Section 1

Models with WIMPs

There are several examples of the models that contain WIMP DM candidates. In this section, two of them **(♣ Really? ♣)** are briefly reviewed. **(♣ EWIMP and WIMP?? ♣)**

1.1 Minimally supersymmetric standard model

The minimally supersymmetric standard model (MSSM) is the simple extension of the SM with $\mathcal{N} = 1$ supersymmetry (SUSY). For a brief review of the $\mathcal{N} = 1$ SUSY, see Sec. **??**. SUSY is well-motivated since it provides a good solution to the so-called hierarchy problem. [1–3].

We summarize the notations and quantum numbers of the chiral and vector superfields in the MSSM in Table 1 and 2, respectively. The supersymmetric part of the MSSM lagrangian is described by the superpotential

$$W = Y_u^{ij} U_i Q_j H_u - Y_d^{ij} D_i Q_j H_d - Y_e^{ij} E_i L_j H_d + \mu H_u H_d, \tag{1.1}$$

where $i, j = 1, 2, 3$ labels the quark and lepton generation, while Q, L, U, D, E are superfields that contain the left-handed quark, left-handed lepton, right-handed up-type quark, right-handed down-type quark, and right-handed charged lepton, respectively. In Eq. (1.1), proper contraction of $SU(3)_C$ and $SU(2)_L$ indices is assumed. Note that two Higgs doublets H_u and H_d with opposite values of $U(1)_Y$ hypercharges are introduced, which is needed to cancel the contributions to the gauge anomaly from Higgs superpartners, Higgsinos.

Since no superpartner of any SM particle is observed yet, SUSY should be broken and superpartners should obtain the SUSY breaking masses. **(♣ ref: boson and fermion**

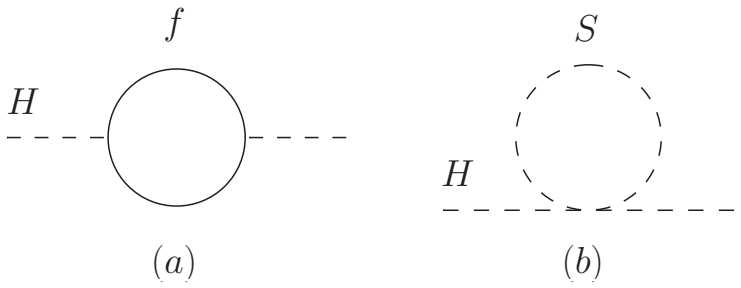

Figure 1: One-loop correction to the Higgs mass from (a) a fermion f and (b) a scalar S.

Notation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\hat{Q}_i$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
$\hat{L}_i$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\hat{U}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\hat{D}_i$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$
$\hat{E}_i$	$\mathbf{1}$	$\mathbf{1}$	1
$\hat{H}_u$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
$\hat{H}_d$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$

Table 1: Notations and quantum numbers of the chiral superfields in the MSSM.

Notation	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\hat{g}$	$\mathbf{8}$	$\mathbf{1}$	0
$\hat{W}$	$\mathbf{1}$	$\mathbf{3}$	0
$\hat{B}$	$\mathbf{1}$	$\mathbf{1}$	0

Table 2: Notations and quantum numbers of the vector superfields in the MSSM.

obtain equal mass ♣) The SUSY breaking part of the lagrangian is expressed as

$$\begin{aligned}\mathcal{L}_{\text{soft}} = &-\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right)\\ &-\left(A_u^{ij}\tilde{U}_i\tilde{Q}_j H_u - A_d^{ij}\tilde{D}_i\tilde{Q}_j H_d - A_e^{ij}\tilde{E}_i\tilde{L}_j H_d\right)\\ &- m_Q^{2ij}\tilde{Q}_i^\dagger\tilde{Q}_j - m_L^{2ij}\tilde{L}_i^\dagger\tilde{L}_j - m_U^{2ij}\tilde{U}_i^\dagger\tilde{U}_j - m_D^{2ij}\tilde{D}_i^\dagger\tilde{D}_j - m_E^{2ij}\tilde{E}_i^\dagger\tilde{E}_j\\ &- m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_u H_d + \text{c.c.})\,,\end{aligned} \tag{1.2}$$

where the tilde is used to express the superpartner of the SM particle contained in a superfield, while a field without a hat nor tilde denotes the other component.

(♣ Relationship between λ parameter above should be clearer ♣) WIMPs with mass around or just above the electroweak scale are theoretically well-motivated in connection with problems of the SM such as the naturalness problem. For example, the minimal supersymmetric extension of the SM (the so-called MSSM) contains several WIMP DM candidate such as Higgsino and Wino.[♮1] Another example is the minimal dark matter (MDM) model [7,11,12], which is a simple extension of the SM with an $SU(2)_L$ electroweak multiplet such as a 5-plet scalar / fermion. In these models, the stability of the DM is ensured by the R-parity (for the MSSM case) and by high dimensionality of the operator that describes the

[♮1] For a review of the MSSM, see for example [10].

WIMP DM candidate	Quntum numbers $SU(2)_L$	$U(1)_Y$	Spin	Masses m_χ/TeV	Δm_χ/MeV
Higgsino	2	1/2	Dirac fermion	1.1	341
Wino	3	0	Majorana fermion	2.9	166
5-plet scalar	5	0	real scalar	9.4	166
5-plet fermion	5	0	Majorana fermion	10	166

Table 3: Table of properties of popular WIMP DM candidates [4–9]. The $SU(2)_L$ electroweak charge, $U(1)_Y$ hypercharge, spin nature, mass, and mass difference compared with a charged component of the multiplet are shown. See Sec. **??** **(♣ Caution!! ♣)** for the details of the last column.

decay of the DM (for the MDM case). The properties of these WIMP DM candidates are summarized in Table 3. The required masses to explain the DM relic abundance through the freezeout mechanism are also shown. Since the non-relativistic annihilation cross section of TeV mass particles is significantly enhanced by the Sommerfeld enhancement effect [6, 13], there are deviations from the rough estimation formula Eq. (**??**). We will return to this point later in Sec. **??**. **(♣ Caution!! ♣)** In addition, in the last column there are mass differences Δm_χ between the DM and its charged couterpart that will be explained in detail in Sec. **??**. **(♣ Caution!! ♣)**

1.2 Minimal dark matter model

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