Hidden Gauginos of an unbroken U(1)

Cosmological Constraints and Phenomenological Prospects

[A. Ibarra, A. Ringwald, C. Weniger; arXiv:0809.3196]

Christoph Weniger
DESY Hamburg

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Dark Matter and Crossroads
Introduction
Motivation

String Theory compactifications motivate the consideration of hidden sectors:

1) Couplings in extensions of SM:
   - 'Higgs-Portal': \( |S|^2 H^\dagger H, \; SH^\dagger H \)
   - Coupling to \( \nu_R \): \( \bar{\nu}_R \tilde{H}^\dagger L \)
   - Gauge kinetic mixing: \( \mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} B^{\mu\nu} \)

2) Couplings in extensions of MSSM:
   - Terms in superpotential: \( W \supset SH_d H_u, \; SL H_u \)
   - Gauge kinetic mixing: \( \mathcal{L} \supset \int d^2 \theta W_B^\alpha W_X^\alpha + \text{h.c.} \)
Gauge kinetic mixing

Gauge kinetic mixing is generated by heavy matter charged under $U(1)_Y$ and $U(1)_X$ according to renormalization group equation:

\[
\frac{d}{dt} \chi = - \frac{1}{8\pi^2} g_X g_B \left( \frac{1}{3} + \frac{2}{3} \right) \text{tr}(Q_X Q_B)
\]

Exact values model-dependent:
- $\chi \sim 10^{-2}$ in simplest field th. constructions
- $\chi \sim 10^{-16}$ in heterotic strings with gauge mediation [Dienes et al., 1997]
- $\chi \sim 10^{-26}$ in non-susy model [Chen et al., 2008]

Gauge kinetic part of the effective Lagrangian at low energies:

\[
\mathcal{L} = \int d^2 \theta \left( \hat{W}_B^\alpha \hat{W}_B \alpha + \hat{W}_X^\alpha \hat{W}_X \alpha + 2\chi \hat{W}_B^\alpha \hat{W}_X \alpha \right) + \text{h.c.}
\]
Decoupling

Supersymmetric gauge part of the model:

\[ \mathcal{L} = \int d^2 \theta \left( \hat{W}_B^\alpha \hat{W}_B \alpha + \hat{W}_X^\alpha \hat{W}_X \alpha + 2 \chi \hat{W}_B^\alpha \hat{W}_X \alpha \right) + \text{h.c.} + \int d^2 \theta d^2 \bar{\theta} \left( \Phi^\dagger e_{Q_B g_y} \hat{B} \Phi + h^\dagger e_{Q_x g_x} \hat{X} \hat{h} \right) \]

Kinetic Terms are brought into canonical form via redefinition of fields:

\[ X = \hat{X} + \chi \hat{B} \quad B = \sqrt{1 - \chi^2 \hat{B}} \]

Hidden sector matter acquires small 'minihypercharge':

\[ \mathcal{L} = \int d^2 \theta \left( W_B^\alpha W_B \alpha + W_X^\alpha W_X \alpha \right) + \text{h.c.} + \int d^2 \theta d^2 \bar{\theta} \left( \Phi^\dagger e_{Q_B g_y'} B \Phi + h^\dagger e_{Q_x g_x} X - Q_x \chi g_x' B \hat{h} \right) \]
Gaugino mass mixing

Decoupling is lifted by breaking of supersymmetry, due to gaugino mass matrix:

$$\mathcal{L}_{gauge} = -\frac{1}{4} (\hat{X}_{\mu \nu} \hat{B}_{\mu \nu}) \mathcal{K} \left( \hat{X}_{\mu \nu} \hat{B}_{\mu \nu} \right) - i (\hat{\lambda}_X^\dagger \hat{\lambda}_B^\dagger) \mathcal{K} \sigma^\mu \partial_\mu \left( \hat{\lambda}_X \hat{\lambda}_B \right)$$

$$\mathcal{K} = \begin{pmatrix} 1 & \chi \\ \chi & 1 \end{pmatrix}$$

where:

$$+ \frac{1}{2} (\hat{D}_X^* \hat{D}_B^*) \mathcal{K} \left( \hat{D}_X \hat{D}_B \right) - \frac{1}{2} (\hat{\lambda}_X \hat{\lambda}_B) \hat{\mathcal{M}} \left( \hat{\lambda}_X \hat{\lambda}_B \right) + \text{h.c.}$$

$$\hat{\mathcal{M}} = \begin{pmatrix} \hat{M}_X & \delta \hat{M} \\ \delta \hat{M} & \hat{M}_B \end{pmatrix}$$

