Direct detection of Wino dark matter

Junji Hisano

(Nagoya Univ.)

PACIFIC 2014

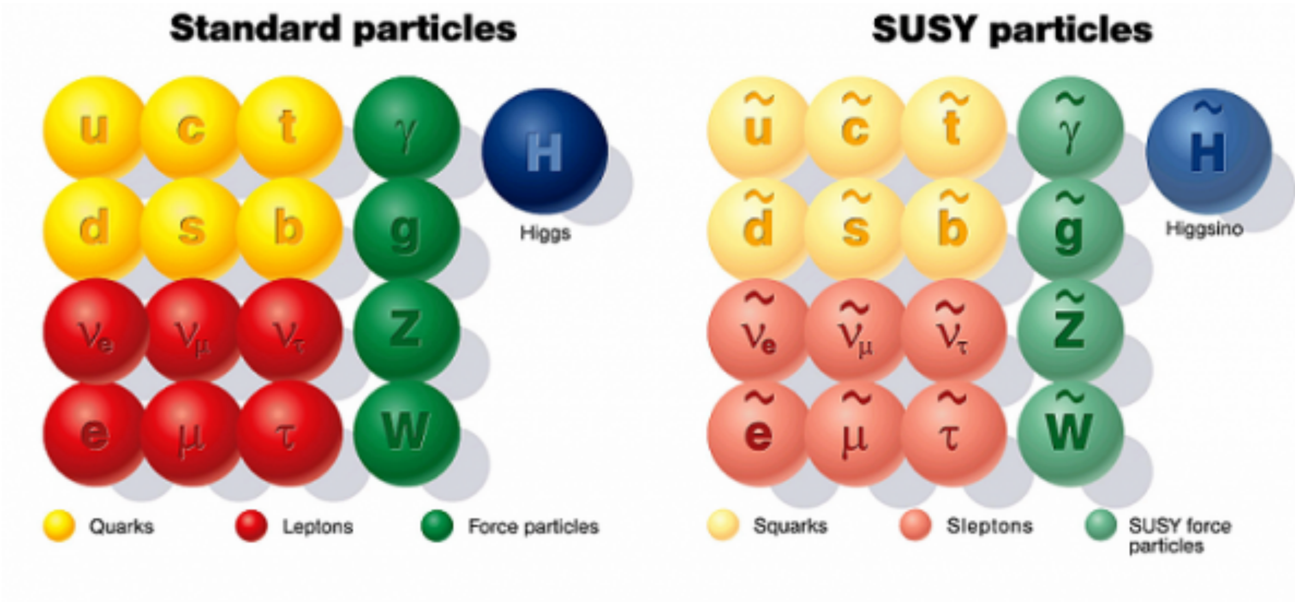
A UCLA Symposium on Particle Astrophysics and Cosmology Including Fundamental Interactions

September 15 - 20, 2014, Moorea, French Polynesia

Contents of my talk

- What is wino?
- Motivation of Wino dark matter
- How to find wino signatures
- Wino dark matter direct detection

What is wino?



- Superpartner of $SU(2)_L$ gauge bosons in SUSY SM.
- $SU(2)_L$ triplet fermions.
- Neutral component of Winos is a candidate of WIMP DM.

SUSY

SUSY GUTs ~ 10^{16} GeV

MSSM @ < O(1) TeV

Standard model

Motivation of Low-scale SUSY (<~1TeV):

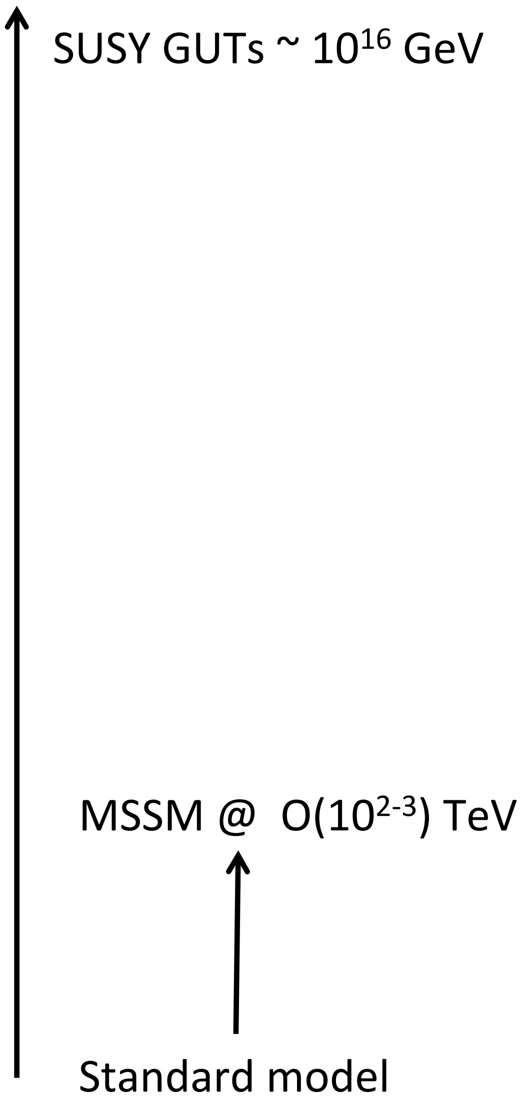
- Naturalness problem
- WIMP dark matter
- Gauge coupling unification

Shortcoming of SUSY :

- FCNC and CP problems
- Gravitino problem in nucleosynthesis
- D=5 proton decay in SUSY GUTs
- 125GeV Higgs mass

These problems favor High-scale SUSY (~O(10^{2-3}) TeV).

High-scale SUSY

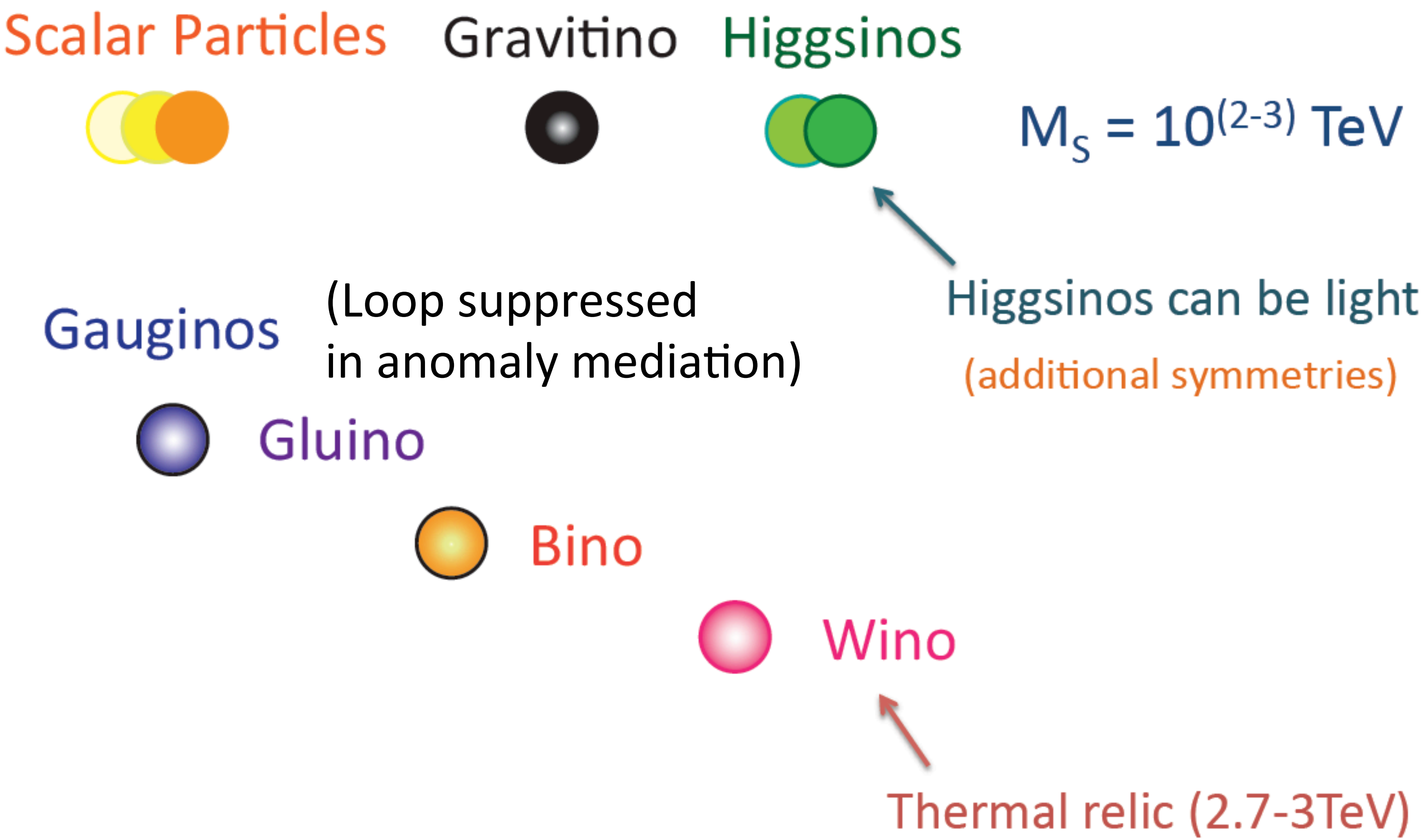


Motivation of High-scale SUSY (~O($10^{2\text{-}3}$) TeV).

