# Wino is a window to SUSY?

## - SUSY standard model(s) at O(100) TeV-

Junji Hisano

(KMI, Nagoya Univ.)

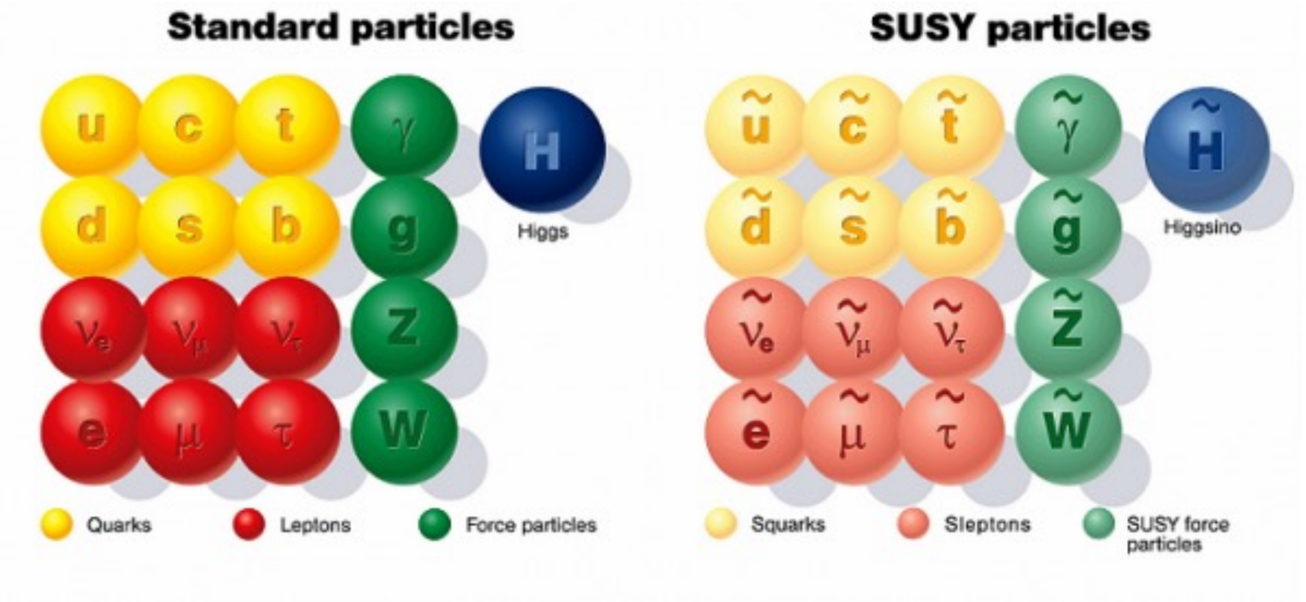
The 2nd DMnet International Symposium on
"Direct and Indirect Dark Matter Search"
Max Planck Insitute for Nuclear Physics, Heidelberg
13-15 Sept. 2022

# Contents of my talk

- Motivation of SUSY standard model(s) at O(100) TeV

- How to find the signature for them
  That comes from wino!

# SUSY standard model



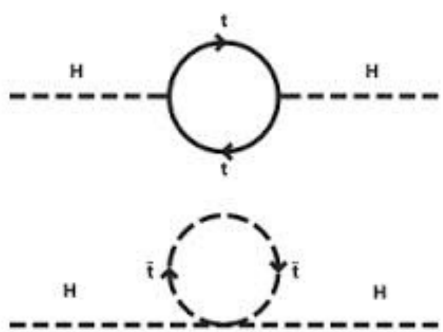

- Superpartners for the standard model particles are introduced.
- The lightest SUSY particle is stable due to the R parity, which comes from proton stability.

# SUSY standard model

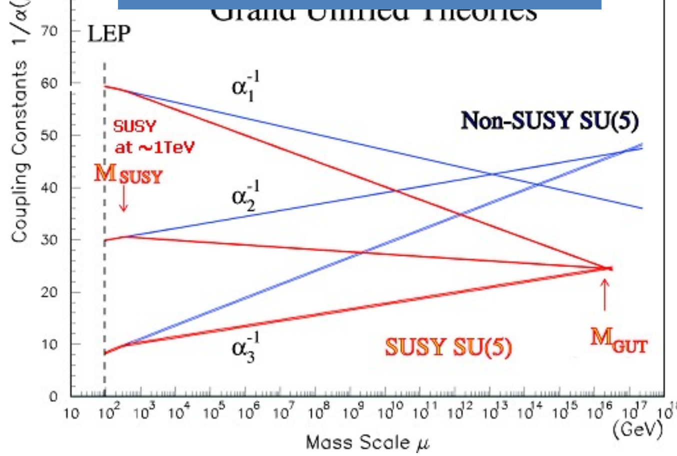
## Leading candidate for BSMs

- Hierarchy problem $(M_Z \ll M_{\rm Planck})$
- Gauge coupling unification $(M_{\rm GUT} \simeq 10^{16}{\rm GeV})$
- WIMP dark matter $(\Omega_{\rm DM} \simeq 22\%)$

