High-Scale Axions without Isocurvature from Inflationary Dynamics

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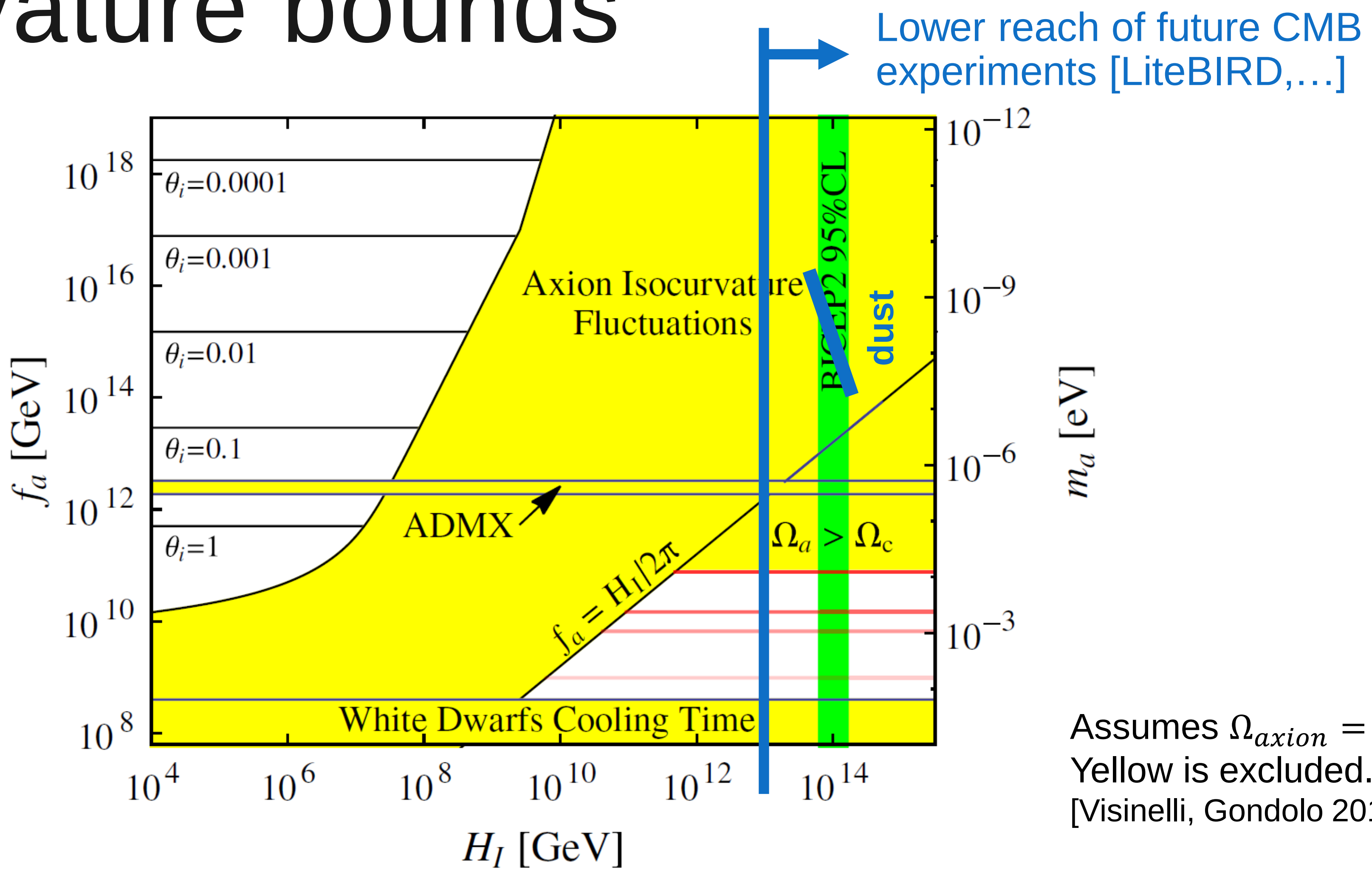
The axion

