Asymmetric Dark Matter

Revealing the history of the universe with underground particle and nuclear research 2019 (3/8/2019)

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**Baryon-DM coincidence Problem**

- DM and Baryon make up 27% and 4% of total energy density of the Universe.

\[ \Omega_{DM} h^2 \sim 0.14 \quad \Omega_B h^2 \sim 0.022 \]

(Planck 2018: \( \Omega_X = \frac{\rho_X}{3 M_{PL}^2 H_0^2} \), \( H_0 = 100h \text{ km/s/Mpc}, h \sim 0.7 \))

**Baryon-DM coincidence?**

\[ \Omega_{DM} : \Omega_B \sim 5 : 1 \]

close with each other...

ex) neutrino-DM: \( \Omega_{DM} : \Omega_{\nu}( \Sigma m_{\nu}=0.06\text{eV} ) = 200 : 1 \)

*Is this a serious problem?*
Baryon-DM coincidence Problem

If it were not for Baryogenesis…

DM mass density can be explained by the WIMP mechanism:

\[ \Omega_{DM} \propto m_{DM} n_{DM} \approx 0.1 \times \left( \frac{10^{-9} \text{ GeV}^{-2}}{\langle \sigma v \rangle} \right) \]

→ the observed density is explained by choosing appropriate mass & couplings

The baryon density is too low due to its large annihilation cross section:

\[ \langle \sigma v \rangle \sim \frac{4\pi}{m_{n}^2} \sim 10 \text{ GeV}^{-2} \]

→ \( \Omega_{DM} : \Omega_{b} \text{ (no-asymmetry)} = 1 : 10^{-10} \)

The observed baryon density is provided by the baryon asymmetry.

\[ \Omega_{b} \text{ (with asymmetry)} = 0.02 \left( \frac{\eta_B}{10^{-9}} \right) \]

\[ \eta_B = \frac{n_B - n_{\bar{B}}}{n_Y} \]

Baryon-DM coincidence = conspiracy between \( n_{DM} \) and Baryogenesis?
Baryon-DM coincidence Problem

Answers?

✓ Just a coincidence, $\Omega_{DM}/\Omega_{B} \sim 5$ is not a big deal.
   → Keep looking for conventional WIMPs!

✓ Anthropic requirement?

For $\Omega_{B}/\Omega_{DM} < 10^{-2-4}$, no disk fragmentation in the galaxies, which makes the star formation rate very low...

['06 Tegmark, Aguirre, Rees, Wilczek]
(These arguments depend on which parameters we fix.)

✓ Some mechanism behind the coincidence?

→ The asymmetric dark matter (ADM) provides an interesting insight!
Asymmetric Dark Matter (ADM)

Basic Idea

- Matter-anti-matter asymmetries in the SM/DM sectors
  \[ \eta_B = \frac{n_B - n_{\overline{B}}}{n_Y} \quad \eta_{DM} = \frac{n_{DM} - n_{\overline{DM}}}{n_Y} \]
  are generated from the common origin so that \( \eta_{DM}/\eta_B = O(1) \).

- The mass densities of the baryon and dark matter are proportional to the asymmetries
  \[ \Omega_B \text{ (with asymmetry)} \propto m_N \eta_B \]
  \[ \Omega_{DM} \text{ (with asymmetry)} \propto m_{DM} \eta_{DM} \]
  \[ \rightarrow \frac{\Omega_{DM}}{\Omega_B} = \left( \frac{m_{DM}}{m_B} \right) \left( \frac{\eta_{DM}}{\eta_B} \right) \]

The baryon-DM ratio \( \frac{\Omega_{DM}}{\Omega_B} \sim 5 \) can be achieved for
\[ m_{DM} \sim 5 m_B \times \left( \frac{\eta_B}{\eta_{DM}} \right) \sim O(1) \text{ GeV} \]
**Asymmetric Dark Matter (ADM)**

*Two main mechanisms*

**Sharing mechanism**

*SM* and *DM* sectors share a primordial asymmetry produced in an arbitrary sector. Asymmetry is thermally distributed in the two sectors:

\[ \eta_{DM} / \eta_B \] is related to the degrees of the freedom in two sectors.

**Cogenesis**

The asymmetries in the two sectors are produced by the same process.

\[ \eta_{DM} / \eta_B \] depends on the branching ratio of the asymmetry.

[ Petraki & Volkas 1305.4939 Zurek 1308.0338 for review]
Asymmetric Dark Matter (ADM)

Two main mechanisms

Sharing mechanism

SM and DM sectors share a primordial asymmetry produced in an arbitrary sector.

Asymmetry is thermally distributed in the two sectors

\[ \eta_{DM}/\eta_B \] is related to the degrees of the freedom in two sectors

In the following, we consider the sharing mechanism.