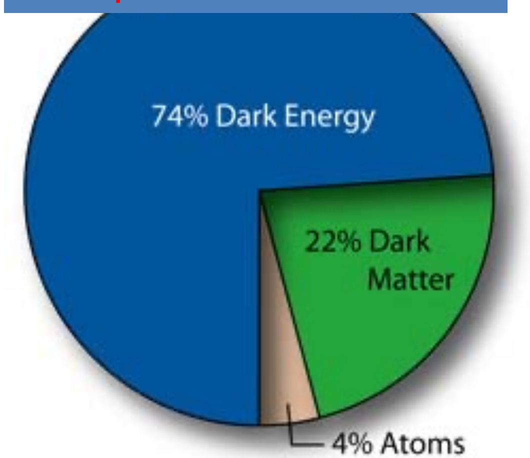
Hierarchy problem




Grand Unified Theories




Composition of Universe



# Higgs mass in the MSSM

Tree level

One-loop correction

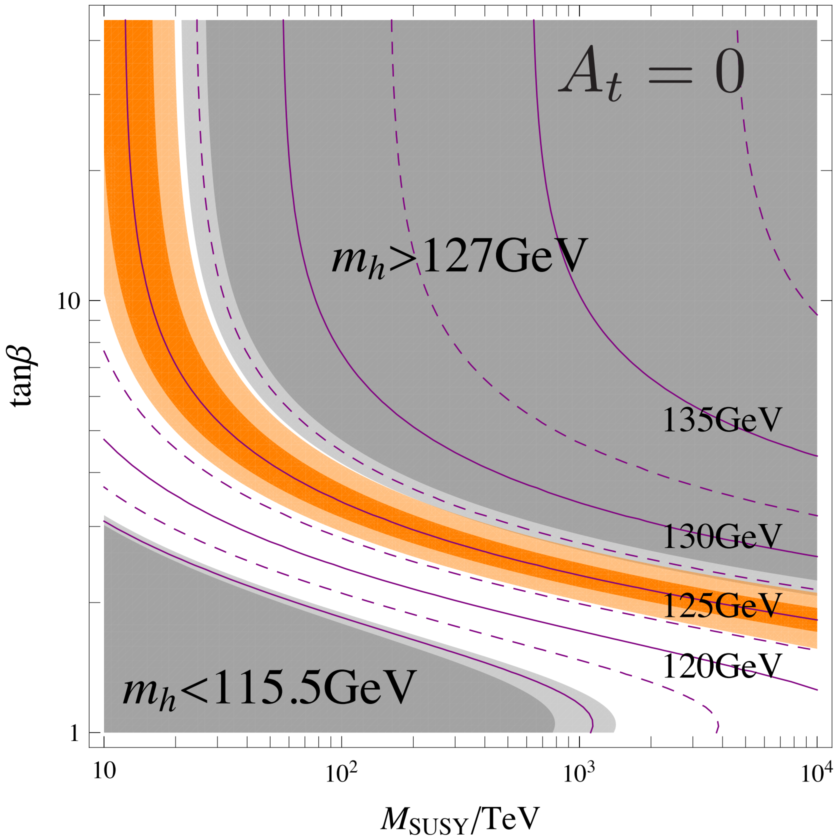
$$m_{h^0}^2 \lesssim m_Z^2 \cos^2\beta + \frac{3}{4\pi} y_t^2 m_t^2 \sin^2\beta \left( \log \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{X_t^4}{m_{\tilde{t}}^4} \right)$$

Large log correction

Finite correction

$$X_t = A_t - \mu/\tan\beta$$

# 125 GeV Higgs mass may suggest High-scale SUSY




(Ibe, Matsumoto, Yanagida (12))

For tanβ~2-5, 125 GeV Higgs mass is well-explained in High-scale SUSY (MSUSY=O($10^{2\text{-}3}$)TeV).

# SUSY

SUSY GUTs ~ $10^{16}$ GeV

MSSM @ < O(1) TeV

Standard model

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

- Hierarchy 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($10^{2\text{-}3}$) TeV).

# SUSY

SUSY GUTs ~ $10^{16}$ GeV

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

- Hierarchy problem

$K^0-\overline{K}^0$ mixing constraints on off-diagonal terms of d-squark mass matrix.

.

$$m_{\tilde{q}} > 10\mathrm{TeV} \times \sqrt{\left|\mathrm{Re}\left(\frac{m^d_{12,LL/RR}}{m^2_{\tilde{q}}}\right)^2\right|}$$

$$m_{\tilde{q}} > 200\mathrm{TeV} \times \sqrt{\left|\mathrm{Re}\left(\frac{m^d_{12,LL}}{m^2_{\tilde{q}}}\frac{m^d_{12,RR}}{m^2_{\tilde{q}}}\right)\right|}$$

(Gabbiani et al (96))

(If CP phases are O(1), squark masses should be ten times larger than above. )

MSSM @

Standard

# High-scale SUSY

SUSY GUTs ~ $10^{16}$ GeV

MSSM @ O($10^{2\text{-}3}$) TeV

↑

Standard model

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

- Solution of following problems
  - FCNC and CP problems
  - Gravitino problem in nucleosynthsis
  - D=5 proton decay in SUSY GUTs
  - 125GeV Higgs mass

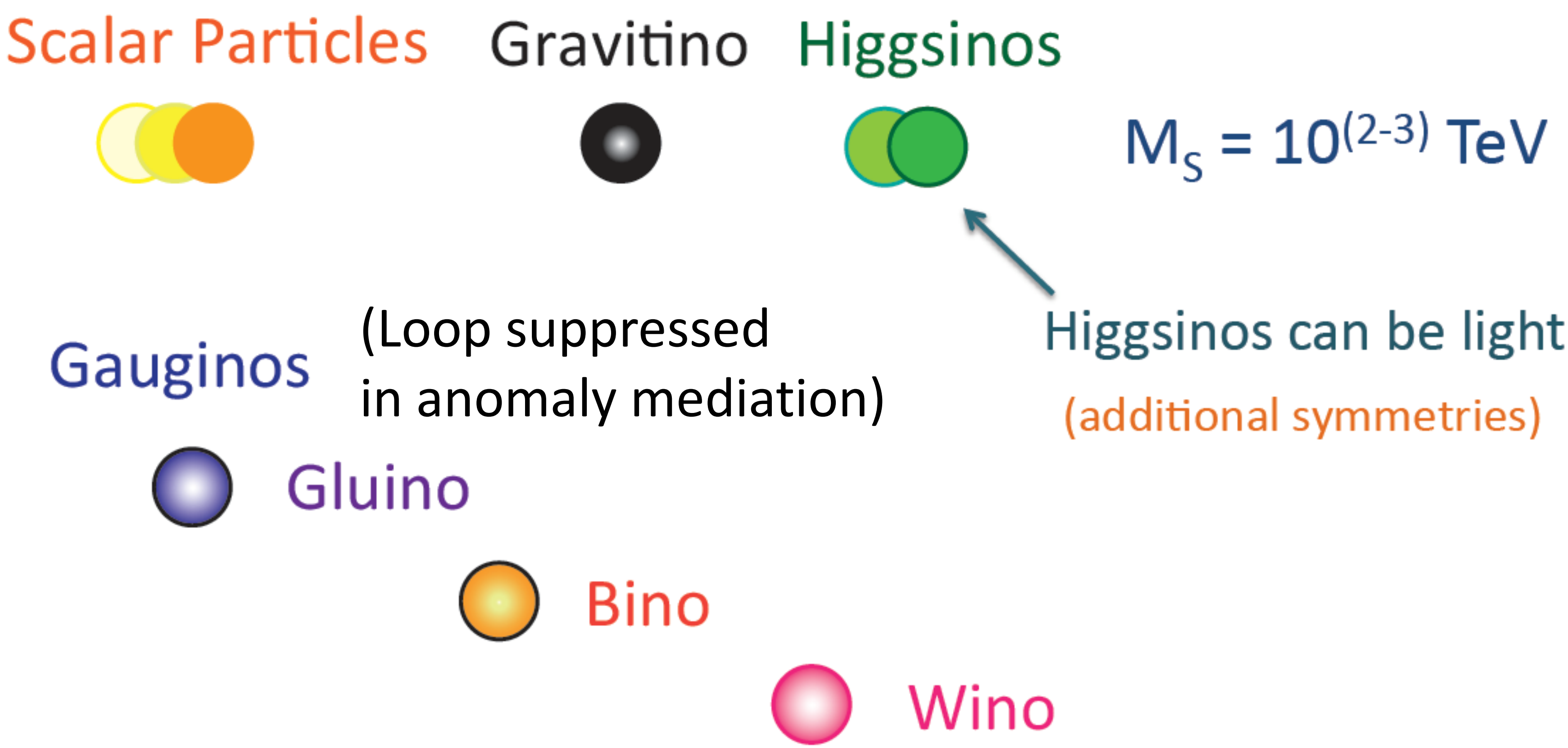
- Easy model building of SUSY breaking

  - Anomaly mediation

    (Randall and Sundrum/ Giudice, Murayama Luty and Rattazzi (98))

