Dark Matter Theory

Current status of WIMP DM

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Revealing the history of the universe with underground particle and nuclear research 2019

Target of the talk

Tons of DM candidates have been proposed so far…

e.g.)

- WIMPs
- Axion → Talks by Andreas & Kawasaki-san
- Asymmetric DM → Talk by Ibe-san
- SIMPs, FIMPs
- etc…

Target of the talk

Tons of DM candidates have been proposed so far…

e.g.)

- WIMPs
- Axion
- Asymmetric DM
- SIMPs, FIMPs
- etc…

Let me focus on WIMP DM in this talk.

WIMP

Weakly-Interacting Massive Particles (WIMPs)

- Electrically neutral and colorless particles.
- Stable.
- Masses of order Electroweak (EW) scale.
- Have interactions comparable to EW interactions.

→ Observed Dark Matter (DM) density can be explained by their thermal relic.

TeV-scale physics and WIMP

DM thermal relic abundance

$$\Omega_{\rm DM}h^2 \simeq \frac{3\times 10^{-27}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma_{\rm ann}v_{\rm rel}\rangle}$$

$$\Omega_{\rm DM}h^2 = 0.12 \quad \Rightarrow \quad \langle\sigma_{\rm ann}v_{\rm rel}\rangle \simeq 10^{-9}\ {\rm GeV}^{-2}$$

e.g.)

$$\langle\sigma_{\rm ann}v_{\rm rel}\rangle \simeq \frac{\alpha^2}{m_{\rm DM}^2} \qquad \alpha \simeq 0.01, \quad m_{\rm DM} \simeq 300\ {\rm GeV}$$

WIMP DM predicted new physics at the TeV scale.

WIMPs often appear in models motivated by naturalness.

Expected to be tested in various experiments (such as LHC).

Goal of the talk

- DM candidates in TeV-scale new physics models have been severely constrained.

Target has been narrowed down.

- On the other hand, the WIMP paradigm itself has not been fully tested yet.

Further exploration is needed.

Outline

- Viable WIMP DM candidates in SUSY
- Current status of WIMP DM
- Summary

DM in SUSY models

Supersymmetry (SUSY)

The LHC results, *i.e.*,

- Bound on SUSY particles
- 125 GeV Higgs mass

➡ SUSY particles are heavier than expected.

Restrict WIMP DM candidates in (simple) SUSY models.

Two simple setups

- Constrained MSSM
- High-scale SUSY

Constrained MSSM (CMSSM)

Constrained MSSM (CMSSM)

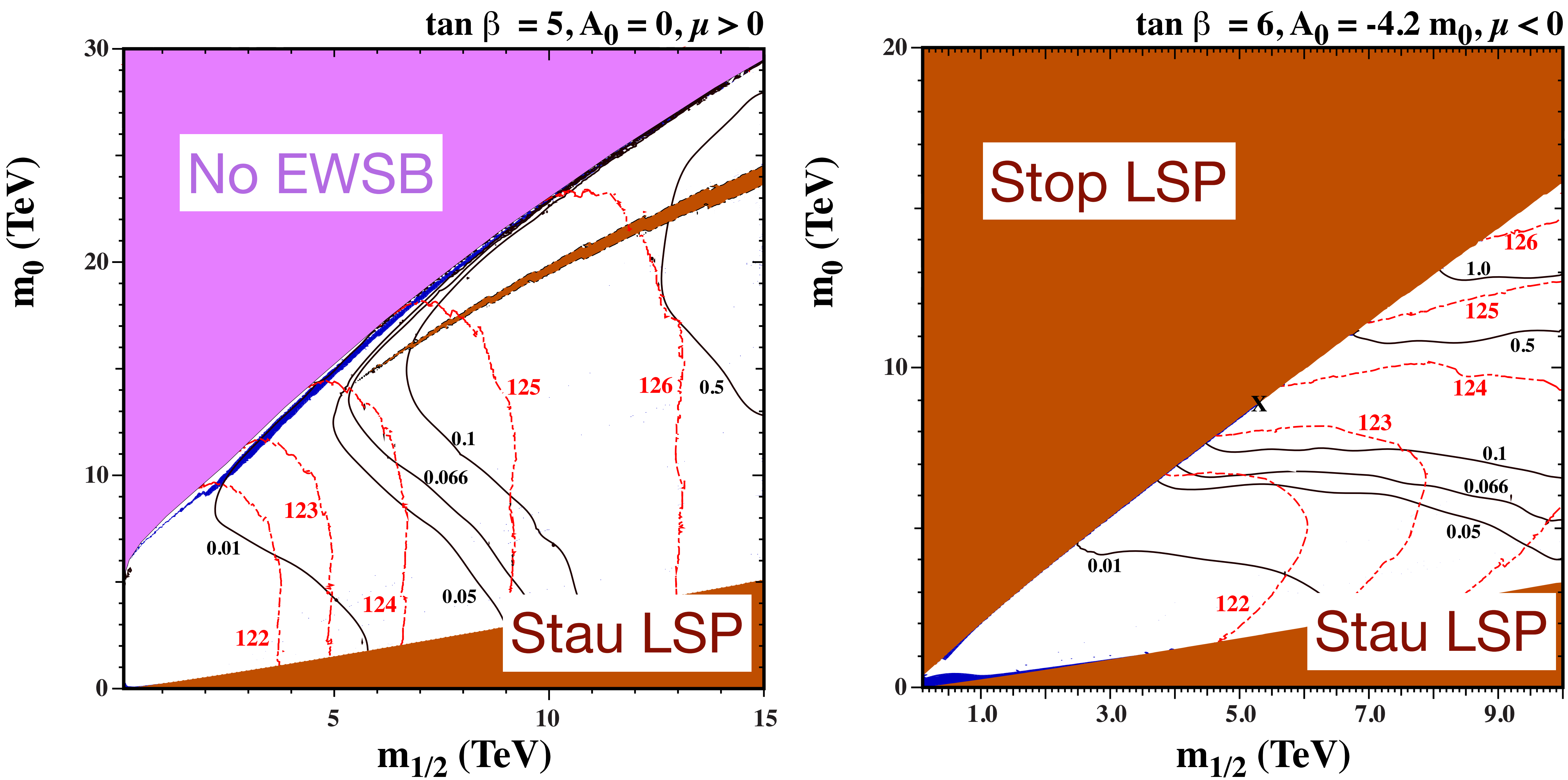
- Traditional benchmark model
- Impose universality conditions at the GUT scale.

Input parameters

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sign}(\mu)$$

Soft parameters at low energies are obtained by using renormalization group equations.

DM in CMSSM



$\Omega_{DM} h^2 = 0.12$ Higgs mass [GeV] Proton lifetime [10^{35} yrs]

Higgsino-like DM (~1 TeV)

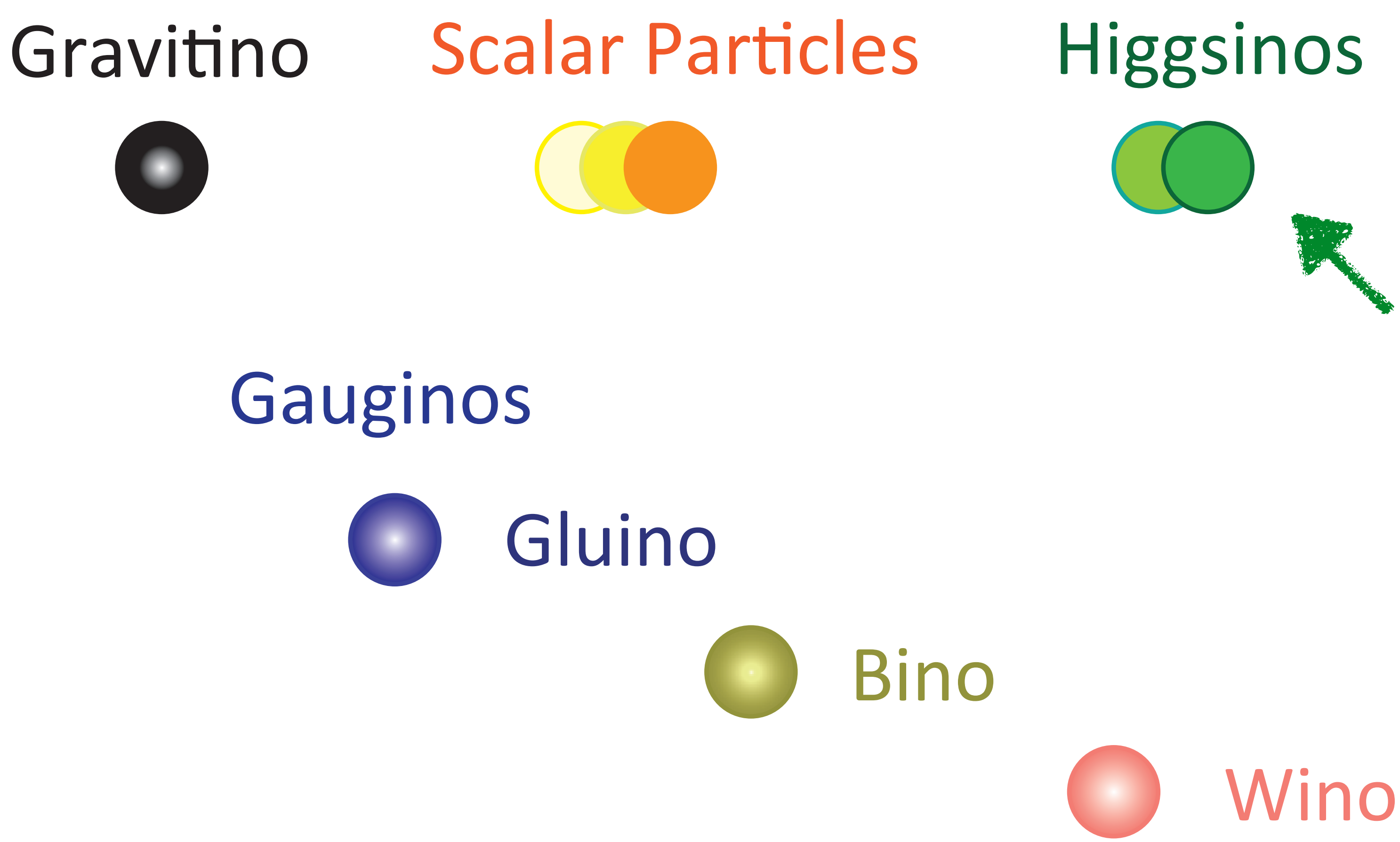
Bino DM (stop/stau coannihilation)

J. Ellis, J. L. Evans, A. Mustafayev, N. Nagata, K. A. Olive, Eur. Phys. J. **C76**, 592 (2016).

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
M. Ibe, S. Matsumoto, T. T. Yanagida (2012)
A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro (2012)
N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski (2012)

Suppose that the SUSY-breaking field is not a singlet:



Higgsinos can be light if there is an additional symmetry.

Gaugino masses are induced at loop level.

e.g.) Anomaly mediation

L. Randall and R. Sundrum (1998)
G. F. Giudice, M. A. Luty, H. Murayama, and R. Rattazzi (1998)

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
M. Ibe, S. Matsumoto, T. T. Yanagida (2012)
A. Arvanitaki, N. Craig, S. Dimopoulos, G. Villadoro (2012)
N. Arkani-Hamed, A. Gupta, D. E. Kaplan, N. Weiner, and T. Zorawski (2012)

Suppose that the SUSY-breaking field is not a singlet:

Gravitino

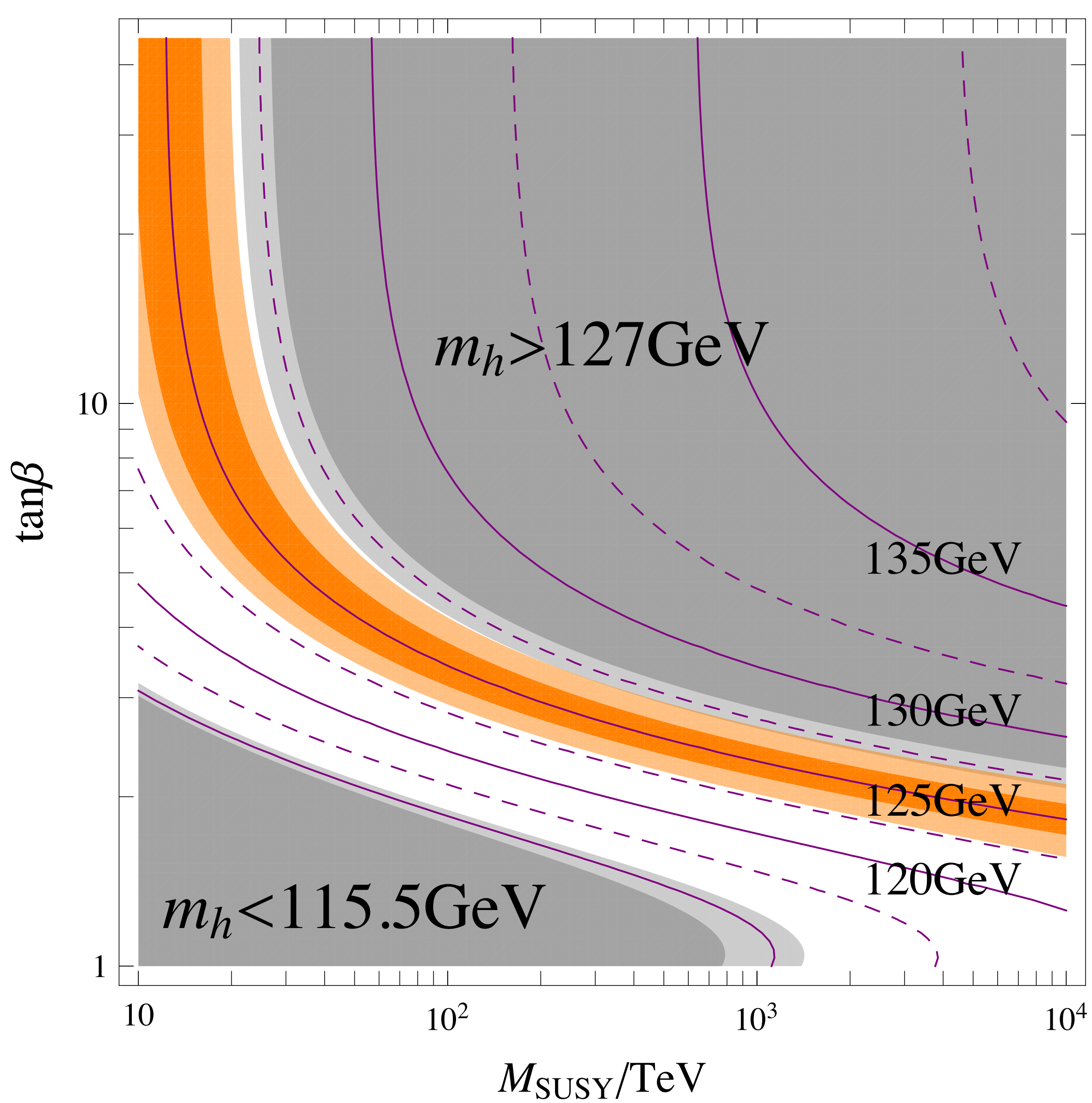
Scalar Particles

Higgsinos

$O(10^{(2\text{-}5)})$ TeV

O(1) TeV

Wino



$$m_h = 125 \text{ GeV}$$

High SUSY-breaking scale.

