- QCD accommodates gauge and Lorentz-inv. renormalizable "theta" term

$$\mathcal{L}_{QCD} \supset -\frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\,\tilde{G}^{a\,\mu\nu}$$

$$\theta \in [-\pi, \pi]$$

Exp: $|\theta| \lesssim 10^{-10}$

- PQ explanation of smallness of $|\theta|$:
promote θ to a dynamical parameter (field);
QCD dynamics $\rightarrow \langle\theta\rangle = 0$
- Easiest way to promote θ to a dynamical parameter: introduce new hidden scalar field respecting spontaneously broken global chiral $U(1)_{PQ}$ symmetry

- Effective θ appear as phase of the scalar field in the expansion around the vev:

$$\sigma = \frac{1}{\sqrt{2}}\left(v_{PQ} + \rho(x)\right) e^{i\frac{A(x)}{v_{PQ}}}$$

$$\mathcal{L}_A \supset \frac{1}{2}(\partial A)^2 - \frac{\alpha_s}{8\pi} \underbrace{\frac{N}{v_{PQ}} A}_{\theta(x)} G\tilde{G}$$

A is Goldstone boson of ~~$U(1)_{PQ}$~~

Its interactions are determined by decay constant

$$f_A \equiv \frac{v_{PQ}}{N_{Ag}}$$

At low energies:

