Rescuing Light Moduli Cosmology from Indirect Searches

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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 φ store energy, dominate energy content of the universe
- φ decays when $\Gamma_\varphi \approx H$ and reheats the universe at $T = T_{\mathrm{RH}}$

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

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

A Solution: Anomaly Mediation and Wino DM

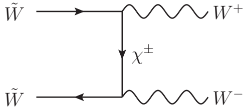
Split spectrum predicted by Anomaly Mediated Supersymmetry Breaking (AMSB)

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

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

Wino DM

- Very efficient annihilation:



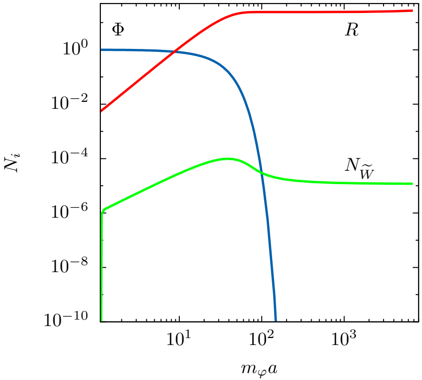
$$\langle \sigma v \rangle \approx 4 \times 10^{-24} \text{ cm}^3/\text{s} \left(\frac{100 \text{ GeV}}{m_{\widetilde{W}}} \right)^2$$

Thermal relic density too small for $m_{\widetilde{W}} < 2.8$ TeV!

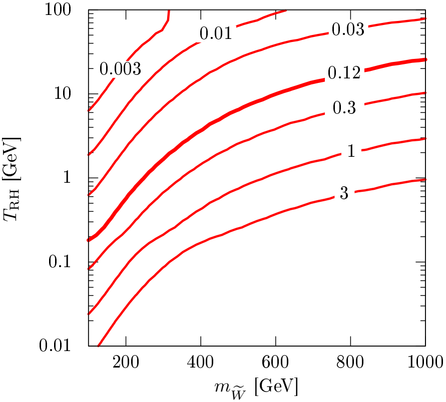
Sub TeV wino produced non-thermally by moduli decays

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

$m_{\widetilde{W}} = 1000$ GeV, $T_{\rm RH} = 38$ MeV

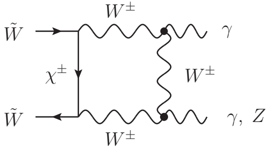


Non-Thermal Abundance $\Omega_{\widetilde{W}} h^2$

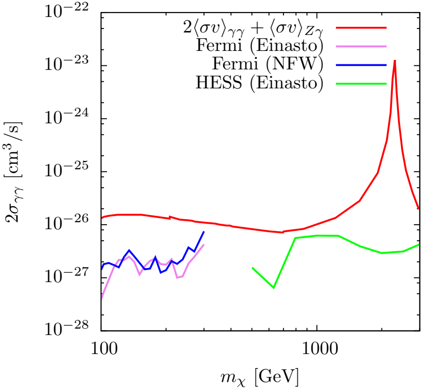


Constraints from Indirect Detection

- 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_{RH} $\Leftrightarrow$ m_φ!

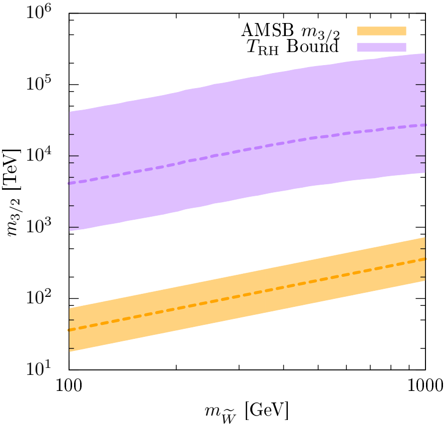
$$\Omega_{\widetilde{W}} \approx \frac{(m_{\widetilde{W}}/20)}{T_{\mathrm{RH}}}\Omega_{\mathrm{f.o.}}$$

