An Exceptionally Light Axion:
Strong CP and Dark Matter

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An exceptionally light axion: Strong CP and Dark Matter

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We explore whether the axion which solves the strong CP problem can naturally be much lighter than the canonical QCD axion. The Z_N symmetry proposed by Hook, with N mirror and degenerate worlds coexisting in Nature and linked by the axion field, is considered and the associated phenomenology is studied in detail. On a second step, we show that dark matter can be accounted for by this extremely light axion. This includes the first proposal of a "fuzzy dark matter" QCD axion. A novel misalignment mechanism occurs – trapped misalignment– due to the peculiar temperature dependence of the Z_N axion potential, which in some cases can also dynamically source the recently proposed kinetic misalignment mechanism. The resulting universal enhancement of all axion interactions relative to those of the canonical QCD axion has a strong impact on the prospects of ALP experiments such as ALPS II, IAXO and many others. For instance, even Phase I of Casper Electric could discover this axion.

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1. Motivation and canonical axion mass

The QCD axion is one of the most motivated scenarios beyond the Standard Model. This simple extension not only explains in an elegant way the absence of CP violation in the strong interactions [1, 2] but could also account for the Dark matter abundance [3–5]. Furthermore, the QCD axion is a highly predictive scenario since a lot of the properties of this pseudoscalar stem from its pseudo-Goldstone boson nature: both the axion mass and the couplings to ordinary matter scale as $1/f_a$, where f_a is the axion decay constant, denoting the scale at which the Peccei-Quinn (PQ) symmetry $U(1)_{\mathrm{PQ}}$ is spontaneously broken.

At the heart of the axion solution to the strong CP problem lies the fact that the QCD anomaly is the only source of explicit PQ breaking. As a byproduct, within the so-called canonical axions the m_a-f_a relation is fixed by QCD [6, 7],

$$m_a^{\mathrm{QCD}} \simeq \frac{f_\pi m_\pi}{f_a} \frac{m_u m_d}{\sqrt{m_u + m_d}} , \tag{1}$$

where m_π, f_π, m_u and m_d denote respectively the pion mass, its decay constant, and the up and down quark masses. The strength of the axion couplings to Standard Model (SM) fields is instead model-dependent: it varies with the matter content of the UV complete axion model.

In recent years there have been many attempts to enlarge the canonical QCD axion window, by considering UV completions of the axion effective Lagrangian which depart from the minimal invisible axion constructions [8–11]. Most approaches actually focused on the possibility of modifying the Wilson coefficient of specific axion-SM effective operators (see Ref. [12] and Refs. therein). A most intriguing possibility consists on departing from the m_a-f_a relation in Eq. (1). Indeed axions which are heavier than the canonical QCD axion have been explored since long and revived in the last years (see e.g. Refs. [13–15]). In contrast, solutions to the strong CP problem with lighter axions were uncharted territory until very recently.

The goal of this work is to study in detail and determine the phenomenological implications of a freshly proposed dynamical –and technically natural– scenario, which solves the strong CP problem with an axion much lighter than the canonical QCD one [16, 17]. Next, we show that dark matter can be accounted for by this extremely light axion and that features a novel production mechanism in the early Universe: the *trapped misalignment mechanism* [18].

2. The non-linearly realized Z_N axion

Let's assume that Nature is endowed with a Z_N symmetry under which N copies of the SM are interchanged and which is non-linearly realized by the axion field [16, 17],

$$Z_N : \quad \mathrm{SM}_k \longrightarrow \mathrm{SM}_{k+1 \, (\mathrm{mod} \, N)} \tag{2}$$

$$a \longrightarrow a + \frac{2\pi k}{N} f_a . \tag{3}$$

Given this symmetry, N mirror and degenerate worlds linked by the axion field would coexist with the same coupling strengths as in the SM, with the exception of the effective θ_k-parameters: for each copy k the effective θ-value is shifted by $2\pi/N$ with respect to that in the neighboring $k - 1$

sector. Thus the total potential for the axion is given by the sum of all the shifted contributions,

