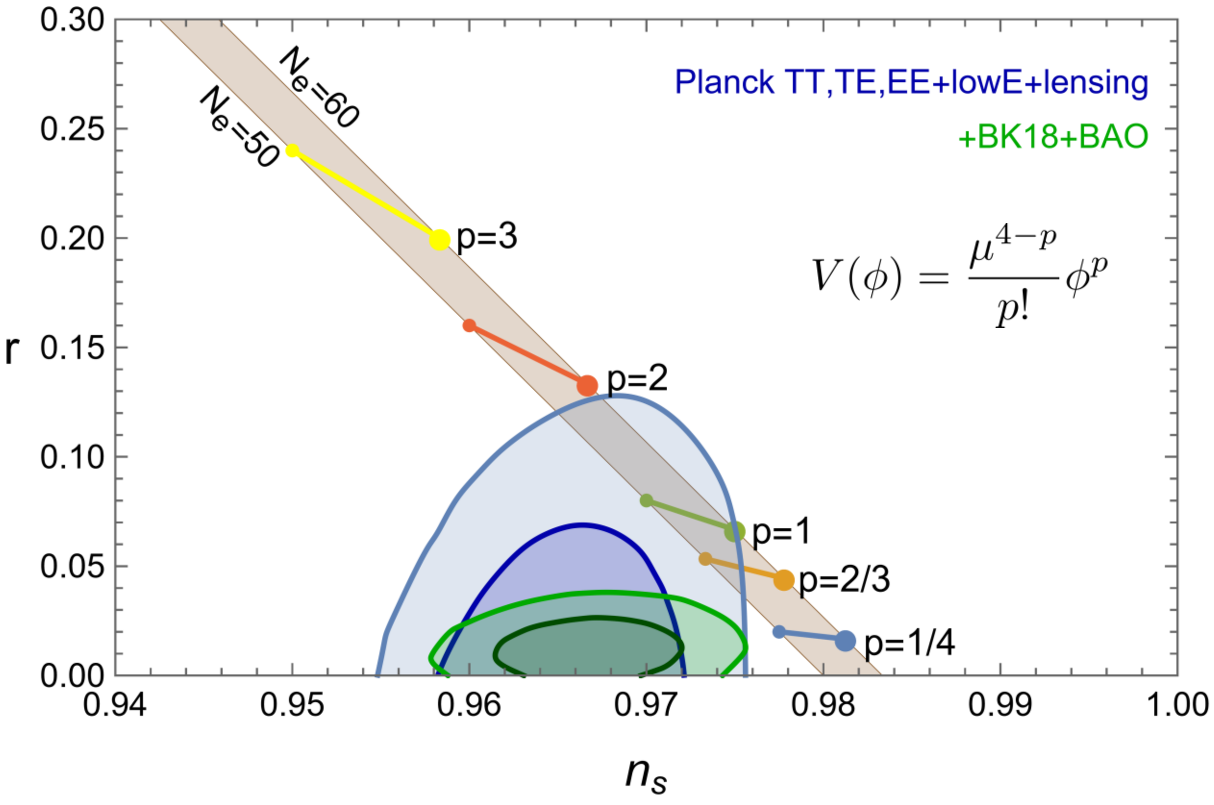
- Two observables of particular interest are:

  - **The spectral tilt:** Measures the deviation from scale invariance:

$$n_s - 1 = \frac{k}{P_\zeta}\frac{dP_\zeta}{dk} = \frac{1}{HP_\zeta}\left.\frac{dP_\zeta}{dt}\right|_{aH=k}$$

  - **The tensor to scalar ratio:** Measures the relation between scalar and tensor power:

$$r = P(k)_T / P(k)_\zeta$$



Swampland Distance Conjecture

- The Swampland Distance Conjecture (SDC) predicts that for large distances in the field space of a scalar, the mass scale of an **infinite tower of states becomes exponentially light**:

$$M_{tower} \propto e^{-\gamma d(\phi)} \qquad \gamma \sim \mathcal{O}(1)$$

[Ooguri & Vafa, hep-th/0605264]

- Since inflation may deal with **superPlanckian displacements** ($\sim \mathcal{O}(10 M_P)$ for power law potentials) it may be interesting couple the inflaton to such a tower of states.

