How robust are axion isocurvature constraints in high-scale inflation?

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in progress

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Axion properties

The axion is a well-motivated candidate to solve the strong CP problem and comprise some or all of the dark matter. Axions also appears naturally in string theories.

Spontaneous symmetry breaking of $U(1)_{PQ}$:

$$V(\phi) = \lambda(|\phi|^2 - f_a^2/2)^2$$

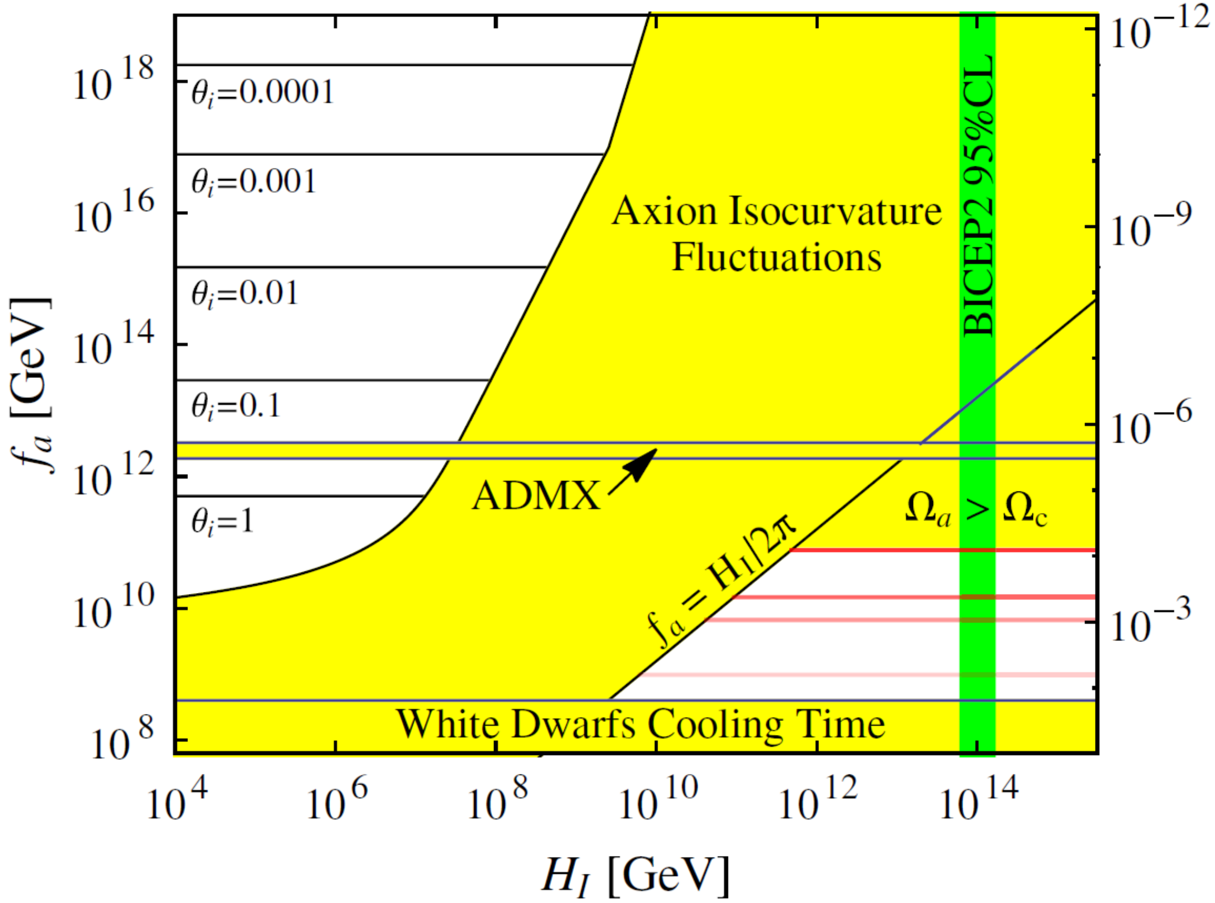
$$\langle|\phi|\rangle = f_a/\sqrt{2}$$

$$a = \frac{f_a}{N} \arg \phi$$

The axion is massless, but couplings to QCD can give it a small, f_a-dependent mass (~meV-peV) when $T < \Lambda_{QCD}$.

Axions are primarily produced by coherent oscillations or topological defects.

Axion cosmology



For PQ symmetry breaking before/during inflation *only*, the massless axion will have isocurvature fluctuations.

