How to discover SUSY

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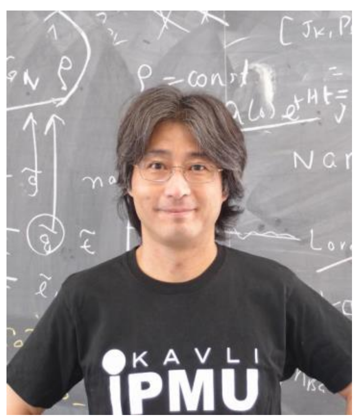
Congratulations on Hitoshi's 60th birthday!

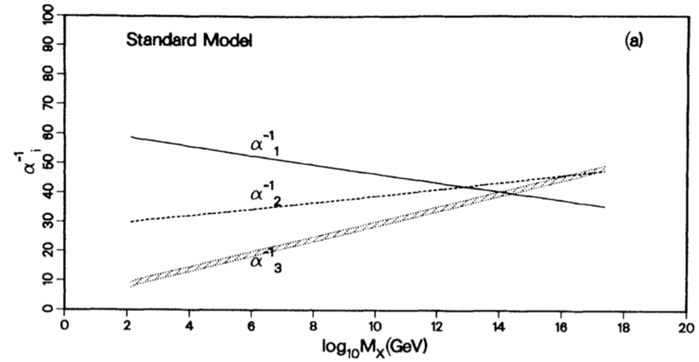
1991: Fortunate starting point of my life as a researcher

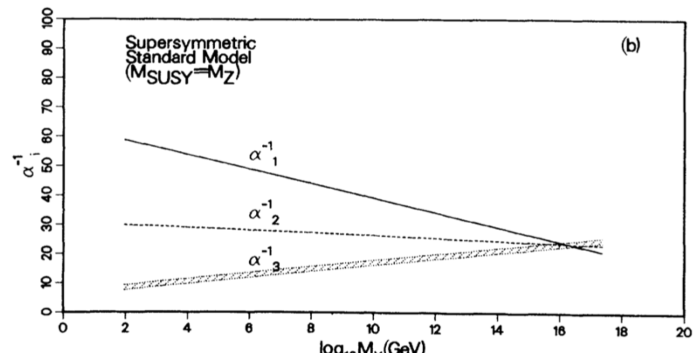
- Prof. Tsutomu Yanagida gave me a subject of master thesis

  “**Proton decay in SUSY GUTs**”

- Hitoshi moved to Tohoku Univ to become an AP.







(Langacker & Luo, 91)

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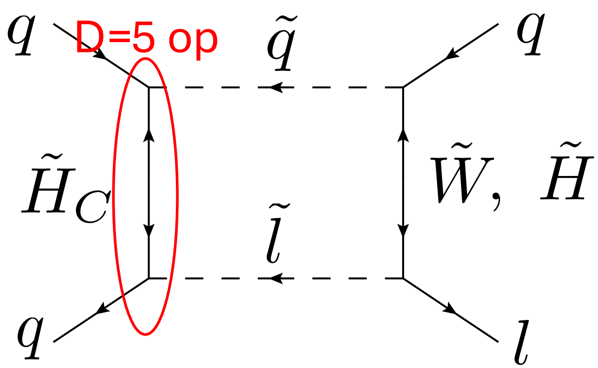
Proton decay is a serious problem in SUSY SU(5) GUT, since the colored Higgs, SU(5) partner of SM Higgs, induces D=5 baryon-number violating operators. (Sakai and Yanagida, Winberg, 82)



$$\tau_p \propto M_{H_C}^2 \times M_{SUSY}^2$$

In the minimal SUSY SU(5) GUT, the colored Higgs mass can be determined by the gauge coupling unification. (JH, Murayama, Yanagida, 92)

$$\left(3\alpha_2^{-1} - 2\alpha_3^{-1} - \alpha_1^{-1}\right)(m_Z) = \frac{1}{2\pi}\left(\frac{12}{5}\log\frac{M_{H_C}}{m_Z} - 2\log\frac{m_{\rm SUSY}}{m_Z}\right)$$

If the SUSY particles in SUSY SM is lighter than O(1) TeV, the minimal model is excluded by the superK experiments.

