Modulated Natural Inflation in the CMB

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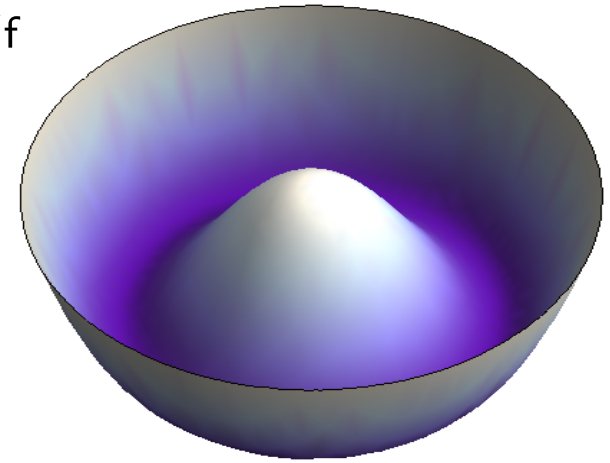
Phys. Lett. B753 (2016) + work in progress
in collaboration with R. Kappl, H.P. Nilles, M. Zatta

Advances in Theoretical Cosmology in Light of Data
July 21, 2017

Natural Inflation

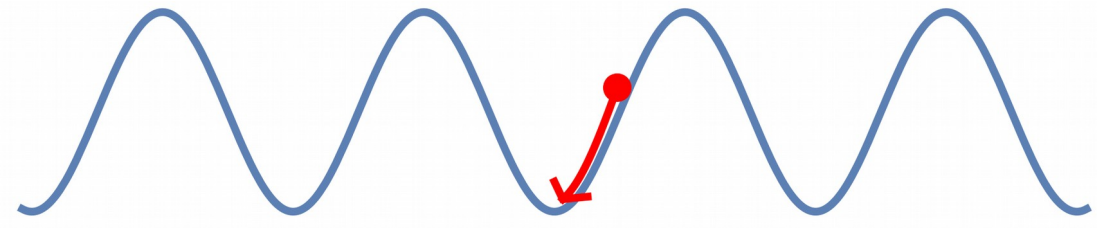
- global U(1) symmetry $\Phi = f\, e^{i\varphi/f}$



- inflaton = goldstone boson (axion)

  Freese, Frieman, Olinto, Phys. Rev. Lett. 65 (1990)

- shift symmetry broken via $\varphi F\tilde{F}$

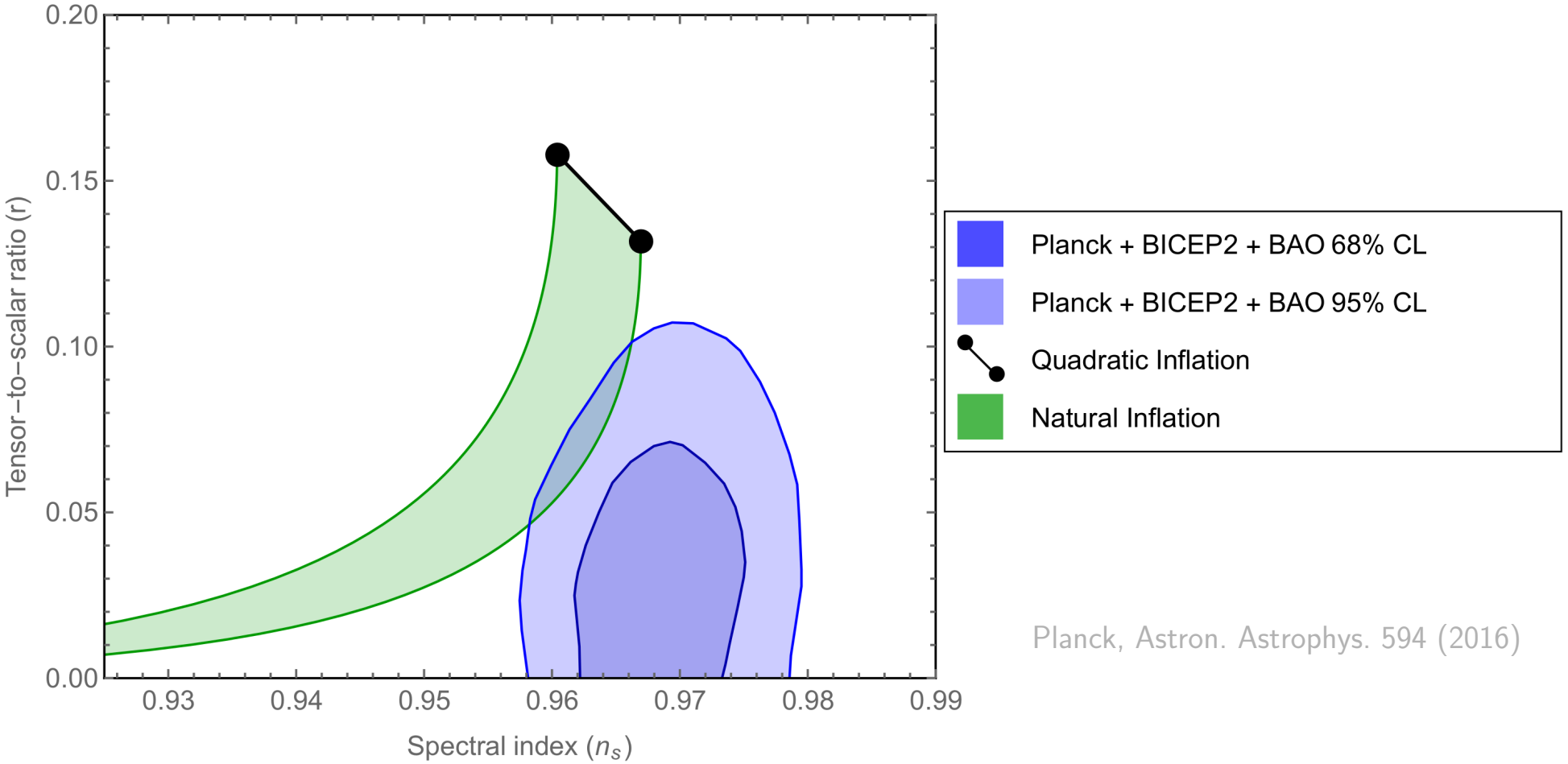


$$V = \Lambda^4 \left(1 - \cos\left[\frac{\varphi}{f}\right]\right) \qquad f = \text{axion decay constant}$$

- string axions inherit shift symmetries from gauge symmetries
- breaking via gaugino condensation or string instantons, e.g. KKLT

  Kachru, Kallosh, Linde, Trivedi, Phys. Rev. D68 (2003)

Natural Inflation and the CMB



Planck, Astron. Astrophys. 594 (2016)

- tension with CMB data
- $f > M_P$ does not arise in controllable regime of string theory

Banks, Dine, Fox, Gorbatov, JCAP 0306 (2003), Svrcek, Witten, JHEP 0606 (2006)