- Solution of following problems
  - FCNC and CP problems
  - Gravitino problem in nucleosynthesis
  - D=5 proton decay in SUSY GUTs
  - 125GeV Higgs mass
- Easy model building of SUSY breaking
- WIMP dark matter
- Improved gauge coupling unification

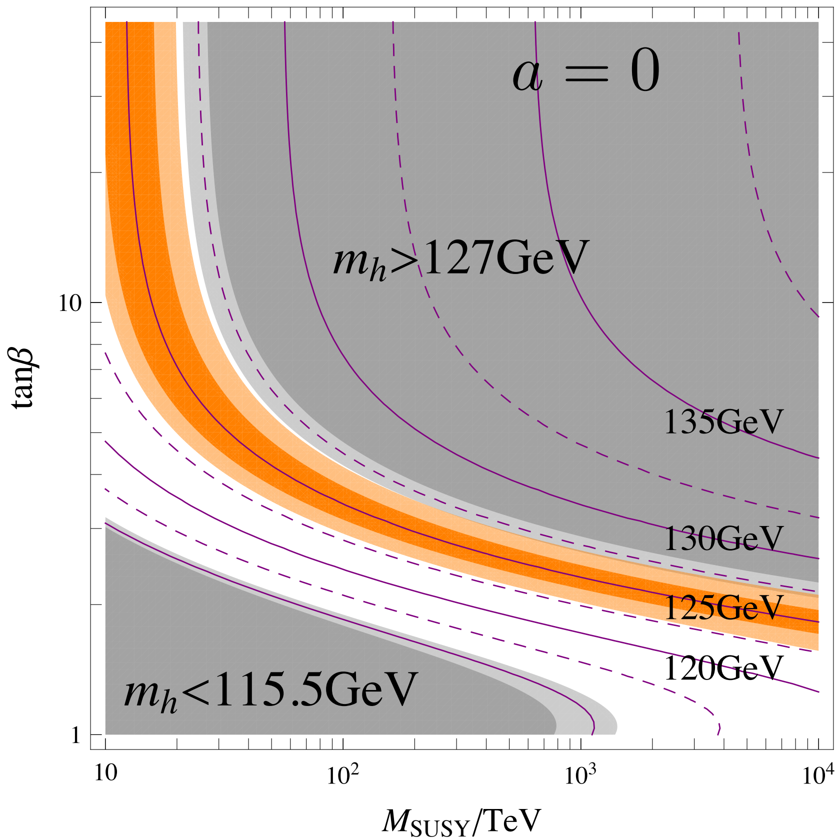
From phenomenological view points, High-scale SUSY works well, while we may have to give up naturalness problem.

Mass spectrum in High-scale SUSY



J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami (2006).

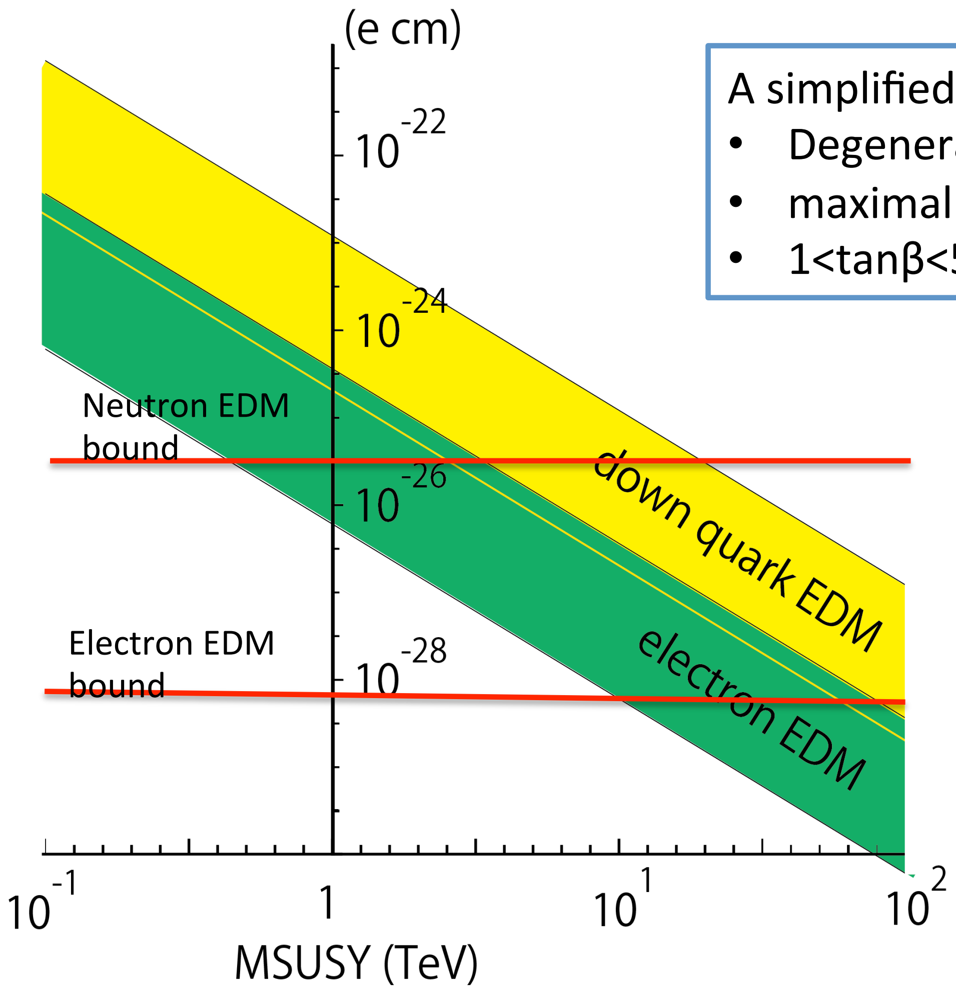
Higgs mass in High-scale SUSY



(Ibe, Matsumoto, Yanagida (12))

For tanβ~2-5, 125 GeV Higgs mass is well-explained in High-scale SUSY.

EDMs in supersymmetric standard model



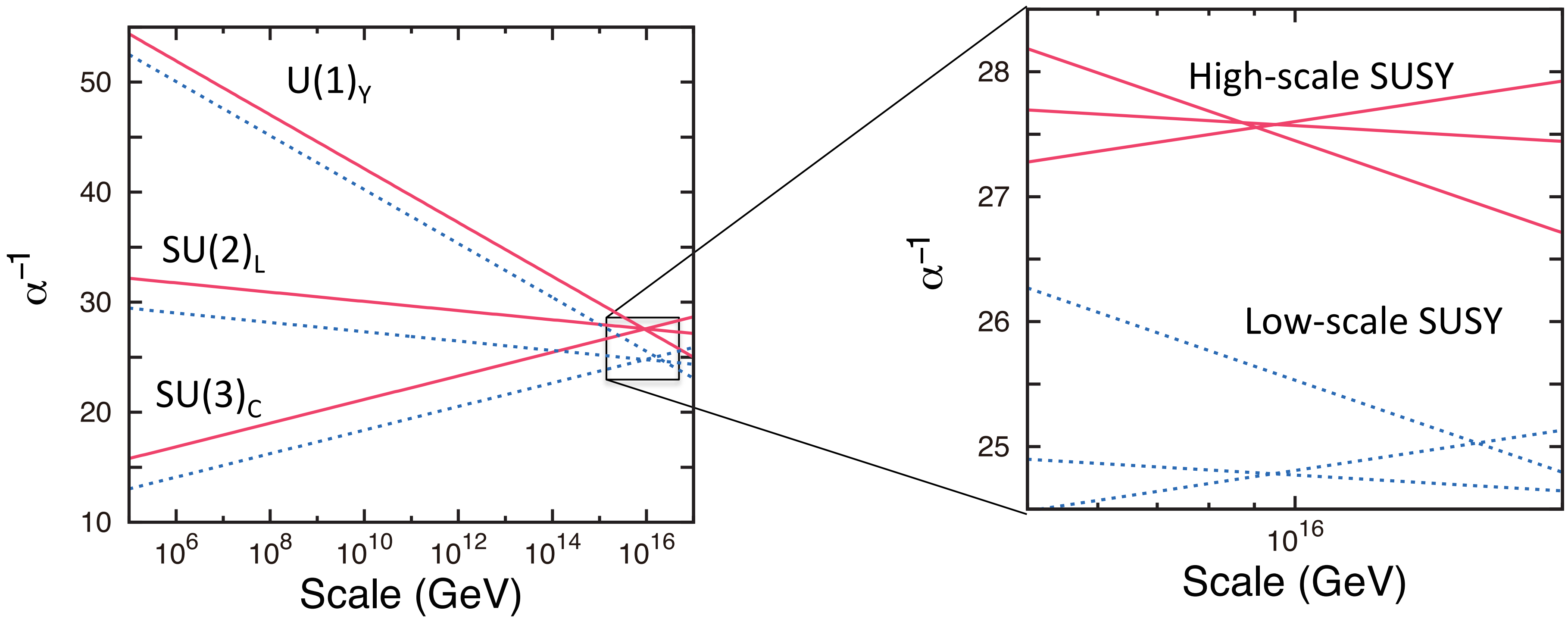
A simplified model
- Degenerate mass spectrum
- maximal CP phase.
- 1<tanβ<50

Electric dipole moments (EDMs) give constraints on CP violation at TeV scale physics. When SUSY particle masses are larger than 10~100 TeV, EDM bounds are safe even if CP violation is O(1).