M. Ibe, S. Matsumoto, T. T. Yanagida (2012).

High-scale SUSY

L. J. Hall, Y. Nomura, S. Shirai (2012)
M. Ibe, S. Matsumoto, T. T. Yanagida (2012)
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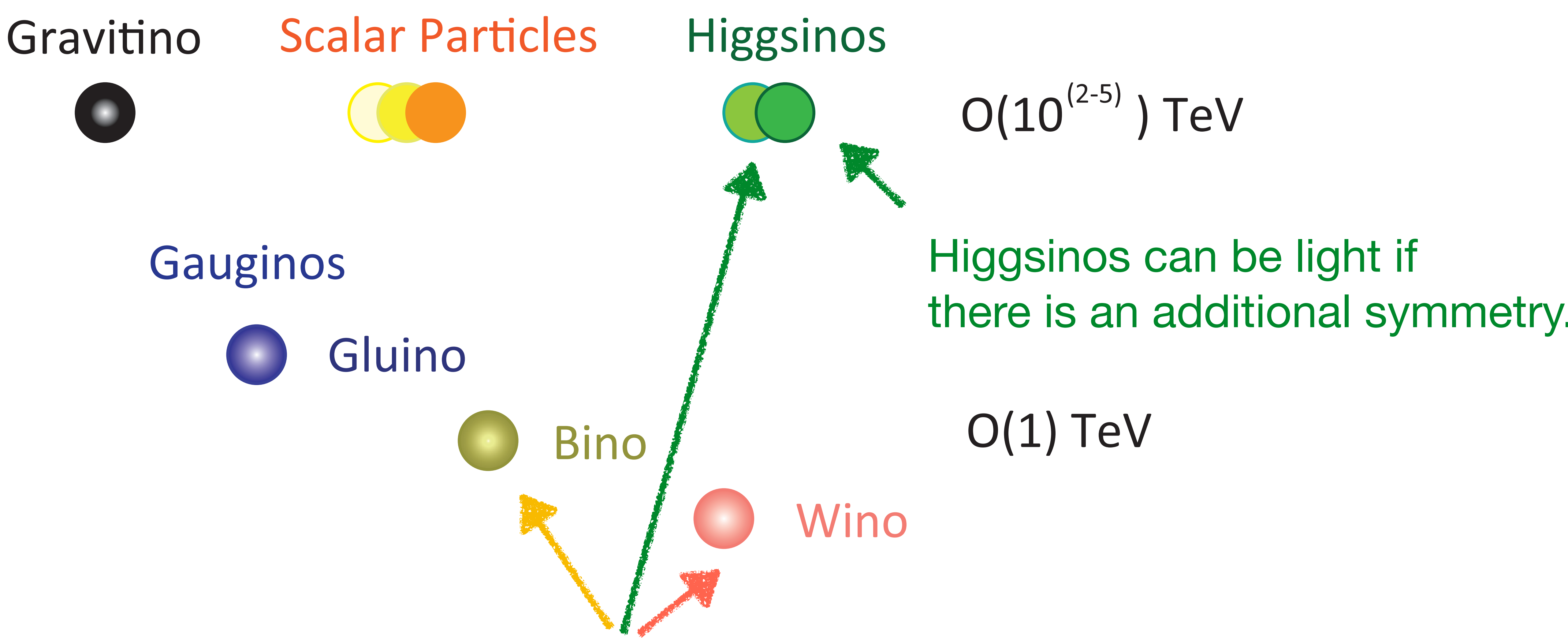


Dark matter candidates in this setup.

DM candidates in High-scale SUSY

WIMP DM candidates

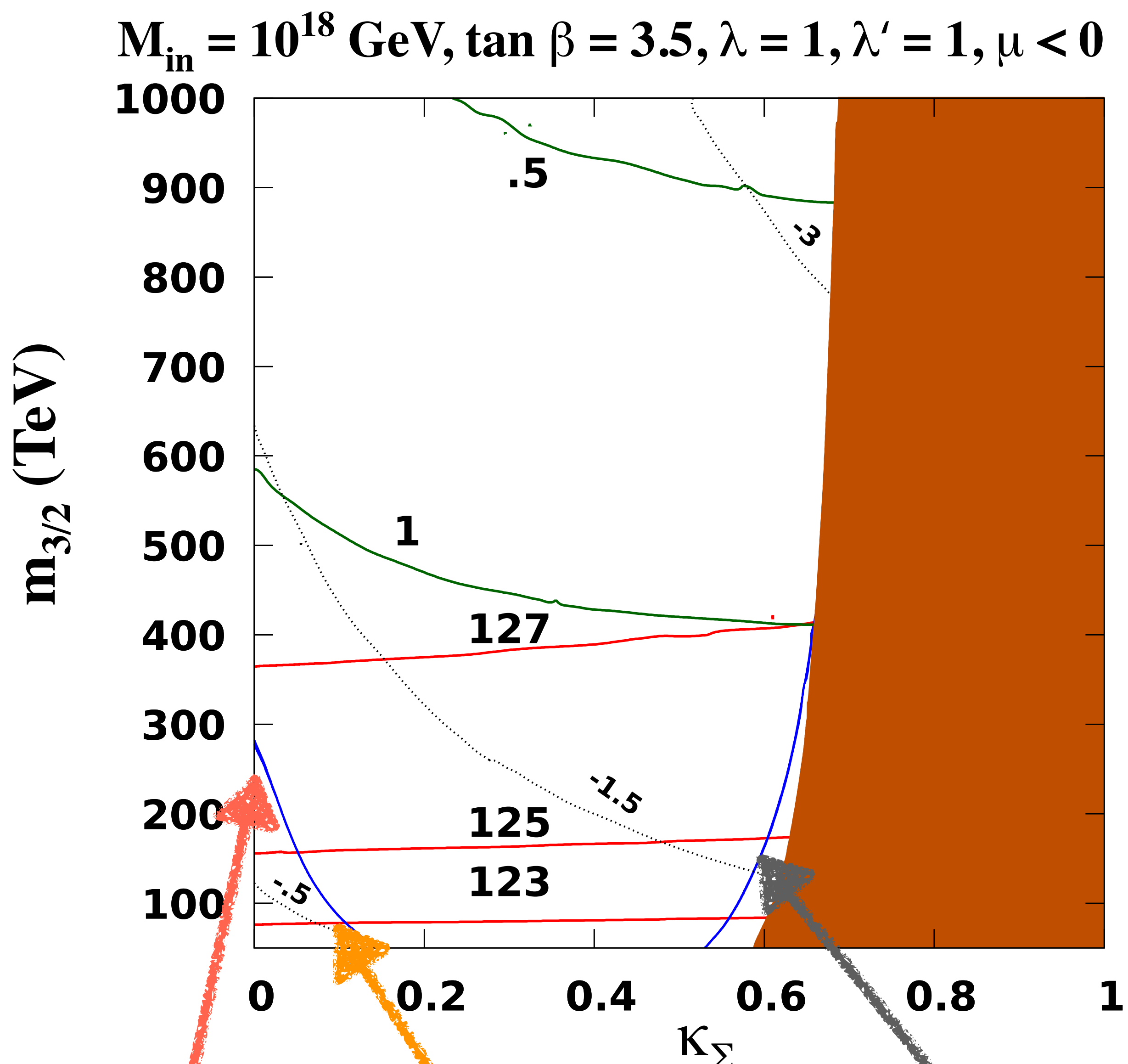
- Wino [3 TeV; anomaly mediation]
- Higgsino [1 TeV]
- Bino [with coannihilation; bino-wino/bino-gluino]

Which of them can actually be realized?

→ Depends on UV physics.

An example

Parameter space in SU(5) SuperGUT PGM.



Gaugino mass contribution

Anomaly mediation

+ GUT threshold corrections.

with $$\frac{\kappa_\Sigma}{\sqrt{3}M_P}(Z+Z^*)|\Sigma|^2$$

Bino-gluino coannihilation

Wino DM Bino-wino coannihilation

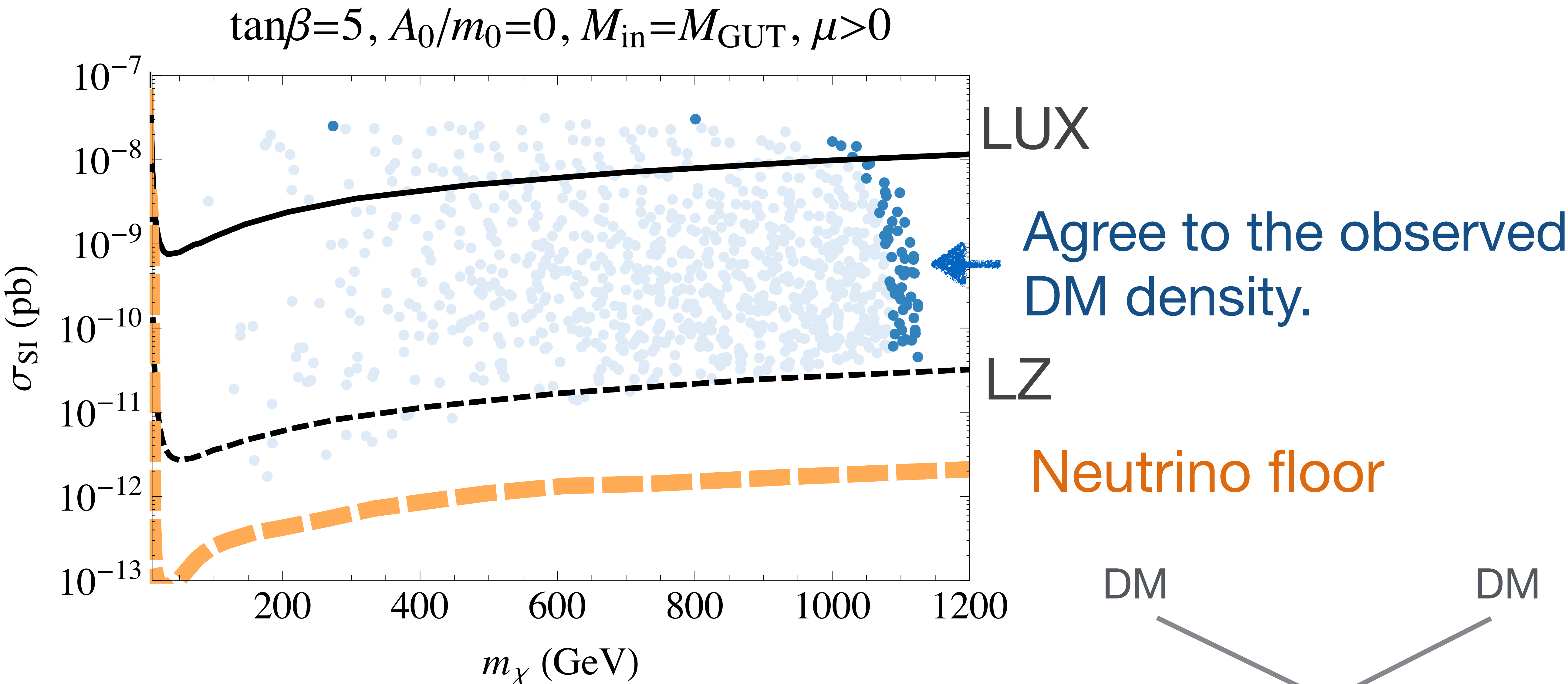
J. L. Evans, N. Nagata, K. A. Olive, 1902.09084.

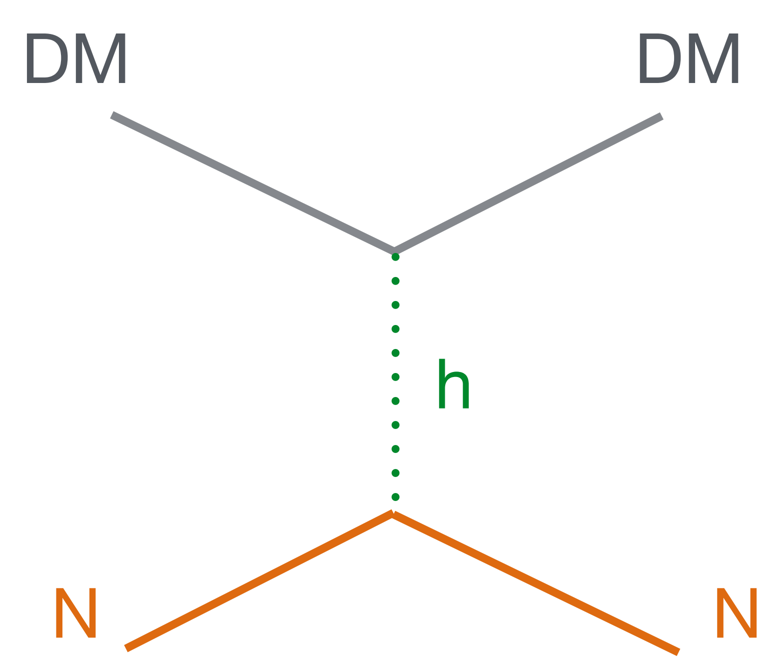
Summary of DM in SUSY models

- CMSSM etc.
  - Higgsino-like DM [~1 TeV]
  - Bino-stop/stau coannihilation
- High-scale SUSY
  - Wino [3 TeV]
  - Higgsino [1 TeV]
  - Bino-gluino/wino coannihilation

How can we probe these scenarios??

Higgsino-like LSP in CMSSM





Can be probed in future direct detection experiments

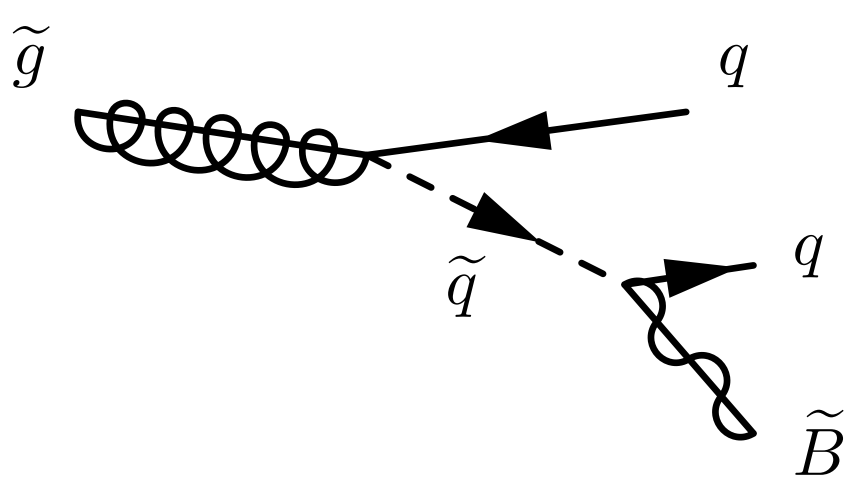
J. Ellis, J. L. Evans, F. Luo, N. Nagata, K. A. Olive, P. Sandick, Eur. Phys. J. **C76**, 8 (2016).

Bino-gluino/bino-wino coannihilation

Coannihilation requires NLSP to be degenerate with LSP in mass.

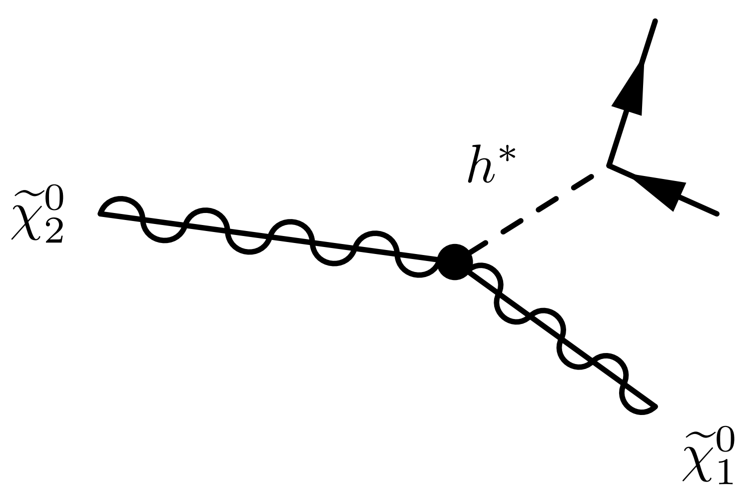
➡ Small mass difference makes NLSP long-lived.