Before Higgs discovery

From my slide for presentation in YITP workshop of particle physics (2006)

Supersymmetric Standard Model (SUSY SM):

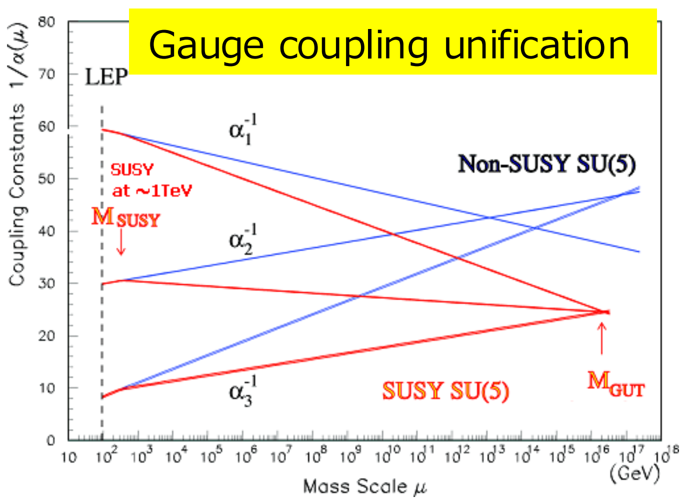
boson $\rightleftarrows$ fermion

SUSY SM is a prototype of BSM in 2000's.

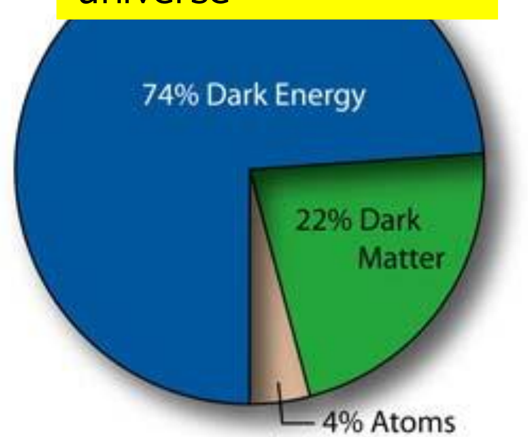
SUSY SM is a promising candidate of BSM nowadays.

- Hierarchy problem $(M_Z \ll M_{\rm Planck})$
- Gauge coupling unification $(M_{\rm GUT} \simeq 10^{16}{\rm GeV})$
- Dark matter $(\Omega_{\rm DM} \simeq 22\%)$
- Light Higgs boson $(m_{h^0} \lesssim 130-140{\rm GeV})$