- WIMP dark matter
- Improved gauge coupling unification

# Mass spectrum in High-scale SUSY



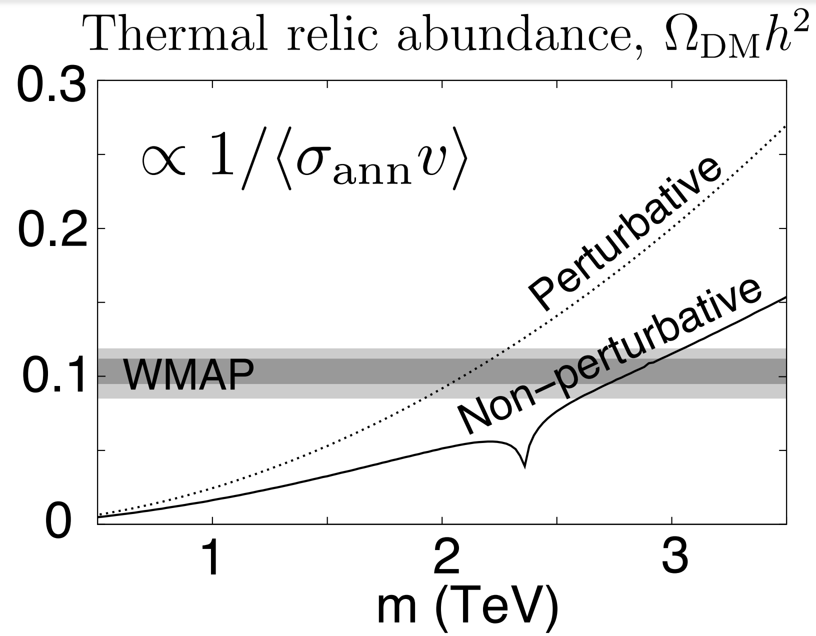
# Wino dark matter

## Thermal Wino dark matter

(Non-rel.) wino pair annihilation cross section into W-boson pair is large due to the SU(2) coupling and also the Sommerfeld enhancement. From the DM thermal relic abundance,

$$m_{\rm wino} \simeq (2.7 - 3.0)\text{TeV}$$

(JH, Matsumoto, Nagai, Senami, Saito (07))




## Non-Thermal Wino dark matter

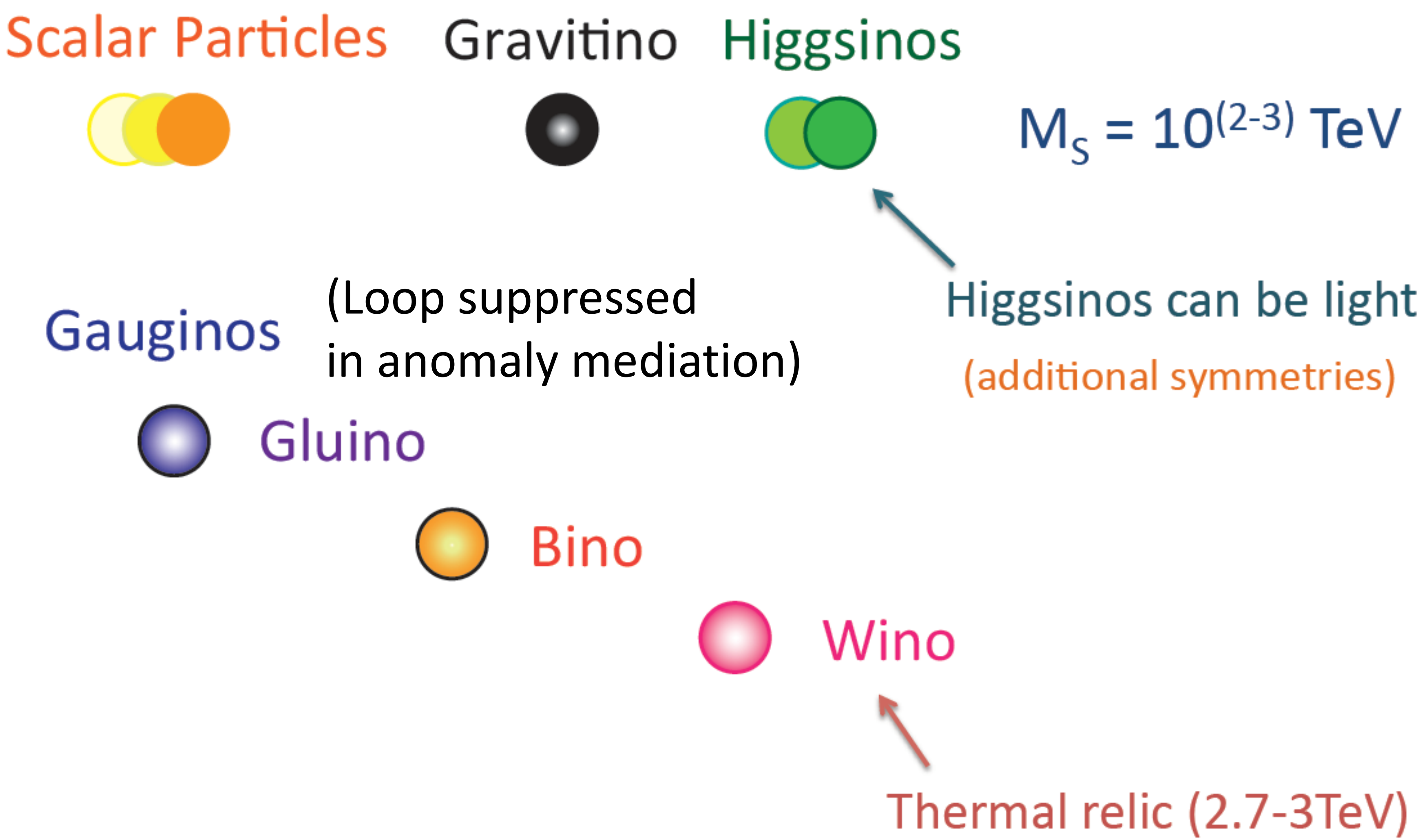
Gravitino decay provides additional wino DM comp.

$$\sigma_{\rm DM}h^2 = 0.16\left(\frac{m_{\rm wino}}{300\text{GeV}}\right)\left(\frac{T_{\rm reheating}}{10^{10}\text{GeV}}\right)$$

(Gherghetta, Giudice, Wells (99), Moroi, Randall (99))

Thermal leptogenesis ( $T_{\rm reheating} > 10^9\text{GeV}$) favors lighter wino.

