Aligned natural inflation: Oscillations in primordial power spectrum

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Suppose we achieve ***super-Planckian axion scale***
through ***alignment mechanism***

$$V(\phi) = \Lambda_1^4\left[1 - \cos\frac{\phi}{f_{\rm eff}}\right] + \Lambda_2^4\left[1 - \cos\left(\frac{\phi}{f} + \delta\right)\right]$$

$$\Lambda_2 \ll \Lambda_1$$

$$f \ll f_{\rm eff}$$

What would be the ***observational consequences*** of this model?

Choi, HK, Shin, in preparation

Natural Inflation

$$V(\phi) = \Lambda^4 \left[1 - \cos\frac{\phi}{f}\right]$$

The amplitude can determined by observed temperature fluctuation

The axion scale is required to be ***super-Planckian***

Axion scale

Especially in string theory,

$$f \simeq \frac{g^2}{8\pi^2} M_P \sim 10^{16}\mathrm{GeV}$$

Axion scale is normally ***sub-Planckian*** in weak coupling limit

Choi, Kim '85

Banks et. al '03

Svrcek, Witten '06

Proposals

Let's introduce ***extra axions!***

Axion alignment	**Kim, Nilles, Peloso '04**
N-flation	**Dimopolous '05**
Other variations	**Choi, HK, Yun '14** **Higaki, Takahashi '14** **Tye, Wong '14** **Ben-Dayan, Pedro, Westphal '14** **Harigaya, Ibe '14** **… … … …**

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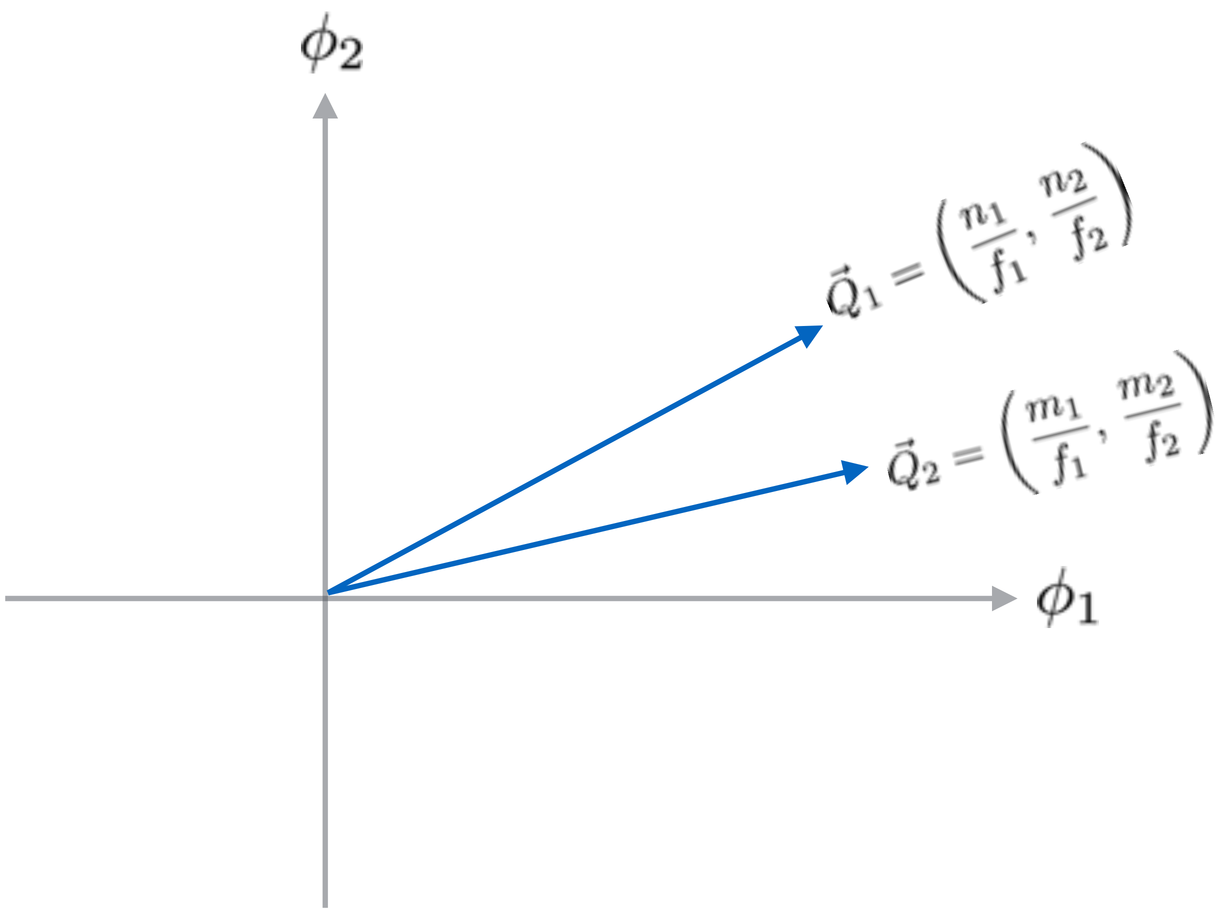
Axion alignment

$$V = \Lambda^4 e^{-S_1}\left[1-\cos\left(\frac{n_1}{f_1}\phi_1+\frac{n_2}{f_2}\phi_2\right)\right]+\Lambda^4 e^{-S_2}\left[1-\cos\left(\frac{m_1}{f_1}\phi_1+\frac{m_2}{f_2}\phi_2\right)\right]$$



