# *Initially asymmetric dark matter*

Osamu Seto (Hokkai-Gakuen Univ.)

With Nobuchika Okada (U. of Alabama)

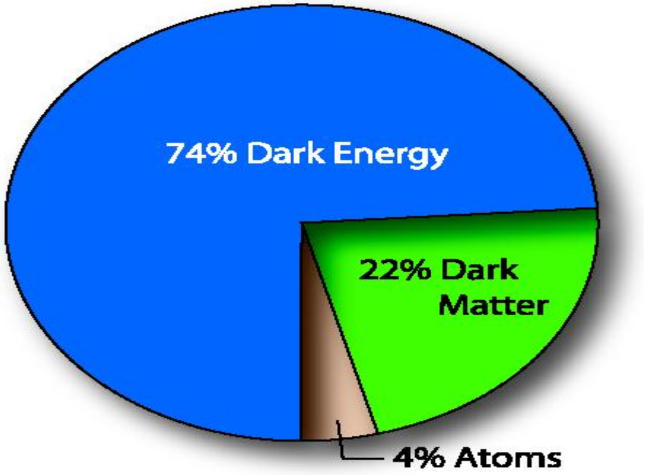
**arXiv:1205.2844 v2** [hep-ph]

# § Introduction

- The origins of baryon as well as dark matter are unknown.
- Those energy densities are close each other nevertheless. $\Omega_b h^2 \approx 0.02$ $\Omega_{DM} h^2 \approx 0.1$

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

Coincidence???



[NASA]

# Some approaches

- The source of both baryon and dark matter is same.

For example, Q-ball $\xrightarrow{\qquad}$ q+LSP

[Enqvist and McDonald 1998, Roszkowski and OS 2006...]

- The resultant number density is actually its number asymmetry.

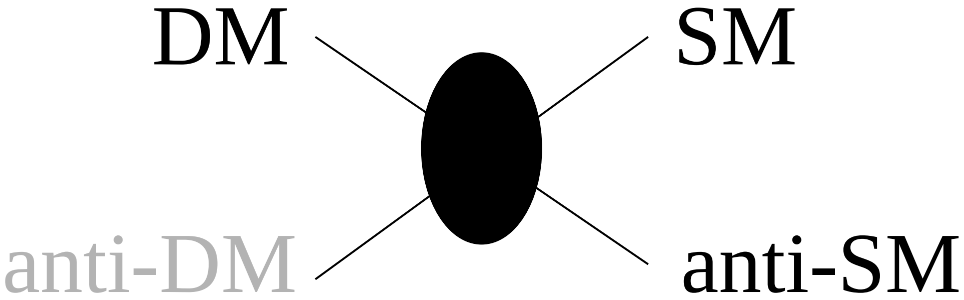
Asymmetric dark matter (ADM)

[Barr 1991, Kaplan 1992, Hooper et al 2005, Kaplan et al 2009...]

$n_{DM} = n_{DM}-n_{anti\text{-}DM}$, c.f., $n_b=n_b-n_{anti\text{-}b}$

# Indirect detection of ADM

- A signal from indirect searches confronts with ADM which does not annihilate now.



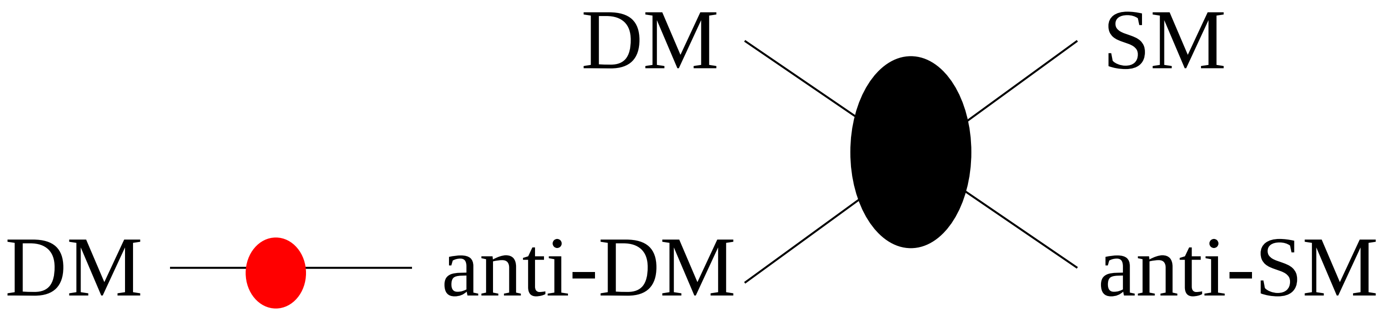
- For a signal, we need a very tiny "dark matter number" violation. [Cohen and Zurek 2011]

$$\lesssim 10^{-41}\ \mathrm{GeV}$$ [Buckley and Profumo 2012]

- From theoretical viewpoint, too tiny!!!