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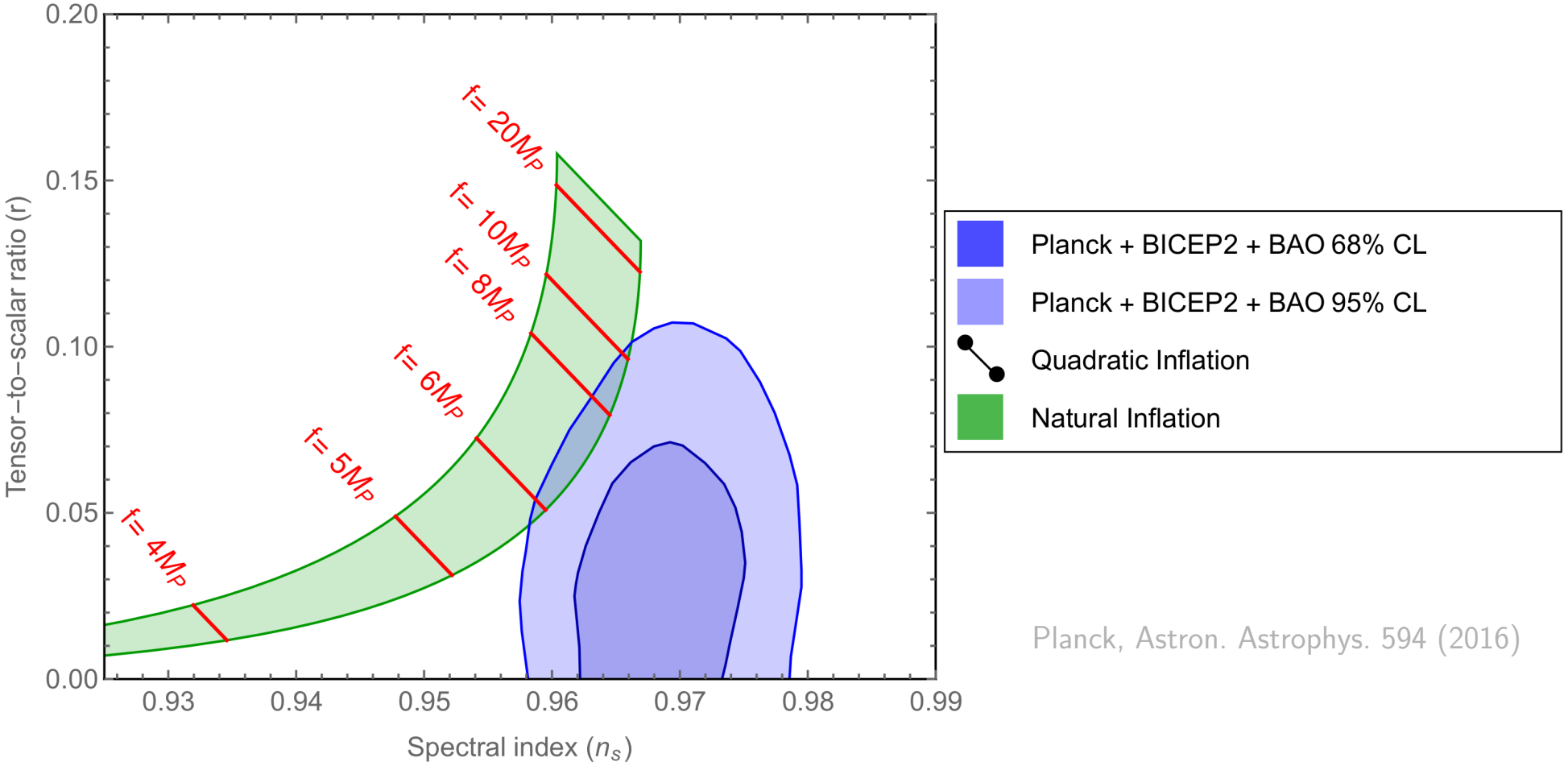

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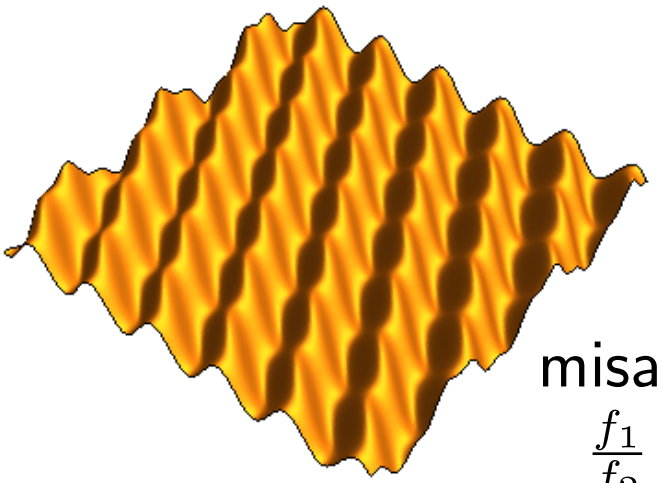
Axion Alignment Mechanism

- two-axion model

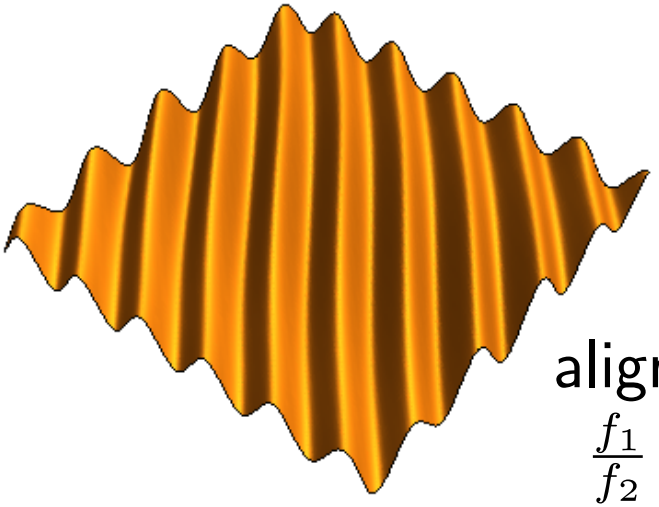
  Kim, Nilles, Peloso, JCAP 01 (2005)

$$V = \Lambda_1^4 \left[1 - \cos\left(\frac{\varphi_1}{f_1} + \frac{\varphi_2}{f_2}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(\frac{\varphi_1}{g_1} + \frac{\varphi_2}{g_2}\right)\right]$$



misalignment

$$\frac{f_1}{f_2} \neq \frac{g_1}{g_2}$$



alignment

$$\frac{f_1}{f_2} \simeq \frac{g_1}{g_2}$$

- integrate out

$$V \simeq \Lambda^4 \left(1 - \cos\frac{\varphi}{f}\right)$$

$$f \propto \frac{1}{f_1 g_2 - g_1 f_2} > 1$$

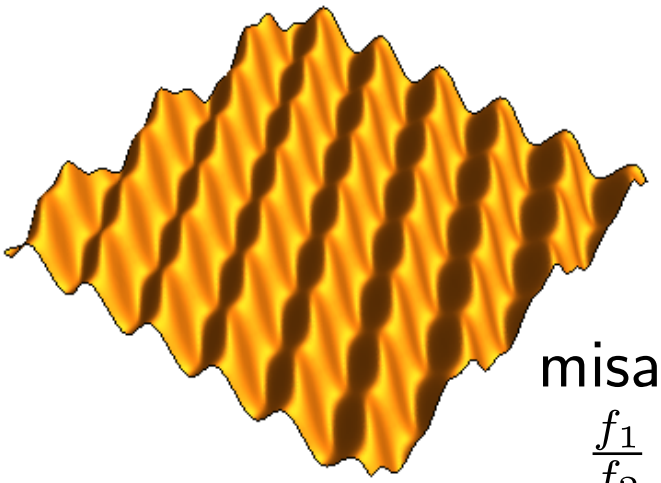
Axion Alignment Mechanism with Higher Harmonics

