A Step in Flux to Suppress Axion Isocurvature

Priyesh Chakraborty, Junyi Cheng, Matthew Reece, **Zekai Wang**

arXiv:2507.12519. JHEP 03 (2026) 046

Phenomenology 2026 Symposium - University of Pittsburgh

Outline

1. **Motivation** — Extradimensional pre-inflation QCD axion and the isocurvature tension
2. **Mechanism** — Monodromy mass from Chern-Simons coupling, flux step cosmology
3. **Predictions** — Broken-power-law isocurvature, new viable parameter region
4. **Conclusions**

The QCD axion: strong CP and dark matter

- Strong CP problem: neutron EDM experiment (Abel et al. '20) $|\theta_{\rm QCD}| \lesssim 10^{-10}$.

The QCD axion: strong CP and dark matter

- Strong CP problem: neutron EDM experiment (Abel et al. '20) $|\theta_{\mathrm{QCD}}| \lesssim 10^{-10}$.
- Axion introduces a dynamical field $\theta(x)$ (Peccei & Quinn '77; Weinberg '78; Wilczek '78);

$$\mathcal{S} \supset \int \frac{1}{2} f_a^2 \, |\mathrm{d}\theta|^2 + \frac{\theta(x) - \bar{\theta}}{8\pi^2} \, \mathrm{tr}(G \wedge G)$$

The QCD axion: strong CP and dark matter

- Strong CP problem: neutron EDM experiment (Abel et al. '20) $|\theta_{\mathrm{QCD}}| \lesssim 10^{-10}$.
- Axion introduces a dynamical field $\theta(x)$ (Peccei & Quinn '77; Weinberg '78; Wilczek '78);

$$\mathcal{S} \supset \int \frac{1}{2} f_a^2 \, |\mathrm{d}\theta|^2 + \frac{\theta(x) - \bar{\theta}}{8\pi^2} \mathrm{tr}(G \wedge G)$$

- Axion dark matter is produced by the misalignment mechanism (Preskill-Wise-Wilczek; Abbott-Sikivie; Dine-Fischler '83); Relic density:

$$\Omega_a h^2 \approx 0.12 \, \theta_i^2 \left(\frac{f_a}{0.8 \times 10^{12}\,\mathrm{GeV}} \right)^{7/6}.$$

The QCD axion: strong CP and dark matter

- Strong CP problem: neutron EDM experiment (Abel et al. '20) $|\theta_{\rm QCD}| \lesssim 10^{-10}$.
- Axion introduces a dynamical field $\theta(x)$ (Peccei & Quinn '77; Weinberg '78; Wilczek '78);

$$\mathcal{S} \supset \int \frac{1}{2} f_a^2 \, |\mathrm{d}\theta|^2 + \frac{\theta(x) - \bar{\theta}}{8\pi^2} \, \mathrm{tr}(G \wedge G)$$

- Axion dark matter is produced by the misalignment mechanism (Preskill-Wise-Wilczek; Abbott-Sikivie; Dine-Fischler '83); Relic density:

$$\Omega_a h^2 \approx 0.12 \, \theta_i^2 \left(\frac{f_a}{0.8 \times 10^{12} \, \mathrm{GeV}} \right)^{7/6} .$$

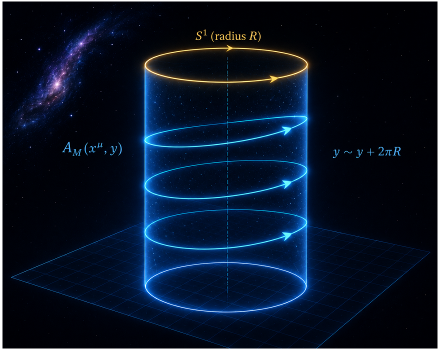
- Two-for-one: solves strong CP *and* good dark matter candidate.

Pre-inflation axions from extra dimensions

- In string theory constructions, axions arise as zero modes of higher-form gauge fields (Choi '03; Reece '24):

$$\theta(x) \;=\; \int_{\Sigma_p} C_p, \quad \text{e.g.} \int_0^{2\pi R} \mathrm{d}y\, A_5,$$

with $y \simeq y + 2\pi R$.

