Rescuing Light Moduli Cosmology 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

August 26, 2014
COSMO 2014

Based on hep-ph:1409.soon
The Moduli Problem and Reheating

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

$$T_{RH} \approx 5.5 \text{ MeV} \left( \frac{m_\phi}{100 \text{ TeV}} \right)^{3/2}, \text{ BBN } \Rightarrow \ T_{RH} \geq 5 \text{ MeV}$$

- If all superpartners at $m_{3/2} \sim m_\phi \gtrsim 100 \text{ TeV}$, bleak prospects for SUSY discovery at LHC
A Solution: Anomaly Mediation and Wino DM

Split spectrum predicted by Anomaly Mediated Supersymmetry Breaking (AMSB)

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

- 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

- Very efficient annihilation:

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

Thermal relic density too small for

\[ m_{\tilde{W}} < 2.8 \text{ TeV!} \]
Non-thermal Wino Dark Matter

Sub TeV wino produced non-thermally by moduli decays

$$\Omega_{\tilde{W}} \approx \left(\frac{m_{\tilde{W}}}{20}\right) \frac{\Omega_{\text{f.o.}}}{T_{\text{RH}}}$$

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

Non-Thermal Abundance $\Omega_{\tilde{W}} h^2$
Constraints from Indirect Detection

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

\[ \tilde{W} \rightarrow W^\pm \rightarrow W^\pm \rightarrow \gamma, \gamma, Z \]

- Large expected signal from galactic center

- HESS and Fermi-LAT put bounds on line fluxes

- $2\langle \sigma v \rangle_{\gamma\gamma} + \langle \sigma v \rangle_{Z\gamma}$
  - Fermi (Einasto)
  - Fermi (NFW)
  - HESS (Einasto)

H.E.S.S. (2013) and Fermi-LAT (2013)

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

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

- In the MSSM this requires
  \[ m_\phi / m_{3/2} \gtrsim 100 \]
  contrary to the generic expectation
  \[ m_\phi \sim m_{3/2} \approx 360 m_{\tilde{W}} \]

Fan and Reece (2013)
Cohen, Lisanti, Pierce and Slatyer (2013)
Ways Out?

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 anti-DM density

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

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

Additional spontaneously broken $U(1)_x$ kinetically mixed with $U(1)_Y$

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

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

$$\Gamma(X \rightarrow \overline{\text{SM}} \text{ SM}) \propto \frac{1}{3} \alpha \epsilon^2 m_x$$
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 solves the late-time annihilation problem, while allowing $\tilde{W}$ decay into the HS

- Dirac fermion or complex scalar $Y$ with $n_Y \gg n_{\bar{Y}}$ 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 $\Rightarrow$ reuse the $U(1)_x$ HS

\[g_x = 0.2, \mu_Y = 2 \text{ GeV}, T_{R_H} = 20 \text{ MeV}\]
Challenges for ADM+ $U(1)_x$

1. Annihilation is not fully efficient, some anti-DM remains:
   - Energy injection during recombination $\Rightarrow$ CMB constraints
   - Indirect detection

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
ADM Works!

\[ \Omega_{\text{adm}}/\Omega_{\text{cdm}} \text{ for } g_x = 0.1 \text{ and } \epsilon = 10^{-4} \]

\[ \Omega_{\text{adm}}/\Omega_{\text{cdm}} \text{ for } \kappa = 5 \times 10^{-3} \text{ and } \epsilon = 10^{-4} \]
An Abelian HS (with or without ADM) can solve the moduli induced MSSM (Wino) LSP problem (or at least relieve tension with ID)

Both cases considered require light $\sim \text{GeV}$ scale scalars

e.g. light HS vector needs a Higgs with a $O(\text{GeV})$ VEV

LHC null searches imply a split spectrum (heavy scalars) in the visible sector

Is there a viable solution with split hidden sector?
Pure $U(1)_x$ does not work: HS neutralino cannot annihilate (no coupling to gauge bosons!)