$$V_\mathcal{N}(\theta_a) = -m_\pi^2 f_\pi^2 \sum_{k=0}^{\mathcal{N}-1} \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\theta_a}{2} + \frac{\pi k}{\mathcal{N}}\right)}, \tag{4}$$

where $\theta_a \equiv a/f_a$ is the angular axion field. Strikingly, the resulting axion is exponentially lighter than the canonical QCD axion in Eq. (1), because the non-perturbative contributions to its potential from the $\mathcal{N}$ degenerate QCD groups conspire by symmetry to suppress each other [16, 17]. Indeed, it has been shown that this kind of $Z_\mathcal{N}$ symmetric potentials have interesting mathematical properties[1] in the large $\mathcal{N}$ limit and for this case the total axion potential is given in all generality by a compact analytical formula [17],

$$V_\mathcal{N}(\theta_a) \simeq -\frac{m_a^2 f_a^2}{\mathcal{N}^2} \cos(\mathcal{N}\theta_a), \qquad m_a^2 f_a^2 \simeq \frac{m_\pi^2 f_\pi^2}{\sqrt{\pi}} \sqrt{\frac{1-z}{1+z}} \, \mathcal{N}^{3/2} z^\mathcal{N}, \tag{5}$$

where the exponential suppression of the $Z_\mathcal{N}$ axion mass squared ($\propto 2^{-\mathcal{N}}$) in comparison to the canonical case $\left(m_a^{\text{QCD}}\right)^2$ in Eq. (1) is controlled by the ratio of light quark masses $z \equiv m_u/m_d \simeq 1/2$.

The solution to the strong CP problem of this $Z_\mathcal{N}$ scenario required $\mathcal{N}$ to be odd. Overall, the ~ 10 orders of magnitude tuning require by the SM strong CP problem is traded by a $1/\mathcal{N}$ adjustment, where $\mathcal{N}$ could be as low as $\mathcal{N} = 3$.
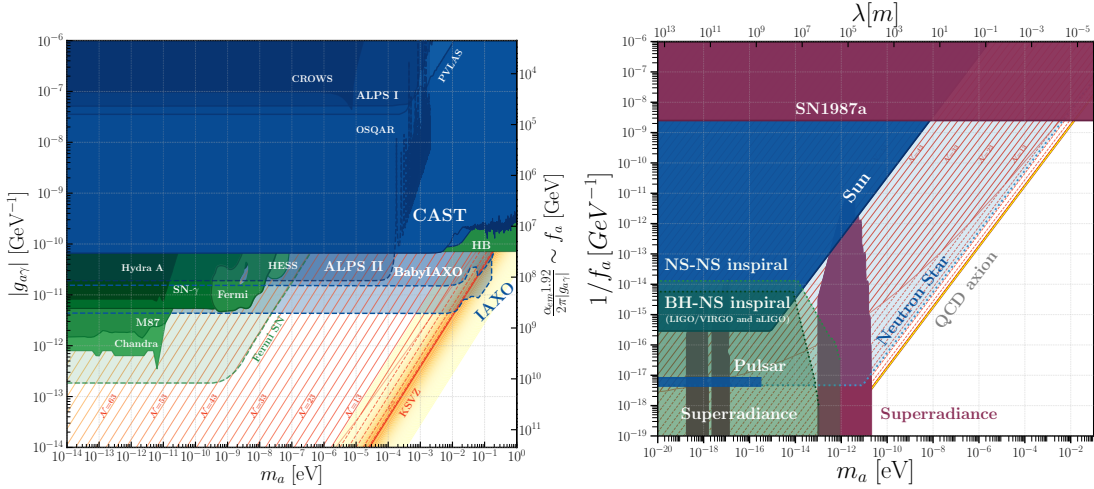
Figure 1: Limits on the axion-photon coupling (left) and on the inverse of the axion decay constant (right) as a function of the axion mass. The **orange** oblique lines represent the theoretical prediction for the $Z_\mathcal{N}$ axion case (assuming vanishing "bare" coupling to photons) for different $\mathcal{N}$. See Refs. [17, 20] for details.