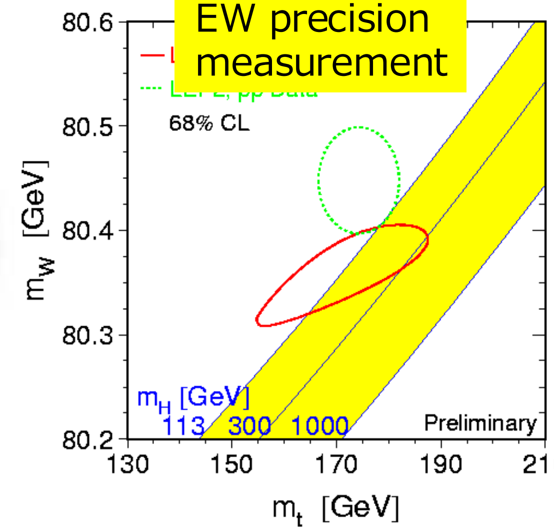
Gauge coupling unification



Composition of the universe



EW precision measurement

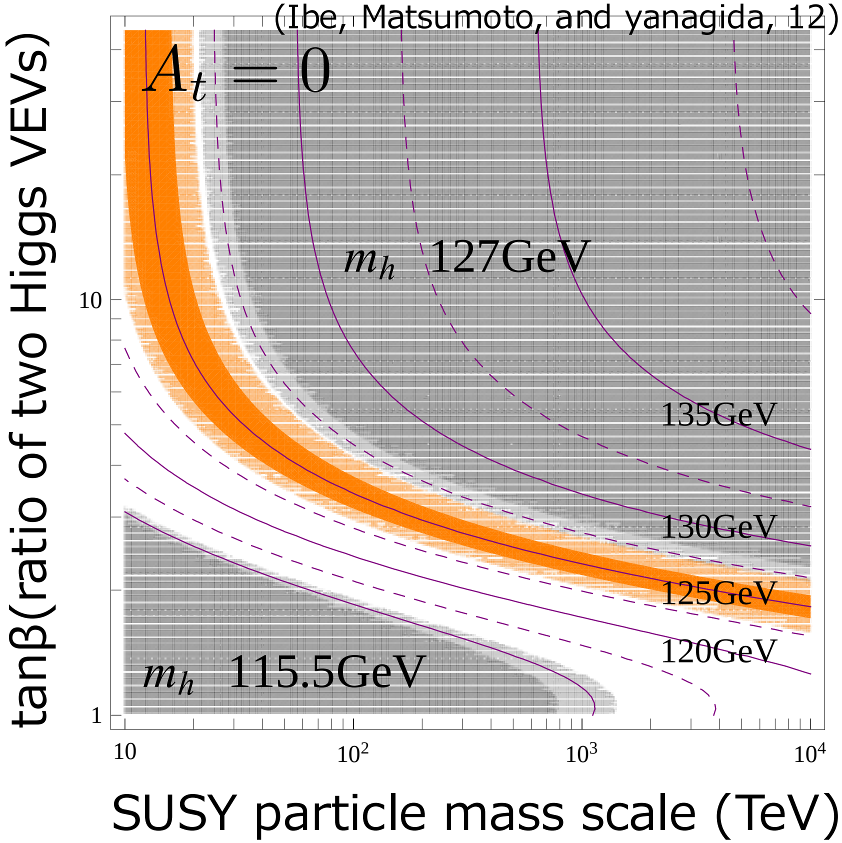


After Higgs discovery (125GeV)

The Higgs boson mass in the minimal SUSY SM

$$m_{h^0}^2 \lesssim \underbrace{m_Z^2 \cos^2\beta}_{\text{Tree level}} + \underbrace{\frac{3}{4\pi} y_t^2 m_t^2 \sin^2\beta \left(\boxed{\log \frac{m_{\tilde{t}}^2}{m_t^2}} + \boxed{\frac{X_t^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{X_t^4}{m_{\tilde{t}}^4}} \right)}_{\text{One-loop correction}}$$

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



SUSY SM

Energy scale

SUSY GUT
~ 10^{16} GeV

SUSY SM
< O(1) TeV

SM

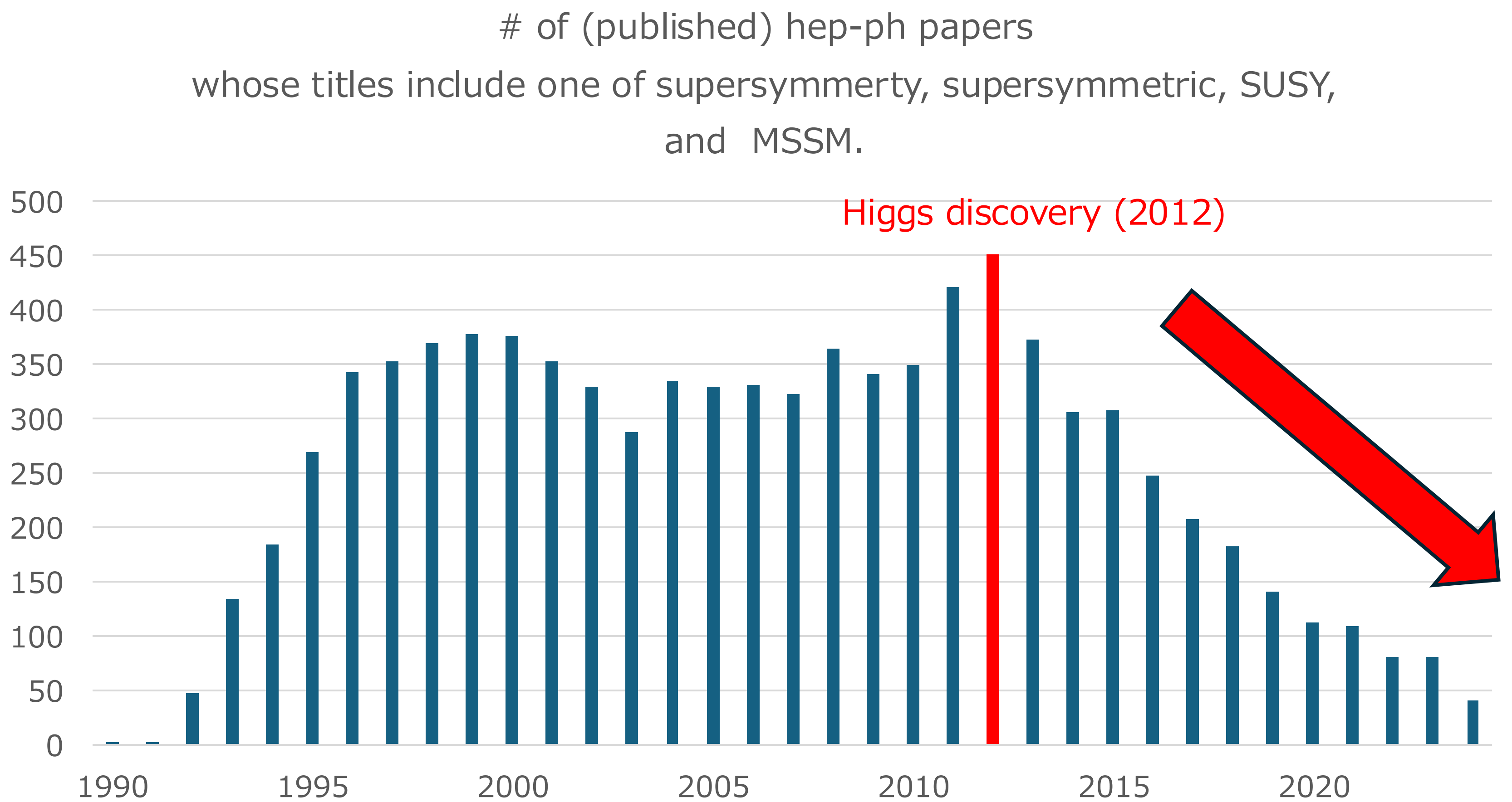
Motivation of low-energy SUSY（<~1TeV)

