WIMP less Dark Matter

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Outline

• The WIMPless “Miracle” and AMSB
• A simple Abelian model: SQED
• Cosmological implications and observables
The WIMP miracle

$$\Omega_X \propto \frac{1}{\langle \sigma_{\text{an}} v \rangle} \sim \frac{m_X^2}{g_X^4}$$

$$g_X \sim g_{\text{weak}} \sim 0.6$$

$$m_X \sim m_{\text{weak}} \sim 100 \text{ GeV} - 1 \text{ TeV}$$

$$\Omega_X \sim 0.1$$
The WIMP miracle

\[ \Omega_X \propto \frac{1}{\langle \sigma_{\text{an}} v \rangle} \sim \frac{m_X^2}{g_X^4} \]

\[ g_X \sim g_{\text{weak}} \sim 0.6 \]

\[ m_X \sim m_{\text{weak}} \sim 100 \text{ GeV} - 1 \text{ TeV} \]

\[ \Omega_X \sim 0.1 \]
WIMPless Dark Matter with AMSB

- In AMSB, SUSY breaking gaugino masses scale like
  \[ m_{\chi} \sim \frac{b g^2}{16\pi^2} M_3^{3/2} \]
  \[ \beta(g) = \frac{b}{16\pi^2} g^3 \]

- Scalar masses scale like
  \[ m_{\phi}^2 = \frac{b g^4}{16\pi^2} M_3^{2} \]
Hidden Sectors

Dictates size of SUSY breaking mass scales

\[ m_{\text{AMSB}}^{\text{soft}} \sim \frac{g^2}{16\pi^2} M_3^{3/2} \]

Visible Sector (SM, MSSM)

Hidden Sector (Dark Matter)

\[ M_3^{3/2} \sim 100 \ \text{TeV} \]
Hidden Sector and Visible Sector

AMSB masses

\[ m_{\text{AMSB}}^{\text{soft}} \sim \frac{g^2}{16\pi^2} M_{3/2} \quad M_{3/2} \sim 100 \text{ TeV} \]

\[ \Omega_X \propto \frac{1}{\langle \sigma_{\text{an}} v \rangle} \sim \frac{m_X^2}{g_X^4} \]

Hidden Sector

\[ \frac{m_X}{g_X^2} \sim \frac{1}{16\pi^2} M_{3/2} \sim \frac{m_{\text{weak}}}{g_{\text{weak}}^2} \]

Visible Sector
Is the Dark Matter mass set just by the AMSB mass?
What if you have a $\mu$-term?

$$\tilde{m}_{\text{phys}} \sim \frac{g^2}{16\pi^2}M_{3/2} + \mu$$

We hope that...

$$\mu \sim \frac{g'^2}{16\pi^2}M_{3/2}$$

$$\tilde{m}_{\text{phys}} \sim \frac{g^2}{16\pi^2} f(R) M_{3/2}$$

$$R = \frac{g'^2}{g^2} = \frac{\mu}{m_{\text{AMSB}}}$$

$$R \sim \mathcal{O}(1)$$

$$\Omega_X \propto \frac{1}{\langle \sigma_{\text{ann}} v \rangle} \sim \frac{m_X^2}{g_X^4} \sim f(R) M_{3/2}$$
• In addition to the right ratio of mass to couplings, the Hidden Sector needs a thermal bath to get freeze-out of the thermal relic.

• This thermal bath contributes to the light degrees of freedom $g^*$ which is constrained at CMB and BBN.

• Usually parameterized as effective number of neutrinos

$$\Delta N_{\text{eff}} \equiv N_{\text{eff}} - N_{\text{eff}}^{\text{SM}}$$

$$\Delta N_{\text{eff}} = 0.19 \pm 1.2 \ (95\% \ CL) \ BBN$$

$$\Delta N_{\text{eff}} = 1.29^{+0.86}_{-0.88} \ (68\% \ CL) \ CMB$$
**Model: SQED with $N_f$ flavors**

$U(1)$ gauge symmetry, photon $\gamma$, photino $\tilde{\gamma}$

$N_f$ chiral electron superfields $\hat{e}^+$

$N_f$ chiral electron superfields $\hat{e}^-$

$$W = \mu \hat{e}^+_i \hat{e}^-_i$$

$$m_{\tilde{\gamma}} = b \frac{g^2}{16\pi^2} M_{3/2}$$

$$m_{e_i} = |\mu|$$

$$m_{\hat{e}_{i1,2}}^2 = \left[ |\mu|^2 - 2b \left( \frac{g^2}{16\pi^2} M_{3/2} \right)^2 \right]^{1/2}$$