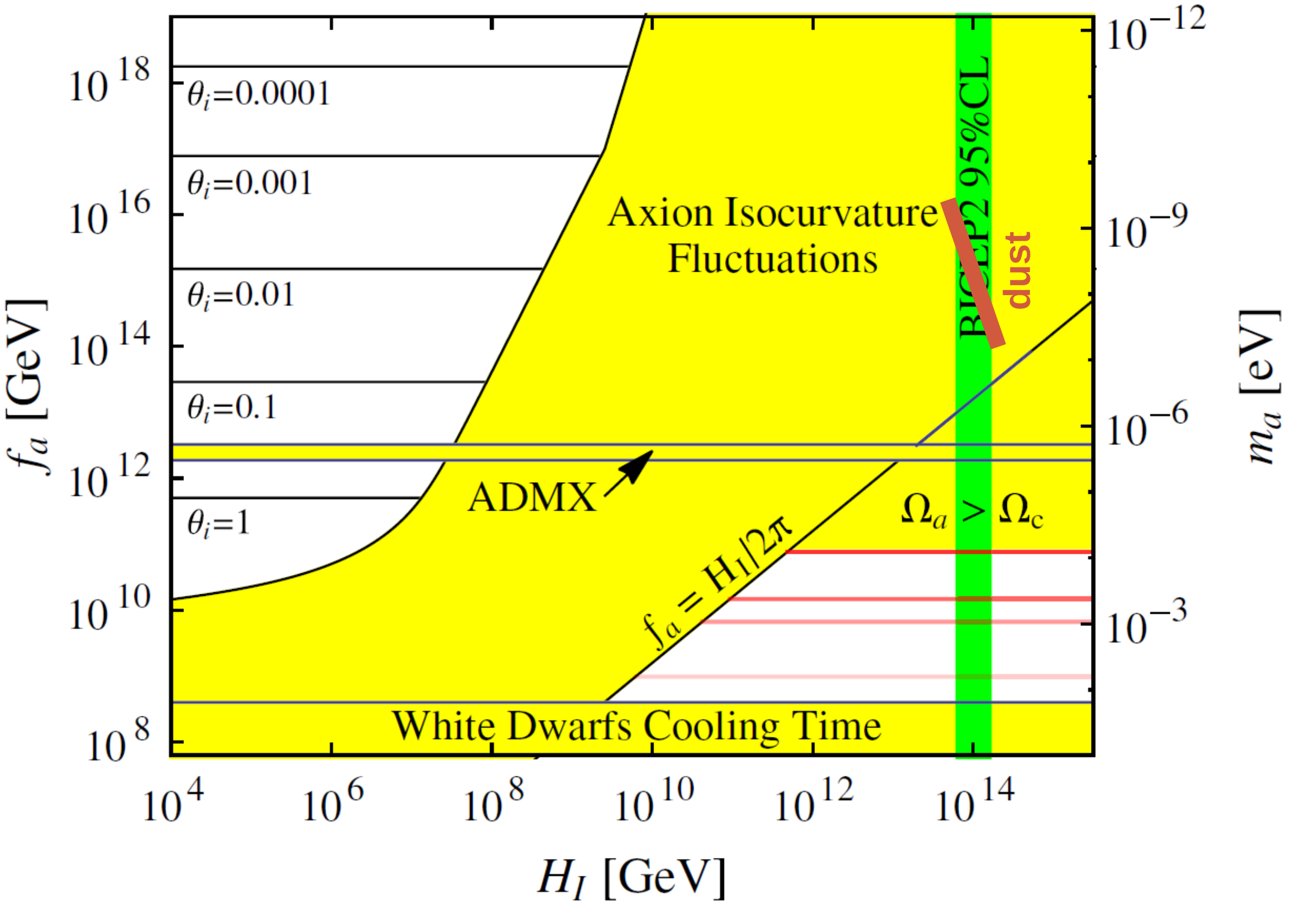
I.e., for $f_a > H_I/2\pi$:

$$\delta a \sim (H_I/2\pi)$$

Isocurvature fluctuations are bounded by Planck.

Plot assumes $\Omega_{axion} = \Omega_{CDM}$.
Yellow is excluded.
[Visinelli, Gondolo 1403.4594]

Axion cosmology



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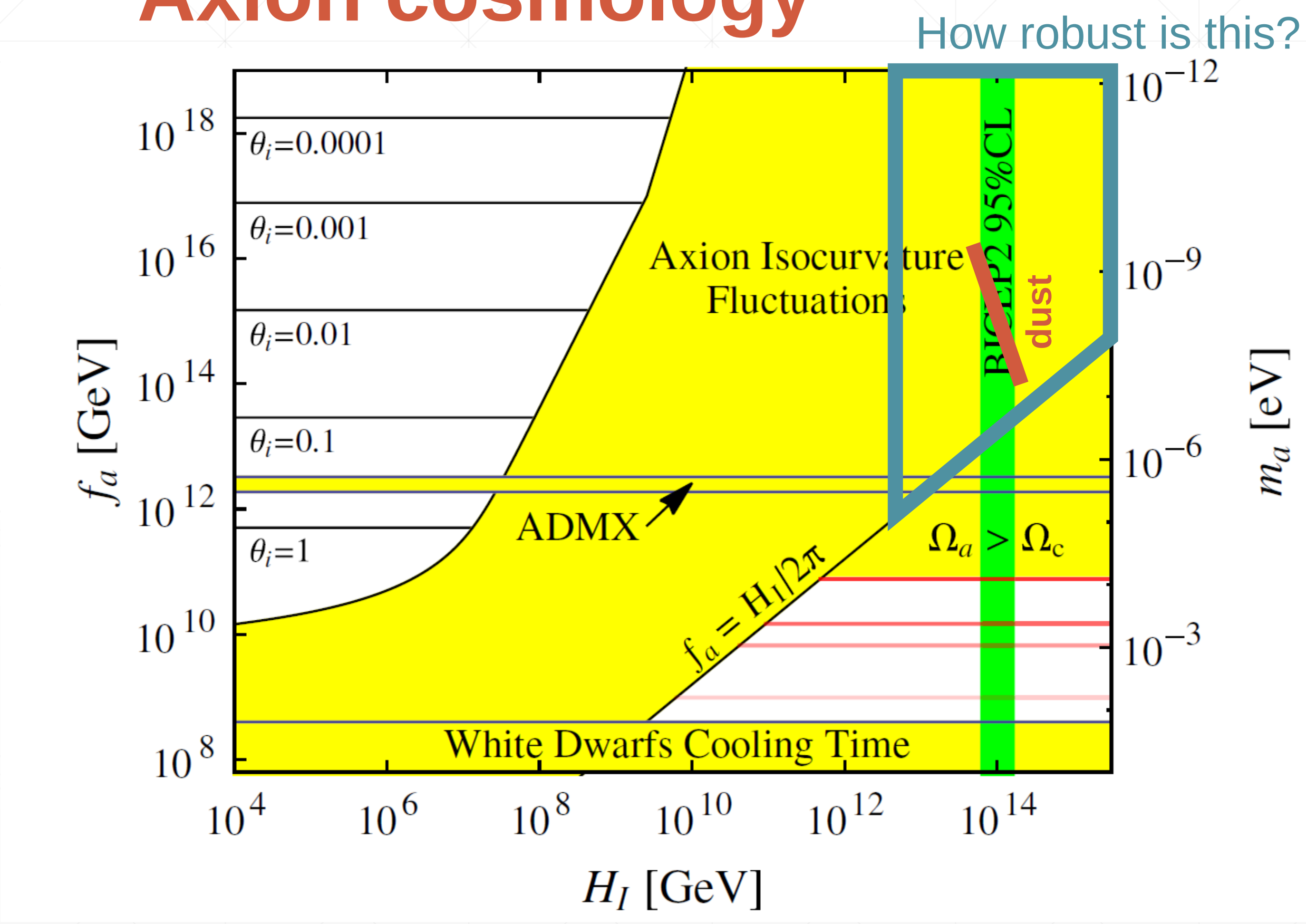

