Axion, axino and neutralino dark matter in minimal supergravity

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2013-XX/balazs_csaba

Dark matter can be a mixture of axions, axinos and neutralinos in a Peccei-Quinn extension of supergravity. To find out which dark matter candidate is preferred by data we perform a Bayesian statistical analysis on four such scenarios. The main experimental constraints on these models come from the Planck satellite and from the Large Hadron Collider. Weaker constrains arise from other astrophysical, collider and low energy measurements. Our study reveals that the Peccei-Quinn scenario featuring axino dark matter is clearly preferred over the minimal supegravity model with neutralino dark matter.

1 Introduction

The 7 and 8 TeV center of mass runs of the Large Hadron Collider strongly constrained the simplest supersymmetric models. The ATLAS and CMS collaborations discovered a Higgs boson with a mass close to 126 GeV [1, 2]. Assuming this is the lightest Higgs, in the framework of the Minimal Supersymmetric Standard Model (MSSM) this implies substantial radiative corrections within the Higgs sector. These radiative corrections enter in the MSSM electroweak symmetry breaking condition, which gives the electroweak scale as the difference of Higgs sector masses and the Higgsino mass parameter, and leads to a fine tuning [3].

This unnatural situation is escalated by dark matter fine tuning in the R-parity conserving constrained versions of the MSSM. The minimal supergravity motivated model, the constrained MSSM (CMSSM), is one of these models. The CMSSM is spanned at the Grand Unification Theory (GUT) scale by four parameters: M_0 a common mass for all spin 0 superpartners, $M_{1/2}$ the mass of all spin 1/2 superpartners, A_0 the coefficient in front of all tri-linear terms in the supersymmetry breaking Lagrangian, and $\tan\beta$ the ratio of the vacuum expectation values of the two Higgs doublets.

In the CMSSM dark matter is the lightest neutralino. The abundance of the lightest neutralino, however, only satisfies the Planck implied relic density observation in very narrow slices of the parameter space. This leads to a serious tension between the CMSSM and observation. It is very hard to satisfy the Higgs mass, the dark matter density, and other low energy constraints (such as the anomalous magnetic moment of the muon) simultaneously in the CMSSM. Even if one makes a reasonable compromise, electroweak naturalness will be sacrificed.

Naturalness, thus, suggests extending the MSSM. There are, however, numerous possible ways to extend the MSSM, ranging from modifying its symmetries to introducing new fields. In this brief submission we consider a Peccei-Quinn extension of the CMSSM. Although this scenario does not improve the electroweak naturalness, we show that the dark matter fine tuning is vastly improved. In our case dark matter is an combination of axions, axinos and neutralinos. We show that in the Peccei-Quinn extension of the of the CMSSM the axino is the preferred dark matter candidate when compared to the CMSSM.

2 Peccei-Quinn extended MSSM

To solve the strong CP problem Peccei and Quinn (PQ) extended the Standard Model with a global $U(1)$ symmetry [4, 5]. The $U(1)_{PQ}$ symmetry is spontaneously broken at a scale Λ_{PQ} and the pseudo-Goldstone boson induced by this breaking is the axion. The axion mass is related to the symmetry breaking scale as [6]

$$m_a \simeq 6\,\frac{10^6\,\mathrm{GeV}}{\Lambda_{PQ}}\,\mathrm{eV}. \tag{1}$$

Supersymmetric Peccei-Quinn models feature the chiral superfield

$$\hat{\Phi}_a = \frac{s+ia}{\sqrt{2}} + i\sqrt{2}\bar{\theta}\tilde{a} + i\bar{\theta}\theta F_a, \tag{2}$$

where s is the scalar axion or saxion, a is the the pseudo-scalar axion, $\tilde{a}$ is the axino, and F_a is an auxiliary field [6]. The masses of these field depend on the supersymmetry breaking mechanism. In most cases the saxion is ultra heavy with a mass of about Λ_{PQ}. For the supergravity inspired model the axino mass takes the following form [7],

$$m_{\tilde{a}} \simeq \left(\frac{\Lambda_{PQ}}{M_{Pl}}\right)^{\kappa} M_{Pl} \qquad \text{with} \qquad \kappa \gtrsim 2. \tag{3}$$

