A complete calculation for direct detection of wino dark matter

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Based on [J. Hisano, K. Ishiwata, N. N., 1004. 4090 and 1007. 2601]

Outline

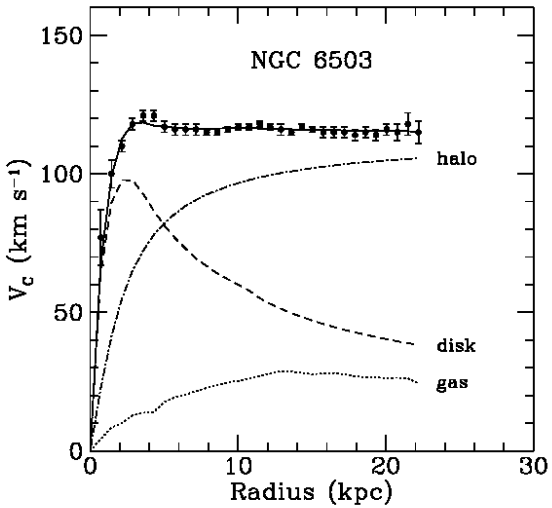
1. Introduction
2. Direct detection of Majorana dark matter
3. Results
4. Summary

1. Introduction

Introduction

Observational evidence for dark matter (DM)

Galactic scale

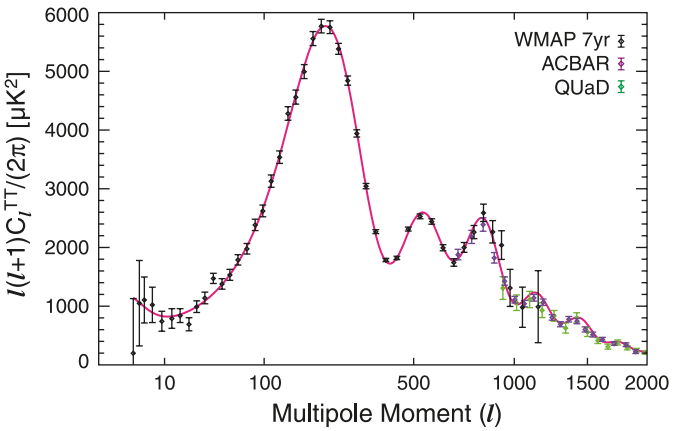


Begeman et. al. (1991).

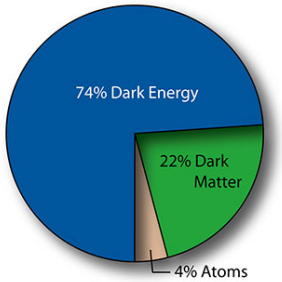
Scale of galaxy clusters

Clowe et. al. (2006).

Cosmological scale



Komatsu et. al. (2010).



http://map.gsfc.nasa.gov/

About 80% of the matter in the Universe is nonbaryonic dark matter.

Wino Dark Matter

In this work, we assume the main ingredient of dark matter in the universe to be

The neutral component of SU(2)_L gauginos

↳ **(Pure) Wino dark matter**

SM SU(2)_L gauge bosons		SU(2)_L Gauginos in MSSM
W^0	$\Longleftrightarrow$	χ^0 : Neutral wino
$W^\pm$		$\chi^\pm$: Charged wino