<u>Bino-gluino</u>



- Δm = O(100) GeV
- cτ = O(1) cm

<u>Bino-wino</u>



- Δm = O(10) GeV
- cτ = 1 cm — 1m

Can be probed in displaced vertex and/or dE/dx searches.

N. Nagata, H. Otono, S. Shirai, Phys. Lett. **B748**, 24 (2015); JHEP **1510**, 086 (2015).

Summary of DM in SUSY models

- CMSSM etc.
  - Higgsino-like DM [~1 TeV] — Direct detection
  - Bino-stop/stau coannihilation — ??
- High-scale SUSY
  - Wino [3 TeV]
  - Higgsino [1 TeV]
  - Bino-gluino/wino coannihilation

To be discussed

Long-lived particle searches

Current status of WIMP DM

Quantum numbers of DM

DM should be electrically neutral and colorless.

→ There still remain many possibilities.

- Spin?
  - Real/complex scalar
  - Majorana/Dirac fermion
  - Vector

  etc.

- $SU(2)_L \times U(1)_Y$ charge?

  (1, 0), (2, ±1/2), (3, 0), (3, ±1), (4, ±1/2), …

$$Q = T_3 + Y = 0$$

Quantum numbers of DM

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  etc.

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Singlet scalar DM

Singlet scalar DM

V. Silveira and A. Zee (1985);
J. McDonald (1994);
C. P. Burgess, M. Pospelov, and T. ter Veldhuis (2001).

Just add a neutral scalar field to the Standard Model.

Lagrangian

$$\mathcal{L}_{\rm int} = -\frac{1}{2}m^2 S^2 - \frac{1}{2}\lambda_{SH} S^2 |H|^2 - \frac{1}{4!}\lambda_S S^4$$

- **Stability**

  Lagrangian has a Z_2 symmetry: S → - S (odd); SM (even).

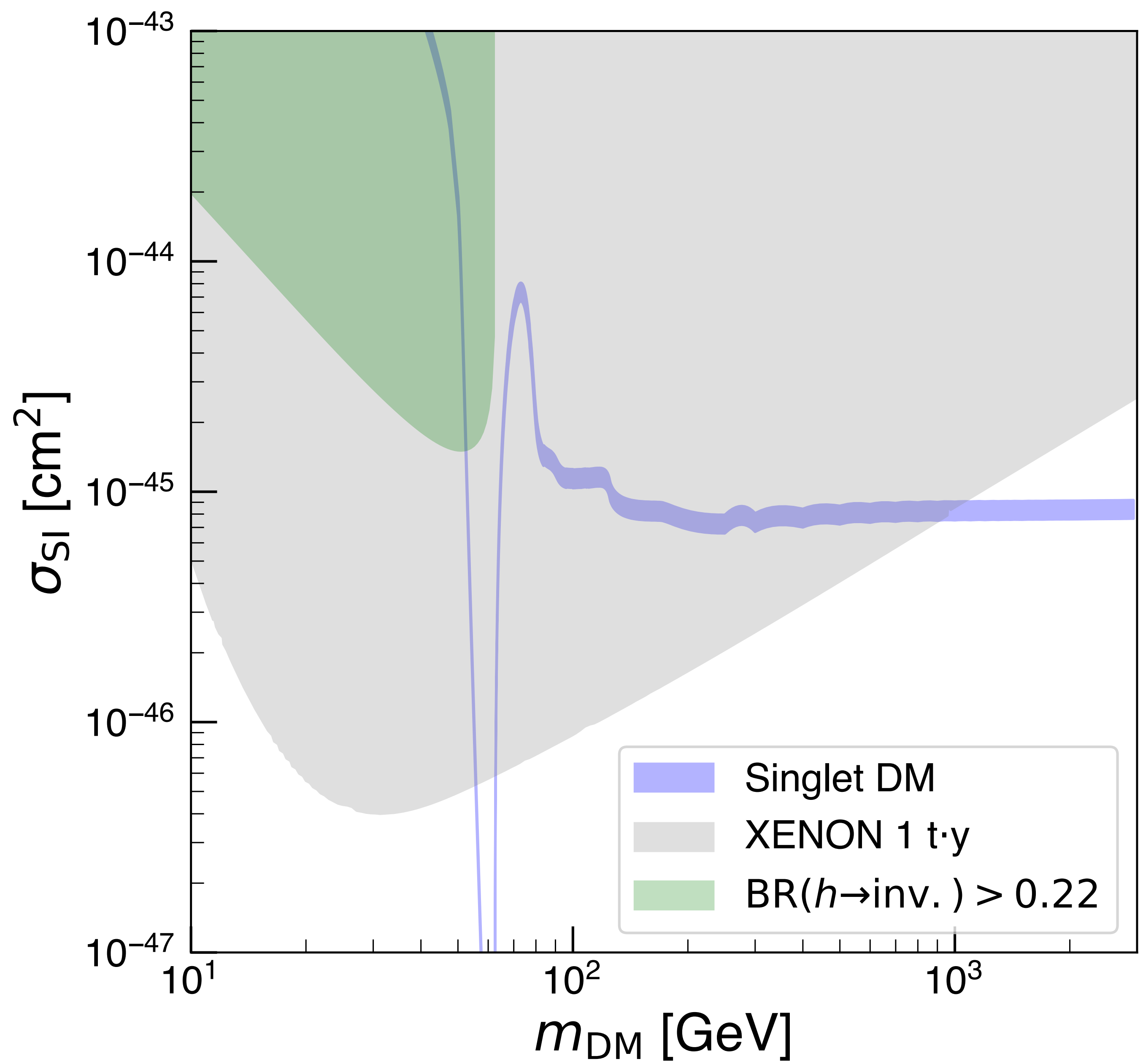
- **Relic abundance**

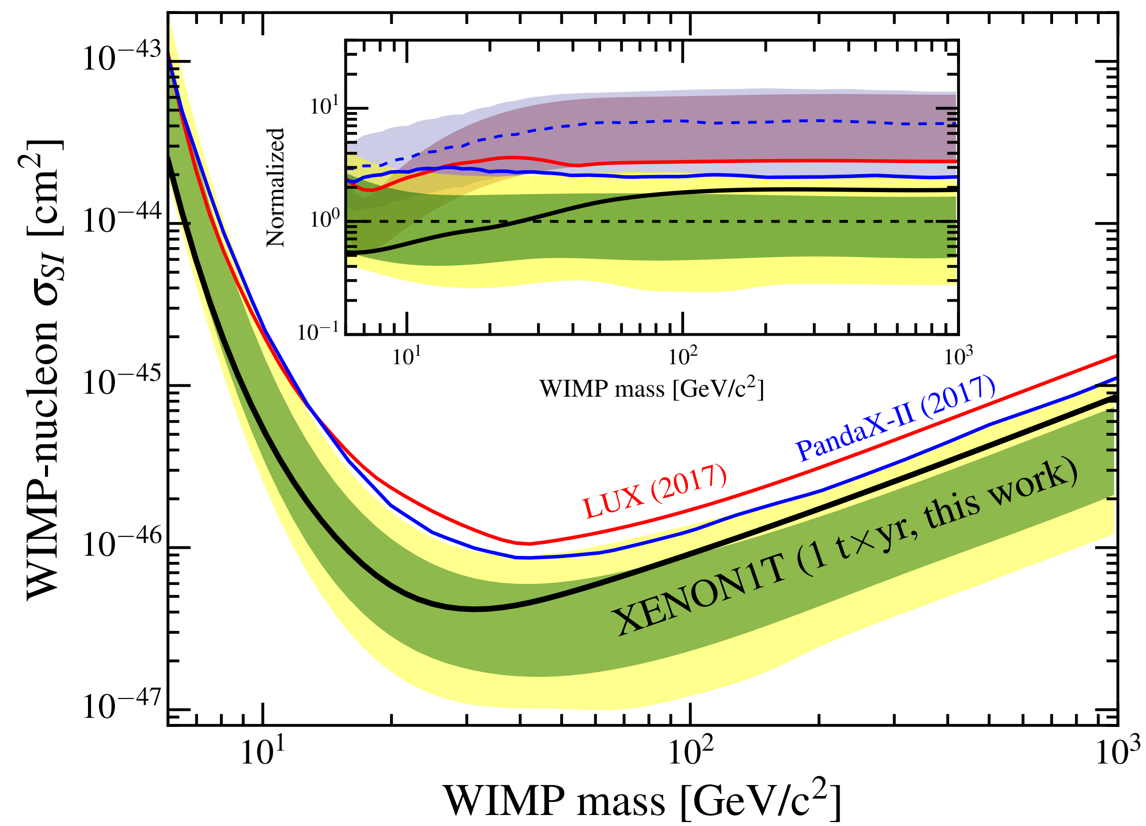
$$\sigma_{\rm ann} v_{\rm rel} \simeq \frac{\lambda_{sH}^2}{16\pi m_{\rm DM}^2}$$

(m_{DM} > weak scale)

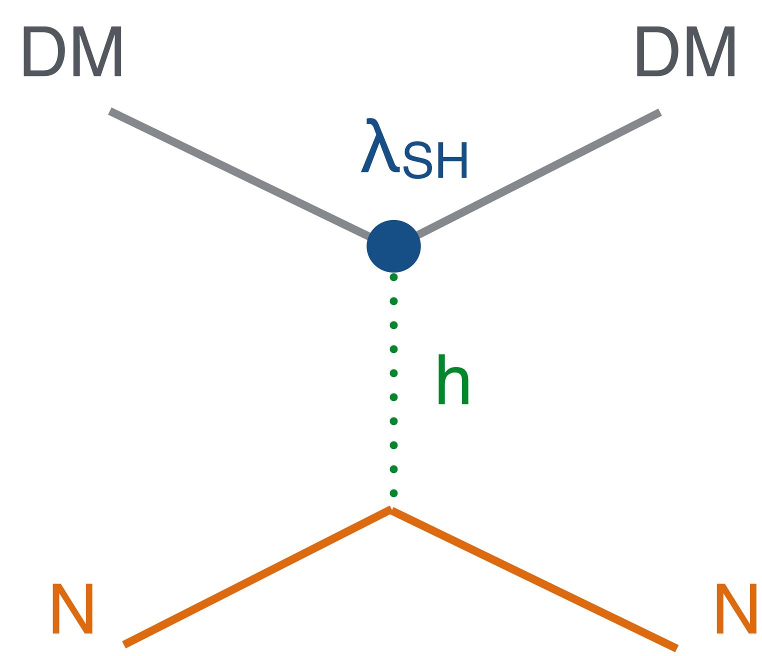
$m_{\rm DM} \simeq 3.3\lambda_{SH}\ {\rm TeV}$ explains the observed DM density.

Singlet scalar DM





XENON Collaboration, arXiv:1805.12562.



Limited up to ~ 1 TeV

Quantum numbers of DM

DM should be electrically neutral and colorless.

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  etc.

- $SU(2)_L \times U(1)_Y$ charge?

  (1, 0), (2, ±1/2), (3, 0), (3, ±1), (4, ±1/2), …

Singlet fermion DM

Singlet fermion DM

Caveat

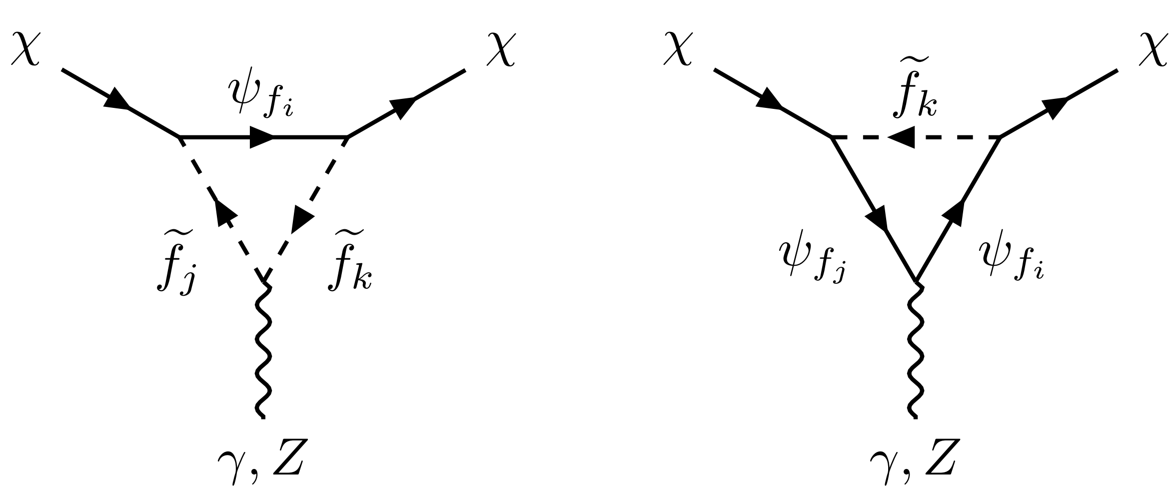
Singlet fermion DM cannot have direct couplings with the SM particles at the renormalizable level.

➡ We need to add some extra particles.

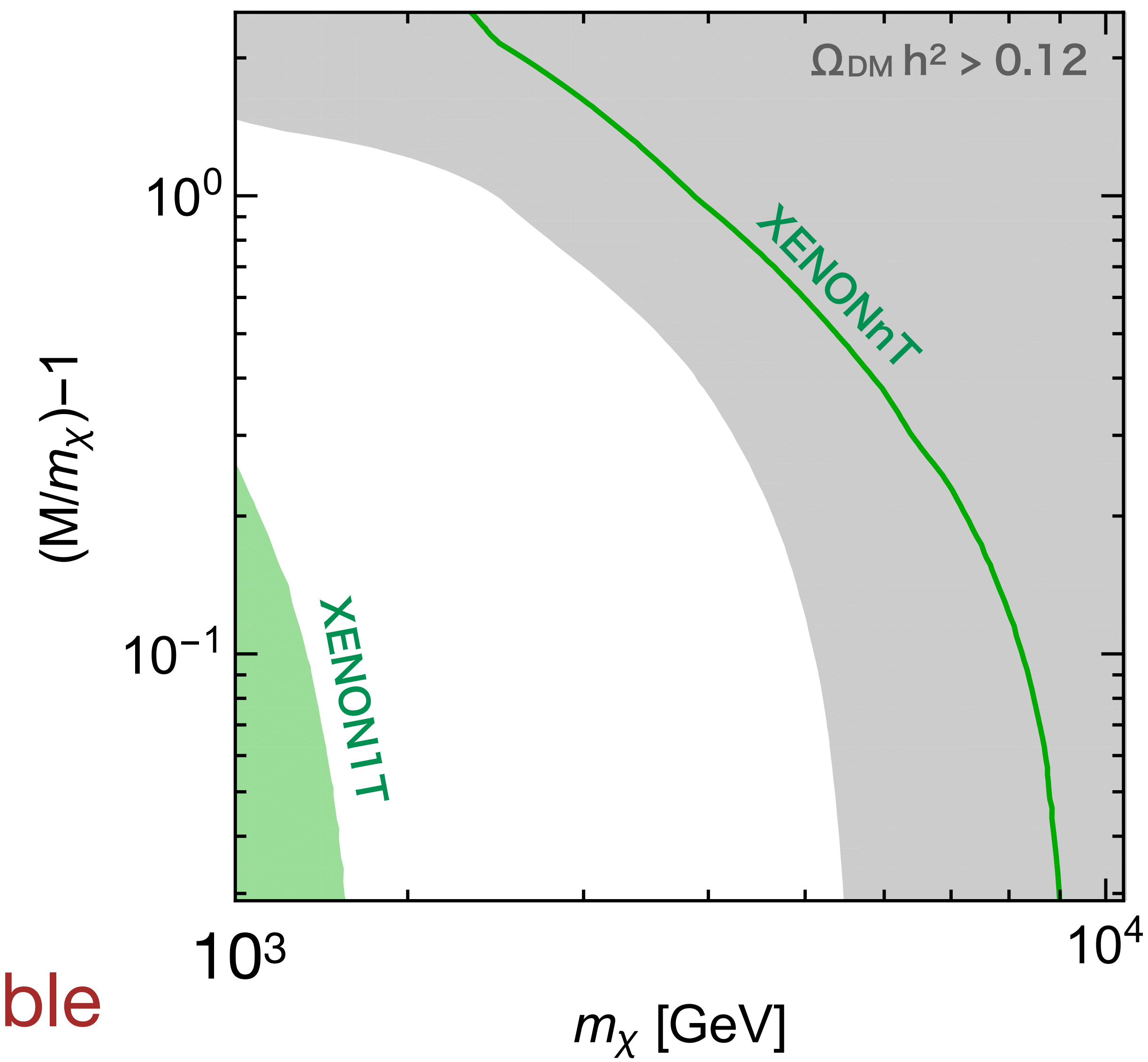
Model-by-model analysis required.