$$\mathcal{L}_A = \frac{1}{2}(\partial A)^2 - \frac{1}{2} m_A^2 A^2$$

$$- \frac{g_{A\gamma}}{4} A F \tilde{F} + \ldots$$

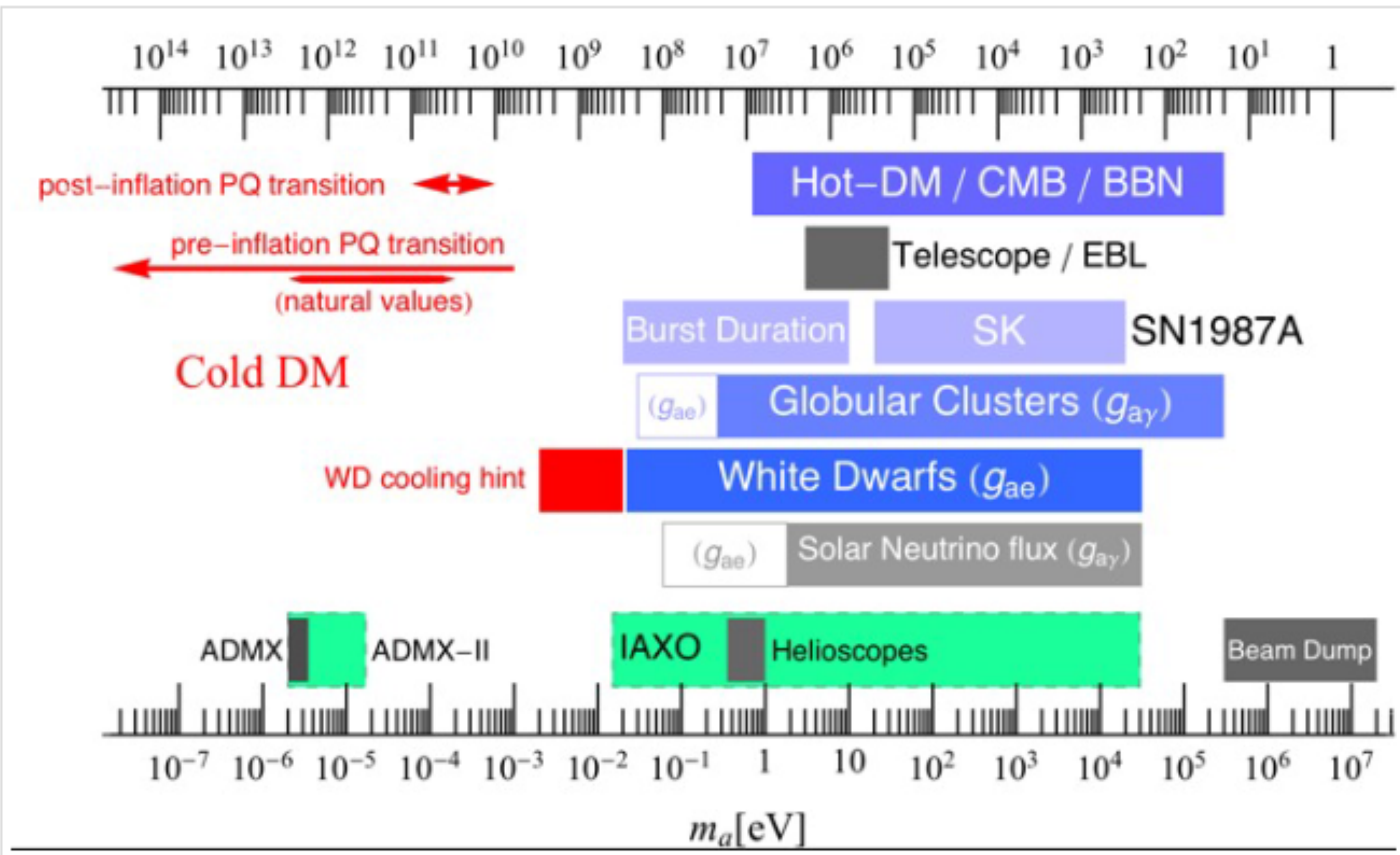
with

$$m_A = \frac{m_\pi f_\pi}{f_A} \cdot \frac{\sqrt{z}}{1+z}$$

$$g_{A\gamma} \sim \frac{\alpha}{2\pi f_A}$$

Strong lower limits on f_A:

$$f_A \gtrsim 4\times 10^{8}\ \text{GeV}$$



DM probes region of large f_A!

- For $f_A \gtrsim 10^9$ GeV, axion can be observed CDM

Inevitably

- Produced by vacuum re-alignment
- ≈ Stable because very weakly coupled

- Vacuum real. prod.:

axion field $\theta = A/f_A$ satisfies

$$\ddot{\theta} + 3H\dot{\theta} - \frac{\nabla^2}{a^2}\theta + m_A^2(T)\sin\theta = 0$$