Improving gauge coupling unification in High-scale SUSY

In High-scale SUSY we do not need to introduce sizable threshold correction to the gauge coupling constants at GUT-scale.

(JH, Kuwahara, Nagata(13))

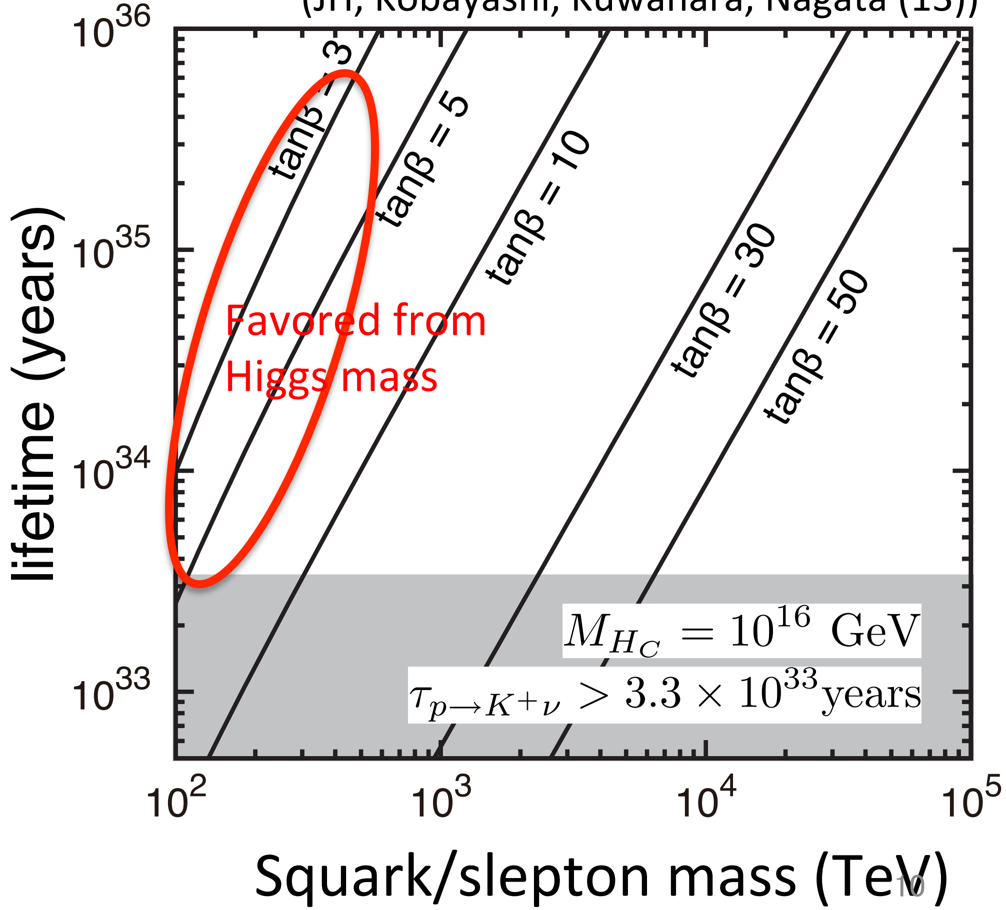


Colored Higgs proton decay in SUSY SU(5) GUT

Colored Higgs, which is SU(5) partner of MSSM Higgs, induces proton decay. The decay rate is suppressed by $1/(M_{H_c}^2 m_{\rm SUSY}^2)$.
The minimal SUSY SU(5) GUT was considered to be excluded.

In High-scale SUSY, the minimal SUSY SU(5) GUT is still viable without introducing any mechanism. In addition, future experiments may be accessible to it, while it depends on parameters.

(JH, Kobayashi, Kuwahara, Nagata (13))



Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it might be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it may be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Strategy to High-scale SUSY

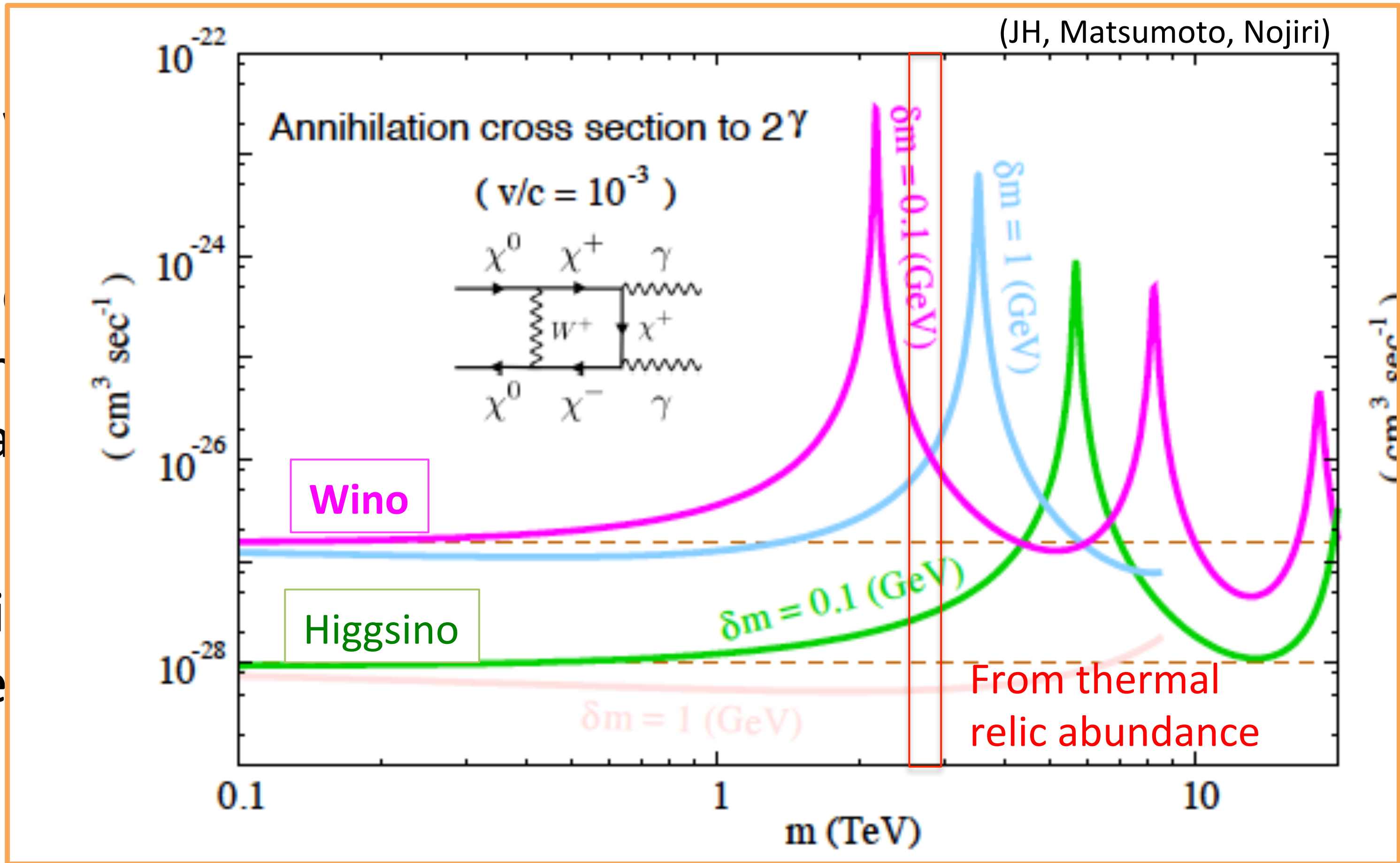
Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it may be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