# Mass spectrum in High-scale SUSY

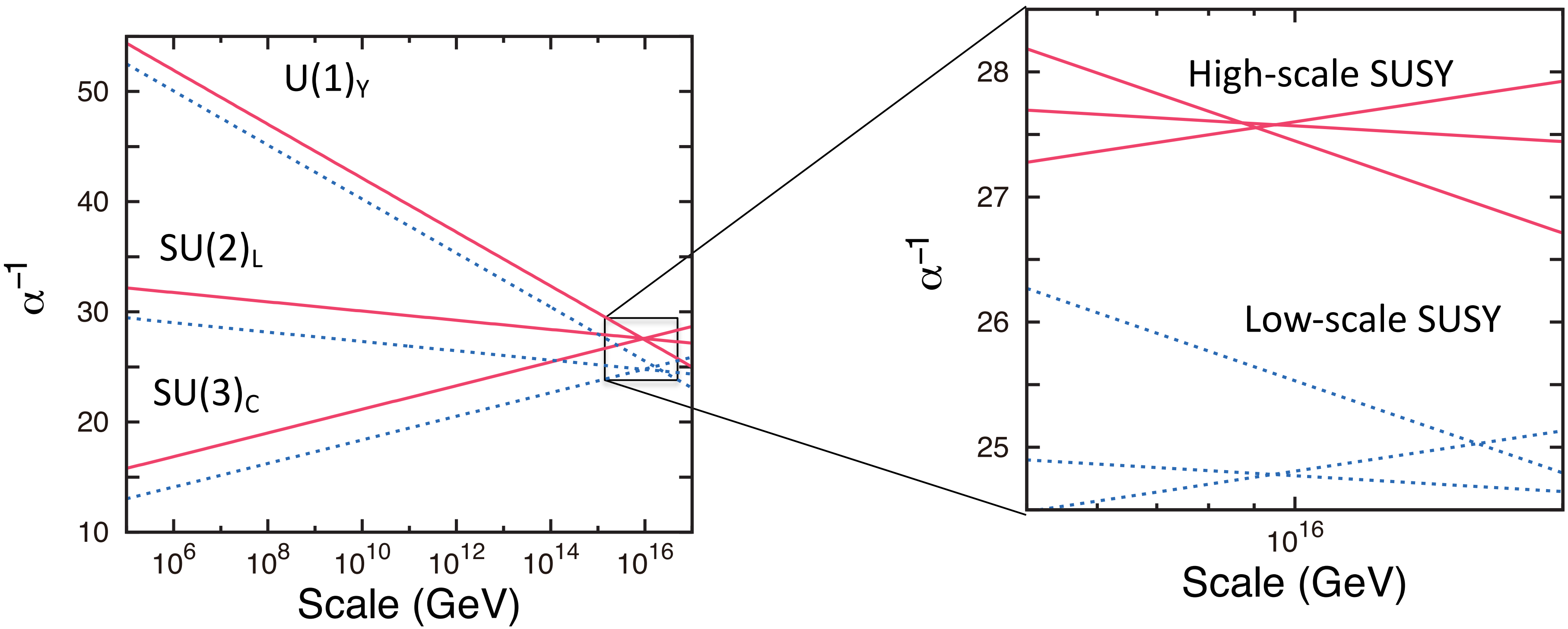



J. Hisano, S. Matsumoto, M. Nagai, O. Saito, M. Senami (2006).

# Improving gauge coupling unification in High-scale SUSY

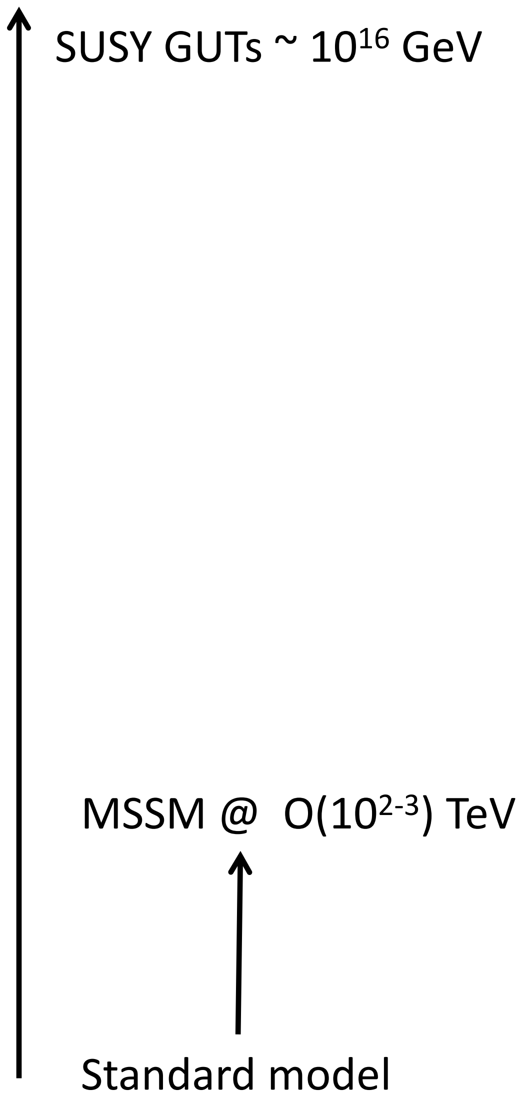
In High-scale SUSY we do not need to introduce sizable threshold correction to the gauge coupling constants at GUT-scale.

(JH, Kuwahara, Nagata(13))




GUT scale moves from $2*10^{16}$GeV to $1*10^{16}$ GeV due to heavier gaugino masses. Proton decay might be accessible?

# High-scale SUSY




Motivation of High-scale SUSY (~O($10^{2-3}$) 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
  - Anomaly mediation
- 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.

# How to find the signature for High-scale SUSY

# 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.

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

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

# Wino in SUSY SM

Wino
(I=1, Y=0, S=1/2)
Partners of weak bosons

$$\chi^0,\ \chi^\pm$$

$$\Delta m_+ = 166\mathrm{MeV} + O(\frac{v^4}{M^3})$$

(EW radiative
correction)

# Strategy to High-scale SUSY

Lightest SUSY particle (LSP):wino

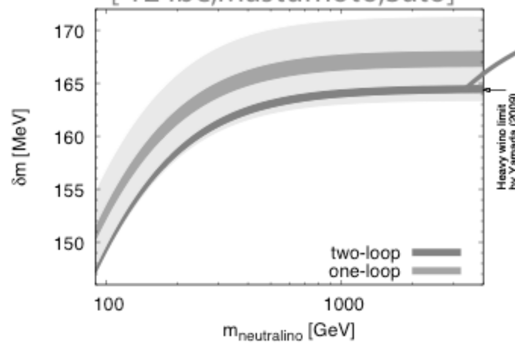
- If wino mass is lighter than ~1TeV, it might be discovered at LHC.
- Indirect detection of wino dark matter. Wino pair annihilation is enhanced by the Sommerfeld effect. Line gamma rays from galactic center will be searched for at CTA.
- Direct detection of wino dark matter. The spin-independent cross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

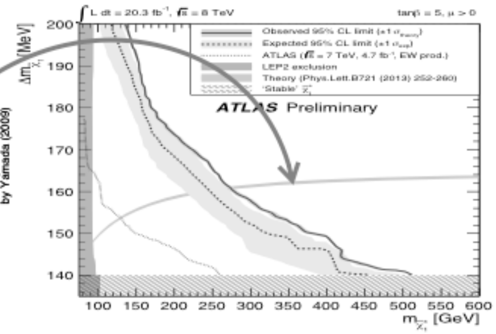
# Direct Wino search at LHC

## Phenomenology of PGM

### Direct Wino Production


['12 Ibe,Mastumoto,Sato]