In the sharing mechanism:

- What is the origin of the asymmetry?
- How the asymmetries are shared?

→ there are lots of possibilities...
Asymmetric Dark Matter via Leptogenesis

Thermal Leptogenesis (at the decay of the right-handed neutrino $N_R$)

$$\mathcal{L}_{N-SM} = \frac{1}{2} M_R \bar{N}_R N_R + y_N H L \bar{N}_R + \text{h.c.}$$

($N_R : \text{right-handed neutrino}, M_R > 10^{10} \text{GeV}$)

Asymmetry in the $SM$ sector
= the asymmetry of the $B-L$ symmetry (if it is generated $T > O(100) \text{GeV}$)

Dark Sector shares the $B-L$ symmetry with the $SM$ through

$$\mathcal{L}_{B-L \text{ portal}} = \frac{1}{M_*^{n}} O_D O_{SM} + \text{h.c.}$$

$O_{SM}$: Neutral (other than $B-L$) consisting of $SM$ fields.

$O_{DM}$: Neutral (other than $B-L$) consisting of $DM$ fields.

The $SM$ and the $DM$ sectors are thermally connected at the high temperature

$$T > T_D \sim M_* (M_* / M_{PL})^{(2n-1)}$$

$ADM$ scenario is achieved by $Thermal \text{ Leptogenesis}$ for $M_R > T_D$. 
Asymmetric Dark Matter via Leptogenesis

$T \sim M_R$

Leptogenesis

$B-L$ asymmetry in $SM + Dark \ sector$

$\eta_{SM} = A_{SM} \eta_{B-L}$ \hspace{1cm} $\eta_{DM} = A_{DM} \eta_{B-L}$ \hspace{1cm} $(A_{SM} + A_{DM} = 1)$

$T_D \sim M_\ast(M_\ast/M_{PL})^{1/(2n-1)}$

$T_{EW} \sim 100 GeV$

$\eta_{SM} = A_{SM} \eta_{B-L}$

$\eta_{DM} = A_{DM} \eta_{B-L}$

$\eta_{B} = A_B \eta_{B-L}$

$\eta_{L} = A_L \eta_{B-L}$

$(A_B/A_{SM} = 30/97)$

$n_B = \eta_B n_Y \rightarrow n_{DM} = (A_{DM}/A_B) n_B = (A_{DM}/A_{SM})(A_{SM}/A_B) n_B$

$\Omega_{DM} = (m_{DM}/m_p)(A_{DM}/A_{SM})(A_{SM}/A_B) \Omega_B$

$m_{DM} = 5 m_p (30/97) (A_{SM}/A_{DM}) \times (\Omega_{DM}/5\Omega_B)$

determined by the degrees of freedom
Models require a large annihilation cross section.

**ADM** models require a large annihilation cross section. The annihilation of the symmetric component of DM should be very efficient! 

\[ \sigma v >> 10^{-9} \text{GeV}^{-2} \]

Lots of possibilities...

- **SM final state** via heavy mediators (→ similarity with the **WIMP** models)
- **final states in the dark sector** (→ the entropy in the dark sector should be transferred to the **SM** sector.)
We prefer ADM models in which

\[ m_{DM} = O(1) \text{ GeV} \]

is achieved without fine-tuning.

The ADM scenario does not solve the coincidence problem but provides a new interpretation in terms of the mass ratio \( m_{DM}/m_N = O(1) \).

The ultimate solution to the problem is obtained when the mass ratio \( m_{DM}/m_N = O(1) \) is explained, which requires higher-energy theory.

At least, \( m_{DM} = O(1) \text{ GeV} \) should not be achieved by fine-tuning to avoid that \( \Omega_{DM}/\Omega_B \sim 5 \) is realized by fine-tuning.
Model Building of Asymmetric Dark Matter

Composite ADM models are highly motivated!

- **DM** annihilation cross section is large!
  \[ \sigma v \sim \frac{4\pi}{m_{DM}^2} \]

Symmetric components annihilates very efficiently!

- **DM** mass can be explained by dynamical transmutation.

  The mass scale \( \sim \) dynamical scale is determined by the gauge coupling constant at the UV scale.

  \[ m_{DM} \sim \Lambda_{dyn} \sim M_{UV} \exp[-8\pi^2/b \ g(M_{UV})^2] \]
  \[ [b = 11/3 \ N_c - 2/3 \ N_F \ for \ SU(N_c) \ N_F-\text{flavor}] \]
Among various possibilities, **ADM** with the **sharing** mechanism through **B-L** connecting operators with **thermal Leptogenesis** is very well motivated!

- **B-L** symmetry is well-motivated in the **SM** (can be gauged, **SO(10) GUT**)
- **Thermal Leptogenesis** is very successful for the **baryogenesis**.
Compositeness is an interesting addition.