- two-axion model

  Kim, Nilles, Peloso, JCAP 01 (2005)

$$\eta(\mathrm{T}) = \mathrm{e}^{-\pi \mathrm{T}/12} - \mathrm{e}^{-25\pi \mathrm{T}/12} + \ldots$$

$$\mathrm{V} = \Lambda_1^4 \left[1 - \cos\left(\frac{\varphi_1}{\mathrm{f}_1} + \frac{\varphi_2}{\mathrm{f}_2}\right)\right] \times \mathcal{F}_1 + \Lambda_2^4 \left[1 - \cos\left(\frac{\varphi_1}{\mathrm{g}_1} + \frac{\varphi_2}{\mathrm{g}_2}\right)\right] \times \mathcal{F}_2$$



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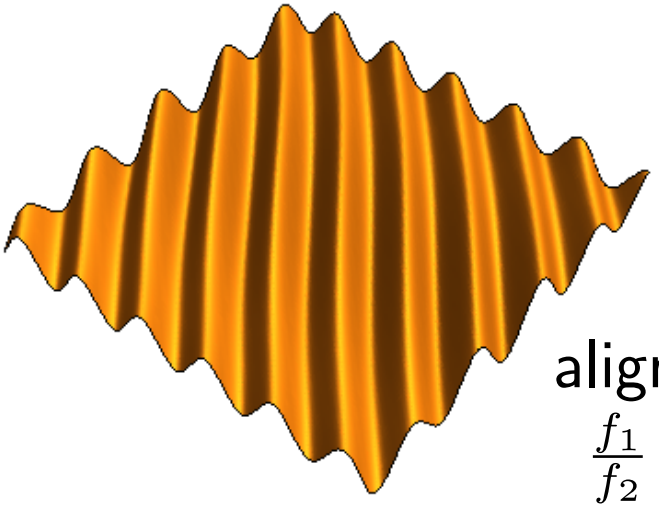

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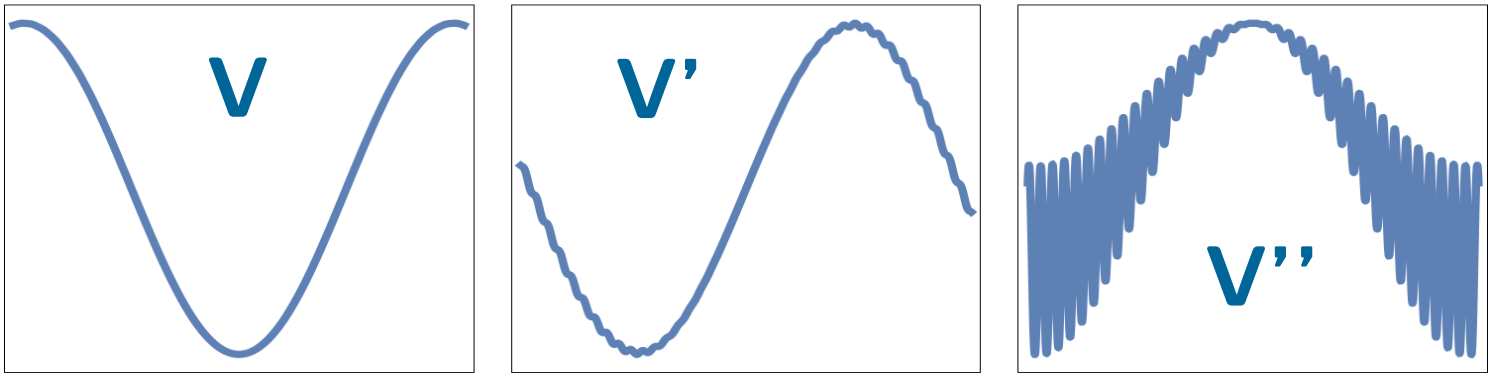
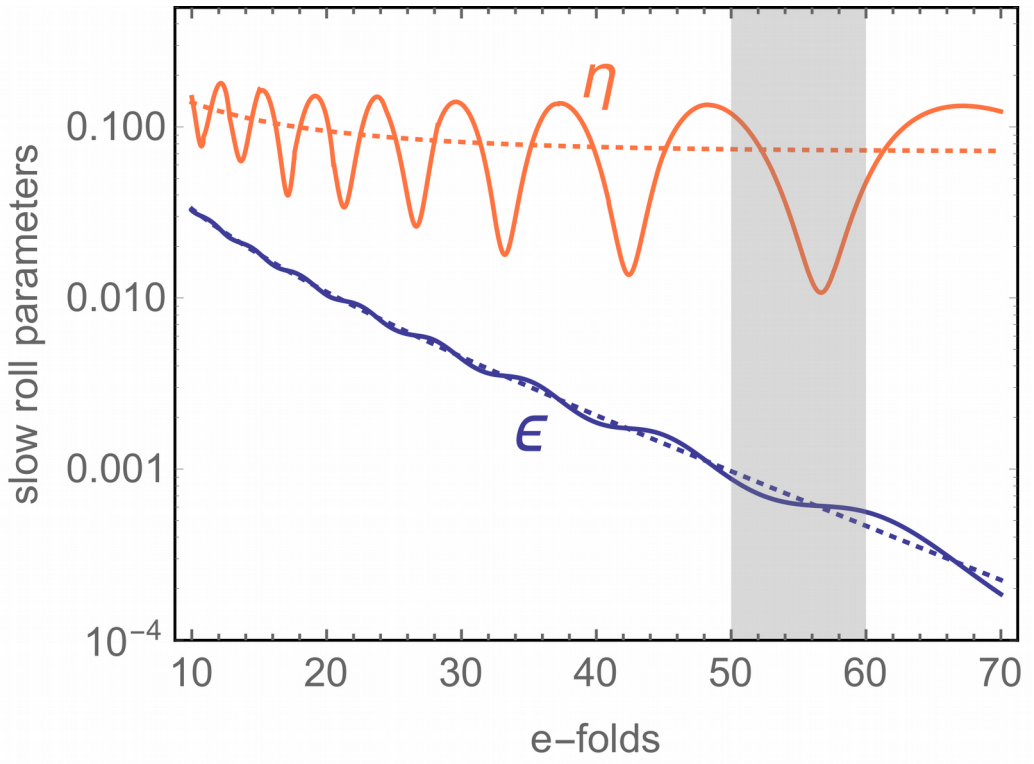
- integrate out

$$\mathrm{V} \simeq \Lambda^4 \left(1 - \cos\frac{\varphi}{\mathrm{f}}\right) \times \left(1 - \delta \cos\frac{\varphi}{\mathrm{f}_{\mathrm{mod}}}\right) \qquad \mathrm{f} \propto \frac{1}{\mathrm{f}_1\mathrm{g}_2 - \mathrm{g}_1\mathrm{f}_2} > 1$$