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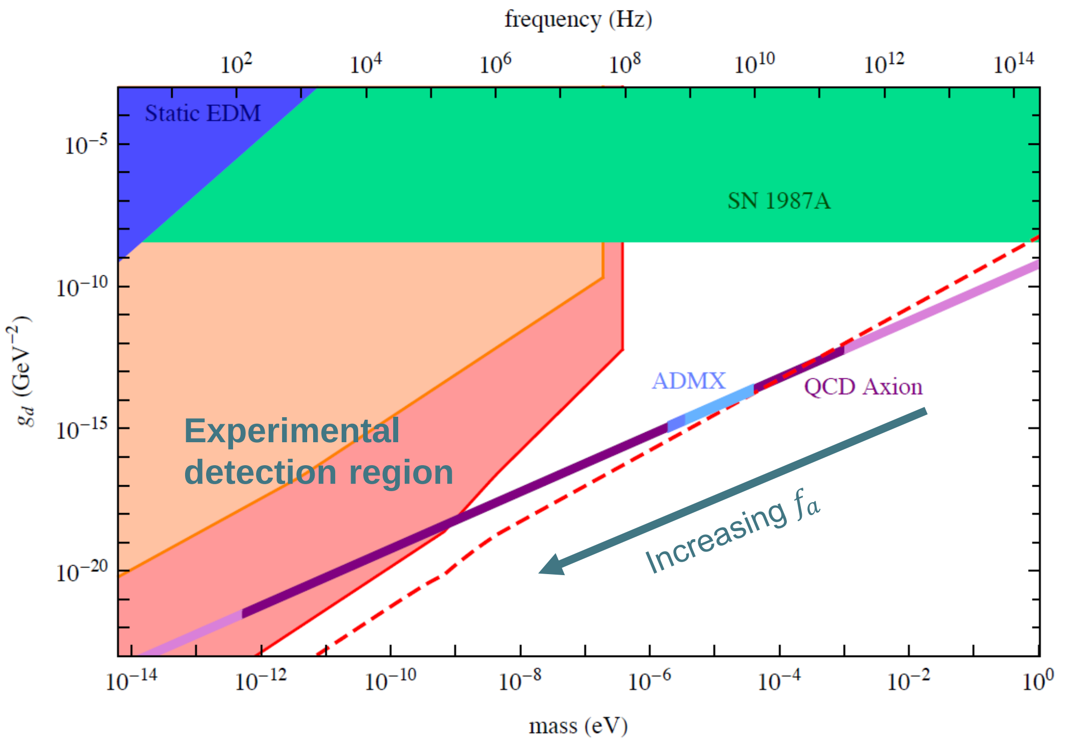
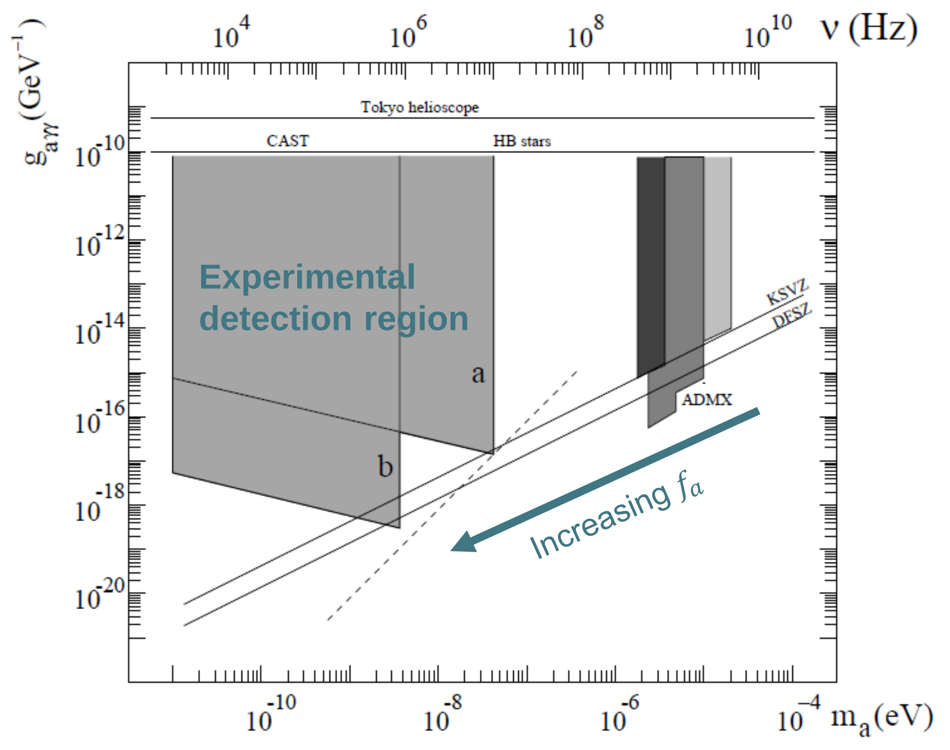
Axion experiments