$N_f, \mu/m_{\tilde{\gamma}}$
$m_{\tilde{\gamma}} = b \frac{g^2}{16\pi^2} M_{3/2}$

$m_{e_i} = |\mu|$

$m_{e_{1,2}} = \left[|\mu|^2 - 2b \left(\frac{g^2}{16\pi^2} M_{3/2}\right)^2\right]^{1/2}$

$m_{\gamma} = 0$  \quad \text{Dark Photon}
Spectrum

\[ M_{3/2} \]

Visible sector

Hidden Sector

\[ m_{\tilde{\gamma}} = b \frac{g^2}{16\pi^2} M_{3/2} \]

\[ m_{e_i} = |\mu| \]

\[ m_{e_{i1,2}}^2 = \left[ |\mu|^2 - 2b \left( \frac{g^2}{16\pi^2} M_{3/2} \right)^2 \right]^{1/2} \]

\[ N_f, \mu/m_{\tilde{\gamma}} \]

\[ b = 2N_f \]

Charged!

MSSM Superpartners

SM particles

SM Photon

Dark Photon

\[ m_\gamma = 0 \]
Annihilation Processes

\[ e_i^+ e_i^- \rightarrow \gamma \gamma \]

\[ \tilde{e}_i^+ \tilde{e}_i^- \rightarrow \gamma \gamma \]

\[ \tilde{\gamma} \tilde{\gamma} \rightarrow \gamma \gamma \]

Photino not a good WIMPless relic!

\[ \sigma \propto \left( \frac{g^2}{16\pi^2} \right)^2 \frac{g^4}{m^2} \]
Ratio of selectron and electron masses
• Dark matter is made up of both electrons and selectrons protected by charge, flavor symmetry
• Halos are like a plasma, so the long range force is actually screened (Debye screening length)
• Dark force! Constraints from self interacting dark matter
• Dark photon contributes to the light degrees of freedom \((g^* or \Delta N_{\text{eff}})\) at CMB and BBN
• Relic Density fixed by \(M_{3/2}\) at each point in the parameter space
Relic Density

\[ \sigma_{\text{an}} v \approx \sigma_0 \equiv k_X \frac{\pi \alpha_X^2}{m_X^2} \]

\[ \Omega_X \approx \xi_f \frac{0.17 \text{ pb}}{\sigma_0} \simeq 0.23 \xi_f \frac{1}{k_X} \left[ \frac{0.025}{\alpha_X} \frac{m_X}{\text{TeV}} \right]^2 \]

(Assuming s-wave annihilation)

\[ \xi_f = \frac{T_f^h}{T_f^{\text{vis}}} \]

\[ \Omega_X = 0.23 \mathcal{F} \left( N_F, \frac{|\mu|^2}{m_{\tilde{\gamma}}^2} \right) \left( \frac{\sqrt{\xi_f} M_{3/2}}{100 \text{ TeV}} \right)^2 \]
Gravitino Mass... ?

Potential Unstable

Photino Overproduction

$\frac{|\mu|}{m_{\gamma}}$ vs. $N_F$

$\sqrt{\xi_f M_{3/2}}$ TeV
What determines $\xi_f = \frac{T_f^h}{T_{vis}^f}$?

- Reheating might heat both sectors differently
- Or we could assume both sectors were in thermal contact in the early universe

\[
\frac{T^h_f}{T_{vis}^f} = \left[ \frac{g^h_*(T^h_\infty)}{g^h_*(T^h_f)} \right]^{\frac{1}{3}} \frac{T^h_\infty}{T_{vis}^\infty}
\]
Energy dumping in the SM

\[ \frac{T_{\text{thermal}}}{T_{\nu}} \frac{T_{\nu}}{T_{\text{thermal}}} = \left[ \frac{\frac{7}{8} (2+2)+2}{2} \right]^{\frac{1}{3}} \frac{T_{\text{thermal}}}{T_{\nu}} \frac{T_{\nu}}{T_{\text{thermal}}} \]

\[ = \left[ \frac{11}{4} \right]^{\frac{1}{3}} \frac{T_{\text{thermal}}}{T_{\nu}} \frac{T_{\nu}}{T_{\text{thermal}}} \]

