An anomaly-free Z' extension of the Standard Model with dark matter and improved gauge unification

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based on work with Karim Benakli and Mark Goodsell

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Main objectives

We look for a *non-supersymmetric* Z' extension of the Standard Model such that:

- the full theory is anomaly-free,
- it contains a viable dark matter candidate,
- the extra matter improves the evolution of the SM gauge couplings,
- and it admits a regime where the Z' may appear before the full new sector.

These requirements are still too broad to determine the model uniquely. Since a general classification of anomaly-free spectra is too difficult, we adopt an ansatz for the field content.

The key message of this talk is existence of a gap between formal anomaly-free charge assignments and a genuinely viable model.

Motivation for the secluded sector field content

We choose the secluded sector to be close to Standard-Model-like matter.

A few guiding ideas

- String-theory and D-brane constructions often favour additional matter in SM-like (bi-)fundamental representations.
- In supersymmetric models, gauge unification is naturally helped by the familiar $SU(5)/SO(10)$ family structure and can be preserved by adding complete family-like copies, up to perturbativity constraints.

In the present work we ask whether a related idea can still be useful in a *non-supersymmetric* anomaly-free Z' model with dark matter.

Why an SM-like secluded sector?

The extension is chosen such that:

- the secluded fermion sector is vector-like under $SU(3)_c \times SU(2)_L \times U(1)_Y$, so no new pure SM-gauge anomalies appear;
- both the SM and the secluded sector are chiral under the extra $U(1)_A$, so the mixed $U(1)_A$-SM anomalies must cancel between the two sectors.

This already favours a secluded sector built from quark-like and lepton-like multiplets.

Gauge-coupling running helps select the field content

To fully sove the anomaly cancelation condition we still need to fix the hypercharges.

We further require:

- integer electric charges for colour-singlet states,
- a neutral dark matter candidate,
- improved gauge-coupling evolution relative to the Standard Model.

A full mirror-like sector worsens the running in the SM case, while a simplified SM-like secluded sector can improve it.

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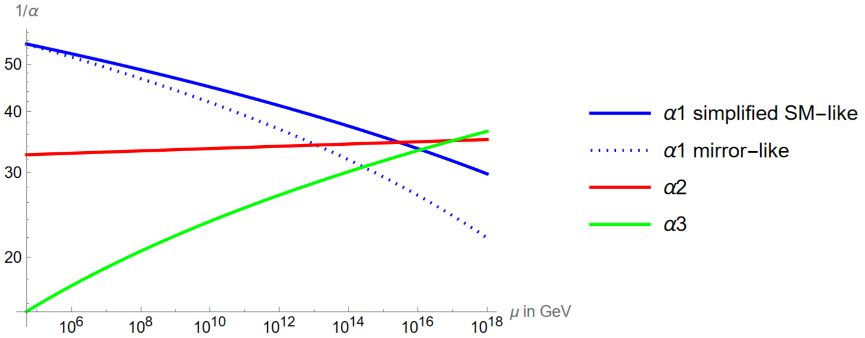

The first important result: the minimal model is not viable

Minimal anomaly-free construction:

- secluded fermions,
- one singlet scalar breaking the extra $U(1)$.

This model is formally consistent, but not phenomenologically viable.

Reason:

- the mass-generating Yukawas preserve too many accidental global symmetries,
- schematically, one keeps separate secluded fermion numbers

$$U(1)_{Q'} \times U(1)_{D'} \times U(1)_{L'} \times U(1)_{E'} \times U(1)_{\nu'},$$

- therefore the lightest state carrying each such number is stable,
- in particular, some exotic coloured states remain stable.

Anomaly-free does not mean viable.

How to fix the model

To remove the unwanted accidental symmetries and obtain viable dark matter, we enlarge the Yukawa structure and the scalar sector.

Higgs singlet and new singlet scalars:

$$S_{3/2}, \qquad S_1, \qquad S_{1/2}, \qquad X_1.$$

We also impose a discrete parity

$$Z_2^{\mathrm{DM}},$$

under which:

- SM fields are even,
- secluded fermions are odd,
- S_1 and $S_{1/2}$ are odd,
- $S_{3/2}$ and X_1 are even.