- ✓ Main decay mode : $\chi^{\pm} \rightarrow \chi^{0} + \pi^{\pm}$ : $\tau_{wino} = O(10^{-10})$ sec.
- ✓ Limits (disappearing track search):

| | | |
|---|---|---|
| $m_{wino} > 130GeV$ ($7TeV\&5fb^{-1}$) | using TRT | [arxiv:1210.2852] |
| $m_{wino} > 270GeV$ ($8TeV\&20fb^{-1}$) | using SCT & TRT | [ATLAS-CONF-2013-069] |

→Prospects: $M_{wino} \sim 500GeV$ ($14TeV,300fb^{-1}$)
$M_{wino} \sim 650GeV$ ($14TeV,3000fb^{-1}$)
$M_{wino} \sim 3TeV$ ($100TeV,3000fb^{-1}$) [1407.7058, Cirelli, Sala, Taoso]



Slide of Ibe @KIST

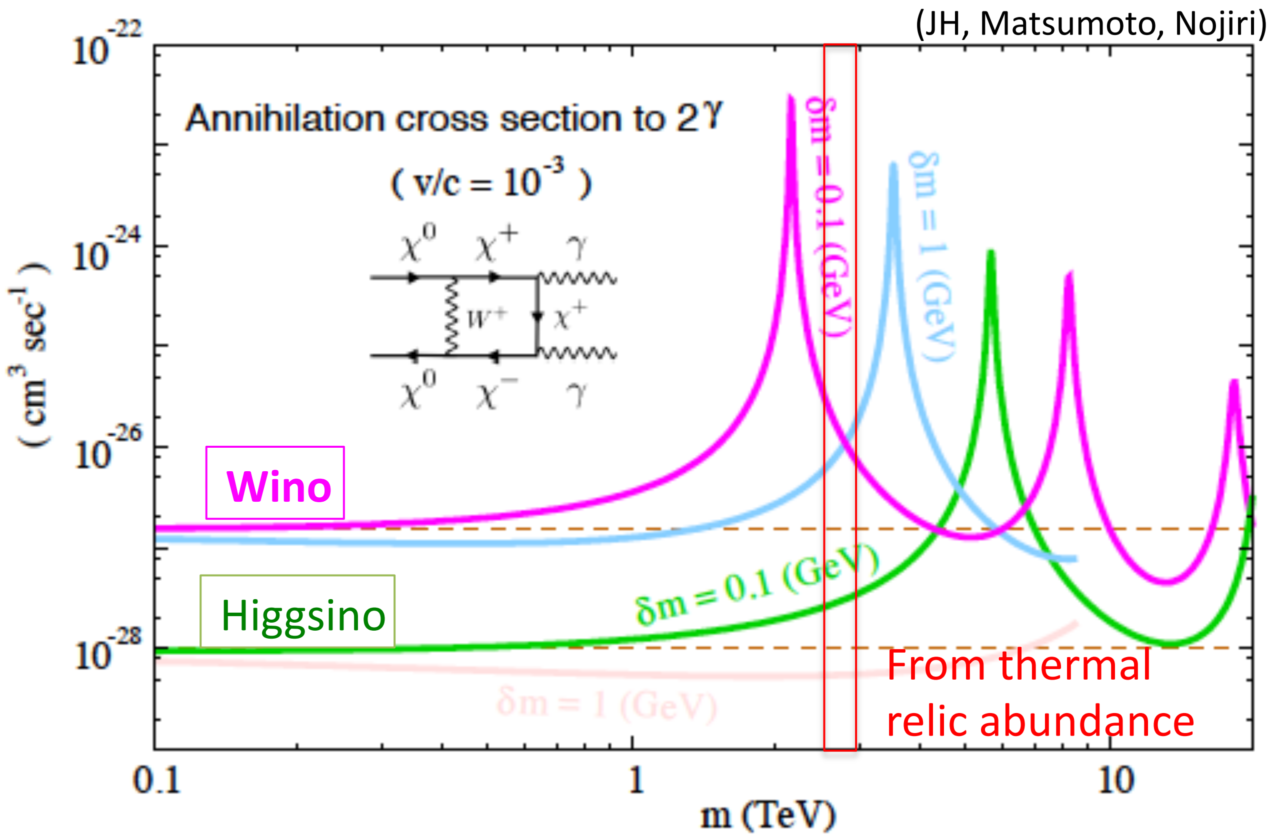
# Strategy to High-scale SUSY

## 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.
- Direct detection of wino dark matter. The spin-independent cross section is ~ $10^{-47}$ cm$^2$, which is not suppressed by wino mass itself.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ $10^{-30}$ ecm.

# Sommerfeld enhancement of wino pair annihilation to 2 line gammas

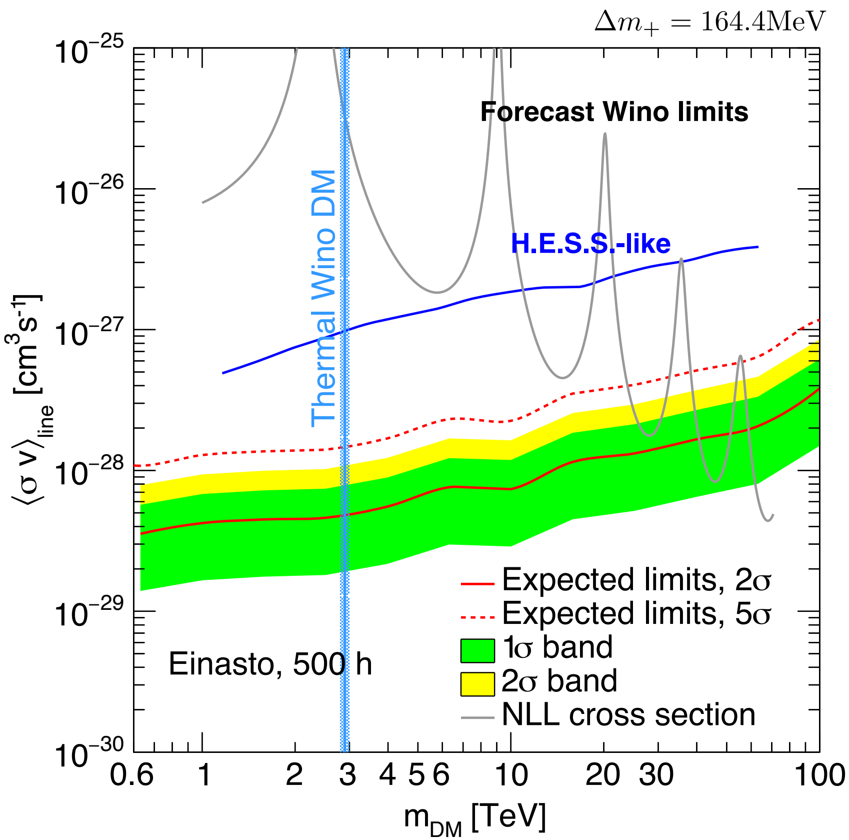
Wino pair annihilation to line gammas in the universe may be a smoking-gun of wino dark matter. While the perturbative contribution is suppressed due to the one-loop process, the cross section at NR limit is enhanced by the Sommerfeld mechanism.