- large annihilation cross section
- $m_{DM} = O(1) \text{GeV}$ without fine-tuning
- Models are rather complicated
- The entropy in the dark sector should be transferred to the SM

**Model Building of Asymmetric Dark Matter**

- **ADM**
  - Sharing
  - Cogenesis
  - **B-L**
  - **Thermal Leptogenesis**
  - Elementary ADM
  - Composite ADM

- Annihilation into SM sector
- Annihilation into DM sector
- portals to the SM sector
Asymmetric Dark Matter and Dark Radiation

What if the final state particle in the dark sector are massless?

At $T > T_D$, the SM and the DM sectors are in the thermal equilibrium

$$\rho_R = \frac{\pi^2}{30} (g_{SM}(T) + g_{DM}(T)) T^4$$

($g$: the number of the effectively massless degree of freedom $g_{SM}(T) = 106.75$)

Below $T > T_D$, the thermal baths of the SM and the DM sectors evolve independently.

The temperatures of the two sectors are different at a later time.
Asymmetric Dark Matter and Dark Radiation

The radiation energy after the neutrino decoupling

\[
\rho_R = \left( 1 + \frac{7}{8} N_\nu \left( \frac{T_\nu}{T_\gamma} \right)^4 + \frac{\bar{g}_{DM}(T_{\nu*})}{2} \left( \frac{g_{DM}(T_D)}{g_{DM}(T_{\nu*})} \right)^{4/3} \left( \frac{g_{SM}(T_{\nu*})}{g_{SM}(T_D)} \right)^{4/3} \left( \frac{T_\nu}{T_\gamma} \right)^4 \right) \rho_\gamma
\]

\[N_\nu = 3.046 \quad T_\nu / T_\gamma = (4/11)^{1/3} \quad g_{SM}(T_D) = 106.75 \quad g_{SM}(T_{\nu*}) = 43/4\]

\[T_{\nu*} : \nu \text{ decoupling temperature (~3MeV)} \quad \bar{g}_{DM} = g_{DM} \times \{1 \ (B), \ 7/8 \ (F)\}\]

\[\Delta N_{\text{eff}} = \frac{4\bar{g}_{DM}(T_{\nu*})}{7} \left( \frac{g_{DM}(T_D)}{g_{DM}(T_{\nu*})} \right)^{4/3} \left( \frac{g_{SM}(T_{\nu*})}{g_{SM}(T_D)} \right)^{4/3} > \frac{4\bar{g}_{DM}(T_D)}{7} \left( \frac{g_{SM}(T_{\nu*})}{g_{SM}(T_D)} \right)^{4/3}\]

[see also 1203.5803 Blennow, Martinez, Mena, Redondo, Serra]

CMB constraints: \(\Delta N_{\text{eff}} < 0.30\) (95%CL) [Planck 2018]

\[g_{DM}(T_D) < 11\]

cf. \(SU(N_c)\) \(N_F\)-flavor model \(g_{DM} = 2(N_c^2 - 1) + 7/2 N_F N_c\)

Even \(N_c = 2\) & \(N_F = 1\) exceeds the bound!

We need a portal to transfer the entropy in the DM sector to the SM sector for composite ADM models!
Composite Asymmetric Dark Matter with Dark Photon

The composite dark sector may have QED-like gauge interaction, i.e. dark QED.

Dark QED can mix with QED through the kinetic mixing.

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} \]

\( F_{\mu\nu} : \text{QED photon} \quad F'_{\mu\nu} : \text{dark QED photon} \quad \epsilon : \text{mixing parameter} \ll 1 \)

Assume dark QED photon obtains a mass via Higgs mechanism…

The massive dark photon couples to QED current with \( \epsilon g_{QED} \).

The massive dark photon can be a good candidate for the portal interaction!


**Composite Asymmetric Dark Matter with Dark Photon**

[1805.0687 Kamada, Kobayashi, Nakano MI]

- Mirror Copy of QCD ( = dark QCD ) with dark QED ( SU(2)_L is not copied )

  e.g.) Matter content for \( N_F = 2 \)

<table>
<thead>
<tr>
<th>( Q )</th>
<th>( SU(3)_D )</th>
<th>( B - L )</th>
<th>( U(1)_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_1 )</td>
<td>3</td>
<td>( q_{B-L} )</td>
<td>2/3</td>
</tr>
</tbody>
</table>
| \( 
\bar{Q}_1 \)  | \( \bar{3} \) | \( -q_{B-L} \) | -2/3        |
| \( Q_2 \)  | 3            | \( q_{B-L} \) | -1/3        |
| \( 
\bar{Q}_2 \)  | \( \bar{3} \) | \( -q_{B-L} \) | 1/3         |