An example

Consider singlet Dirac fermion DM coupling with extra heavy fermion & scalar quarks:



This DM can have MDM/EDM at loop level.



Direct detection possible

- Can be probed in direct detection experiments.
- O(1) TeV fermion/scalar quarks can be probed at colliders.

J. Hisano, R. Nagai, N. Nagata, JHEP **1812**, 059 (2018).

Quantum numbers of DM

DM should be electrically neutral and colorless.

➡ There still remain many possibilities.

- Spin?
  - Real/complex scalar
  - Majorana/Dirac fermion
  - Vector

  etc.

- $SU(2)_L \times U(1)_Y$ charge?

  (1, 0), (2, ±1/2), (3, 0), (3, ±1), (4, ±1/2), …

Electroweak-interacting DM

Electroweak-Interacting DM

The neutral component of $SU(2)_L$ n-tuplet, hypercharge Y is regarded as a DM candidate.

Examples:

- n = 2, Y = 1/2 (higgsino)
- n = 3, Y = 0 (wino)
- n = 5, Y = 0 (Minimal Dark Matter)

Interactions

$$\mathcal{L}_{\rm int} = \frac{g_2}{4}\sqrt{n^2-(2Y-1)^2}\,\overline{\chi^+}\not{W}^+\chi^0 + \frac{g_2}{4}\sqrt{n^2-(2Y+1)^2}\,\overline{\chi^0}\not{W}^+\chi^- + \text{h.c.} + i g_Z Y \overline{\chi^0}\not{Z}\eta^0 \ .$$

The DM phenomenology is (almost) completely determined by the gauge interactions.

For scalar DM cases, the DM-Higgs couplings also exist.

Electroweak-Interacting DM

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Finite naturalness bound in TeV	σ_{SI} in 10^{-46} cm^2
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6)\, 10^{-3}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(0.25 \pm 056)\, 10^{-3}$
3	0	0	HH^*	$2.0 \to 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
3	0	1/2	LH	$2.4 \to 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.12 ± 0.03
3	1	0	HH, LL	$1.6 \to ?$	540	$0.22 \times \sqrt{\Delta}$	$(1.3 \pm 1.1)\, 10^{-2}$
3	1	1/2	LH	$1.9 \to ?$	526	$1.0 \times \sqrt{\Delta}$	$(1.3 \pm 1.1)\, 10^{-2}$
4	1/2	0	HHH^*	$2.4 \to ?$	353	$0.14 \times \sqrt{\Delta}$	0.27 ± 0.08
4	1/2	1/2	(LHH^*)	$2.4 \to ?$	347	$0.6 \times \sqrt{\Delta}$	0.27 ± 0.08
4	3/2	0	HHH	$2.9 \to ?$	729	$0.14 \times \sqrt{\Delta}$	0.15 ± 0.07
4	3/2	1/2	(LHH)	$2.6 \to ?$	712	$0.6 \times \sqrt{\Delta}$	0.15 ± 0.07
5	0	0	(HHH^*H^*)	$5.0 \to 9.4$	166	$0.10 \times \sqrt{\Delta}$	1.0 ± 0.2
5	0	1/2	stable	$4.4 \to 10$	166	$0.4 \times \sqrt{\Delta}$	1.0 ± 0.2
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	4 ± 1

($\to$: Sommerfeld enhancement)

M. Farina, D. Pappadopulo, A. Strumia, JHEP **1308** (2013) 022.

Features

- Relatively heavy mass gives correct DM abundance.
- Small mass difference among the multiplet components.

Electroweak-Interacting DM

These DM candidates are still waiting to be tested.

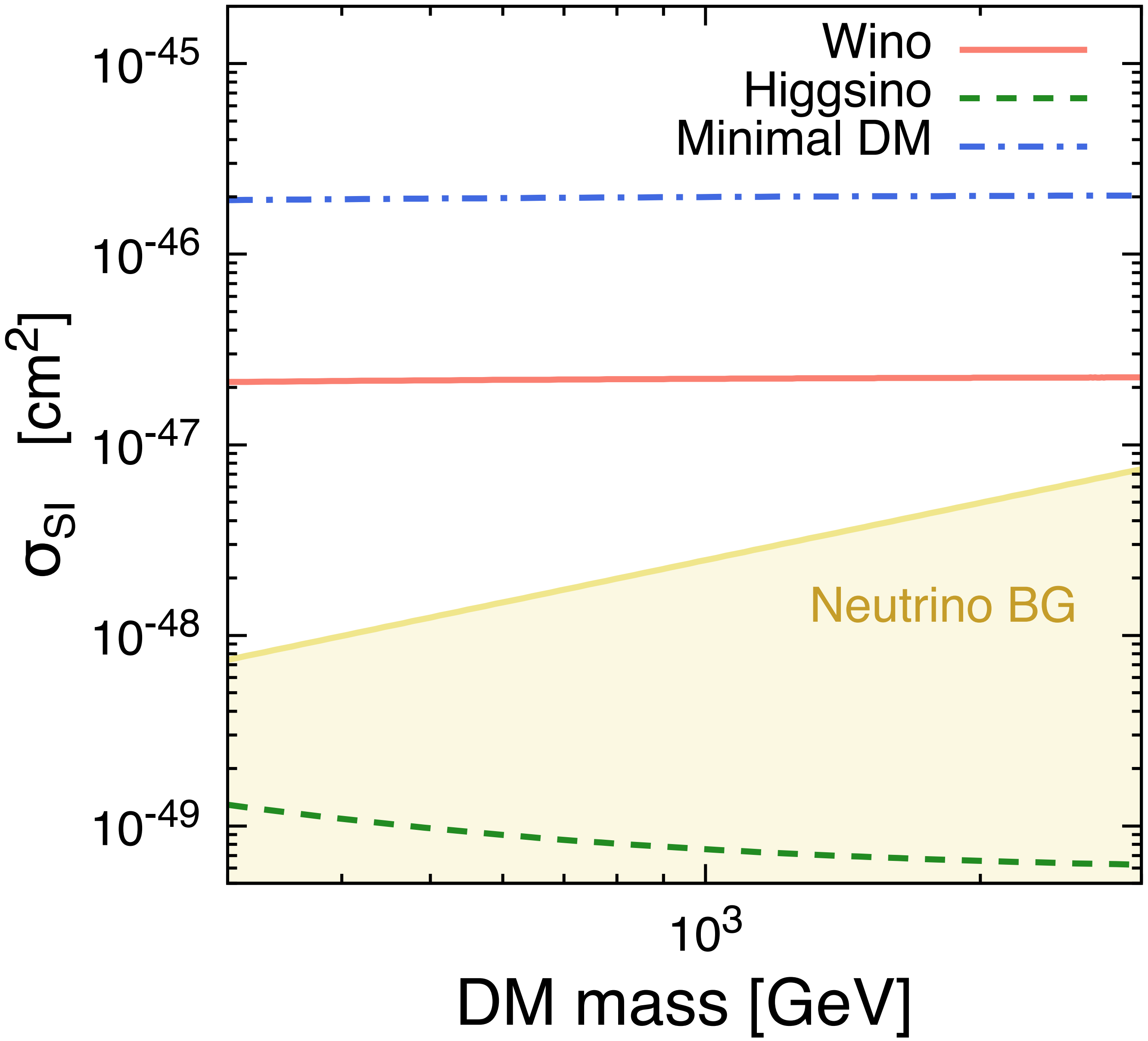
Search methods

- Indirect searches are promising.

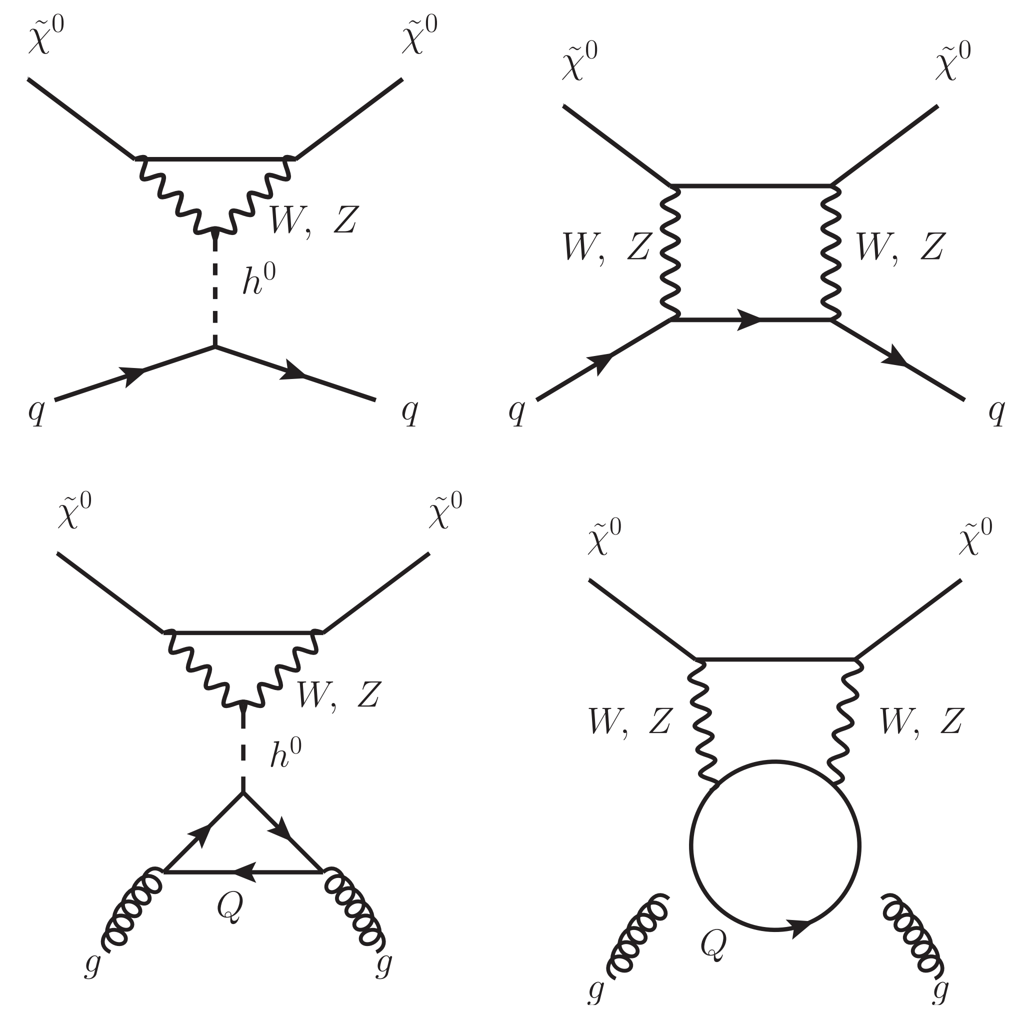
  Large annihilation cross section.

- Collider searches are challenging but doable.
  - Small production cross section.
  - Small mass difference.
    - Disappearing track search (+α)
    - Indirect search via quantum corrections.
- Direct searches are also possible.

Electroweak interacting DM



Diagrams



- Triplet (pure wino), Minimal DM can be tested.
- Doublet (pure higgsino) is hard to probe.

J. Hisano, K. Ishiwata, N. Nagata, JHEP **1506**, 097 (2015).

Conclusion

Message of the talk

- WIMP DM candidates in SUSY models have been narrowed down.
  - Wino [3 TeV]
  - Higgsino [1 TeV]
  - Coannihilation [bino-stop/gluino/wino/stau]
- WIMP paradigm has not been fully tested yet.
- We can explore it in future experiments.

Backup

Thermal relic scenario (cold DM)

WIMPs were in thermal equilibrium with the SM particles in the early Universe.

For $T \lesssim m_{\rm DM}$

$$n_{\rm DM} \simeq \left(\frac{m_{\rm DM} T}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_{\rm DM}}{T}}$$

DM number rapidly decreases.

➡ Annihilation rate also rapidly decreases!

Annihilation precess freezes out when

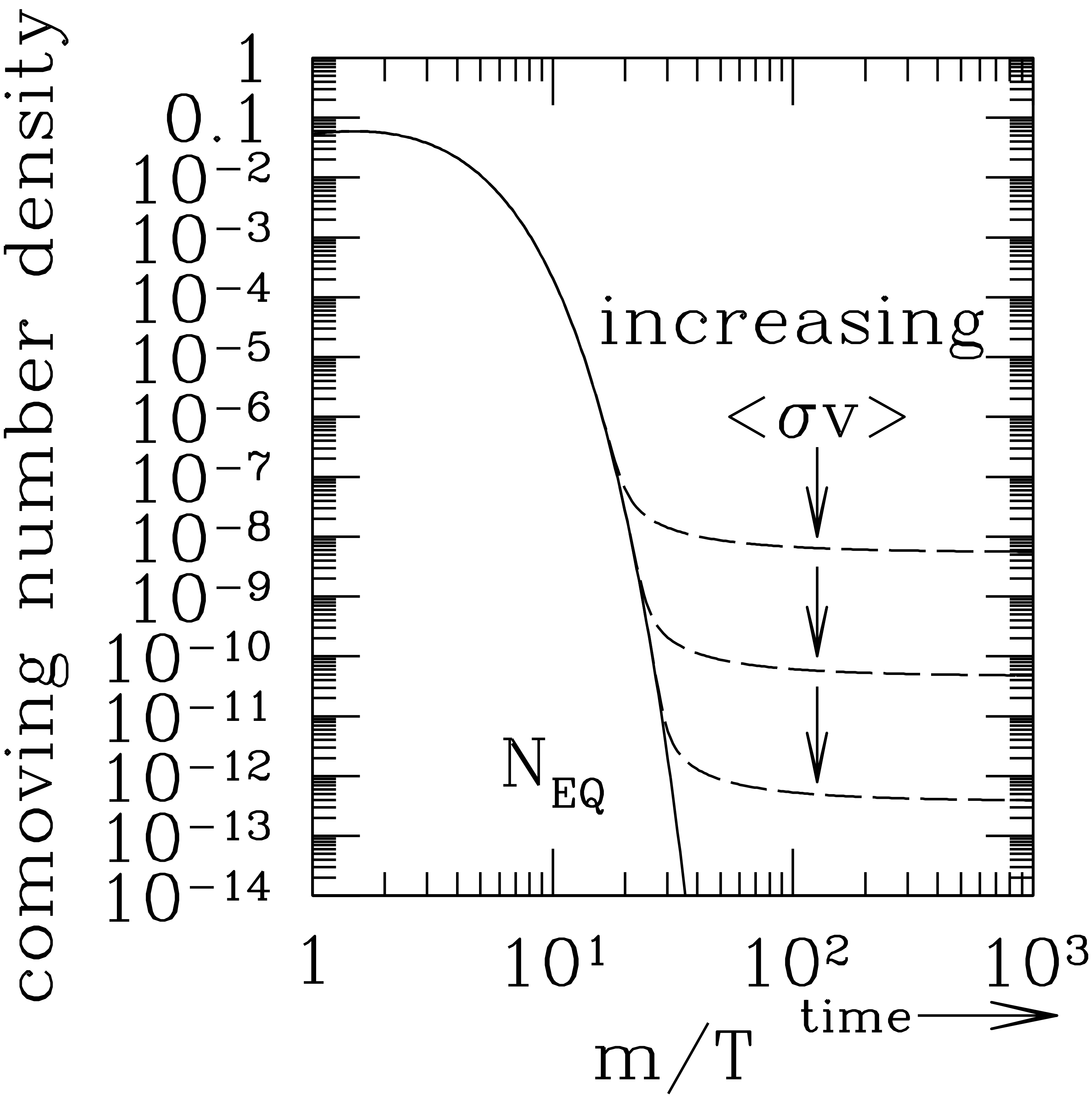
$$n_{\rm DM}(T_{\rm FO}) \cdot \langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq H(T_{\rm FO}) \quad \Rightarrow \quad T_{\rm FO} \simeq \frac{m_{\rm DM}}{25}$$