CASPEr
[Budker, Graham, Ledbetter, Rajendran, Sushkov 1306.6089]



LC circuit detector
[Sikivie, Sullivan, Tanner 1310.8545]

Simple model

One way isocurvature constraints may be avoided is if

$$\delta m_a > H_I$$

A solution that has been posited to do this is a coupling of the form [Higaki, Jeong, Takahashi 1403.4186 and many others]

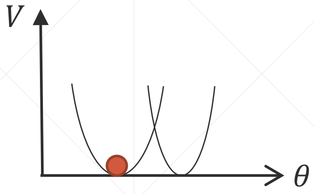
$$V \supset -\frac{I^m \phi^n}{M_P^{m+n-4}} + h.c.$$

Idea: the inflaton (I) takes large field values during inflation and modifies dynamics of PQ field. After reheating, the inflaton is stabilized at the origin and this term is unimportant.

In the following: assume that the radial component of ϕ is sufficiently heavy (i.e., the wine-bottle potential is sufficiently steep) so that it is fixed at its minimum.

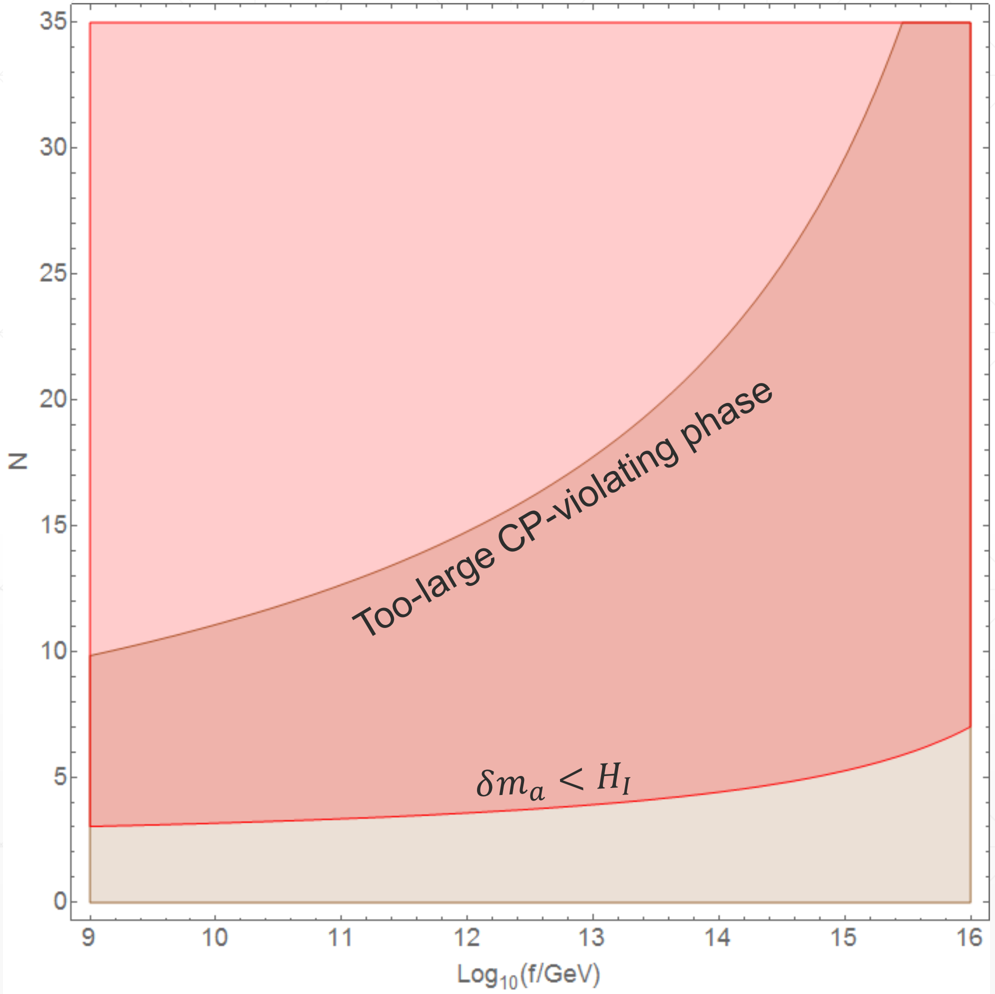
Some possible bounds

- Isocurvature
- CP-violating θ angle today from altered axion potential



- Corrections (tree and radiative) to the inflaton potential during inflation
- Parametric resonance leading to PQ symmetry restoration
- Dark radiation
- Cross-correlation [Kadota, Gong, Ichiki, Matsubara 1411.3974]