( \( q_{B-L} = 1/3 \) )

Asymmetry Ratio :

\[
\left( A_{SM} / A_{DM} \right) = 237 / \left( 22N_F \right) \rightarrow m_{DM} \sim 8.5 \text{ GeV} \left( 2 / N_F \right)
\]

[ see also 1411.4014 Fukuda, Matsumoto, Mukhopadhyay ]

- We need at least \( N_F > 1 \) to allow the \( B-L \) portal interaction.

\[
\mathcal{L}_{B-L_{\text{portal}}} = \frac{1}{M^*_n} \mathcal{O}_{D} \mathcal{O}_{SM} + \text{h.c.}
\]

\( \mathcal{O}_{SM} : \text{Neutral (other than B-L) consisting of SM fields.} \)

\( \mathcal{O}_{DM} : \text{Neutral (other than B-L) consisting of DM fields.} \)
**Composite Asymmetric Dark Matter with Dark Photon**

[1805.0687 Kamada, Kobayashi, Nakano MI]

Dark QCD exhibits confinement at $O(1-10)$ GeV.

- **Dark Matter** = Dark protons and Dark neutrons ($m_{N'} \sim O(1)$ GeV)
  
  \[ p' \propto Q_1 Q_1 Q_2, \quad \bar{p}' \propto \bar{Q}_1 \bar{Q}_1 \bar{Q}_2, \quad n' \propto Q_1 Q_2 Q_2, \quad \bar{n}' \propto \bar{Q}_1 \bar{Q}_2 \bar{Q}_2. \]

- **Dark baryons** annihilate into Dark pions ($m_{\pi'} = O(100)\text{MeV} - O(1)\text{GeV}$)
  
  \[ \pi'^0 \propto Q_1 \bar{Q}_1 - Q_2 \bar{Q}_2, \quad \pi'^+ \propto Q_1 \bar{Q}_2, \quad \pi'^- \propto Q_2 \bar{Q}_1. \]

- **Dark pions** annihilate/decay into dark photons ($m_{\gamma'} < m_{\pi'} < m_{N'}$)

\[ \sigma v \sim 4\pi / m_{DM}^2 \quad \sigma v \sim \pi \alpha'^2 / m_{\pi'}^2 \quad \Gamma \sim \alpha'^2 / 64\pi^3 x m_{\pi'}^3 / f_{\pi}^2 \]

The dark sector ends up with the dark baryonic matter and dark photon due to the asymmetry! ($\Omega_{p'} : \Omega_{n'} \sim 1 : 1$)
Dark photons eventually decay into a pair of the electrons or the muons
\[ \Gamma_{\gamma'} = N_{\text{ch}} \frac{1}{3} \epsilon^2 \alpha m_{\gamma'} \simeq 0.3 \text{s}^{-1} \times N_{\text{ch}} \left( \frac{\epsilon}{10^{-10}} \right)^2 \left( \frac{m_{\gamma'}}{100 \text{MeV}} \right) \]

Lifetime of $O(1)$ sec $\leftrightarrow \epsilon \sim 10^{-10}$

Constraints on dark photon parameter space

For $m_{\gamma'} < 20 \text{MeV}$, the $\gamma'$ shares the thermal energy with $\gamma, e, \nu$ at $T > m_{\gamma'}$. Some portion of $\gamma'$ releases its energy into $e^+e^-$ below $T_{\nu^*}$, which reduces $\Delta N_{\text{eff}}$.

The $\gamma'$ decay after the $\nu$ decouple also reduces $\Delta N_{\text{eff}}$. 
The ADM model with a dark photon can be tested by the direct detection experiments.

**Composite Asymmetric Dark Matter with Dark Photon**

[1805.0687 Kamada, Kobayashi, Nakano MI]

**Dark Matter direct detection via the dark photon exchange.**

**Dark proton couples to the proton!**

\[
\frac{d\sigma_{XT}}{dq^2} = \frac{4\pi\alpha_{em}\alpha_{X}e^2\gamma^2}{(q^2 + m_{\phi}^2)^2} \frac{1}{v^2} \mathcal{F}_T(q^2) \propto Z^2
\]

Region above the red line are excluded by Panda-X (54 ton x day exposure) for \( m_{DM} = 8.5\text{GeV} \) (roughly corresponding to \( \sigma < 10^{-44}\text{cm}^2 \))

The ADM model with a dark photon can be tested by the direct detection experiments.
Composite Asymmetric Dark Matter with Dark Photon