- Hierarchy problem（?）
- WIMP dark matter
- Gauge coupling unification

Shortcomings:

- FCNC・CP problem
- Gravitino problem
- Proton decay by D=5 operators
- 125GeV Higgs boson

Phenomenological studies of SUSY



Mini-split SUSY SM (Hall and Nomura, Ibe and Yanagida, 12)

エネルギースケール

SUSY GUT
$\sim 10^{16}$ GeV

SUSY SM
$O(10^{2\text{-}3})$ TeV

SM

Motivation of Mini-split SUSY ($O(10^{2\text{-}3})$ TeV)

- WIMP dark matter
- Gauge coupling unification
- Solved shortcomings of low-energy SUSY

  FCNC・CP problem
  Gravitino problem
  Proton decay by D=5 operators
  125GeV Higgs boson

Shortcoming

- Little Hierarchy problem

  (Anthropic principle？)

Mini-split SUSY SM

Scalar Particles Gravitino Higgsinos

$M_S = 10^{(2\text{-}3)}$ TeV

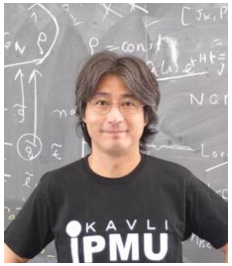
Gauginos (loop-factor suppression)

Gluino

Bino

Wino

Anomaly Mediation
(Randall and Sundrum
Giudice, Luty, Murayama,
and Rattazzi, 98)



If DM comes from thermal process
in early hot universe, (2.7-3)TeV

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

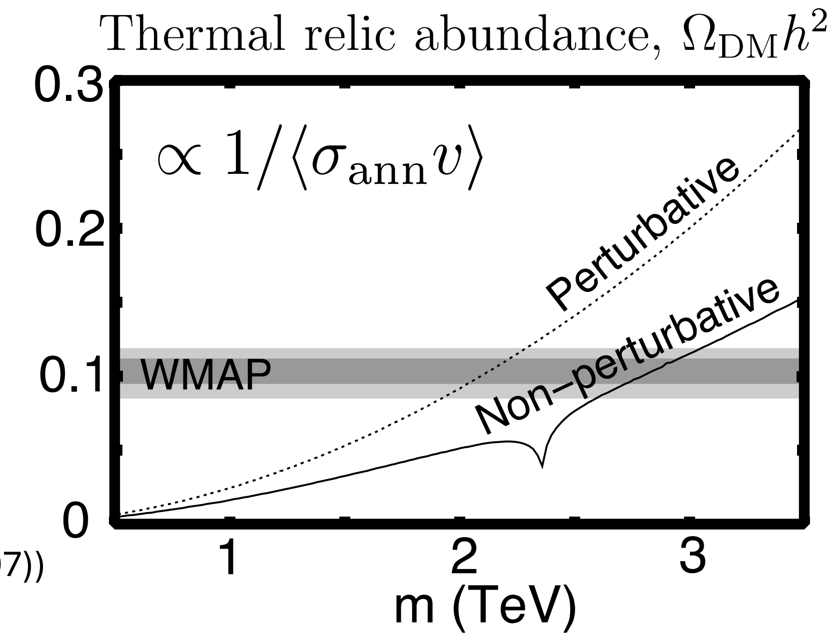
Wino dark matter

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,

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

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



Non-Thermal Wino dark matter

Gravitino decay provides additional wino DM comp.

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

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

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

How to find the signature of Mini-split SUSY

Strategy to discover Mini-split 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 may reach to ~ 10^{-31} ecm.