# Indirect detection of ADM

- A signal from indirect searches confronts with ADM which does not annihilate now.

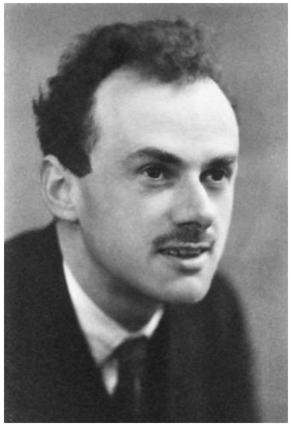


- For a signal, we need a very tiny "dark matter number" violation. [Cohen and Zurek 2011]

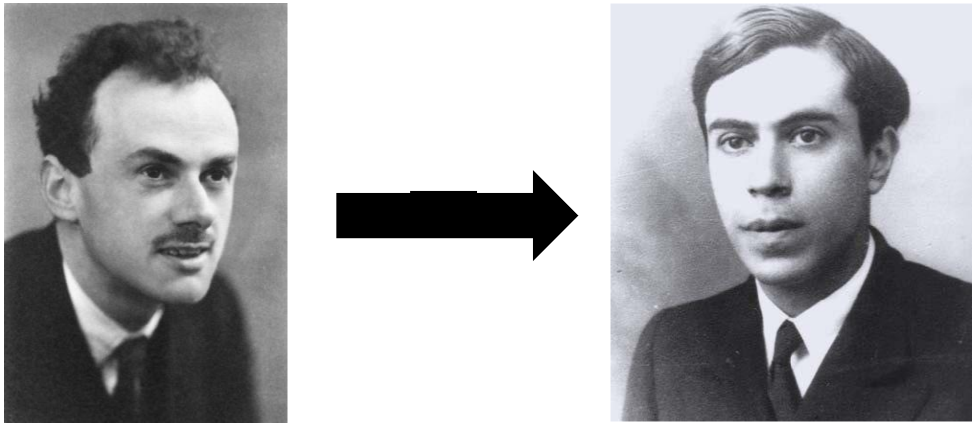
● $\lesssim 10^{-41}\ \mathrm{GeV}$ [Buckley and Profumo 2012]

- From theoretical viewpoint, too tiny!!!

# § Feature of our model

- Motivated by $\lesssim 10^{-41}\ \mathrm{GeV}$, self-annihilatable ADM without a too tiny parameter.
- The dark matter relic density was set by DM asymmetry in the early Universe due to a large annihilation cross section.
- Dark matter particle is Majorana.
-  =  ???

# § Feature of our model

- Motivated by $\lesssim 10^{-41}\ \mathrm{GeV}$, self-annihilatable ADM without a too tiny parameter
- The dark matter relic density was set by DM asymmetry in the early Universe due to a large annihilation cross section.
- Dark matter particle is Majorana.
-  !