Dark Sector Shares $B$-$L$ symmetry with the $SM$ via

$$\mathcal{L}_{B-L_{\text{portal}}} = \frac{1}{M^*_n} \mathcal{O}_D \mathcal{O}_{\text{SM}} + \text{h.c.}$$

$$= \frac{1}{M^*_3} (\bar{Q}_1 \bar{Q}_2 \bar{Q}_2) LH$$

**Dark neutron operator**

Through this operator, the dark nucleon decays into anti-neutrinos!

$$N' \to \pi' + \bar{\nu}$$

$$\tau \sim 10^{24} \text{ sec} \left( \frac{M_*}{10^9 \text{ GeV}} \right)^6 \left( \frac{10 \text{ GeV}}{m_{\text{DM}}} \right)^5$$

[1003.5662 Feldstein, Fitzpatrick]

[1411.4014 Fukuda, Matsumoto, Mukhopadhyay]

**Composite ADM leads to a monochromatic anti-neutrino signal!**
Composite Asymmetric Dark Matter with Dark Photon

Constraints on the $\nu$- flux from DM decay

**full-sky averaged neutrino flux**

For 1 TeV, $\tau_{DM}=10^{26}$ sec NFW profile

Constraint on the dark matter lifetime

$SK, 1679.6$ live days, $\Delta \theta_{GC}=30^\circ$

$[\text{'09 Covi, Grefe, Ibarra, Tran } ]$

$\tau_{DM}(DM \rightarrow X + \nu) > 10^{23}$ sec for $m_{DM} \sim 10$GeV.

(SK 90%CL constraints on the neutrino flux)

$\rightarrow M_\ast \gtrsim 10^{8.5}$ GeV

In the ADM models, neutrino detectors sensitive to $O(100)$MeV - $O(1)$GeV play important roles!
**Composite Asymmetric Dark Matter with Dark Photon**

Constraints from **CMB** (work in progress with **Kobayashi, Nagai Nakano**)

The dark neutron decay ends up with electrons.

\[
n' \rightarrow \pi^0' + \bar{\nu} \\
\gamma' + \gamma' \rightarrow e^+ + e^- + e^+ + e^- 
\]

The electromagnetic energy injection by the decay of dark matter affects the spectrum of the **CMB** anisotropy.

![Graph](image)

The model with dark photon can be tested by the CMB anisotropy!

\[\tau_{DM} > 10^{24-25} \text{ sec}\]

(In the present model, the neutrino carries away the half of the dark matter energy…)
**Composite Asymmetric Dark Matter with Dark Photon**

**Dark neutron - Anti dark neutron oscillation**

The portal operator

\[ \mathcal{L}_{B-L_{\text{portal}}} = \frac{1}{M^3_*} (\bar{Q}_1 \bar{Q}_2 Q_2) LH \]

is generated by the seesaw mechanism:

\[ \mathcal{L}_{N-SM} = \frac{1}{2} M_R \bar{N}_R N_R + y_N H L \bar{N}_R + \frac{1}{M^2_*} (\bar{Q}_1 Q_2 Q_2) \bar{N}_R + h.c. \]

\[ \rightarrow \mathcal{L}_{\text{eff}} = \frac{y^2_N}{2M_R} LHHLH + \frac{y_N}{M_R M^2_*} (\bar{Q}_1 \bar{Q}_2 Q_2) LH + \frac{1}{2M_R M^4_*} (\bar{Q}_1 \bar{Q}_2 Q_2)^2 \]

\text{neutrino mass} \hspace{2cm} \text{portal operator} \hspace{2cm} \text{Majorana Mass of } n' \]

The Majorana mass of \( n' = \text{oscillation time scale of the } n' \text{ and } \bar{n}' \)

\[ \Delta m'_n \sim \frac{\Lambda^6_{\text{QCD}'} M^4_{R M^4_*}}{M^6_R M^4_*} \sim 10^{-47} \text{GeV} \left( \frac{\Lambda_{\text{QCD}'}}{3 \text{GeV}} \right)^6 \left( \frac{10^{10} \text{GeV}}{M_R} \right) \left( \frac{10^{10} \text{GeV}}{M_*} \right)^4 \]

\text{cf. } H_0 \sim 10^{-42} \text{GeV}

Some fraction of dark neutron has been converted to anti-dark neutron!