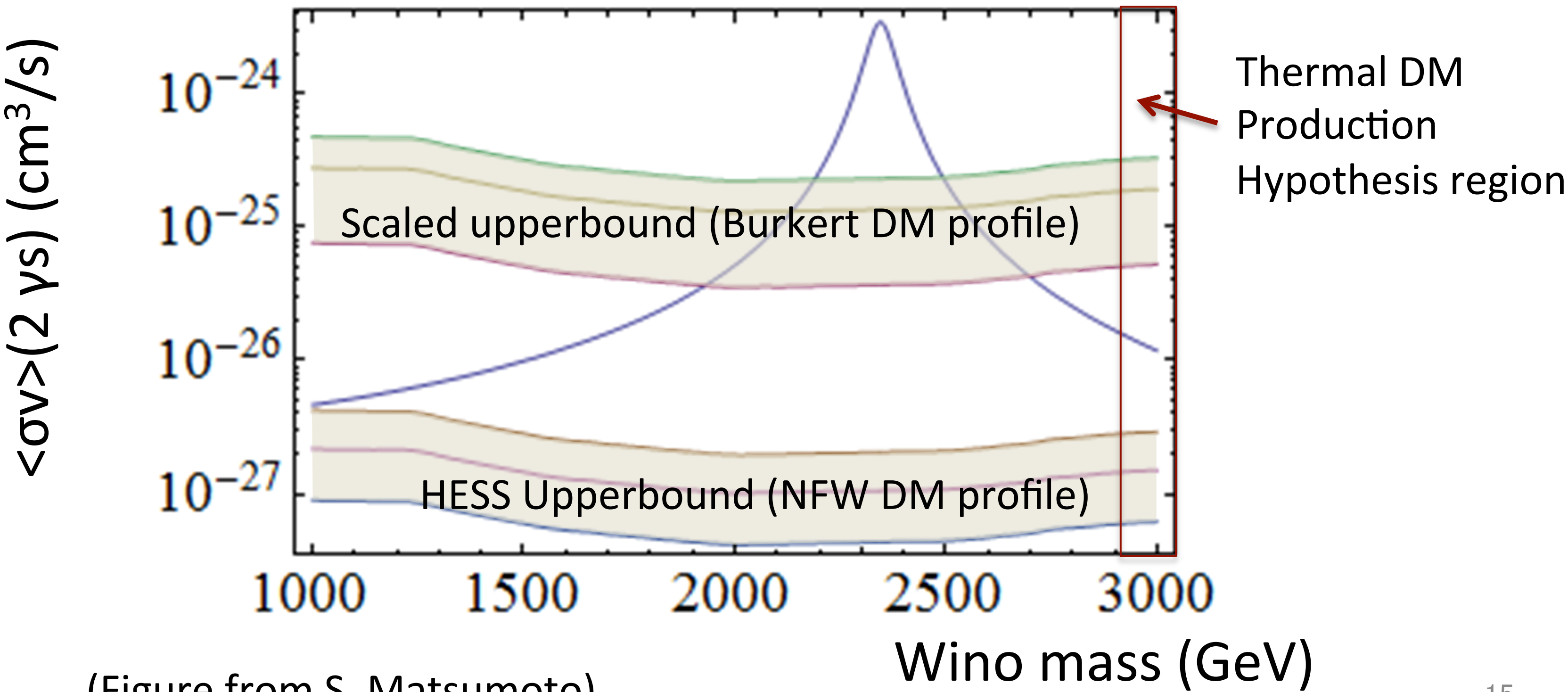
- If ... LHC.
- In ... on is er ... ga ...
- Di ... t cross se ... s itself.



ICRR activities are important to study High-scale SUSY.

Line gamma rays from GC

Line gamma rays are considered to be smoking-gun of WIMP dark matter. HESS gives constraints on line gamma rays from GC. Wino is constrained with even too heavy mass to be access at LHC. The constraint depends on DM density profile at GC. Sensitivities will be improved at CTA.



(Figure from S. Matsumoto)

Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it may be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

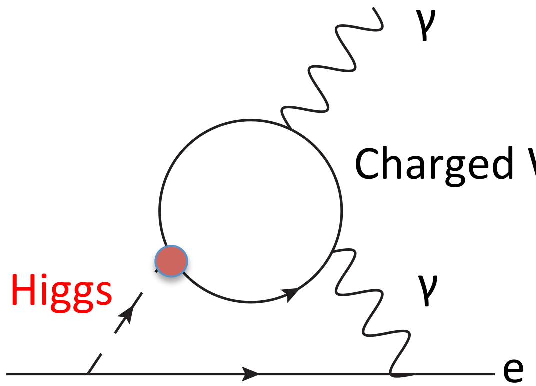
Current bound on electron EDM

$|d_e| < 8.7\times10^{-29}$ e cm (ACME, 13)

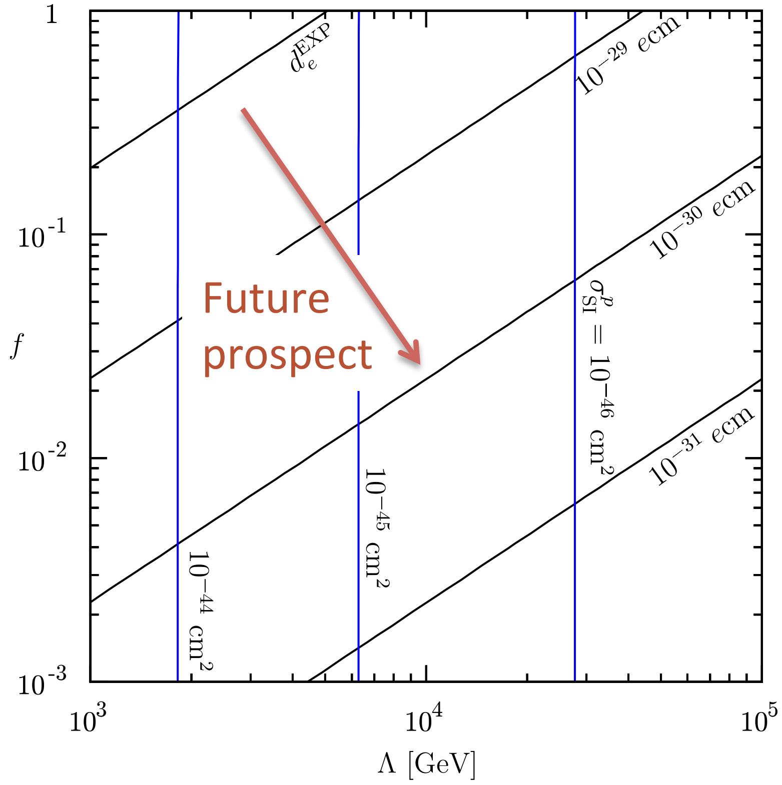
Integrating out Higgsinos gives

$$\mathcal{L} = -\frac{1}{2\Lambda}\overline{\tilde{\chi}^a}(1+i\gamma_5 f)\tilde{\chi}^a|H|^2$$

Barr-Zee diagrams contributing to electron EDM



Wino mass 3TeV



(JH, Kobayashi, Mori, Senaha)

Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

- If wino mass is lighter than ~1TeV, it may be discovered at LHC.

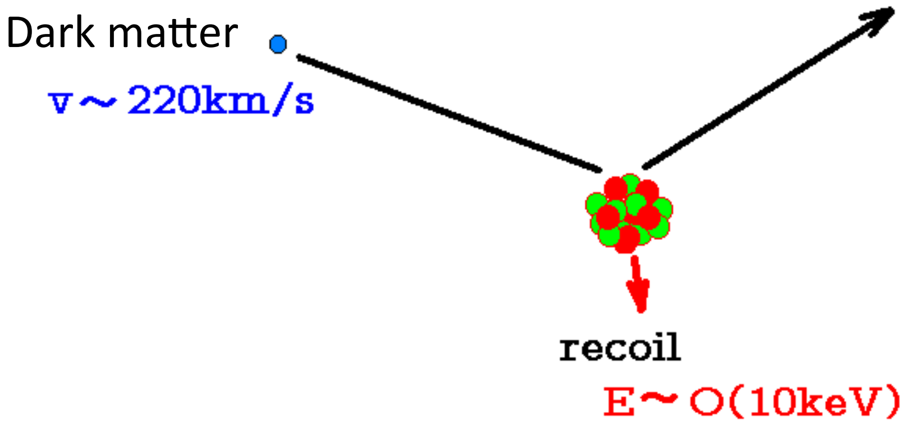
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.

- EDMs induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} ecm.

- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Wino dark matter direct detection

Dark matter direct detection experiments



$$\mathcal{L} = \sum_{N=p,n} f_N \overline{\tilde{\chi}^0} \tilde{\chi}^0 \overline{N} N + a_N \overline{\tilde{\chi}^0} \sigma_a \tilde{\chi}^0 \overline{N} \sigma_a N$$

Spin-independent (SI) interaction

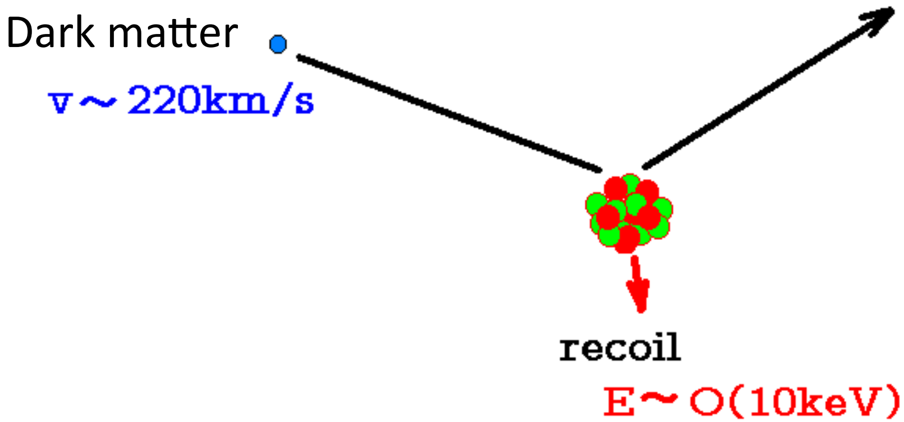
Spin-dependent (SD) interaction

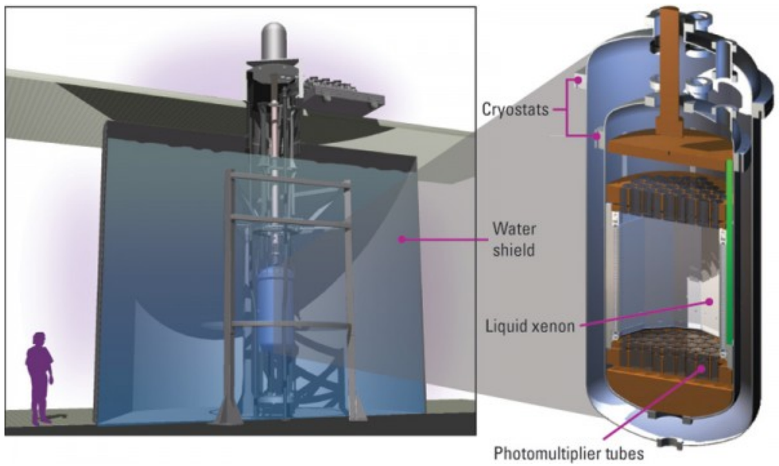
Elastic scattering cross section with nucleus (mass m_T , # of proton and neutron $n_{p/n}$)