# § § large annihilation

- Cross section enhancement
- Through SU(2) interaction

  c.f., Higgsino
- Through resonances

  c.f., funnel

# § A model

- Particle content

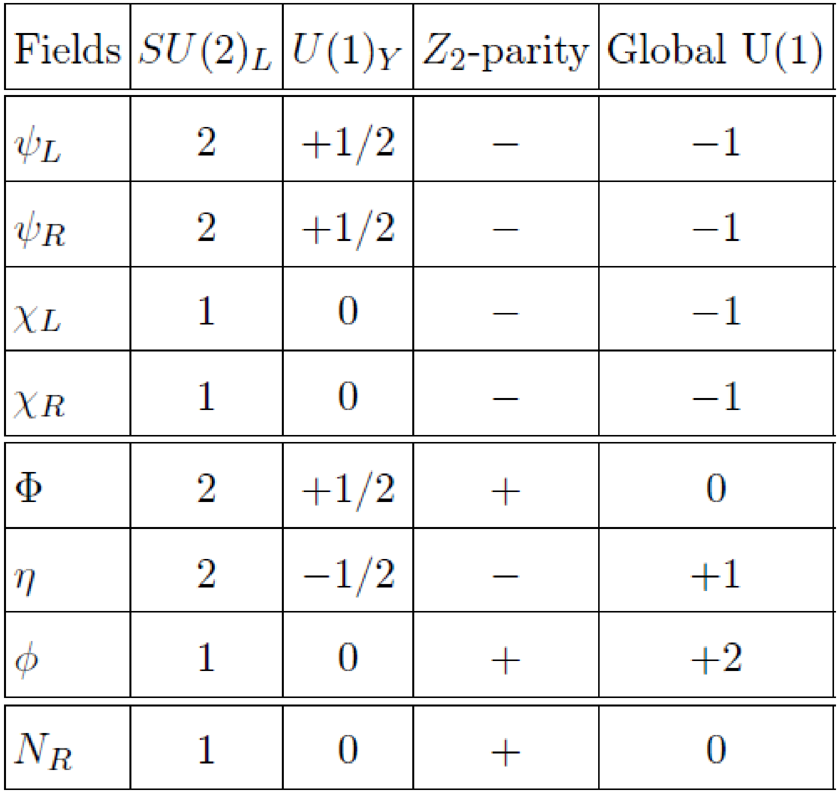


TABLE I: Particle contents of Model A

| Fields | $SU(2)_L$ | $U(1)_Y$ | $Z_2$-parity | Global U(1) |
|---|---|---|---|---|
| $\psi_L$ | 2 | $+1/2$ | $-$ | $-1$ |
| $\psi_R$ | 2 | $+1/2$ | $-$ | $-1$ |
| $\chi_L$ | 1 | 0 | $-$ | $-1$ |
| $\chi_R$ | 1 | 0 | $-$ | $-1$ |
| $\Phi$ | 2 | $+1/2$ | $+$ | 0 |
| $\eta$ | 2 | $-1/2$ | $-$ | $+1$ |
| $\phi$ | 1 | 0 | $+$ | $+2$ |
| $N_R$ | 1 | 0 | $+$ | 0 |

- Interactions

$$-\mathcal{L} \supset \frac{1}{2} y \bar{\chi^c_R} \phi \chi_R + \frac{1}{2} y \bar{\chi^c_L} \phi \chi_L + \frac{1}{2} \bar{N^c_R} M_N$$

$$+\mu_\chi \bar{\chi_L} \chi_R + \mu_\psi \bar{\psi_L} \psi_R + Y \bar{\psi_L} \Phi \chi_R + Y \bar{\chi_L} \Phi^\dagger \psi_R + Y_N \bar{\psi_L} \eta^\dagger N_R +$$

# § § Its history

- Stage 1: DM asymmetry generation
- From a CP violating out of equilibrium decay of heavy particle *N<sub>R</sub>*

$$\frac{n_\psi}{s} = \frac{\kappa_\psi}{g_*}\epsilon_{(N_R\to\psi\eta)} \times \mathrm{Br}(N_R \to \psi\eta)$$

- C.f. Leptogenesis from $N_R$

$$\frac{n_L}{s} = \frac{\kappa_L}{g_*}\epsilon_{(N_R\to L\Phi)} \times \mathrm{Br}(N_R \to L\Phi)$$

# § § Its history

- Stage 2: after EWSB to T ≳ $M_{DM}/20$
- Dirac fermion DM mass

$$(\bar{\chi}_L \bar{\chi}^c_R \bar{\psi}_L \bar{\eta}^c_R) M \begin{pmatrix} \chi^c_L \\ \chi_R \\ \psi^c_L \\ \psi_R \end{pmatrix} \qquad M = \begin{pmatrix} 0 & \mu_\chi & 0 & Y\frac{v}{\sqrt{2}} \\ \mu_\chi & 0 & Y\frac{v}{\sqrt{2}} & 0 \\ 0 & Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi \\ Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi & 0 \end{pmatrix}$$

- The ψ–like lighter state annihilates well through SU(2) interactions.