The crucial properties of such a light axion are generic and do not depend on the details of the putative UV completion. An important byproduct of this construction is an enhancement of all axion interactions which is *universal*, that is, model-independent and equal for all axion couplings, at fixed m_a, see Fig. (1). The detailed exploration of the $Z_\mathcal{N}$ paradigm and of the phenomenological constraints which do not require the axion to account for DM can be found in Ref. [17]. It is

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[1]See Ref. [19] for a generalization of the mechanism for non-abelian discrete symmetries.

particularly enticing that experiments set *a priori* to hunt only for ALPs may in fact be targeting solutions to the strong CP problem. For instance, ALPS II is shown to be able to probe the Z_N scenario here discussed down to $N \sim 25$ for a large enough axion-photon coupling, while IAXO and BabyIAXO may test the whole N landscape for values of that coupling even smaller, see Fig. (1).

Furthermore, highly dense stellar bodies allow one to set even stronger bounds in wide regions of the parameter space. These exciting limits have an added value: they avoid model-dependent assumptions about the axion couplings to SM particles, because they rely exclusively on the anomalous axion-gluon interaction needed to solve to the strong CP problem. A dense medium of ordinary matter is a background that breaks the Z_N symmetry. This hampers the symmetry-induced cancellations in the total axion potential: the axion becomes heavier inside dense media *and* the minimum of the potential is located at $\theta_a = \pi$. The corresponding bounds from present solar data, together with projections with neutron stars are shown in Fig. (1) (right). Moreover, gravitational wave data from NS-NS and BH-NS mergers by LIGO/VIRGO and Advanced LIGO will allow to further probe this setup [21, 22].

For the sake of illustration, we have also developed two examples of UV completed models featuring this mechanism [17]. Specially interesting is the Z_N KSVZ model, which is shown to enjoy an improved PQ quality behaviour in large regions of the parameter space, depicted in solid orange lines in Fig. (1), see e.g. Refs. [23, 24] for alternative solutions to the PQ quality problem.

3. Z_N **axion dark matter**

The evolution of the Z_N axion field and its contribution to the DM relic abundance departs drastically from the standard case [18]. The cosmological impact of hypothetical parallel "mirror" worlds has been studied at length in the literature (for a review, see e.g. Ref. [25]). Crucially, the constraints on the number of effective relativistic species N_{eff} imply that the mirror copies of the SM must be less populated[2] –cooler– than the ordinary SM world. As a consequence of
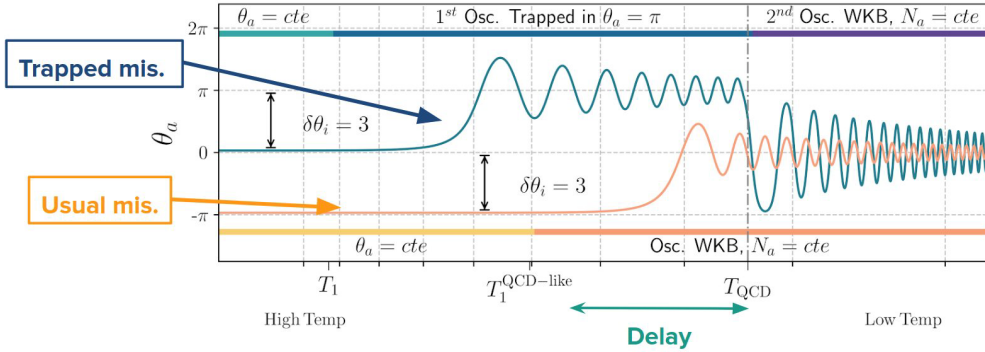

Figure 2: Comparison of the evolution of the axion field in the trapped case vs standard misalignment

this temperature asymmetry among the worlds, and similarly to the previously described finite density effects, the temperature dependence of the Z_N axion potential presents some particular features that modify the production of DM axions in terms of the misalignment mechanism. The