The hidden U(1) gaugino in general couples to MSSM neutralinos via mass mixing:

$$\mathcal{M}_N = \begin{pmatrix} M_X & \delta M & 0 & 0 & 0 \\ \delta M & M_B & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W \\ 0 & 0 & M_W & M_Z c_\beta c_W & -M_Z s_\beta c_W \\ 0 & -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu \\ 0 & M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 \end{pmatrix}$$

where

$$\delta M \simeq \delta \hat{M} - \chi \hat{M}_X$$
Mixing angle

If gaugino masses come from single spurion field, \( \langle \hat{Z} \rangle = M_P + \theta^2 F \)
with
\[
\mathcal{L} \supset \int d\theta^2 d\bar{\theta}^2 \frac{\hat{Z}^\dagger}{M_P} (\hat{W}_B \hat{W}_B + 2\chi \hat{W}_B \hat{W}_X + \hat{W}_X \hat{W}_X). + \text{h.c.}
\]
the mass mixing vanishes at tree level: \( \delta M = 0 \)

At low energies, the mass mixing is in general non zero due to quantum effects:
\[
\delta M_{\text{EW}} \simeq \frac{1}{8\pi^2} g_X^2 \text{tr}(Q_X Q_X) \ln \left( \frac{M_P}{M_{\text{hid}}} \right) \chi_{\text{EW}} M_X
\]

The mixing angle between interaction- and mass-eigenstates of bino and hidden U(1) gaugino is given by:
\[
\Theta \simeq \frac{\delta M_{\text{EW}}}{M_B^{\text{EW}} - M_X^{\text{EW}}} \simeq C \cdot \chi_{\text{EW}} \frac{M_X^{\text{EW}}}{M_B^{\text{EW}} - M_X^{\text{EW}}}
\]
with \( 10^{-2} \lesssim C \lesssim 1 \)

subsequently: \( C = 1 \)
Masses in gravity mediation

RGEs will drive $M_X$ to lower values. It can potentially become the lightest supersymmetric particle in the theory if there is an enough number of (heavy) hidden sector matter states.
Masses in hybrid model

\[ M_{\text{SUSY}} > M_X \sim M_{\tilde{G}} \]

\( M_X \) is naturally small if messenger for SUSY breaking only charged under MSSM gauge groups.

Gravitino will have mass similar to \( M_X \) in this case.
Following the above discussion, we concentrate on spectra with and without light gravitinos, where the lightest SUSY particle in the visible sector is a slepton or a neutralino:

| NNLSP | stau  | stau  |
|-------|-------|-------|
| NLSP  | stau  | neutralino | gravitino | $\lambda_x$ |
| LSP   | $\lambda_x$ | $\lambda_x$ | $\lambda_x$ | gravitino |

Mixing Parameters: $10^{-16} < \chi < 10^{-2}$

Particle Masses: 1 – 200 GeV
Constraints
Overproduction

- Hidden U(1) gauginos are produced in the primeval MSSM plasma, similar to gravitinos and axions.
- Since coupling renormalizable, production strongest at low temperatures, when particles become nonrelativistic.
- Hard thermal loop approximation does not work, since QCD coupling becomes of order one.

Production can be estimated by calculating relativistic collision integral for hidden U(1) gauginos in superQCD sector:

\[
\frac{d^4 n_X}{dV dt} = \frac{308}{3\pi^3} \alpha' \alpha_s \Theta(T)^2 \left(1 - \frac{4}{7} \gamma_E - \frac{4}{7} \ln \frac{k^*}{T}\right) T^4
\]

Excluding overproduction yields the bound:

\[
\Theta \lesssim 5 \times 10^{-12} \left(\frac{M_X}{M_B}\right)^{-1/2}
\]
Overproduction

Here, $M_B=180$ GeV. For comparison we show lifetime isocurves for a slepton NLSP with $M_f=150$ GeV.
SuperWIMPs

If the hidden U(1) gaugino is not overproduced, it can acquire the right abundance to be dark matter through the late decay of MSSM relics like staus or neutralinos:

\[ \Omega_{\text{LSP}} = \frac{M_{\text{LSP}}}{M_{\text{NLSP}}} \Omega_{\text{NLSP}} \]