- Solution to the strong CP problem
- Can make up dark matter
- Pseudo-Nambu Goldstone boson of a spontaneously broken PQ symmetry with breaking scale f_a
  For concreteness, will consider a $U(1)_{PQ}$ symmetry

$$S = \frac{1}{\sqrt{2}} (\sigma + f) \exp\left[\frac{ia}{f}\right]$$

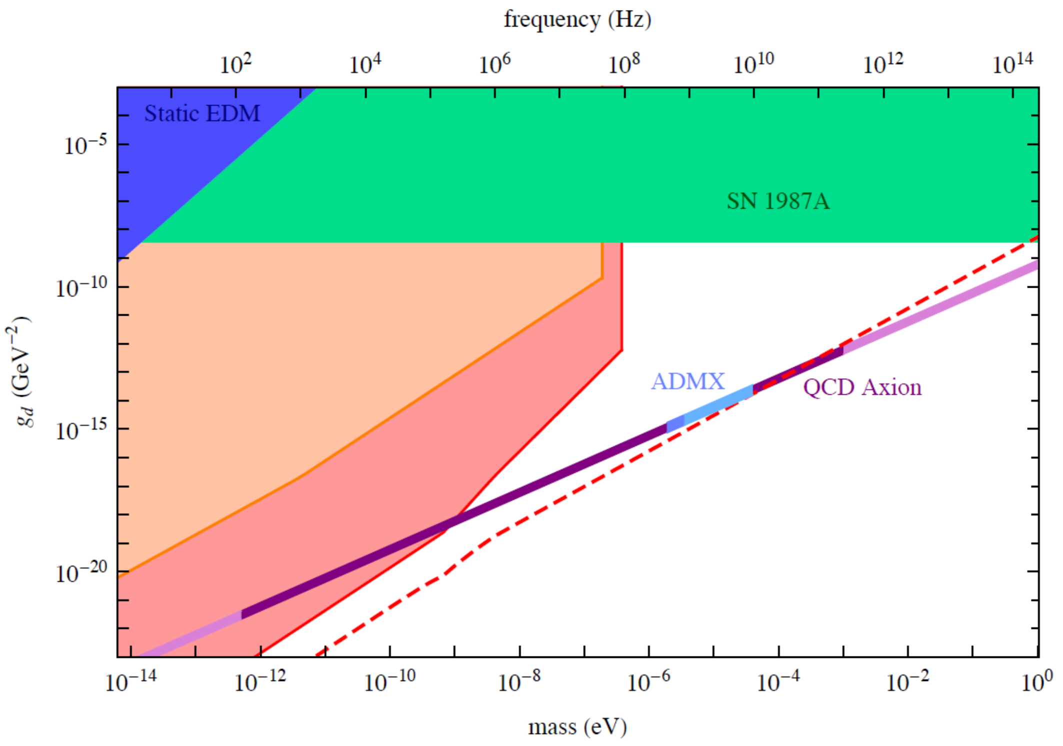
- If the PQ symmetry is broken before inflation ends ($f_a > \frac{H_I}{2\pi}$), the massless axion will have isocurvature fluctuations ($\delta a \sim \frac{H_I}{2\pi}$).