↑ Annihilation rate

↑ Hubble expansion rate

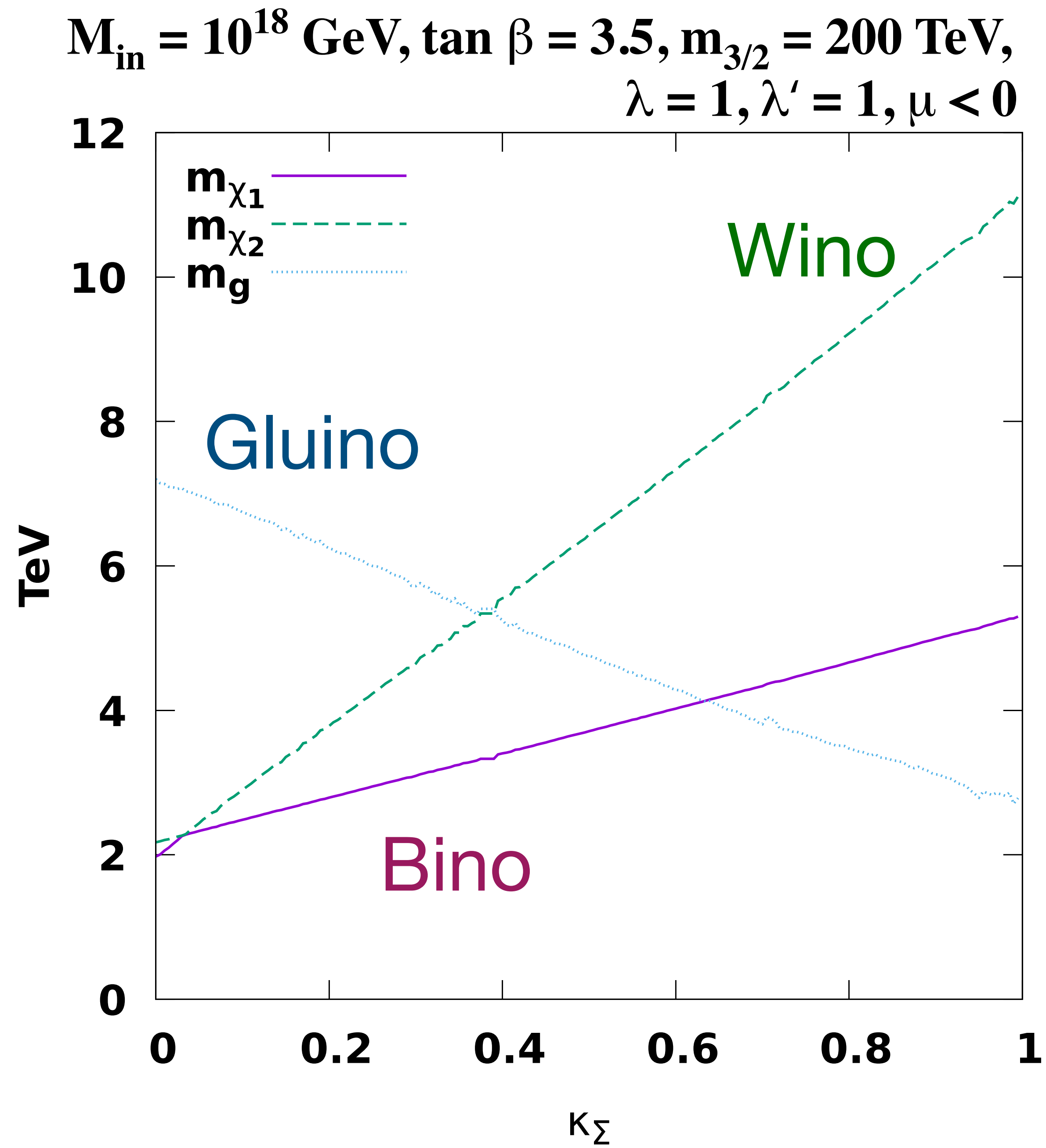
Cold DM

Thermal relic scenario (cold DM)



P. Gondolo, astro-ph/0403064

Gaugino masses in SuperGUT PGM



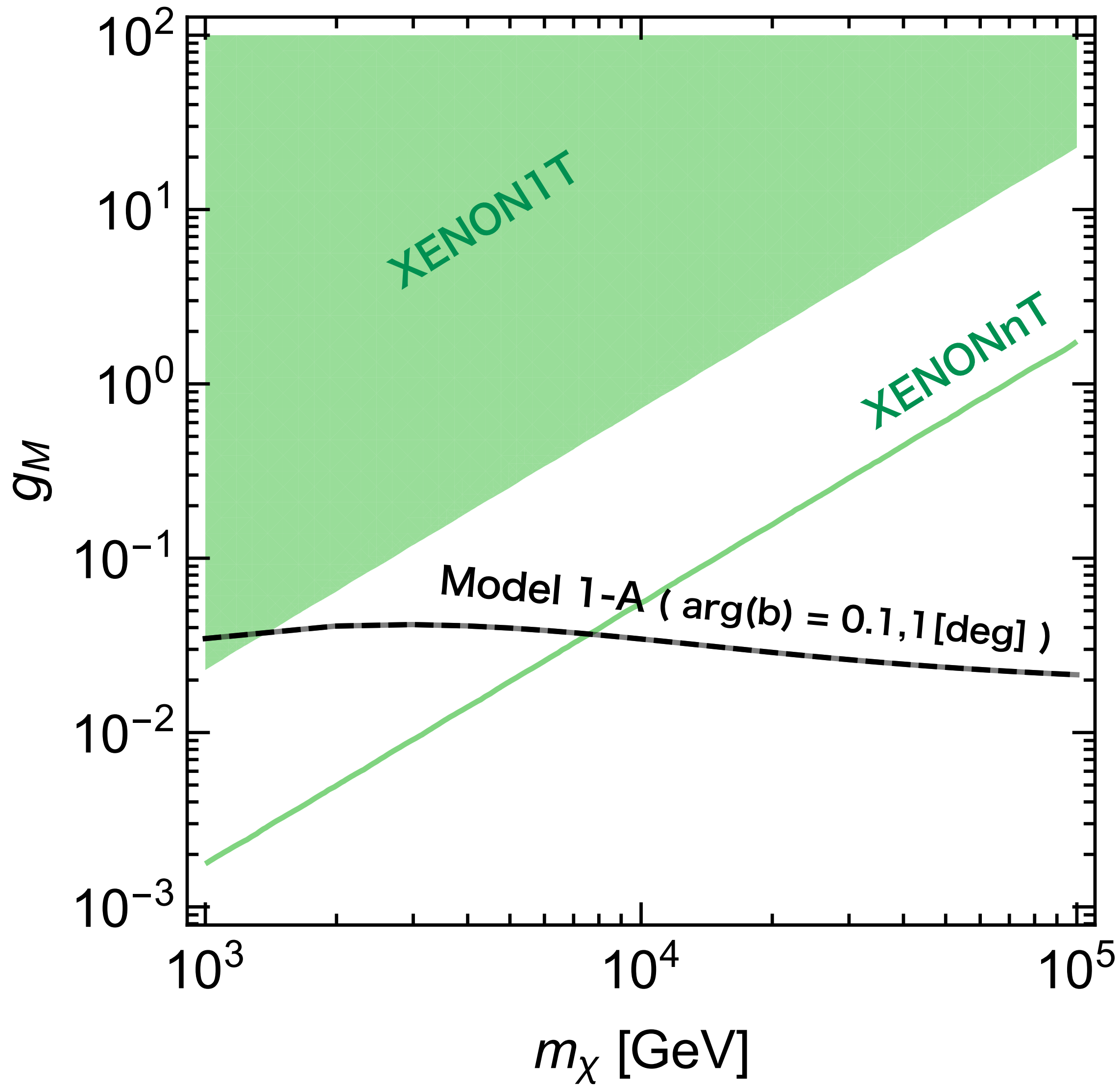
$$\frac{\kappa_\Sigma}{\sqrt{3}M_P}(Z+Z^*)|\Sigma|^2$$

$$\Delta A_{\lambda'} = 3\kappa_\Sigma m_{3/2},$$
$$\Delta B_\Sigma = 2\kappa_\Sigma m_{3/2}$$

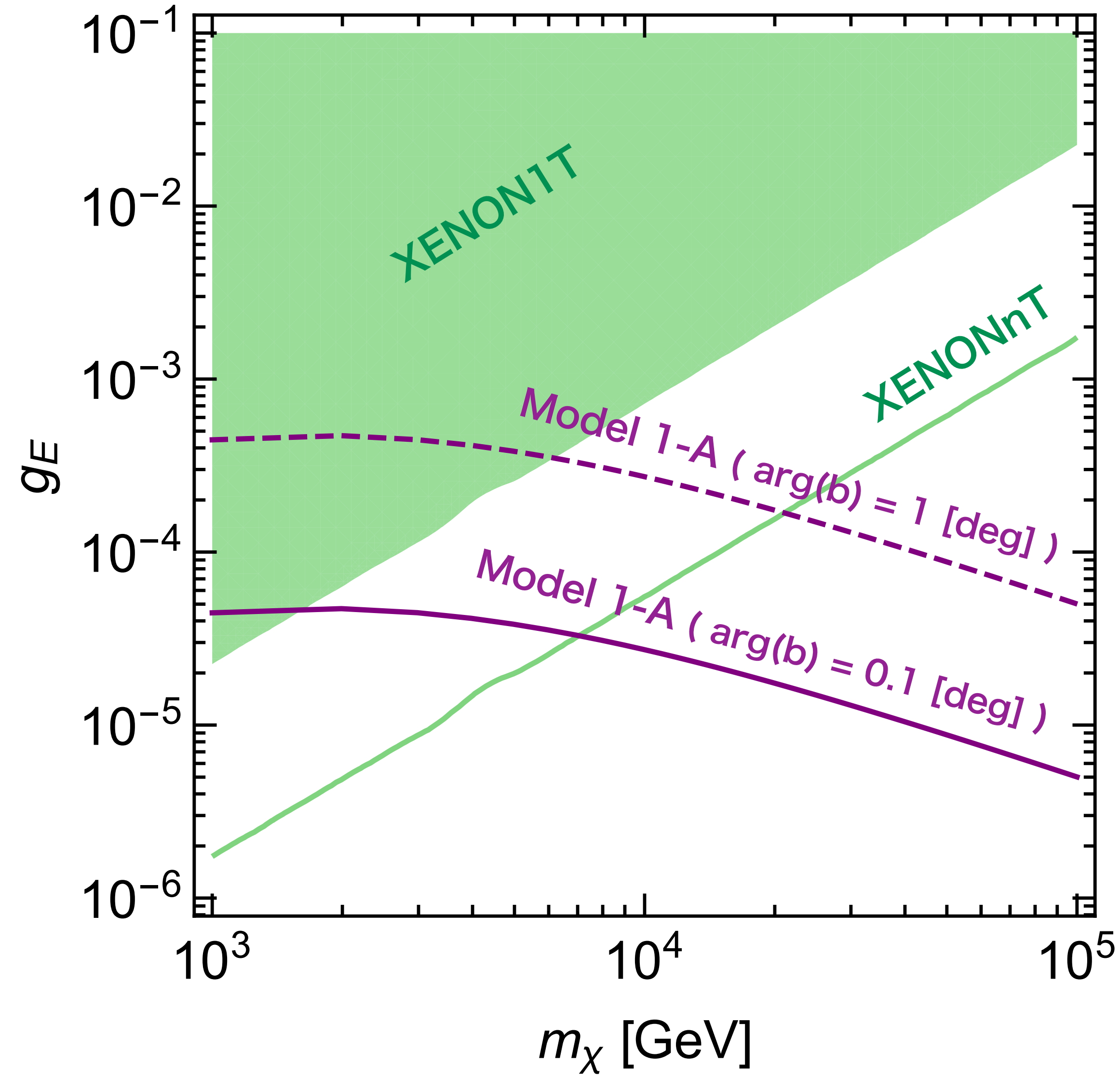
J. L. Evans, N. Nagata, K. A. Olive, 1902.09084.

Singlet Dirac Fermion DM

Magnetic dipole moment



Electric dipole moment

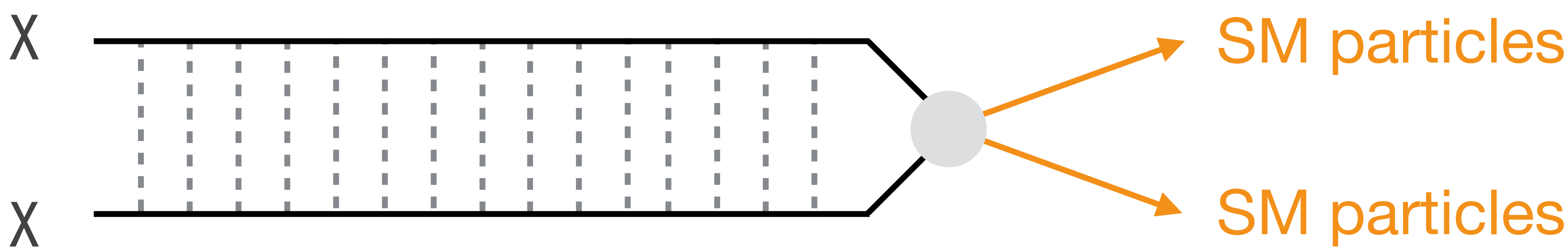


J. Hisano, R. Nagai, N. Nagata, JHEP **1812**, 059 (2018).

Sommerfeld effects

J. Hisano, S. Matsumoto, and M. M. Nojiri, Phys. Rev. Lett. **92**, 031303 (2004).

Electroweak-interacting DM has self-interactions via EW interactions.



Incoming wave-functions deviate from plane waves due to long-distance self-interactions.

