Cogeneration and Pre-Annihilation of Dark Matter from Non-Standard Model Non-abelian Gauge Interaction

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Cogeneration of Dark Matter and ordinary (baryonic and leptonic) matter is an attractive idea suggested by $\Omega_{DM} \approx 5\Omega_B$

Many scenarios have been suggested.

One of the first scenarios discussed in the literature is that **sphalerons convert B, L, and X into one another.** SMB, R.S. Chivukula and E. Farhi, Phys.Lett B241, 387 (1990); SMB, Phys. Rev. D44, 3062 (1991); D.B. Kaplan, Phys. Rev. Lett. 68, 741 (1992)

This is a generalization of the leptogenesis idea.

Equilibrium of these sphaleron processes tends to make $n_B \sim n_L \sim n_X$

$$n_X \sim n_B \Longrightarrow m_\zeta \sim 5 m_p$$

where ζ is the Dark Matter particle

In the first models, it was **electroweak $SU(2)_L$ sphaleron** processes that did cogeneration. But this has drawbacks.

DRAWBACK: $X \neq 0$ fermions must be chiral under $SU(2)_L$ in order for electroweak sphalerons to violate X. They therefore tend to have mass of order the weak scale. If light they would be seen e.g. in Z width, etc. And if heavy they do not decouple, and would affect precision EW tests (e.g. S and T parameters).

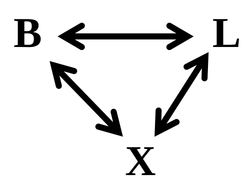
Simpler models result if sphaleron processes that violate X are of a new non-SM interaction.

M. Blennow, B. Dasgupta, E. Fernandez-Martinez, and N. Rius, JHEP 1103, 014 (2011).
S.M. Barr and H.Y. Chen, JHEP 1310, 129 (2013).

The $\boldsymbol{X \neq 0}$ fermions must be chiral under G_* (the gauge group of the new interaction), but can be vectorlike (and even be singlets) under the electroweak $SU(2)_L$.

EW sphalerons

G_* sphalerons



NICE FEATURE: There are TWO sphaleron equilibrium conditions. These determine the TWO ratios L/B and X/B. This predicts n_X today, and therefore $m_{DM} (\equiv m_\zeta)$.

GUTs are a natural context for this scenario. They can contain new gauge interactions, and new SM-singlet fermions that can be the DM.

EXAMPLE 1:

$$SU(7) \supset SU(5) \times SU(2)_* \supset [SU(3)_c \times SU(2)_L \times U(1)_Y] \times SU(2)_*$$

$$\begin{aligned} 21 + 3(\overline{7}) \longrightarrow\ & (10,1) && \longrightarrow 10 \\ & + (5,2) + 3(\overline{5},1) && \longrightarrow \overline{5} + 2(5+\overline{5}) \\ & + (1,1) + 3(1,2) && \longrightarrow 7(1) \end{aligned}$$

Note: The Standard Model singlets can be the "dark" particles that carry $X \neq 0$. There are quarks and leptons --- in (5,2) --- that transform under $SU(2)_*$ and also "dark" particles --- in (1,2). So the $SU(2)_*$ sphalerons violate B, L and X.

EXAMPLE 2:

$$E_6 \supset SU(6) \times SU(2)_* \supset SU(5) \times SU(2)_* \supset [SU(3)_c \times SU(2)_L \times U(1)_Y] \times SU(2)_*$$

$$\begin{aligned} 27 \longrightarrow\ & (15,1) + (\overline{6},2) && \\ \longrightarrow\ & (10,1) && \longrightarrow 10 \\ & + (5,1) + (\overline{5},2) && \longrightarrow \overline{5} + (5+\overline{5}) \\ & + (1,2) && \longrightarrow 2(1) \end{aligned}$$

Issue: Annihilating the "symmetric component", i.e. the anti-dark matter

Sphalerons relate $n_X - n_{\bar{X}}$ to $n_B - n_{\bar{B}}$, i.e. the asymmetries. But if $n_X + n_{\bar{X}} > n_X - n_{\bar{X}}$, then the asymmetry is irrelevant. So we want $n_{\bar{X}} < n_X \sim 10^{-10} s$

The DM particles ζ have mass in the GeV range, so EW interactions will not annihilate ζ and ζ^c efficiently enough.

One possibility:

Posit the existence of new GeV-scale particles to mediate interactions that annihilate ζ and ζ^c AND massless sterile states into which ζ and ζ^c can annihilate. But *ad hoc.*

S.M. Barr and H.Y. Chen, JHEP 1310, 129 (2013).

Another possibility: In M. Blennow, B. Dasgupta, E. Fernandez-Martinez, and N. Rius, JHEP 1103, 014 (2011), the DM particles are bound into GeV-scale "baryons" of new confining force, and GeV-scale "dark mesons" mediate the interactions by which they annihilate.