[see also 1202.0283 Tulin, Yu, Zurek, 1402.42500 Hardy, Lasenby, Unwin]
**Composite Asymmetric Dark Matter with Dark Photon**

- Dark matter can annihilate in the present universe!

\[
n' \rightarrow \pi^0' \quad p' \rightarrow \pi^+'
\]

\[
\bar{n}' \rightarrow \pi^0' \quad \bar{n}' \rightarrow \pi^0'
\]

\[
(\, e^+ + e^- \,) \times 4 \quad (\, e^+ + e^- \,) \times 2
\]

**Effective cross section:** \( f_{\text{anti}} \sigma v \)

\[
f_{\text{anti}} \sim \min[1, \Delta m_{n'}/H] \quad \sigma v \sim [\sigma v]_{\text{nucleon}} \times (m_N/m_{N'})^2
\]

**Very large!**

**Typical electron/positron energy:** \(< E_e > = O(1) GeV\)

**Constraints from indirect dark matter searches (work in progress)!**

- \( e^+ + e^- \) leads to the inverse Compton & synchrotron radiation
  - \( \rightarrow \) constraints on the galactic \( \gamma \)-ray flux by Fermi-LAT

\[
f_{\text{anti}}(z=1) \sigma v \leq 10^{-26} cm^3/s \ [1604.02263 \text{ Ando, Ishiwata }]
\]

- \( e^+ + e^- \) injection distorts \( CMB \)

\[
f_{\text{anti}}(z \sim 600) \sigma v \leq 10^{-26} cm^3/s \ [\text{Planck 2018}]
\]
UV completion of the Composite Asymmetric Dark Matter

The dark photon model requires a tiny parameter $\varepsilon$

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

For $U(1) \times U(1)$ gauge theory, $\varepsilon$ is an arbitrary parameter…

For non-abelian gauge theory, the kinetic mixing is forbidden.

Small kinetic mixing can be achieved in the non-abelian GUT theory!

[1811.10232 Kamada, Kobayashi, Kuwahara, Nakano MI]

Table 2: Charge assignment of fermions and scalars in the minimal unified model. The upper rows of the tables show the assignment in SU(5)GUT while the lower rows show those in SU(4)DGUT.

$$< \Sigma > = v_5 (2, 2, 2, -3, -3) \quad < \Xi > = v_4 (1, 1, 1, -3)$$

$U(1)_5 = $ GUT commuting $B-L$
UV completion of the Composite Asymmetric Dark Matter

Mixing term originates from the higher dimensional operator

$$\mathcal{L}_\epsilon = \frac{1}{M_{Pl}^2} \text{tr}(F_{G\mu\nu} \Sigma) \text{tr}(F_D^{\mu\nu} \Xi') \quad \rightarrow \epsilon \sim v_5 v_4 / M_{Pl}^2$$

$$\epsilon \sim 10^{-10} \quad \leftrightarrow \quad v_4 \sim 10^{10} \text{GeV}$$

Portal operators are generated by integrating out the colored Higgs in $SU(4)_{DGUT}$

$$\mathcal{L}_{\text{Yukawa}} = -Y_D \epsilon^{\alpha\beta\gamma\delta} H'_\alpha Q'_U[\beta\gamma] Q'_D \delta - Y_D H'^\dagger_\alpha Q'_U[\alpha\beta] \overline{Q}'_D \beta - Y_N H'_\alpha \overline{Q}'_D \alpha N + \text{h.c.} ,$$

$$\rightarrow \mathcal{L}_{\text{portal}} = \frac{Y_N Y^*_D}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a D'^b) (\overline{D}'^c N) - \frac{Y_N Y^*_D}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a D'^b) (\overline{D}'^c N) + \text{h.c.}$$

Portal scale is explained by the dark GUT scale $M_c \sim v_4 \sim 10^{10} \text{GeV}$

$SU(5)_{GUT} \times SU(4)_{DGUT}$ provides a good UV completion of the composite ADM!

($v_5 \sim 10^{16} \text{GeV} \& v_4 \sim 10^{10} \text{GeV}$)
Summary

- The Baryon-DM coincidence problem can be an important hint for the origin of dark matter.

- The Asymmetric Dark Matter scenario can be a good starting point to find a solution to the coincidence problem!
  
  (In the ADM, $\Omega_{DM}/\Omega_B \sim 5$ can be interpreted by $m_{DM}/m_N \sim O(1)$)

- The ADM via thermal Leptogenesis is very attractive scenario where the asymmetry in the DM/SM sectors are shared through B-L portal.

- The composite ADM is well-motivated as it provides the large annihilation cross section & the DM mass via dimensional transmutation.

- The dark photon portal provides an efficient way to transfer the entropy in the DM sector to the SM sector.
  
  (A tiny mixing parameter can be achieved in non-abelian extensions)
  
  → The dark photon also provides a high testability of the ADM models!

- The dark neutron-dark anti-neutron oscillation makes phenomenology of the ADM richer!

