Relic Densities of Gauged Axions and Supersymmetry

(a theory for axion-like particles)

Claudio Corianò

Physics Department
University of Salento, Lecce
INFN Lecce, Italy

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References

Work in collaboration with Marco Guzzi (SMU, Dallas) and Antonio Mariano (Univ. of Salento)

“Relic Densities of Dark Matter in the U(1)-extended NMSSM with a gauged axion multiplet”, to appear

related work with Guzzi, Mariano and Lazarides (Univ. of Thessaloniki)) (2010)

“Cosmological properties of a gauged axion”, to appear on PRD

A supersymmetric formulation of the axion/neutralino contributions (without the saxion) is in

“Axion and Neutralinos from Supersymmetric Extensions of the Standard Model with anomalous U(1)'s “ PRD 2009

A non-supersymmetric analysis of the axion for LHC purposes is in

“Axions from intersecting branes and Decoupled Chiral Fermions at the LHC”, Nucl Phys B 2009.

PVLAS claims on the discovery of an axion-like particle “withdrawn”

Notice that two types of interactions Are called for: axion-gauge field \[ \theta F \bar{F} \]
Scalar- gauge field \[ \phi F \bar{F} \]

Both interactions appear automatically in the Stuckelberg multiplet Since b is a complex scalar:

\[ \text{Re } b \rightarrow \text{saxion} \]
\[ \text{Im } b \rightarrow \text{axion} \]
I discuss the structure of the effective action derived from the gauging of anomalous U(1) symmetries. These generalizations have been formulated in the context of special vacua of string theory but they turn out to be quite general.

For instance, they capture the effective description of the Green-Schwarz mechanism of anomaly cancellation in string theory, which requires an axion.

I describe the salient features of this axion, its misalignment at the electroweak and the QCD phase transition and the constraints emerging on these types of theories in the supersymmetric case. Two models developed so far in the analysis of these types of relic densities are:

The **MLSOM** (Minimal Low Scale Orientifold Model) (2005) (with Irges and Kiritsis)

The **USSM-A** (2009, 2010) (Mariano, Guzzi, C.C.)

USSM= U(1) extended NMSSM (-A = anomalous extension)
Abelian extensions of the Standard Model abound

Anomalous abelian extensions are peculiar. They have much more structure compared to their non-anomalous siblings.

This structure involves: 1) an anomalous gauge boson
   2) a physical axion (a gauged axion)

The gauging: a local shift

\[ b \rightarrow b - M\theta(x) \]

Under a gauge transformation

\[ B_\mu \rightarrow B_\mu + \partial_\mu \theta \]

b is called a “Stuckelberg field” and may not be a physical field, due to its derivative coupling to the B gauge boson. In fact the only gauge invariant mass term that one can write down is

\[ \frac{1}{2} (\partial_\mu b + M_{St} B_\mu)^2 \]

\[ M_{St} \equiv M \]
This term is the “Stuckelberg mass term”.

Notice that this term is no different from the usual term that one writes down after spontaneous symmetry breaking for the coupling of the Goldstone to the massive gauge bosons in a gauge theory

\[ M_Z Z_\mu \partial^\mu G_Z + \ldots \]

\[ M_{St} B_\mu \partial^\mu b \]

For this reason there is a close analogy between the Stuckelberg mass term and the Higgs mechanism, if one takes the Higgs field and decouples the radial component from its phase.

The field b may develop a physical component in the presence of an “extra potential”. This extra potential involves b in the form of a phase

\[ V' \sim \lambda_0 e^{i(q_1 - q_2) \frac{b}{M_{St}}} H_1^\dagger H_2 \]

The shift in b can compensate for the change in the phases of the Higgses
The presence of an anomalous structure requires the appearance of PQ-like interactions to leave the effective action invariant

\[ \frac{b}{M_{St}} F \tilde{F} \]

We can then build a gauge invariant effective action in the form

\[ -\frac{1}{4} F_B^2 + \frac{1}{2} (\partial_\mu b + M_{St} B_\mu)^2 + \bar{\psi} (g_V \gamma_\mu + g_A \gamma_\mu \gamma_5) B^\mu + c \frac{b}{M_{St}} F_B \tilde{F}_B \]

This theory has a single chiral fermion, it is anomalous, but we can use gauge invariance to fix the counterterm \( c \).
Gauged axions can be lighter than ordinary PQ axions depending on the way the anomalous symmetry is realized (i.e. the types of anomalies)

The presence of mixed anomalies BYY, BGG, BWW makes the Stuckelberg field sensitive both to weak and to strong interactions. For this reason the misalignment induced at the EWPT and at the QCDPT can be sequential. In this case the mass is defined by the potential of larger size.

