# *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.

$$\Omega_{DM} h^2 \sim 0.14 \qquad \Omega_B h^2 \sim 0.022$$

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

***Baryon-DM coincidence ?***

$$\Omega_{DM} : \Omega_b \sim 5 : 1$$

***close with each other…***

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

***Is this a serious problem ?***

# Baryon-DM coincidence Problem

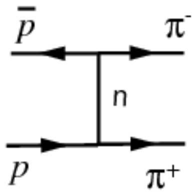
***If it were not for Baryogenesis…***

- DM mass density can be explained by the WIMP mechanism :

$$\boldsymbol{\Omega_{DM} \propto m_{DM}\, n_{DM}} \simeq 0.1 \times \left(\frac{10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle}\right)$$

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

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




$$\langle \sigma v \rangle \sim \frac{4\pi}{m_n^2} \sim 10\,\mathrm{GeV}^{-2}$$

→ $\boldsymbol{\Omega_{DM} : \Omega_b}$ ***( no-asymmetry ) = 1 : $10^{-10}$***

- The observed baryon density is provided by the baryon asymmetry.

$$\boldsymbol{\Omega_b\ (\text{with asymmetry}) = 0.02\ (\eta_B / 10^{-9})}$$

$$\boldsymbol{\eta_B = (n_B - n_{\bar{B}}) / n_\gamma}$$

***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 $\Omega_B/\Omega_{DM} < 10^{-(2\text{-}4)}$, 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)*

**[1990 Barr Chivukula, Farhi , 1992 D. B. Kaplan, 2009 D. E. Kaplan, Luty and Zurek]**

***Basic Idea***

✓ Matter-anti-matter asymmetries in the SM/DM sectors

$$\eta_B = ( n_B - n_{\bar{B}} )/ n_\gamma \qquad \eta_{DM} = ( n_{DM} - n_{\overline{DM}} )/ n_\gamma$$

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

$$\Omega_b \text{ (with asymmetry) } \propto m_N \eta_B$$

$$\Omega_{DM} \text{ (with asymmetry) } \propto m_{DM} \eta_{DM}$$

$$\rightarrow \Omega_{DM} / \Omega_B = ( m_{DM} / m_B ) (\eta_{DM} / \eta_B )$$

The baryon-DM ratio $\Omega_{DM} / \Omega_B \sim 5$ can be achieved for

$$m_{DM} \sim 5\, m_B \times (\eta_B / \eta_{DM} ) \sim O(1) \text{ GeV}$$

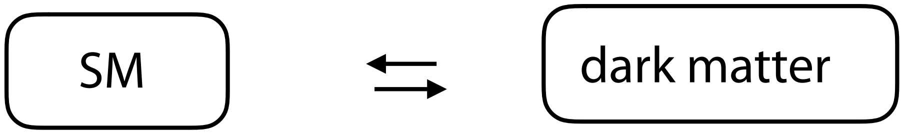
# ✓ *Asymmetric Dark Matter (ADM)*

***Two main mechanisms***

✓ ***Sharing mechanism***

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

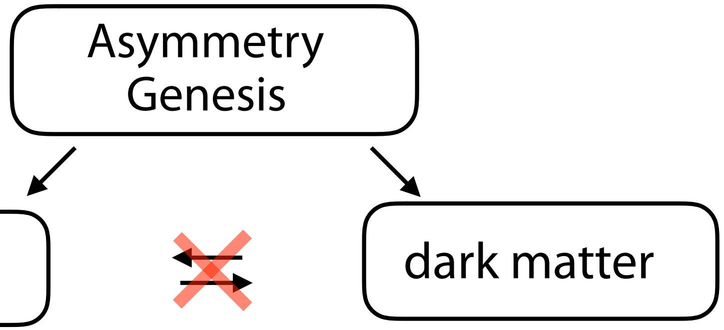
Asymmetry is thermally distributed in the two sectors




$\eta_{DM}/\eta_B$ 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

SM ⇄ dark matter

$\eta_{DM} / \eta_B$ 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 $N_R$)***

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

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

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

✔ Dark Sector shares the ***B-L*** symmetry with the ***SM*** through

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

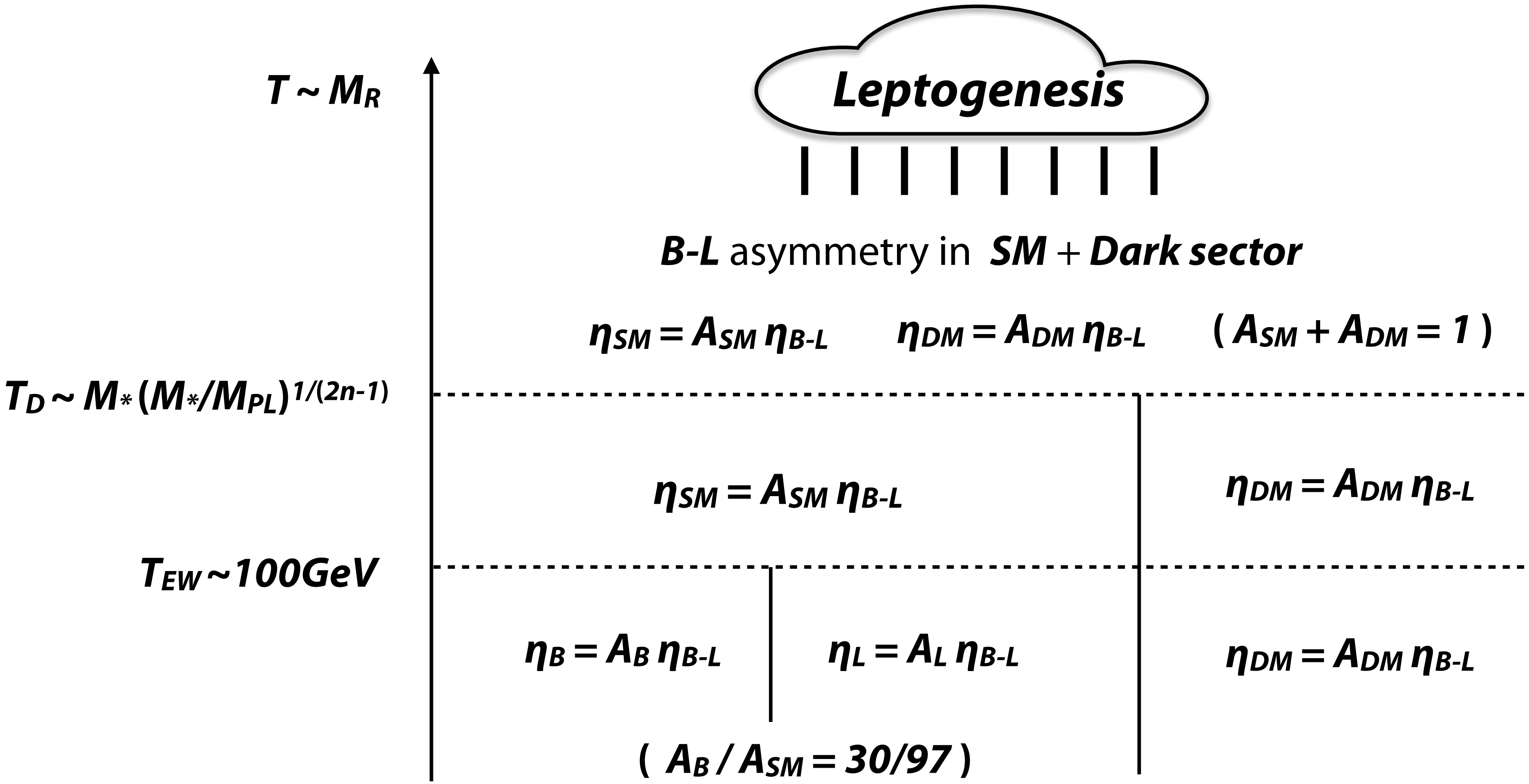
***$O_{SM}$ : Neutral (other than B-L) consisting of SM fields.***