Isocurvature bounds

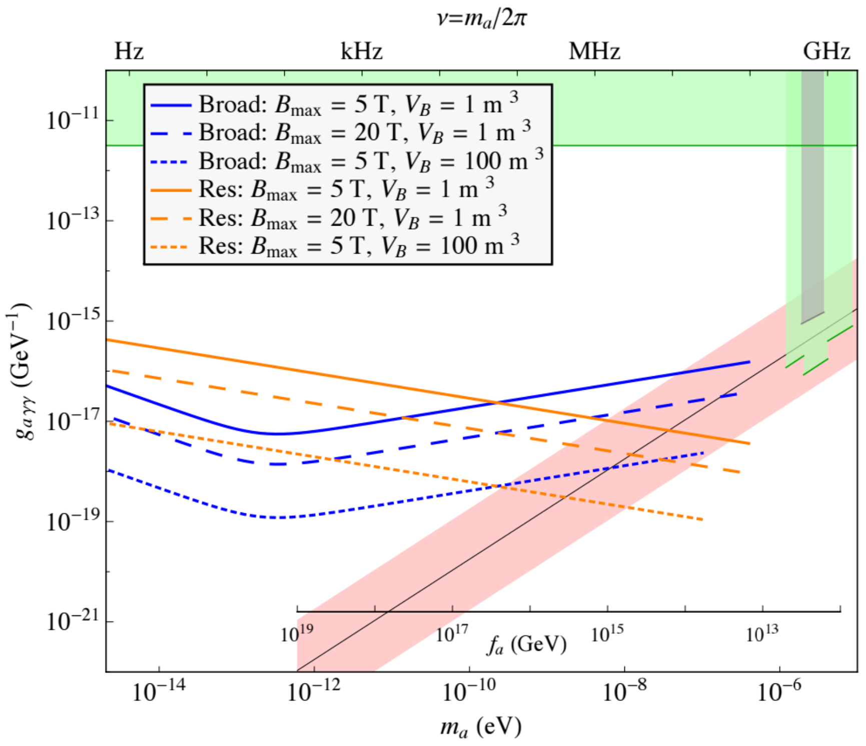


Assumes $\Omega_{axion} = \Omega_{CDM}$.
Yellow is excluded.
[Visinelli, Gondolo 2014]

Proposed axion searches at large f_a



CASPEr
[Budker, Graham, Ledbetter, Rajendran, Sushkov 2013]



ABRACADABRA—small scale proof of concept in development
[Kahn, Safdi, Thaler 2016]

Avoiding isocurvature

Can isocurvature constraints be avoided so large/detectable H_I and large f_a are not mutually exclusive?

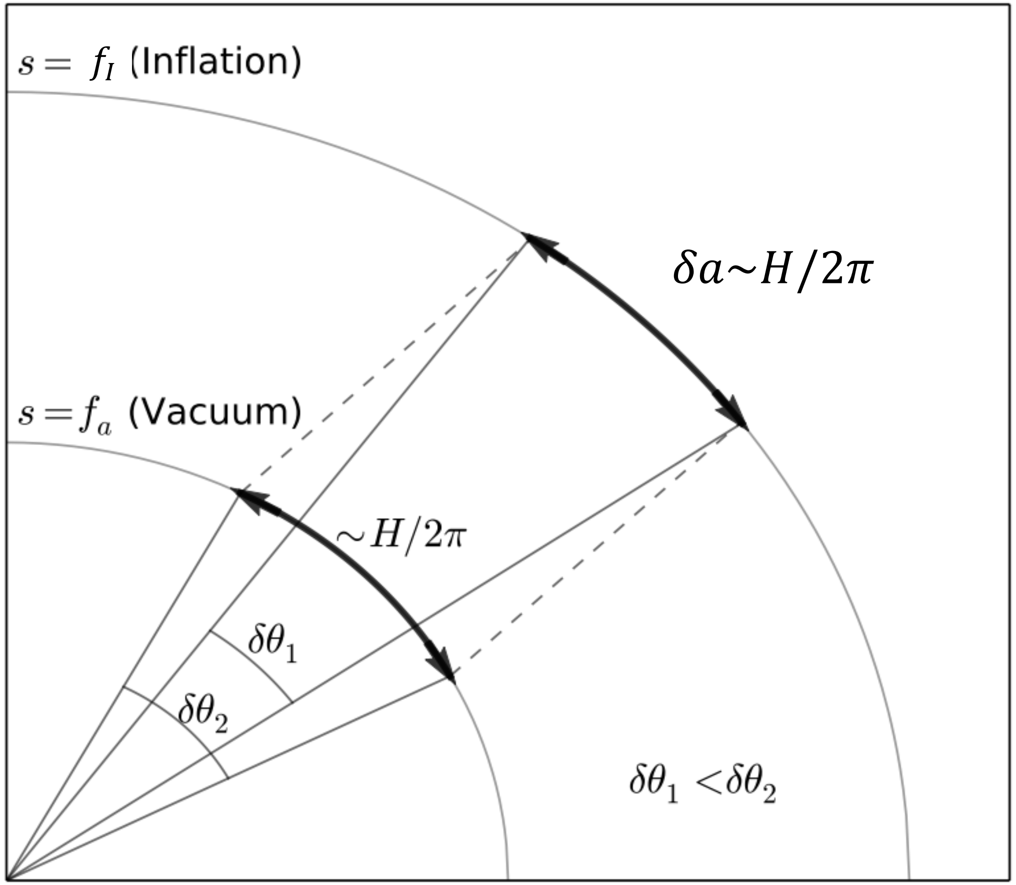
We revisit and clarify two approaches to reduce axion isocurvature:

1. Wave function renormalization—PQ breaking scale during inflation is much greater than today $(f_I \gg f_a)$
   [Lyth, Linde 1990-1; Higaki, Jeong, Takahashi 2014; Chun 2014; Fairbairn, Hogan, Marsh 2014]
2. Enhanced explicit PQ symmetry breaking during inflation ($m_a \gtrsim H_I$)
   [Dine, Anisimov 2004; Higaki, Jeong, Takahashi 2014]

Wave function renormalization

$f_I \gg f_a$

Wave function renormalization



[Fairbairn, Hogan, Marsh 2014]

Isocurvature fluctuations are reduced by a factor of (f_I/f_a).

CMB constraints on isocurvature require

$$\frac{f_I}{f_a} \gtrsim 1.4 \times 10^4 \sqrt{R_a \left(\frac{r}{.002}\right) \left(\frac{.0019}{\alpha_{\mathrm{iso,max}}}\right)} \left(\frac{10^{-1} M_P}{f_a}\right)^{5/12}$$

Note:

- Large hierarchy between f_I and f_a
- $f_I > M_P$ for $f_a > 4 \times 10^{-7} M_P$

R_a: axion dark matter fraction
α_{iso}: isocurvature parameter, bounded $< .0019$
r: tensor-to-scalar ratio, can be probed to .002 at near-future experiments

Parametric resonance constraints

After inflation, when H decreases sufficiently the radial field will oscillate about its minimum.

These oscillations can induce parametric resonance.

In particular, they will excite fluctuations in the axial field. If these fluctuations grow too large $(\sim f_a)$, topological defects form.

Topological defects lead to overclosure of the universe, so must be avoided.

Lattice simulations [Kawasaki, Yanagida, Yoshino 2013] indicate topological defects form if the initial oscillation amplitude is too large:

$$|S|_i \gtrsim 10^4 \left(\frac{f_a}{\sqrt{2}} \right)$$

Parametric resonance constraints

Cannot simultaneously suppress isocurvature and avoid topological defects for $f_a \lesssim 10^{-1} M_P$

Meanwhile, $f_a \gtrsim 10^{-1} M_P$ requires $f_I \gtrsim 100 M_P$. Likely to disrupt inflation.
(Problems may also arise in string theories [Banks, Dine, Fox Gorbatov 2003],
possibly related to the weak gravity conjecture [Arkani-Hamed, Motl, Nicolis, Vafa 2006]).

One way out: late-decaying scalar that dilutes the axion abundance.
Leads to new requirement

$$\frac{f_I}{f_a} \gtrsim 3.0 \times 10^3 \sqrt{R_a \left(\frac{r}{.002}\right)\left(\frac{.0019}{\alpha_{\rm iso,max}}\right)\left(\frac{T_{\rm RH}}{6\ {\rm MeV}}\right)}$$

Barely allowed for smallest detectable r and current α_{iso} bounds.