Notice:

Compared to the PQ case there is no potential and SSB of the U(1) symmetry.

The U(1) symmetry is at the largest scale in the “Stuckelberg phase”, it is nevertheless a broken symmetry

The physical axion appears only after the appearance of the “extra potential” $V'$
Anomalous U(1) symmetries in the flavour sector

Studied by Ramond, Binetruy, Irges, Lavignac in the late 90’s using Froggat-Nielsen.

Goal: use the anomalous symmetries to get constraints on the neutrino mass matrix. Anomalies cancelled by the GS mechanism. The construction is supersymmetric.

Missing in these analysis: discussion of the physics of the axion. More work needed. The axion does not decouple for general anomalous symmetries. In the susy case the neutralino sector is affected, as I am going to show.

Open question: is there an alternative formulation of the effective action that does not require a Stuckelberg multiplet? If not, then simulations of relic densities set a strong bound on the Stuckelberg scale.
Our first encounter with axions goes back to Peccei-Quinn in their attempt to solve the strong CP problem. Proposed the existence of an anomalous (global) $U(1)$ symmetry (1977) (reviews by Raffelt, Sikivie, Kim).

Why is the theta parameter of QCD so small?

\[
L_\theta = \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\]

\[
L_m = \frac{\alpha_s \text{Arg}(\det M)}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\]

\[
\bar{\theta} = \theta + \text{Arg}(\det M)
\]

\[
L = \sum_{n=1}^{N} \bar{\psi}_n (i \gamma^\mu D_\mu - m_n) \psi_n - \frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} + \frac{\alpha_s \bar{\theta}}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}
\]
Theta is a dynamical field, the phase of a potential describing a global U(1) symmetry, which is

1) spontaneously broken at a very large scale

2) explicitly at the QCD phase transition by the QCD vacuum, due to Instantons (non perturbative effects). A tilting of the potential is induced.

Oscillations take place when

\[ m_a(T) \sim 3H(T) \]

For an electroweak axion oscillations have not yet begun

\[ 10^{-33} \text{eV} \]

Axions “reappear” in string theory (see analysis by Svrceck and Witten, Dine et al) both as to global and local symmetries.
The presence of anomalous **gauge symmetries**

Allows to “relax” the relation between $f_a$ and $m_a$
Reason:
Gauge invariance leaves the WZ counterterm completely independent from the axion mass

\[ \frac{b}{M_{St}} F \tilde{F} \]

The mass of the axion will be related to an “extra potential” \( V' \) whose size is, in principle, free.

\[ V' \sim \lambda_0 e^{i(q_1 - q_2)} \frac{b}{M_{St}} H_1^+ H_2 \]

What is the size of \( \lambda_0 \)?

\( \lambda_0 \) could be of electroweak origin (tiny). In this case the axion has a mass which is typical of a PQ axion, since the mass induced at the EWPT would be tiny. The QCD misalignment, in this case wins, if there is a sequential misalignment \( \sim 10^{-3} \) eV.

But could also be larger. In this case the axion could be more massive. In this case would not be dark matter since its decay would be sizeable \( \tau \sim 10^{18} \text{ sec} \).
Mixed anomalies cancelled by PQ interactions
The physical axion emerges at the electroweak scale.
No direct expression of the potential at the large scale

Motivated by the theory of intersecting branes
IN THE GAUGED CASE:

Anomalous U(1) symmetries with gauge anomalies require an axion for anomaly cancellation and involve (in a minimal formulation)

-- an **anomalous Extra Z prime**

-- a **pseudoscalar** with (contact) Peccei-Quinn (Wess Zumino) interactions.