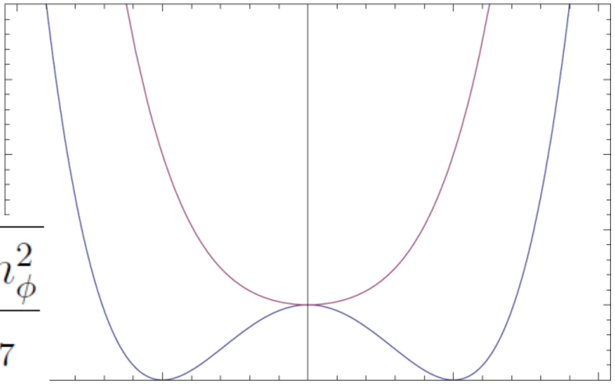
# § § Its history

- Stage 3: $\phi$ SB at T < M<sub></sub>DM/20
- From Dirac to Majorana

$$(\bar{\chi}_L \bar{\chi}^c_R \bar{\psi}_L \bar{\eta}^c_R) M \begin{pmatrix} \chi_L^c \\ \chi_R \\ \psi_L^c \\ \psi_R \end{pmatrix} \qquad M = \begin{pmatrix} y\frac{v_s}{\sqrt{2}} & \mu_\chi & 0 & Y\frac{v}{\sqrt{2}} \\ \mu_\chi & y\frac{v_s}{\sqrt{2}} & Y\frac{v}{\sqrt{2}} & 0 \\ 0 & Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi \\ Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi & 0 \end{pmatrix}$$

by the symmetry breaking of $\phi$

$$V(\Phi, \eta, \phi) \sim -m_\phi^2 |\phi|^2 + \lambda_7 |\phi|^4$$



$$T_c \simeq \sqrt{\frac{6m_\phi^2}{\lambda_7}}$$

# § § Its history

- Stage 3(cont’d.): $\phi$ SB at $T < M_{DM}/20$
- Where did $\eta$ go?
- After $\eta\eta^*$ annihilation, $\eta$ decays

$$\tau(\eta \to \nu\bar{\chi}) \simeq 33 \times 10^{-6} \left(\frac{10^{-4}}{Y_N}\right)^2 \left(\frac{0.1\text{eV}}{m_\nu}\right) \left(\frac{M_N}{M_\eta}\right) [\text{sec}]$$

- The final DM number density

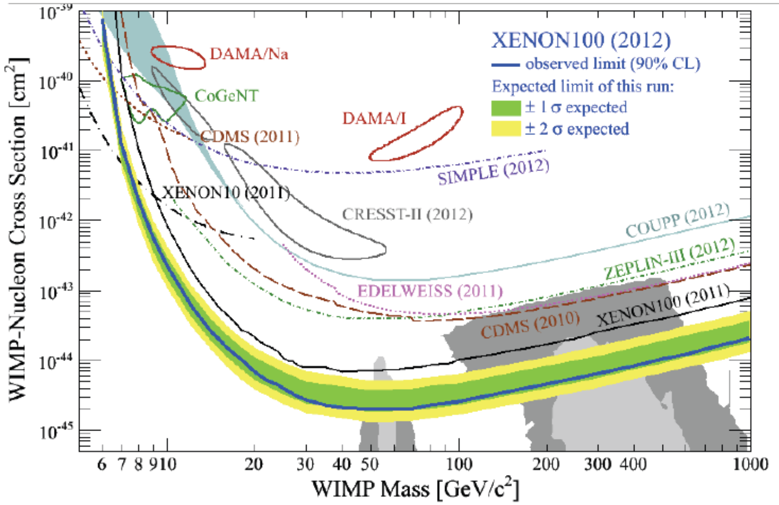
$$\begin{aligned} n_{DM} &= (n_\psi - n_{\bar{\psi}}) + (n_{\eta^*} - n_\eta) \\ &= 2(n_\psi - n_{\bar{\psi}}). \end{aligned}$$