Aside 1: treating the radial field as the inflaton is similarly constrained (see paper)
Aside 2: hard to arrange for field to adiabatically relax to minimum rather than oscillating (see paper)

Explicit symmetry breaking

$m_a \gtrsim H_I$

Explicit PQ-symmetry breaking

Fluctuations are suppressed when $m_a \gtrsim H_I$

Try explicit breaking of $U(1)_{PQ} \rightarrow \mathbb{Z}_N$ to generate axion mass

Strong CP problem sets strict bounds on breaking today:

True vs QCD min

$$\left\langle \left| \frac{a}{f_a} - \theta_0 \right| \right\rangle \leq \bar{\theta} \simeq 10^{-11}$$

$$m_{\mathrm{eff},0}^2 \lesssim \frac{\bar{\theta} m_{\mathrm{QCD}}^2}{|\theta_N - \theta_0|}$$

New operator min vs QCD min

Effect must be large during inflation but small today ($m_{a,I} \gg m_{a,0}$).

Single PQ field

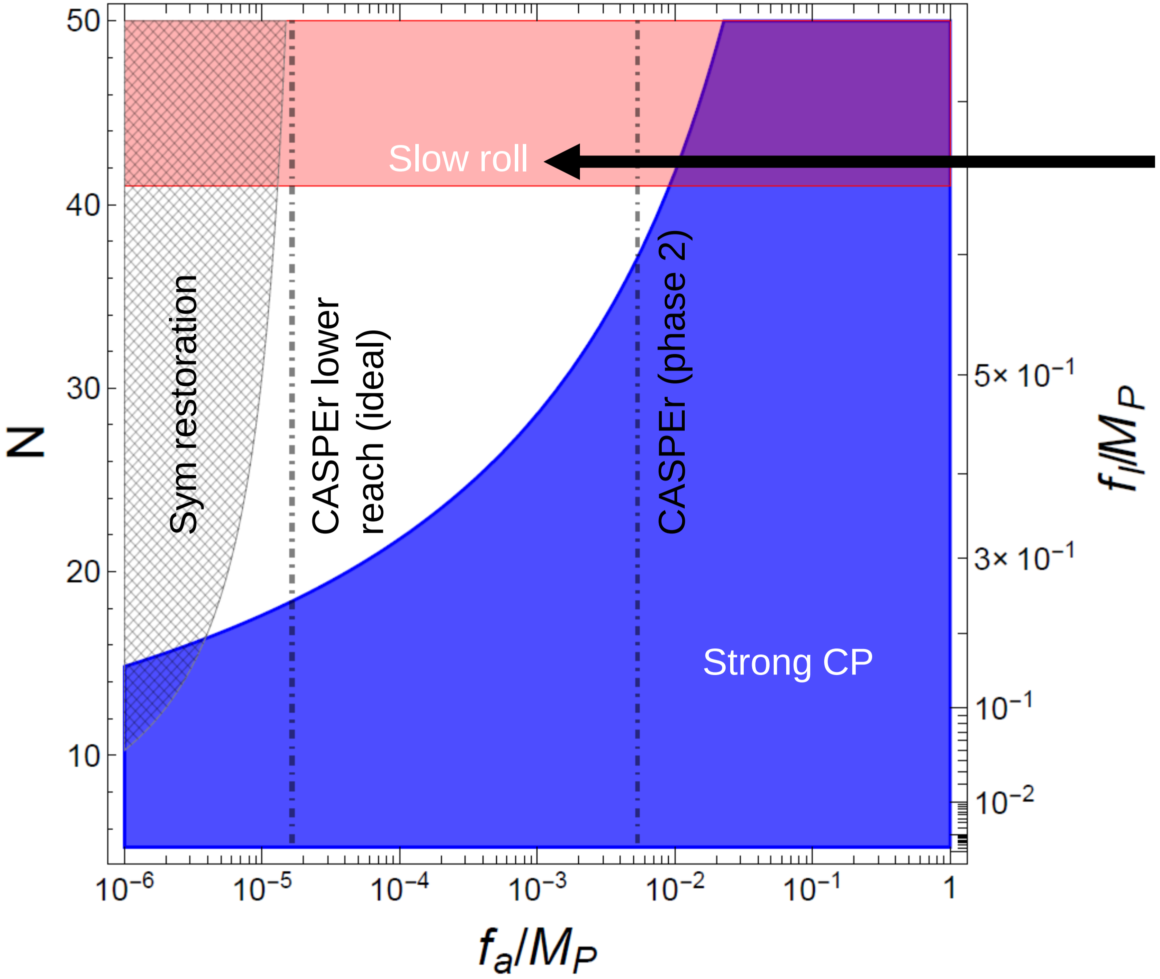
Model 1:

$$V \supset \lambda \left(|S|^2 - \frac{f_a^2}{2} \right)^2 - \frac{\delta}{2} I^2 |S|^2 + \left(\frac{k S^N}{M_P^{N-4}} + \text{ h.c.} \right)$$

Third term: Explicit $U(1)_{PQ} \rightarrow \mathbb{Z}_N$ breaking.

Second term: Need large inflationary $|S|$ vev for $m_{a,I} \gg m_{a,0}$.
May disrupt slow-roll conditions.

Single PQ field



Slow roll parameters should not exceed maximal values consistent with CMB 95% confidence bounds on n_s and r

$f_a < f_I < M_P$

Inflaton-sourced mass

Can we extend the reach in f_a?

Only change

Model 2:

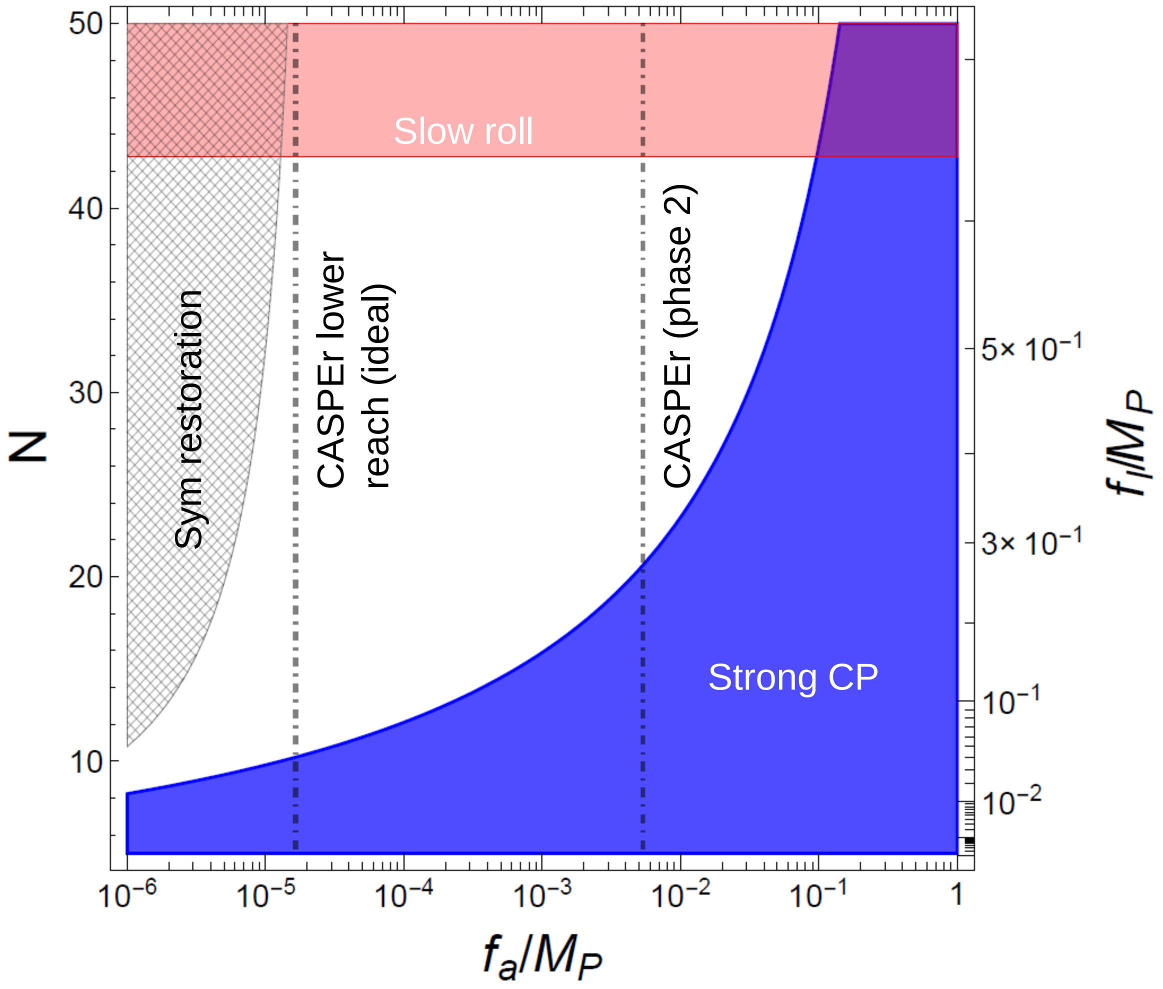
$$V \supset \lambda\left(|S|^2 - \frac{f_a^2}{2}\right)^2 - \frac{\delta}{2} I^2 |S|^2 + \left(\frac{kIS^N}{M_P^{N-3}} + \text{ h.c.}\right)$$