The anomaly mediated SUSY breaking scenario

On the assumption of generic Kahler potential,

Gravitino Scalar Particles Higgsinos

O(10) TeV

Gauginos

Gluino

Bino

Wino

O(1) TeV

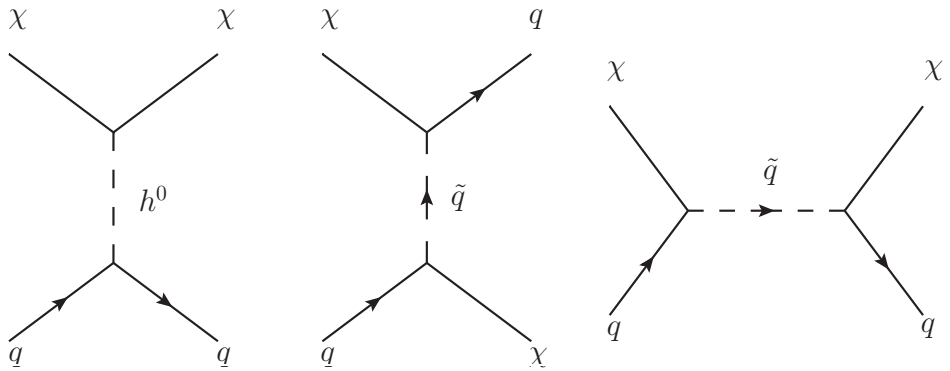
Suppressed by one-loop factor

Proportional to the gauge coupling beta functions

the Split SUSY scenario

The neutral Wino can be the lightest SUSY particle in the anomaly mediation scenario

Tree-level contribution | Wino-like neutralino DM



In the present situation, all of these tree diagrams are suppressed.

the Wino-nucleon scattering process is dominated by loop diagrams

■ Previous works

- J. Hisano, S. Matsumoto, M. Nojiri, O. Saito, Phys. Rev. D **71** (2005) 015007
- M. Cirelli, N. Fornengo, A. Strumia, Nucl. Phys. B **753** (2006) 178
- R. Essig, Phys. Rev. D **78** (2008) 015004

- In these works, they calculate the one-loop contribution, but their results are not consistent with each other.
- The two-loop gluon contribution is neglected in their works.

2. Direct Detection of Majorana DM

Effective Lagrangian for Majorana Dark Matter

$$\mathcal{L}_q = d_q \bar{\tilde{\chi}}^0 \gamma^\mu \gamma_5 \tilde{\chi}^0 \bar{q} \gamma_\mu \gamma_5 q + f_q m_q \bar{\tilde{\chi}}^0 \tilde{\chi}^0 \bar{q} q + \frac{g_q^{(1)}}{M} \bar{\tilde{\chi}}^0 i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}^q_{\mu\nu} + \frac{g_q^{(2)}}{M^2} \bar{\tilde{\chi}}^0 i\partial^\mu i\partial^\nu \tilde{\chi}^0 \mathcal{O}^q_{\mu\nu}$$

$$\mathcal{L}_g = f_G \bar{\tilde{\chi}}^0 \tilde{\chi}^0 G^a_{\mu\nu} G^{a\mu\nu} + \frac{g_G^{(1)}}{M} \bar{\tilde{\chi}}^0 i\partial^\mu \gamma^\nu \tilde{\chi}^0 \mathcal{O}^g_{\mu\nu} + \frac{g_G^{(2)}}{M^2} \bar{\tilde{\chi}}^0 i\partial^\mu i\partial^\nu \tilde{\chi}^0 \mathcal{O}^g_{\mu\nu}$$

$\tilde{\chi}^0$: DM
m_q : quark mass
M : DM mass

—: Spin-dependent
—: Spin-independent
—: negligible

Twist-2 operators

$$\mathcal{O}^q_{\mu\nu} \equiv \frac{1}{2}\bar{q} i \left(D_\mu \gamma_\nu + D_\nu \gamma_\mu - \frac{1}{2} g_{\mu\nu} \not{D} \right) q \ ,$$

$$\mathcal{O}^g_{\mu\nu} \equiv \left(G^{a\rho}_\mu G^a_{\rho\nu} + \frac{1}{4} g_{\mu\nu} G^a_{\alpha\beta} G^{a\alpha\beta} \right) \ .$$

Majorana condition

$$\bar{\tilde{\chi}}^0 \gamma^\mu \tilde{\chi}^0 = 0$$

$$\bar{\tilde{\chi}}^0 \sigma^{\mu\nu} \tilde{\chi}^0 = 0 \qquad \sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

We focus on the spin-independent (SI) interactions hereafter.

