Asymmetric Dark Matter in a Stueckelberg Extension

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Outline

1. Motivation
2. Model Overview
3. Depleting the Symmetric Component
4. Model Detection
5. Concluding Remarks

Motivation

- Baryon and anti-Baryon asymmetry with a non-vanishing $B - L$
  - Possible mechanisms include: Baryogenesis, Leptogenesis
  - For this talk, we assume a $B - L$ excess has been generated already in the early universe
- Cosmic Coincidence
  - $100\Omega_{\mathrm{B}} h_0^2 = 2.255 \pm 0.054$ [WMAP-7; Astrophys. J. Suppl. **192**, 18 (2011)]
  - $\Omega_{\mathrm{DM}} h_0^2 = 0.1126 \pm 0.0036$ [WMAP-7; Astrophys. J. Suppl. **192**, 18 (2011)]
  - $\frac{\Omega_{\mathrm{DM}} h_0^2}{\Omega_{\mathrm{B}} h_0^2} = 4.99 \pm 0.20 \approx 5$

Basic Overview (Part I):

Assuming there is a $B - L$ excess existing already in the early universe.

1. One issue is to come up with a mechanism to create the asymmetry in dark mater from the $B - L$ asymmetry
2. Another issue is how to deplete the symmetric component of dark matter generated via thermal processes

i.e., asymmetric dark matter (AsyDM)

Basic Overview (Part II):

Such a mechanism can be accomplished through a Stueckelberg $U(1)_X$ extension[1] since it ...

1. ... is anomaly free (SM)
2. ... can be gauged
   - $L_e - L_\mu,\ L_\mu - L_\tau,\ L_e - L_\tau,$ or $B - L$
3. ... leads to terms in the Lagrangian that annihilate the symmetric component of DM
4. ... does not suffer from oscillations of DM to anti-DM
   1. Such oscillations could wash out the asymmetric DM via pair annihilation
   2. Due to gauge invariance, oscillations are forbidden using this extension

[1] Kors and Nath, JHEP **0507**, 069 (2005); Feldman, Liu, Nath, and GP, Phys. Rev. D **81**, 095017 (2010); Liu, Nath, and GP, Phys. Lett. B **701**, 601 (2011)

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AsyDM Model Overview

In Lagrangian include a term that transfers $B-L$ from matter to dark matter[2], i.e.

$$\mathcal{L}_{\rm asy} = \frac{1}{M_{\rm asy}^n} X^k \mathcal{O}_{\rm asy}$$

- $M_{\rm asy}$ is the scale of interaction and decouples at $T_{\rm int}$
- $\mathcal{O}_{\rm asy}$ is made up of SM fields with a non-vanishing $B-L$ quantum number
- X^k is the dark matter fields with an opposite $B-L$ quantum number (could be a fermion or boson)

$B-L$ transfer (SM) examples include[3]

- $\frac{1}{M_{\rm asy}^3}\psi^3 LH$, $\frac{1}{M_{\rm asy}^3}\phi^2(LH)^2$, $\frac{1}{M_{\rm asy}^5}\psi^3 Lqd^c$, or $\frac{1}{M_{\rm asy}^5}\psi^3 u^c d^c d^c$

[2] Kaplan, Luty, and Zurek, Phys. Rev. D **79**, 115016 (2009)

[3] See Feng, Nath, and GP, arXiv:1204.5752 for more examples including MSSM and 2HD

AsyDM Model Overview (cont.)

At temperatures above the decoupling of the interaction, the asymmetry in the number density of particle i is given by

$$n_i - n_{\bar{i}} = \frac{g_i}{2\pi^2}\int_0^\infty \mathrm{d}q q^2 \left[\left(e^{(E_i(q)-\mu_i)/T} \mp 1\right)^{-1} - \left(e^{(E_i(q)+\mu_i)/T} \mp 1\right)^{-1}\right]$$
$$\equiv \frac{g_i T^3}{6} \times \begin{cases} \beta\mu_i c_i(b) & \text{bosons}\,, \\ \beta\mu_i c_i(f) & \text{fermions}\,. \end{cases}$$