Bounds



$$V \supset -\frac{\phi^N}{M_P^{N-4}} + h.c.$$

Brown: too large CP-violating phase
Red: induced axion mass during inflation too small to suppress isocurvature ($\delta m_a < H_I$)

This is basically the statement:
Want:

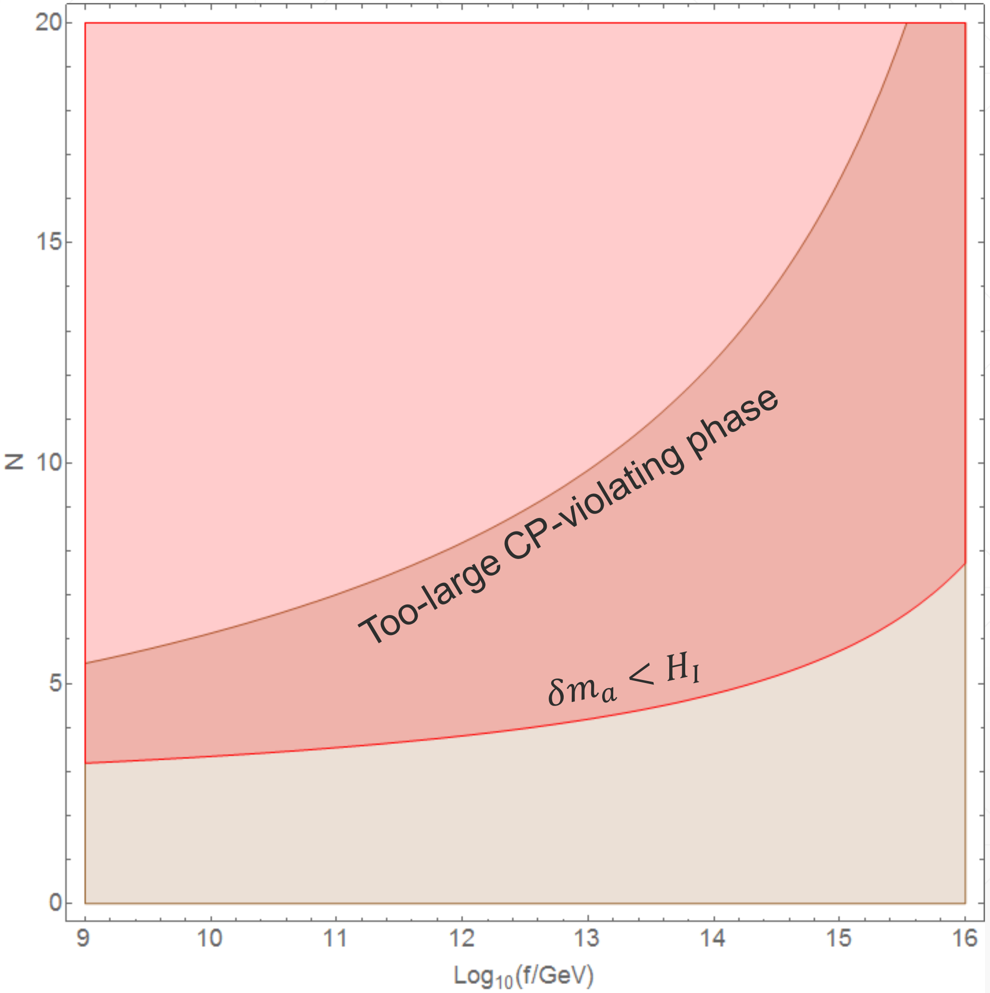
$\delta m_a > H_I$ during inflation
$\delta m_a < m_{a,QCD}$ today.

But:

δm_a is the same for both.

Some gains can be made by making $f_I > f_a$, but this does not happen naturally without adding more Langrangian terms.

Bounds



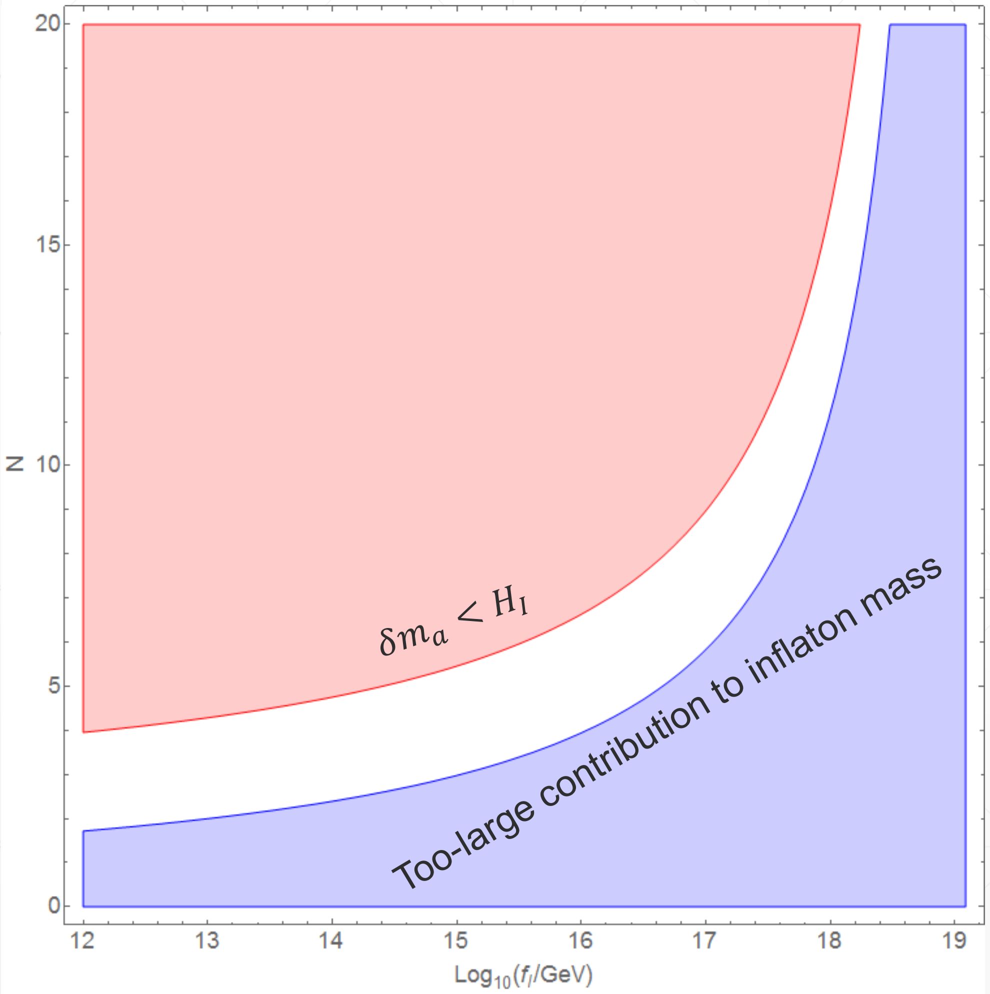
$$V \supset m^2|I|^2 - \frac{I\phi^N}{M_P^{N-3}} + h.c.$$

