Rescuing the Wino from Indirect Searches

Nikita Blinov\textsuperscript{1,2}, David Morrissey\textsuperscript{1}, Jonathan Kozaczuk\textsuperscript{1}, Arjun Menon\textsuperscript{3}

\textsuperscript{1}TRIUMF, Vancouver BC
\textsuperscript{2}University of British Columbia, Vancouver BC
\textsuperscript{3}University of Oregon, Eugene OR

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The Moduli Problem and Reheating

- Scalars (moduli) with $M_{Pl}^{-1}$ suppressed interactions ubiquitous in string theory
- **At least one modulus with** $m_\varphi \approx m_{3/2} \leftarrow$ SUSY breaking scale
- Coherent oscillations of $\varphi$ store energy, dominate energy content of the universe
- $\varphi$ decays when $\Gamma_\varphi \approx H$ and reheats the universe at $T = T_{RH}$

$$T_{RH} \approx 7.7 \text{ MeV} \left(\frac{m_\varphi}{100 \text{ TeV}}\right)^{3/2}$$

- If all superpartners at $m_{3/2} \sim m_\varphi \gtrsim 100$ TeV, bleak prospects for SUSY discovery at LHC
Split spectrum predicted by Anomaly Mediated Supersymmetry Breaking (AMSB)

\[ m_\lambda \sim (\text{loop factor}) \times m_{3/2}, \ m_f \sim m_{3/2} \]

- Gauginos can be light, despite \( m_{3/2} \gtrsim 100 \text{ TeV} \)
- For SM \( M_1 : M_2 : M_3 \approx 7 : 1 : 3 \Rightarrow \text{Wino LSP} \)

Wino DM

- \( \tilde{W}\tilde{W} \) annihilation:

\[
\langle \sigma v \rangle \approx 4 \times 10^{-24} \text{ cm}^3/\text{s} \left( \frac{100 \text{ GeV}}{m_{\tilde{W}}} \right)^2
\]
Non-thermal Wino Dark Matter

Sub TeV wino produced non-thermally by moduli decays

\[ \Omega_{\tilde{W}} h^2 \approx \frac{(m_{\tilde{W}}/20)}{T_{RH}} \Omega_{f.o.} \]

\[ m_{\tilde{W}} = 1000 \text{ GeV}, \ T_{RH} = 38 \text{ MeV} \]

![Graph showing non-thermal abundance \( \Omega_{\chi} h^2 \) and \( \Phi, R, N_{\tilde{W}}, N_i \) against \( m_\phi a \) and \( T_{RH} \) and \( m_\chi \).]
Constraints from Indirect Detection

- Large annihilation cross-section to $\gamma$ lines & continuum $\gamma$s

$\chi^\pm \rightarrow W^\pm \gamma$

$\tilde{W} \rightarrow W^\pm \gamma$

$\chi^\pm \rightarrow W^\pm \gamma, Z$

- Large expected signal from galactic center

- HESS and Fermi-LAT put bounds on line fluxes

$H.E.S.S. \ (2013) \ \text{and} \ \text{Fermi-LAT} \ (2013)$

Fan and Reece (2013) \ \text{and} \ Cohen, Lisanti, Pierce and Slatyer (2013)
Implications for Scale of SUSY Breaking

- ID constraints limit $\tilde{W}$ abundance $\Leftrightarrow T_{RH} \Leftrightarrow m_\phi$!
  
