Rescuing the Wino from Indirect Searches

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The Moduli Problem and Reheating

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

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

- If all superpartners at $m_{3/2} \sim m_\varphi \gtrsim 100\ {\rm TeV}$, bleak prospects for SUSY discovery at LHC

A Solution: Anomaly Mediation and Wino DM

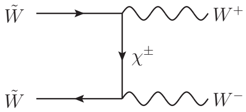
Split spectrum predicted by Anomaly Mediated Supersymmetry Breaking (AMSB)

$$m_\lambda \sim (\text{loop factor}) \times m_{3/2}, \;\; m_{\tilde{f}} \sim m_{3/2}$$

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

Wino DM

- $\widetilde{W}\widetilde{W}$ annihilation:

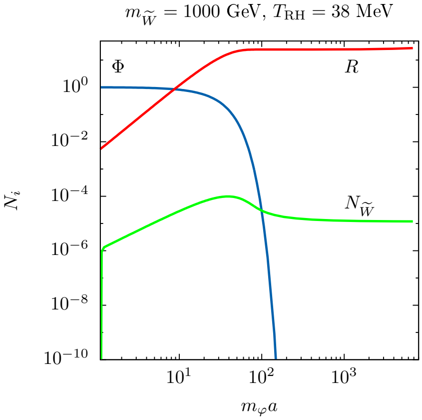


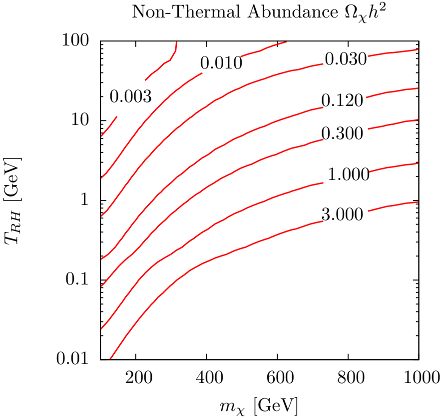
$$\langle \sigma v \rangle \approx 4\times 10^{-24}\ \text{cm}^3/\text{s} \left(\frac{100\ \text{GeV}}{m_{\widetilde{W}}} \right)^2$$

Non-thermal Wino Dark Matter

Sub TeV wino produced non-thermally by moduli decays

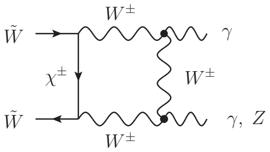
$$\Omega_{\widetilde{W}} h^2 \approx \frac{(m_{\widetilde{W}}/20)}{T_{\rm RH}} \Omega_{\rm f.o.}$$



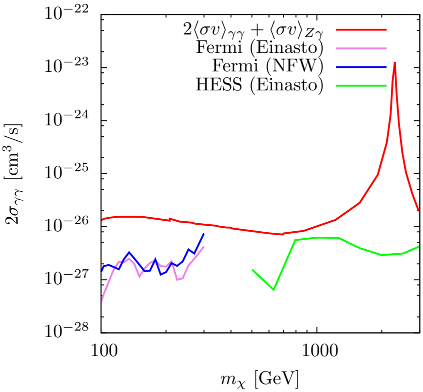


Constraints from Indirect Detection

- Large annihilation cross-section to γ *lines* & continuum γs



- Large expected signal from galactic center
- HESS and Fermi-LAT put bounds on line fluxes



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 $\widetilde{W}$ abundance $\Leftrightarrow T_{\rm RH} \Leftrightarrow m_\varphi$!

$$\Omega_{\widetilde{W}} h^2 \approx \frac{(m_{\widetilde{W}}/20)}{T_{\rm RH}} \Omega_{\rm f.o.}$$

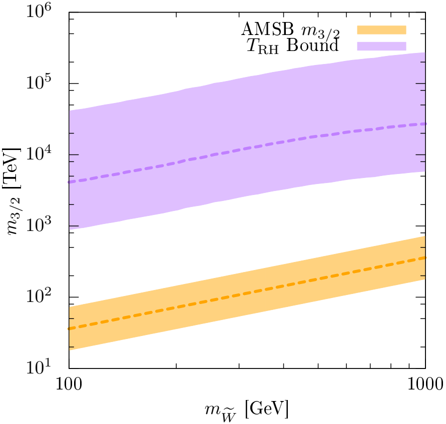
- If MSSM+AMSB is correct then

$$m_{3/2} \sim \frac{g_2}{\beta_2(g_2)} m_{\widetilde{W}}$$

and

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

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



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:** $\widetilde{W} \to \chi_1^x + \ldots$
   No direct annihilation into SM
2. **Asymmetric DM**
   Annihilations suppressed by small $\overline{\mathrm{DM}}$ density
3. R-parity violation: $\widetilde{W} \to \mathrm{SM} + \overline{\mathrm{SM}}$
4. ???

$U(1)'$ Hidden Sector

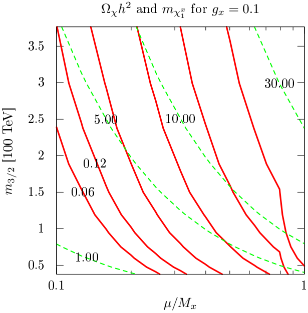
Spontaneously broken $U(1)'$ kinetically mixed with $U(1)_Y$

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

HS Neutralino, χ_1^x can be lighter than $\widetilde{W}$ and allows for $\widetilde{W} \to X_\mu \chi_1^x$

- χ_1^x annihilates directly to HS
- Non-thermal WIMP miracle can be realized with χ_1^x
- **On-shell annihilation products decay into SM**

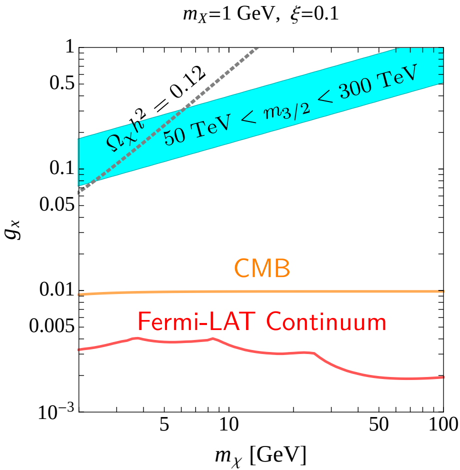
$$\Gamma(X \to \overline{\rm SM}\ {\rm SM}) \propto \frac{1}{3}\alpha\epsilon^2 m_x$$



Indirect Detection and Cosmology Constraints

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

Hütsi, Chluba, Hektor & Raidal (2011), Galli, Iocco, Bertone & Melchiorri (2011)



Asymmetric Dark Matter

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

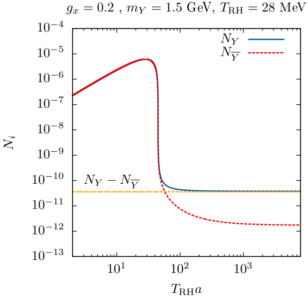
- Dirac fermion or complex scalar Y with $(n_Y - n_{\overline{Y}})/s = \eta$ and $n_Y \gg n_{\overline{Y}}$ at late times

Kaplan, Luty, & Zurek (2009)

- Efficient annihlation required to deplete $n_{\overline{Y}}$

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

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



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

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

Note: ϵ cannot be arbitrarily small - $\widetilde{W}$ must decay before BBN, maintain kinetic equilibrum between HS and MSSM

The HS spectrum must accomodate the decay $\chi_1^x \to Y\widetilde{Y}^*$

Observations

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

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

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

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