

# 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).<sup>b1</sup> One of the motivations to introduce SUSY is to solve the so-called hierarchy (or naturalness) problem [1–3] in the SM. The problem is related to the quantum correction to the SM Higgs boson mass from heavy new physics particles. For example, we can consider the one-loop correction to the Higgs mass from a Weyl fermion  $f$  and a complex scalar  $S$  as illustrated in Fig. 1. The corrections to the Higgs mass is given by

$$\Delta m_h^2 = -\frac{|\lambda_f|^2}{8\pi^2} \left[ \Lambda_{\text{UV}}^2 - 2m_f^2 \ln \left( \frac{\Lambda_{\text{UV}}}{m_f} \right) + \dots \right] \quad (\text{fermion}), \quad (1.1)$$

$$\Delta m_h^2 = \frac{\lambda_S}{16\pi^2} \left[ \Lambda_{\text{UV}}^2 - 2m_S^2 \ln \left( \frac{\Lambda_{\text{UV}}}{m_S} \right) + \dots \right] \quad (\text{scalar}), \quad (1.2)$$

(**♣ Check this! ♣**) where  $\lambda_f$  and  $m_f$  are the Higgs-fermion coupling constant and the fermion mass, respectively, and  $\lambda_S$  and  $m_S$  are those for the scalar  $S$ . We take the cut-off scale of the theory to be  $\Lambda_{\text{UV}}$  to regularize the otherwise divergent loop integral and neglect

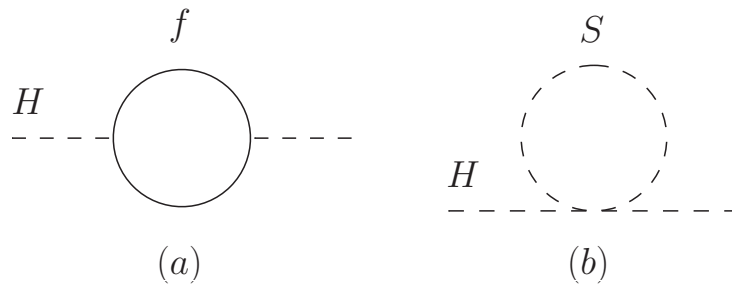


Figure 1: One-loop correction to the Higgs mass from (a) a Weyl fermion  $f$  and (b) a complex scalar  $S$ .

<sup>b1</sup> For a brief review of the  $\mathcal{N} = 1$  SUSY, see Sec. ??.

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

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

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

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

the lower order terms of  $\Lambda_{UV}$ . Eqs. (1.1) and (1.2) show the quadratic dependence of  $\Delta m_H^2$  on  $\Lambda_{UV}$ , which means that the Higgs mass is sensitive to the energy scale of the beyond the SM physics. However, there is at least one extremely high energy scale physics in the nature, gravity at the Planck scale  $M_{\text{pl}} \sim 10^{18-19} \text{ GeV}$ . By substituting  $\Lambda_{UV} = M_{\text{pl}}$  in Eqs. (1.1) and (1.2) and assuming  $\lambda_f \sim \lambda_S \sim \mathcal{O}(1)$ , we notice that orders-of-magnitude fine-tuning is required to obtain the correct Higgs mass  $m_h = 125.09 \text{ GeV}$  (**♣ Reference ♣**), which is unnatural.

SUSY provides a nice solution to this fine-tuning problem. As is summarized in Appendix ??, (**♣ summarize later ♣**) each Weyl fermion in a supersymmetric model has two complex scalars with the same mass  $m_f = m_S$ . In addition, their coupling constants should have a relationship  $|\lambda_f|^2 = \lambda_S$  due to the fact that  $\lambda_S$  is a coupling constant in the F-term potential sourced by a superpotential term proportional to  $\lambda_f$ . (**♣ description of F-term ♣**) By using both equations and summing the corrections (1.1) and (1.2) with factor of two multiplied to the latter, we obtain a result independent of the cut-off scale  $\Lambda_{UV}$  without fine-tuning. This cancellation is ensured by the so-called non-renormalization theorem. (**♣ Reference ♣**)

We now 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

$$W = Y_u^{ij} U_i Q_j H_u - Y_d^{ij} D_i Q_j H_d - Y_e^{ij} E_i L_j H_d + \mu H_u H_d, \quad (1.3)$$

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. (1.3), 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 obtain equal mass ♣**) The SUSY breaking part of the lagrangian is expressed as

$$\begin{aligned} \mathcal{L}_{\text{soft}} = & -\frac{1}{2} \left( M_3 \tilde{g} \tilde{g} + M_2 \tilde{W} \tilde{W} + M_1 \tilde{B} \tilde{B} + \text{c.c.} \right) \\ & - \left( A_u^{ij} \tilde{U}_i \tilde{Q}_j H_u - A_d^{ij} \tilde{D}_i \tilde{Q}_j H_d - A_e^{ij} \tilde{E}_i \tilde{L}_j H_d \right) \\ & - m_Q^{2ij} \tilde{Q}_i^\dagger \tilde{Q}_j - m_L^{2ij} \tilde{L}_i^\dagger \tilde{L}_j - m_U^{2ij} \tilde{U}_i^\dagger \tilde{U}_j - m_D^{2ij} \tilde{D}_i^\dagger \tilde{D}_j - m_E^{2ij} \tilde{E}_i^\dagger \tilde{E}_j \\ & - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + \text{c.c.}), \end{aligned} \quad (1.4)$$

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.

Under the spontaneously broken SUSY, the cancellation of the quantum correction to the Higgs boson discussed above is not exact. One obvious consequence of the SUSY breaking in Eqs. (1.1) and (1.2) is the hierarchy between  $m_f$  and  $m_S$  that appear in the second term of each contribution. In the case of the MSSM, the largest contribution comes from the top quark and its partner that have the largest Yukawa coupling with the Higgs boson

(**♣ More precisely, we need RGE calculation ♣**)

## 1.2 Need review

(**♣ Relationship between  $\lambda$  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.<sup>‡2</sup> 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

<sup>‡2</sup> For a review of the MSSM, see for example [10].

WIMP DM candidate	Quantum numbers			Masses	
	$SU(2)_L$	$U(1)_Y$	Spin	$m_\chi/\text{TeV}$	$\Delta m_\chi/\text{MeV}$
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.

$R$ -parity (for the MSSM case) and by high dimensionality of the operator that describes the 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  $\Delta m_\chi$  between the DM and its charged counterpart that will be explained in detail in Sec. ??. (**♣ Caution!! ♣**)

### 1.3 Minimal dark matter model

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