Then:

- heavy exotics can decay,
- the lightest neutral odd state is stable,
- the scalar sector becomes very rich.

The relevant interactions

The first Yukawa sector generates the leading secluded masses through the $S_{3/2}$ vev:

$$\psi_L^Q \psi_R^Q S_{3/2}, \qquad \psi_L^D \psi_R^D S_{3/2}, \qquad \psi_L^L \psi_R^L S_{3/2},$$
$$\psi_R^E \psi_L^E S_{3/2}, \qquad \psi_L^\nu \psi_R^\nu S_{3/2}.$$

Additional Yukawas, most of them connect visible and secluded sectors:

$$d_R \psi_R^D S_{1/2}, \qquad Q_L \psi_R^Q S_{1/2}, \qquad L_L \psi_R^L S_1,$$
$$\psi_R^E S_1 \nu_R, \qquad S_1 \psi_R^\nu \nu_R, \qquad \psi_L^E \psi_L^\nu X_1, \qquad \psi_L^\nu \psi_L^\nu X_1.$$

Important scalar interactions also appear, for example

$$S_{3/2} S_1 S_{1/2}, \qquad \bar{X}_1 S_{1/2}^2, \qquad S_{1/2} S_{3/2} S_1 X_1.$$

These are *structurally important*: they affect the symmetry structure and the neutral/scalar sectors.

Spectrum after symmetry breaking

The symmetry-breaking pattern is

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}}, \qquad \langle S_{3/2} \rangle = \frac{v_S}{\sqrt{2}}, \qquad \langle X_1 \rangle = \frac{v_X}{\sqrt{2}}$$

Then the extra gauge boson mass is approximately

$$m_{Z'} \simeq \frac{3}{2} g_X v_S$$

up to mixing effects.

The physical secluded spectrum contains:

- one up-type quark-like state,
- three down-type quark-like states,
- one electron-type lepton-like state,
- six neutral secluded states,
- an extended scalar sector.

The lightest Z_2^{DM}-odd neutral state is the dark matter candidate.

Spectrum after symmetry breaking

The symmetry-breaking pattern is

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}}, \qquad \langle S_{3/2} \rangle = \frac{v_S}{\sqrt{2}}, \qquad v_S \gg v.$$

Then the extra gauge boson mass is approximately

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Phenomenological regime of interest

The model itself does not require a hierarchical spectrum.

In the phenomenological analysis, however, we focus on the regime

$$m_{Z'} \gtrsim \text{few TeV}, \qquad m_{\text{heavy secluded}} > m_{Z'}, \qquad m_{\text{DM}} < m_{Z'}.$$

This is the regime where:

- the Z' can appear first,
- part of the secluded sector remains heavier,
- the dark matter candidate stays in the low-energy theory.

This is also the regime relevant for future FCC-scale colliders.

Numerical implementation

We implemented the model using:

- `SARAH`,
- `SPheno`,
- `MicrOMEGAs`,
- `SModelS`,
- `HiggsTools`.

The scan tests simultaneously:

- spectrum consistency,
- perturbativity,
- improved gauge-coupling evolution,
- relic density,
- collider bounds,
- Higgs constraints.

Thus the viable points solve a much harder problem than anomaly cancellation alone.

Dark matter phenomenology

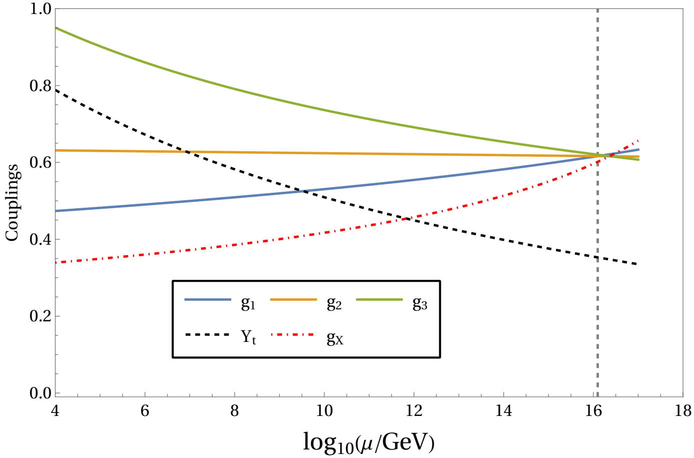
The model contains a WIMP dark matter with a mass around ~ 100GeV. The viable relic density is not governed only by a trivial Z'-portal resonance.