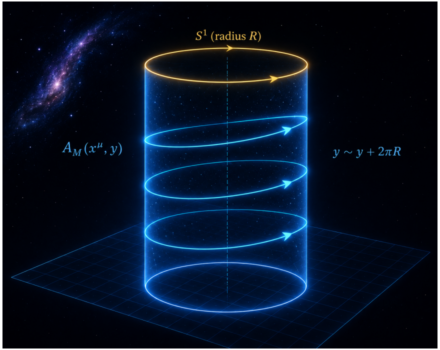


Pre-inflation axions from extra dimensions

- In string theory constructions, axions arise as zero modes of higher-form gauge fields (Choi '03; Reece '24):

$$\theta(x) = \int_{\Sigma_p} C_p, \quad \text{e.g.} \int_0^{2\pi R} \mathrm{d}y\, A_5,$$

  with $y \simeq y + 2\pi R$.
- Exponentially good quality in general $\sim \mathrm{e}^{-mR}$.

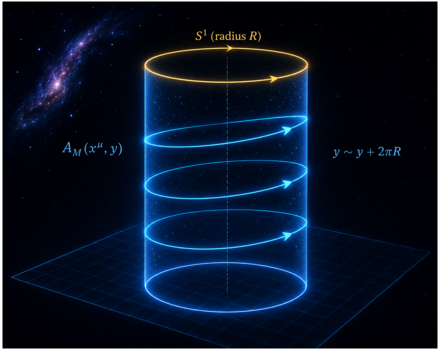


Pre-inflation axions from extra dimensions

- In string theory constructions, axions arise as zero modes of higher-form gauge fields (Choi '03; Reece '24):

$$\theta(x) = \int_{\Sigma_p} C_p, \quad \text{e.g.} \int_0^{2\pi R} \mathrm{d}y \, A_5,$$

  with $y \simeq y + 2\pi R$.
- Exponentially good quality in general $\sim \mathrm{e}^{-mR}$.
- Manifestly pre-inflation axion. No PQ symmetry, no symmetry breaking.

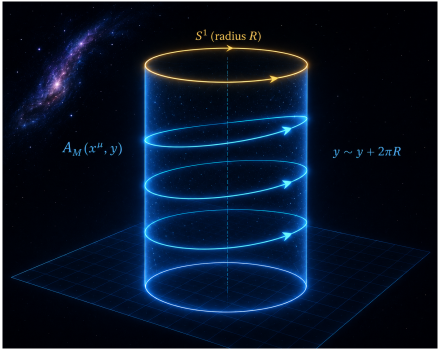


Pre-inflation axions from extra dimensions

- In string theory constructions, axions arise as zero modes of higher-form gauge fields (Choi '03; Reece '24):

$$\theta(x) = \int_{\Sigma_p} C_p, \quad \text{e.g.} \int_0^{2\pi R} \mathrm{d}y\, A_5,$$

  with $y \simeq y + 2\pi R$.
- Exponentially good quality in general $\sim \mathrm{e}^{-mR}$.
- Manifestly pre-inflation axion. No PQ symmetry, no symmetry breaking.
- Pre-inflation axion + high-scale inflation $\Rightarrow$ *isocurvature tension*.



The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.

The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.
- A pre-inflation axion with $m_a \ll H_I$ during inflation acquires fluctuations, which is tightly constrained by CMB (Planck '20):

$$\beta_{\rm iso}^{(\rm axion)} = \left(\frac{\Omega_a}{\Omega_c}\right)^2 \frac{1}{A_s} \frac{H_I^2}{\pi^2 f_I^2 \langle \theta_i^2 \rangle} < 0.038$$

The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.
- A pre-inflation axion with $m_a \ll H_I$ during inflation acquires fluctuations, which is tightly constrained by CMB (Planck '20):

$$\beta_{\rm iso}^{\rm (axion)} = \left(\frac{\Omega_a}{\Omega_c}\right)^2 \frac{1}{A_s} \frac{H_I^2}{\pi^2 f_I^2 \langle \theta_i^2 \rangle} < 0.038$$

- Axion not overproduce dark matter constraints:

$$H_I < \left(\frac{f_I}{\theta_i f_a}\right) \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{-0.165} 2.5 \times 10^7 \mathrm{GeV}$$

The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.
- A pre-inflation axion with $m_a \ll H_I$ during inflation acquires fluctuations, which is tightly constrained by CMB (Planck '20):

$$\beta_{\rm iso}^{\rm (axion)} = \left(\frac{\Omega_a}{\Omega_c}\right)^2 \frac{1}{A_s} \frac{H_I^2}{\pi^2 f_I^2 \langle \theta_i^2 \rangle} < 0.038$$