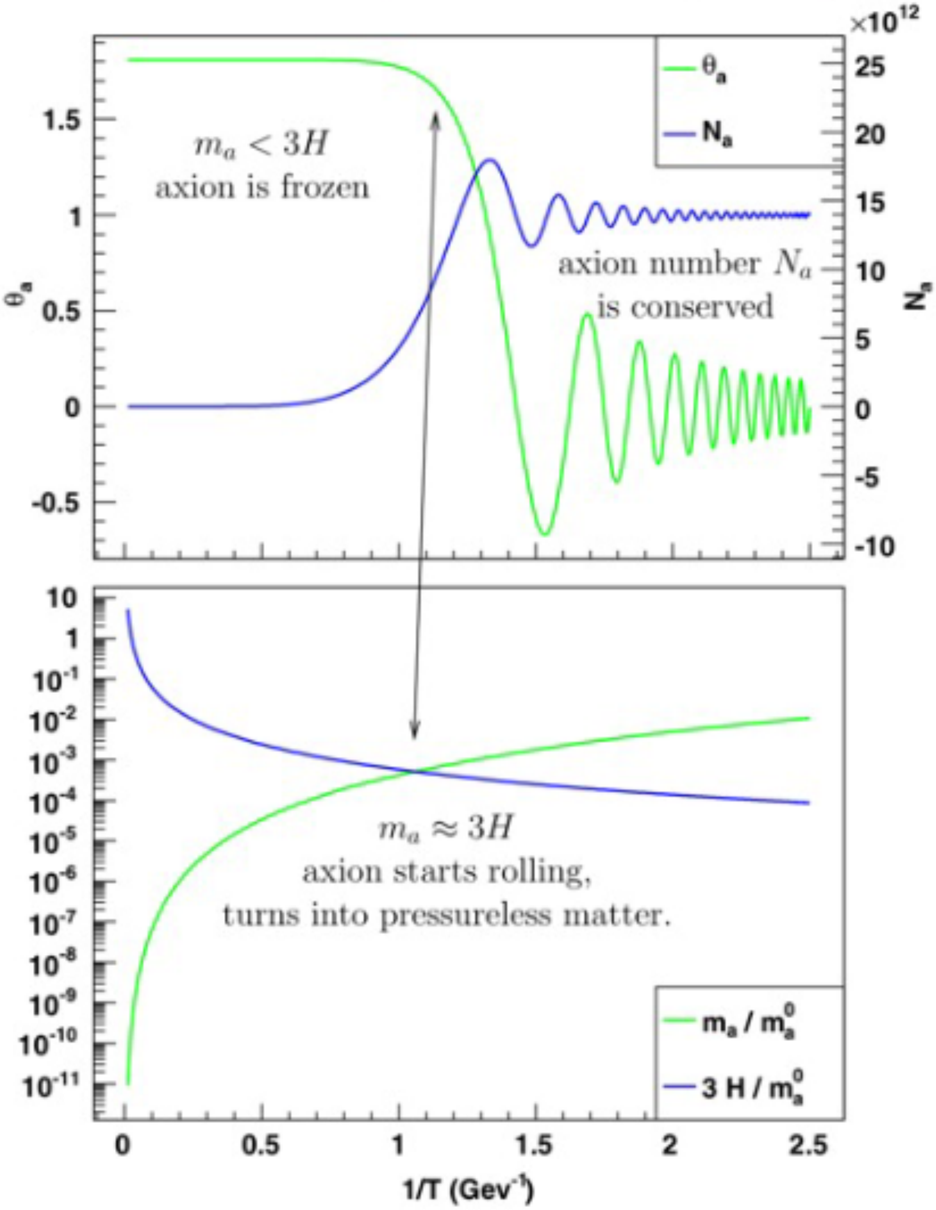


FIG. 4 (color online). As long as the axion Compton wavelength is well outside the horizon, the axion zero mode is frozen; this corresponds to the late-time solution of (26) with m_a neglected. The axion starts to feel the pull of its mass at $m_a \approx 3H$, and evolves to its minimum at $\theta_a = 0$, i.e. the PQ mechanism to solve the strong CP problem. After a few oscillations the axion number per comoving volume stays constant as long as the axion mass and the scale factor change slowly (adiabatic approximation). This is then used to extrapolate the result to today.

Fractional axion energy density from vacuum re-alignment mechanism:

$$\Omega_a h^2 \approx \begin{cases} 0.54 g_{*,R}^{-0.41} \theta_a^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.19} \\ 0.0064 g_{*,R}^{-0.25} \theta_a^2 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{1.5} \end{cases} .$$

with $\theta_a^2 \equiv \langle \theta^2 \rangle$

$\langle \theta^2 \rangle$ spatial average over our Hubble volume of initial misalign.

$$\langle \theta^2 \rangle = \theta_i^2 + \sigma_\theta^2$$

mean — standard deviation

- If PQ breakdown happens after inflation:

$$\theta_i = \langle \theta \rangle = 0 \, , \; \sigma_\theta^2 = \frac{\pi^2}{3}$$

- If PQ symmetry breaking occurs before inflation ends

$$f_A > T_{GH} = \frac{H_I}{2\pi}$$

H_I ... Hubble scale during inflation

and if it is not restored afterwards,

i.e., if at the same time

$$f_A > T_{max}$$

max. thermal. temp. after inflation

$$T_{max} \sim \left(T_{RH}^2 \, M_{PR} \, H_I \right)^{1/4}$$

Then spatial variations in θ smoothed out over our Hubble volume $((\nabla^2\theta/a) \to 0)$