- What observational consequences can arise from having an infinite tower of states coupled to the inflation via an exponential mass term before the **breakdown of the EFT**? [Scalisi & Valenzuela, 1812.07558]

Swampland Distance Conjecture

- The breakdown is due to a drop off of the QG cut-off which goes below the Hubble scale. This is given by the **species scale**. [Dvali et. al, hep-th/0106058]
- For an **infinite tower of scalars**, with linear mass separation (e.g. KK-modes, winding modes):

$$m_n = n \cdot M e^{-\gamma d(\phi)} \qquad \Lambda_{QG} = \frac{M_P}{\sqrt{N}} = M_P^{2/3} M_{\text{Tower}}^{1/3} = M_P^{2/3} M^{1/3} e^{-\frac{\gamma}{3} d(\phi)}$$

- Where N is the number of states with masses below the cutoff.

Scenarios

- We consider an **inflaton** φ coupled to an **infinite tower of scalar fields** χ_n.
- Motivated by the **SDC** we analyze 2 scenarios with **exponential coupling**:

I. $$V(\varphi, \chi_n) = \frac{g^2}{2} e^{-\alpha\varphi} (\varphi - \varphi_{0n})^2 \chi_n^2$$

II. $$V(\varphi, \chi_n) = \frac{m_n^2}{2} e^{-\alpha\varphi} \chi_n^2$$

Scenario I

- We consider an infinite tower of states as:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) + \sum_i \frac{1}{2}\partial_\mu\chi_i\partial^\mu\chi_i - \frac{g^2}{2}e^{-\alpha\varphi}(\varphi - \varphi_{0i})^2\chi_i^2$$

[Trapped inflation
Silverstein et al., 0902.1006
Peloso et al., 1603.08021]

- The quantua are only produced when $\varphi \simeq \varphi_{0i}$, when the χ_i are massless.

$$\Delta = |\varphi_{0i+1} - \varphi_{0i}| \qquad\qquad \Lambda_{QG} \propto e^{-\frac{\alpha}{6}\varphi}$$

Scenario I

- We have three distinct timescales:

$$t_p = \frac{1}{\sqrt{g|\dot{\varphi}_{0i}|e^{-\alpha\varphi_0/4}}} \qquad t_H = \frac{1}{H} \qquad t_{QG} = \frac{6}{\alpha\dot{\varphi}}$$

- During inflation there must be several episodes of particle production.
- Inflation must occur before the breakdown of the EFT.

$$t_p \ll t_H \ll t_{QG} \qquad \frac{|\alpha\dot{\varphi}|}{H} \ll 1$$

Scenario I

- We can then compute the power spectra:

$$P_\zeta = P_{\zeta_h} + P_{\zeta_s} \simeq P_{\zeta_s} = 5.7 \cdot 10^{-4} \, \frac{g^{9/4} e^{-9\alpha\varphi_0/8} \, H}{\Delta^{1/2} \, |\dot{\varphi}_0|^{1/4}} \left(1 + \frac{10}{7} \frac{\alpha \dot{\varphi}_0}{H}\right)$$