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

The ***SM*** and the ***DM*** sectors are thermally connected at the high temperature
$T > T_D \sim M_* (M_*/M_{PL})^{1/(2n-1)}$

***ADM*** scenario is achieved by ***Thermal Leptogenesis*** for $M_R > T_D$ .

## Asymmetric Dark Matter via Leptogenesis




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

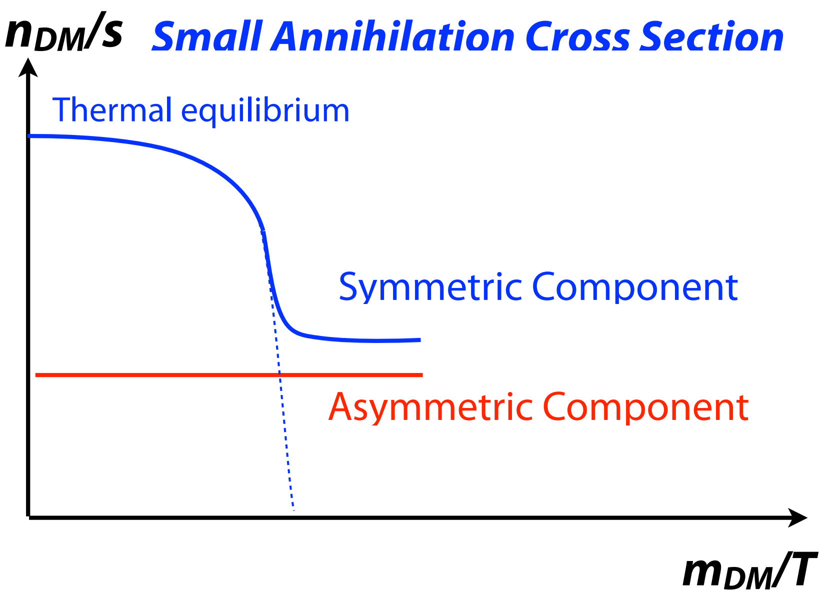
$$\Omega_{DM} = (m_{DM}/m_p)\,(A_{DM}/A_{SM})\,(A_{SM}/A_B)\,\Omega_B$$

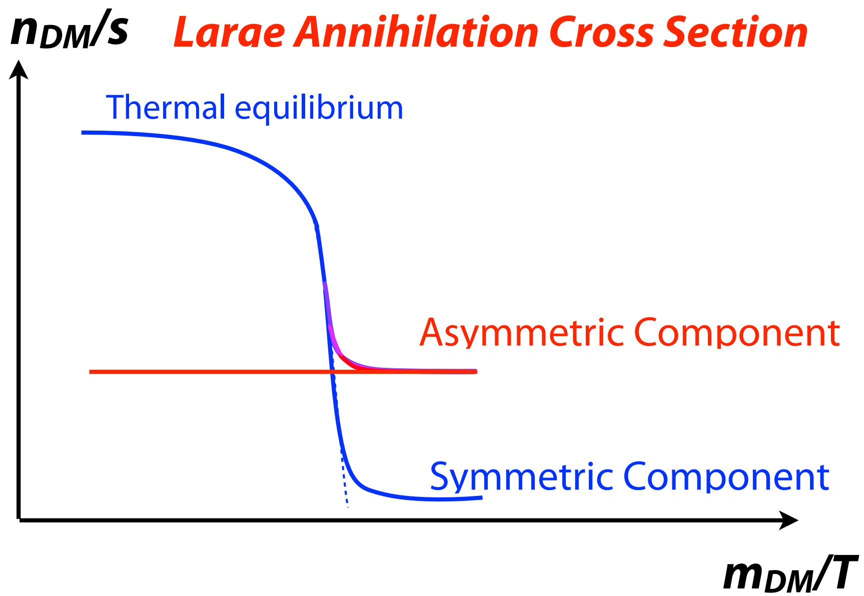
$$m_{DM} = 5\, m_p\, (30/97)\, \underline{(A_{SM}/A_{DM})} \times (\Omega_{DM}/5\Omega_B)$$

determined by the degrees of freedom

# ✓ *Model Building of Asymmetric Dark Matter*

✓ ***ADM*** models require a large annihilation cross section




Annihilation of the symmetric component of ***DM*** should be very efficient !

$$\sigma v \gg 10^{-9}\,\mathrm{GeV}^{-2}$$

***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.)

# ***Model Building of Asymmetric Dark Matter***

- We prefer ***ADM*** models in which

$$m_{DM} = O(1)\ GeV$$

is achieved without fine-tuning.