- In the MSSM this requires

$$m_\varphi/m_{3/2} \gtrsim 100$$

contrary to the generic expectation

$$m_\varphi \sim m_{3/2} \approx 360 m_{\widetilde{W}}$$



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

$U(1)_x$ Hidden Sector

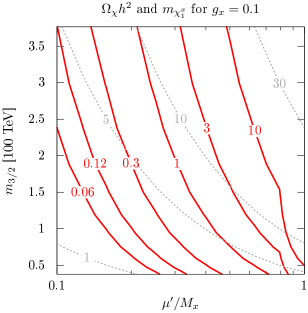
Additional spontaneously broken $U(1)_x$ kinetically mixed with $U(1)_Y$

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

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**

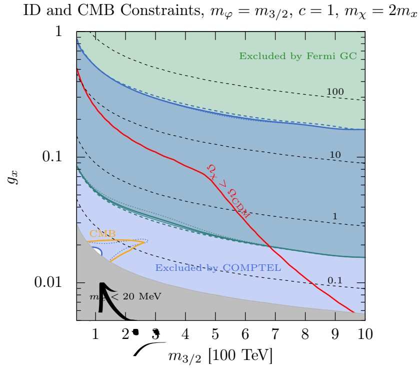
$$\Gamma(X \to \overline{\text{SM}}\,\text{SM}) \propto \frac{1}{3}\alpha\epsilon^2 m_x$$



Indirect Detection and Cosmology Constraints

- SM decay products generally produce HE photons from hadronization and radiation
- 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

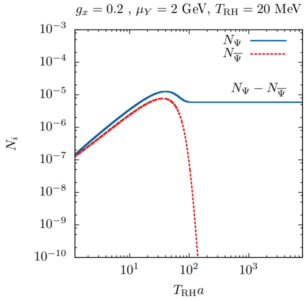
- Dirac fermion or complex scalar Y with $n_Y \gg n_{\overline{Y}}$ at late times

Kaplan, Luty, & Zurek (2009)

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

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

- Light mediators needed $\Rightarrow$ reuse the $U(1)_x$ HS



Challenges for ADM+$U(1)_x$

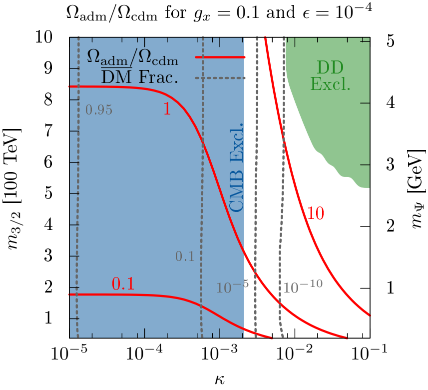
1. Annihilation is not fully efficient, some anti-DM remains:
   Energy injection during recombination $\Rightarrow$ CMB constraints
   Indirect detection

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

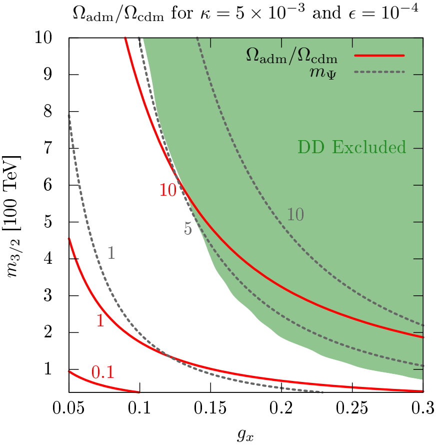
$$\tilde{\sigma}_n \approx 2 \times 10^{-38}\ \mathrm{cm}^2 \left(\frac{\epsilon}{10^{-3}}\right)^2 \left(\frac{g_x}{0.1}\right)^2 \left(\frac{\mu_n}{1\ \mathrm{GeV}}\right)^2 \left(\frac{1\ \mathrm{GeV}}{m_x}\right)^4 .$$

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

ADM Works!



$\Omega_{adm}/\Omega_{cdm}$ for $g_x = 0.1$ and $\epsilon = 10^{-4}$
$\Omega_{adm}/\Omega_{cdm}$
DM Frac.
DD
Excl.
CMB Excl.
0.95
1
0.1
10^{-5}
10^{-10}
10
0.1
$m_{3/2}$ [100 TeV]
m_Ψ [GeV]
κ



$\Omega_{adm}/\Omega_{cdm}$ for $\kappa = 5 \times 10^{-3}$ and $\epsilon = 10^{-4}$
$\Omega_{adm}/\Omega_{cdm}$
m_Ψ
DD Excluded
10
10
5
1
1
0.1
$m_{3/2}$ [100 TeV]
g_x

Observations So Far

- 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 $\sim \mathrm{GeV}$ scale scalars

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

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

  Is there a viable solution with split hidden sector?