Kim, Nilles, Peloso ’04

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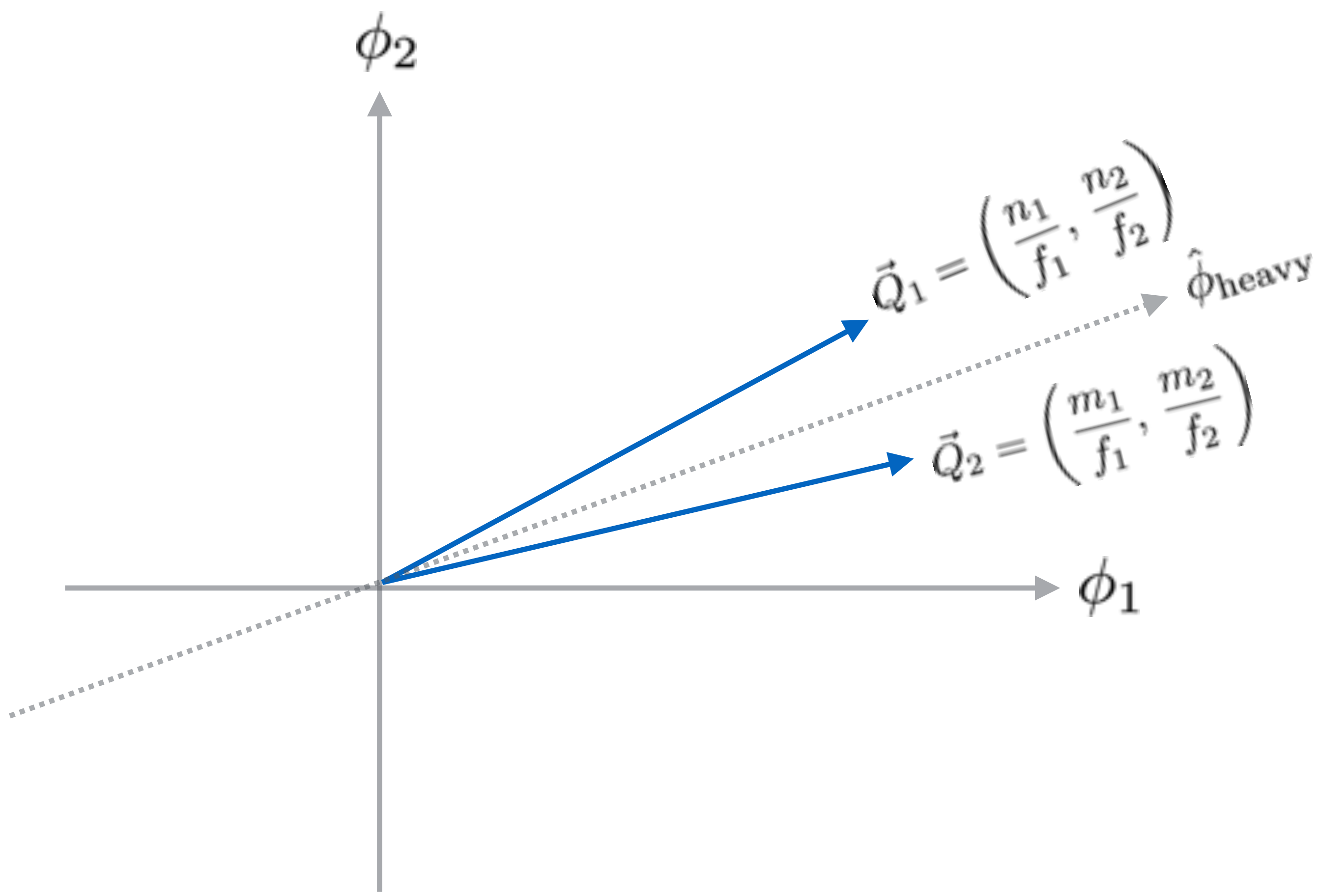

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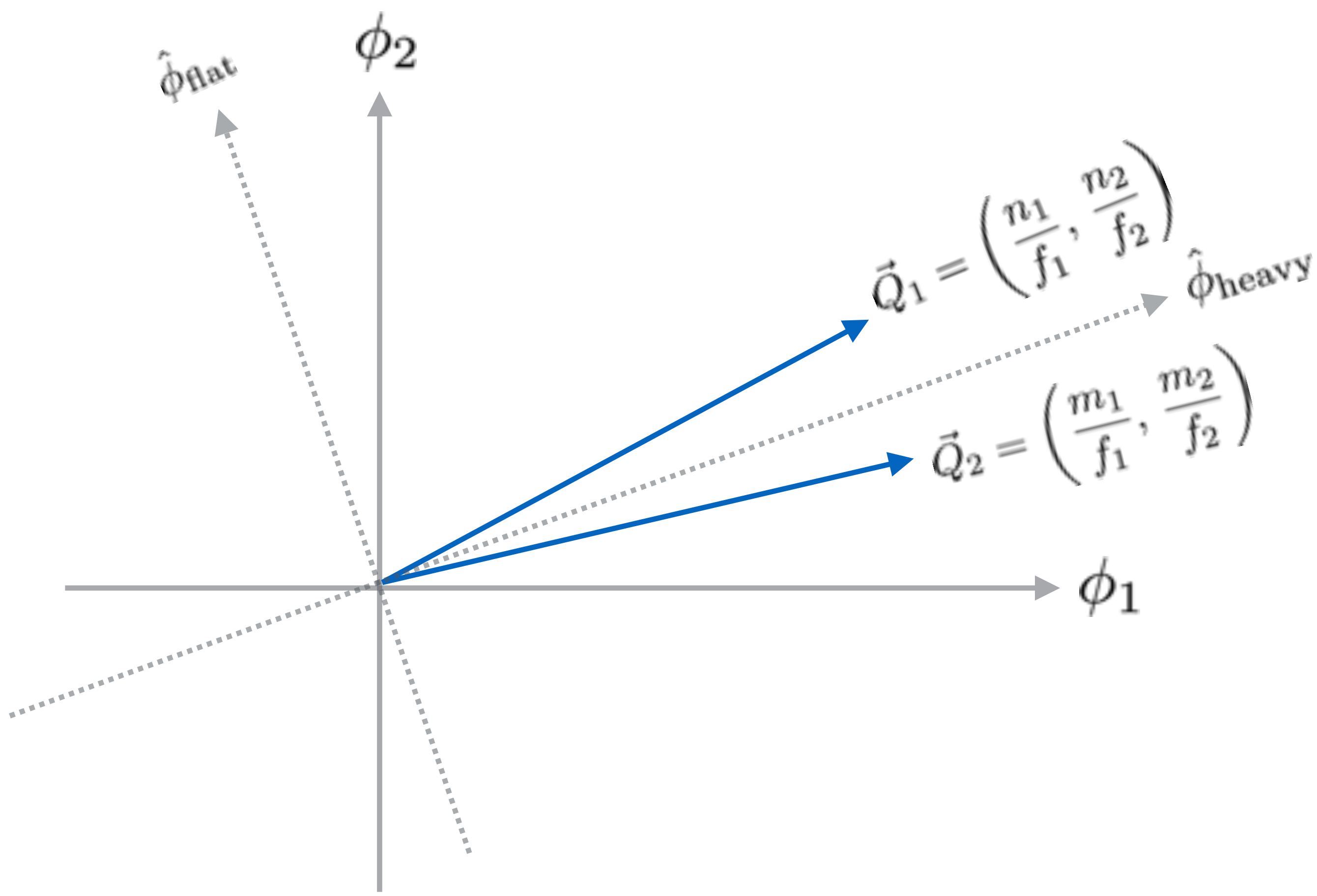