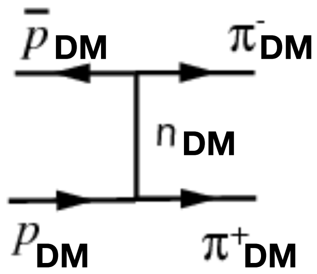
> The ***ADM*** scenario ***does not solve*** the coincidence problem but provides a new interpretation in terms of the mass ratio $m_{DM}/m_N = O(1)$ .
>
> The ultimate solution to the problem is obtained when the mass ratio $m_{DM}/m_N = O(1)$ is explained, which requires higher-energy theory.

At least, $m_{DM} = O(1)\ GeV$ 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 !**

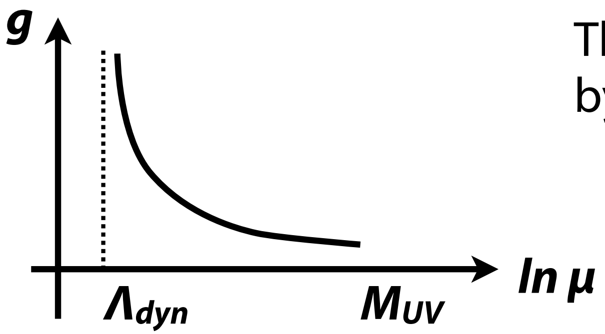
- ***DM*** annihilation cross section is large !




$$\sigma v \sim 4\pi / m_{DM}{}^2$$

***Symmetric components annihilates very efficiently !***

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

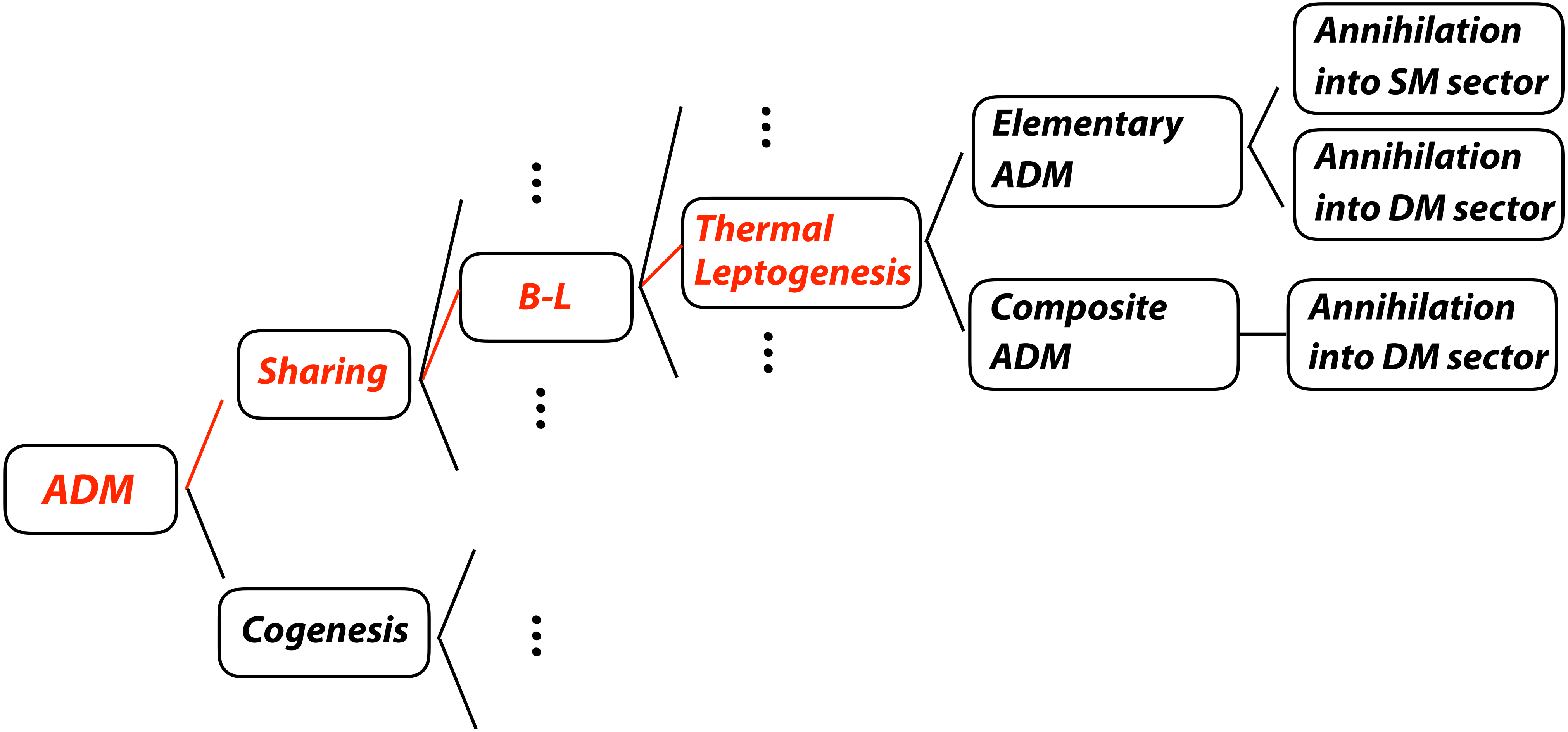



The mass scale ~ dynamical scale is determined by the gauge coupling constant at the UV scale.