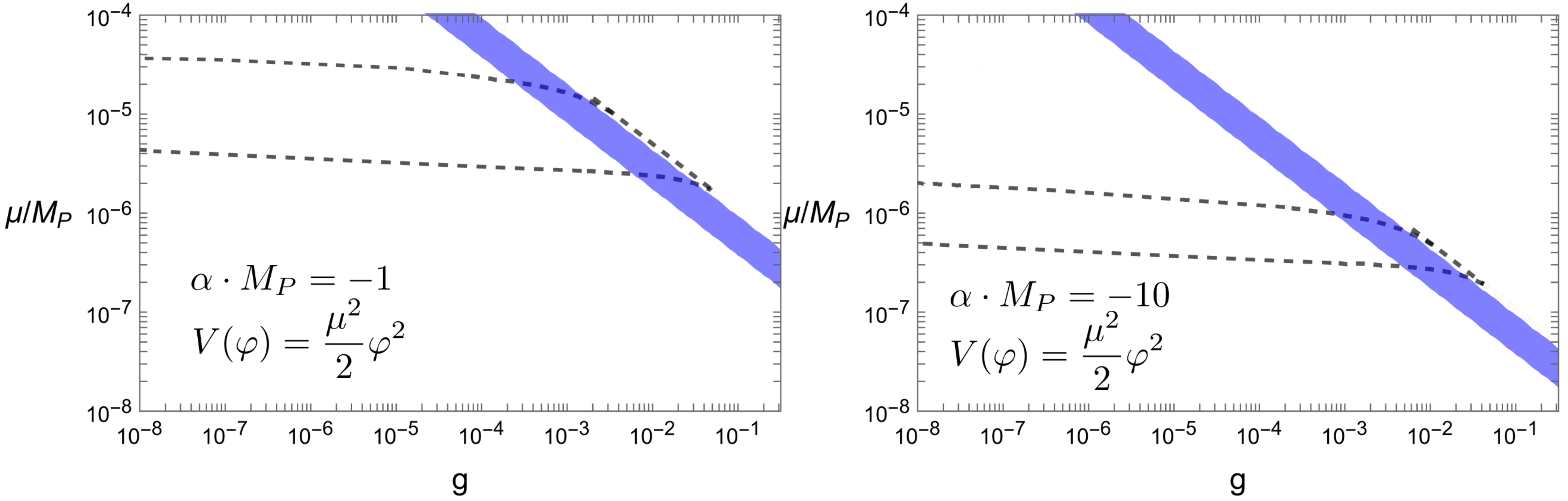
$$P_T = P_{T_h} + P_{T_s} \simeq P_{T_h} = \frac{2H^2}{\pi^2 M_p^2}$$

- The scalar power spectrum receives large contributions from particle production, while the tensor power spectrum is dominated by the unsourced term.
- This brings down the tensor to scalar ratio.

Scenario I

- Given the experimental constraints:

$$n_s - 1 = -0.035 \pm 0.004$$
$$r < 0.036$$



- This is in agreement with the SDC, which predicts $\alpha \sim \mathcal{O}(M_P^{-1})$

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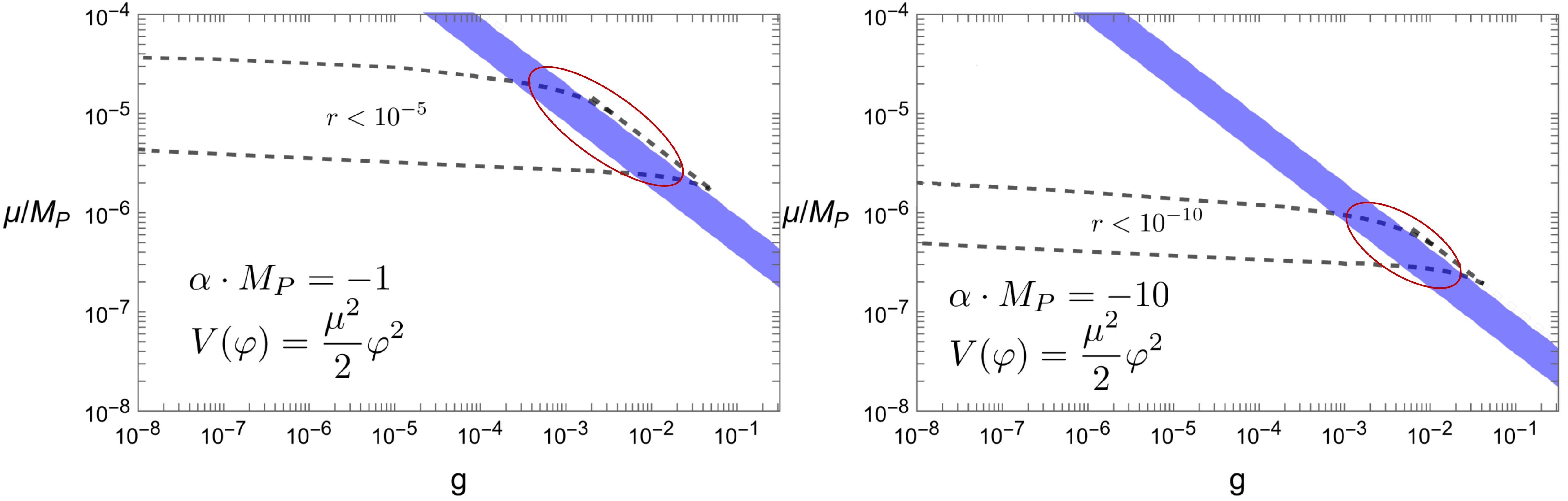