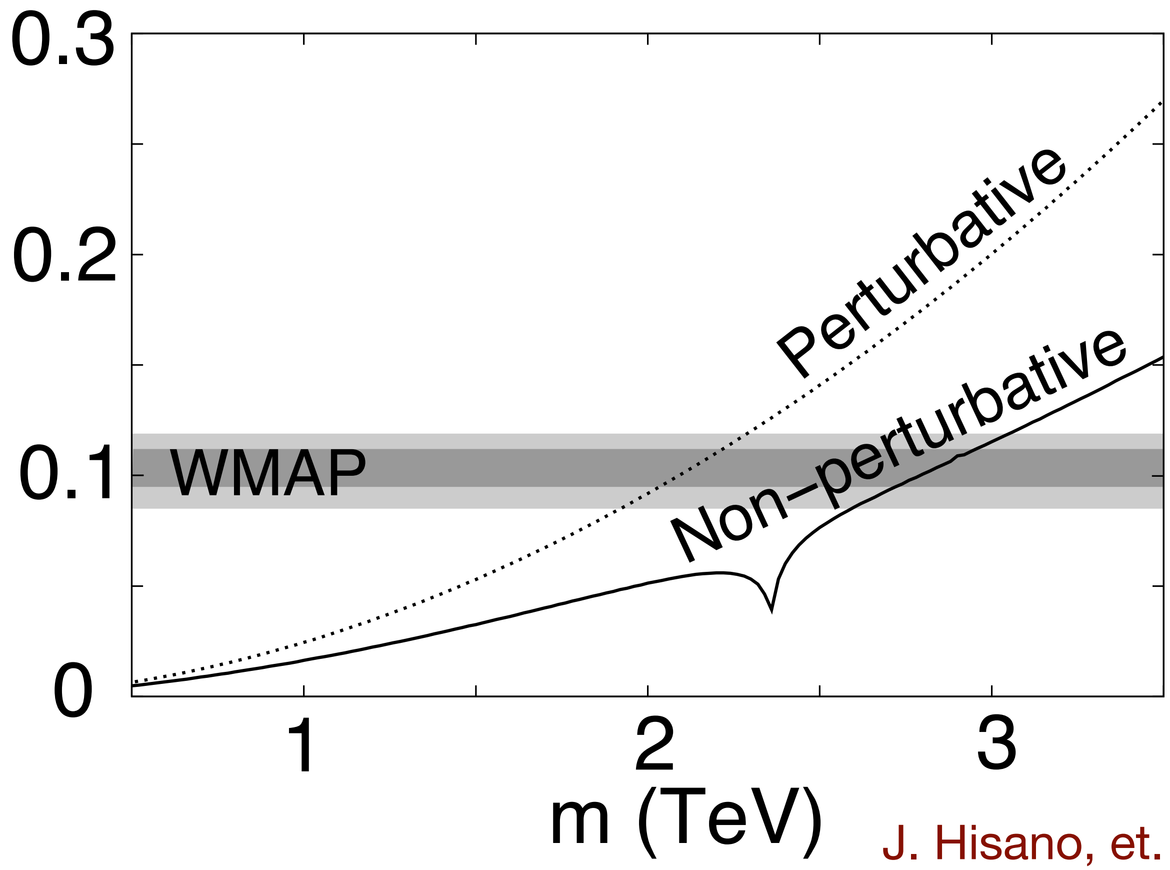
⇒ Sommerfeld effect

This effect becomes important when the interaction range becomes longer than the Bohr radius of the two-body system.

$$\frac{1}{m_W} \gtrsim \frac{1}{\alpha_2 m_{\rm DM}}$$

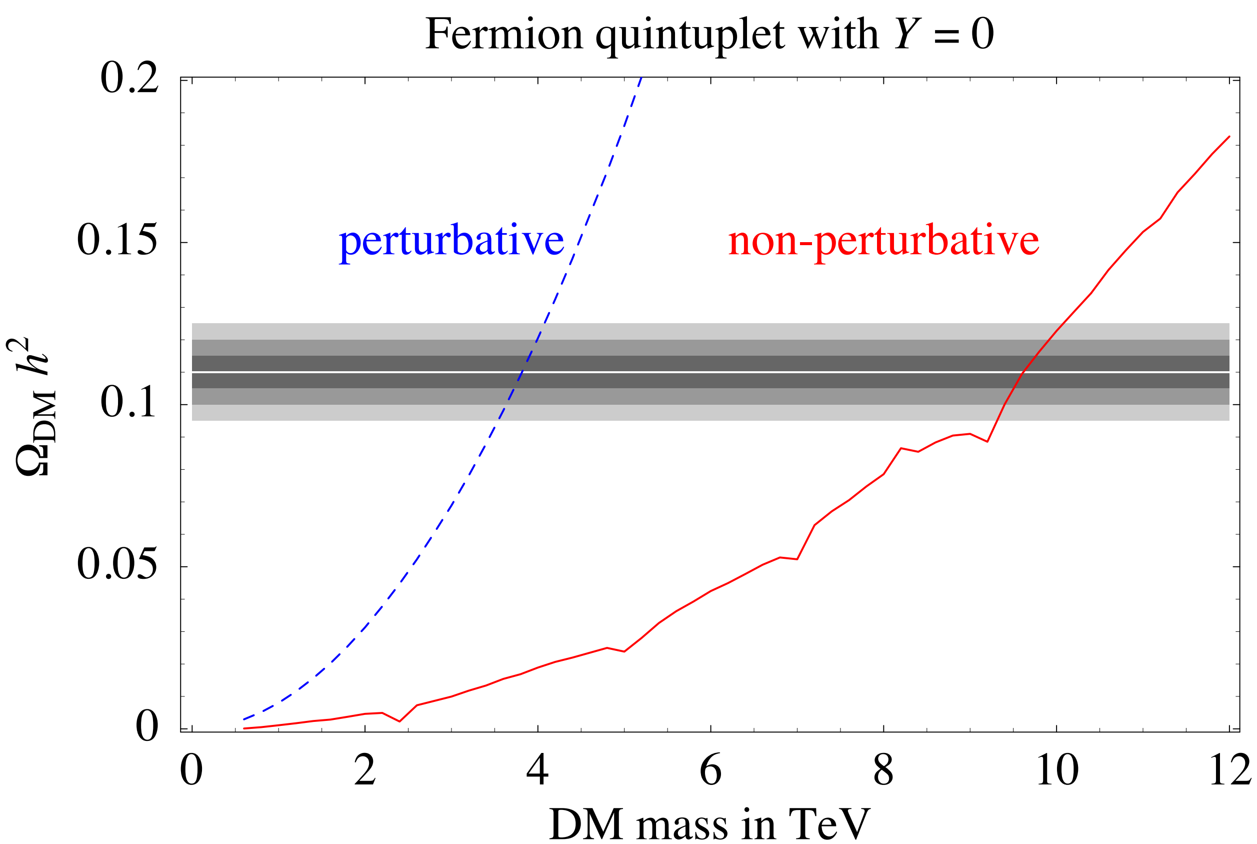
Sommerfeld effects

Triplet



J. Hisano, et. al., (2006).

Quintuplet



M. Cirelli, et. al., (2007).

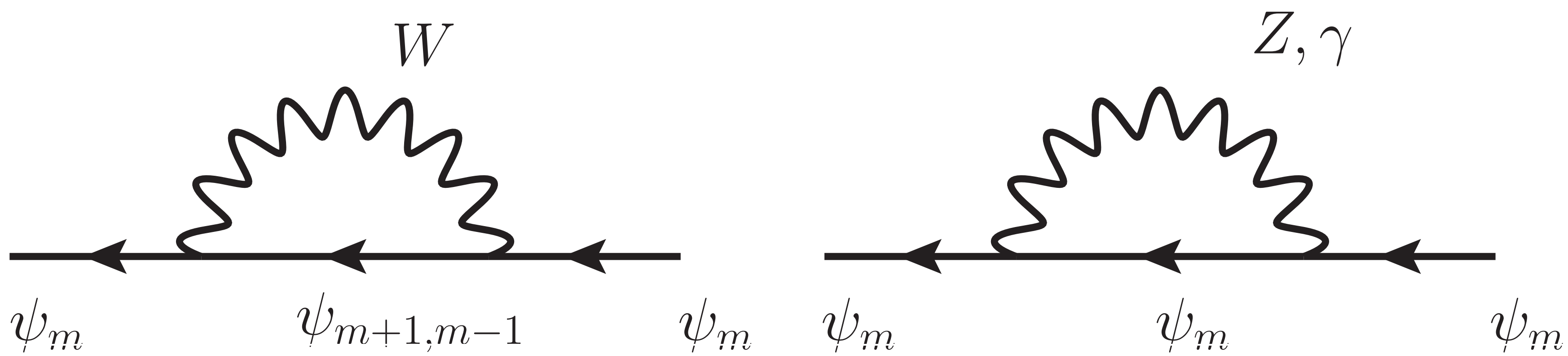
Sommerfeld effect significantly enhances annihilation cross sections.

A heavier mass is favored in terms of thermal relic.

In order to make a precise prediction for the DM mass, we need to take this effect into account.

Mass splitting

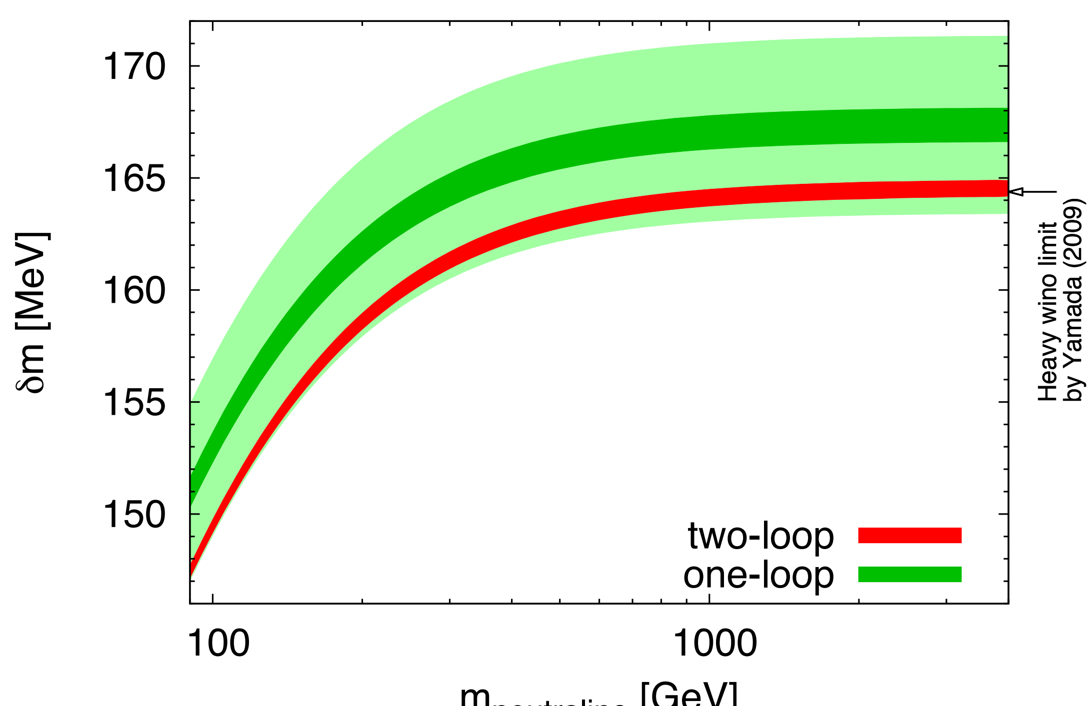
Charged-neutral mass splitting of a wino or Higgsino is generated via IR radiative corrections by EW gauge boson loops.



$$\Delta M \simeq \alpha_2 m_W \sin^2\frac{\theta_W}{2} + \alpha_2 Y m_W \left(\frac{1}{\cos\theta_W} - 1\right)$$

O(100) MeV.

Non-decoupling effect



Two-loop calculation (wino, Y = 0)

$$\Delta M \simeq 165\ \mathrm{MeV}$$

M. Ibe, S. Matsumoto, R. Sato (2012).

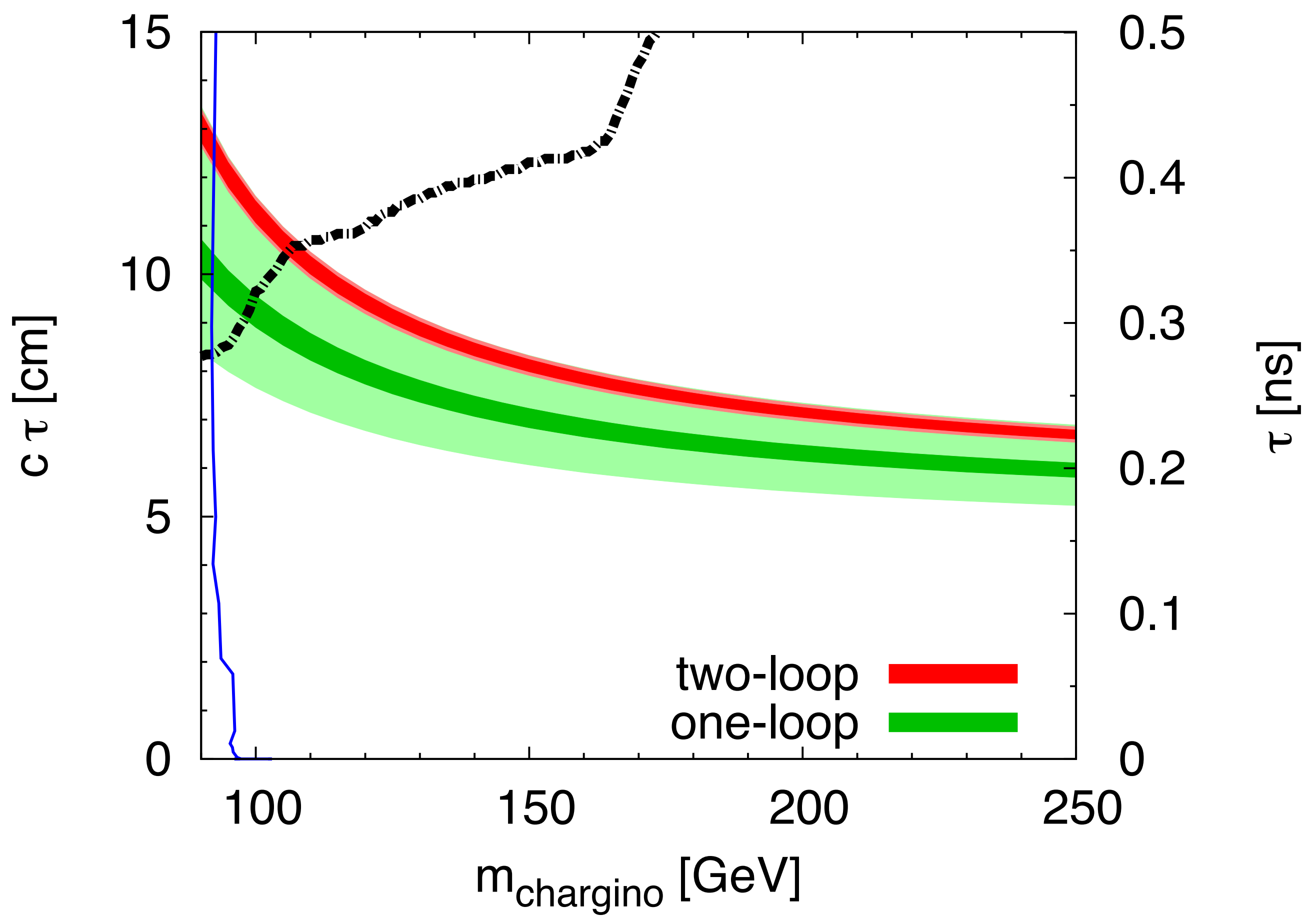
Wino lifetime

Due to the small mass splitting, wino becomes rather long-lived.

Main decay channel: $\chi^{\pm} \to \chi^{0} + \pi^{\pm}$

Branching fraction for the leptonic decay modes (three-body decay) is a few %.

$$\Gamma(\chi^{\pm} \to \chi^{0} + \pi^{\pm}) = \frac{4G_F^2 V_{ud}^2 f_\pi^2}{\pi} \Delta M^3 \left(1 - \frac{m_\pi^2}{\Delta M^2}\right)^{\frac{1}{2}}$$



M. Ibe, S. Matsumoto, R. Sato (2012).

$$\tau \simeq 0.2 \text{ ns}$$
$$c\tau \simeq 6 \text{ cm}$$

Decay within a detector!

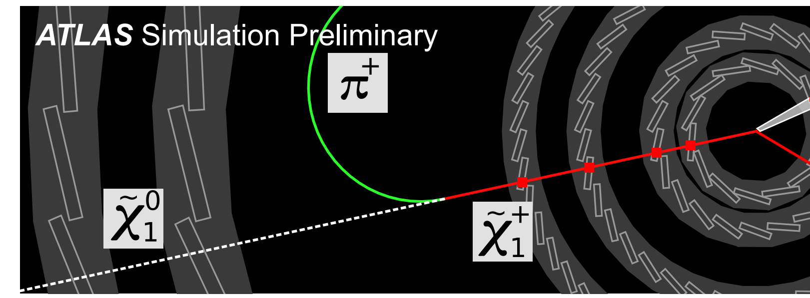
Disappearing track searches

A charged wino with a decay length of O(1) cm leaves a disappearing track in detectors.