- Axion not overproduce dark matter constraints:

$$H_I < \left(\frac{f_I}{\theta_i f_a}\right) \left(\frac{f_a}{10^{12}{\rm GeV}}\right)^{-0.165} 2.5 \times 10^7 {\rm GeV}$$

- Two unappealing escapes:

The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.
- A pre-inflation axion with $m_a \ll H_I$ during inflation acquires fluctuations, which is tightly constrained by CMB (Planck '20):

$$\beta_{\rm iso}^{\rm (axion)} = \left(\frac{\Omega_a}{\Omega_c}\right)^2 \frac{1}{A_s} \frac{H_I^2}{\pi^2 f_I^2 \langle \theta_i^2 \rangle} < 0.038$$

- Axion not overproduce dark matter constraints:

$$H_I < \left(\frac{f_I}{\theta_i f_a}\right) \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{-0.165} 2.5 \times 10^7\,\mathrm{GeV}$$

- Two unappealing escapes:
  - Lower $H_I \Rightarrow$ In tension with most inflation model, indicate more fine tunning (Linde '85; East et al. '15).

The axion isocurvature tension

- Isocurvature perturbations are fluctuations *uncorrelated* to the adiabatic perturbation — relative density variations between species.
- A pre-inflation axion with $m_a \ll H_I$ during inflation acquires fluctuations, which is tightly constrained by CMB (Planck '20):

$$\beta_{\rm iso}^{(\rm axion)} = \left(\frac{\Omega_a}{\Omega_c}\right)^2 \frac{1}{A_s} \frac{H_I^2}{\pi^2 f_I^2 \langle \theta_i^2 \rangle} < 0.038$$

- Axion not overproduce dark matter constraints:

$$H_I < \left(\frac{f_I}{\theta_i f_a}\right) \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{-0.165} 2.5 \times 10^7 \mathrm{GeV}$$

- Two unappealing escapes:
  - Lower H_I $\Rightarrow$ In tension with most inflation model, indicate more fine tunning (Linde '85; East et al. '15).
  - Smaller θ_i $\Rightarrow$ Fine tuning of initial condition.

Idea: monodromy mass from a CS coupling

- Chern-Simons couple to a 4-form field strength $F_4 = dA_3$ (Kaloper-Sorbo '09; Kaloper-Lawrence-Sorbo '11):

$$\mathcal{S} \supset -\int \frac{n}{2\pi} (\theta - \theta_0) F_4 - \frac{1}{2e_A^2} |F_4|^2 .$$

Idea: monodromy mass from a CS coupling

- Chern-Simons couple to a 4-form field strength $F_4 = dA_3$ (Kaloper-Sorbo '09; Kaloper-Lawrence-Sorbo '11):

$$\mathcal{S} \supset -\int \frac{n}{2\pi} (\theta - \theta_0) F_4 - \frac{1}{2e_A^2} |F_4|^2.$$

- Dualizing F_4 generates a quantized monodromy mass for axion:

$$V_{\text{eff}}(\theta, j) = \frac{1}{2} m_\theta^2 f_a^2 \left(\theta - \theta_0 - \frac{2\pi j}{n}\right)^2, \qquad m_\theta = \frac{n e_A}{2\pi f_a}, \qquad n \in \mathbb{Z}.$$

Idea: monodromy mass from a CS coupling

- Chern-Simons couple to a 4-form field strength $F_4 = dA_3$ (Kaloper-Sorbo '09; Kaloper-Lawrence-Sorbo '11):

$$\mathcal{S} \supset -\int \frac{n}{2\pi}(\theta - \theta_0)\, F_4 - \frac{1}{2e_A^2}|F_4|^2.$$

- Dualizing F_4 generates a quantized monodromy mass for axion:

$$V_{\text{eff}}(\theta, j) = \frac{1}{2} m_\theta^2 f_a^2 \left(\theta - \theta_0 - \frac{2\pi j}{n}\right)^2, \qquad m_\theta = \frac{n e_A}{2\pi f_a}, \qquad n \in \mathbb{Z}.$$

- Heavy axion during inflation suppresses isocurvature when $e_A \gg f_a H_I$.