But there is a simpler possibility: Pre-annihilation of the dark anti-particles.

R. Kitano and I. Low, Phys. Rev. D71, 023510 (2005)
Zhaofeng Kang and Tianjun Li, JHEP 210, 150 (2012)
J. Unwin, JHEP 1306, 090 (2013)
have used this idea in other contexts.

The idea of pre-annihilation of DM and anti-DM:

The "dark sector" $(X \neq 0)$ has two kinds of particles:
$\chi + \chi^c$ = heavy $(\gg M_W)$ metastable particles
$\zeta + \zeta^c$ = light (GeV-scale) stable particles

Stages: (1) **An asymmetry in $\chi + \chi^c$ is produced**.

(2) When $T \sim m_\chi$ **the "symmetric component" annihilates away** through a new interaction and n_{χ^c} is driven to be much smaller than n_χ , so only the asymmetry remains.

(3) **Planck or GUT suppressed d=5 operators cause χ and χ^c to decay out of equilibrium** when $T \sim T_{dec} \ll m_\chi$.

$$\chi \longrightarrow \zeta + \text{SM particles}$$
$$\chi^c \longrightarrow \zeta^c + \text{SM particles}$$

The $\zeta + \zeta^c$ "inherit" the X asymmetry.

(4) No "symmetric component" of ζ, ζ^c survives from the reheating after inflation, because they do not couple to the inflaton, and couple very weakly (only through the d=5 Planck or GUT-suppressed operators to any other light particles.

In the scenarios where cogeneration is done by sphalerons of a new non-SM gauge interaction, The same gauge interaction can do the pre-annihilation.

Recall the model that is embeddable in E_6.

$$\begin{array}{lllll} E_6 & \supset & SU(6)\times SU(2)_* & \supset & SU(5)\times SU(2)_* \\ \mathbf{27} & \longrightarrow & (\mathbf{15},\mathbf{1}) + (\bar{\mathbf{6}},\mathbf{2}) & \longrightarrow & (\mathbf{10},\mathbf{1}) \\ & & & & (\mathbf{5},\mathbf{1}) \leftrightarrow (\bar{\mathbf{5}},\mathbf{2}) \\ & & & & \qquad (\mathbf{1},\mathbf{2}) \leftrightarrow \mathbf{2}(\mathbf{1},\mathbf{1}) \end{array}$$

Heavy masses: $(5,1)(\bar{5},2)\,\langle(1,2)_H\rangle \;=\; 5_{heavy}\;\bar{5}_{heavy}\;\langle\Omega\rangle$ Mass $\sim M_*$ for vectorlike particles

$(1,2)(1,1)\,\langle(1,2)_H\rangle \;=\; \chi\;\chi^c\;\langle\Omega\rangle$ Mass $\sim M_*$ for dark $\boldsymbol{\chi}+\boldsymbol{\chi}^c$

And mass $\sim M_*$ for $SU(2)_*$ gauge bosons

EW-scale Masses: $(10,1)(10,1)\,\langle(5,1)_H\rangle \;=\; u\;u^c\,\langle h\rangle$

$(10,1)(\bar{5},2)\langle(\bar{5},2)_H\rangle \;=\; d\;d^c\;\langle h'\rangle,\quad \ell^+\ell^-\langle h'\rangle$

Dim-5 GUT- or Planck-suppressed operator:

$$(1,2)(1,1)(5,1)_H(\bar{5},2)_H \;=\; \frac{c_5}{M_{GUT}}\boldsymbol{\chi}\;\zeta^c\;\boldsymbol{h}\;\;\boldsymbol{h}'$$

Cosmological constraints:

(1) Pre-Annihilation must drive $n_\chi/s < 10^{-10}$ *and* $r \equiv n_{\chi^c}/n_\chi < 1$

For s-wave annihilation $\sigma \sim \alpha_*/M_*^2 \sim \alpha_*/m_\chi^2$

So $r_\infty \approx exp\left\{-\frac{0.264\ \epsilon_X\ \alpha_*\ M_{Pl}\ \sqrt{g_{*f}}}{m_\chi x_f}\right\}$ where $x_f \equiv m_\chi/T_f$

Requiring that |exponent| > 1

and using $\epsilon_X \approx 10^{-10}$, $\sqrt{g_{*f}} \approx 20$, $\alpha_* \approx 10^{-2}$, $x_f \approx 1/20$, one obtains

$$m_\chi < 10^6\ \text{GeV} = 10^3\ \text{TeV}$$

(2) The decay lifetime t_{dec} of χ and χ^c must not be too short, or too many χ^c will decay to ζ^c when T is still $\sim m_\chi$ and the χ^c are not Boltzmann suppressed