Destabilizes I from the origin.

Take $m \sim 10^{13}$ GeV as required by density perturbations. (Bounds not much improved for other choices, e.g. $m \sim M_P$)

Same story with f_I and f_a, but the two need not be as far apart.

Bounds



$$V \supset -\frac{I^2\phi^N}{M_P^{N-2}} + h.c.$$

Blue: contribution to the inflaton mass too large
Red: $\delta m_a < H_I$

The inflaton can be stabilized at the origin today, so there is no constraint from the CP-violating phase.

The constraints are only on f_I, not on f_a.

For I^m with $m > 2$, both curves are largely unchanged since $I_{inf} \sim M_P$.

pepsi

Disclaimer: This is a work of science. Any resemblance to brand logos is purely coincidental.

Parametric resonance

The direct coupling of the inflaton to the axion can lead to a resonant enhancement in the axion when the inflaton begins oscillating after inflation [Kofman, Linde, Starobinsky hep-th/9405187].

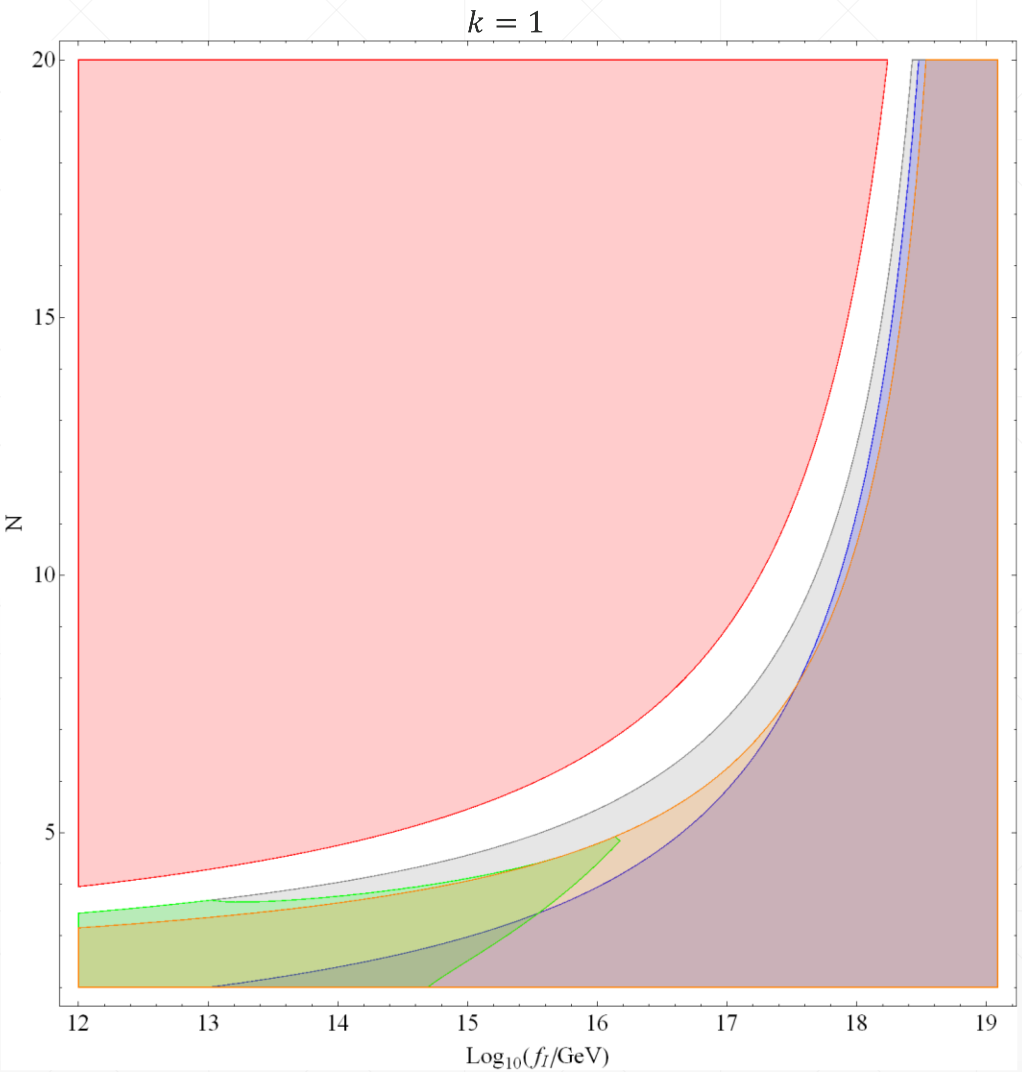
The degree to which this occurs, and whether it occurs at all, depends on the axion-inflaton coupling constant (parametrized by, e.g., gI^2a^2) and the inflaton's oscillation amplitude.