$$m_{DM} \sim \Lambda_{dyn} \sim M_{UV}\, Exp[\, -8\pi^2/b\, g(M_{UV})^2\, ]$$

$$[\, b = 11/3\, Nc - 2/3\, N_F \text{ for } SU(Nc)\ N_F\text{-flavor}\, ]$$

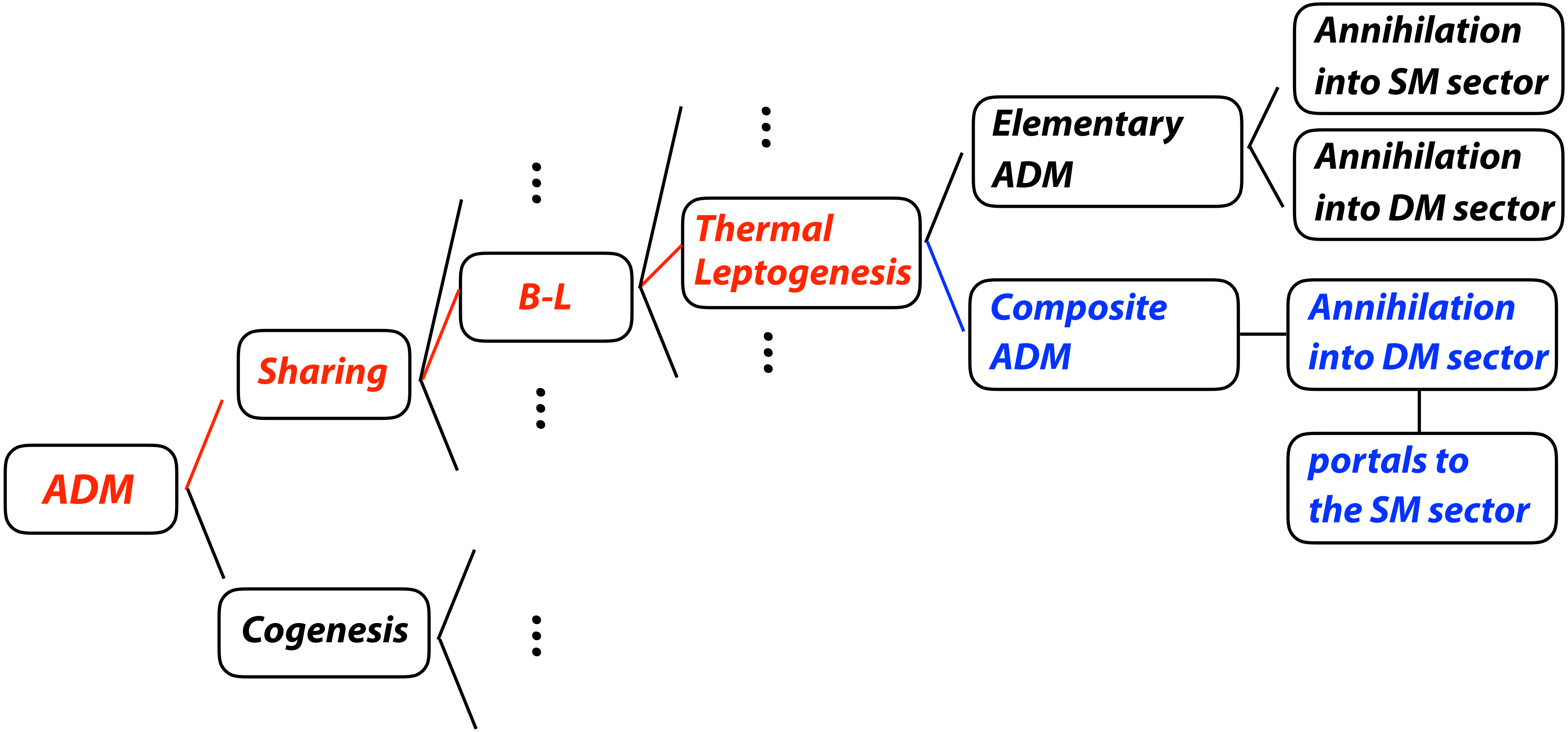
## ✓ Model Building of Asymmetric Dark Matter




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.***

## ✓ *Model Building of Asymmetric Dark Matter*




Compositeness is an interesting addition.

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

# *Asymmetric Dark Matter and Dark Radiation*

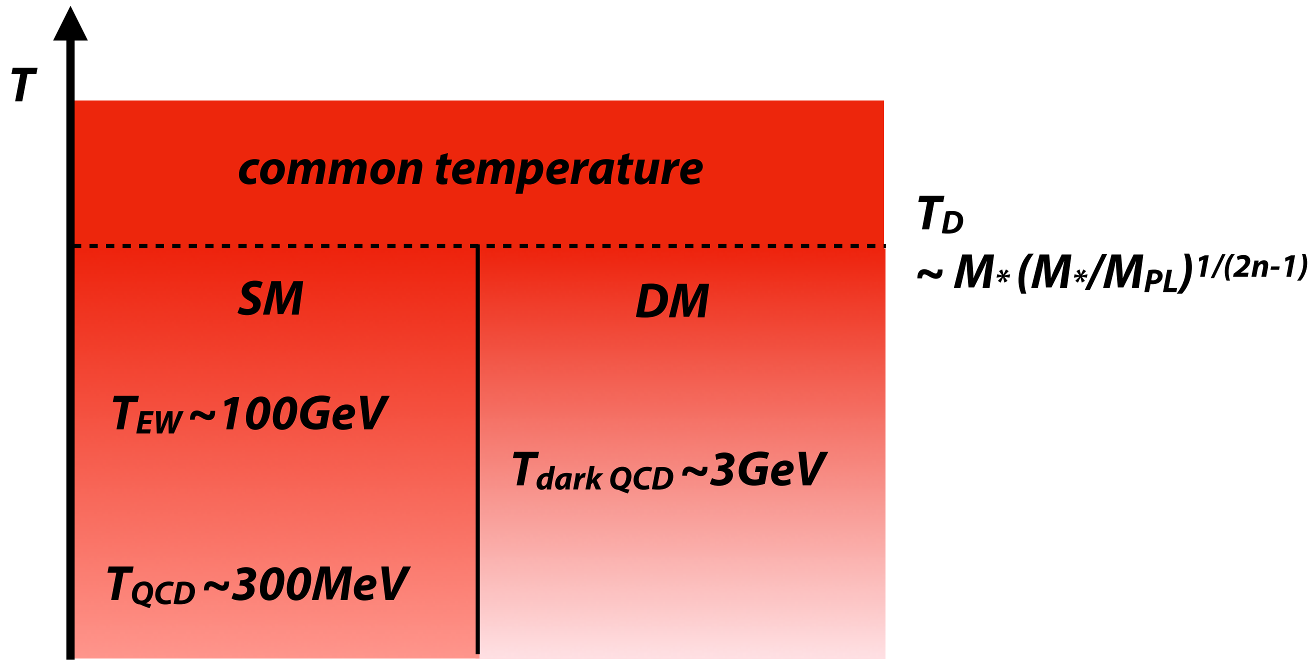
***What if the final state particle in the dark sector are massless ?***

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

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

( $g$ : 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

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

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

***$T_{\nu *}$ : ν decoupling temperature (~3MeV)*** ***$\bar{g}_{DM} = g_{DM}$ x {1 (B), 7/8 (F)}***

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

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

***CMB*** constraints : ***$\Delta N_{eff}$ < 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

**[1805.0687 Kamada, Kobayashi, Nakano MI]**

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

- ***Dark QED*** can mix with ***QED*** through the kinetic mixing.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \underbrace{\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}}_{\text{kinetic mixing}}$$

***$F_{\mu\nu}$ : QED photon*** ***$F'_{\mu\nu}$ : dark QED photon*** ***$\varepsilon$ : mixing parameter << 1***

- Assume ***dark QED photon*** obtains a mass via Higgs mechanism…

  The massive ***dark photon*** couples to ***QED*** current with ***$\varepsilon\, g_{QED}$***.