# § § Detection prospect

- Spin independent

For instance, for $M_{H_2} \simeq 120$ GeV and $Y \simeq 0.2$, we fin

$$\sigma_{\rm SI}^{(p)} \simeq 10^{-9}{\rm pb},$$

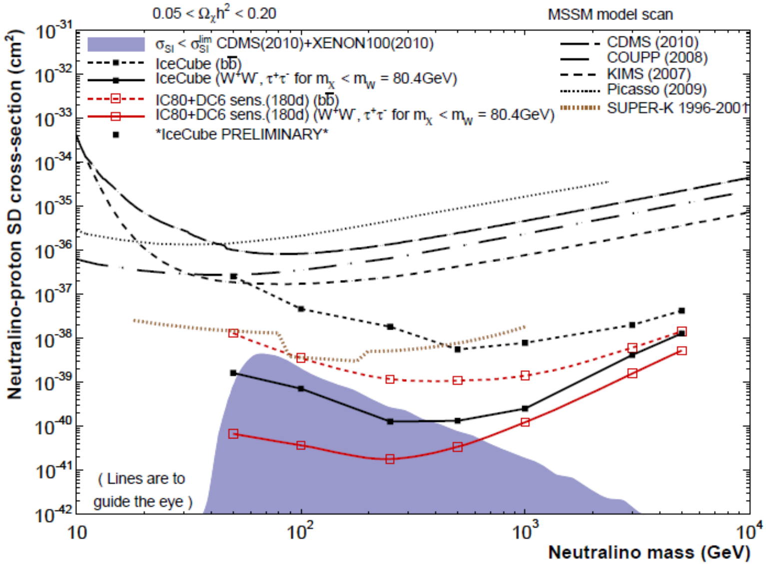


- Spin dependent

Similarly, we estimate the spin-dependent cross sect

$\mu \simeq 100$ GeV and $(Y_1, Y_2) \simeq (0.4, 0.2)$, we obtain

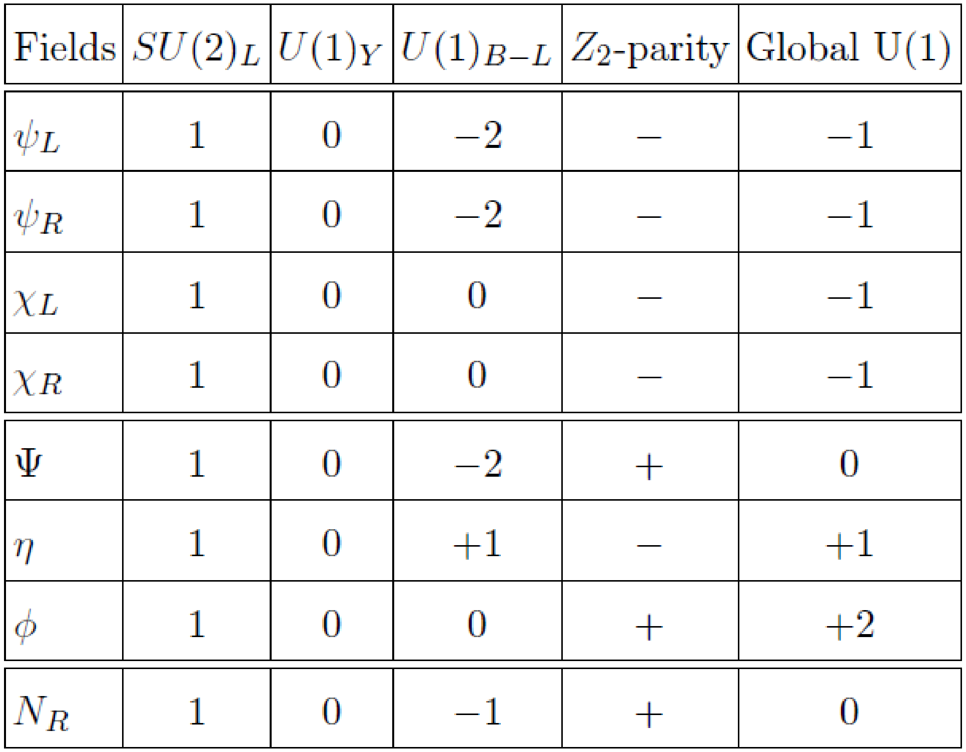
$$\sigma_{\rm SD}^{(p)} \simeq 3 \times 10^{-4}{\rm pb},$$



# § Another model

- Particle content

TABLE II: Particle contents of Model B



| Fields | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{B-L}$ | $Z_2$-parity | Global U(1) |
|---|---|---|---|---|---|
| $\psi_L$ | 1 | 0 | $-2$ | $-$ | $-1$ |
| $\psi_R$ | 1 | 0 | $-2$ | $-$ | $-1$ |
| $\chi_L$ | 1 | 0 | 0 | $-$ | $-1$ |
| $\chi_R$ | 1 | 0 | 0 | $-$ | $-1$ |
| $\Psi$ | 1 | 0 | $-2$ | $+$ | 0 |
| $\eta$ | 1 | 0 | $+1$ | $-$ | $+1$ |
| $\phi$ | 1 | 0 | 0 | $+$ | $+2$ |
| $N_R$ | 1 | 0 | $-1$ | $+$ | 0 |