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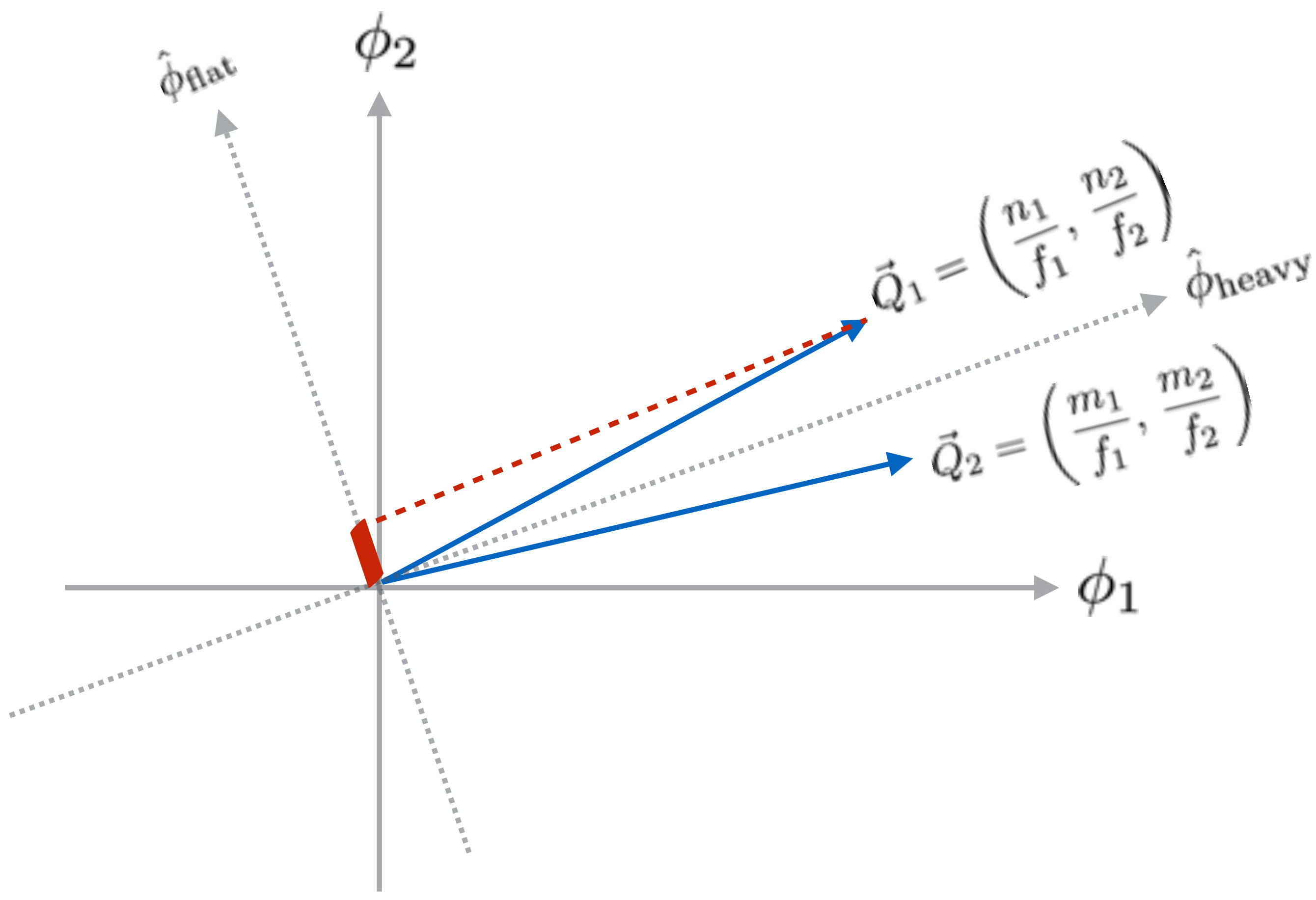