Idea: monodromy mass from a CS coupling

- Chern-Simons couple to a 4-form field strength $F_4 = dA_3$ (Kaloper-Sorbo '09; Kaloper-Lawrence-Sorbo '11):

$$\mathcal{S} \supset -\int \frac{n}{2\pi}(\theta - \theta_0)\, F_4 - \frac{1}{2e_A^2}|F_4|^2.$$

- Dualizing F_4 generates a quantized monodromy mass for axion:

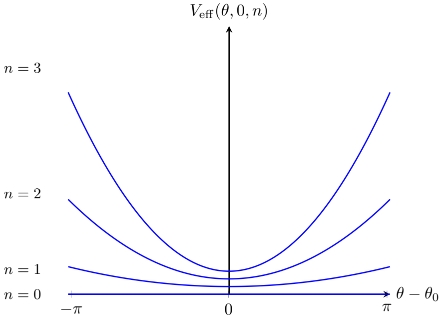
$$V_{\text{eff}}(\theta, j) = \frac{1}{2} m_\theta^2 f_a^2 \left(\theta - \theta_0 - \frac{2\pi j}{n}\right)^2, \qquad m_\theta = \frac{n e_A}{2\pi f_a}, \qquad n \in \mathbb{Z}.$$

- Heavy axion during inflation suppresses isocurvature when $e_A \gg f_a H_I$.
- To solve strong CP we need vanishing monodromy mass today. Make n a *dynamical integer*.

$B2$-branes step the flux $n: 1 \to 0$

- Take n as the electric flux of another 3-form gauge field B_3: $n \sim -\frac{1}{e_B^2} * \mathrm{d}B_3$

$$S \supset -\int \frac{1}{2e_B^2} \left|\mathrm{d}B_3 - \frac{1}{2\pi}(\theta - \theta_0) F_4\right|^2$$

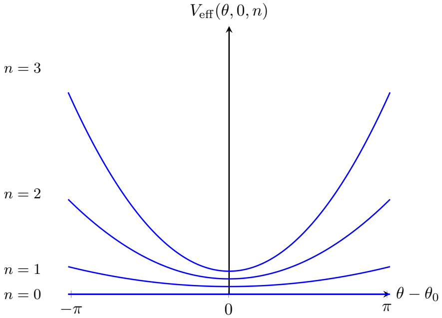


$B2$-branes step the flux $n : 1 \to 0$

- Take n as the electric flux of another 3-form gauge field B_3: $n \sim -\frac{1}{e_B^2} * \mathrm{d}B_3$

$$S \supset -\int \frac{1}{2e_B^2}\left|\mathrm{d}B_3 - \frac{1}{2\pi}(\theta - \theta_0)F_4\right|^2$$

- n changes across objects carry electric charge under B_3, these are $B2$-branes (Domain Walls).

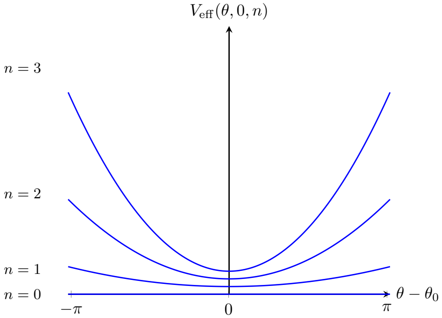


$B2$-branes step the flux $n : 1 \to 0$

- Take n as the electric flux of another 3-form gauge field B_3: $n \sim -\frac{1}{e_B^2} * \mathrm{d}B_3$

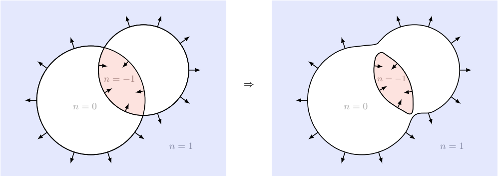
$$S \supset -\int \frac{1}{2e_B^2}\left|\mathrm{d}B_3 - \frac{1}{2\pi}(\theta-\theta_0)F_4\right|^2$$

- n changes across objects carry electric charge under B_3, these are $B2$-branes (Domain Walls).
- Energy of B_3 field $\propto n^2$ and possibly other n-dependent contribution in axion effective potential $V_{\text{eff}}(\theta, j, n)$.