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[2]Mechanisms that source this world-asymmetric initial temperatures while preserving the Z_N symmetry may arise naturally in the cosmological evolution [26, 27].

scenario results in a novel type of misalignment, with a large value of the misalignment angle. In particular, the relic density is enhanced because the axion field undergoes two stages of oscillations, that are separated by an unavoidable and drastic –non-adiabatic– modification of the potential. The axion field is first *trapped* in the wrong minimum (with $\theta = \pi$), which effectively delays the onset of the true oscillations and thus enhances the DM density. We will call this new production mechanism *trapped misalignment*, see Fig. (2). Furthermore, in some regions of the parameter space, trapped misalignment will automatically source the recently proposed kinetic misalignment mechanism [28]. In the latter, a sizeable initial axion velocity is the source of the axion relic abundance as opposed to the conventionally assumed initial misalignment angle. The early stage of oscillations in the Z_N axion framework naturally flows out into kinetic misalignment.
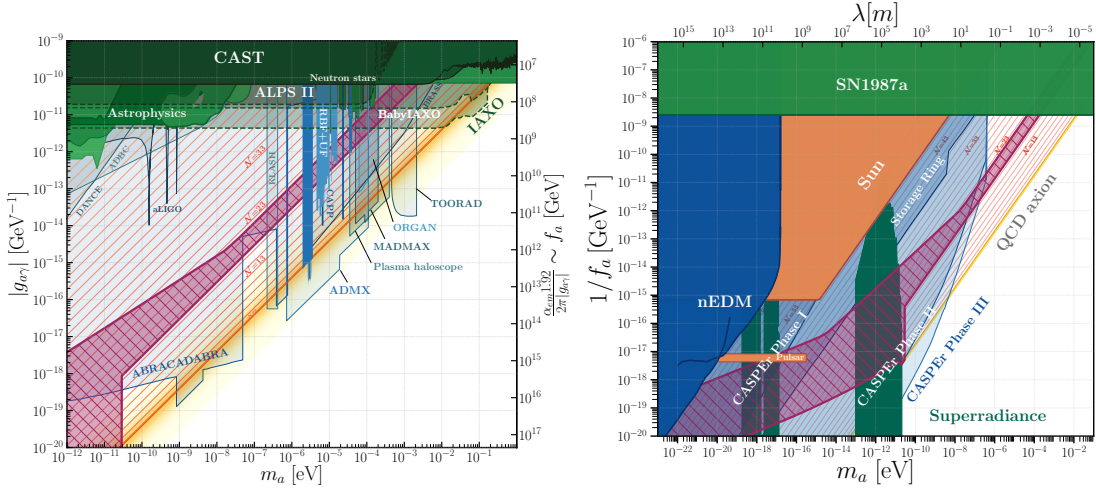
Figure 3: Limits on the axion-photon coupling (left) and on the inverse of the axion decay constant (right) as a function of the axion mass, assuming the axion accounts for the entire DM relic density. See Refs. [18, 20].

The interplay of the different mechanisms together with the implications of the Z_N reduced-mass axion for axion DM searches is studied in detail in [18], including the experimental prospects to probe its coupling to photons, nucleons, electrons and the nEDM operator. As an example the bounds and projections of the Z_N axion assuming it accounts for all the DM abundance are depicted in Fig. (3) for the coupling to photons and to gluons (i.e. $1/f_a$). The **purple** band in Fig. (3) encompasses the region where the prediction of the Z_N axion relic density within the different regimes of the trapped misalignment can account for the entire DM abundance. As a wonderful byproduct of the lower-than-usual f_a values allowed in the Z_N axion paradigm to solve the strong CP problem, all axion-SM couplings are equally enhanced for a given m_a. This increases the testability of the theory in current and future experiments, see Fig. (3). It follows that the Z_N paradigm is –to our knowledge– the only true axion theory that could explain a positive signal in CASPEr-Electric phase I and in a large region of the parameter space in phase II. Moreover, the Z_N axion scenario includes –to our knowledge– *the first technically natural axion model of fuzzy DM that can also solve the strong CP problem.*

Acknowlegments

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