***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 ***$N_F = 2$***

| | $SU(3)_D$ | $B-L$ | $U(1)_D$ |
|---|---|---|---|
| $Q_1$ | $\mathbf{3}$ | $q_{B-L}$ | $2/3$ |
| $\bar{Q}_1$ | $\bar{\mathbf{3}}$ | $-q_{B-L}$ | -2/3 |
| $Q_2$ | $\mathbf{3}$ | $q_{B-L}$ | -1/3 |
| $\bar{Q}_2$ | $\bar{\mathbf{3}}$ | $-q_{B-L}$ | $1/3$ |

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

Asymmetry Ratio :

***$( A_{SM} / A_{DM} ) = 237 / ( 22 N_F ) \rightarrow m_{DM} \sim 8.5\ \mathrm{GeV} ( 2 / N_F )$***

**[ see also 1411.4014 Fukuda, Matsumoto, Mukhopadhyay ]**

✓ We need at least ***$N_F > 1$*** to allow the ***B-L*** portal interaction.

$$\mathcal{L}_{B-L\,\mathrm{portal}} = \frac{1}{M_*^n} \mathcal{O}_D \mathcal{O}_{\mathrm{SM}} + \mathrm{h.c.}$$

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

***$O_{DM}$ : 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.***

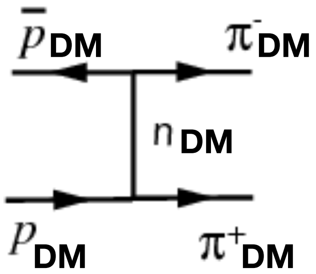
- ***Dark Matter = Dark protons and Dark neutrons*** ( $m_{N'} \sim O(1)$ GeV )

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

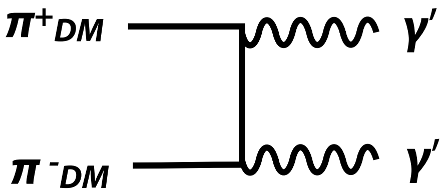
- ***Dark baryons*** annihilate into ***Dark pions*** ( $m_{\pi'} = O(100)\mathrm{MeV} - O(1)\mathrm{GeV}$ )

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

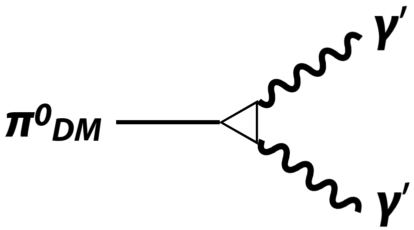
- ***Dark pions*** annihilate/decay into ***dark photons*** ( $m_{\gamma'} < m_{\pi'} < m_{N'}$ )




$\sigma v \sim 4\pi / m_{DM}^2$




$\sigma v \sim \pi \alpha'^2 / m_{\pi'}^2$




$\Gamma \sim \alpha'^2/64\pi^3 \times m_{\pi'}^3/f_\pi^2$

***The dark sector ends up with the dark baryonic matter and dark photon due to the asymmetry !*** ( $\Omega_{p'} : \Omega_{n'} \sim 1:1$ )

# Composite Asymmetric Dark Matter with Dark Photon

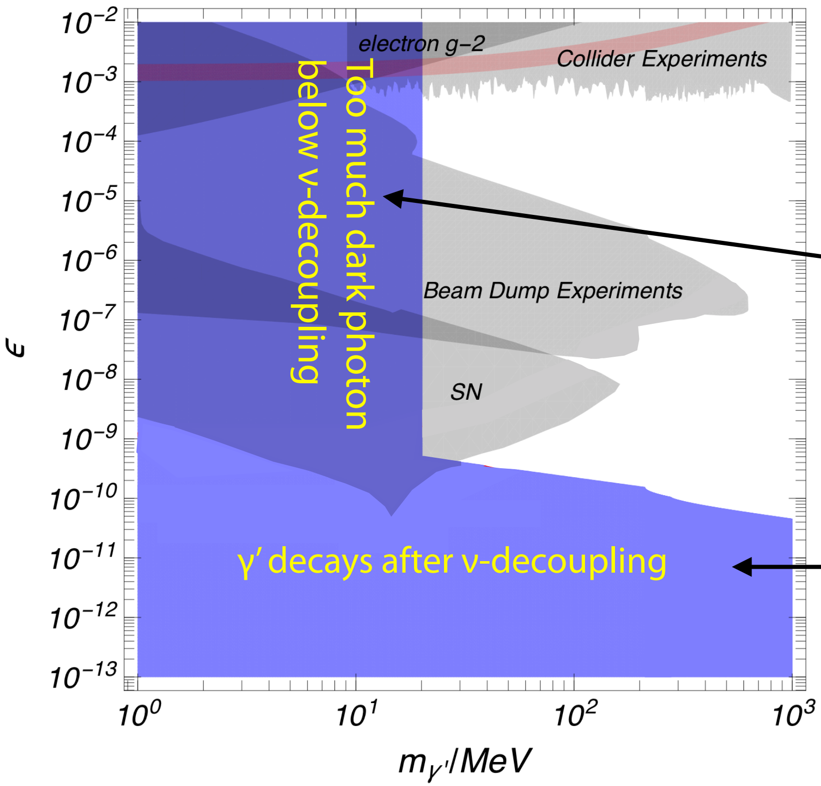
[1805.0687 Kamada, Kobayashi, Nakano MI]

- ***Dark photons*** eventually decay into a pair of the ***electrons*** or the ***muons***

$$\Gamma_{\gamma'} = N_{\rm ch}\frac{1}{3}\epsilon^2\alpha m_{\gamma'} \simeq 0.3\,{\rm s}^{-1} \times N_{\rm ch}\left(\frac{\epsilon}{10^{-10}}\right)^2\left(\frac{m_{\gamma'}}{100\,{\rm MeV}}\right)$$

***Lifetime of O(1) sec ↔ $\varepsilon \sim 10^{-10}$***

***Constraints on dark photon parameter space***




- For $\boldsymbol{m_{\gamma'} < 20}$***MeV***, the ***γ'*** shares the thermal energy with ***γ, e, ν*** at **T > $m_{\gamma'}$**.