Two main mechanisms appear in the viable regions:

1. **co-annihilation** with nearby secluded states,
2. **annihilation into light pseudoscalars** from the extended scalar sector.

So the enlarged scalar sector is important not only for consistency, but also directly for the dark matter phenomenology.

Gauge-coupling evolution



- The chosen secluded matter content improves the evolution of the SM gauge couplings relative to the SM.
- This is one of the main criteria that selected the non-minimal field content.

Conclusions

- We constructed an explicit *non-supersymmetric* anomaly-free Z' extension of the Standard Model.
- The minimal anomaly-free model fails:
  - accidental global symmetries remain,
  - some exotic coloured states are stable.
- Viability requires:
  - extra singlet scalars,
  - extra Yukawa couplings,
  - a more structured secluded sector.
- Viable points exist with:
  - a heavy Z',
  - heavier secluded states,
  - a neutral dark matter candidate,
  - improved gauge-coupling evolution.

Anomaly cancellation is only the beginning; viability forces a much richer structure.

Thank you for your attention!

Feel free to write to us at: goudeau@lpthe.jussieu.fr

Backup: field content

Secluded fermions:

$$\psi_L, \quad \psi_E, \quad \psi_\nu, \quad \psi_Q, \quad \psi_D.$$

Additional singlet scalars:

$$S_{3/2}, \quad S_1, \quad S_{1/2}, \quad X_1.$$

The sector is vector-like under the SM gauge group and chiral under the extra $U(1)$.

Backup: Higgs sector

Even Z_2^{DM} scalars develop non-vanishing VEVs:

$$H^0 = \frac{v}{\sqrt{2}} \qquad S_{3/2} = \frac{v_S}{\sqrt{2}} \qquad X_1 = \frac{v_X}{\sqrt{2}}$$

Schematically the scalar potential contains: $V \subset \lambda_{ij} \phi_i \phi_i^\dagger \phi_j \phi_j^\dagger$.

These terms will result in mass mixing among these 3 scalars, leading to the Higgs low-energy spectrum: h_1, h_2, h_3 and A_1

We are limited by `SARAH` to the cases where A_1 is light.

Backup: why the minimal model fails

With only secluded fermions and one singlet:

- each secluded Dirac pair carries its own conserved number,
- the lightest state carrying each such number is stable,
- some of these stable states are coloured.

This is why anomaly cancellation alone is not enough.

Backup: rôle of the extra Yukawas

The extra Yukawas do three things:

1. break the accidental global symmetries,
2. allow heavy exotics to decay,
3. generate the non-trivial neutral odd sector relevant for dark matter.

backup: a brief comment on neutrinos

In the present analysis, visible neutrino masses are treated at leading order through the standard Yukawa coupling

$$Y_\nu \, H L_L \nu_R .$$

The full model contains additional neutral-sector couplings, so the complete neutrino mass matrix is richer than this leading-order treatment.

A dedicated analysis of the full loop-corrected neutral sector is left for future work.

backup: apparent anomaly

With the hierarchy considered in the analysis at the Z' mass the relevent EFT possess apparent anomalies.

Extra gauge noninvariant terms, the variations of which cancel the one-loop anomalies.
[2402.02577] by Anastasopoulos, Antoniadis, Benakli and Rondeau

backup: $U(1)_A$ non unification

In the analysis we can fix the gauge coupling from the unification value or let it vary. Fixing it from unification leads to a small hierachy $m_{Z'} < m_{\text{secluded}}$ Allowing it to be smaller leads to a much stronger hierachy with up to one order of magnitude difference.

backup: contour plot