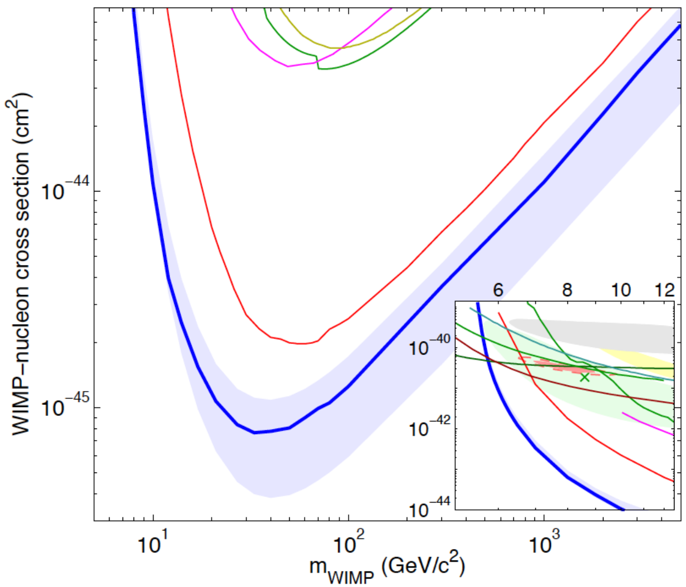
$$\sigma = \frac{4}{\pi} \left(\frac{m_{\tilde{\chi}^0} m_T}{m_{\tilde{\chi}^0} + m_T} \right)^2 \left[\underbrace{(n_p f_p + n_n f_n)^2}_{\text{SI}} + 4 \frac{J+1}{J} \underbrace{(a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2}_{\text{SD}} \right]$$

The SI cross section is enhanced for large atomic number nucleus.

Dark matter direct detection experiments







LUX gives the latest upperbound on SI cross section.

$$\sigma_{\rm SI} < 0.8(30) \times 10^{-45}{\rm cm}^2 \ \ (40 \ {\rm GeV}(3 \ {\rm TeV}))$$

Effective interaction of at parton level

Effective SI interactions at parton level up to D=7 in a non-rel. limit.

$$\mathcal{L}_q^{\rm eff} = f_q m_q \overline{\tilde{\chi}^0}\tilde{\chi}^0 \bar{q}q + \frac{g_q^{(1)}}{m_{\tilde{\chi}^0}} \overline{\tilde{\chi}^0} i\partial^\mu\gamma^\nu\tilde{\chi}^0 \mathcal{O}_{\mu\nu}^q + \frac{g_q^{(2)}}{m_{\tilde{\chi}^0}^2} \overline{\tilde{\chi}^0}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}^0 \mathcal{O}_{\mu\nu}^q$$

$\tilde{\chi}^0$: WIMP
$M_{\tilde{\chi}^0}$: WIMP mass
m_q : quark mass

$$\mathcal{L}_g^{\rm eff} = f_G \overline{\tilde{\chi}^0}\tilde{\chi}^0 G^a_{\mu\nu}G^{a\mu\nu} + \frac{g_G^{(1)}}{m_{\tilde{\chi}^0}} \overline{\tilde{\chi}^0} i\partial^\mu\gamma^\nu\tilde{\chi}^0 \mathcal{O}_{\mu\nu}^g + \frac{g_G^{(2)}}{m_{\tilde{\chi}^0}^2} \overline{\tilde{\chi}^0}(i\partial^\mu)(i\partial^\nu)\tilde{\chi}^0 \mathcal{O}_{\mu\nu}^g$$

Twist-2 operators for quarks and gluon:

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

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

Coefficients $f_q,\ g_{q/G}^{(1/2)}$ have dimension -3.

Nuclear matrix elements

- Scalar operators :

$$m_N f_{Tq}^{(N)} = \langle N | m_q \bar{q} q | N \rangle \qquad m_N f_{TG}^{(N)} = -\frac{9\alpha_s}{8\pi} \langle N | G^a_{\mu\nu} G^{a\mu\nu} | N \rangle$$

Trace-anomaly of energy momentum tensor in QCD.

$$m_N = \langle N | \theta^\mu_\mu | N \rangle = -\frac{9\alpha_s}{8\pi} \langle N | G^{\mu\nu} G_{\mu\nu} | N \rangle + \sum_{q=u,d,s} \langle N | m_q \bar{q} q | N \rangle$$

Sum rule: $f_{TG}^{(N)} + \sum_{q=u,d,s} f_{Tq}^{(N)} = 1$

- Twist-2 operators:

$$\langle N(k) | \mathcal{O}^g_{\mu\nu} | N(k) \rangle = \frac{1}{m_N} (k_\mu k_\nu - m_N^2 g_{\mu\nu}/4) \; G_N(2)$$

$$\langle N(k) | \mathcal{O}^q_{\mu\nu} | N(k) \rangle = \frac{1}{m_N} (k_\mu k_\nu - m_N^2 g_{\mu\nu}/4) \; (q_N(2) + \bar{q}_N(2))$$

The 2nd moments of parton-distribution functions (PDFs)

$$q_N(2) + \bar{q}_N(2) = \int_0^1 dx \; x \; [q_N(x) + \bar{q}_N(x)]$$

$$G_N(2) = \int_0^1 dx \; x \; g_N(x)$$

SI interaction with nucleon

Mass fraction	
(proton)	
$f_{Tu}^{(p)}$	0.019(5)
$f_{Td}^{(p)}$	0.027(6)
$f_{Ts}^{(p)}$	0.009(22)
(neutron)	
$f_{Tu}^{(n)}$	0.013(3)
$f_{Td}^{(n)}$	0.040(9)
$f_{Ts}^{(n)}$	0.009(22)

Second moment at $\mu = m_Z$			
$u(2)$	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

- Mass fractions come from Lattice QCD.
- 2nd moments of PDFs comes from CTEQ PDFs.

$$\mathcal{L} = \sum_{N=p,n} f_N \overline{\tilde{\chi}^0} \tilde{\chi}^0 \overline{N} N$$

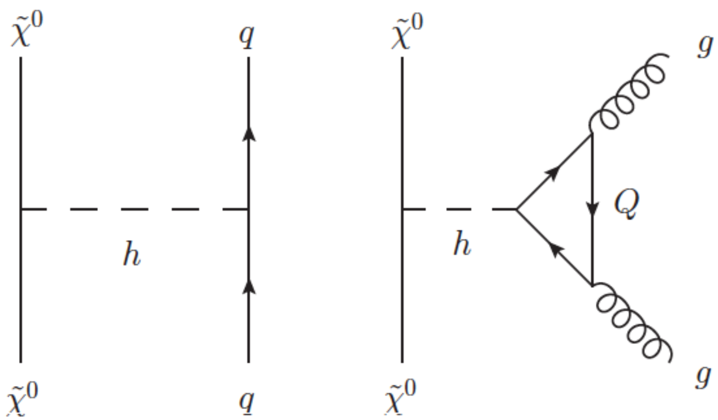
$$\frac{f_N}{m_N} = f_{Tq}^{(N)} f_q + \frac{3}{4}\left(q_N(2) + \bar{q}_N(2)\right)\left(g_q^{(1)} + g_q^{(2)}\right)$$
$$- \frac{8\pi}{9\alpha_s} f_{TG}^{(N)} f_G + \frac{3}{4} G_N(2)\left(g_G^{(1)} + g_G^{(2)}\right)$$

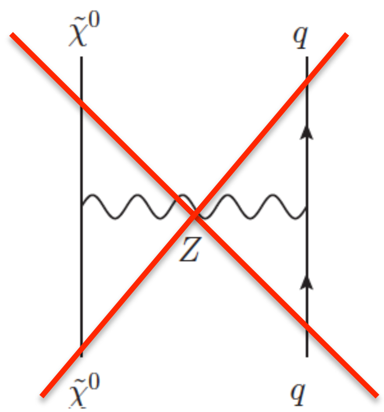
Gluon contribution is dominant even if it is suppressed by a loop factor

Suppressed by a loop factor of $\alpha_s/4\pi$.

Tree-level contribution to SI interaction

Higgsino-Wino mixing induces to tree-level coupling with Higgs boson, though it is suppressed by m_W/μ (μ:Higgsino mass).