Parametric resonance

For axion models that couple directly to I, parametric resonance may produce several constraints:

- If the amplitude of χ_k is large enough, PQ symmetry may be restored. Subsequent breaking after inflation will lead to overproduction from cosmic strings and potentially a domain wall problem.
- If the amplitude is not that large
  - Axions that are produced will behave as dark radiation
  - Saxions that are produced will decay to axions, which behave as dark radiation

Bounds



$$V \supset -\frac{kI^2\phi^N}{M_P^{N-2}} + h.c.$$

Blue: contribution to the inflaton mass too large

Red: $\delta m_a < H_I$

Gray: parametric resonance occurs (*not a bound*)

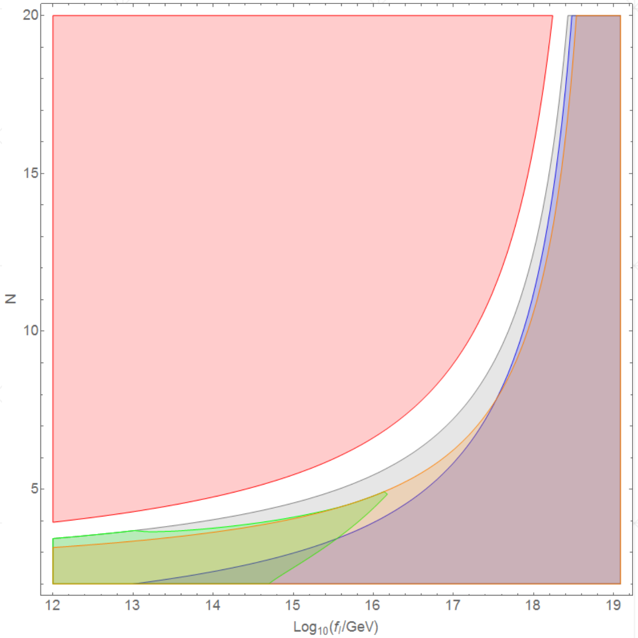
Green: parametric resonance leads to symmetry restoration => overproduction

Orange: dark radiation may be overproduced during parametric resonance

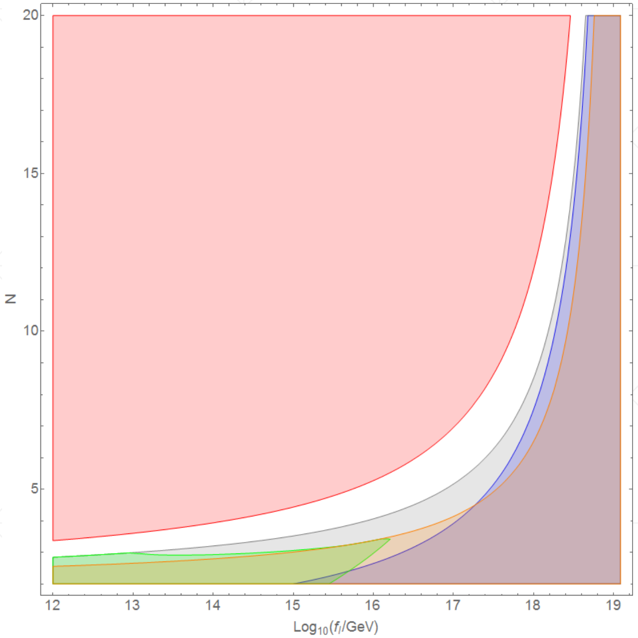
Still some allowed parameter space!