- This is in agreement with the SDC, which predicts $\alpha \sim \mathcal{O}(M_P^{-1})$

Scenario I

- We can reproduce the **cosmological experimental constraints** within the computational regime used.

- The values predicted for **tensor-to-scalar ratio** are much lower than those obtained for **single field inflation**.

- The **exponential coupling** admits values $\alpha \gtrsim M_P^{-1}$.

Scenario II

- We consider the inflaton coupled to an infinite tower of states

$$V(\varphi, \chi_n) = \frac{m_n^2}{2} e^{-\alpha\varphi} \chi_n^2$$

[Reece et al., 2204.11869]

$$m_n = n \cdot m_1$$

- We once again compare the scales of inflation and quantum gravity, such that:

$$\frac{|\alpha\dot{\varphi}|}{H} \ll 1$$

- We compute the power spectra as:

$$P_\zeta = P_{\zeta_h} + P_{\zeta_s} \simeq P_{\zeta_s} \simeq \frac{H^2}{\dot{\varphi}_0^2} \frac{\alpha^2 m_1^4 e^{-2\alpha\varphi_0} \left(\frac{N}{10}\right)^5}{2\pi^2}$$

$$P_T = P_{T_h} + P_{T_s} \simeq P_{T_h} = \frac{2\,H^2}{\pi^2\,M_P^2} \left[1 + 3.55 \frac{H^2 N}{M_p^2 \pi^3}\right]$$

$$N = \frac{M_P^2}{\Lambda_{QG}^2}$$

Scenario II

- Given the experimental constraints:

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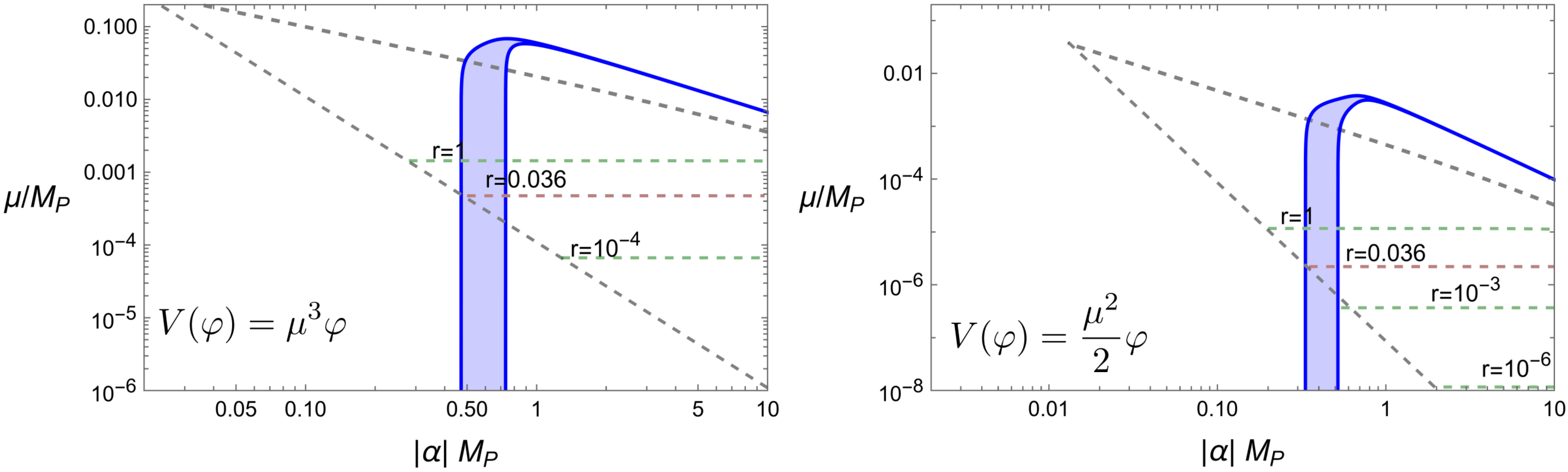
$$r < 0.036$$