In the ultra relativistic limit ($\beta m_i \ll 1$) and a weakly interacting plasma ($\beta\mu_i \ll 1$), where $\beta \equiv 1/T$, the asymmetry in the number density becomes

$$n_i - n_{\bar{i}} \sim \frac{g_i T^3}{6} \times \begin{cases} 2\beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) & \text{bosons}\,, \\ \beta\mu_i + \mathcal{O}\left((\beta\mu_i)^3\right) & \text{fermions}\,. \end{cases}$$

AsyDM Mass

Letting B define the total baryon number in the Universe and X to be the total dark matter number, from the cosmic coincidence, we have

$$\frac{\Omega_{\rm DM} h_0^2}{\Omega_{\rm matter} h_0^2} = \frac{X \cdot m_{\rm DM}}{B \cdot m_{\rm B}} \approx 5$$

Thus we get the DM mass to be

$$m_{\rm DM} \approx 5 \cdot \frac{B}{X} \cdot 1 \text{ GeV}$$

B and X can be written in terms of $B - L$ by solving the chemical potentials by using:

- Conservation of charge or hypercharge
- Yukawa and gauge interactions
- Sphaleron interactions
- Conservation of $B - L$ in $\mathcal{L}_{\rm asy}$

X is determined based on the scale of $T_{\rm int}$. Possible Models include:

Model A	SM	$T_{\rm int} > T_{\rm EWPT}$
Model B		$T_{\rm EWPT} > T_{\rm int} > M_t$
Model C		$M_t > T_{\rm int} > M_W$
Model D	2HD	$T_{\rm int} > T_{\rm EWPT}$
Model E	MSSM	$T_{\rm int} > M_{\rm SUSY}$
Model F		$T_1 > T_{\rm int} > M_2 > T_{\rm EWPT}$

- $T_{\rm EWPT}$ is the Electroweak phase transition scale
- M_t (M_W) is where the top (W) mass
- $M_{\rm SUSY}$ is the (largest) soft breaking mass
- T_1 is where the first two generation of sparticles drop out of the thermal bath
- M_2 is the mass of the third generation sparticles, the gauginos, the Higgses and the Higgsinos
- These model classes lead to DM mass $\lesssim 20~{\rm GeV}$

The Relic Density produced thermally is

$$\Omega_{\rm DM} h_0^2 = \Omega_{\rm DM}^{\rm asy} h_0^2 + \Omega_{\rm DM}^{\rm sym} h_0^2$$

To significantly deplete symmetric component require

$$\Omega_{\rm DM}^{\rm sym} h_0^2 / \Omega_{\rm DM} h_0^2 < 0.1$$

Accomplished in the Stueckelberg formalism by gauging $L_\mu - L_\tau$

- This requires DM to have non-vanishing μ or τ lepton number

and the Lagrangian becomes

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{U(1)} + \mathcal{L}_{\rm Stueckelberg}$$

where in the unitary gauge for the massive Z' vector boson $\mathcal{L}_{\rm int}$ is given by

$$\mathcal{L}_{\rm int} = \frac{1}{2} g_C Q_C^\psi \bar{\psi} \gamma^\mu \psi Z'_\mu + \frac{1}{2} g_C Q_C^f \bar{f} \gamma^\mu f Z'_\mu$$

where f denotes μ, τ families

Z' Constraints $(g_\mu - 2)$

In our case we have a strong constraint on $g_\mu - 2$ and the Z' contribution is

$$\Delta a_\mu \equiv \Delta(g_\mu - 2)/2 = \frac{1}{2}\left(\frac{1}{2} g_C Q_C^\mu\right)^2 \frac{m_\mu^2}{6\pi^2 M_{Z'}^2} = (3.0 \pm 0.8) \times 10^{-9}$$

We impose the constraint that the Z' boson contribution be less than the experimental (4σ) deviation[4]

[4] K. Nakamura *et al.* J. Phys. G **G37**, 075021 (2010); Miller *et al.* Rept. Prog. Phys. **70**, 795 (2007)

This allows the symmetric component to be depleted via the process $\psi\bar{\psi} \to Z' \to f\bar{f}$. Relic Densities of $\psi, \bar{\psi}$ are governed by Boltzmann equations, i.e.