Mini-Split With a Non-Abelian Hidden Sector

Pure $U(1)_x$ does not work: HS neutralino cannot annihilate (no coupling to gauge bosons!)
$\therefore$ 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)

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

- MSSM LSP must decay to HS via high-dimension operators
  $\Rightarrow$ 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

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

$c_i =$ modulus branching fraction.

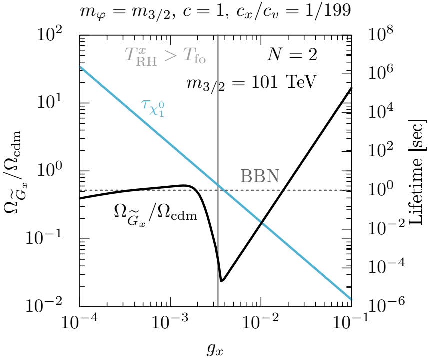
Cyburt, Fields, Olive and Skillman (2004)

- 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



$T^x_{\rm RH} > T_{\rm fo}$: thermal production $\Omega_{\widetilde{G}_x} \sim \text{const}$

$T^x_{\rm RH} \sim T_{\rm fo}$: thermal production (non RD universe) $\Omega_{\widetilde{G}_x} \sim M_x^{-3} \propto g_x^{-6}$

$T^x_{\rm RH} < T_{\rm fo}$: non-thermal production with reannihilation $\Omega_{\widetilde{G}_x} \sim M_x \propto g_x^2$

Conclusions

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

  Low $T_{\rm RH} \Rightarrow$ 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 possibilies: *e.g.* R-parity violation with axion DM

Thank you!

Backup

Moduli Decays and Reheating

Boltzmann equations for moduli reheating and self-conjugate DM production:

$$\frac{d\rho_\varphi}{dt} = -3H\rho_\varphi - \Gamma_\varphi \rho_\varphi$$
$$\frac{d\rho_R}{dt} = -3H(\rho_R + p_R) + \Gamma_\varphi \rho_\varphi$$
$$\frac{dn_\chi}{dt} = -3Hn_\chi \frac{\mathcal{N}_\chi \Gamma_\varphi}{m_\varphi}\rho_\varphi - \langle \sigma v \rangle (n_\chi^2 - n_{\rm eq}^2)$$

For ADM, asymmetry generation is modelled by

$$\frac{dn_{\Psi,\overline{\Psi}}}{dt} + 3Hn_\Psi = (1 \pm \kappa/2)\frac{\mathcal{N}_\Psi \Gamma_\varphi}{m_\varphi}\rho_\varphi + \ldots$$

Mass Spectrum and Confinement in $SU(N)_x$

- The hidden gluino soft mass is

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

$r_x = 3N$ for pure AMSB.

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

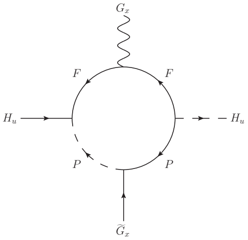
$$\Lambda_x = M_x \exp\left(-\frac{3r_x}{22N}\frac{m_{3/2}}{M_x}\right) \ .$$

For $M_x < 1000\,\mathrm{GeV}$, $r_x = 3N$, and that $M_x < M_2$, $\Lambda_x < 10^{-61}\,\mathrm{GeV}$.

Connectors to the MSSM

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

$$W \supset \lambda_u H_u F P + \lambda_d H_d F^c P^c + \mu_F F F^c + \mu_P P P^c \ .$$



$$\Gamma \simeq (1 \times 10^{-6}\,\mathsf{s})^{-1} (N^2 - 1) N_F^2 |\mathbf{N}_{13}|^2$$
$$\times \left(\frac{\alpha_x}{10^{-3}}\right)^2 \left(\frac{\lambda_u}{0.75}\right)^4 \left(\frac{m_{\chi_1^0}}{200\,\mathrm{GeV}}\right)^3 \left(\frac{100\,\mathrm{TeV}}{\mu_F}\right)^4$$