Nucleon matrix elements

- The mass fractions (for the scalar-type quark operators)

$$\langle N|m_q\bar{q}q|N\rangle/m_N \equiv f_{Tq} \ , \qquad 1-\sum_{q=u,d,s} f_{Tq} \equiv f_{TG}$$

m_N : nucleon mass

- For the twist-2 operators

$$\begin{aligned}\langle N(p)|\mathcal{O}^q_{\mu\nu}|N(p)\rangle &= \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\ (q(2)+\bar{q}(2)) \ , \\ \langle N(p)|\mathcal{O}^g_{\mu\nu}|N(p)\rangle &= \frac{1}{m_N}(p_\mu p_\nu - \frac{1}{4}m_N^2 g_{\mu\nu})\ G(2) \ .\end{aligned}$$

■ The second moments of the parton distribution functions (PDFs)

$$\begin{aligned} q(2)+\bar{q}(2) &= \int_0^1 dx\ x\ [q(x)+\bar{q}(x)] \ , \\ G(2) &= \int_0^1 dx\ x\ g(x) \ . \end{aligned}$$

Trace anomaly of energy-momentum tensor in QCD

The matrix element of gluon field strength tensor can be evaluated by using the trace anomaly of the energy-momentum tensor in QCD

■The trace anomaly of the energy-momentum tensor in QCD

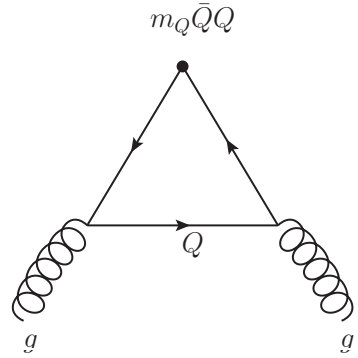
$$\Theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s} G^a_{\mu\nu} G^{a\mu\nu} + \sum_{q=u,d,s} m_q \bar{q} q + \sum_{Q=c,b,t} m_Q \bar{Q} Q$$

m_N

$$\beta(\alpha_s) = -\frac{7\alpha_s^2}{2\pi} \quad (\text{for} \quad N_F = 6)$$

$$\sum_{q=u,d,s} m_N f_{Tq}$$

$$m_Q \bar{Q} Q \to -\frac{\alpha_s}{12} G^a_{\mu\nu} G^{a\mu\nu}$$



$$m_N f_{TG} = -\frac{9\alpha_s}{8\pi} \langle N | G^a_{\mu\nu} G^{a\mu\nu} | N \rangle$$

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Lett. B **78** (1978) 443.

SI coupling of Majorana DM with nucleon

The effective coupling of DM with nucleon is given as follows:

$$\mathcal{L}_{eff} = f_N \bar{\tilde{\chi}} \tilde{\chi} \bar{N} N$$

$$\begin{aligned} f_N/m_N &= \sum_{q=u,d,s} f_q f_{Tq} + \sum_{q=u,d,s,c,b} \frac{3}{4}\left(q(2)+\bar{q}(2)\right)\left(g_q^{(1)}+g_q^{(2)}\right) \\ &- \frac{8\pi}{9\alpha_s} f_{TG} f_G + \frac{3}{4} G(2)\left(g_G^{(1)}+g_G^{(2)}\right) . \end{aligned}$$

Suppressed by α_s

The gluon contribution can be comparable to the quark contribution even if the DM-gluon interaction is induced by higher loop diagrams.