$$\frac{\mathrm{d}n_\psi}{\mathrm{d}t} + 3Hn_\psi = \langle \sigma v \rangle \left(n_\psi n_{\bar{\psi}} - n_\psi^{\mathrm{eq}} n_{\bar{\psi}}^{\mathrm{eq}} \right)$$
$$\frac{\mathrm{d}n_{\bar{\psi}}}{\mathrm{d}t} + 3Hn_{\bar{\psi}} = \langle \sigma v \rangle \left(n_\psi n_{\bar{\psi}} - n_\psi^{\mathrm{eq}} n_{\bar{\psi}}^{\mathrm{eq}} \right)$$

where $\langle \sigma v \rangle$ is the thermally averaged cross section. Allowing for AsyDM one can obtain significant effects to the relic density. However, in our model we are helped by the Breit-Wigner pole. Using

- $f_\psi \equiv n_\psi/(hT^3)$
- $f_{\bar{\psi}} \equiv n_{\bar{\psi}}/(hT^3)$
- h is the entropy degrees of freedom
- $x \equiv T/m_\psi$

Thus the Boltzmann equations become

$$\frac{\mathrm{d}f_\psi}{\mathrm{d}x} = \alpha\langle\sigma v\rangle(f_\psi f_{\bar\psi} - f_\psi^{\mathrm{eq}} f_{\bar\psi}^{\mathrm{eq}})$$

$$\frac{\mathrm{d}f_{\bar\psi}}{\mathrm{d}x} = \alpha\langle\sigma v\rangle(f_\psi f_{\bar\psi} - f_\psi^{\mathrm{eq}} f_{\bar\psi}^{\mathrm{eq}})$$

$$\gamma \equiv f_\psi - f_{\bar\psi}$$

$$\alpha(T) = \sqrt{90} m_\psi M_{\mathrm{Pl}} \frac{h}{\sqrt{g}\pi}\left(1 + \frac{1}{4}\frac{T}{g}\frac{\mathrm{d}g}{\mathrm{d}T}\right)$$

- γ is a constant and numerically it is 1.3×10^{-10}
- g is the degrees of freedom in the energy per unit volume at the photon temperature, i.e., $\rho = \frac{\pi^2}{30} g T^4$
- $\alpha(T) = 6.7 \times 10^{20}\ \mathrm{GeV}^2$ for $g = h = 68$ at $T = 0.5\ \mathrm{GeV}$

for calculation of numerical constants see Feng, Nath, and GP, arXiv:1204.5752

Thus the relic densities are

$$\Omega_\psi h_0^2 = 2.2\times 10^{-11}\sqrt{g(x_f)}h(x_0,x_f)\left(\frac{T_\gamma}{2.73}\right)^3\left(\frac{1}{\xi}-\frac{f_{\bar\psi}(x_f)}{\xi f_\psi(x_f)}e^{-\xi J(x_f)}\right)^{-1}$$

$$\Omega_{\bar\psi} h_0^2 = 2.2\times 10^{-11}\sqrt{g(x_f)}h(x_0,x_f)\left(\frac{T_\gamma}{2.73}\right)^3\left(\frac{f_\psi(x_f)}{\xi f_{\bar\psi}(x_f)}e^{\xi J(x_f)}-\frac{1}{\xi}\right)^{-1}$$

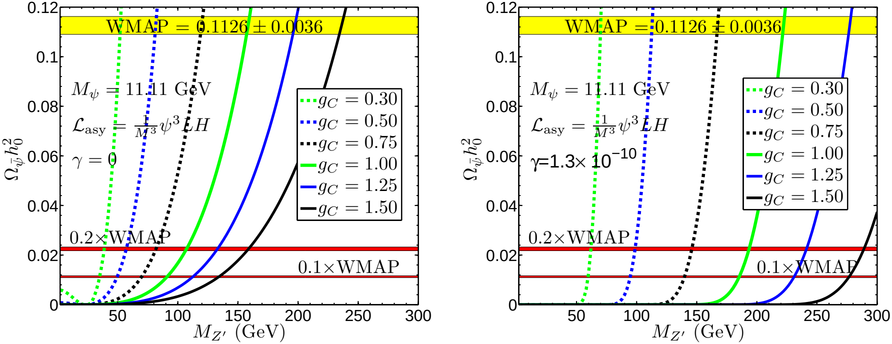
where

- $J(x_f) \equiv \int_{x_0}^{x_f}\langle\sigma v\rangle\,\mathrm{d}x$
- $h(x_0,x_f) \equiv \frac{h(x_0)}{h(x_f)}\left[1+\frac{1}{4}\left(\frac{T}{g}\frac{\mathrm{d}g}{\mathrm{d}T}\right)_{x_f}\right]^{-1}$
- $\xi \equiv \alpha(x_f)\gamma$