Modulations





- slow roll parameters
- CMB observables

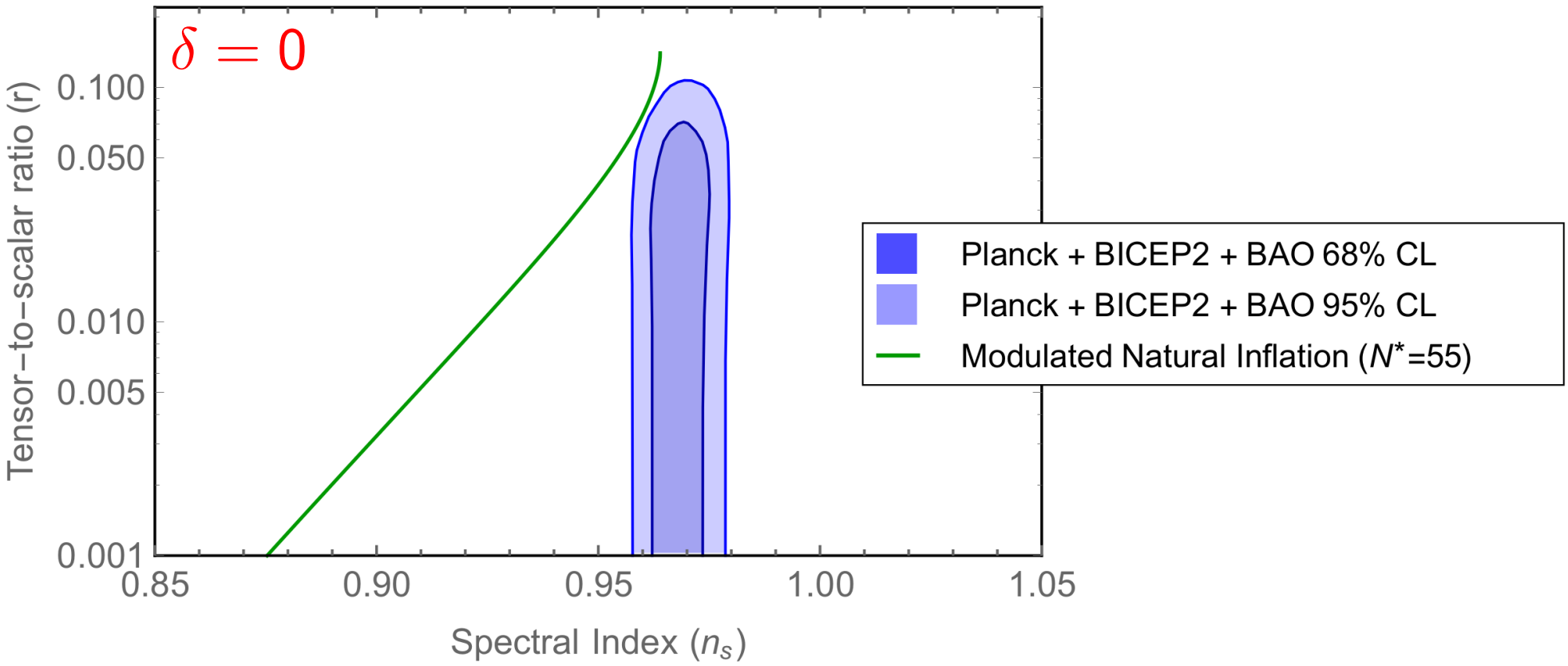
$$r \simeq 16\epsilon$$

$$n_s \simeq 1 - 4\epsilon + 2\eta$$

modulations mainly affect n_s

other inflation models with higher harmonics: Abe, Kobayashi, Otsuka, JHEP 04 (2015), Higaki, Takahashi, JHEP 03 (2015)

CMB Observables



$$V = \Lambda^4 \left(1 - \cos\frac{\varphi}{f}\right) \times \left(1 - \delta\, \cos\frac{\varphi}{f_{mod}}\right) \qquad f_{mod} = 0.1\, M_P$$

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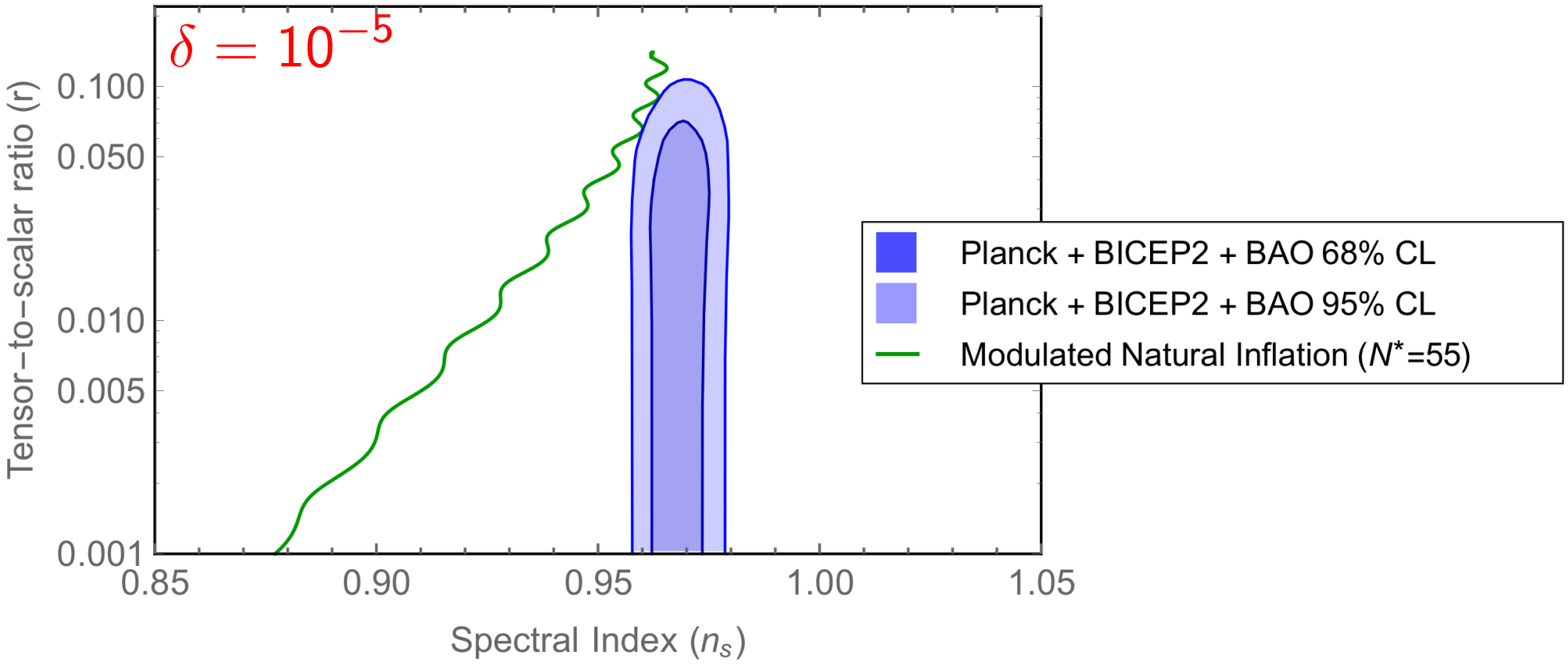