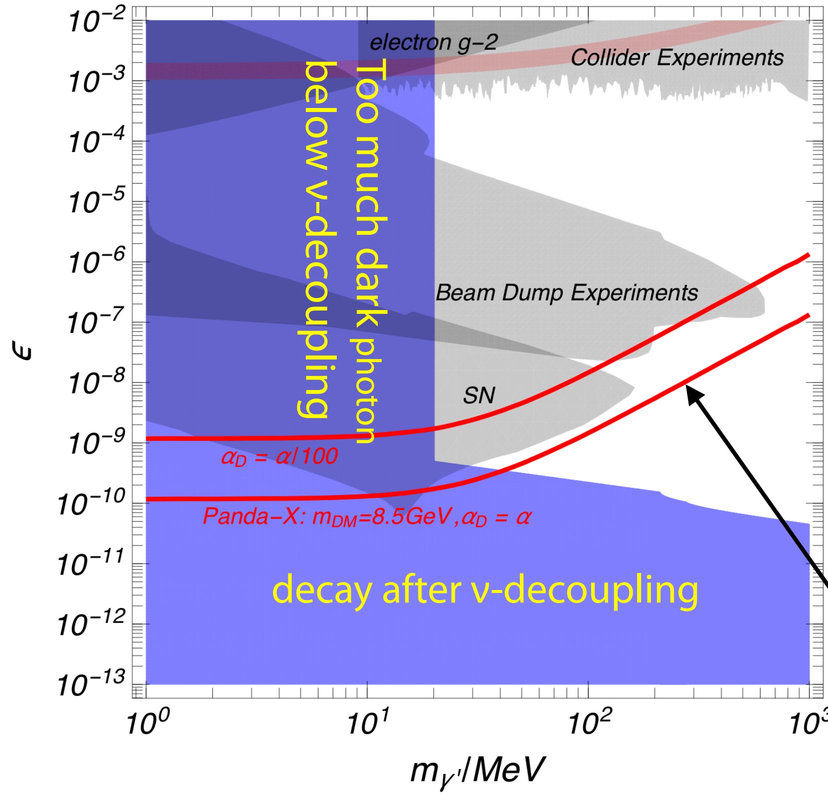
Some portion of ***γ'*** releases its energy into ***$e^+$+$e^-$*** below ***$T_{\nu*}$***, which reduces ***$\Delta N_{eff}$***.

- The ***γ'*** decay after the ν decouple also reduces ***$\Delta N_{eff}$***.

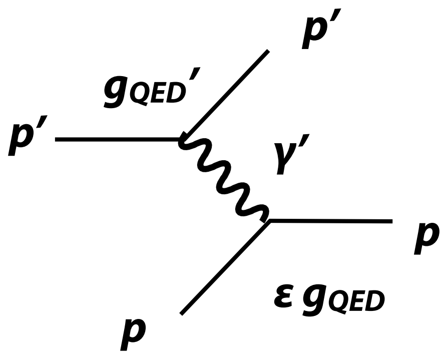
# ✔ *Composite Asymmetric Dark Matter with Dark Photon*

**[1805.0687 Kamada, Kobayashi, Nakano MI]**

✔ Dark Matter direct detection via the dark photon exchange.




***Dark proton couples to the proton !***




$$\frac{d\sigma_{XT}}{dq^2} = \frac{4\pi\alpha_{\rm em}\alpha_X\epsilon_\gamma^2 Z^2}{(q^2+m_\phi^2)^2}\frac{1}{v^2}F_T^2(q^2) \ \propto Z^2$$

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

***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

$$\mathcal{L}_{B-L\,\mathrm{portal}} = \frac{1}{M_*^n}\mathcal{O}_D\mathcal{O}_{\mathrm{SM}} + \mathrm{h.c.}$$
$$= \frac{1}{M_*^3}(\bar{Q}_1\bar{Q}_2\bar{Q}_2)LH$$

***Dark neutron operator***

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

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

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

**[1003.5662 Feldstein, Fitzpatrick]**

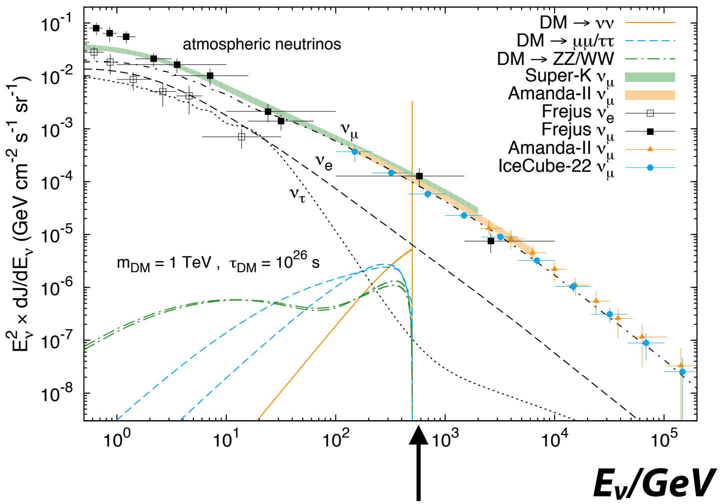
**[1411.4014 Fukuda, Matsumoto, Mukhopadhyay ]**