In the limit $\gamma,\xi\to 0$ one has $f_\psi(x_f)/f_{\bar\psi}\to 1$ and thus

$$\Omega_{\bar\psi} h_0^2 = \Omega_\psi h_0^2 = 2.2\times 10^{-11}\sqrt{g(x_f)}h(x_0,x_f)\left(\frac{T_\gamma}{2.73}\right)^3\frac{1}{J(x_f)}$$

recovering the well-known result



An exhibition of the thermal relic density of the symmetric component of the relic density as a function of Z' mass for different couplings with $\gamma = 0$ (left) and $\gamma = 1.3 \times 10^{-10}$ (right). Analysis shows that the symmetric DM can be efficiently annihilated.[5]

[5] See Feng, Nath, and GP, arXiv:1204.5752 for more details

AsyDM in MSSM

We can extend this to a multicomponent DM model[6] in the MSSM case. The superpotential for generating AsyDM becomes

$$\mathcal{W}_{\rm asy} = \frac{1}{M_{\rm asy}^n} X^k \mathcal{O}_{\rm asy}$$

where examples of $\mathcal{O}_{\rm asy}$ include:

- LH_u, LLE^c, LQD^c, $U^c D^c D^c$

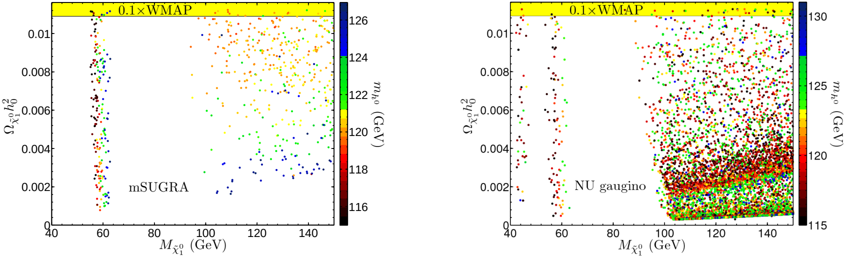
The Stueckelberg Lagrangian becomes

$$\mathcal{L}_{\rm St} = \int {\rm d}\theta^2 {\rm d}\bar{\theta}^2 \left[MC + S + \bar{S}\right]^2$$

C is the $U(1)_C$ vector multiplet and $S, \bar{S}$ are the chiral multiplets

[6] Feldman, Liu, Nath, and GP, Phys. Rev. D **81**, 095017 (2010)

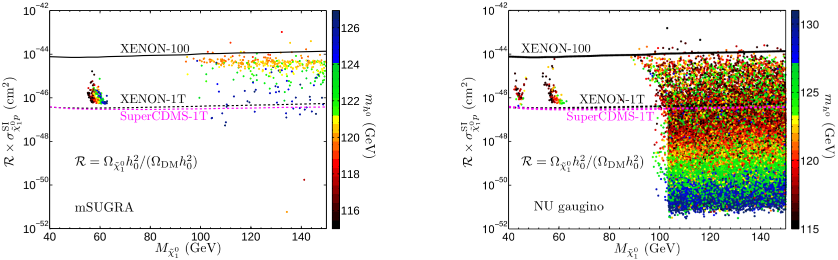
Depletion of Neutralino



A display of the thermal relic density contributed by the neutralino. Parameter points are displayed by their light CP even Higgs mass and pass experimental constants. The yellow band shows 10% of the WMAP value. Thus we have a two component dark matter picture with the conventional neutralino component being subdominant.[7]