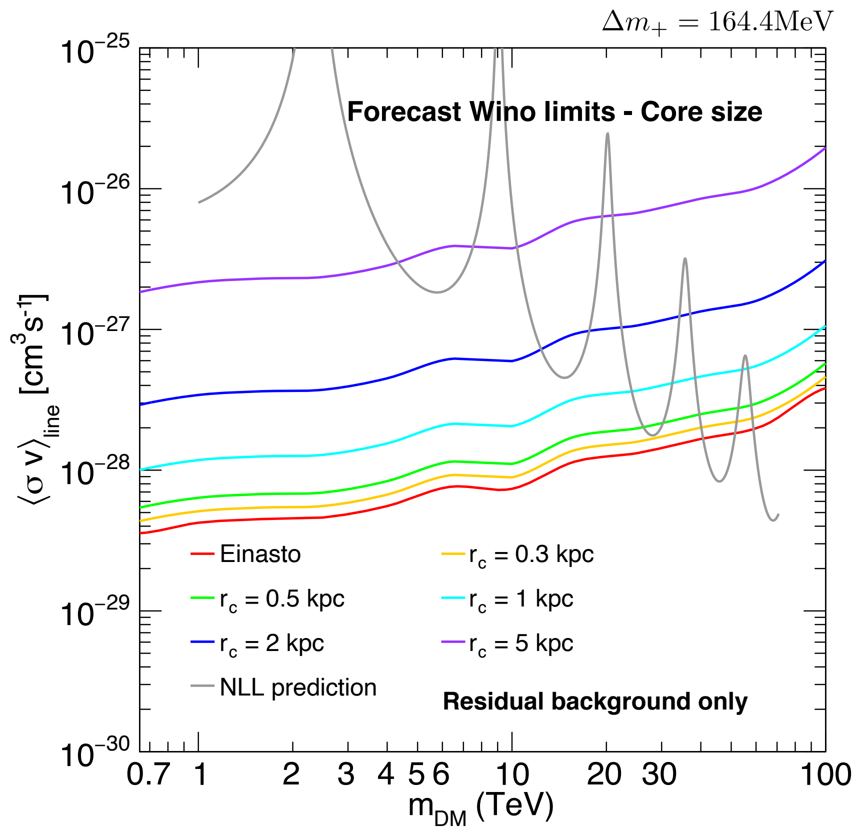


# Line gamma rays from Galactic Center

## CTA Prospect for Wino DM (Rinchiuso, Slatyer, et al (20))

(Resummation of Sudalov double log, continuum emission, endpoint photons, energy resolution of CTA are included.)



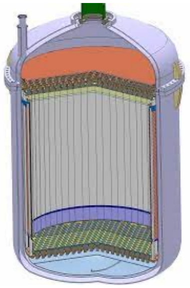

The precise evaluation of thermal relic abondance is important since the x section to line gamma is quite sensitive to wino mass (Tobias's talk).

# 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.
- Direct detection of wino dark matter. The spin-independent cross section is ~ $10^{-47}$ $cm^2$, which is not suppressed by wino mass itself.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ $10^{-30}$ ecm.

# Dark matter direct detection experiments



XENONnT LZ Darwin

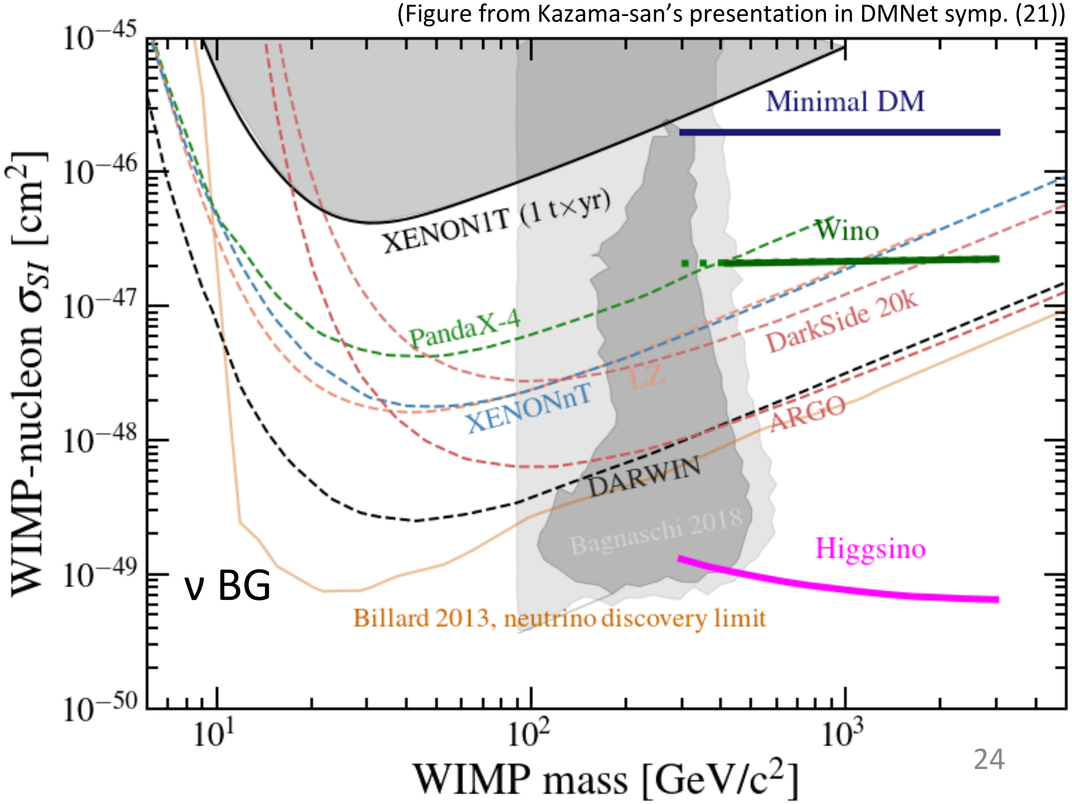
→ Future

Experiments are sensitive to Spin-indep. DM-nucleon elastic scattering.

$$f\chi\chi\bar{N}N$$

In near future, experiments will reach close to neutrino BG.