***Composite ADM leads to a monochromatic anti-neutrino signal !***

## ✔ *Composite Asymmetric Dark Matter with Dark Photon*

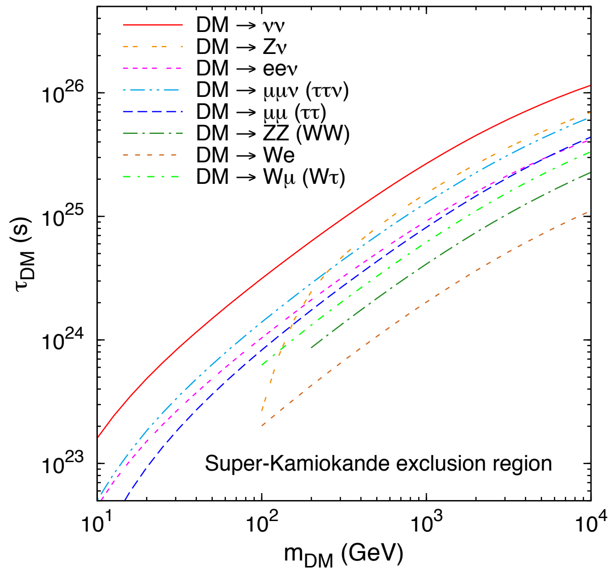
✔ Constraints on the ***ν*-** flux from DM decay

***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, $\Delta\theta_{GC} = 30°$***

**['09 Covi, Grefe, Ibarra, Tran ]**

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

***( SK 90%CL constraints on the neutrino flux )***

$$\rightarrow M_* \gtrsim 10^{8.5}\,\text{GeV}$$

***In the ADM models, neutrino detectors sensitive to O(100)MeV - O(1)GeV play important roles !***

# *Composite Asymmetric Dark Matter with Dark Photon*

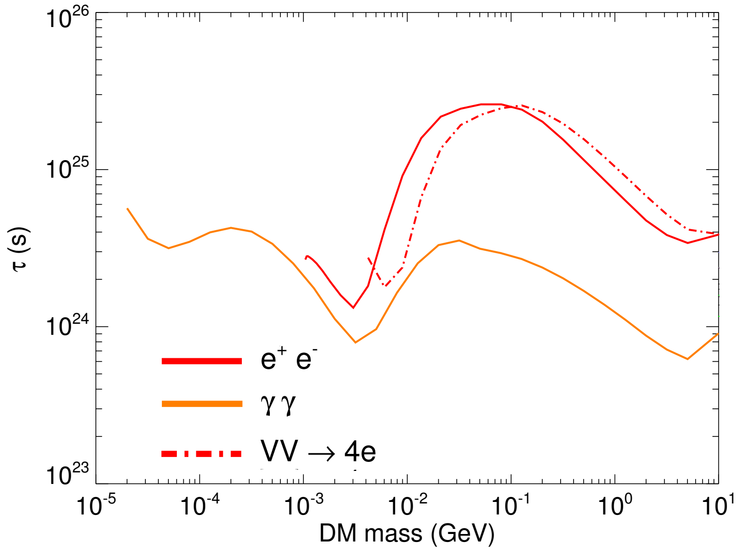
- Constraints from ***CMB*** (work in progress with ***Kobayashi, Nagai Nakano*** )

The dark neutron decay ends up with electrons.

$$n' \to \pi^{0\prime} + \bar{\nu}$$
$$\quad\quad \hookrightarrow \gamma' + \gamma' \to e^+ + e^- + e^+ + e^-$$

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

**[1610.06933 Slatyer, Wu ]**




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

$$\tau_{DM} > 10^{24\text{-}25}\,\text{sec}$$

( 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

$$\mathcal{L}_{B-L\,\mathrm{portal}} = \frac{1}{M_*^3}(\bar{Q}_1\bar{Q}_2\bar{Q}_2)LH$$

is generated by the seesaw mechanism:

$$\mathcal{L}_{N\text{-SM}} = \frac{1}{2}M_R\bar{N}_R\bar{N}_R + y_N HL\bar{N}_R + \frac{1}{\bar{M}_*^2}(\bar{Q}_1\bar{Q}_2\bar{Q}_2)\bar{N}_R + h.c.$$

$$\rightarrow \quad \mathcal{L}_{\mathrm{eff}} = \underbrace{\frac{y_N^2}{2M_R}LHLH}_{\text{neutrino mass}} + \underbrace{\frac{y_N}{M_R\bar{M}_*^2}(\bar{Q}_1\bar{Q}_2\bar{Q}_2)LH}_{\text{portal operator}} + \underbrace{\frac{1}{2M_R\bar{M}_*^4}(\bar{Q}_1\bar{Q}_2\bar{Q}_2)^2}_{\text{Majorana Mass of n'}}$$

The Majorana mass of ***n' = oscillation time scale of the n' and $\bar{n}$'***

$$\Delta m'_n \sim \frac{\Lambda_{QCD'}^6}{M_R\bar{M}_*^4} \sim 10^{-47}\mathrm{GeV}\left(\frac{\Lambda_{QCD'}}{3\mathrm{GeV}}\right)^6\left(\frac{10^{10}\mathrm{GeV}}{M_R}\right)\left(\frac{10^{10}\mathrm{GeV}}{\bar{M}_*}\right)^4$$

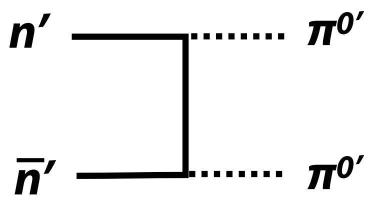
***cf. $H_0 \sim 10^{-42}$ GeV***

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

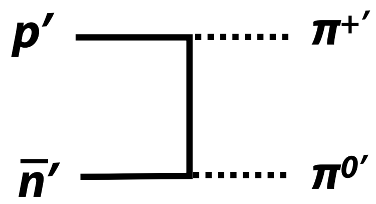
**[see also 1202.0283 Tulin, Yu, Zurek, 1402.42500 Hardy, Lasenby, Unwin]**

## ✓ *Composite Asymmetric Dark Matter with Dark Photon*

✓ Dark matter can annihilate in the present universe !