J. L. Feng, T. Moroi, L. Randall, M. Strassler, S. F. Su (1999);
M. Ibe, T. Moroi, T. T. Yanagida (2006), etc…

$$\chi^{\pm} \to \chi^{0} + \pi^{\pm}$$

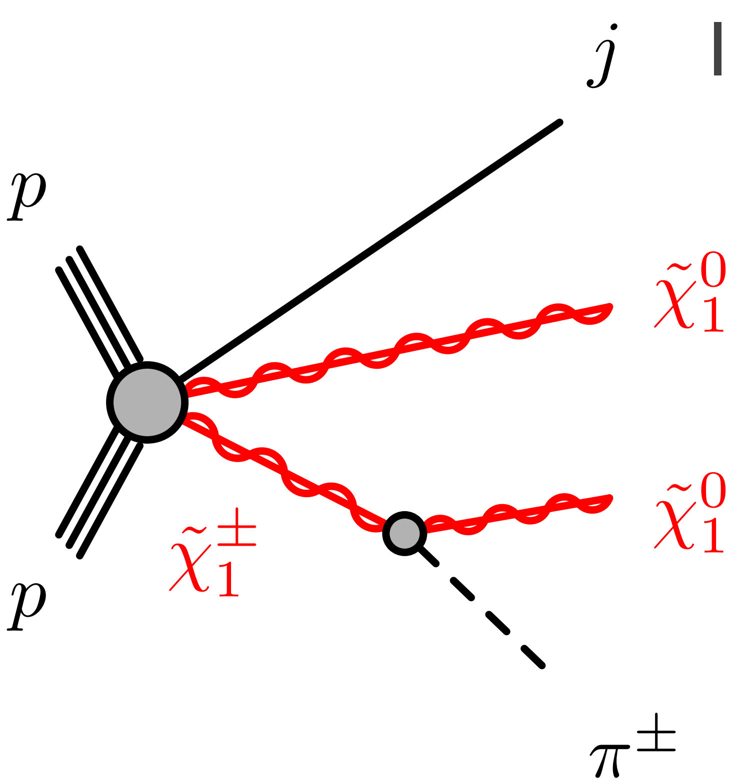
Charged track | E_T^{miss} | Too soft to be detected



Requiring this signature, we can reduce SM BG significantly.

Ryu Sawada's talk

Signal topology



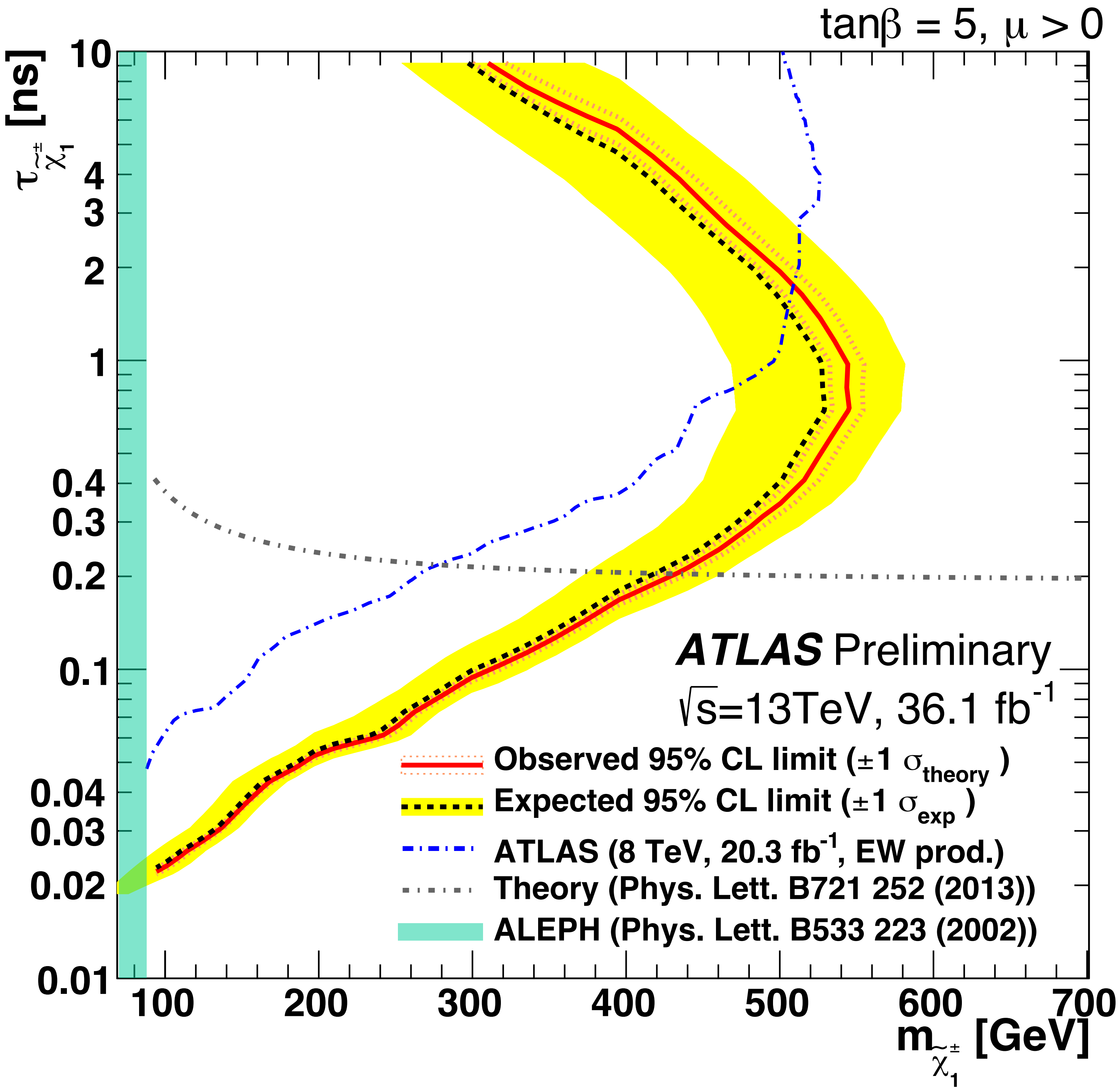
Initial State Radiation (ISR)

Large E_T^{miss}
Single jet
Disappearing track

Role of ISR

- Trigger
- Boost the system

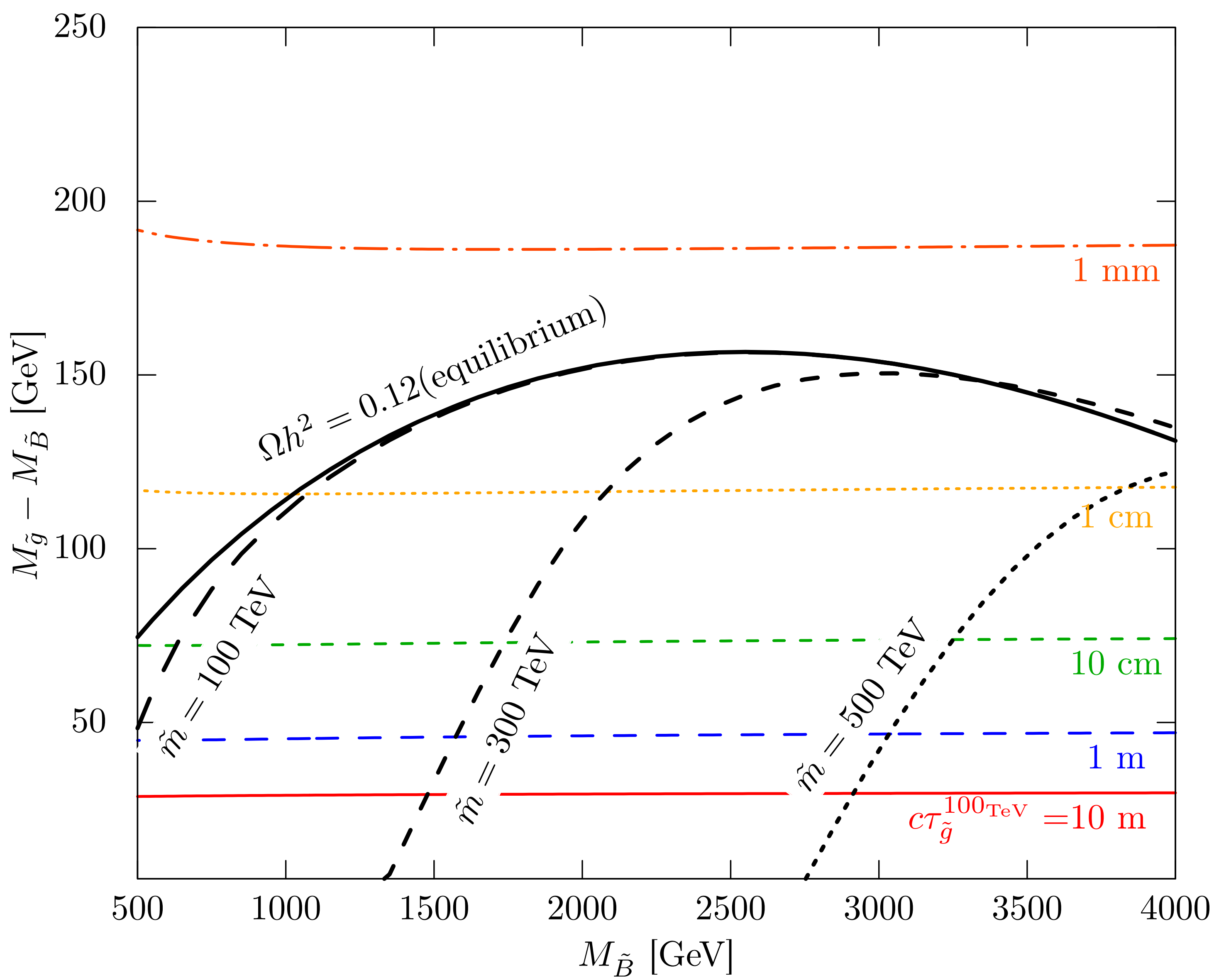
ATLAS limit

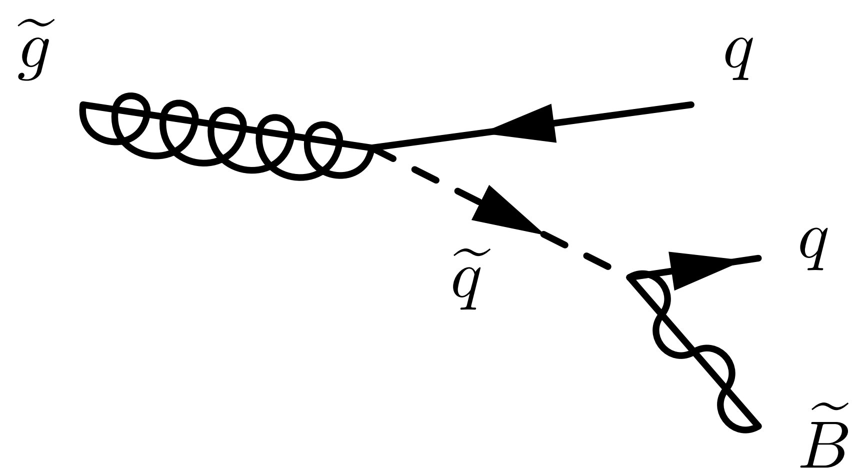


Wino with a mass up to 430 GeV has been excluded!

ATLAS Collaboration, JHEP **1806**, 022 (2018).

Gluino decay length

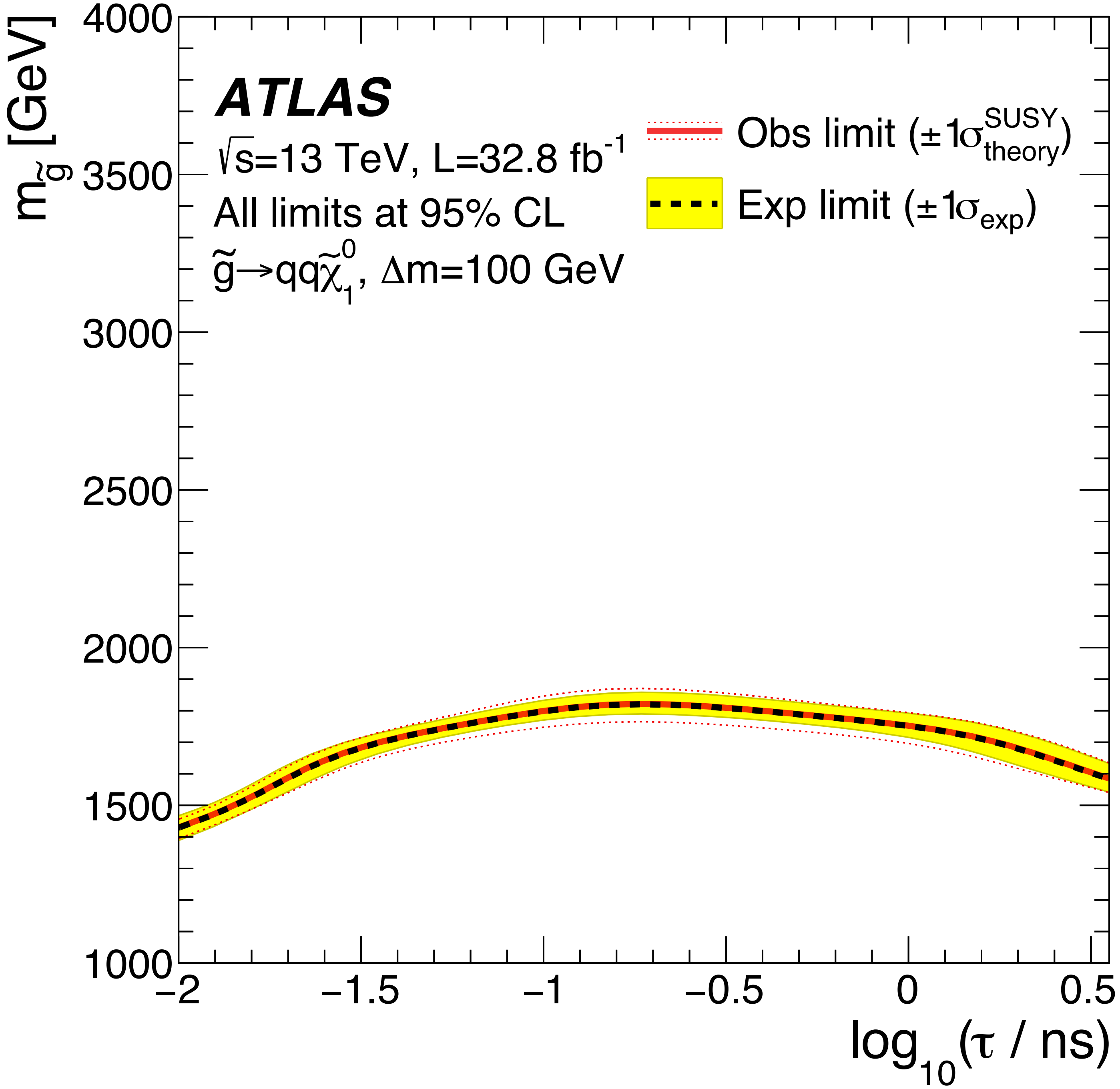




$$c\tau_{\tilde{g}} \simeq \left(\frac{\Delta M}{100\ \mathrm{GeV}}\right)^{-5} \left(\frac{\tilde{m}}{100\ \mathrm{TeV}}\right)^{4}\ \mathrm{cm}$$