A broken Peccei-Quinn symmetry contributes to the neutron electric-dipole moment (nEDM) at tree level [8]. The current experimental limit on the nEDM is $d_n < \left|1.9\times 10^{-26}\right|\, e\,\mathrm{cm}$ at 90% CL [9]. This translates into a lower bound on the PQ breaking scale. A model dependent upper bound has also been obtained for the supergravity case [10], leading to

$$1\times 10^9\ \mathrm{GeV} < \Lambda_{PQ} < 5\times 10^{11}\ \mathrm{GeV}. \tag{4}$$

Due to the bounds on the Peccei-Quinn breaking scale in Eq.(4), the axion mass is always restricted in the range between about 10^{-5} eV and about 6×10^{-3} eV. The axino mass can take values between 2 GeV and 1 TeV for the case $\kappa = 2$, and about 1 eV and 7 keV for $\kappa = 3$. Thus the axion is always the lightest of the three and it also serves as a good hot dark matter candidate. The axino, covering a wide range of masses between a few eV to about a TeV, can be lighter, degenerate or heavier than the lightest neutralino. This makes the PQ violating supergravity (PQSuGra) scenario very interesting since both the axino and the neutralino can contribute to the cold matter abundance.

For $\kappa = 2$, for example, three qualitatively different PQSuGra scenarios are possible depending on the relation between the lightest neutralino mass, $m_{\tilde{\chi}_1}$ and the axino mass, $m_{\tilde{a}}$. These are

- **PQ-1** (neutralino LSP): $m_{\widetilde{\chi}_1^0} < m_{\tilde{a}}$,
- **PQ-2** (axino-neutarlino co-LSPs): $m_{\tilde{a}} \simeq m_{\widetilde{\chi}_1^0}$,
- **PQ-3** (axino LSP): $m_{\tilde{a}} < m_{\widetilde{\chi}_1^0}$.

In the first (third) case the lightest neutralino $\tilde{\chi}_1^0$ (axino $\tilde{a}$) is the dark matter candidate. In the second case they are both cold dark matter candidates.

For $\kappa > 2$ the axino is always the lightest superpartner. However, scenarios with $\kappa > 3$ are unable to generate sufficient dark matter relic density and hence are less interesting. Therefore in the current work we will only analyze the PQSuGra scenarios with $\kappa = 2$ (**PQ-1, PQ-2** and **PQ-3** as defined above) and $\kappa = 3$ (**PQ-3′**).

Following Ref.s [10, 11], we calculate the relic densities for the axions and axinos using

$$\Omega_a h^2 \simeq \frac{1}{4}\left(\frac{6\times 10^{-6}\ \text{eV}}{m_a}\right)^{7/6}, \qquad \Omega_{\tilde{a}}^{NTP} h^2 = \frac{m_{\tilde{a}}}{m_{\widetilde{\chi}_1^0}} \Omega_{\widetilde{\chi}_1^0} h^2, \tag{5}$$

$$\Omega_{\tilde{a}}^{TP} h^2 \simeq 5.5 g_s^6 \ln\left(\frac{1.211}{g_s}\right)\left(\frac{10^{11}\ \text{GeV}}{\Lambda_{PQ}/N}\right)^2 \left(\frac{m_{\tilde{a}}}{0.1\ \text{GeV}}\right)\left(\frac{T_R}{10^4\ \text{GeV}}\right). \tag{6}$$

Here, $\Omega_a h^2$ is the axion relic density, $\Omega_{\tilde{a}}^{NTP} h^2$ is the relic abundance of non-thermally produced axinos from neutralino decay and $\Omega_{\tilde{a}}^{TP} h^2$ is the relic abundance of thermal produced axinos.