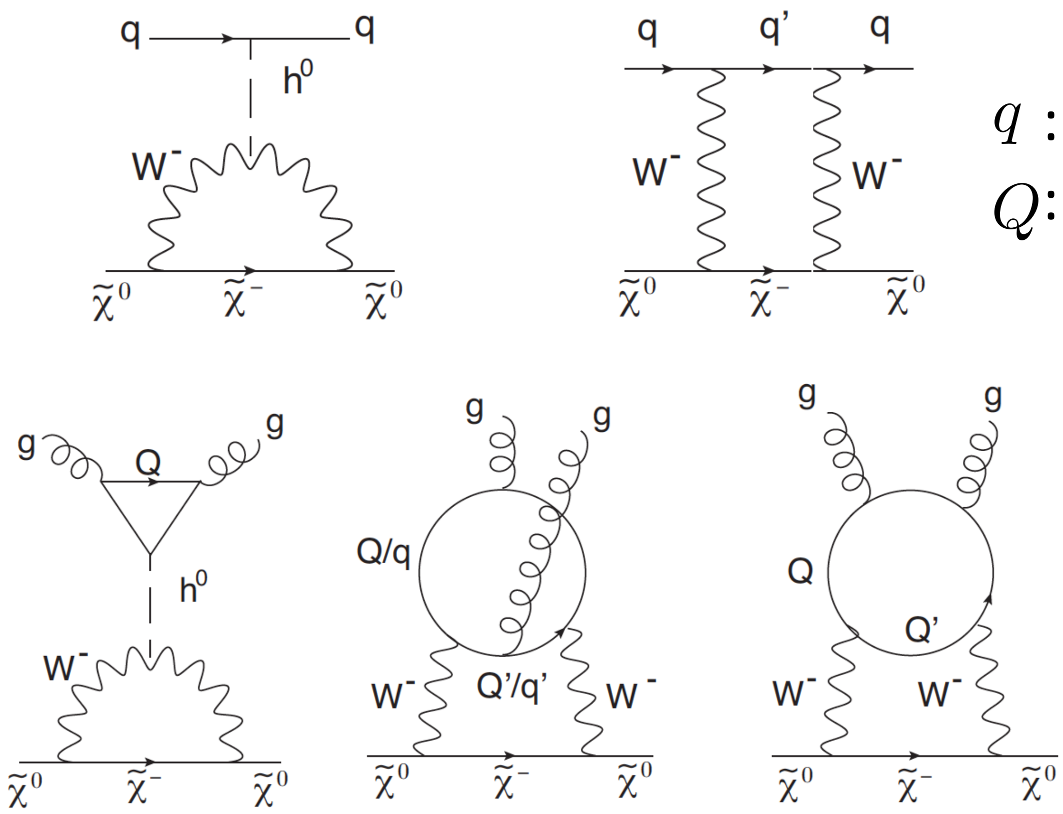




q : light quarks (u,d,s)
Q: heavy quarks (c,b,t)

Contribution to SD interaction.

Loop-level contribution to SI interaction

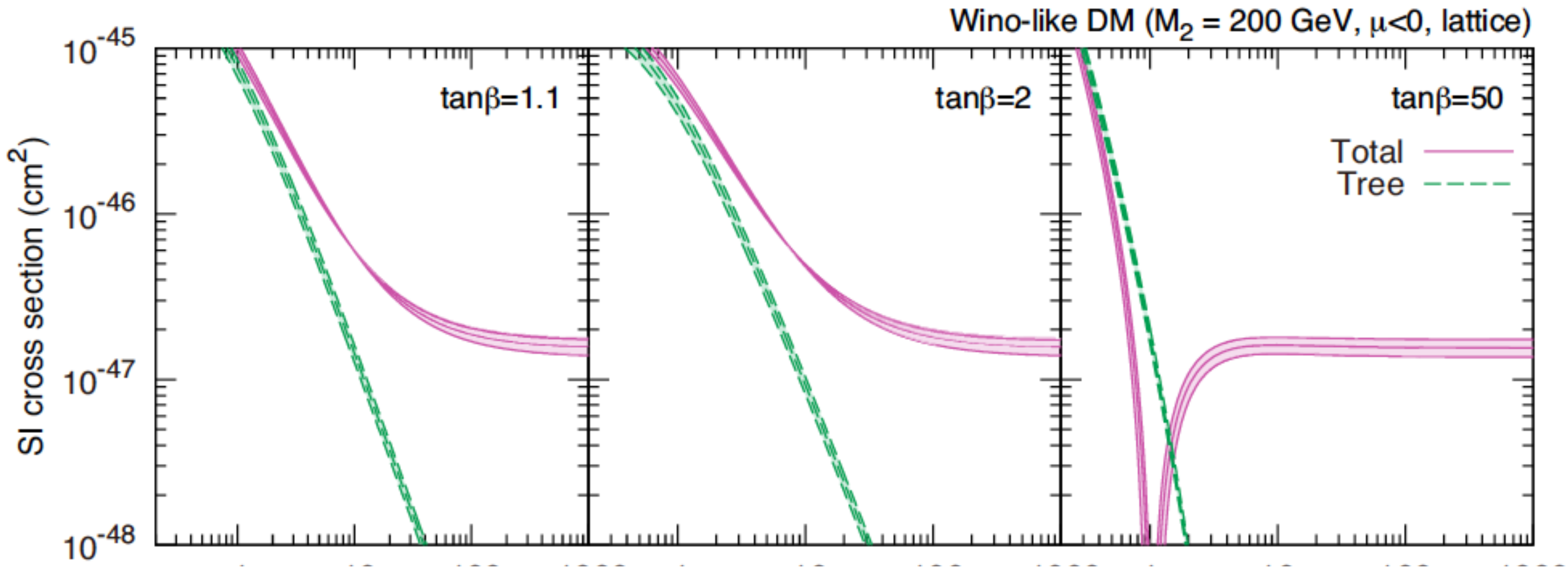


q : light quarks (u,d,s)

Q: heavy quarks (c,b,t)

These contributions are not suppressed by power of of wino mass. When Higgsino mass (μ) is much heavier than wino one, loop-level contribution dominates over tree-level one. (JH, Matsumoto, Nojiri, Saito)

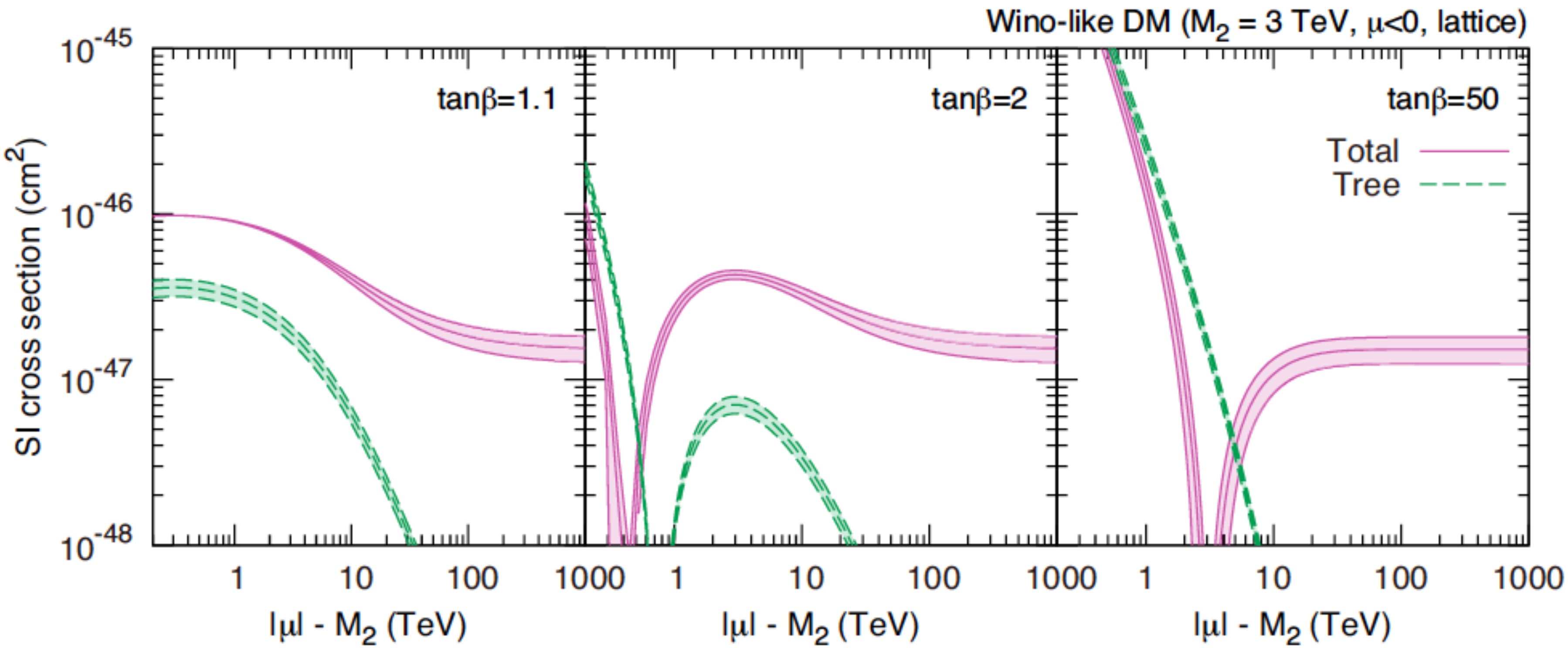
SI cross section of Wino DM (200GeV)



(Higgsino mass – Wino mass) (TeV) (JH, Ishiwata, Nagata)

When SI cross section at tree level is suppressed, one-loop contribution dominates over it. SI cross section is $2*10^{-47}$ cm^2 in the limit.