$$V(\phi) \simeq \Lambda^4 e^{-S}\left[1-\cos\frac{\phi}{f_{\rm eff}}\right]$$

$$f_{\rm eff} \sim \frac{f}{\theta} \propto \frac{f}{|n_1 m_2 - n_2 m_1|}$$

Kim, Nilles, Peloso ’04

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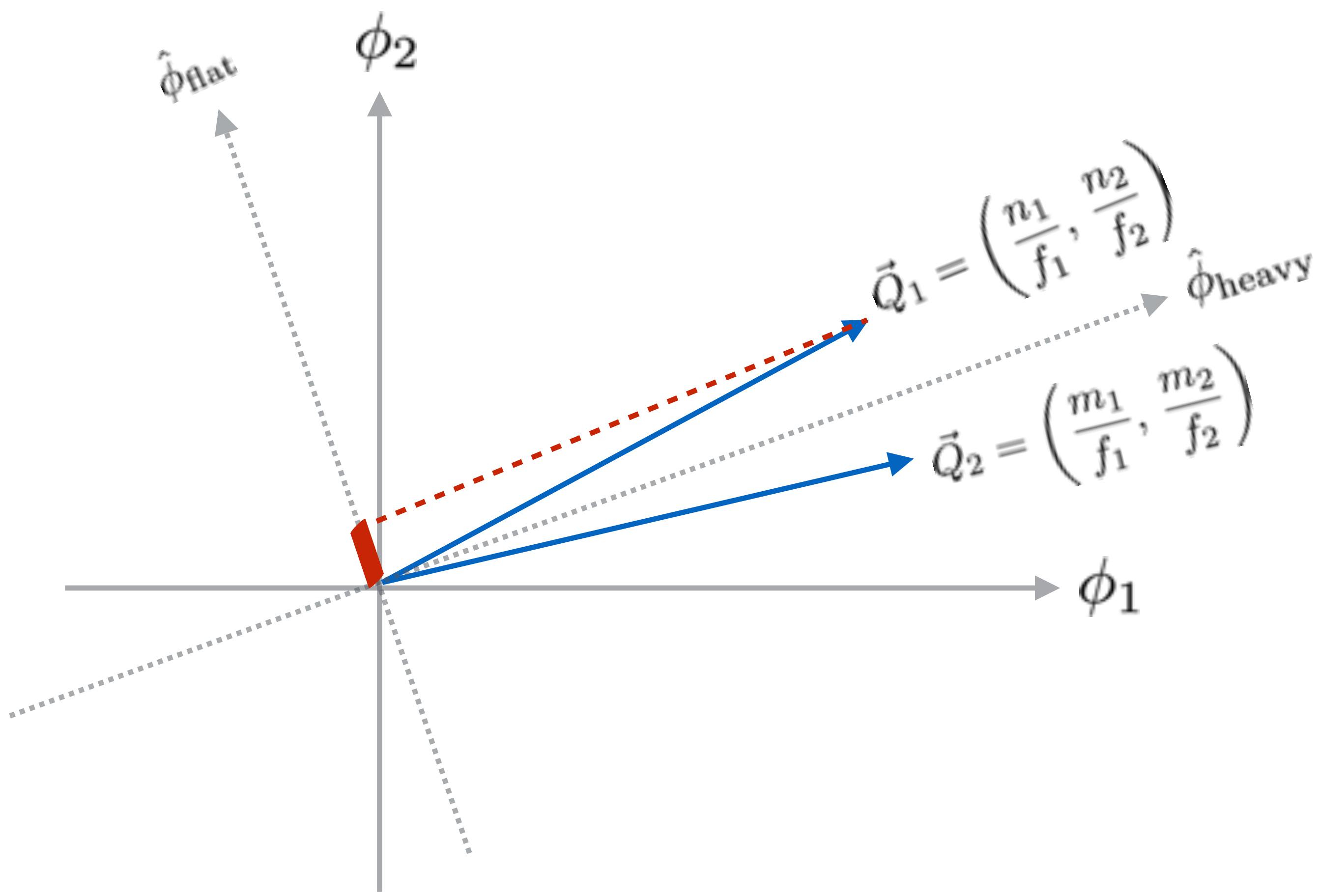

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Kim, Nilles, Peloso ’04

Weak gravity conjecture on axions

Consider a theory of ***U(1) gauge boson* + *gravity***

$$q \geq \frac{m}{M_P}$$

Consider a theory of ***axion* + *gravity***

$$\frac{1}{f} \geq \frac{S_{\mathrm{inst}}}{M_P} \quad \Leftrightarrow \quad f \leq \frac{M_P}{S_{\mathrm{inst}}}$$

axion scale is ***bounded*** from above!

Arkani-Hamed et. al. ’06

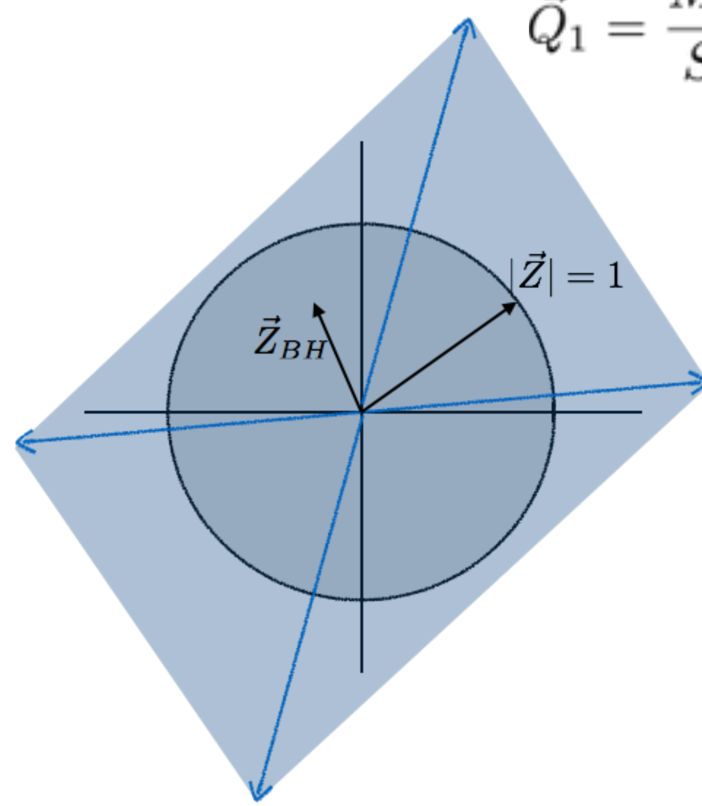
Weak gravity conjecture on axions

How about ***N axions?***

Convex Hull condition **Cheung et. al. '14**

$$V = \Lambda^4 e^{-S_1}\left[1-\cos\left(\frac{n_1}{f_1}\phi_1+\frac{n_2}{f_2}\phi_2\right)\right]+\Lambda^4 e^{-S_2}\left[1-\cos\left(\frac{m_1}{f_1}\phi_1+\frac{m_2}{f_2}\phi_2\right)\right]$$