$\longrightarrow (e^+ + e^-) \times 4$




$\longrightarrow (e^+ + e^-) \times 2$

Effective cross section : $f_{anti}\, \sigma v$

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

*very large !*

Typical electron/positron energy : $\langle E_e \rangle = O(1) GeV$

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

✓ $e^+ + e^-$ leads to the inverse Compton & synchrotron radiation

→ constraints on the galactic $\gamma$-ray flux by Fermi-LAT

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

✓ $e^+ + e^-$ injection distorts ***CMB***

$f_{anti}(z \sim 600)\, \sigma v \lesssim 10^{-26} cm^3/s$ **[ Planck 2018 ]**

# ✓ UV completion of the Composite Asymmetric Dark Matter

✓ The dark photon model requires a tiny parameter ***ε***

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

For ***U(1) x U(1) gauge theory***, ***ε*** 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]**

**SM : *SU(3)xSU(2)xU(1)* → *SU(5)<sub></sub>***

**SM :** $SU(3)\times SU(2)\times U(1) \rightarrow SU(5)_{GUT}$

**DM :** $SU(3)\times U(1) \rightarrow SU(4)_{DGUT}$

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

| | $SU(5)_{\rm GUT}$ | $SU(4)_{\rm DGUT}$ | $U(1)_5$ |
|---|---|---|---|
| $\Psi_i$ | $\mathbf{10}$ | $\mathbf{1}$ | $1$ |
| $\Phi_i$ | $\overline{\mathbf{5}}$ | $\mathbf{1}$ | $-3$ |
| $\overline{N}_i$ | $\mathbf{1}$ | $\mathbf{1}$ | $5$ |
| $Q'_U$ | $\mathbf{1}$ | $\mathbf{6}$ | $0$ |
| $Q'_D$ | $\mathbf{1}$ | $\mathbf{4}$ | $5/2$ |
| $\overline{Q'_D}$ | $\mathbf{1}$ | $\overline{\mathbf{4}}$ | $-5/2$ |

| | $SU(5)_{\rm GUT}$ | $SU(4)_{\rm DGUT}$ | $U(1)_5$ |
|---|---|---|---|
| $H$ | $\mathbf{5}$ | $\mathbf{1}$ | $2$ |
| $\Sigma$ | $\mathbf{24}$ | $\mathbf{1}$ | $0$ |
| $H'$ | $\mathbf{1}$ | $\mathbf{4}$ | $-5/2$ |
| $\Xi'$ | $\mathbf{1}$ | $\mathbf{15}$ | $0$ |

**$U(1)_5$ = GUT commuting *B-L***

## UV completion of the Composite Asymmetric Dark Matter

- Mixing term originates from the higher dimensional operator

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

$\varepsilon \sim 10^{-10} \leftrightarrow v_4 \sim 10^{10}$ GeV

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

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

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

Portal scale is explained by the dark GUT scale ***Mc ~ v4 ~ 10$^{10}$GeV***

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

***( $v_5 \sim 10^{16}$GeV & $v_4 \sim 10^{10}$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

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

$$m_{N'} \simeq m_N \times \frac{\Lambda_{\mathrm{QCD}'}}{\Lambda_{\mathrm{QCD}}} \qquad m_{n'} - m_{p'} \simeq \delta m_{n\text{-}p}^{\mathrm{QED}} \times \frac{\Lambda_{\mathrm{QCD}'}}{\Lambda_{\mathrm{QCD}}} \times \alpha_D + \kappa_N (m_1 - m_2)$$

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

## The dark pions

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

$$m_{\pi'^0}^2 \simeq m_{\pi^0}^2 \times \frac{\Lambda_{\mathrm{QCD}'}}{\Lambda_{\mathrm{QCD}}} \frac{m_1 + m_2}{m_u + m_d} \qquad m_{\pi'^\pm}^2 \simeq m_{\pi'^0}^2 + \alpha_D \Lambda_{\mathrm{QCD}'}^2$$

## UV completion of the Composite Asymmetric Dark Matter

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

| | $SU(5)_{\rm GUT}$ | $SU(4)_{\rm DGUT}$ | $U(1)_5$ |
|---|---|---|---|
| $\Psi_i$ | $\mathbf{10}$ | $\mathbf{1}$ | $1$ |
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| $\overline{N}_i$ | $\mathbf{1}$ | $\mathbf{1}$ | $5$ |
| $Q'_U$ | $\mathbf{1}$ | $\mathbf{6}$ | $0$ |
| $Q'_D$ | $\mathbf{1}$ | $\mathbf{4}$ | $5/2$ |
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$SU(4)_{\rm DGUT}$ is decomposed as $\mathbf{6} \to \mathbf{3}_{2/3} + \overline{\mathbf{3}}_{-2/3}$:

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

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

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

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

## ✔ UV completion of the Composite Asymmetric Dark Matter

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# DM capture at the SUN

$$\frac{dN}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} \qquad \Gamma_{\rm ann} = \frac{1}{2}\int d^3x\, n^2(\vec{x})\, \langle \sigma v \rangle = \frac{1}{2} C_{\rm ann} N^2$$

$$\rightarrow \quad N_{DM} = \sqrt{\frac{\Gamma_{\rm capt}}{C_{\rm ann}}} \tanh\left(t\sqrt{\Gamma_{\rm capt} C_{\rm ann}}\right)$$

- Capture rate at the SUN for $m_{DM} \lesssim 10$ *GeV*

  $\Gamma_{capt} \sim 10^{30}$/sec x ($\sigma_{SI}$/pb) [e.g. Cirelli, PPPC ν]

  **$\sigma_{SI}$ : spin-independent DM-nucelon cross section**

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

  $M_{DM} \sim m_{DM} \times \Gamma_{capt} \times (5 \times 10^9$ **year** )

  $\sim 10^{40}$ *GeV* ( $m_{DM}$/10 *GeV* ) x ( $\sigma_{SI}$ / $10^{-44}$ cm$^2$ )

  **cf.** $M_\odot \sim 10^{57}$ *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*

$$\frac{dN}{dt} = \Gamma_{\rm capt} - 2\Gamma_{\rm ann} \qquad \Gamma_{\rm ann} = \frac{1}{2}\int d^3x\, n^2(\vec{x})\,\langle\sigma v\rangle = \frac{1}{2}C_{\rm ann}N^2$$

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✓ Capture rate at the SUN for $m_{DM} \lesssim 10$ GeV

**$\Gamma_{capt}$ ~ $10^{30}$/sec x ($\sigma_{SI}$/pb)** **[e.g. Cirelli, PPPC ν]**

**$\sigma_{SI}$ : spin-independent DM-nucelon cross section**

✓ Annihilation rate at the SUN : $\Gamma_{ann} < \Gamma_{capt} / 2$

The energy injection from the DM annihilation

$$m_{DM}\Gamma_{ann} < m_{DM}\Gamma_{capt}/2$$
$$\sim 10^{23}\ \mathrm{GeV/sec}\ (m_{DM}/10\ \mathrm{GeV})\ \mathrm{x}\ (\sigma_{SI}/10^{-44}\mathrm{cm}^2)$$

***cf. solar power : ~ $10^{36}$ GeV / sec***