Then

$$\theta_i = \langle\theta\rangle \in [-\pi, \pi]$$

$$G_\theta = \frac{T_{GH}}{2\pi f_A} = \frac{H_I}{2\pi f_A}$$

quantum fluctuation

(in de Sitter space)

- At the same time, when

$$f_A > \max\left(\frac{H_I}{2\pi}, T_{max}\right),$$

then isocurvature fluctuations are generated from the axion field,

$$\delta\rho = 0 \; ; \; \delta\left(\frac{n_A}{s}\right) \neq 0$$

and are not washed out after inflation.

Since axion
inevitably provides
some or all of
DM ⇝
perturbations
contribute to
temp. + polaris.
fluctuations in CMB

Fluctuations of
axion field record
to fluct. of
inflaton:
primordial scale
power spectrum ^
incoherent sum

adiabatic

$$P(k) = \langle |R(k)|^2 \rangle$$

$$+ \langle |S(k)|^2 \rangle$$

isocurvature

with

$$\langle |R(k)|^2 \rangle = \frac{H_I^2}{\pi M_{pl}^2 \varepsilon}$$

Spectrum of entropy
= isocurvature pert.

$$\mathcal{S}(k) = \frac{\Theta^2 - \langle \Theta^2 \rangle}{\langle \Theta^2 \rangle}.$$

assuming $\Theta^2 - \langle \Theta^2 \rangle$ gaussian:

$$\langle |\mathcal{S}(k)^2| \rangle = \frac{2\sigma_\Theta^2 \left(2\Theta_{\mathrm{i}}^2 + \sigma_\Theta^2\right)}{(\Theta_{\mathrm{i}}^2 + \sigma_\Theta^2)^2}, \quad \left(\frac{\Omega_A}{\Omega_{DM}}\right)^2$$

↑ if $\Omega_A < \Omega_{DM}$.

thus: Isocurvature fraction:

$$\alpha = \frac{\langle |S^2| \rangle}{\langle |R^2| \rangle + \langle |S^2| \rangle}\Bigg|_{k=k_0}$$

$$\alpha \equiv \left. \frac{\langle |\mathcal{S}(k)^2| \rangle}{\langle |\mathcal{R}(k)^2| \rangle + \langle |\mathcal{S}(k)^2| \rangle} \right|_{k=k_0} \simeq \begin{cases} \frac{H_I^2}{A_\mathrm{S} \pi^2 f_\mathrm{a}^2 \Theta_\mathrm{i}^2} & \text{for } \Theta_\mathrm{i}^2 \gg \sigma_\Theta^2, \\ \frac{2}{A_\mathrm{S}} & \text{for } \Theta_\mathrm{i}^2 \ll \sigma_\Theta^2, \end{cases}$$