- A large annihilation by s-channel resonances of Higgs or $Z'$ boson

# § § Its history

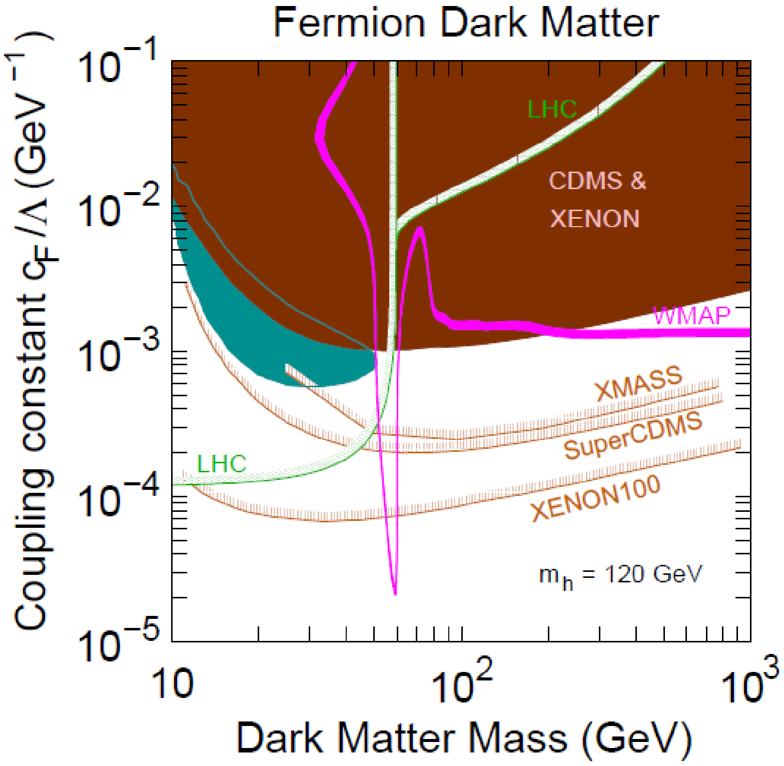
- Stage 2: after EWSB to $T \gtrsim M_{DM}/20$
- Dirac fermion DM mass

$$(\bar{\chi}_L \bar{\chi}^c_R \bar{\psi}_L \bar{\eta}^c_R) M \begin{pmatrix} \chi^c_L \\ \chi_R \\ \psi^c_L \\ \psi_R \end{pmatrix} \qquad M = \begin{pmatrix} 0 & \mu_\chi & 0 & Y\frac{v}{\sqrt{2}} \\ \mu_\chi & 0 & Y\frac{v}{\sqrt{2}} & 0 \\ 0 & Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi \\ Y\frac{v}{\sqrt{2}} & 0 & \mu_\psi & 0 \end{pmatrix}$$

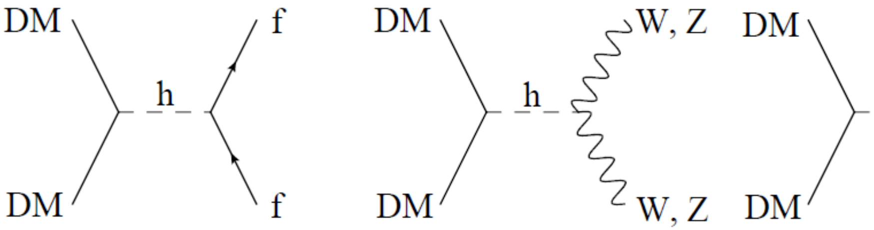
- The lighter state annihilates well through resonances.[Okada and OS 2010, Kanemura et al 2011, Burell and Okada 2012...]

# § § Detection prospect

- Comparison with Higgs portal dark matter



$$\frac{1}{2}\bar{\chi}\left(i\not{\partial} - M_F\right)\chi - \frac{c_F}{2\Lambda}|H|^2\bar{\chi}\chi$$



[Kanemura et al 2010]

$\sigma_{\text{ours-p}} > \sigma_{\text{WIMP-p}}$

# § Summary

- DM was originally asymmetric at the early Universe but is now a Majorana particle.
- Concrete models

- Looks WIMP but $\Omega_{DM}h^2=0.1$ free self annihilation cross section
- Larger $\sigma_{DM\text{-}p}$ than WIMP's
- Possible annihilation to detect indirectly without a incredibly tiny parameter