- Thermal bath
- \( \nu \)’s decouple
- \( e^+ e^- \rightarrow \gamma \gamma \)
Energy dumping

Visible Sector
Hidden Sector

MSSM superpartners decouple

Freeze-out (Massive d.o.f. decouple)

Temperature

Time
\[ M_{3/2} \]

**Visible sector**

MSSM Superpartners

**Hidden Sector**

\[ m_{\tilde{\gamma}} = b \frac{g^2}{16\pi^2} M_{3/2} \]

\[ N_f, \mu/m_{\tilde{\gamma}} \]

\[ b = 2N_f \]

**SM particles**

\[ m_{e_i} = |\mu| \]

\[ m_{e_1,2}^2 = \left[ |\mu|^2 - 2b \left( \frac{g^2}{16\pi^2} M_{3/2} \right)^2 \right]^{1/2} \]

**SM Photon**

\[ m_{\gamma} = 0 \]

**Dark Photon**
Gravitino mass

*With assumptions of a desert
Effective number of neutrinos

\[ \Omega_{\text{DR}} \propto g_*^h(T^h_{\text{CMB}})T^h_{\text{CMB}}^4 \]

\[ \Omega_\nu \propto g_*^\nu(T^\nu_{\text{CMB}})T^\nu_{\text{CMB}}^4 \]

\[ \propto \frac{7}{8} 2N_{\nu} \left[ \frac{4}{11} \right]^{\frac{4}{3}} T^\text{vis}_{\text{CMB}}^4 \]

\[ \Delta N_{\text{eff}} = \left( \frac{\xi_f}{2.60} \right)^4 \left[ \frac{106.75}{g_*^\nu(T^\nu_f)} \right]^{\frac{4}{3}} \]

(in general)

\[ \Delta N_{\text{eff}} = 0.20 \left( \frac{N_F + \frac{8}{15}}{3} \right)^{\frac{4}{3}} \xi_\infty^4 \]

(With the assumption of a desert)
Effective number of neutrinos

\[ \Delta N_{\text{eff}} \equiv N_{\text{eff}} - N_{\text{eff}}^{\text{SM}} \]

\[ \Delta N_{\text{eff}} = 0.19 \pm 1.2 \quad (95\% \text{ CL}) \quad \text{BBN} \]

\[ \Delta N_{\text{eff}} = 1.29^{+0.86}_{-0.88} \quad (68\% \text{ CL}) \quad \text{CMB} \]
Self interaction constraints

• Dark matter in halos is an ionic plasma of positively and negatively charged electrons and selectrons

• Strongest self interaction constraint is from halo shapes of dwarf galaxies

• Elliptical halos would become spherical if the dark matter particles could exchange an O(1) fraction of their energy
Self interaction constraint

\[ \tau_r \sim \frac{m_X^3 v_0^3}{4 \sqrt{\pi} \alpha_X^2 \rho_X C} \]

Relaxation time for halos

\[ \tau_r \simeq 9.0 \times 10^9 \text{ yr} \left( \frac{m_X}{\text{TeV}} \right)^3 \left( \frac{0.01}{\alpha_X} \right)^2 \frac{90}{C} \]

Requiring this to be greater than the age of the universe:

\[ \tau_r > 10^{10} \text{ yr} \]

\[ m_{e_i} > m_{\text{DM}}^{\text{min}} = \left[ \frac{6.6}{N_F (\mu/m_{\tilde{\chi}})} \right]^2 \left( \frac{100 \text{ TeV}}{M_{3/2}} \right)^2 \text{ TeV} \]

or \( \alpha > \alpha_{\text{min}} \)
Perturbativity constraint

\[ m_{\tilde{\gamma}} < \frac{M_3}{2} \]
\[ 2 N_F \alpha_X / (4\pi) < 1 \]

- Perturbativity sets an upper bound on the coupling at each point in the parameter space.
- Halo shapes sets a lower bound on the coupling at each point in the parameter space.
- If they are in conflict that region of parameter space is excluded.
Summary and conclusions

• WIMPless dark matter suggests a \textit{larger range of dark matter masses and couplings} than previously assumed
• Simple model shows that AMSB WIMPless models are predictive and have a rich phenomenology
• Requirement of freeze out in the Hidden sector requires a long range force
• Leads to a \textit{prediction for the effective number of neutrinos}
• Constrained/could be \textit{further tested by signals of dark matter self interactions}
QUESTIONS, COMMENTS, SUGGESTIONS?