- a **saxion**

Special formulations of supergravity theories - from the gauging of axionic symmetries, contain the same structure (Van Proeyen, Zagermann and Coll., Ferrara, Andrianopoli Lledo; Derendinger, Prezas, Petropoulos; D’Auria, Fre’, Trigiante)
Example of gauged sugra's

- $(D=4)$ with fields of spin 2, 1, 0, 3/2, 1/2

\[
e^{-1} \mathcal{L} = \frac{1}{2} R + \frac{1}{4} (\text{Im } \mathcal{N}_{IJ}) \mathcal{F}^I_{\mu\nu} \mathcal{F}^{\mu\nu} J
- \frac{1}{8} (\text{Re } \mathcal{N}_{IJ}) \varepsilon^{\mu\nu\rho\sigma} \mathcal{F}^I_{\mu\nu} \mathcal{F}^J_{\rho\sigma}
- \frac{1}{2} g_{uv} D_\mu \varphi^u D^\mu \varphi^v - V(\varphi)
\left\{ -\bar{\psi}_\mu i \gamma^{\mu\nu\rho} D_\nu \psi_\rho^i
- \frac{1}{2} g_A B^B \bar{\lambda}^A \slashed{D} \lambda_B + \text{h.c.} \right\} + \ldots
\]

A. Van Proeyen @ D’Auria fest 2010
The susy model

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<td>$\psi_B(x)$</td>
<td>$F_B(x)$</td>
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<td>$\hat{S}(x, \theta, \bar{\theta})$</td>
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<td>$\tilde{S}(x)$</td>
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<td>$\hat{L}(x, \theta, \bar{\theta})$</td>
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<td>$\hat{R}(x, \theta, \bar{\theta})$</td>
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<td>$\tilde{R}(x)$</td>
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<tr>
<td>$\hat{B}(x, \theta, \bar{\theta})$</td>
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<td>$\lambda_B(x)$</td>
<td>$D_B(x)$</td>
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<td>$\hat{Y}(x, \theta, \bar{\theta})$</td>
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<td>$\lambda_Y(x)$</td>
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<td>$\hat{G}^a(x, \theta, \bar{\theta})$</td>
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<td>$\lambda_a(x), \bar{\lambda}_a(x)$</td>
<td>$D_{G^a}(x)$</td>
</tr>
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Same field content of the NSSM with an extra abelian symmetry
Gauge invariance is restored by a Stuckelberg multiplet and PQ interactions. Supersymmetry is preserved.

\[ \hat{b} = b + i\sqrt{2}\theta\psi_b - i\theta\sigma^\mu\bar{\theta}\partial_\mu b + \frac{\sqrt{2}}{2}\theta\theta\bar{\theta}\sigma^\mu\partial_\mu\psi_b - \frac{1}{4}\theta\theta\bar{\theta}\bar{\theta}b + \theta\theta F_b, \]

The vector multiplet of the B gauge boson and the Stuckelberg multiplet combine into a single massive multiplet whose mass is the “Stuckelberg mass”.

\[ \hat{\mathbb{b}} = (Re b, Im b, \psi_b) \]
\[ \hat{\mathbb{B}} = (B_\mu, \lambda_B) \]

Massive Dirac fermion of mass \( \lambda_B, \psi_b \)
Massive gauge boson of mass \( B_\mu \)
Saxion
All of mass \( M_{St} \)
The axion/saxions/axinos are dynamical

Stuckelberg mass term for the axion multiplet

\[ \mathcal{L}_{St} = \frac{1}{4} \int d^4 \theta (\hat{b} + \hat{b}^\dagger + 2 M_{St} \hat{B})^2 \]

Wess Zumino/PQ interactions

\[ \mathcal{L}_{WZ} = -\frac{1}{2} \int d^4 \theta \left\{ \left[ \frac{1}{2} \frac{c_G}{M_{St}} \text{Tr}(GG) \hat{b} + \frac{1}{2} \frac{c_W}{M_{St}} \text{Tr}(WW) \hat{b} \right. \\
+ \frac{c_Y}{M_{St}} \hat{b} W^Y Y,\alpha + \frac{c_B}{M_{St}} \hat{b} W^B B,\alpha + \frac{c_Y B}{M_{St}} \hat{b} W^Y W^B,\alpha \left. \right] \delta(\hat{\theta}^2) + h.c. \right\} , \]