Strong constraints on these 'superWIMP' models come from

- Consistency of standard BBN
  - Dissociation of atomic nuclei
  - Catalytic \(^6\)Li and \(^9\)Be production
- Structure formation and Free Streaming
BBN I: Dissociation of elements

Energy, released from decaying particles during and after BBN, alter the predicted abundances of light elements

- Electromagnetic showers
  - Dissociates $^4$He for $\tau > 10^3$ s, raises $^3$He & D abundance

- Hadronic energy
  - Dissociates $^4$He for $\tau > 10^3$ s, raises $^3$He, D, $^6$Li & $^7$Li abundance
  - Raises n/p for $\tau < 10^3$ s -> increased $^4$He abundance

[Kawasaki, Kohri, Moroi, 2005]
BBN II: Catalytic $^6$Li production

- If the decaying particle is charged, it can form bound states with $^4$He.
- This enhances the interaction rate of D and $^4$He by several orders of magnitude.

Lifetime of charged particle is required to satisfy:

$$
\tau \lesssim 2 \times 10^3 \text{s}
$$

Bound can be avoided if abundance of charged particle is extremely diluted ($Y=n/s < 10^{-16}$)
Free streaming

SuperWIMPs have similar impact on structure formation than warm dark matter:

Density fluctuations are erased on scales below the free streaming length:

\[ \lambda_{FS} = \int_{0}^{z_{prod}} dz \frac{\nu(z)}{H(z)} \]

By recycling of bounds on sterile neutrino dark matter \((m_s > 10 \text{--} 13 \text{ keV})\), Kaplinghat \textit{et al.} find

\[ \lambda_{FS} \lesssim 0.5 \text{ Mpc} \]

[Strigari, Kaplinghat, Bullock, 2007]
Stau NLSP

- Large region of parameter space excluded by overproduction and BBN
- Small phenomenologically allowed region remains for a mixing parameter
  \[ \chi \sim 10^{-13} - 10^{-10} \]
- Free Streaming bounds always subdominant

(For definiteness, we take \( \tilde{\ell}_L \))
We specialize to a bino-like neutralino

The hole parameter space down to

$$\chi \sim \lesssim 10^{-16}$$

is excluded by combination of overproduction and BBN bounds

This is due to the relatively long lifetime and the large hadronic branching fraction of the neutralino
BBN bounds with gravitino

Typical decay widths between the three lightest SUSY particles

The stau decays dominantly into hidden U(1) gauginos, hence OP and BBN bounds don't change with respect to the case without a gravitino.

(red: decay into gravitinos dominant)
Mixed dark matter

Typical decay widths between the three lightest SUSY particles:

$$\Gamma^{-1} \lesssim 10^3 \text{s}$$
$$\tilde{t} \ 150 \text{ GeV}$$
$$\Gamma^{-1} \approx 10^9 \text{s}$$
$$\tilde{G} \ 100 \text{ GeV}$$
$$\Gamma^{-1} \approx 10^7 \text{s}$$
$$\lambda_X \ 50 \text{ GeV}$$

NLSP decay generates warm dark matter component ($\Lambda$CWDM):

$$\Omega_{DM} = f\Omega_{WDM} + (1 - f)\Omega_{CDM}$$

Free streaming length of the warm component:

$$\lambda_{FS} \sim \mathcal{O}(1-50 \text{ Mpc})$$

A complete Analysis in ($f$, $\lambda_{FS}$) space is lacking. We just take $f<0.2$ and $f<0.02$ for reference.

(red: decay into gravitinos dominant)
Mixed dark matter

Hidden gaugino LSP: \( \Lambda \)CWDM bounds constrain thermal gravitino abundance, and hence reheating temperature (see below).

Gravitino LSP: \( \Lambda \)CWDM bounds constrain hidden gaugino abundance, hence the mixing parameter (dashed lines).