The ADM is an attractive alternative to the WIMP!
Back up
**Composite Asymmetric Dark Matter with Dark Photon**

- The quark mass term

\[ \mathcal{L} = m_1 \bar{Q}_1 Q_1 + m_2 \bar{Q}_2 Q_2 \]

- The dark nucleon

\[ p' \propto Q_1 Q_1 Q_2, \quad \bar{p}' \propto \bar{Q}_1 \bar{Q}_1 \bar{Q}_2, \quad n' \propto Q_1 Q_2 Q_2, \quad \bar{n}' \propto \bar{Q}_1 \bar{Q}_2 \bar{Q}_2. \]

\[ m_{N'} \simeq m_N \times \frac{\Lambda_{QCD'}}{\Lambda_{QCD}} \quad m_{n'} - m_{p'} \simeq \delta m_{n-p}^{QED} \times \frac{\Lambda_{QCD'}}{\Lambda_{QCD}} \times \alpha_D + \kappa_N (m_1 - m_2) \]

\[ \delta m_{n-p}^{QED} = -0.178^{+0.004}_{-0.064} \text{ GeV} \quad \kappa_N = 0.95^{+0.08}_{-0.06} \]

- The dark pions

\[ \pi'^0 \propto Q_1 \bar{Q}_1 - Q_2 \bar{Q}_2, \quad \pi'^+ \propto Q_1 \bar{Q}_2, \quad \pi'^- \propto Q_2 \bar{Q}_1 \]

\[ m_{\pi'^0}^2 \simeq m_{\pi'^0}^2 \times \frac{\Lambda_{QCD'}}{\Lambda_{QCD}} \frac{m_1 + m_2}{m_u + m_d} \quad m_{\pi'^\pm}^2 \simeq m_{\pi'^0}^2 + \alpha_D \Lambda_{QCD}'^2 \]
**UV completion of the Composite Asymmetric Dark Matter**

Table 2: Charge assignment of fermions and scalars in the minimal \(SU(5)_{GUT}\) \(SU(4)_{DGUT}\) unified model. The upper rows of the tables show the assignment in \(SU(5)_{GUT}\) sector while the lower rows show those in \(SU(4)_{DGUT}\) sector.

<table>
<thead>
<tr>
<th>(SU(5)_{GUT})</th>
<th>(SU(4)_{DGUT})</th>
<th>(U(1)_{GUT})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Psi_i)</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>(\Phi_i)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>(\overline{N}_i)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(Q'_U)</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>(Q'_D)</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>(\overline{Q}'_D)</td>
<td>1</td>
<td>4</td>
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</thead>
<tbody>
<tr>
<td>(H)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>(\Sigma)</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>(H')</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>(\Xi')</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

\(SU(4)_{DGUT}\) is decomposed as \(6 \rightarrow 3_{2/3} + \overline{3}_{-2/3}\):

\[
Q'_U = \frac{1}{\sqrt{2}} \begin{pmatrix}
0 & \overline{U}^{\prime 3} & -\overline{U}^{\prime 2} & U'_1 \\
-\overline{U}^{\prime 3} & 0 & \overline{U}^{\prime 1} & U'_2 \\
\overline{U}^{\prime 2} & -\overline{U}^{\prime 1} & 0 & U'_3 \\
-U'_1 & -U'_2 & -U'_3 & 0
\end{pmatrix},
Q'_D = \begin{pmatrix}
D'_1 \\
D'_2 \\
D'_3 \\
E
\end{pmatrix},
\overline{Q}'_D = \begin{pmatrix}
\overline{D}'^1 \\
\overline{D}'^2 \\
\overline{D}'^3 \\
\overline{E}'
\end{pmatrix}.

Portal operators are generated by integrating out the colored Higgs in \(SU(4)_{DGUT}\):

\[
\mathcal{L}_{\text{Yukawa}} = -Y_D \epsilon^{\alpha\beta\gamma\delta} H'_\alpha Q'_U H'^{\prime \alpha} Q'_D \delta - Y_D^* H'^{\prime \alpha} Q'_D \mathcal{Q}'_D \delta - Y_N H'_\alpha \mathcal{Q}'_D \alpha \overline{N} + \text{h.c.},
\]

\[
\mathcal{L}_{\text{portal}} = \frac{Y_N Y_D}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a \overline{D}^b) (D'^c \overline{N}) - \frac{Y_N Y_D^*}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a \overline{D}^{\prime b}) (D'^c \overline{N}) + \text{h.c.}
\]
UV completion of the Composite Asymmetric Dark Matter

Table 2: Charge assignment of fermions and scalars in the minimal $SU(5)_{GUT}$ $SU(4)_{DGUT}$ unified model. The upper rows of the tables show the assignment in $SU(5)_{GUT}$ sector while the lower rows show those in $SU(4)_{DGUT}$ sector.