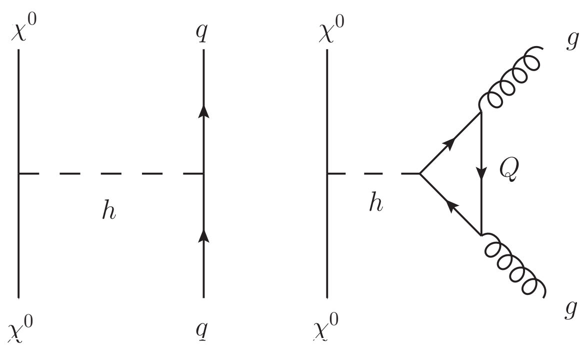
(Figure from Kazama-san's presentation in DMNet symp. (21))



# Tree-level contribution to SI interaction

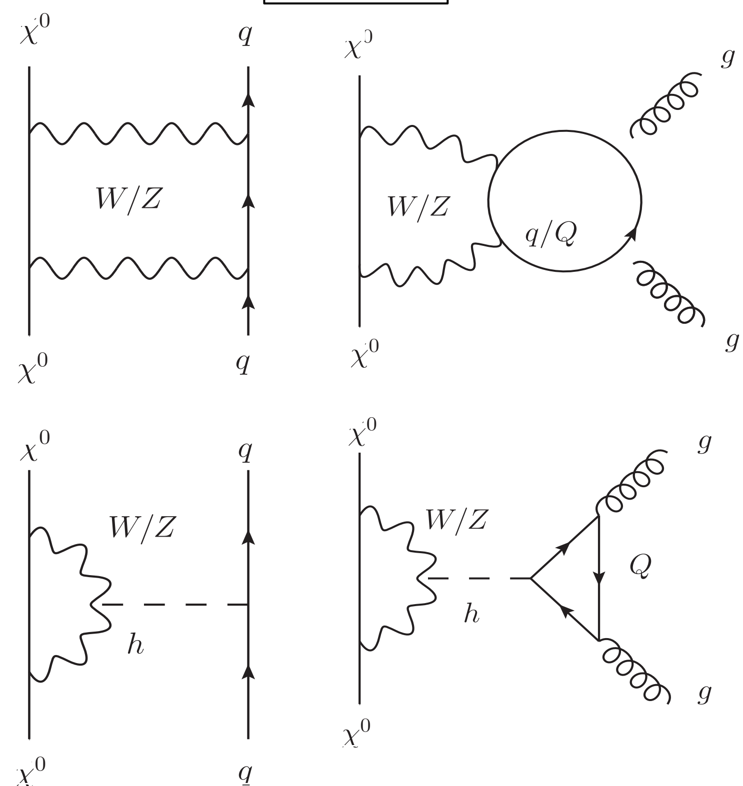
## Spin-independent DM-nucleon elastic scattering

TREE




Leading, but suppressed by Gaugino-Higgsino mixing.

LOOP

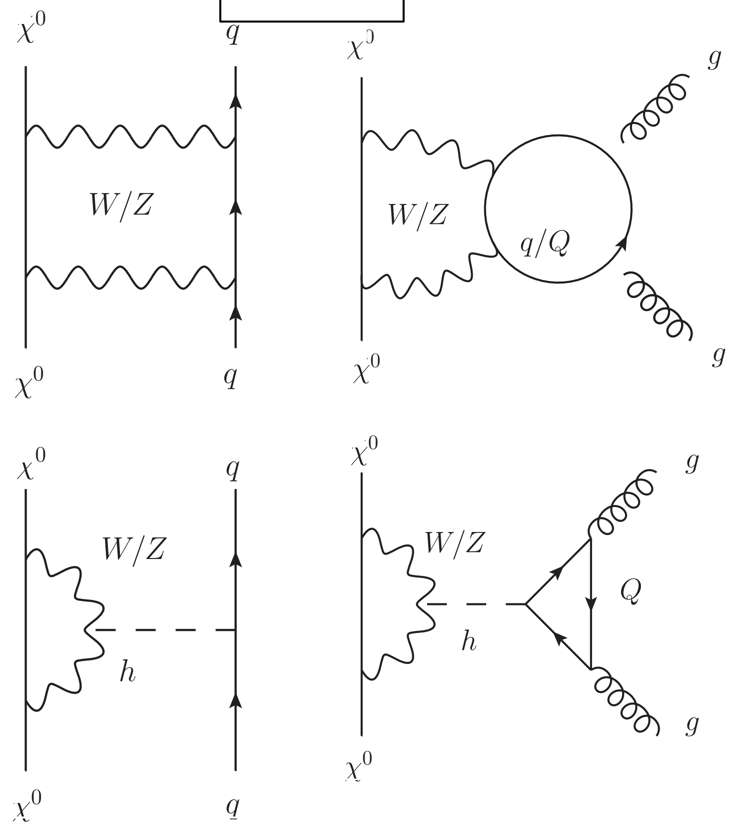



Subleading, but not suppressed by Gaugino-Higgsino mixing. The x section is suppressed by weak boson mass squared.