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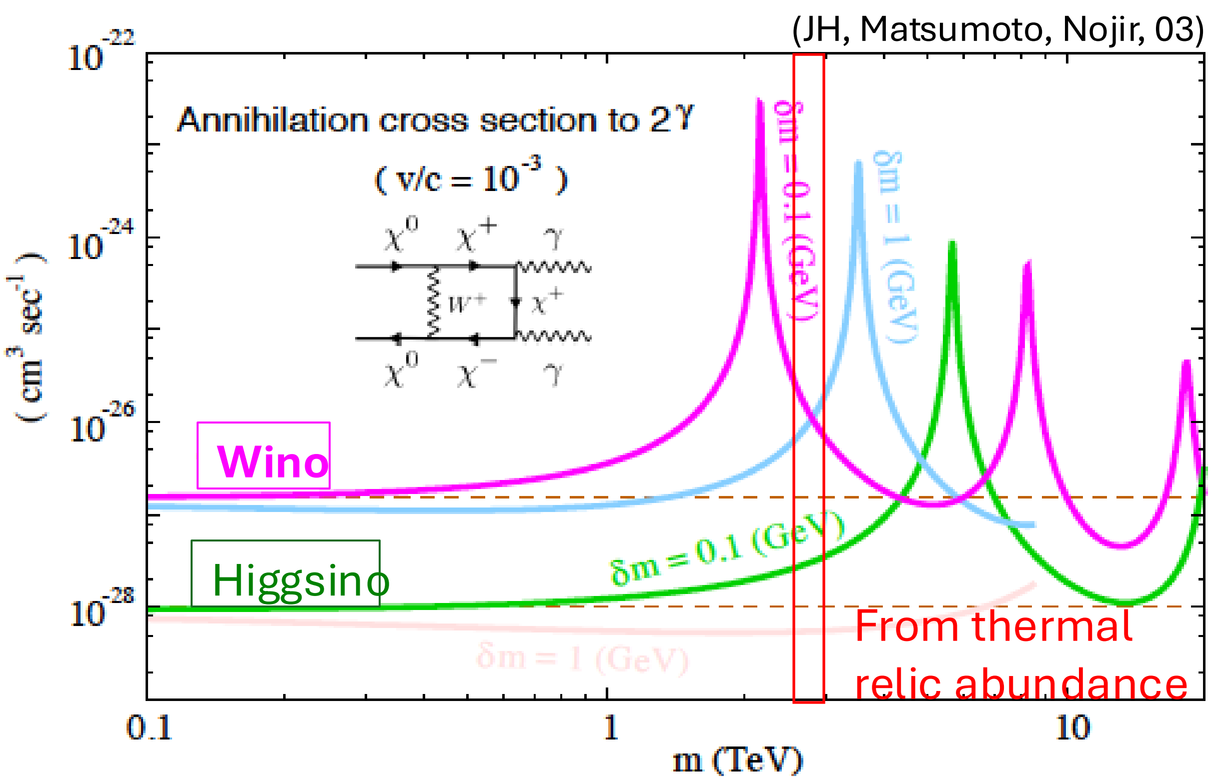
Sommerfeld enhancement of wino pair annihilation to 2 line gammas

WIMP pair annihilation to line gammas in the universe may be a smoking-gun of the dark matter.
While the perturbative contribution is suppressed due to the one-loop process, the cross section of wino at NR limit is enhanced by the Sommerfeld mechanism when $m_{\rm wino} \gg m_W$.