NMSSM superpotential

\[ \mathcal{W} = \lambda \hat{S} \hat{H}_1 \cdot \hat{H}_2 + y_e \hat{H}_1 \cdot \hat{L} \hat{R} + y_d \hat{H}_1 \cdot \hat{Q} \hat{D}_R + y_u \hat{H}_2 \cdot \hat{Q} \hat{U}_R. \]
\[ \{U(1)_B^3\}, \{U(1)_B, U(1)_Y^2\}, \{U(1)_B, U(1)_Y\}, \{U(1)_B, SU(2)^2\}, \{U(1)_B, SU(3)^2\}. \]

\[
A_{BBB} = -3B_{H_1}^3 - 3B_{H_1}^2(3B_L + 18B_Q - 7B_S) - 3B_{H_1}(3B_L^2 + (18B_Q - 7B_S)B_S) \\
+ 3B_L^3 + B_S(27B_Q^2 - 27B_S B_Q + 8B_S^2)
\]

\[
A_{BYY} = \frac{1}{2}(-3B_L - 9B_Q + 7B_S)
\]

\[
A_{BBY} = 2B_{H_1}(3B_L + 9B_Q - 5B_S) + (12B_Q - 5B_S)B_S
\]

\[
A_{BWW} = \frac{1}{2}(3B_L + 9B_Q - B_S)
\]

\[
A_{BGG} = \frac{3}{2}B_S.
\]
Scalar potential: D and F terms + scalar mass terms
The mu-term is generated via the singlet S

\[ V = V_D + V_F + V_{SMT} \]

\[ V_D = -\frac{1}{2} \left[ \tilde{D}_{B,OS}^2 - 8 \text{Re} b \frac{c_{YB}}{M_{St}} \tilde{D}_{Y,OS} \tilde{D}_{B,OS} + \tilde{D}_{Y,OS}^2 \right] + \frac{g_2^2}{8} \left( |H_1|^2 + |H_2|^2 \right)^2 + \frac{g_2^2}{2} |H_1^+ H_2|^2 \]

\[ V_F = |\lambda H_1 \cdot H_2|^2 + |\lambda S|^2 (|H_1|^2 + |H_2|^2) \]

\[ V_{SMT} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + m_S^2 |S|^2 + (a_\lambda S H_1 \cdot H_2 + h.c.) \]

The saxion generates an infinite number of interactions suppressed by the Stuckelberg mass

\[ \tilde{D}_{B,OS} = \frac{1}{12(-1 + 16 \text{Re} b^2 c_{YB}^2 / M_{St}^2)} \left[ 12 \xi_B + 6 g_B (B_{H_1} |H_1|^2 + B_{H_2} |H_2|^2 + B_S |S|^2) \right. \]

\[- 24 \frac{c_{YB}}{M_{St}} g_Y \text{Re} b \left( |H_1|^2 - |H_2|^2 \right) + \left. 48 \frac{c_{YB}}{M_{St}} \xi_Y \text{Re} b + 12 M_{St} \text{Re} b \right], \]

\[ \tilde{D}_{Y,OS} = \frac{1}{12(-1 + 16 \text{Re} b^2 c_{YB}^2 / M_{St}^2)} \left[ 12 \xi_Y - 6 g_Y (|H_1|^2 - |H_2|^2) + \right. \]

\[ 24 \frac{c_{YB}}{M_{St}} g_B \text{Re} b \left( B_{H_1} |H_1|^2 + B_{H_2} |H_2|^2 + B_S |S|^2 \right) + \left. 48 \frac{c_{YB}}{M_{St}} \xi_B \text{Re} b + 48 c_{YB} \text{Re} b^2 \right]. \]

We have included also Fayet-Iliopoulos terms which are allowed by the symmetry
The corrections of the neutral mass sector follow a typical Pattern of “decoupling”
Z prime gets massive as the Stuckelberg mass grows

\[ m_Z^2 = \frac{1}{4} g^2 v^2 - \frac{g^2 x_B^2}{16 M_{St}^2}, \]
\[ m_Z'^{2} = M_{St}^2 + \frac{g^2 x_B^2}{16 M_{St}} + \frac{1}{4} N_{BB}, \]

\[ N_{BB} = g_B^2 \left( B_{H_1}^2 v_1^2 + B_{H_2}^2 v_2^2 + B_S^2 v_3^2 \right), \]
\[ x_B = g_B \left( B_{H_1} v_1^2 - B_{H_2} v_2^2 \right) \]
\[ v = v_1^2 + v_2^2. \]

Anomalous Extra Z prime at the LHC
NNLO
Guzzi, C.C, NPB 2009

Zoom on the Z resonance for anomalous Drell–Yan in the \( \mu_F = \mu_R = Q \) at NLO/NNLO for all the models.
Non supersymmetric case: the Stuckelberg is a real field

Goldstone modes

Inverting the relation:

The gauged axion is gauge invariant

\[ b = O_{13}^x G_0^x + O_{23}^x G_0^2 + O_{33}^x \chi, \]

\[ \chi = O_{31}^x \text{Im} H_d + O_{32}^x \text{Im} H_u + O_{33}^x b. \]

\[ g_{\chi \gamma \gamma} F_{\gamma} \tilde{F}_{\gamma} \]

\[ g_{\gamma \gamma}^x = \frac{g_B g_Y^2 g_2^2}{32 \pi^2 M g^2} O_{33}^x \sum_f \left( -q_{fL}^B + q_{fR}^B \left( q_{fR}^Y \right)^2 - q_{fL}^B \left( q_{fL}^Y \right)^2 \right). \]

\[ V' = 4 v_u v_d \left( \lambda_2 v_d^2 + \lambda_3 v_u^2 + \lambda_0 \right) \cos \left( \frac{\chi}{\sigma_\chi} \right) + 2 \lambda_1 v_u^2 v_d^2 \cos \left( 2 \frac{\chi}{\sigma_\chi} \right), \]

\[ m_\chi^2 = \frac{2 v_u v_d}{\sigma_\chi^2} \left( \bar{\lambda}_0 v_u^2 + \lambda_2 v_d^2 + \lambda_3 v_u^2 + 4 \lambda_1 v_u v_d \right) \approx \lambda v^2. \]
Misalignment both at the electroweak and at the QCD transition

Mass is generated at the QCD transition

\[ m_\chi \sim \Lambda_{QCD}^2 v / M_{St}^2, \]
\[ \theta' = \chi v / M_{St}^2. \]

\[ Y_\chi(T_i) = \left( \frac{v}{M_{St}} \right) \frac{45 M_{St}^2 (\theta'(T_i))^2}{2 \sqrt{5 \pi g_{*,T} T_i M_P}}. \]

Cosmological abundances are significant only if
The Stuckelberg scale gets very large
Comparisons with the PQ axion

\[ M_{St}^2/\nu \sim f_a, \]

In the non-supersymmetric case the two mechanism of misalignments are Justified
1) by the nature of the charge assignment: the axion shifts both under SU(2) and SU(3), due to the mixed anomalies

2) By the possibility of defining an “extra potential” which is allowed by the symmetry of the theory.

\[
V_{PQ} = \mu_u^2 H_u^\dagger H_u + \mu_d^2 H_d^\dagger H_d + \lambda_{uu}(H_u^\dagger H_u)^2 + \lambda_{dd}(H_d^\dagger H_d)^2 - 2\lambda_{ud}(H_u^\dagger H_u)(H_d^\dagger H_d) + 2\lambda'_{ud}|H_u^T \tau_2 H_d|^2
\]

\[
V_{PQ} = \lambda_0(H_u^\dagger H_d e^{-i g B (q_u - q_d) \frac{g}{2 M}}) + \lambda_1(H_u^\dagger H_d e^{-i g B (q_u - q_d) \frac{g}{2 M}})^2 + \lambda_2(H_u^\dagger H_u)(H_d^\dagger H_d e^{-i g B (q_u - q_d) \frac{g}{2 M}})
\]

The extra potential
periodic as in the QCD instanton potential
but of electroweak origin
PQ axion vs gauged axion (MLSOM)
Supersymmetric axion

Sufficiently long lived to be dark matter if its mass is in the millieV range (USSM-A)
What about the saxion (Re b)?

Has all order interactions with the remaining fields of the model

Its mass is given by the Stuckelberg mass

The saxion decays rather fast and is heavy. Does not interfere with the nucleosynthesis. No late entropy release.
The spectrum of the USSM-A for a 1.5 TeV Stuckelberg mass
\[ \tilde{\chi}_i^0 = a_{i1} \lambda_{W3} + a_{i2} \lambda_Y + a_{i3} \lambda_B + a_{i4} \tilde{H}_1^1 + a_{i5} \tilde{H}_2^2 + a_{i6} \tilde{S} + a_{i7} \psi_b. \]

Neutralino spectrum

Singlino dominance of the LSP

The neutralino mass gets light as The Stuckelberg mass grows “neutralino see-saw”

\[ \{-i\lambda_{W3}, -i\lambda_Y, -i\lambda_B, \tilde{H}_1^1, \tilde{H}_2^2, \tilde{S}, -i\psi_b\} \]
Non-supersymmetric case