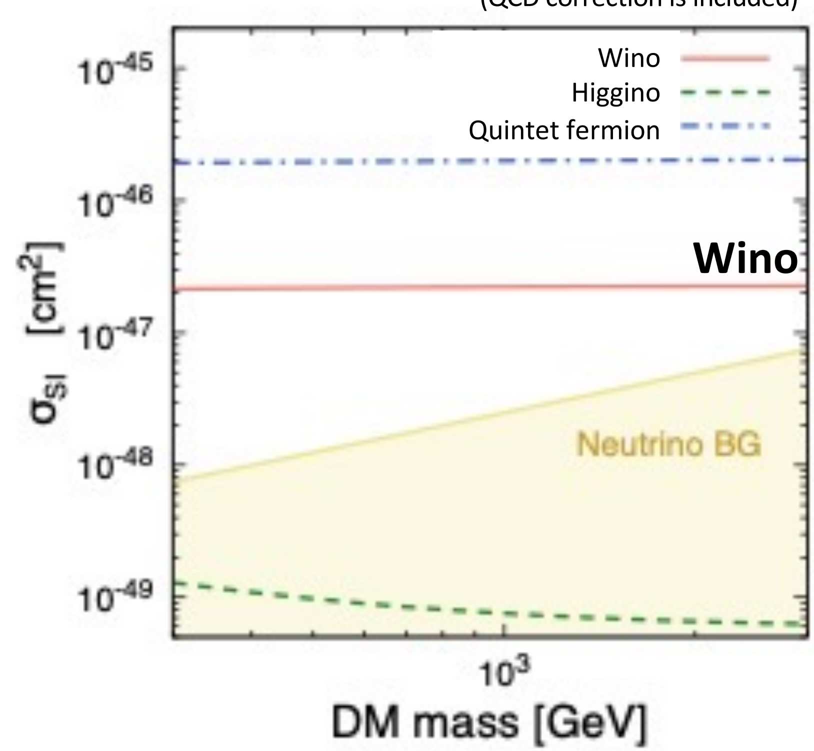
# Direct Detection of Wino

Spin-independent DM-nucleon elastic scattering

LOOP



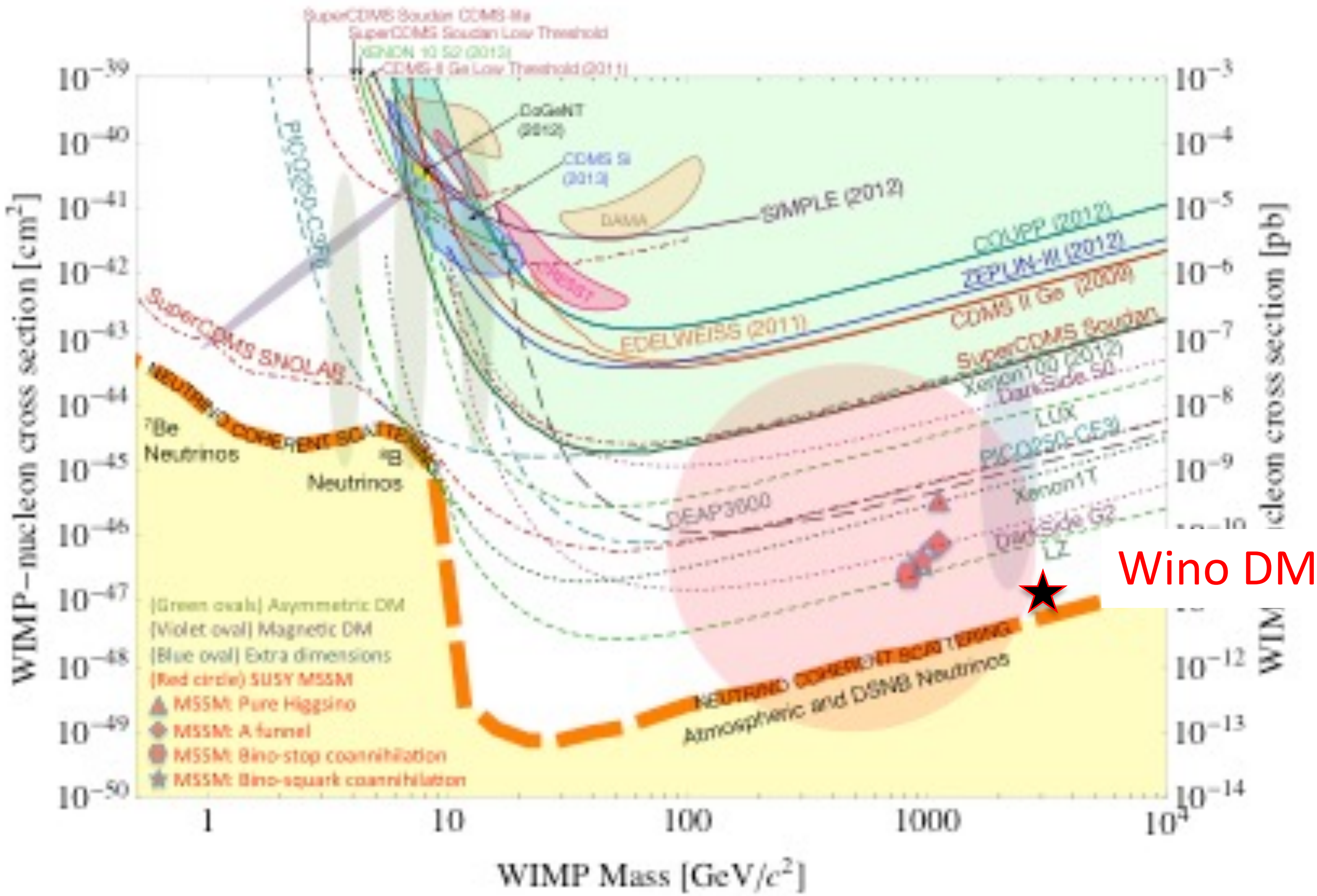

(QCD correction is included)




(JH, Ishiwata, Nagata (15))

X section of wino is above the neutrino BG, and wino DM can be tested.

# Future prospects




(From snowmass report)

# 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.
- Direct detection of wino dark matter. The spin-independent cross section is ~ $10^{-47}$ cm$^2$, which is not suppressed by wino mass itself.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ $10^{-30}$ ecm.

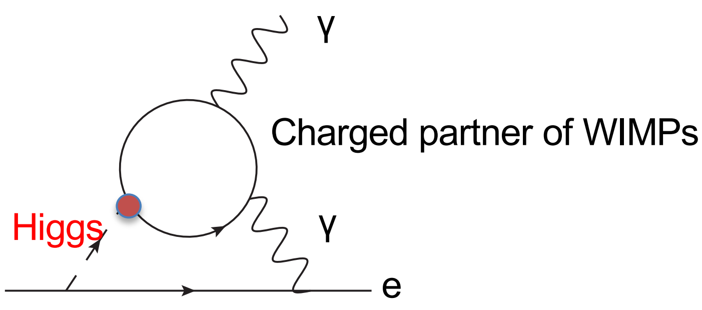
# Wino-contribution to electron EDM

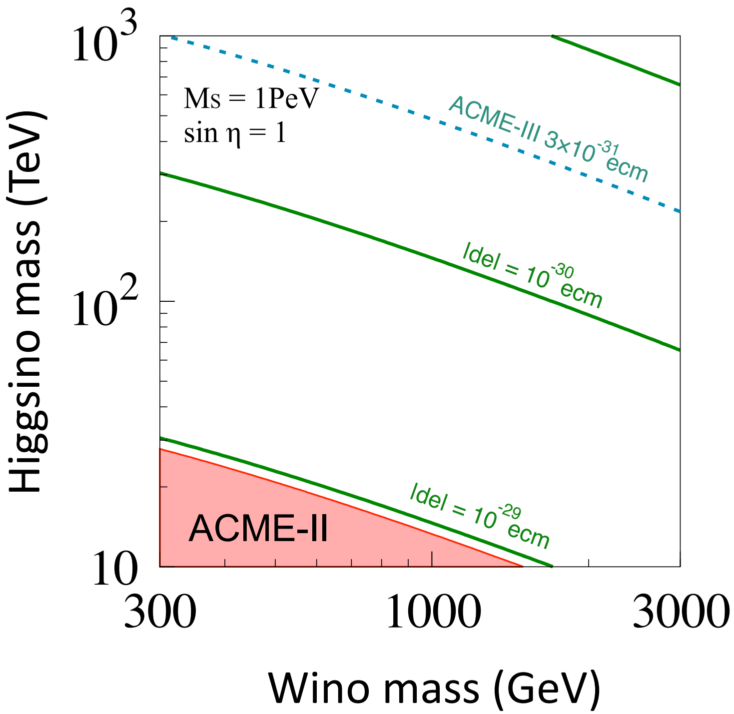
Integrating out Higgsinos gives

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

$\gamma_5$ interaction is CP violating.

Barr-Zee diagrams contribute to electron EDM.




(Kuramoto, Kuwahara, and Nagai (19))

Current bound on electron EDM:

$|d_e| < 1.1 \times 10^{-29}$ e cm (ACME-II, 17)

# Summary (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.
- Direct detection of wino dark matter. The spin-independent cross section is ~ $10^{-47}$ $cm^2$, which is not suppressed by wino mass itself.
- EDM induced by Barr-Zee diagrams. Even if Higgsino mass is 100TeV, electron EDM reach to ~ $10^{-30}$ ecm.

# Summary (A dream)

- At 202X, finite values for EDMs are discovered.

- At 202X, peak on gamma ray spectrum from galactic center are discovered around 3TeV at CTA.

- At 202X, DARWIN finds excess of counting rate, which is larger than neutrino BGs.

- At 20XX, wino is discovered at 100TeV pp collider.