SI cross section of Wino DM (3TeV)



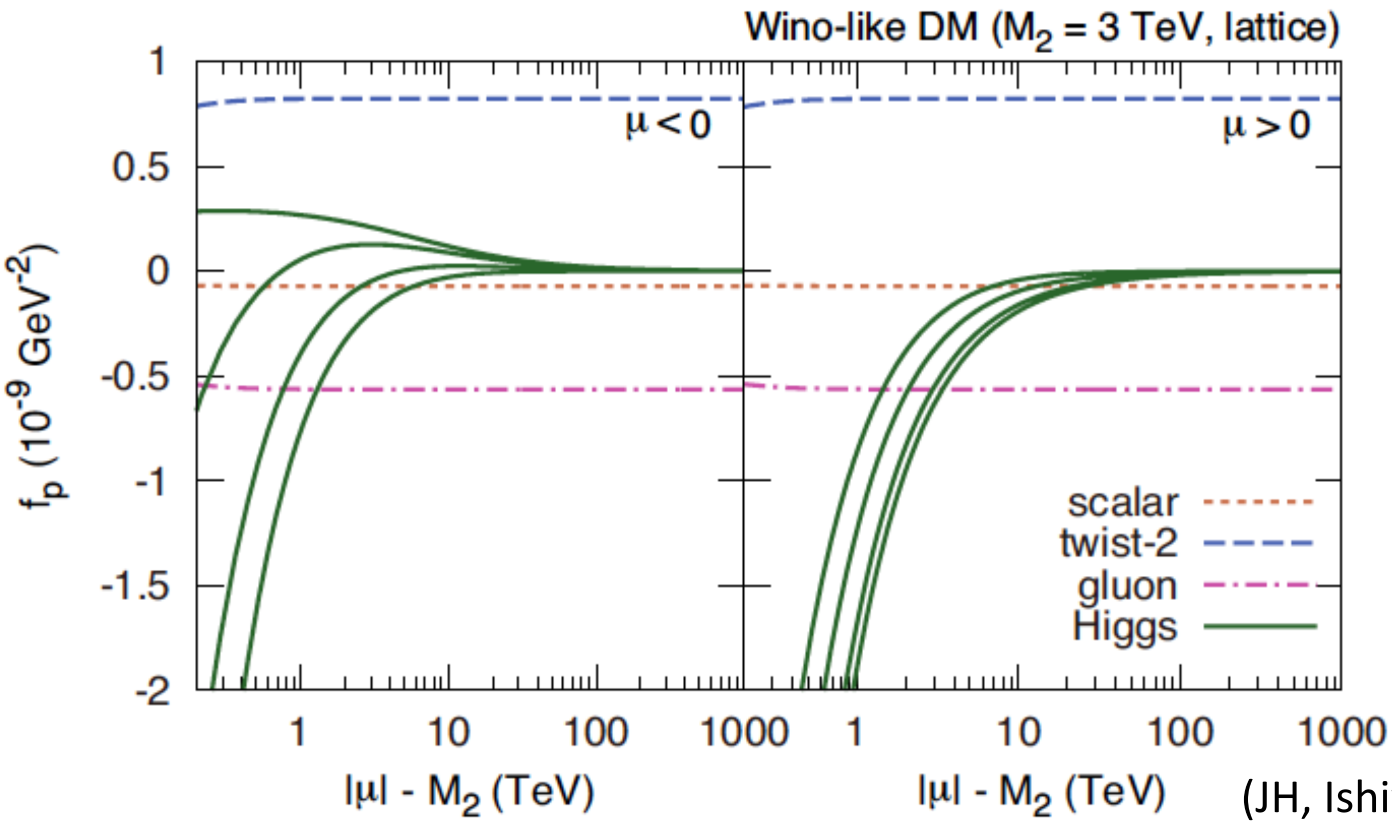
Higgsino mass – Wino mass (TeV)

(JH, Ishiwata, Nagata)

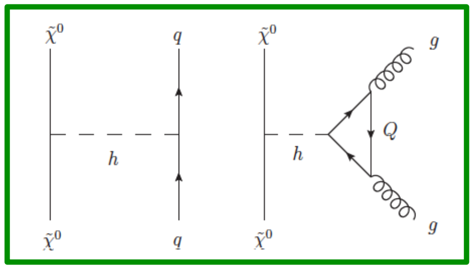
Even if wino is much heavier than weak scale, SI cross section is insensitive to the wino mass.

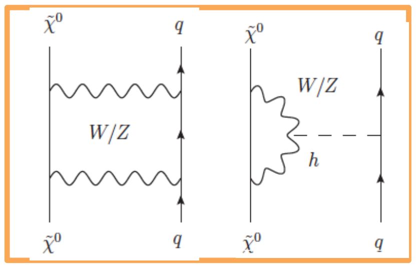
Accidental cancelation

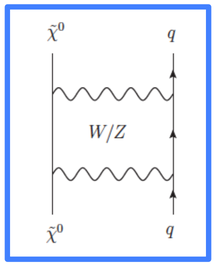
SI coupling of wino with nucleon has various contributions :

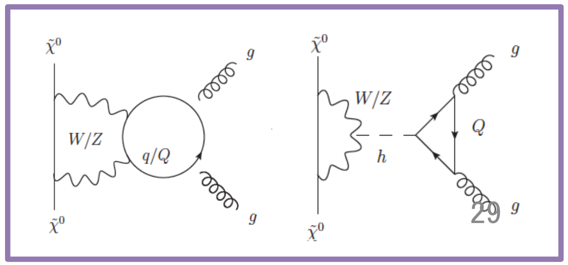


(JH, Ishiwata, Nagata)