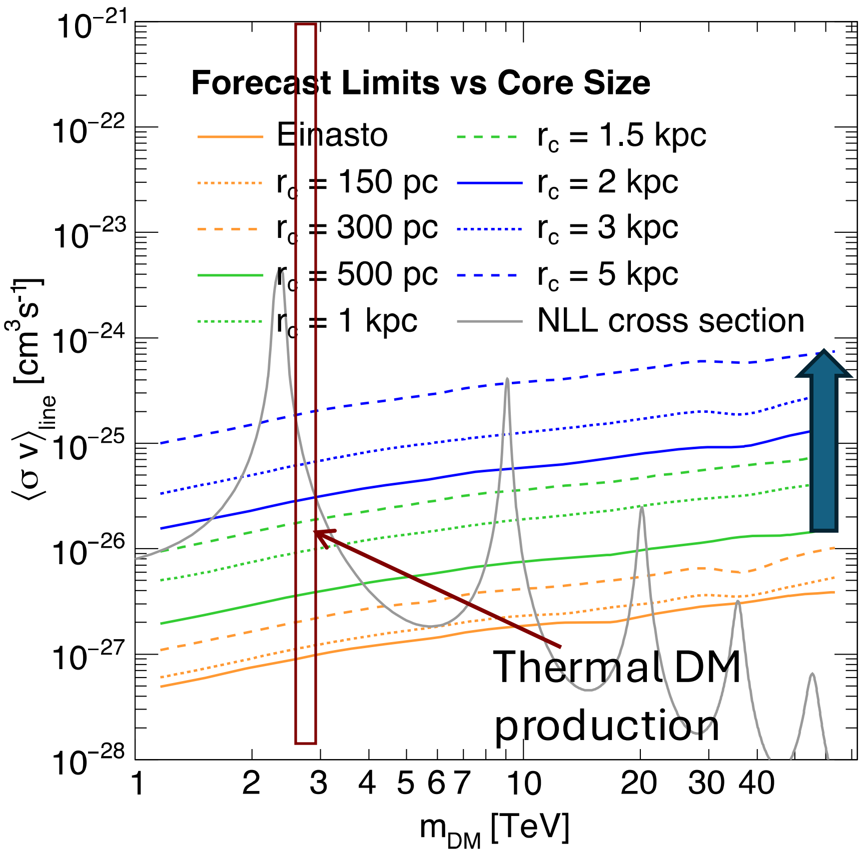


Line gamma rays from Galactic Center (GC)

HESS and Magic give constraints on line gamma rays from GC.

The constraint depends on DM density profile (ρ) at GC since the flux is proportional to ρ^2.

Sensitivities will be improved at CTA in future.



Core size in DM profile Is larger

(Figure from Rinchiuso et al, 20)

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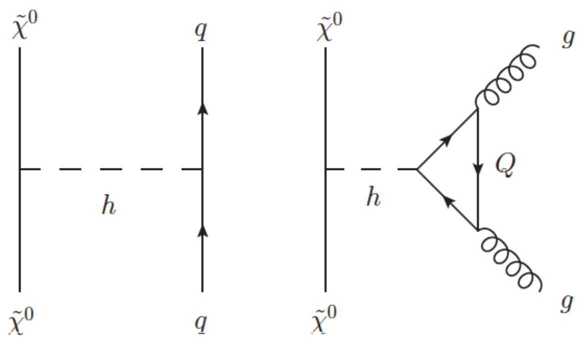
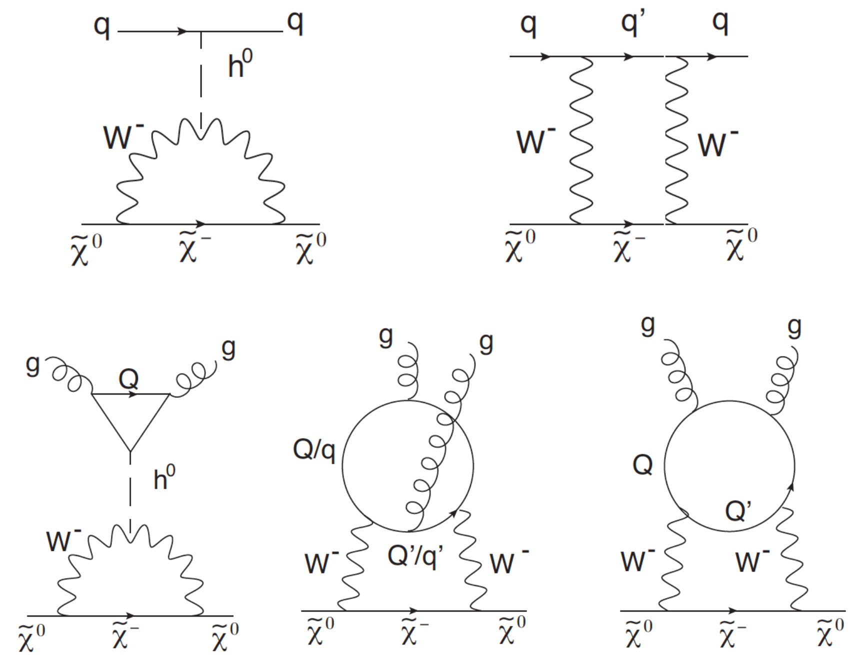
Wino-nucleon SI scattering





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

LO contribution is suppressed by wino-Higgsino mixing.
NLO contribution is not suppressed by wino-Higgsino mixing, and also by wino mass. When Higgsino mass is much heavier than wino one, NLO contribution dominates over LO one. (JH, Matsumoto, Nojiri, Saito, 04)

Current status of DM search

Wino-nucleon SI cross section in a limit of $m_{\rm wino} \gg m_W$

$$\sigma^p_{\rm SI} = 2.3\,^{+0.2}_{-0.3}\,^{+0.5}_{-0.4} \to 10^{-47}\ {\rm cm}^2$$