$$V \supset -\frac{kI^2\phi^N}{M_P^{N-2}} + h.c.$$

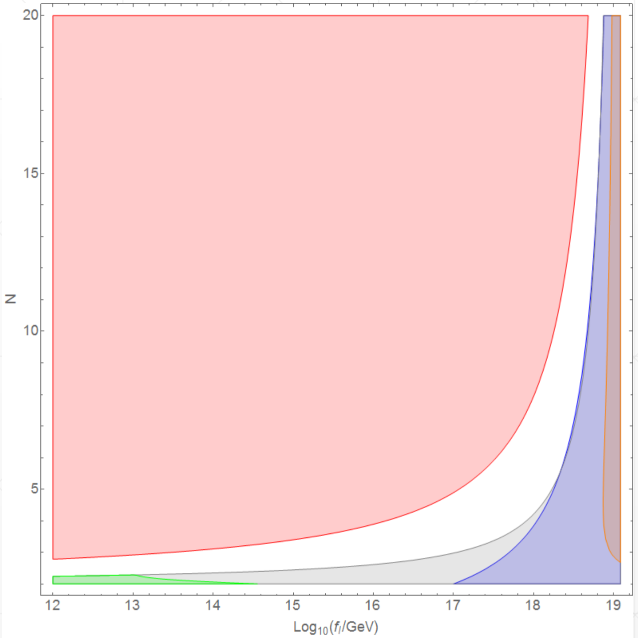
$k = 1$



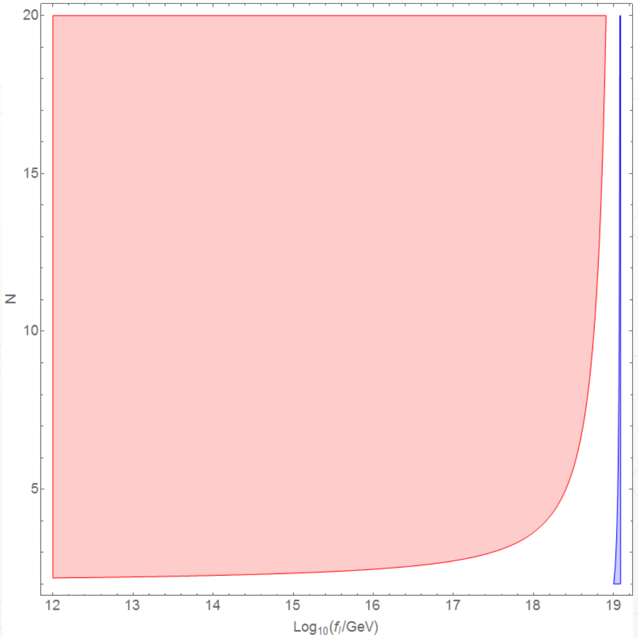
$k = 10^{-4}$



$k = 10^{-8}$



$k = 10^{-12}$



Why care about this model?

This model reveals that many issues can arise when coupling the inflaton to the PQ field.

Can supersymmetry help?

Past studies have noted that SUSY can protect some terms from these oscillations via choices for the Kähler potential that couple fields to the *kinetic* and *potential* terms of the inflaton equally ($T + V = \text{const}$). [Dine, Randall, Thomas hep-ph/9503303]

We argue that in order to simultaneously produce an axion mass term (of the form $I^m \phi^n$) and a viable model of inflation requires a tuning between various couplings in the Kähler potential and superpotential.

Thus, SUSY theories generically suffer from parametric resonance as well.

Why care about this model?

Nevertheless, this indicates that it is possible to evade isocurvature constraints.

A detection of primordial gravitational waves does not rule out high-PQ scale axions.

What's left?

We are in the process of extending these results for the case of a lighter saxion that is not pinned at its minimum, particularly in the context of SUSY models (where $m_s \sim m_{3/2} < H_I$) [Banks, Dine, Graesser hep-ph/0210256].

Thank you

Backup slides

Motivation

$U(1)_A$ problem: expect $m_\eta \lesssim \sqrt{3} m_\pi$, contradicted by experiment.

Resolution: Lagrangian should contain:

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

More accurately:

$$\theta \to \bar{\theta} = \theta + \mathrm{Arg}\det M$$

Predicts neutron EDM:

$$d_n \simeq (5 \times 10^{-16} \ e\mathrm{cm})\bar{\theta}$$

Experimentally:

$$d_n < 2.9 \times 10^{-26} \ e\mathrm{cm} \implies \bar{\theta} \lesssim 10^{-10}$$

Motivation

Add the following term with the field a:

$$\mathcal{L} \supset C \frac{a}{f_a} \frac{g^2}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

Then, the potential of a is minimized at:

$$\langle a \rangle = -f_a \bar{\theta}/C$$

This cancels the $\bar{\theta}$ term and solves the strong CP problem.

QCD instantons break the PQ symmetry and give the axion a mass below the QCD phase transition:

$$V(a) = \left(m_a \frac{f_a}{N} \right)^2 \left(1 - \cos\left(\frac{a}{f_a/N} \right) \right)$$

$$m_a = \left\{ \begin{array}{ll} 6.2\ \mu\text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a/N} \right) & T \lesssim \Lambda_{\text{QCD}} \\ m_a(T=0) b \left(\frac{\Lambda_{\text{QCD}}}{T} \right)^4 & T \gtrsim \Lambda_{\text{QCD}} \end{array} \right\}$$

Axion cosmology

For PQ symmetry breaking before/during inflation *only*, the massless axion will have $(H/2\pi)$ isocurvature fluctuations.

The isocurvature power spectrum is bounded by Planck:

$$\mathcal{P}_a \equiv 4\xi^2 \frac{(H_I/2\pi)^2}{(F_I\theta_i)^2 + (H_I/2\pi)^2} \lesssim 0.04\,\mathcal{P}_\mathcal{R}$$

$$\xi \equiv \Omega_a/\Omega_{CDM} \qquad \mathcal{P}_\mathcal{R} \simeq 2.2 \times 10^{-9}$$

SUSY model

Adding a term to the Kahler potential

$$\delta K = \frac{1}{M_P^2}|I|^2|\phi|^2$$

produces the scalar potential term

$$V = H^2 M_P^2 f(\phi/M_P)$$

In particular,

$$\delta W = \frac{\lambda}{(n+3)M_P^n}\phi^{n+3}$$

produces

$$V = (C_m H^2 + m_\phi^2)|\phi|^2 + \left[\frac{(C_A H + A)\lambda}{n+3}\frac{\phi^{n+3}}{M_P^n} + h.c.\right] + |\lambda|^2\frac{|\phi|^{2n+4}}{M_P^{2n}}$$

[Dine, Randall, Thomas hep-ph/9503303, Chun, Dimopoulos, Lyth hep-ph/0402059, and many others]