(red: decay into gravitinos dominant)
$^6$Li bounds on $T_R$

Catalytic $^6$Li production during BBN constraints the lifetime of charged relic particles, and hence the gravitino mass:

$$\tau_i = \frac{1}{48\pi M_P^2 M_i^5} \left( 1 - \frac{M_G^2}{M_i^2} \right)^4$$

$$\tau \lesssim 2 \times 10^3 \text{s} \quad \Rightarrow \quad M_{\tilde{G}} \lesssim 1 \text{GeV}$$

Requiring, that the gravitino is not overproduced, this translates into bound on reheating temperature via

$$\Omega_{\tilde{G}} h^2 \simeq 0.27 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{M_{\tilde{G}}} \right)^2 \left( \frac{m_{\tilde{g}}}{1 \text{ TeV}} \right)^2$$

[e.g. Bolz et al., 2001]

It follows, that reheating temperatures as high as $10^9 \text{ GeV}$ are problematic in scenarios with gravitino dark matter and stau NLSP

 Bounds can be avoided if stau abundance is extremely diluted ($Y=n/s<10^{-16}$)
Relaxation of reheating bounds

Hidden U(1) gaugino LSP
• Gravitino decay generates WDM fraction $f$
• Reheating bounds depend on allowed values in $(f, \lambda_{FS})$ plane

Gravitino LSP
• Gravitino mass decoupled
• Reheating temperature only bounded by overproduction
• Stau decay generates WDM

$^6$Li bounds on stau abundance are effectively replaced by bounds on $\Lambda$CWDM models
-> 2-3 order of magnitudes weaker
Prospects
Long lived staus at colliders

In models with gravitino LSP, the NLSP lifetime is mainly determined by the planck- and the gravitino mass, which allows a microphysical determination of the planck scale via

\[
M_P^2 \text{(supergr.)} = \frac{M_i^5}{48\pi M_G^2 \Gamma_i} \left(1 - \frac{M_G^2}{M_i^2}\right)^4
\]

If gravitino mass and NLSP lifetime are decoupled this leads to an apparent lower microphysical planck scale in our case.

\[
M_{\tilde{G}} \sim M_X \Rightarrow \Gamma_{\tilde{G}} \ll \Gamma_X
\]

\[
M_P(\text{meas.}) \sim M_P(\text{grav.}) \sqrt{\frac{\Gamma_{\tilde{G}}}{\Gamma_X}} \ll M_P(\text{grav.})
\]

[Buchmüller et al., 2004; Hamaguchi et al., 2004]
Angular distribution

Spin 3/2 and spin $\frac{1}{2}$ can be distinguished in angular distribution of 3-body decays:

\[
\tilde{\tau} \rightarrow \tau + \gamma + \lambda_X
\]

For example:

\[
\tilde{\tau} \rightarrow \tau + \gamma + \tilde{G}
\]

[Buchmüller et al., 2004]

In forward direction, $\cos(\Theta) > 0$, bremsstrahlung dominates and final states similar.

In backward direction, $\cos(\Theta) < 0$, left diagram is important and angular distributions differ significantly.

\[
M_{\tilde{\tau}} = 150 \text{ GeV} \\
M_X = M_{\tilde{G}} = 75 \text{ GeV}
\]
Decaying neutralino dark matter

For anomalously small mixing parameters around $\chi < 10^{-19}$, a neutralino NLSP can be long lived enough to be today's dark matter. It would be subject to decay via:

\[
\begin{align*}
\lambda_B & \rightarrow Z \lambda_X \\
\lambda_B & \rightarrow h \lambda_X \\
\lambda_B & \rightarrow f \bar{f} \lambda_X \\
\lambda_B & \rightarrow \gamma \lambda_X
\end{align*}
\]

The decay products can potentially be observed in measurements of cosmic ray fluxes.

Comparing predictions for the gamma ray flux with EGRET data gives an upper bound on the mixing parameter.

[Sreekumar et al., 1998]
Gamma ray bounds

A conservative bound can be derived from the channel:

$$\lambda_B \rightarrow \gamma \lambda_X$$

The halo signal dominates the total spectrum of this decay and resembles an extragalactic component.

Requiring that this peak does not exceed the flux measured by EGRET bounds the mixing parameter:

$$\chi \lesssim 10^{-20}$$
Conclusions & Outlook

• The decoupling of kinetically mixed unbroken U(1)s is elevated by the breaking of supersymmetry

• If the hidden U(1) is light, overproduction arguments and consistency of BBN provide strong constraints
  – Bino NLSP excluded in large part of parameter space
  – An allowed band remains in the case of a slepton NLSP

• If gravitino is dark matter
  – $^6$Li bounds on the reheating temperature can be relaxed
  – The underlying mechanism could show up at future colliders as unexpected behaviour of long lived sleptons

• Anomalously small mixings can lead to decaying neutralino dark matter, being strongly constrained by observation of cosmic rays

• Outlook
  – Cosmic ray flux of decaying neutralinos
  – Is the elevation of the reheating bound a more general property?
Thank you