$$\times \left(\frac{\Omega_A}{\Omega_{DM}} \right)^2$$

with

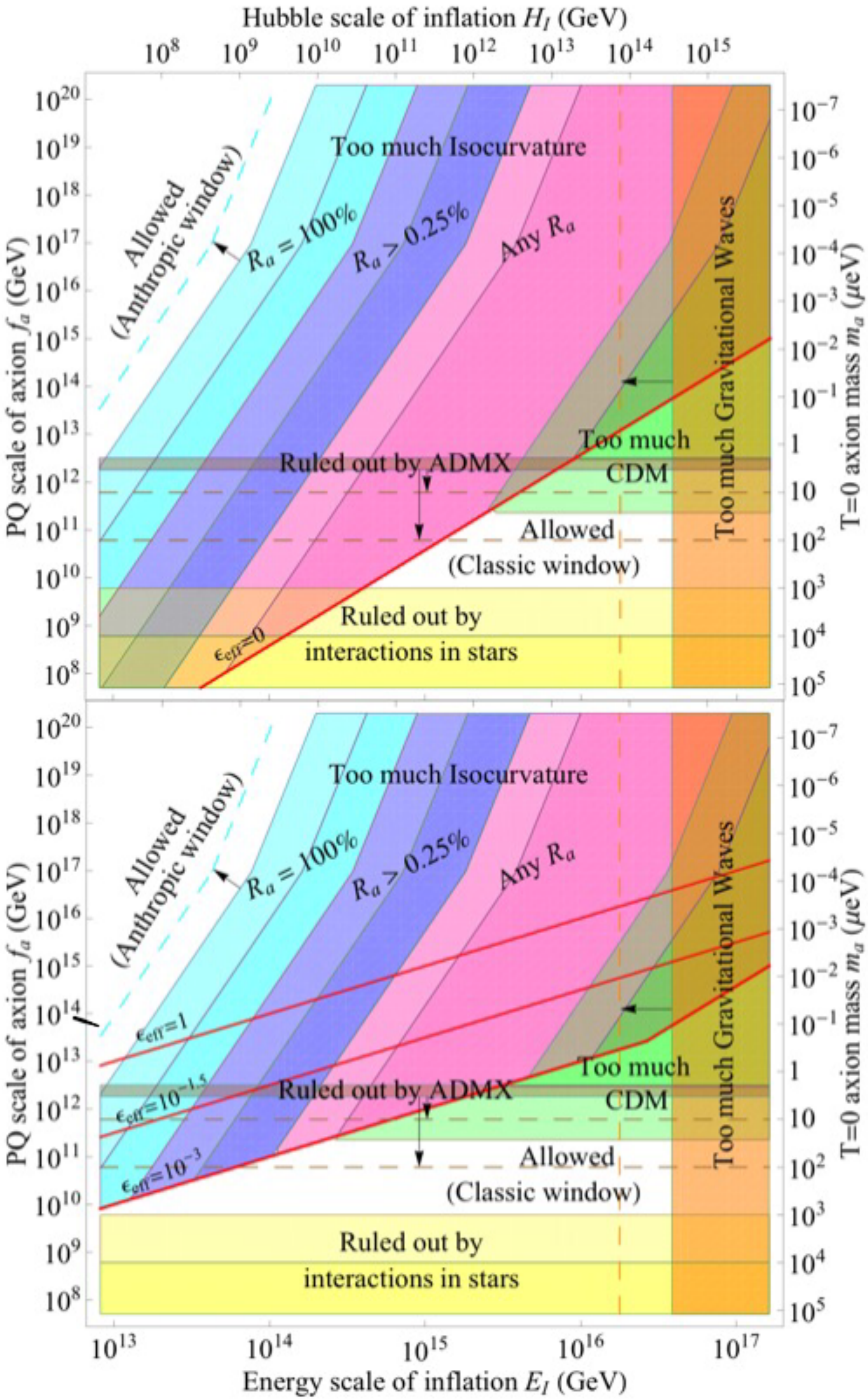
$$P(k=k_0) = A_s \simeq 2.4\times 10^{-9}$$

Isocurvature
fraction
observationally
constrained:

$\alpha < 0.072$

Thus:
constraint on
H_I

Isocurvature
constraint can
be fulfilled, if
H_I "small"


Hubble scale of inflation H_I (GeV)
10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
PQ scale of axion f_a (GeV)
10^{20} 10^{19} 10^{18} 10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^9 10^8
T=0 axion mass m_a (μeV)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4 10^5
Too much Isocurvature
Allowed (Anthropic window)
$R_a = 100\%$
$R_a > 0.25\%$
Any R_a
Too much Gravitational Waves
Too much CDM
Ruled out by ADMX
Allowed (Classic window)
Ruled out by interactions in stars
$\epsilon_{eff}=0$
$\epsilon_{eff}=1$
$\epsilon_{eff}=10^{-1.5}$
$\epsilon_{eff}=10^{-3}$
Energy scale of inflation E_I (GeV)
10^{13} 10^{14} 10^{15} 10^{16} 10^{17}