∴ Consider a hidden $SU(N)_x$

Feng and Shadmi (2011)
Boddy, Feng, Kaplinghat and Tait (2014)

- Spectrum contains $N^2 - 1$ (unconfined) massless gluons and massive gluinos (DM)

$$M_x = r_x \frac{g^2_x}{(4\pi)^2} m_{3/2},$$

- MSSM LSP must decay to HS via high-dimension operators
  ⇒ matter charged under SM gauge group and $SU(N)_x$ at some high scale

- Two sectors never thermalize: HS gluons another radiation bath and set of massless d.o.f.s
Constraints on $SU(N)_x$

- HS gluons another set of massless d.o.f.s

$$\Delta N_{\text{eff}} \simeq \left(\frac{4}{7}\right) (N^2 - 1) \left(\frac{c_x}{c_v}\right), \Delta N_{\text{eff}} \lesssim 1.0$$

$c_i = \text{modulus branching fraction.}$


- HS gluinos remain kinetically coupled to the HS gluon bath (even today!)

Dark acoustic oscillations can leave imprint on galaxy distributions and CMB
At most 5% of DM can strongly interact with dark radiation

Cyr-Racine, de Putter, Raccanelli and Sigurdson (2013)

HS gluinos cannot make up all of DM
HS Gluino Abundance

\[ \Omega_{\tilde{G}_x}/\Omega_{\text{cdm}} \]

\[ m_\varphi = m_{3/2}, \ c = 1, \ c_x/c_v = 1/199 \]

\[ T_{\text{RH}}^x > T_{\text{fo}} \]: thermal production \( \Omega_{\tilde{G}_x} \sim \text{const} \)

\[ T_{\text{RH}}^x \sim T_{\text{fo}} \]: thermal production (non RD universe) \( \Omega_{\tilde{G}_x} \sim M_x^{-3} \propto g_x^{-6} \)

\[ T_{\text{RH}}^x < T_{\text{fo}} \]: non-thermal production with reannihilation \( \Omega_{\tilde{G}_x} \sim M_x \propto g_x^2 \)
Conclusions

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

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

- New gauge sectors can solve the moduli induced LSP problem (with a bit of work), while maintaining collider accessible MSSM gauginos

- Other possibilities: e.g. $R$-parity violation with axion DM

Thank you!
Backup
Boltzmann equations for moduli reheating and self-conjugate DM production:

\[
\frac{d\rho_\varphi}{dt} = -3H\rho_\varphi - \Gamma_\varphi \rho_\varphi \\
\frac{d\rho_R}{dt} = -3H(\rho_R + p_R) + \Gamma_\varphi \rho_\varphi \\
\frac{dn_\chi}{dt} = -3Hn_\chi \frac{N_\chi \Gamma_\varphi}{m_\varphi} \rho_\varphi - \langle \sigma v \rangle (n_\chi^2 - n_{eq}^2)
\]

For ADM, asymmetry generation is modelled by

\[
\frac{dn_{\Psi, \overline{\Psi}}}{dt} + 3Hn_\Psi = (1 \pm \kappa/2) \frac{N_\Psi \Gamma_\varphi}{m_\varphi} \rho_\varphi + \ldots
\]
The hidden gluino soft mass is

\[ M_x = r_x \frac{g_x^2}{(4\pi)^2} m_3/2 , \]

\[ r_x = 3N \text{ for pure AMSB.} \]

Confining transition at \( \Lambda_x \) to a theory of massive glueball (and glueballino) bound states.

\[ \Lambda_x = M_x \exp \left( -\frac{3r_x m_{3/2}}{22N M_x} \right) . \]

For \( M_x < 1000 \text{ GeV} \), \( r_x = 3N \), and that \( M_x < M_2 \), \( \Lambda_x < 10^{-61} \text{ GeV} \).
Connectors to the MSSM

Decay of lightest MSSM superpartner requires matter charged under both MSSM and $SU(N)_x$. For example:

\[ W \supset \lambda_u H_u FP + \lambda_d H_d F^c P^c + \mu_F FF^c + \mu_P PP^c . \]

\[
\Gamma \simeq (1 \times 10^{-6} \text{ s})^{-1} (N^2 - 1) N_F^2 \left| N_{13} \right|^2 \\
\times \left( \frac{\alpha_x}{10^{-3}} \right)^2 \left( \frac{\lambda_u}{0.75} \right)^4 \left( \frac{m_{\chi_1^0}}{200 \text{ GeV}} \right)^3 \left( \frac{100 \text{ TeV}}{\mu_F} \right)^4
\]