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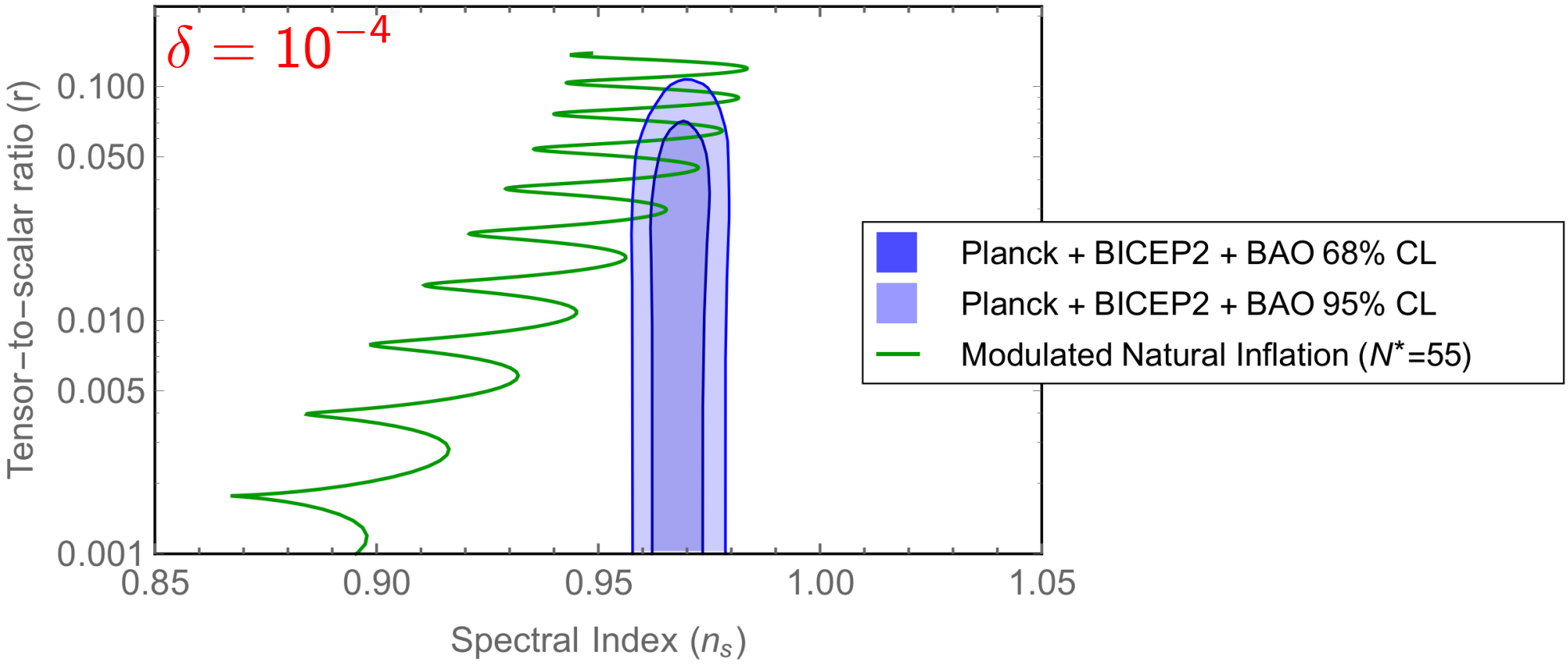

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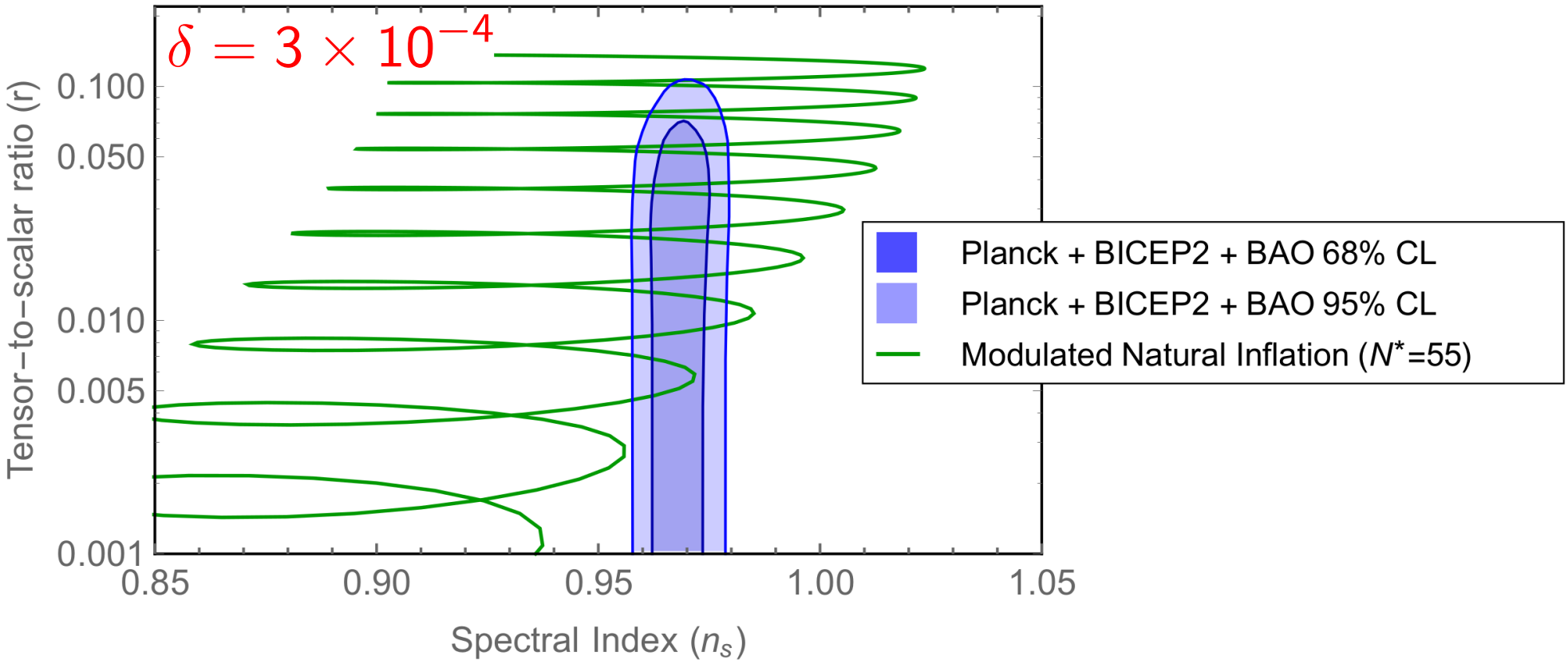

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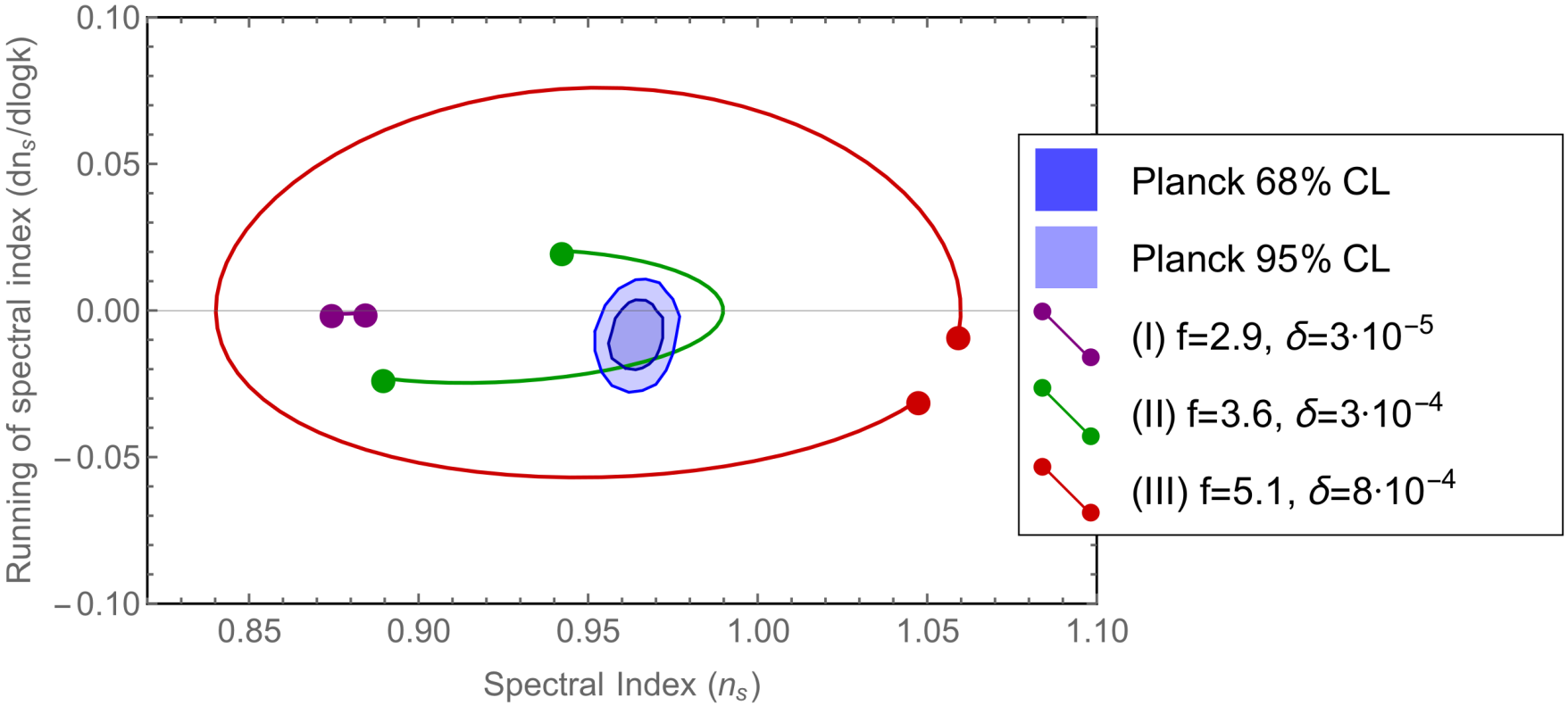
Running of the Spectral Index