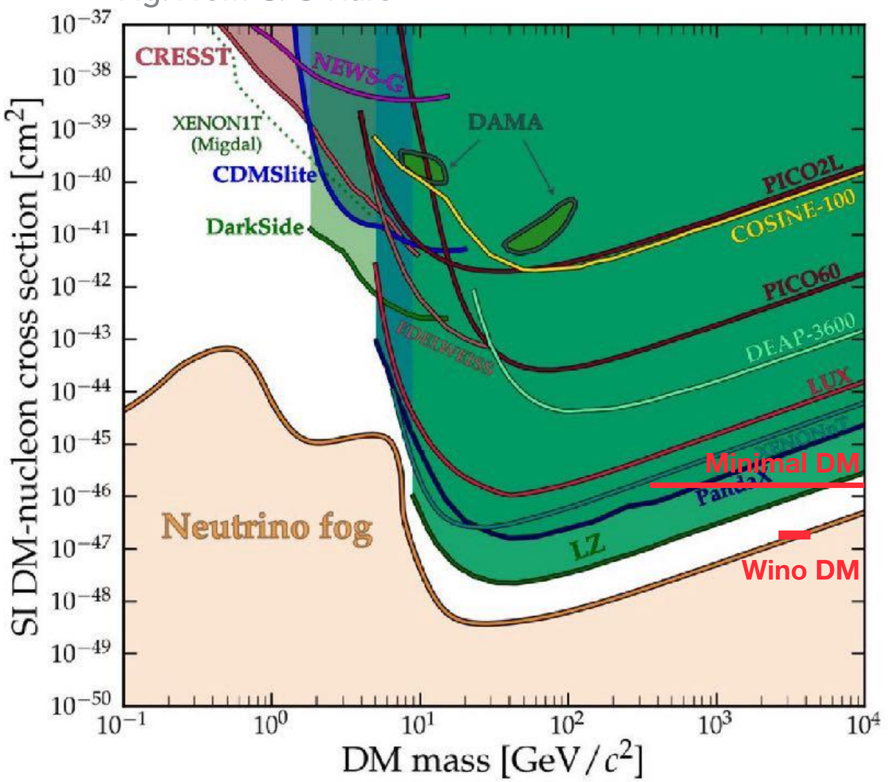
(JH, Ishiwata and Nagata, 15)

Dominant NLO QCD corrections are included.

The latest result of LZ experiment pushed down the upperbound on the cross section, which is close to the Neutrino Fog (irreducible background from neutrinos).

The next generation experiment, such as Darwin/XLZD, will reach to the prediction of the wino DM.

Fig. From C. O'Hare



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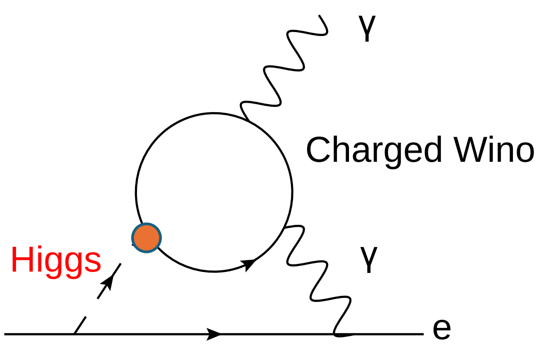
Wino-contribution to electron EDM

Integrating out Higgsino gives

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

γ_5 interaction is CP violating.

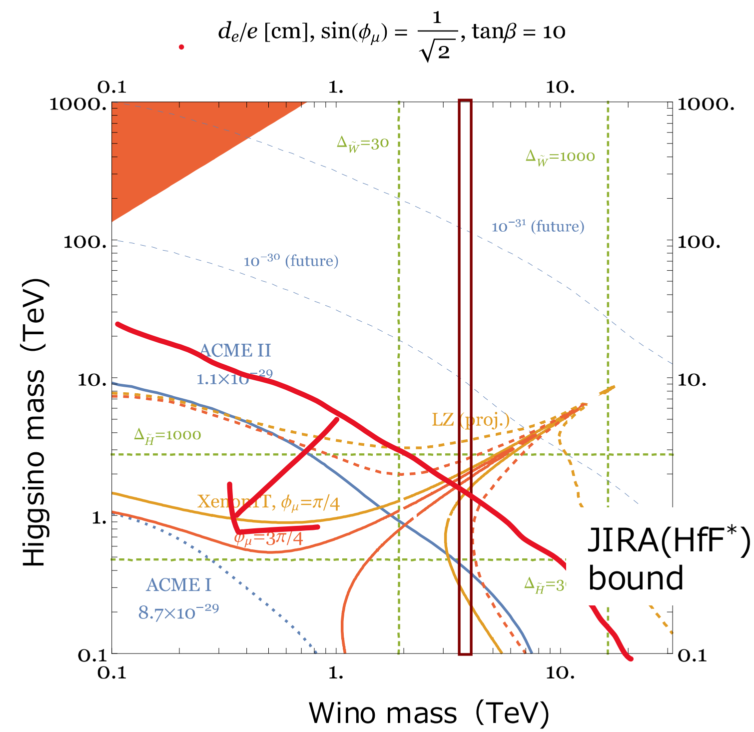
Barr-Zee diagrams contribute to electron EDM.