Axino dark matter lends the PQSuGra model considerably more flexibility compared to the minimal SuGra model. The properties of axino dark matter, such as its abundance and couplings to standard matter, are governed by its mass and Λ_{PQ} which are independent from the CMSSM parameters. Thus, obtaining a Higgs mass of about 126 GeV, a neutralino abundance of 0.22 ρ_C and low fine tuning is impossible in CMSSM. The PQSuGra model not only accommodates these requirements much easier but its Bayesian evidence suggests that, despite of its extra parameters, it is more viable.

3 Statistical analysis of the PQSuGra model

The Peccei-Quinn extended supergravity model is parametrized by

$$\mathcal{P} = \left\{M_0, M_{1/2}, A_0, \tan\beta, sgn(\mu), \Lambda_{PQ}\right\}. \tag{7}$$

We use a modified version of `SUSY-HIT` [12] to calculate sparticle masses and decay rates, and `MicrOmegas 2.4.5` [13] to calculate the relic density of the lightest neutralinos. The calculation of Bayesian evidences involves the sampling of the likelihood function over the parameter space of the model. Motivated by naturalness, this scan is done over the following parameter ranges:

$$M_0 \in [10, 2000]\,\text{GeV}, \qquad M_{1/2} \in [10, 2000]\,\text{GeV}, \qquad A_0 \in [-3000, 4000]\,\text{GeV},$$
$$\tan\beta \in [0, 62], \qquad \Lambda_{PQ} \in \left[1\times 10^9, 5\times 10^{11}\right]\text{GeV}. \tag{8}$$

The likelihood function includes the following observables:

- LHC Higgs searches: $m_h, \mathcal{R}_{gg\gamma\gamma}, \mathcal{R}_{gg2l2\nu}, \mathcal{R}_{gg4l}$,
- Precision observables (POs): $\delta\rho, (g-2)_\mu^{SUSY}, BR(b\to s\gamma)$,
- LEP-2/Tevatron: $m_{\widetilde{\chi}_1^0}, m_{\widetilde{\chi}_1^\pm}, m_{\tilde{l}}$,

- Planck dark matter abundance: Ω_{DM}.

Here $\mathcal{R}_{gg\gamma\gamma}, \mathcal{R}_{gg2l2\nu}$, and, $\mathcal{R}_{gg4l}$ are ratios of diphoton, $2l2\nu$, and $4l$ event rates in PQSuGra relative to the Standard Model. We calculate posterior probabilities for the SuGra and PQ-SuGra models for two choices of priors: (a) the flat (uniform) prior which is constant in a finite parameter region; and (b) the log prior $\propto (M_0 M_{1/2})^{-1}$.

The calculation of the Bayesian evidences is described in detail in Ref. [14]. The ratio of the evidences allows us to calculate the Bayes factors presented in Table 1. This table shows that the PQSuGra scenario is somewhat preferred over the CMSSM when only constraints from Higgs and precision observables (POs) are imposed. However, scenarios where the axino is dark matter are strongly preferred over the CMSSM. This is because in the latter it is hard to satisfy the LHC Higgs mass constraint, Planck and $g_{mu} - 2$ simultaneously. In contrast, the $PQ-3$ (and $PQ-3'$) models satisfy Planck in a wider range of the PQSuGra parameter space.

Observables	**PQ-1**	**PQ-2**	**PQ-3**	**PQ-3′**
LHC Higgs	0.244	0.305	0.663	0.506
+ POs & LEP	0.238	0.322	0.724	0.626
+ Planck	0.181	0.231	1.693	2.466

Table 1: Bayes factors for various Peccei-Quinn extended supergravity scenarios against the CMSSM. These factors should be interpreted according to Jeffreys: $0-0.5$ "no preference", $0.5-1$ "moderate preference", $1-2$ "strong preference", >2 "decisive evidence".

In conclusion, in the framework of the Peccei-Quinn extended simplest supergravity model a wide variety of experimental data clearly prefers axino over axion or neutralino dark matter.

4 Acknowledgments

This work was supported by the *ARC Centre of Excellence for Particle Physics*. The use of Monash University Sun Grid, a high-performance computing facility, is gratefully acknowledged.

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