First-order phase transition by bubble nucleation

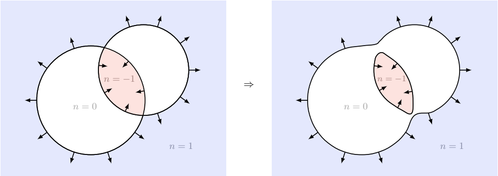
- First order phase transition with decay rate $\Gamma = A\, e^{-B}$.(Coleman '77; Coleman & De Luccia '80)



Strong CP solved; misalignment turns on at QCD scale to make DM. $\theta_i \approx |\theta_0 - \bar{\theta}|$

First-order phase transition by bubble nucleation

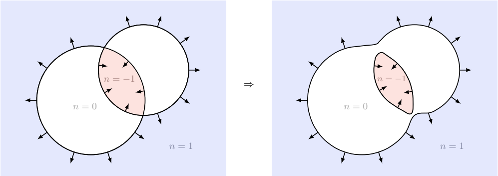
- First order phase transition with decay rate $\Gamma = A\,e^{-B}$.(Coleman '77; Coleman & De Luccia '80)
- During inflation: $n = 1 \Rightarrow$ heavy axion, fluctuations frozen out.



Strong CP solved; misalignment turns on at QCD scale to make DM. $\theta_i \approx |\theta_0 - \bar{\theta}|$

First-order phase transition by bubble nucleation

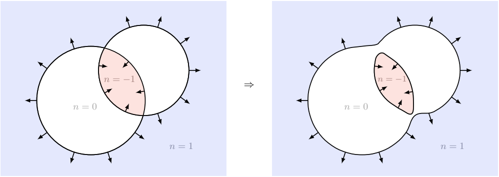
- First order phase transition with decay rate $\Gamma = A\, e^{-B}$.(Coleman '77; Coleman & De Luccia '80)
- During inflation: $n = 1 \Rightarrow$ heavy axion, fluctuations frozen out.
- After transition: $n = 0$ *exactly*. $\Rightarrow$ Mass is quantized — no fine-tuning.



Strong CP solved; misalignment turns on at QCD scale to make DM. $\theta_i \approx |\theta_0 - \bar{\theta}|$

First-order phase transition by bubble nucleation

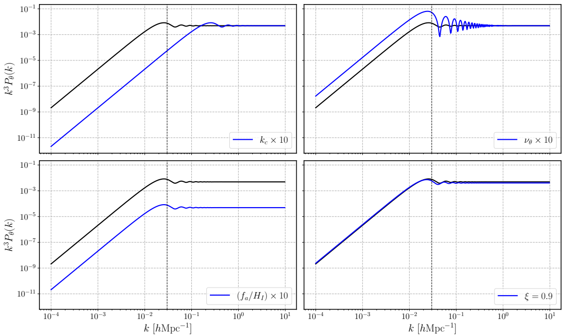
- First order phase transition with decay rate $\Gamma = A\, e^{-B}$.(Coleman '77; Coleman & De Luccia '80)
- During inflation: $n = 1 \Rightarrow$ heavy axion, fluctuations frozen out.
- After transition: $n = 0$ *exactly*. $\Rightarrow$ Mass is quantized — no fine-tuning.
- Tune inflaton coupling:
  $\Gamma(t_i) \ll H_I^4, \qquad \Gamma(t_f) \sim H_I^4.$



Strong CP solved; misalignment turns on at QCD scale to make DM. $\theta_i \approx |\theta_0 - \bar{\theta}|$

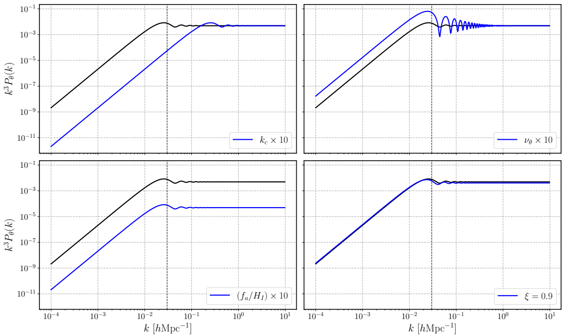
Isocurvature spectrum: a broken power law

- Modes that exit before the transition see a *heavy* axion — isocurvature suppressed.