For proton	
f_{Tu}	0.023
f_{Td}	0.034
f_{Ts}	0.025
For neutron	
f_{Tu}	0.019
f_{Td}	0.041
f_{Ts}	0.025

Second moment at $\mu = m_Z$			
$G(2)$	0.48		
$u(2)$	0.22	$\bar{u}(2)$	0.034
$d(2)$	0.11	$\bar{d}(2)$	0.036
$s(2)$	0.026	$\bar{s}(2)$	0.026
$c(2)$	0.019	$\bar{c}(2)$	0.019
$b(2)$	0.012	$\bar{b}(2)$	0.012

Elastic scattering cross section

One can derive the SI cross section by using the SI effective couplings as follows :

$$\sigma_{\rm SI}^{T} = \frac{4}{\pi}\left(\frac{M m_T}{M+m_T}\right)^2 |n_p f_p + n_n f_n|^2$$

m_T : the mass of the target nucleus
n_p : the number of proton
n_n : the number of neutron

From now on, we just show the results for the SI cross section of DM with a proton as a reference value.

3. Results

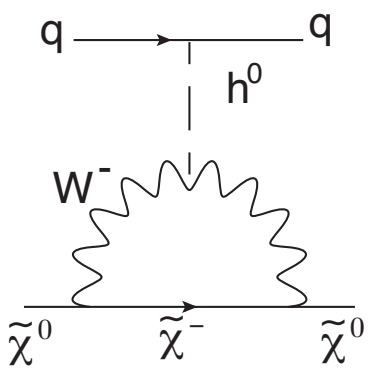
Pure Wino DM | Quark contribution | 1-loop

The interaction Lagrangian:

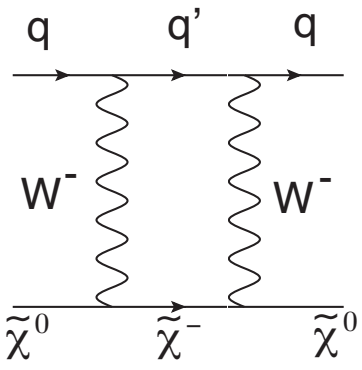
$$\mathcal{L}_{\rm int} = -g_2(\bar{\tilde{\chi}}^0 \gamma^\mu \tilde{\chi}^- W_\mu^\dagger + {\rm h.c.})$$

$\tilde{\chi}^0$: DM $\quad W_\mu$: W boson
$\tilde{\chi}^-$: charged wino
g_2 : weak coupling constant

1-loop diagrams:



(a)



(b)

Effective couplings:

$$f_q = \frac{\alpha_2^2}{4 m_W m_{h^0}^2} g_{\rm H}(x),$$

$$d_q = \frac{\alpha_2^2}{m_W^2} g_{\rm AV}(x),$$

$$g_q^{(1)} = \frac{\alpha_2^2}{m_W^3} g_{\rm T1}(x), \qquad \alpha_2 \equiv \frac{g_2^2}{4\pi}$$

$$g_q^{(2)} = \frac{\alpha_2^2}{m_W^3} g_{\rm T2}(x), \qquad x \equiv \frac{m_W^2}{M^2}$$

Remark:

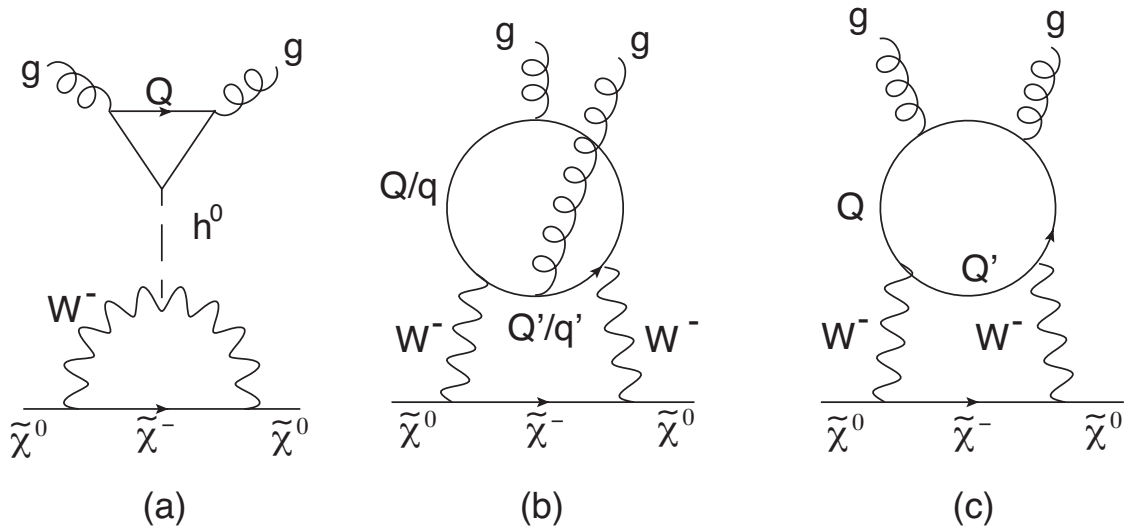
The SI effective interaction is not suppressed even if the Wino mass is much larger than the W boson mass.