Breaks $U(1)_{PQ}$ to $\mathbb{Z}_{2N}$, with $I \rightarrow -I$ and $S^N \rightarrow -S^N$.

Idea: I large during inflation, but $I = 0$ today $\Rightarrow$ no explicit breaking today.

Problem: third term destabilizes inflaton from 0, leading to explicit breaking.
(This inflaton-induced breaking dominates higher-order S^{2N} term)

Inflaton-sourced mass



Inflaton-sourced mass

Better bounds from $I^M S^N$ with $M > 1$? (Would eliminate tadpole in I)

- If $I \in \mathbb{R}$, either S^N or IS^N allowed by discrete symmetry (depending if M is even or odd). Reduces to previous cases.
- If $I \in \mathbb{C}$, could charge both I and S under a $U(1)$ symmetry.
  BUT still have massless d.o.f. This $U(1)$ indistinguishable from $U(1)_{PQ}$.
  Hard to make the massless d.o.f. heavy without also making the inflaton too heavy.
- Holomorphy in SUSY can help forbid lower-order terms, but not by enough when SUSY breaking is included (see paper).

Additional $U(1)_{PQ}$ fields

Model 3: two fields charged under $U(1)_{PQ}$ (charges 1 and $-K$) broken to $\mathbb{Z}_{KN}$