Relic densities due to misalignment are sizeable only for a large Stuckelberg mass

Grey area are the WMAP Bounds.
Axions Interactions

Neutralino interactions
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<tr>
<th>in</th>
<th>s-channel</th>
<th>out</th>
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<td>$\chi_i^0 \chi_j^0$</td>
<td>$Z,Z', H^\pm H^\mp, H_0^k H_0^l H_0^l H_0^5, Z'/Z' H_0^k, f \bar{f}, f^\dagger \bar{f}$</td>
<td>$H^\pm H^\mp, H_0^k H_0^l H_0^l H_0^5, Z'/Z', f \bar{f}$</td>
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<td>$H_0^k H_0^l H_0^l H_0^5, Z'/Z', f \bar{f}$</td>
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<td>$H_0^4, H_0^5$</td>
<td>$H_0^k H_0^l H_0^l H_0^5, Z'/Z' H_0^k, f \bar{f}, f^\dagger \bar{f}$</td>
<td>$Z'/Z', Z'/Z'$, $W^\pm W^\mp, f \bar{f}, f^\dagger \bar{f}$</td>
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Relic densities of neutralinos in terms of symmetry breaking parameters and of the Stuckelberg mass. In green the co-annihilation region.
This terms grows as The Stuckelberg mass Grows. It involves a Gaugino and an axino. Comes from the supersymmetric Stuckelberg kinetic term. A large Stuckelberg mass generates a very light LSP.

\[
M_{\chi^0} = 
\begin{pmatrix}
M^{11}_{\chi^0} & 0 & 0 & M^{14}_{\chi^0} & M^{15}_{\chi^0} & 0 & M^{17}_{\chi^0} \\
0 & M^{22}_{\chi^0} & M^{23}_{\chi^0} & M^{24}_{\chi^0} & M^{25}_{\chi^0} & 0 & M^{27}_{\chi^0} \\
0 & 0 & M^{33}_{\chi^0} & M^{34}_{\chi^0} & M^{35}_{\chi^0} & M^{36}_{\chi^0} & 0 \\
0 & 0 & 0 & M^{45}_{\chi^0} & M^{46}_{\chi^0} & 0 & M^{56}_{\chi^0} \\
0 & 0 & 0 & 0 & M^{56}_{\chi^0} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & M^{77}_{\chi^0} \\
\end{pmatrix}
\]

Neutralino mass matrix
This implies that the Stuckelberg mass can’t be above 2 TeV, otherwise we have too much dark matter.

Summary

The fate of the axion in anomalous U(1) model is tied to two parameters

1) The Stuckelberg mass, i.e. the mass of the anomalous gauge boson

2) The size of the “extra potential” generated around the electroweak scale

If this potential is generated by instanton effects at the EW scale then the axion mass is generated (dominantly) at the QCD hadron transition

Relics are sizeable for a Stuckelberg mass of the order of $10^7$ GeV

The particle is close in nature to a PQ axion
If the extra potential is more sizeable, the axion is not dark matter. It behaves more like a light Higgs, has decayed.

In the susy case the Stuckelberg mass can’t be made large $< 1.5 \text{ TeV}$

Due to the generation of a very light neutralino from the axino component

This implies that at the LHC we should find an anomalous extra Z prime soon, or the model is excluded.
The axion obtained by a WZ counterterm can be dark matter only if its very light.

Guzzi, C.C.

A heavier axion is Higgs-like.

Figure 2: Study of the branching ratios of the axi-Higgs. We analyze the dependence on the free parameters $g_B, \tan \beta$. 
Gauged axions appear to be a fundamental component of Theories at the Planck scale

The phenomenology is quite rich and these theories area good laboratory to understand axions in a generalized setting, when anomalous gauge symmetries and modified mechanisms of anomaly cancellation are present, in extensions of the Standard Model.

Strong constraints emerge on the mass of the anomalous extra Z prime which accompanies the axion in these models.

Connection with the flavour/neutrino sector and CP violation. These points will be analyzed in the near future (Froggatt-Nielsen construction of mass matrices). These constructions should be accompanied by an axion

Connection with gauged supergravities (Van Proeyen and Coll.; De Wit and Coll.; Derendinger, Petropoulos and Prezas;...). I believe that the gauging of these theories, built bottom up, naturally leads to gauged supergravities. Open doors for cosmological applications