SU(4)$_{DGUT}$ is decomposed as $6 \rightarrow 3_{2/3} + 3_{-2/3}$:

$$Q'_U = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{U}^3 & -\bar{U}''^2 & U'_1 \\ -\bar{U}''^3 & 0 & \bar{U}'^1 & U'_2 \\ \bar{U}'^2 & -\bar{U}^1 & 0 & U'_3 \\ -U'_1 & -U'_3 & -U'_3 & 0 \end{pmatrix}, \quad Q'_D = \begin{pmatrix} D'_1 \\ D'_2 \\ D'_3 \\ E \end{pmatrix}, \quad \bar{Q}'_D = \begin{pmatrix} \bar{D}'^1 \\ \bar{D}'^2 \\ \bar{D}'^3 \\ E' \end{pmatrix}.$$

Portal operators are generated by integrating out the colored Higgs in SU(4)$_{DGUT}$

$$\mathcal{L}_{Yukawa} = -Y_D \epsilon^{\alpha\beta\gamma\delta} H'_\alpha Q'_{U[\beta\gamma]} Q'_{D\delta} - Y_D H'^{\dagger\alpha} Q'_{U[\alpha\beta]} \bar{Q}'_D - Y_N H'_\alpha \bar{Q}'_D \epsilon^{\alpha} \bar{N} + \text{h.c.},$$

$$\Rightarrow \mathcal{L}_{portal} = \frac{Y_N Y_D}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a D'^b) (\bar{D}'^c \bar{N}) - \frac{Y_N Y_D^*}{\sqrt{2} M_C^2} \epsilon_{abc} (U'^a D'^b) (\bar{D}'^c \bar{N}) + \text{h.c.}$$
**DM capture at the SUN**

\[
\frac{dN}{dt} = \Gamma_{\text{capt}} - 2\Gamma_{\text{ann}} \quad \Gamma_{\text{ann}} = \frac{1}{2} \int d^3x n^2(\vec{x}) \langle \sigma v \rangle = \frac{1}{2} C_{\text{ann}} N^2
\]

\[
\rightarrow N_{DM} = \sqrt{\frac{\Gamma_{\text{capt}}}{C_{\text{ann}}}} \tanh \left(t \sqrt{\frac{\Gamma_{\text{capt}} C_{\text{ann}}}{\Gamma_{\text{evap}}}} \right)
\]

- Capture rate at the SUN for \( m_{DM} \leq 10 \text{ GeV} \)

\[ \Gamma_{\text{capt}} \sim 10^{30}/\text{sec} \times (\sigma_{SI}/\text{pb}) \quad [\text{e.g. Cirelli, PPPC v}] \]

\( \sigma_{SI} \): spin-independent DM-nucleon cross section

- The total DM mass in the SUN for non-annihilating DM

\[ M_{DM} \sim m_{DM} \times \Gamma_{\text{capt}} \times (5 \times 10^9 \text{ year}) \]

\[ \sim 10^{40} \text{ GeV} \left( \frac{m_{DM}}{10 \text{ GeV}} \right) \times \left( \frac{\sigma_{SI}}{10^{-44}\text{cm}^2} \right) \]

\[ \text{cf. } M_{\odot} \sim 10^{57} \text{ GeV} \]

For a scalar ADM without annihilation, the ADM captured in the neutron star may form a black hole inside the neutron star!

[1011.2907 McDermott, Yu, Zurek]
**DM capture at the SUN**

\[
\frac{dN}{dt} = \Gamma_{\text{capt}} - 2\Gamma_{\text{ann}} \quad \Gamma_{\text{ann}} = \frac{1}{2} \int d^3 \vec{x} n^2(\vec{x}) \langle \sigma v \rangle = \frac{1}{2} C_{\text{ann}} N^2
\]

\[
\rightarrow N_{DM} = \sqrt{\frac{\Gamma_{\text{capt}}}{C_{\text{ann}}}} \tanh \left( t \sqrt{\frac{\Gamma_{\text{capt}}}{C_{\text{ann}}}} \right)
\]

**Capture rate at the SUN for** \( m_{DM} \lesssim 10 \text{ GeV} \)

\[
\Gamma_{\text{capt}} \sim 10^{30}/\text{sec} \times (\sigma_{SI}/\text{pb}) \quad \text{[e.g. Cirelli, PPPC v]}
\]

\( \sigma_{SI} \): spin-independent DM-nucleon cross section

**Annihilation rate at the SUN**: \( \Gamma_{\text{ann}} < \Gamma_{\text{capt}} / 2 \)

The energy injection from the DM annihilation

\[
m_{DM} \Gamma_{\text{ann}} < m_{DM} \frac{\Gamma_{\text{capt}}}{2} \approx 10^{23} \text{ GeV/sec} \left( \frac{m_{DM}}{10 \text{ GeV}} \right) \times \left( \frac{\sigma_{SI}}{10^{-44}\text{cm}^2} \right)
\]

*cf. solar power: \( \sim 10^{36} \text{ GeV/sec} \)*