- in string/supergravity model modulations grow with increasing f



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- observable tensor modes predicted r $\sim$ 0.001 – 0.05

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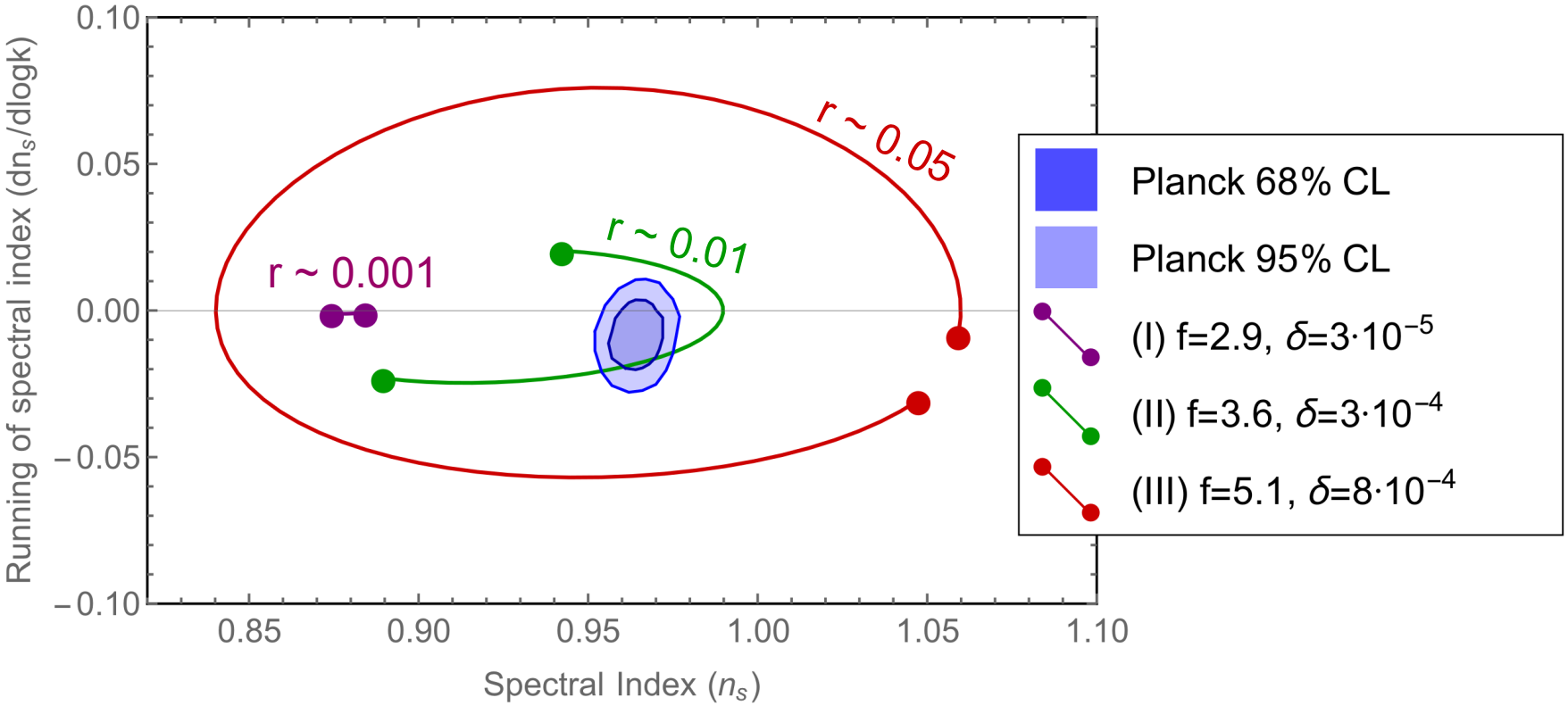