- For both linear and quadratic potentials we obtain $\alpha \sim 0.5 M_P^{-1}$

Scenario II

- Given the experimental constraints:

$$n_s - 1 = -0.035 \pm 0.004$$
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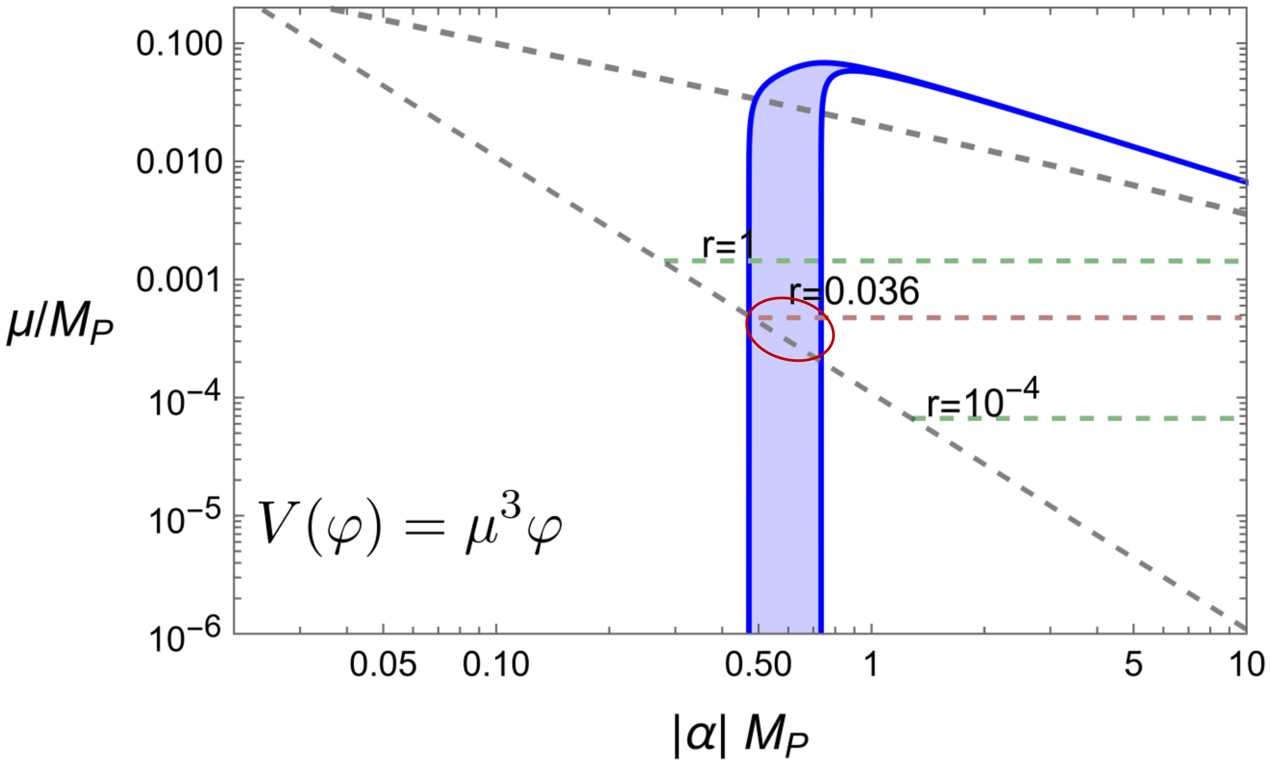
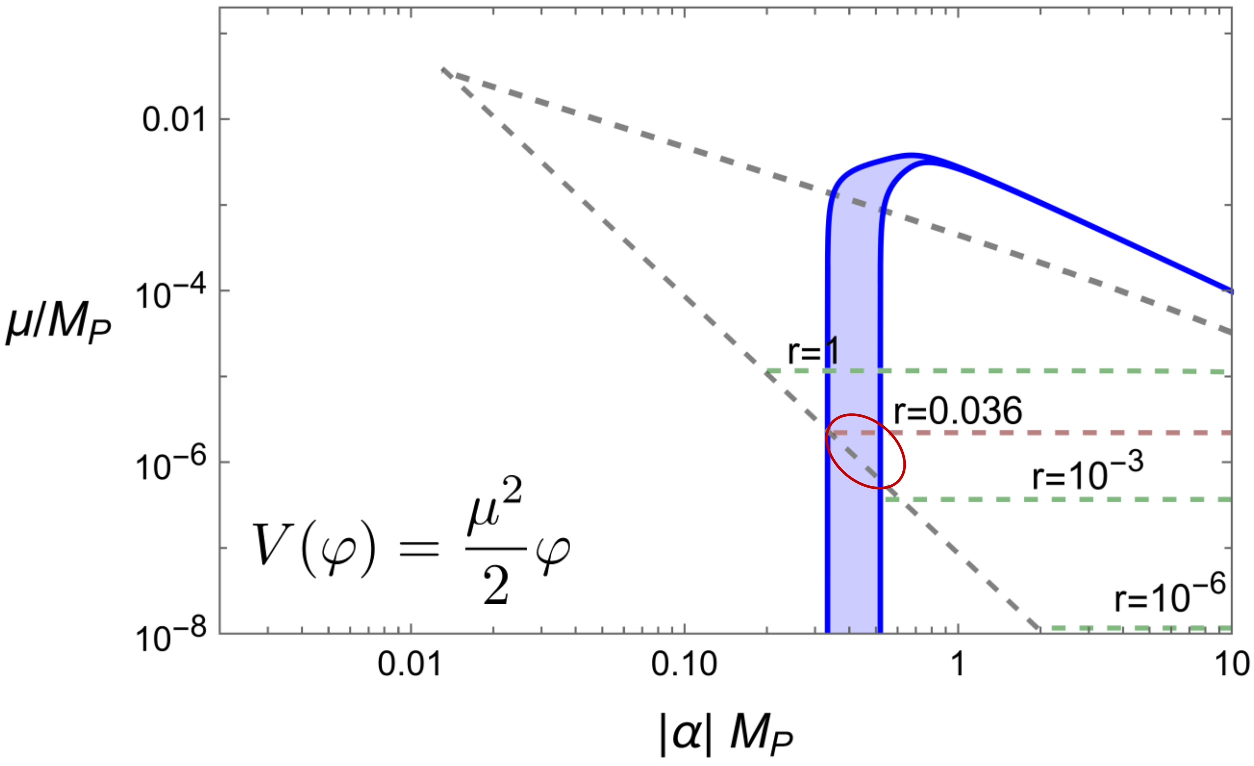