Denote the temperature at t_{dec} by T_{dec}, and the time when $T = m_\chi$ by t_{m_χ}. Then

$$\left(\frac{n_{\zeta^c}}{s}\right)_{t_{dec}} \sim \frac{t_{m_\chi}}{t_{dec}}\left(\frac{n_{\chi^c}}{s}\right)_{t_{m_\chi}} \sim \frac{t_{m_\chi}}{t_{dec}}\frac{1}{g_{*m_\chi}}$$

$$\sim \frac{\left(\sqrt{g_{*m_\chi}}\, m_\chi^2\right)^{-1}}{\left(\sqrt{g_{*dec}}\, T_{dec}^2\right)^{-1}}\frac{1}{g_{*m_\chi}} < \epsilon_X = \left(\frac{5m_p}{m_\zeta}\right)\epsilon_B \sim 10^{-10}\left(\frac{5m_p}{m_\zeta}\right)$$

$$T_{dec}/m_\chi < \left(\frac{5\,m_p}{m_\zeta}\right)^{1/2}\frac{g_{*m_\chi}{}^{3/4}}{g_{*dec}{}^{1/4}}\epsilon_B{}^{1/2} \Rightarrow T_{dec}/m_\chi < 10^{-4}\left(\frac{5\,m_p}{m_\zeta}\right)^{1/2}$$

(3) The decay lifetime t_{dec} of χ and χ^c must not be too long, or dark matter (ζ) will be hot.

$$\lambda_{FS} \approx t_{NR} \frac{R_0}{R_{NR}} \left(2 + ln\left(t_{eq}/t_{NR}\right)\right)$$

When $\chi \rightarrow \zeta$ the ζ initially have momentum $\left(p_\zeta\right)_{in} \sim m_\chi/3 \gg T_{dec}$

This momentum redshifts, so $p_\zeta \sim \frac{R_{dec}}{R} m_\chi/3$. The ζ become non-relativistic when $p_\zeta \sim m_\zeta$, so $R_{NR} = R_{dec} \frac{m_\chi}{3m_\zeta}$.

$$\Rightarrow T_{NR} = T_{dec} \left(\frac{3m_\zeta}{m_\chi}\right) \left(\frac{g_{*dec}}{g_{*NR}}\right)^{1/3}$$

$$\Rightarrow t_{NR} \approx 0.3 \left(\frac{M_{Pl}}{T_{dec}{}^2}\right) \left(\frac{m_\chi}{3m_\zeta}\right)^2 \frac{g_{*NR}{}^{1/6}}{g_{*dec}{}^{2/3}}$$

And $\frac{R_0}{R_{NR}} = \frac{3m_\zeta}{m_\chi} \left(\frac{T_{dec}}{T_0}\right)\left(\frac{g_{*dec}}{43/4}\right)\left(\frac{11}{4}\right)^{1/3}$

Assembling these gives $\lambda_{FS} \approx 0.2\, pc \left(\frac{5m_p}{m_\zeta}\right)\left(\frac{m_\chi}{T_{dec}}\right)\frac{g_{*NR}{}^{1/6}}{g_{*dec}{}^{1/3}}\left(1 - 0.04\, ln\left(m_\chi/T_{dec}\right)\right)$

Therefore $\lambda_{FS} < 100\, kpc \Rightarrow T_{dec}/m_\chi > 2 \times 10^{-7} \left(\frac{5m_p}{m_\zeta}\right)$

We can express these bounds on T_{dec}/m_χ as bounds on the coefficient of the dim-5 operator that causes the decay.

From $T_{dec}/m_\chi = (g_{*dec})^{-1/4} \frac{\sqrt{m_\chi M_{Pl}}}{M_{GUT}/c_5}$ we obtain

$$10^{16}\,GeV \left(\frac{m_\zeta}{5m_p}\right)^{1/2} \left(\frac{m_\chi}{10^6 GeV}\right) < \frac{M_{GUT}}{c_5} < 10^{19}\,GeV \left(\frac{m_\zeta}{5m_p}\right)\left(\frac{m_\chi}{10^6 GeV}\right)^{1/2}$$

(4) The reheating temperature must be low enough not to produce a significant number of ζ and ζ^c during reheating.

The only interaction that can produce them is the dim-5 operator, so one finds

$$T_{rh} < \frac{(M_{GUT}/c_5)^2}{3 \times 10^{25}\,GeV}\left(\frac{5m_p}{m_\zeta}\right)$$

CONCLUSION:

Unified theories with large groups are a natural context for cogeneration of ADM and ordinary matter. They contain SM-singlet fermions that can be the DM, and new non-abelian interactions whose sphalerons can relate n_X, n_B, n_L, and which can accomplish the elimination of the "symmetric component" of DM by pre-annihilation.