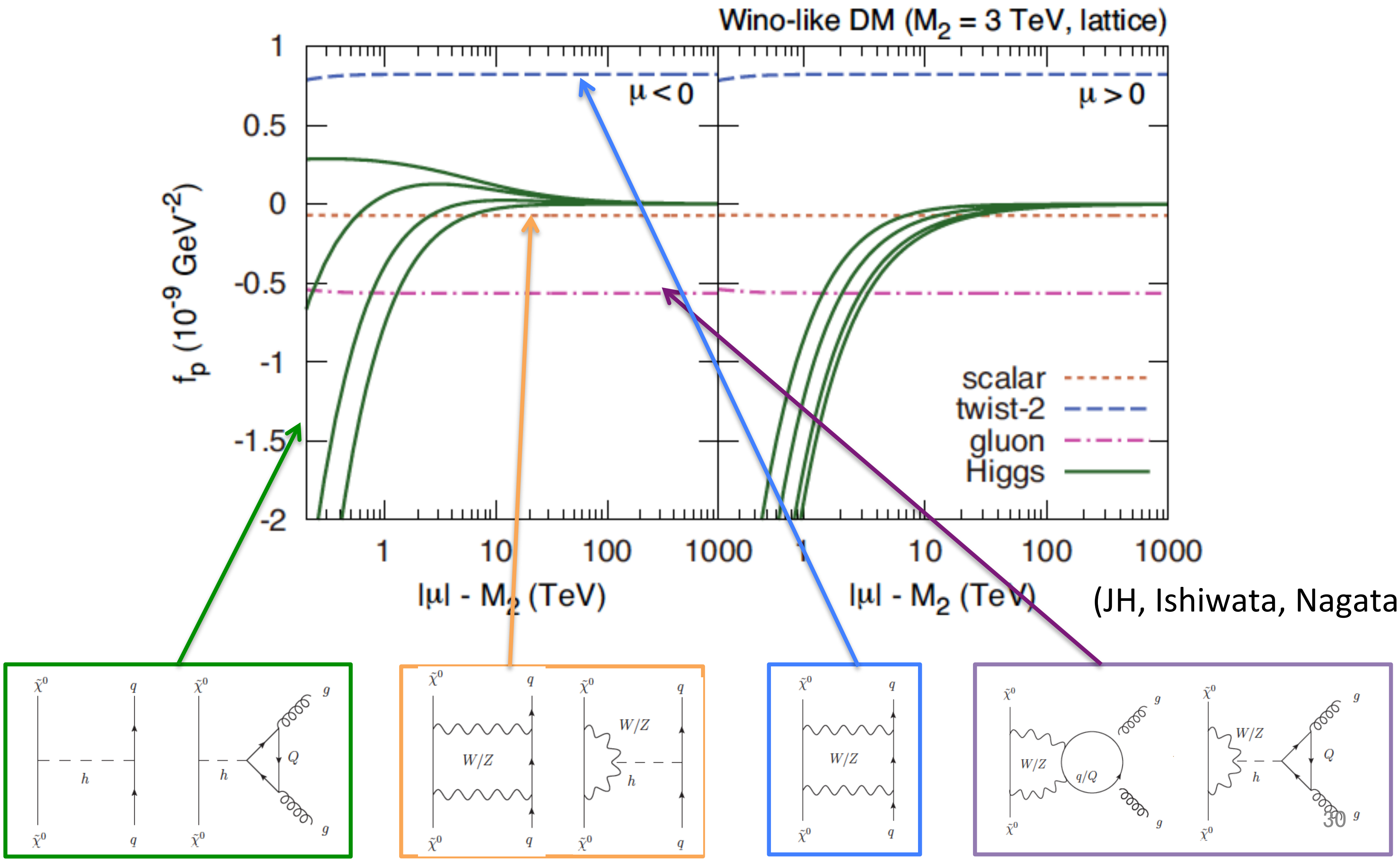






Accidental cancelation

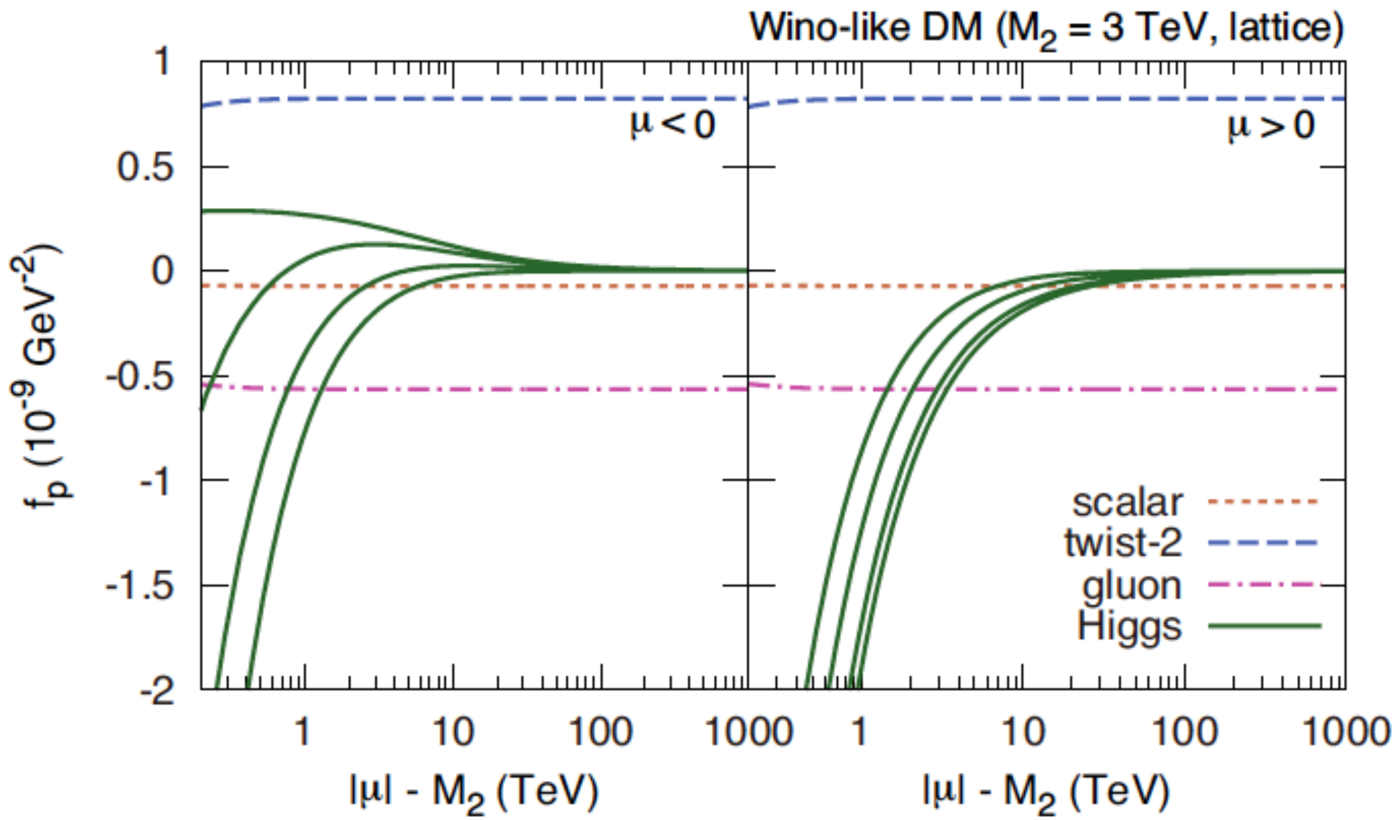
SI coupling of wino with nucleon has various contributions :



(JH, Ishiwata, Nagata)

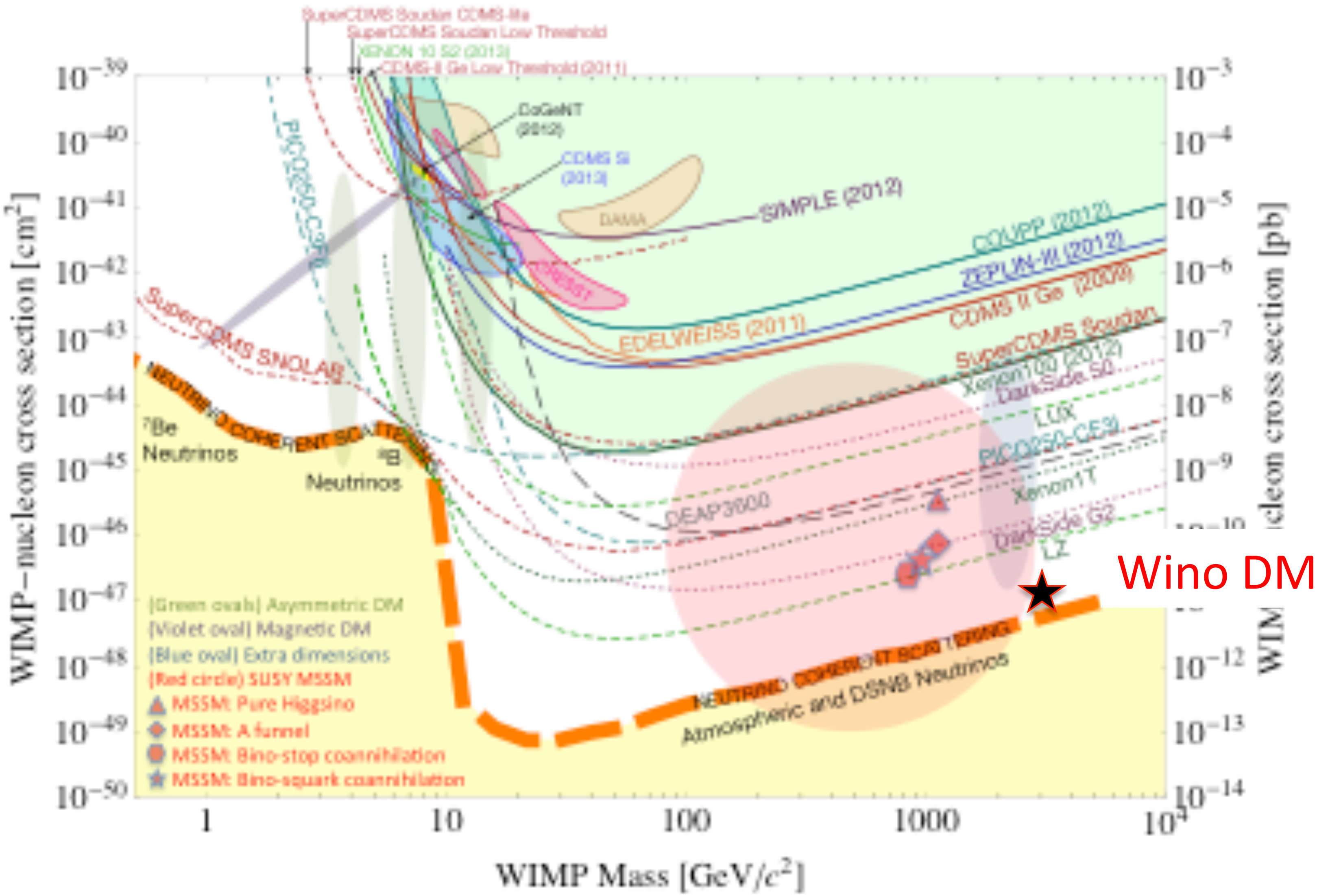
Accidental cancellation

SI coupling of wino with nucleon:



Accidental cancellation reduces the SI cross section. NLO QCD correction might change it by a factor 2. (Now we are calculating.)

Future prospects



(From snowmass report)

Summary (Strategy to High-scale SUSY)

Wino is electroweak-interacting dark matter.

- If wino mass is lighter than ~1TeV, it may be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ 10^{-30} e cm.
- Direct detection of wino dark matter. The spin-independent cross section is ~ 10^{-47} cm^2, which is not suppressed by wino mass itself.

Summary (A dream)

- At 201X, finite values for EDMs are discovered.
- At 202X, peak on gamma ray spectrum from galactic center are discovered around 3TeV at CTA.
- At 202X, Argon detection of dark matter finds excess of counting rate, which is larger than neutrino BGs.
- At 20XX, wino is discovered at 100TeV pp collider.

Though, I still hope that LHC run2 will find SOMETHING, since I still consider that the naturalness is important.