  
  $\Omega_{\tilde{W}} h^2 \approx \frac{(m_{\tilde{W}}/20)}{T_{RH}} \Omega_{\text{f.o.}}$

- If MSSM+AMSB is correct then
  
  $m_{3/2} \sim \frac{g_2}{\beta_2(g_2)} m_{\tilde{W}}$

  and

  $m_{3/2} \sim m_\phi$

- Serious conflict between annihilation bound and $\tilde{W}$ mass prediction

Fan and Reece (2013)
Cohen, Lisanti, Pierce and Slatyer (2013)
If we want superpartners at LHC with AMSB-like spectrum, must suppress Wino abundance or annihilations into photons

Options:

1. **Light hidden sector (HS) with the real LSP**: \( \tilde{W} \rightarrow \chi_1^x + \ldots \)
   
   No direct annihilation into SM

2. **Asymmetric DM**
   
   Annihilations suppressed by small \( \overline{DM} \) density

3. **\( R \)-parity violation**: \( \tilde{W} \rightarrow SM + \overline{SM} \)

4. ???
$U(1)'$ Hidden Sector

Spontaneously broken $U(1)'$ kinetically mixed with $U(1)_Y$

$$W = W_{\text{MSSM}} + \mu' HH^c; \quad \mathcal{L} \supset \frac{\epsilon}{2} \int d^2 \theta X^\alpha B^\alpha$$

HS Neutralino, $\chi_1^x$ can be lighter than $\tilde{W}$ and allows for $\tilde{W} \rightarrow X_\mu \chi_1^x$

- $\chi_1^x$ annihilates directly to HS
- Non-thermal WIMP miracle can be realized with $\chi_1^x$
- **On-shell annihilation products decay into SM**

$$\Gamma(X \rightarrow \overline{\text{SM}} \text{SM}) \propto \frac{1}{3} \alpha \epsilon^2 m_x$$

$$\Omega_x h^2 \text{ and } m_{\chi_1} \text{ for } g_x = 0.1$$

![Graph showing $\Omega_x h^2$ and $m_{\chi_1}$ for $g_x = 0.1$.](image)
Indirect Detection and Cosmology Constraints

- SM decay products generally produce HE photons from hadronization and radiation.
- $\gamma$ lines also possible, but the rate is negligible.
- Annihilations during recombination at $z \sim 1000$ distorts surface of last scattering.

Asymmetric Dark Matter

Asymmetric Dark Matter solves the late-time annihilation problem, while allowing $\tilde{W}$ decay into the HS

- Dirac fermion or complex scalar $Y$ with $(n_Y - n_{\bar{Y}})/s = \eta$ and $n_Y \gg n_{\bar{Y}}$ at late times

Kaplan, Luty, & Zurek (2009)

- Efficient annihilation required to deplete $n_{\bar{Y}}$

$$\langle \sigma v \rangle \gg 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

- Light mediators needed for efficient annihilation $\Rightarrow$ reuse the $U(1)'$ HS

$g_x = 0.2$, $m_Y = 1.5$ GeV, $T_{RH} = 28$ MeV
Challenges for ADM+ $U(1)'$

Efficient annihilation requires

1. Sizable $g_x \gtrsim 0.1$

2. A light mediator $\Rightarrow$ Spin-independent scattering off nuclei

$$\tilde{\sigma}_n \approx 2 \times 10^{-38} \text{ cm}^2 \left( \frac{\epsilon}{10^{-3}} \right)^2 \left( \frac{g_x}{0.1} \right)^2 \left( \frac{\mu_n}{1 \text{ GeV}} \right)^2 \left( \frac{1 \text{ GeV}}{m_x} \right)^4.$$  

Note: $\epsilon$ cannot be arbitrarily small - $\tilde{W}$ must decay before BBN, maintain kinetic equilibrium between HS and MSSM

The HS spectrum must accommodate the decay $\chi_1^x \rightarrow Y\tilde{Y}^*$
Observations

- Non-thermal WIMP miracle with small $T_{RH}$ (i.e. low $m_{3/2}$) is extremely constrained

  \[ \text{Low } T_{RH} \Rightarrow \text{large annihilation rate needed } \Rightarrow \text{High ID rate (if annihilation products are/decay down to SM)} \]

- Even simple extensions like a plain $U(1)^\prime$ are robustly ruled out by ID

- Moduli and DM problems can be solved using ADM, while maintaining collider accessible MSSM gauginos