$$\vec{Q}_1 = \frac{M_P}{S_1}\left(\frac{n_1}{f_1}, \frac{n_2}{f_2}\right)$$



$$\vec{Q}_2 = \frac{M_P}{S_2}\left(\frac{m_1}{f_1}, \frac{m_2}{f_2}\right)$$

Brown et. al. '15

$$f_{\rm eff} < M_P$$

Rudelius '15

Montero et. al. '15

…

Weak gravity conjecture on axions

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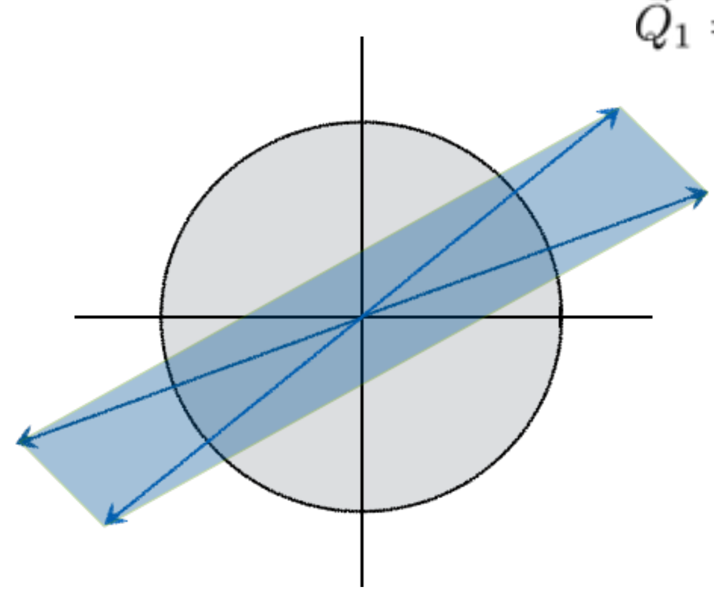
$$\vec{Q}_1=\frac{M_P}{S_1}\left(\frac{n_1}{f_1},\frac{n_2}{f_2}\right)$$

$$\vec{Q}_2=\frac{M_P}{S_2}\left(\frac{m_1}{f_1},\frac{m_2}{f_2}\right)$$

Brown et. al. ’15



Alignment case

$$f_{\text{eff}} < M_P$$

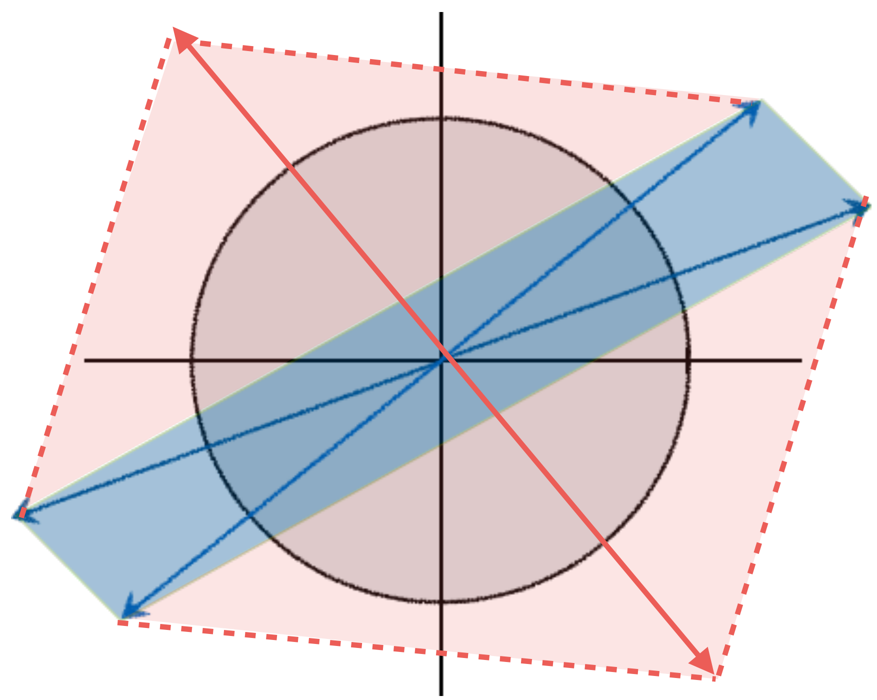
Rudelius ’15

Montero et. al. ’15

…

Weak gravity conjecture on axions

One way of circumventing this is to ***add extra instanton!***



$$f \ll f_{\rm eff}$$

$$S \ll S_{\rm large}$$

$$V(\phi) = \Lambda^4 e^{-S}\left[1-\cos\frac{\phi}{f_{\rm eff}}\right] + \Lambda^4 e^{-S_{\rm large}}\left[1-\cos\left(\frac{\phi}{f}+\delta\right)\right]$$

Brown et. al. '15

Back to the original question

If the modulation is natural consequence
of alignment mechanism,

$$V(\phi) = \Lambda_1^4\left[1 - \cos\frac{\phi}{f_{\rm eff}}\right] + \Lambda_2^4\left[1 - \cos\left(\frac{\phi}{f} + \delta\right)\right]$$

$$f \ll f_{\rm eff}$$

How do they change the shape of primordial power spectrum?

How could they be constrained by the recent observational data?

Former study: Axion monodromy

Axion monodromy potenial with cosine modulation

$$V(\phi) = \mu^3 \phi + \Lambda^4 \cos\left(\frac{\phi}{f} + \delta\right)$$

induces oscillations in primordial power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}*}\left(\frac{k}{k_*}\right)^{n_s - 1}\left[1 + \delta n_s \cos\left(\frac{\phi_k}{f} + \alpha\right)\right]$$

R. Flauger et. al. '09

R. Flauger et. al. '14

Natural inflation with modulations

Natural inflation with cosine modulation

$$V(\phi) = \Lambda_1^4 \left[1 - \cos\frac{\phi}{f_{\rm eff}}\right] + \Lambda_2^4 \left[1 - \cos\left(\frac{\phi}{f} + \delta\right)\right]$$

also induces oscillations in primordial power spectrum

$$\mathcal{P}_\mathcal{R}(k) = A_{\mathcal{R}*} \left(\frac{k}{k_*}\right)^{n_s - 1} \left[1 + \delta n_s \cos\left(\frac{\phi_k}{f} + \alpha\right)\right]$$

Choi, HK, Shin, work in progress

Natural inflation with modulations

Natural inflation with cosine modulation

$$\delta n_s = \left(\frac{\Lambda_2^4}{\Lambda_1^4}\frac{f_{\rm eff}}{f}\right)\frac{3\sqrt{2\pi\gamma\coth\frac{\pi}{2\gamma}}}{\sin(\phi_*/f_{\rm eff})\sqrt{(1+\frac{3}{2}\,\gamma^2/f_{\rm eff}^2)^2+(3\gamma)^2}} \qquad \gamma = f_{\rm eff}\,f\tan\frac{\phi_*}{2f_{\rm eff}}$$

also induces oscillations

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}*}\left(\frac{k}{k_*}\right)^{n_s-1}\left[1+\delta n_s\cos\left(\frac{\phi_k}{f}+\alpha\right)\right]$$