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Probing a QCD String Axion with Precision Cosmological Measurements

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ABSTRACT

String and M-theory compactifications generically have compact moduli which can potentially act as the QCD axion. However, as demonstrated here, such a compact modulus can not play the role of a QCD axion and solve the strong CP problem if gravitational waves interpreted as arising from inflation with Hubble constant $H_{\rm inf} \gtrsim 10^{13}$ GeV are observed by the PLANCK polarimetry experiment. In this case axion fluctuations generated during inflation would leave a measurable isocurvature and/or non-Gaussian imprint in the spectrum of primordial temperature fluctuations. This conclusion is independent of any assumptions about the initial axion misalignment angle, how much of the dark matter is relic axions, or possible entropy release by a late decaying particle such as the saxion; it relies only on the mild assumption that the Peccei-Quinn symmetry remains unbroken in the early universe.

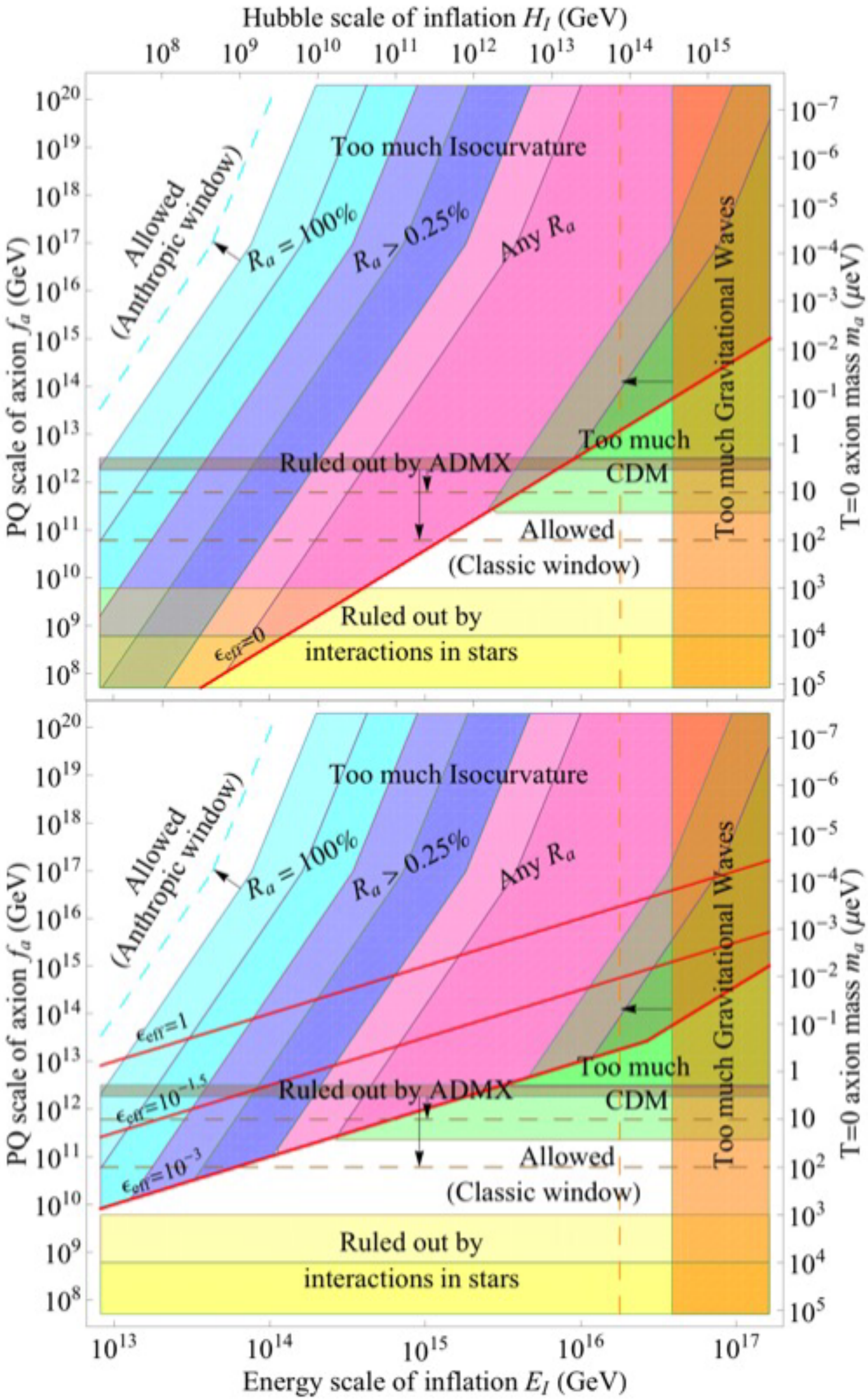
BICEP2:

$r = 0.2^{+0.07}_{-0.05}$

$\Rightarrow$ in single field infl. models,

$$H_I = \frac{1}{4}\sqrt{A_s r}\, M_{pl}$$

$$= 1.1 \times 10^{14}\ \text{GeV} \left(\frac{A_s}{2.19 \times 10^{-9}} \frac{r}{0.2}\right)^{1/2}$$



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10^{13} 10^{14} 10^{15} 10^{16} 10^{17}
Energy scale of inflation E_I (GeV)

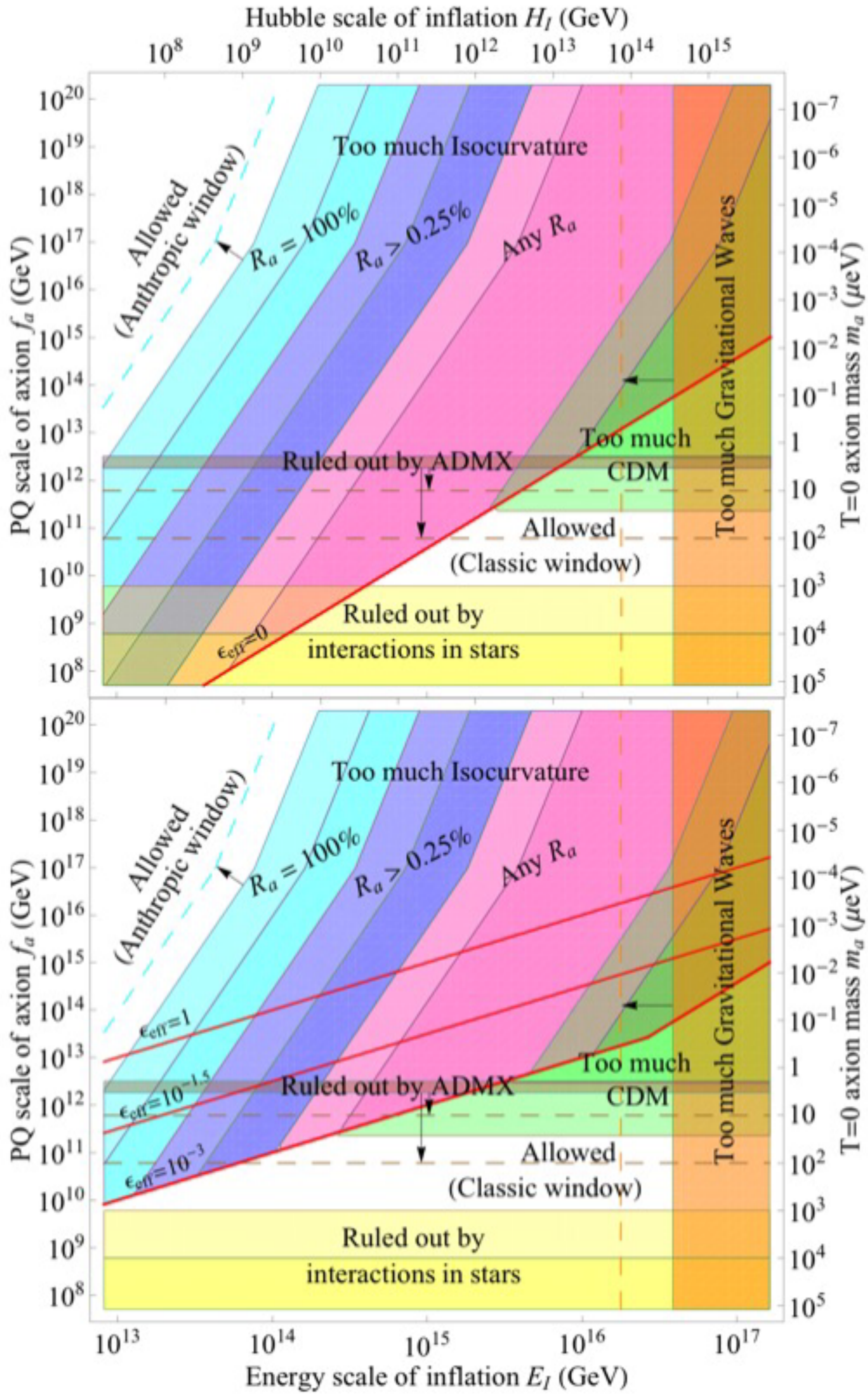
Isocurvature fluctuations + BICEP2 meas. of H_I strongly disfavor axion models with