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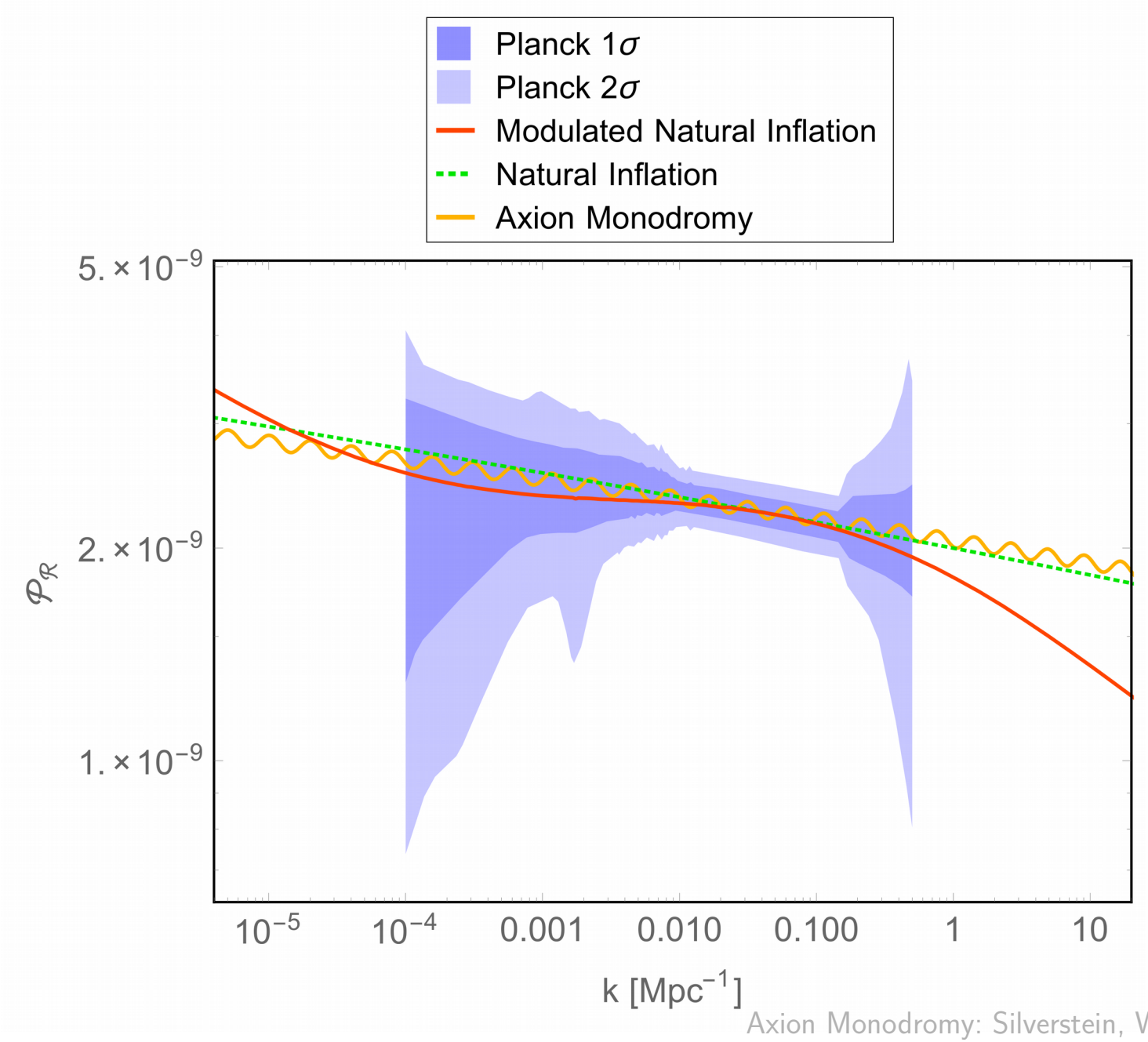
Primordial Scalar Power Spectrum



Axion Monodromy: Silverstein, Westphal, Phys.Rev. D78 (2008)

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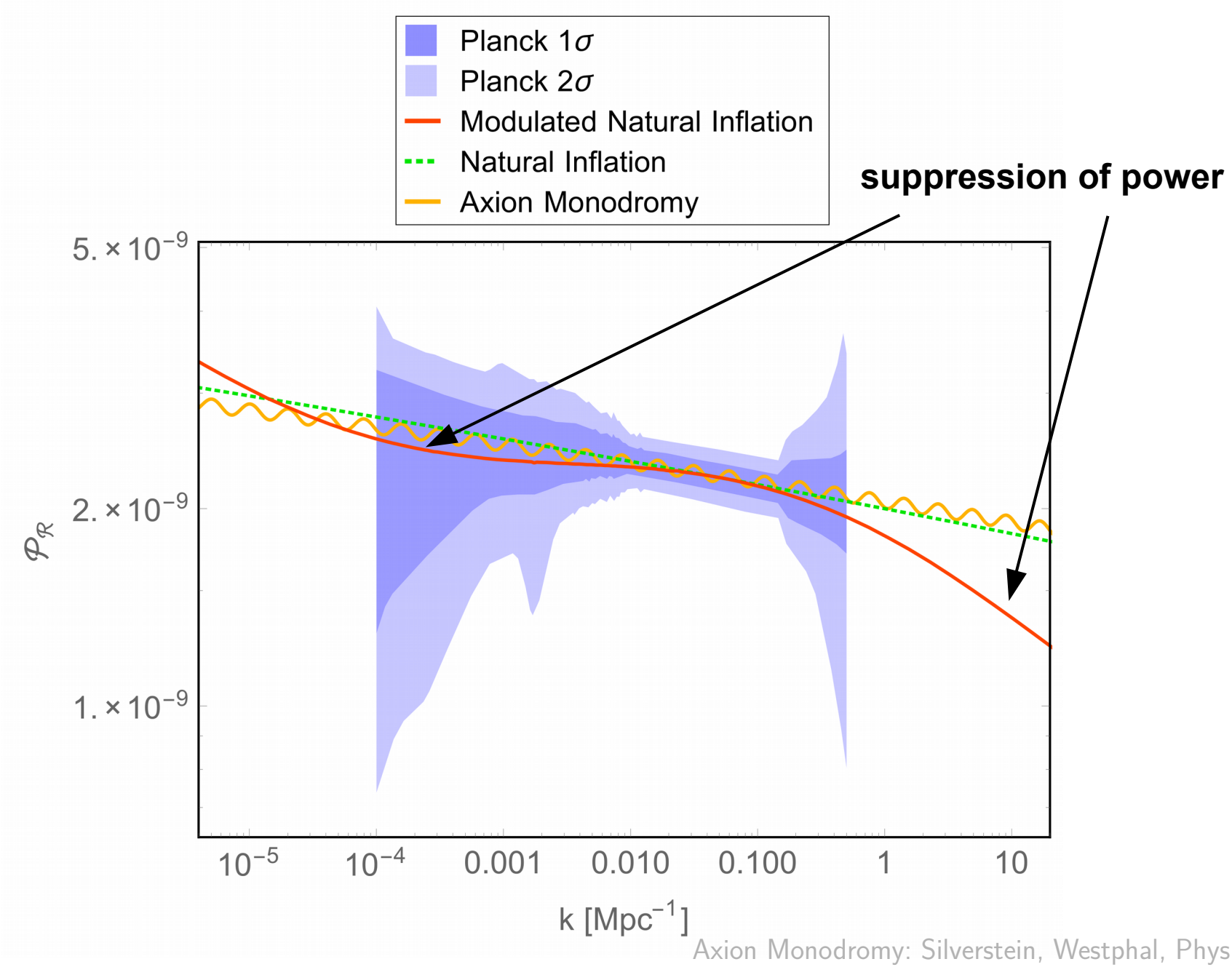