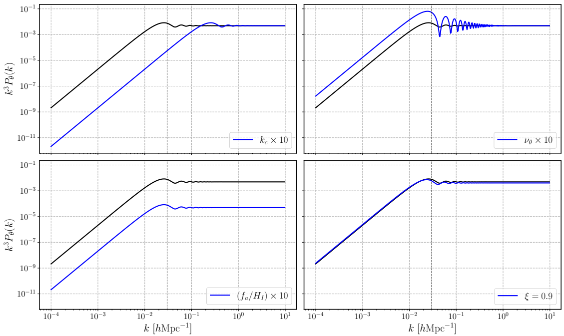
Isocurvature spectrum: a broken power law

- Modes that exit before the transition see a *heavy* axion — isocurvature suppressed.
- Modes that exit afterwards see a *massless* axion — Generate large isocurvature.



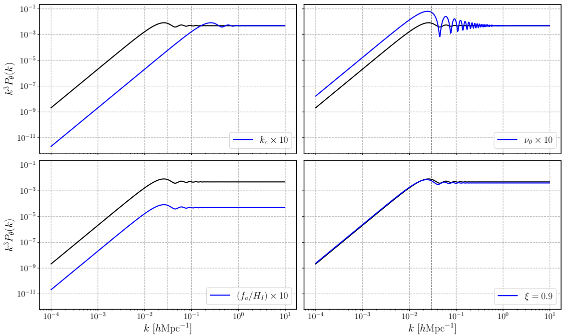
Isocurvature spectrum: a broken power law

- Modes that exit before the transition see a *heavy* axion — isocurvature suppressed.
- Modes that exit afterwards see a *massless* axion — Generate large isocurvature.
- Result: broken power-law isocurvature.



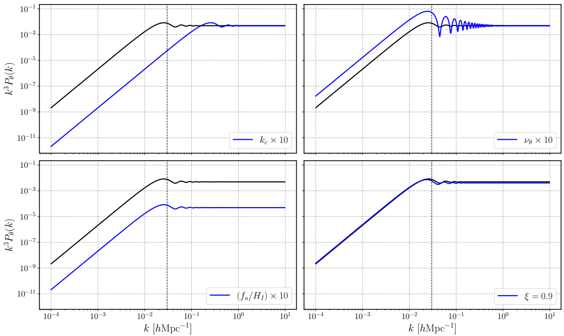
Isocurvature spectrum: a broken power law

- Modes that exit before the transition see a *heavy* axion — isocurvature suppressed.
- Modes that exit afterwards see a *massless* axion — Generate large isocurvature.
- Result: broken power-law isocurvature.
  - Suppressed at CMB scales.

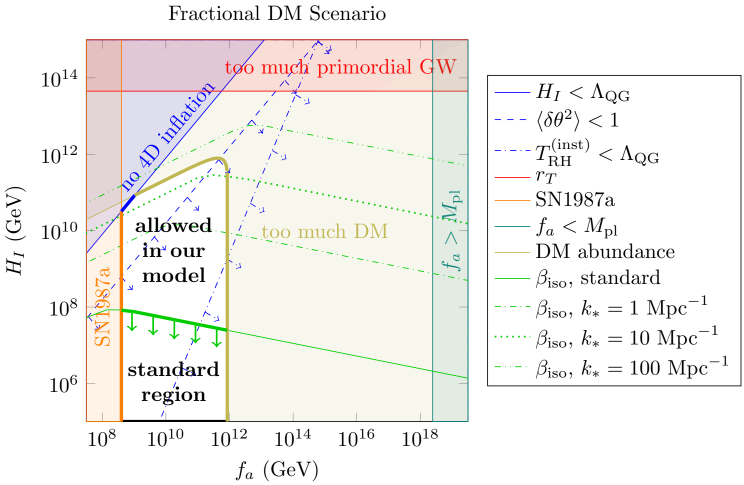


Isocurvature spectrum: a broken power law

- Modes that exit before the transition see a *heavy* axion — isocurvature suppressed.
- Modes that exit afterwards see a *massless* axion — Generate large isocurvature.
- Result: broken power-law isocurvature.
  - Suppressed at CMB scales.
  - Possible signal at *small scales*.



Result: new viable region in (f_a, H_I)



Conclusions

- Extradimensional pre-inflation QCD axion + high-scale inflation are *compatible* via a quantized monodromy mass.
- Mechanism is quantized: a $B2$-brane bubble transition steps $n : 1 \to 0$ *exactly* — no tuning, strong CP problem solved.
- Predicts a broken power-law isocurvature spectrum — suppressed at CMB scales, potentially observable at small scales.
- Opens a large new viable region in the (f_a, H_I) parameter space.