$$g_{\rm H}(x) \simeq -2\pi, \quad g_{\rm T1}(x) \simeq \pi/3, \quad (\text{for} \quad x \to 0)$$

J. Hisano, S. Matsumoto, M. Nojiri, O. Saito, Phys. Rev. D **71** (2005) 015007.

Pure Wino DM | Gluon contribution | 2-loop

2-loop diagrams:



The effective scalar coupling of gluon:

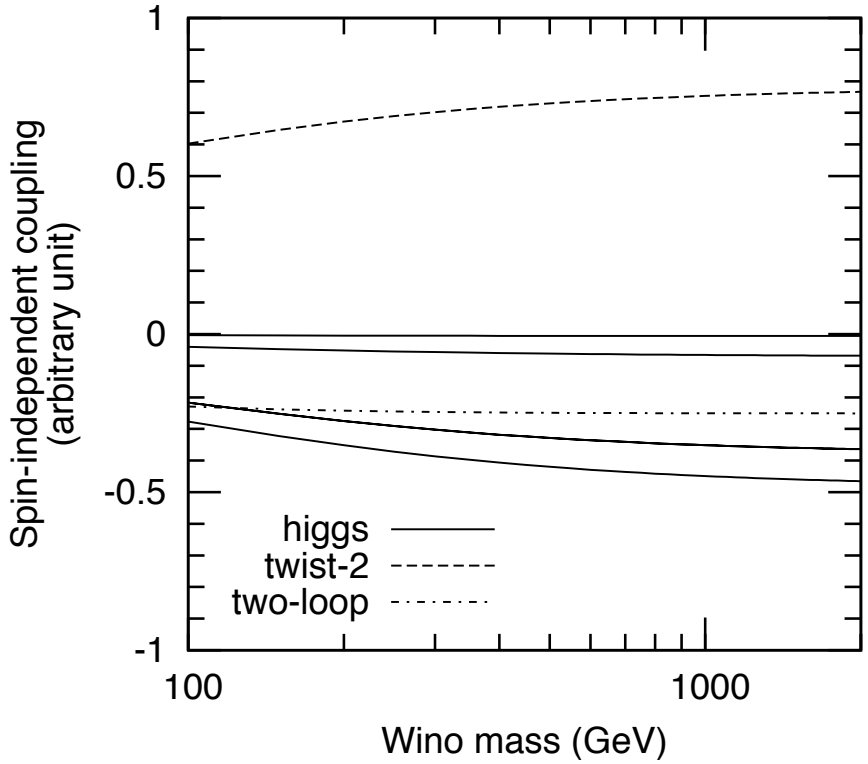
$$f_G = -3 \times \frac{\alpha_s}{12\pi} \frac{\alpha_2^2}{4 m_W m_{h^0}^2} g_H(x) + \frac{\alpha_s}{4\pi} \frac{\alpha_2^2}{m_W^3} g_{B3}(x, y) + 2 \times \frac{\alpha_s}{4\pi} \frac{\alpha_2^2}{m_W^3} g_{B1}(x),$$

$$x \equiv \frac{m_W^2}{M^2} \qquad y \equiv \frac{m_t^2}{M^2}$$

$$g_{B3}(x, y) \simeq \frac{(3\sqrt{y} + 2\sqrt{x})x}{24(\sqrt{x} + \sqrt{y})^3}\pi, \qquad g_{B1}(x) \simeq \frac{\pi}{12}. \qquad (\text{for } \; x, y \to 0)$$