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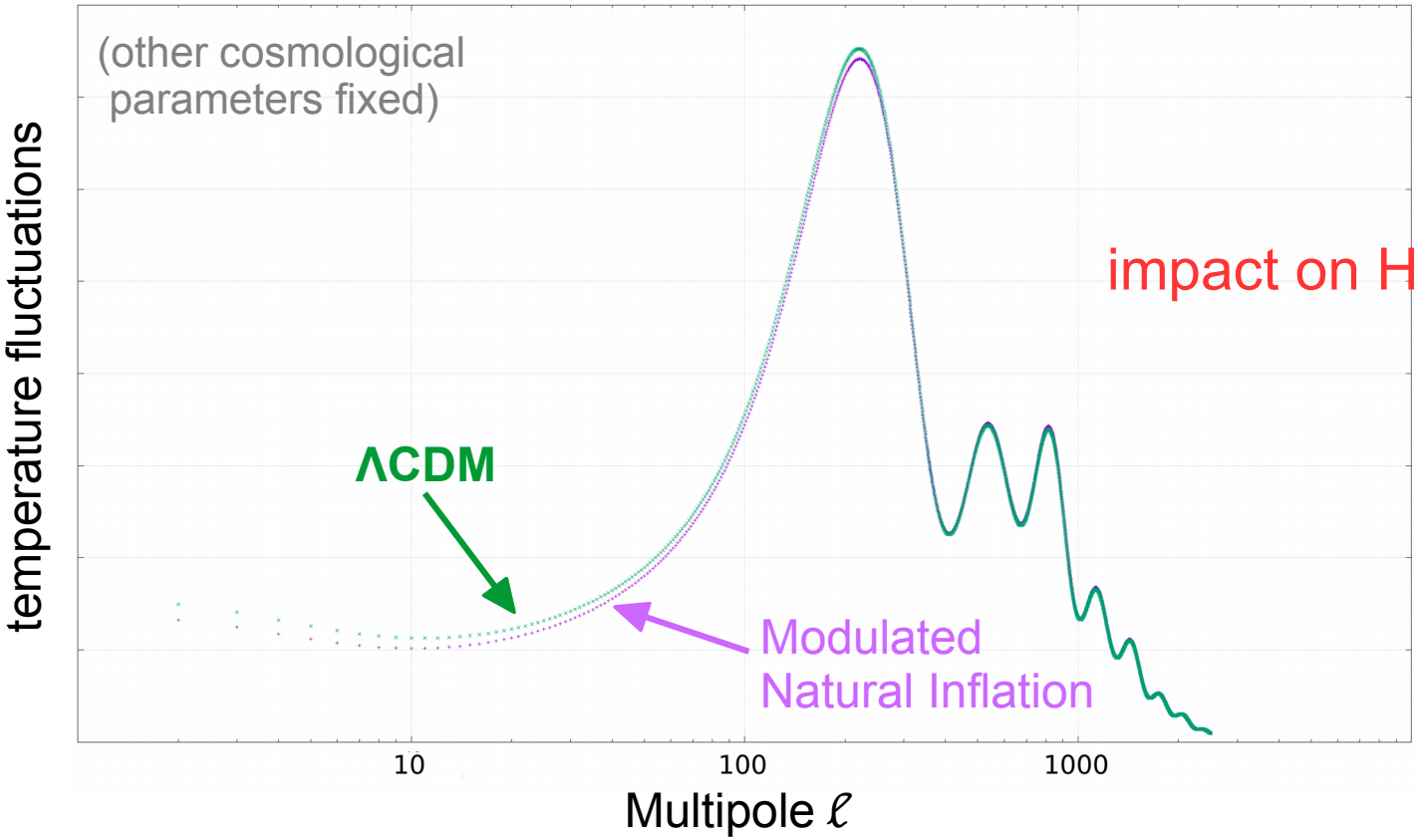
CMB Temperature Power Spectrum



impact on H_0, m_ν , ...?

- small scale suppression hardly visible in CMB power spectrum
- suppressed μ-distortion in CMB

PIXIE

Conclusion

- in string realization of natural inflation higher harmonics cause modulations on the potential

- this leads to a primordial power spectrum which is observationally distinguishable from ΛCDM

Backup Slides

Model

- instanton-induced coupling between matter fields ψ_i

$$W = \psi_1\psi_2\psi_3 \cdot \eta^n(T) + \psi_1\psi_4\psi_5 \qquad (\psi_{2\ldots4} \text{ get vev})$$

T: Kähler modulus, $\eta(T) = e^{-\pi T/12}(1 - e^{-2\pi T} + \ldots)$

- resulting potential for $T = T_0 + \chi + i\varphi$

$$V \simeq \Lambda^4 \frac{e^{-\chi/f}}{T_0 + \chi}\left(\cosh\left[\frac{\chi}{f}\right] - \cos\left[\frac{\varphi}{f}\right]\right) \qquad f = \frac{6\sqrt{2}}{n\pi T_0}$$

The Weak Gravity Conjecture

- U(1) gauge symmetry requires particle with $q/m > 1$

  Arkani-Hamed, Motl, Nicolis, Vafa, JHEP 06 (2007)

- two U(1)s: convex hull of vectors $\left(\frac{q_1}{m}, \frac{q_2}{m}\right)$ must contain unit ball

- axion related to U(1) via chain of dualities $q \to f^{-1}$, $m \to S$

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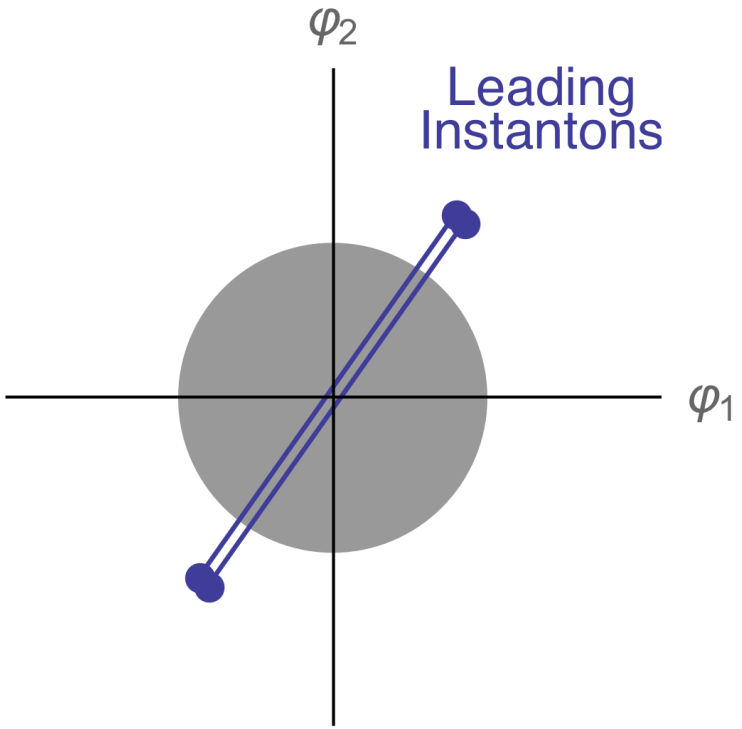

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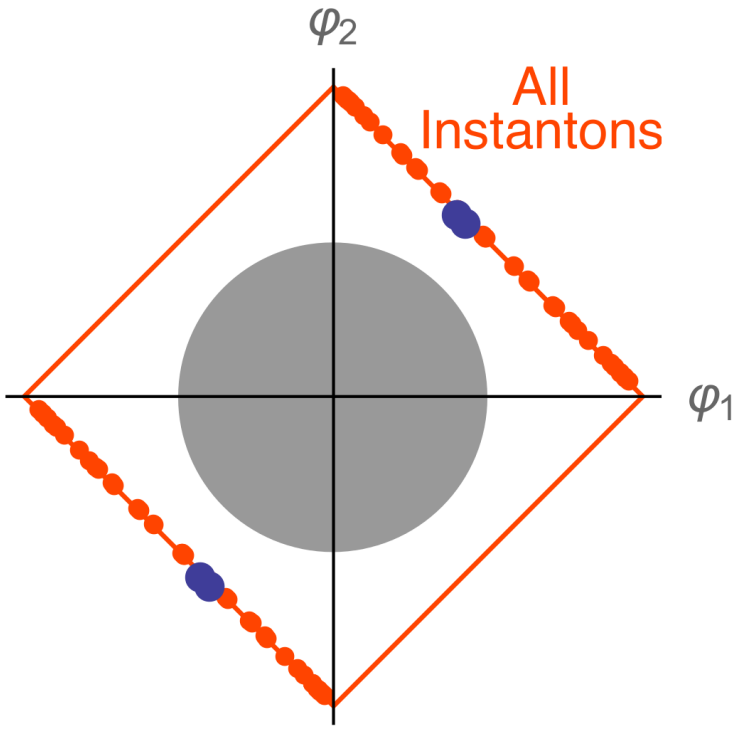

- alignment mechanism seems to violate convex hull condition
- resolved by subleading instantons

$$\eta(T) = e^{-\pi T/12}(1 - e^{-2\pi T} + \dots)$$