Choi, HK, Shin, work in progress

Oscillations in power spectrum

For ordinary slow-roll inflation, power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = A_* \left(\frac{k}{k_*}\right)^{(n_s-1)+\frac{1}{2}\frac{dn_s}{d\ln k}\ln(k/k_*)+\frac{1}{6}\frac{d^2n_s}{d\ln k^2}\ln^2(k/k_*)+\cdots}$$

is described by a set of parameters

$$A_* \quad n_s \quad \frac{dn_s}{d\ln k} \quad \frac{d^2n_s}{d\ln k^2} \quad \cdots$$

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$$A_* \quad n_s \quad \frac{dn_s}{d\ln k} \quad \frac{d^2n_s}{d\ln k^2} \quad \cdots$$

Oscillations in power spectrum

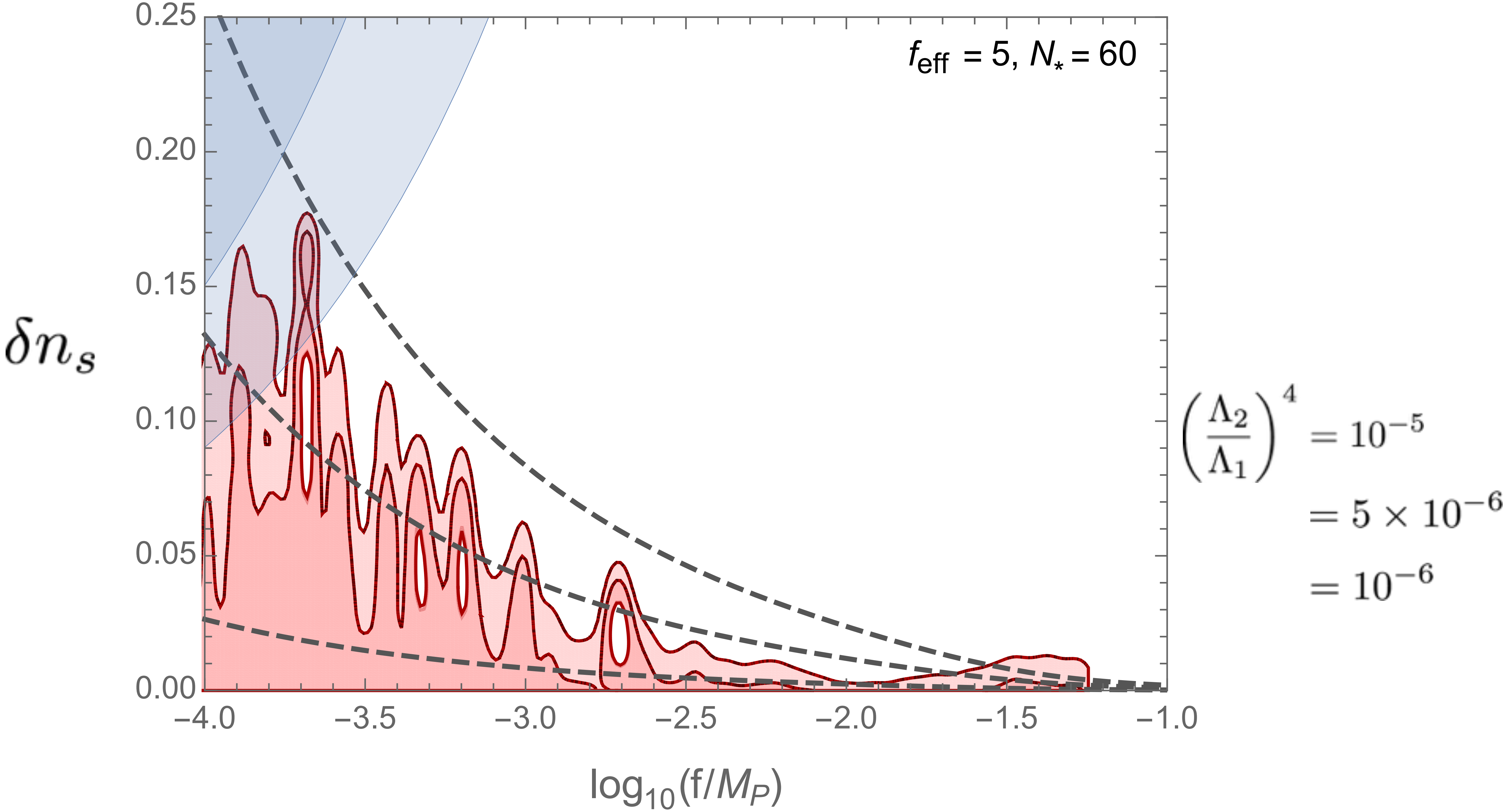
In this scenario, power spectrum looks like

$$\mathcal{P}_{\mathcal{R}}(k) = A_{\mathcal{R}*} \left(\frac{k}{k_*}\right)^{n_s - 1} \left[1 + \delta n_s \cos\left(\frac{\phi_k}{f} + \alpha\right)\right]$$

the standard template $(A_{\mathcal{R}*}, n_s)$

does not capture characteristic features of this scenario.