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Lett. B **690** (2010) 311.

Spin-Independent effective coupling (Wino DM)



Higgs mass

1 TeV
300 GeV
130 GeV
115 GeV

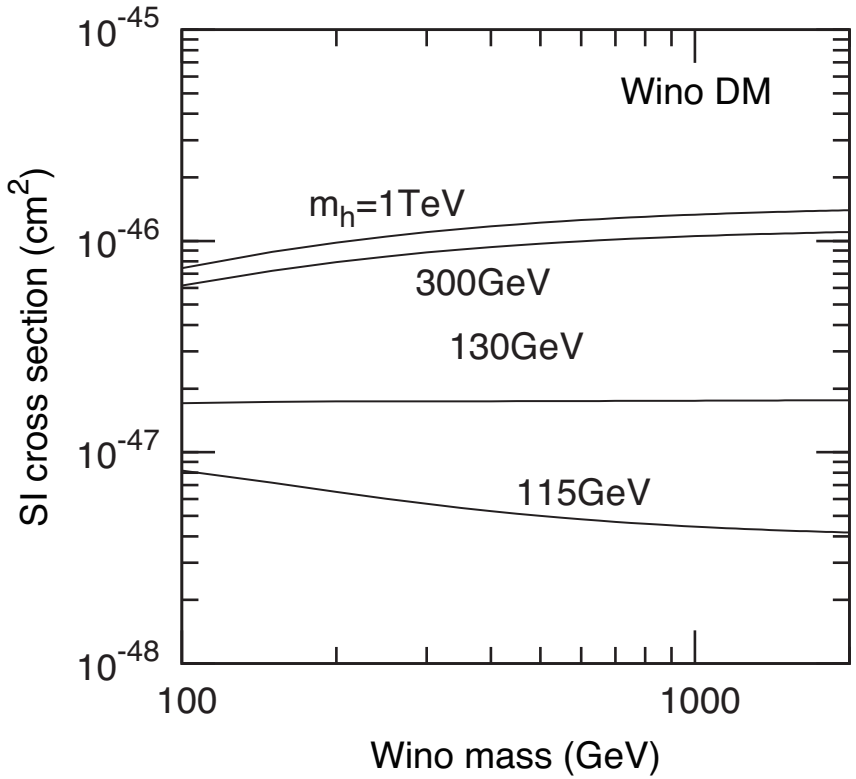
(from top to bottom)

Each contribution in the spin-independent effective coupling, f_p

- The contribution of twist-2 operator is dominant.
- The other contributions yield substantial contribution by the opposite sign.
- There is a cancellation among these contributions.

J. Hisano, K. Ishiwata, and N. Nagata, Phys. Lett. B **690** (2010) 311.

Spin-Independent scattering cross section (Wino DM)



The SI scattering cross section of Wino DM with a proton

- While the SI cross section is almost independent of the Wino mass, it is quite sensitive to the Higgs mass due to the cancellation.
- This cross section is smaller than those in the previous works by more than an order of magnitude.

4. Summary

Summary

- We evaluate the wino-nucleon elastic scattering cross sections based on the method of effective theory.
- The interaction of DM with gluon as well as quarks yields sizable contribution to the cross section, though the gluon contribution is induced at higher loop level.
- In the wino dark matter scenario we find the cross section is smaller than the previous results by more than an order of magnitude.