- For both linear and quadratic potentials we obtain $\alpha \sim 0.5 M_P^{-1}$

Scenario II

- We can reproduce the **cosmological experimental constraints** within the computational regime used.

- The values predicted for **tensor-to-scalar** ratio are lower than those obtained for **single field inflation**, but might still be in **tension** with the experimental constraints.

- The **exponential coupling** requires $\alpha \sim 0.5 M_P^{-1}$.

Conclusions and Outlook

- The effects of particle production during inflation can **strongly modify the predictions**.
- The scalar power spectrum receives **a large contribution from particle production**, while the tensor spectrum is mostly unchanged.
- The **exponential coupling** can take values **in agreement with the SDC**.

What's next…

- Extend the discussion to **hilltop and plateau models.**
- Study this models in the regime in which **the inflation and QG scales are close.**
- Explore the possibility of generating **primordial black holes** and analyze whether these could play the same role as the PBHs discussed within the **dark dimension scenario**.

[Montero, Vafa & Valenzuela, 2205.12293] [Anchordoqui, Antoniadis & Lüst, 2206.07071]

Scenario I

- We fix the distance between two consecutive points

$$V(\varphi,\chi_i)=\frac{g^2}{2}e^{-\alpha\varphi}(\varphi-\varphi_{0i})^2\chi_i^2 \qquad \Delta=|\varphi_{0i+1}-\varphi_{0i}|$$

- In order to deduce the scaling of the states we look at the tower when

$$\varphi=\varphi_{00} \qquad m_{\chi_0}=0$$

- The masses of the tower, and the scale of QG are then:

$$m_{\chi_i}=ige^{-\alpha\varphi/2}\Delta \qquad \Lambda_{QG}=\frac{M_P}{\sqrt{N}}\simeq M_P^{2/3}(g\Delta)^{1/3}e^{-\frac{\alpha}{6}\varphi}$$

$$\Lambda_{QG}\simeq\Lambda_{QG_0}e^{-\frac{\alpha}{6}\dot{\varphi}t}=\Lambda_{QG_0}e^{-t/t_{QG}}$$

Scenario I

- We have 5 parameters:

$$N_e \qquad \Delta \qquad g \qquad \mu \qquad \alpha$$

- The number of e-folds has to be around 50 $\quad N_e = 60$

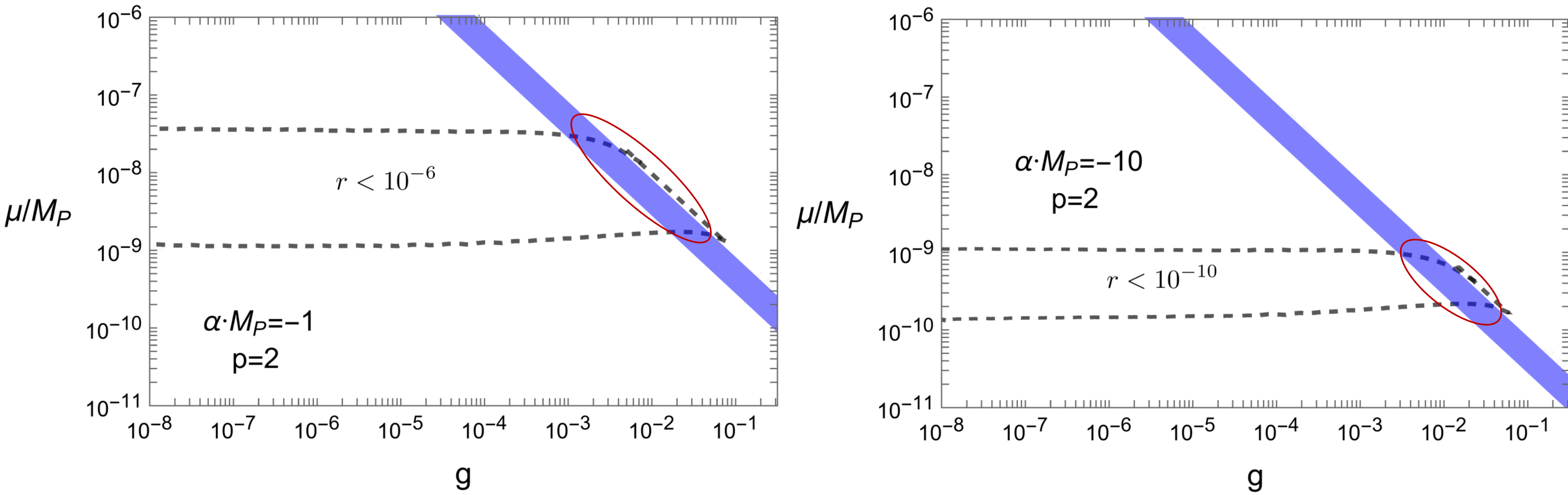
- The value of Δ can be fixed in term of the other parameters

Scenario I

- Given the experimental constraints:

$$V(\varphi) = \frac{\mu^{4-p}}{p!}\varphi^p$$

$$n_s - 1 = -0.035 \pm 0.004$$
$$r < 0.036$$



- This is in agreement with the SDC, which predicts $\alpha \sim \mathcal{O}(M_P^{-1})$

Scenario II

- We have 4 parameters:

$$N_e \qquad m_1 \qquad \mu \qquad \alpha$$

- The number of e-folds has to be around 50 $\quad N_e = 60$

- The value of m_1 can be fixed in term of the other parameters by requiring that the measured value of the scalar power spectrum is reproduced