Constraints on oscillations



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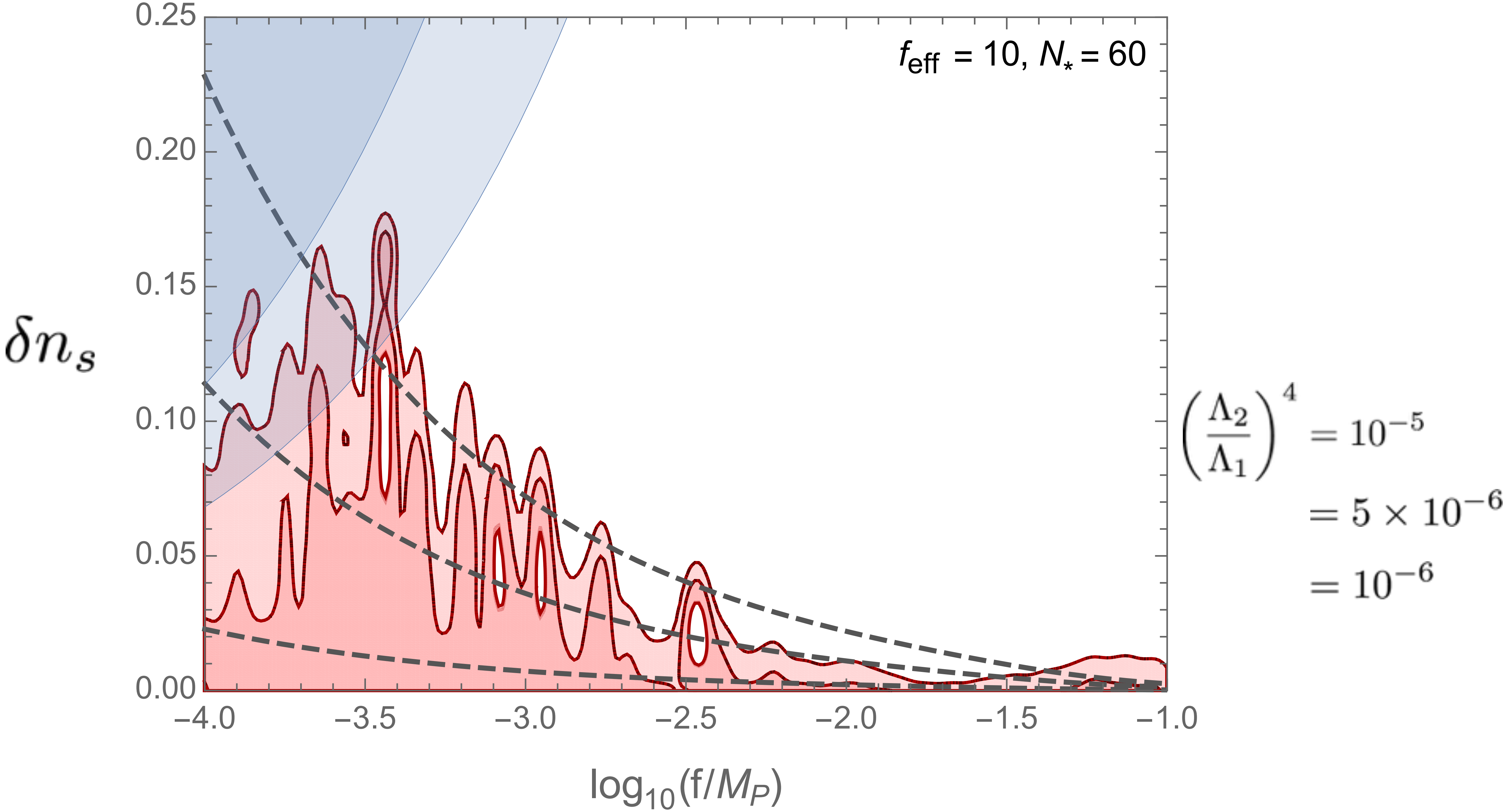