$$f_A > H_I/2\pi \simeq 1.8\times 10^{13}\,\mathrm{GeV}$$

Remaining:

classic axion window

$$f_A \sim 10^{9\div 12}\ \text{GeV}$$



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- Way around is curvature bound; apart from consider

$$f_A < \max\left(T_{GH}, T_{max}\right)$$

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Is there a Peccei–Quinn phase transition?

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Abstract. The nature of axion cosmology is usually said to depend on whether the Peccei–Quinn (PQ) symmetry breaks before or after inflation. The PQ symmetry itself is believed to be an accident, so there is not necessarily a symmetry during inflation at all. We explore these issues in some simple models, which provide examples of symmetry breaking before and after inflation, or in which there is no symmetry during inflation and no phase transition at all. One effect of these observations is to relax the constraints from isocurvature fluctuations due to the axion during inflation. We also observe new possibilities for evading the constraints due to cosmic strings and domain walls, but they seem less generic.

Keywords: dark matter, inflation, axions

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Axion dark matter and Planck favor non-minimal couplings to gravity ☆

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ABSTRACT

Constraints on inflationary scenarios and isocurvature perturbations have excluded the simplest and most generic models of dark matter based on QCD axions. Considering non-minimal kinetic couplings of scalar fields to gravity substantially changes this picture. The axion can account for the observed dark matter density avoiding the overproduction of isocurvature fluctuations. Finally, we show that assuming the same non-minimal kinetic coupling to the axion (dark matter) and to the standard model Higgs boson (inflaton) provides a minimal picture of early time cosmology.

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Solving the Tension between High-Scale Inflation and Axion Isocurvature Perturbations

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Abstract

The BICEP2 experiment announced the discovery of the primordial B-mode polarization, which determines the Hubble parameter during inflation to be about 10^{14} GeV. Such high inflation scale is in tension with the QCD axion dark matter if the Peccei-Quinn symmetry remains broken during and after inflation, because too large axion isocurvature perturbations would be generated. The axion isocurvature perturbations can be suppressed if the axion acquires a sufficiently heavy mass during inflation. We show that this is realized if the Peccei-Quinn symmetry is explicitly broken down to a discrete symmetry and if the breaking is enhanced during inflation. Such enhancement is possible if during inflation the saxion acquires a vacuum expectation value much larger than in the present vacuum, or if the symmetry breaking operators depend on the inflaton field value. The latter possibility can be implemented easily in a large-field inflation model.

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