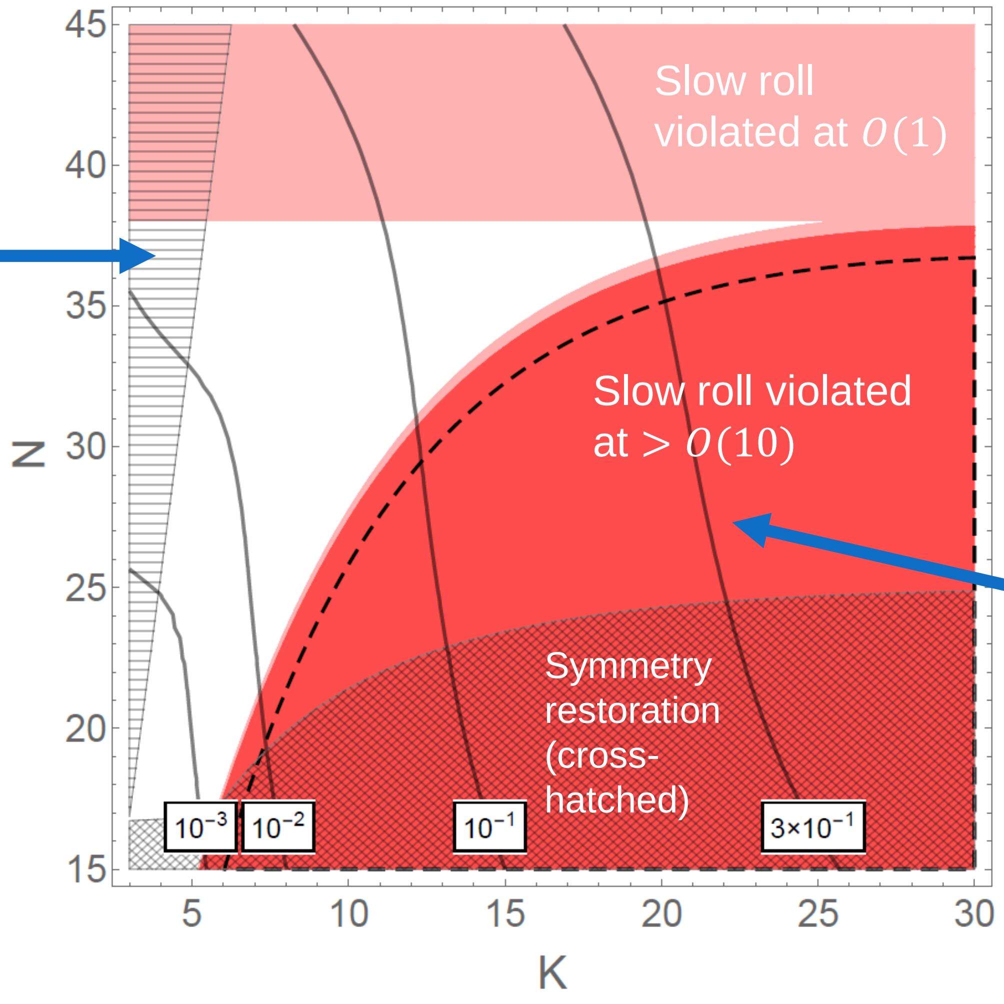
$$V \supset \lambda_S \left(|S|^2 - \frac{f_{\bar{S}}^2}{2} \right)^2 + m_{\bar{S}}^2 \left|\bar{S}\right|^2 + \frac{\lambda_{\bar{S}}}{4} \left|\bar{S}\right|^4 - \frac{\delta_{\bar{S}}}{2} I^2 \left|\bar{S}\right|^2 + \frac{k\bar{S}S^K}{M_P^{K-3}} + \frac{k'\bar{S}^N}{M_P^{N-4}} + \frac{k''S^{KN}}{M_P^{KN-4}} + \text{ h.c.}$$

S's axial component is the dominant part of the axion today. It "feels" less explicit breaking from S^{KN} (larger exponent), so strong CP bounds less severe.

$|\bar{S}|$ is enhanced during inflation to give both axial components large masses.

Additional $U(1)_{PQ}$ fields

Reduces to single PQ field case (horizontal hatched)



All points have parameters chosen so all radial and axial PQ fields have mass $\gtrsim H_I$

Contours of maximum f_a/M_P satisfying strong CP constraints

Summary

- Isocurvature constraints generally preclude high-scale axions with detectably-large primordial gravitational waves.
- Wave function renormalization ($f_I \gg f_a$) faces problems because parametric resonance can restore the PQ symmetry.
- Enhanced explicit PQ symmetry breaking ($m_{a,I} \gtrsim H_I \gg m_{a,0}$) can allow large f_a.
  We show how to build models to do this.
  Explicit breaking term alone is not enough, need enhanced PQ-breaking scale.
  Constraints arise from the inflation sector.