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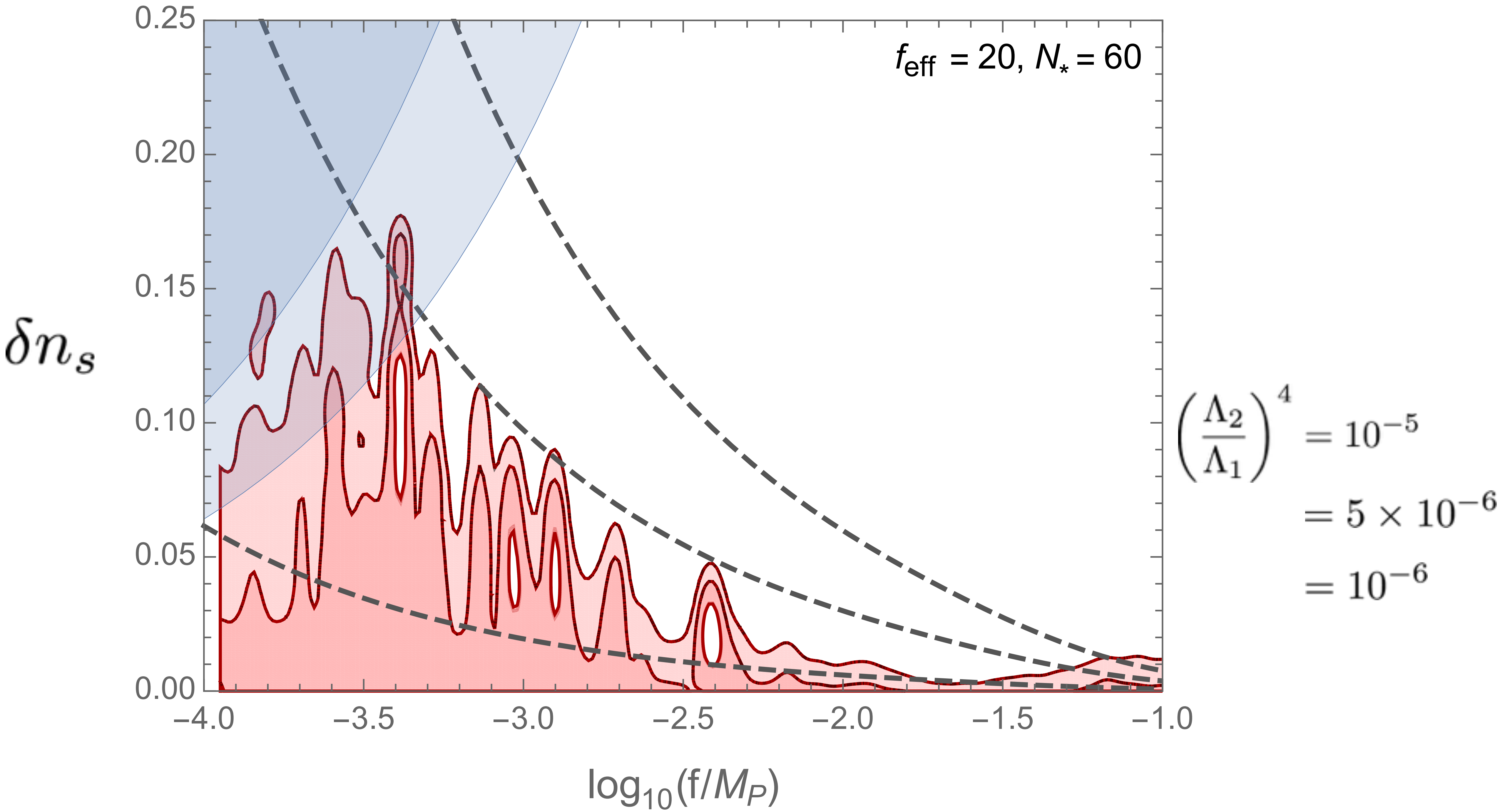
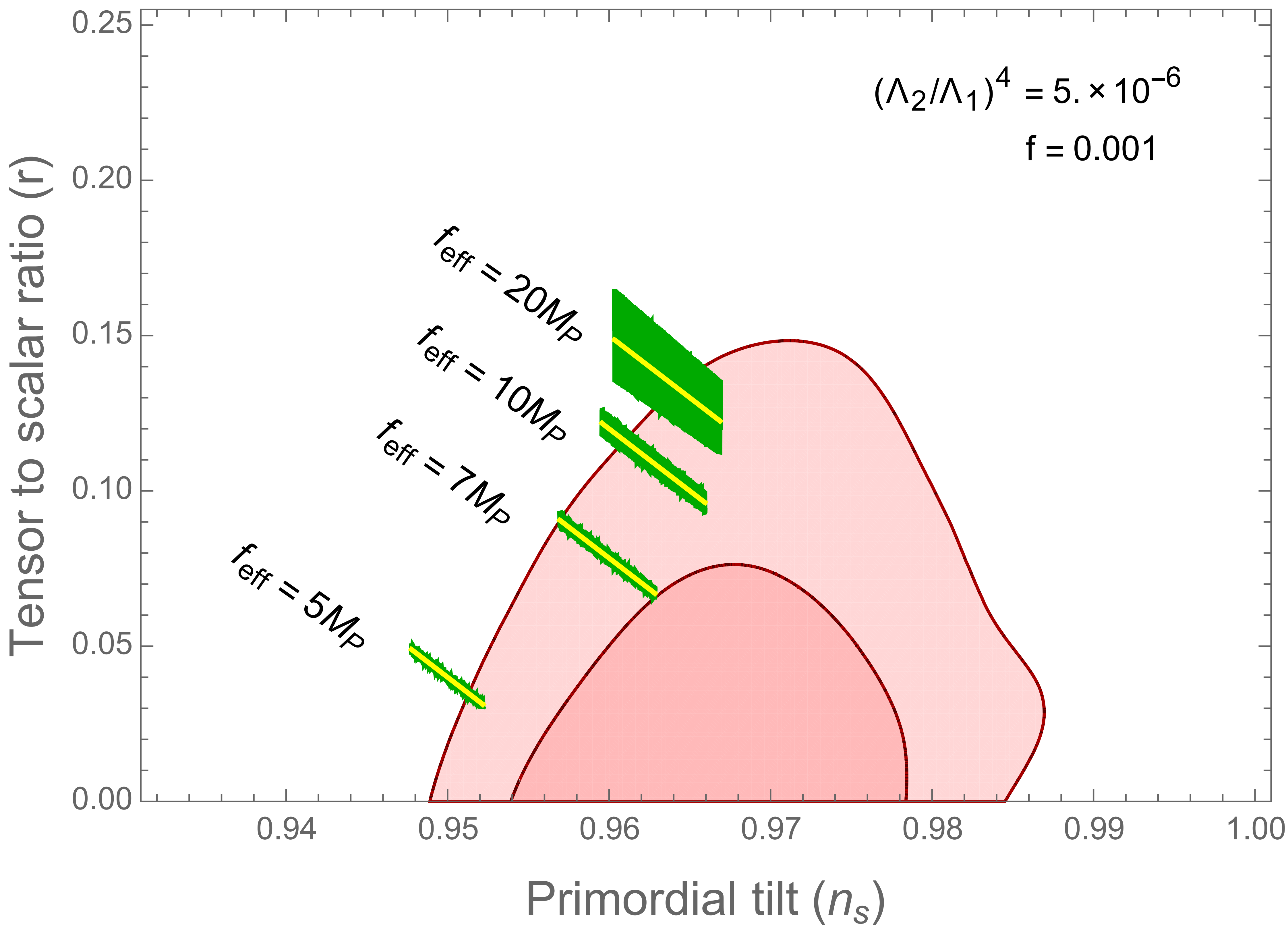


tensor-to-scalar ratio?

tensor-to-scalar ratio can change, but only by

$$r = \frac{\mathcal{P}_t}{\mathcal{P}_\mathcal{R}} = \frac{r_0}{1 + \delta n_s \cos(\phi_k / f)}$$

as the amplitude of oscillation is constrained by observation, only ***~10%*** change is possible



$(\Lambda_2/\Lambda_1)^4 = 5. \times 10^{-6}$
f = 0.001
$f_{eff} = 20M_P$
$f_{eff} = 10M_P$
$f_{eff} = 7M_P$
$f_{eff} = 5M_P$
Tensor to scalar ratio (r)
0.25
0.20
0.15
0.10
0.05
0.00
0.94
0.95
0.96
0.97
0.98
0.99
1.00
Primordial tilt (n_s)

Summary

$$V(\phi) = \Lambda_1^4\Big[1 - \cos\frac{\phi}{f_{\rm eff}}\Big] + \Lambda_2^4\Big[1 - \cos\Big(\frac{\phi}{f} + \delta\Big)\Big]$$

Observational signature?

Oscillations!

Any contraints?

Amplitude of oscillation leads to $(\Lambda_2/\Lambda_1)^4 \lesssim 5 \times 10^{-6}$

tensor-to-scalar ratio can change by $\sim 10\%$