Current bound on electron EDM:

$|d_e| < 4.1 \times 10^{-30}$ e cm

(JIRA HfF⁺ experiment, 23)



(Figure from Nakai et al, 16)

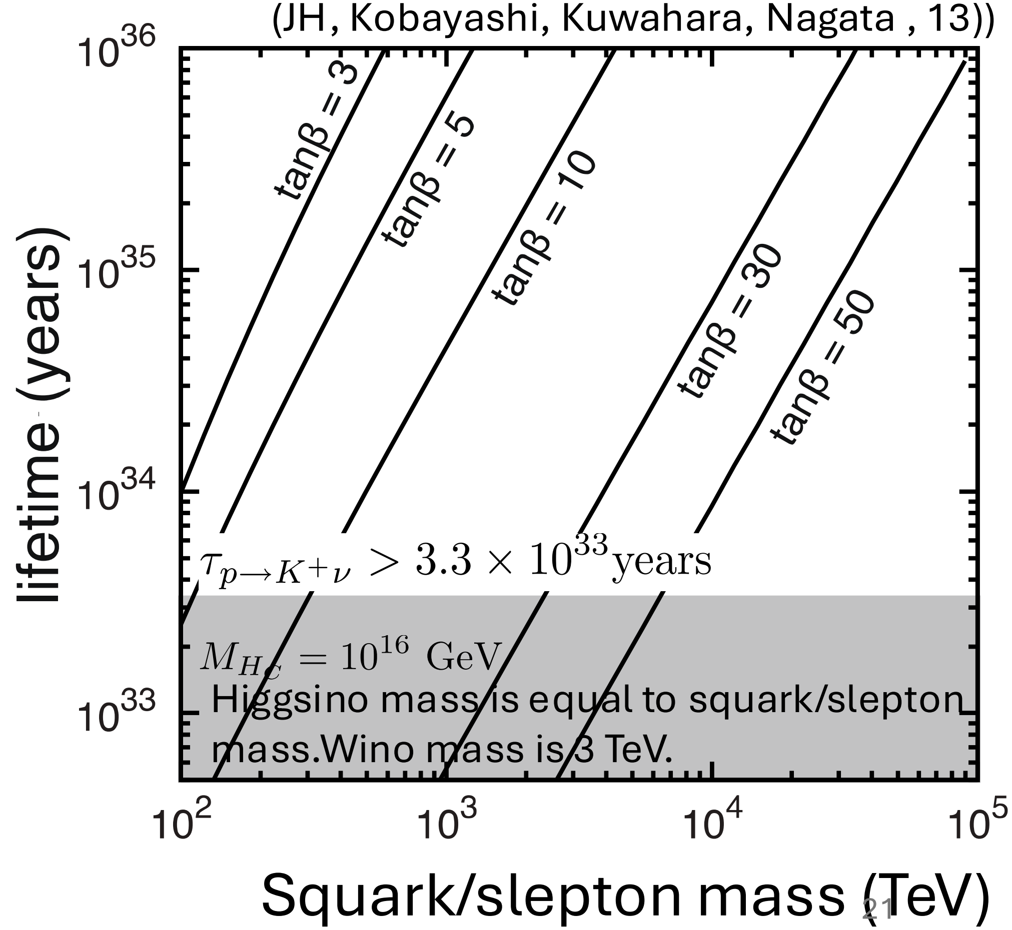
Colored Higgs proton decay (Again)

$$\tau_p \simeq 2 \times 10^{35}\text{year} \times \sin^4 2\beta \left(\frac{M_{H_C}}{10^{16}\text{GeV}}\right)^2 \left(\frac{m_{\text{SUSY}}}{100\text{TeV}}\right)^2$$

Colored Higgs proton decay escapes from experimental bound, and the minimal SUSY SU(5) GUT is still viable without introducing any mechanism.

Future experiments, such as HyperKamiokande, may be accessible to it, while it depends on parameters.

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



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- SUSY SM is still a phenomenologically successful model if assuming the SUSY breaking scale is $10^{2\text{-}3}$ TeV and anomaly mediation.

- It can be tested in near future.

Stay tuned!