[7] See Feng, Nath, and GP, arXiv:1204.5752 for more details

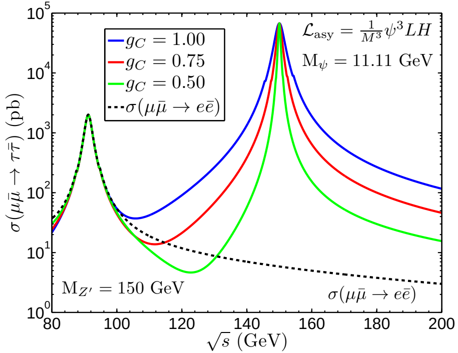
Detection of Subdominant Neutralino Dark Matter



An exhibition of the neutralino-proton spin-independent cross section as a function of the neutralino mass for mSUGRA (left) and non-universal gauginos (right). To account for the reduced relic density of the neutralino component of dark matter the spin-independent cross section has been corrected by a factor $\mathcal{R} = \Omega_{\tilde{\chi}_1^0} h_0^2 / \left(\Omega_{\rm DM} h_0^2\right)$. [8]

[8] See Feng, Nath, and GP, arXiv:1204.5752 for more details

Muon Collider Smoking Gun



Smoking gun signal for Z' in the $\tau^-\tau^+$ channel compared to e^-e^+ channel at a muon collider. Such a smoking gun signal could be an indication of $L_\mu - L_\tau$ gauge symmetry

Conclusion

- One issue for AsyDM models is depleting the symmetric component of DM
- Using a Stueckelberg $U(1)$ extension we are able to explain the cosmic coincidence and deplete the symmetric component of DM
- This Stueckelberg model has interesting signals at a muon collider
    - In the MSSM case, the neutralino component can still be seen at direct detection DM experiments

Additional Slides

$\psi\bar{\psi} \to f\bar{f}$

$$\sigma_{\psi\bar{\psi}\to f\bar{f}} = a_\psi \left|\left(s - M_{Z'}^2 + i\Gamma_{Z'} M_{Z'}\right)\right|^{-2}$$

$$a_\psi = \frac{\beta_f (\frac{1}{2} g_C^2 Q_C^\psi Q_C^f)^2}{64\pi s \beta_\psi} \left[s^2(1 + \frac{1}{3}\beta_f^2 \beta_\psi^2) + 4M_\psi^2 (s - 2m_f^2) + 4m_f^2(s + 2M_\psi^2)\right]$$

$$\Gamma_{Z'\to f\bar{f}} = \left(\frac{1}{2} g_C Q_C^f\right)^2 r_f \frac{M_{Z'}}{12\pi}, \quad f = \mu, \nu_\mu, \tau, \nu_\tau$$

$$\Gamma_{Z'\to\psi\bar{\psi}} = \left(\frac{1}{2} g_C Q_C^\psi\right)^2 \frac{M_{Z'}}{12\pi} \left(1 + \frac{2M_\psi^2}{M_{Z'}^2}\right)\left(1 - \frac{4M_\psi^2}{M_{Z'}^2}\right)^{1/2} \Theta\left(M_{Z'} - 2M_\psi\right)$$

- $\beta_{f,\psi} = (1 - 4m_{f,\psi}^2/s)^{1/2}$
- $r_f = 1$ for $f = \mu, \tau$
- $r_f = 1/2$ for $f = \nu_\mu, \nu_\tau$

Freeze-out Temperature

Define x_f such that for $x = x_f = T_f/m_\psi$ we have

$$\frac{\mathrm{d}f_{\bar\psi}^{\mathrm{eq}}}{\mathrm{d}x} = \alpha\langle\sigma v\rangle f_\psi^{\mathrm{eq}} f_{\bar\psi}^{\mathrm{eq}}$$

where

- $f_{\bar\psi}^{\mathrm{eq}}(x) = a_{\bar\psi}\, x^{-3/2} e^{-1/x}$
- $a_{\bar\psi} = g_{\bar\psi}(2\pi)^{-3/2} h^{-1}(T) \approx 9.3 \times 10^{-4} g_{\bar\psi}$ around $T = 0.5\ \mathrm{GeV}$
- $g_{\bar\psi}$ denotes the degrees of freedom of the dark particle

Plugging this in and solving to first order we get

$$x_f \simeq x_f^0 \left[1 - a_{\bar\psi}^{-1}\gamma(x_f^0)^{5/2} e^{1/x_f^0}\right]$$