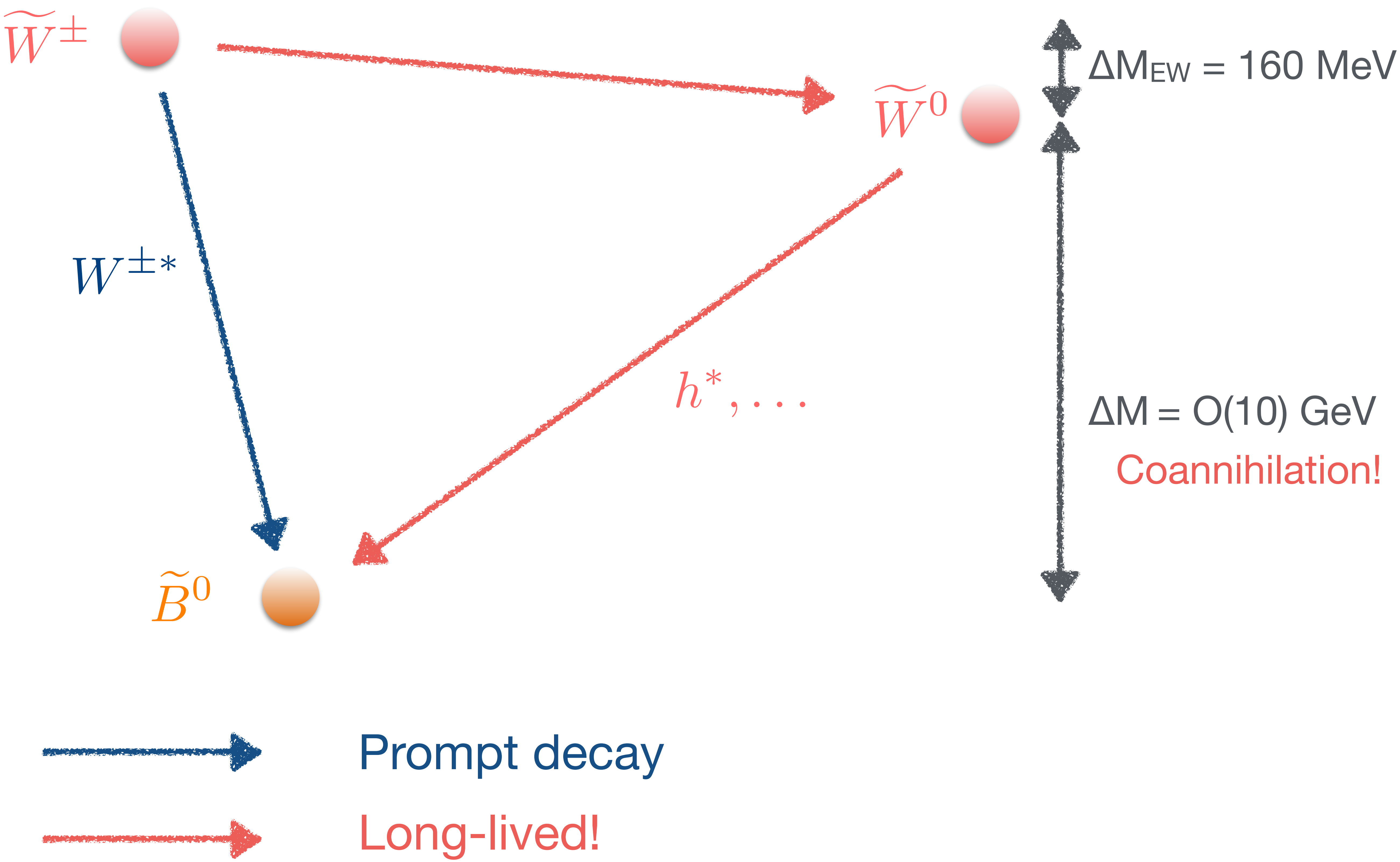
N. Nagata, H. Otono, S. Shirai, Phys. Lett. **B748**, 24 (2015) [arXiv: 1504.00504]

ATLAS limit



ATLAS Collaboration, Phys. Rev. **D97**, 052012 (2018).

Mass spectrum and decay chains

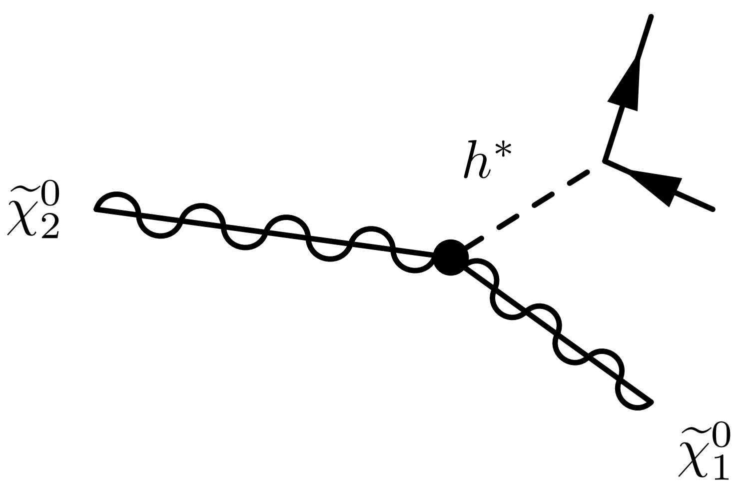


Neutral wino decay

A neutral wino can decay into the bino LSP via Higgsino mixing.

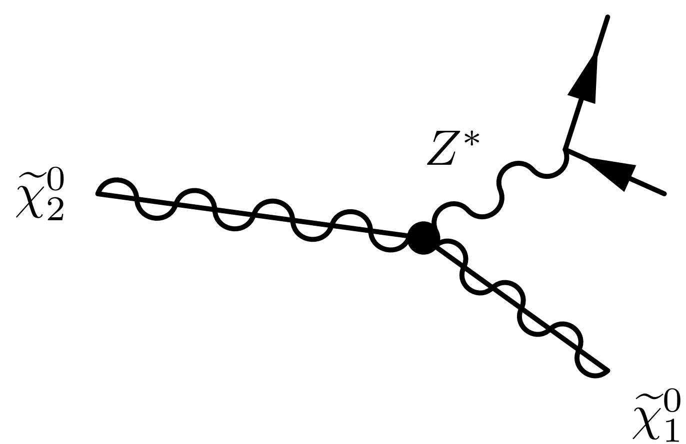
The decay rate is suppressed for a large Higgsino mass.

Dominant diagram

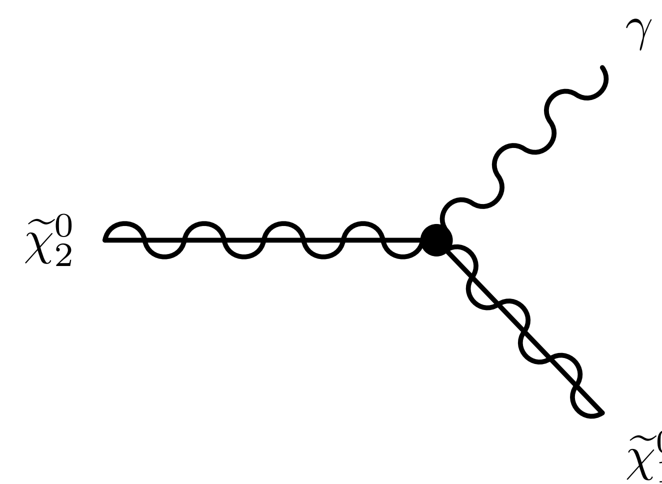


$$\propto y_f \sin(2\beta)\frac{m_W}{\mu}$$

Sub-dominant diagrams



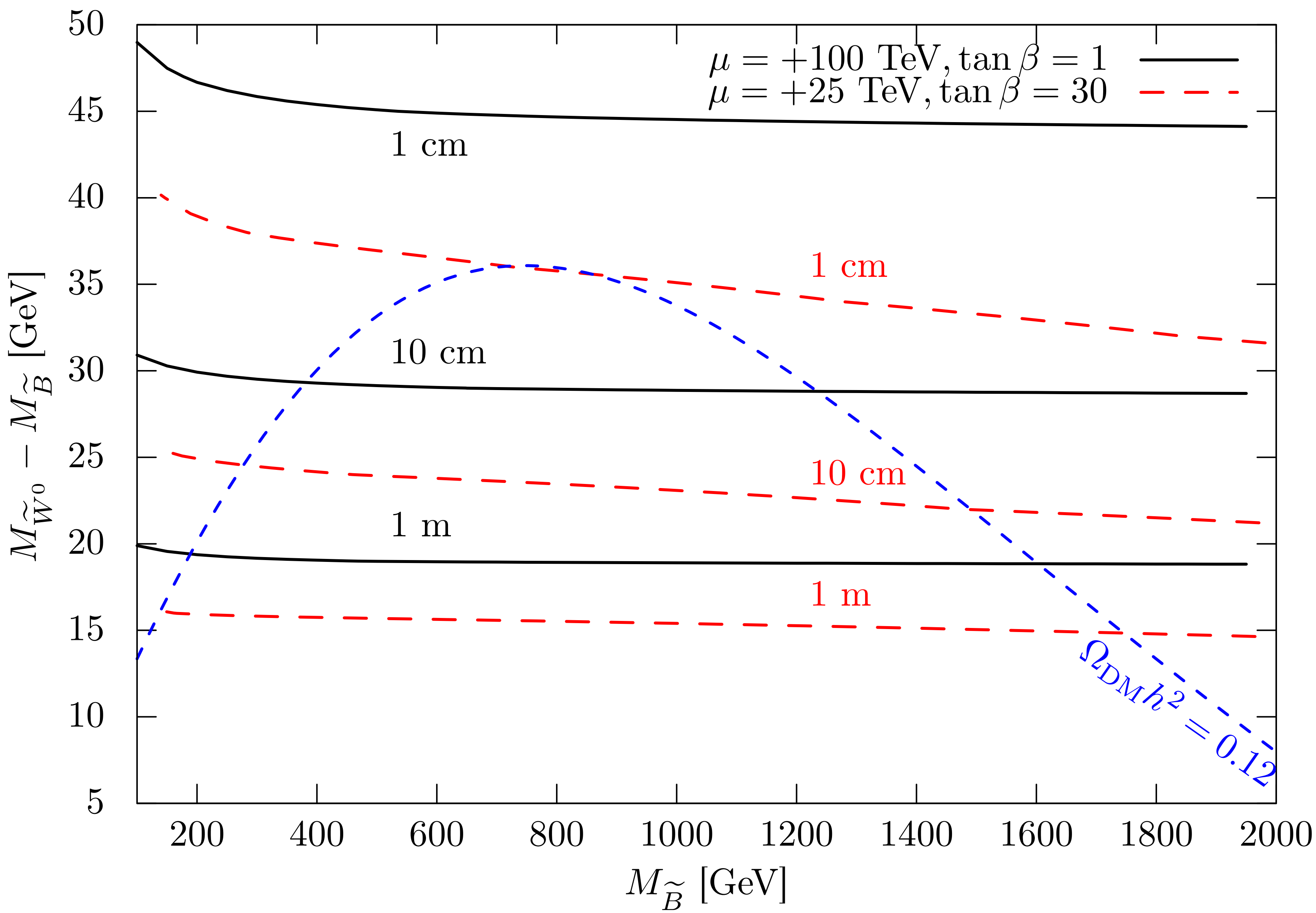
$$\propto \cos(2\beta)\frac{m_Z^2}{|\mu|^2}$$



$$\propto \cos(2\beta)\frac{M_{\tilde{\chi}^0}}{16\pi^2|\mu|^2}$$

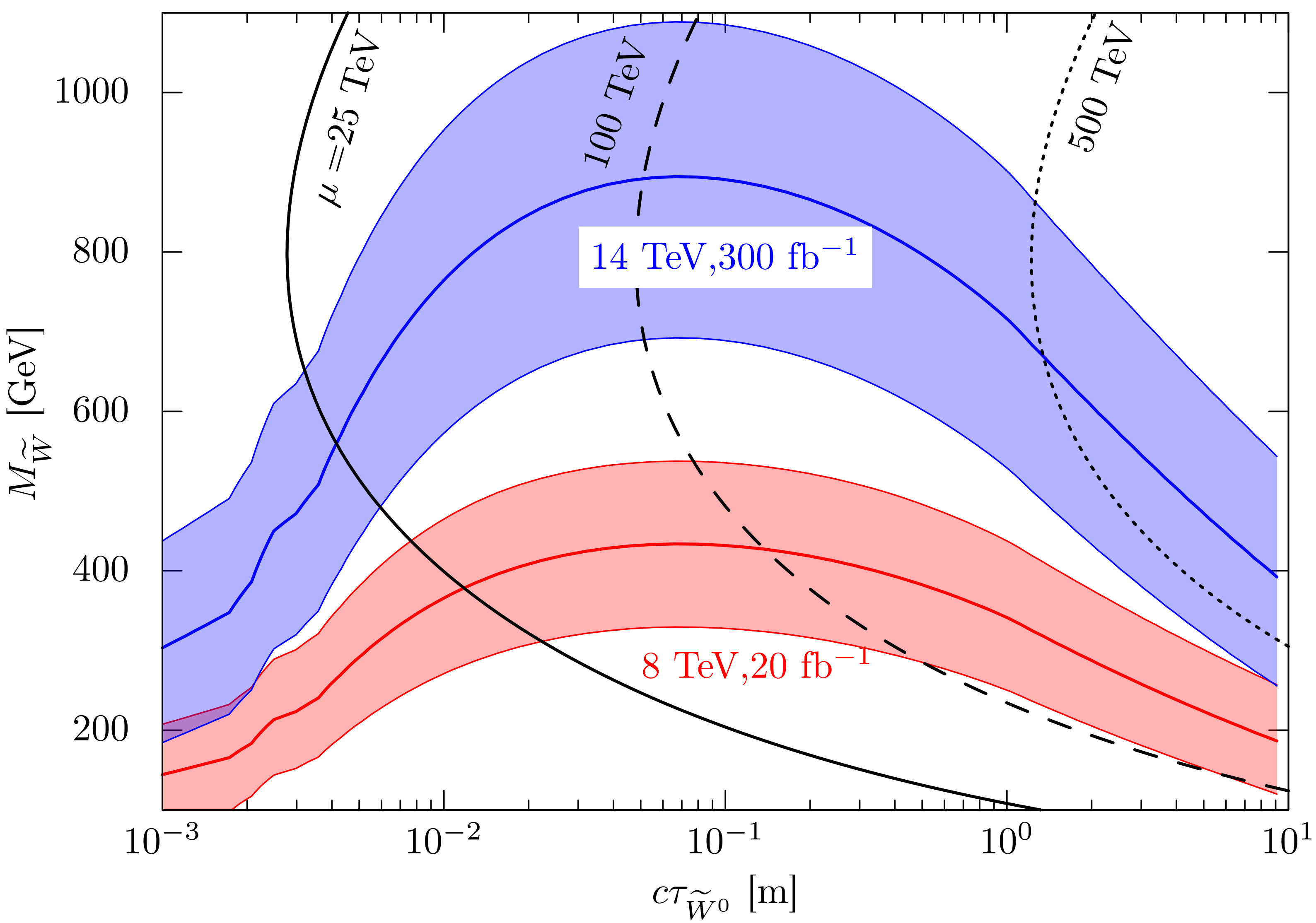
When Higgsino mass is quite large, the neutral wino $\widetilde{W}^0$ becomes long-lived.

Decay length of neutral wino



N. Nagata, H. Otono, S. Shirai, JHEP **1510**, 086 (2015) [arXiv: 1506.08206]

Prospects for the long-lived wino search



$\Delta M = 30$ GeV

$\tan\beta = 2$

Acceptance rate is varied by a factor of three.

400 GeV (800 GeV) wino can be probed at 8 (14) TeV LHC.

N. Nagata, H. Otono, S. Shirai, JHEP **1510**, 086 (2015) [arXiv: 1506.08206]

Indirect search

Indirect searches, especially those search for γ rays, are quite promising since electroweak-charged DM has a large annihilation cross sections.

Galactic Center

Large uncertainty from DM profile.

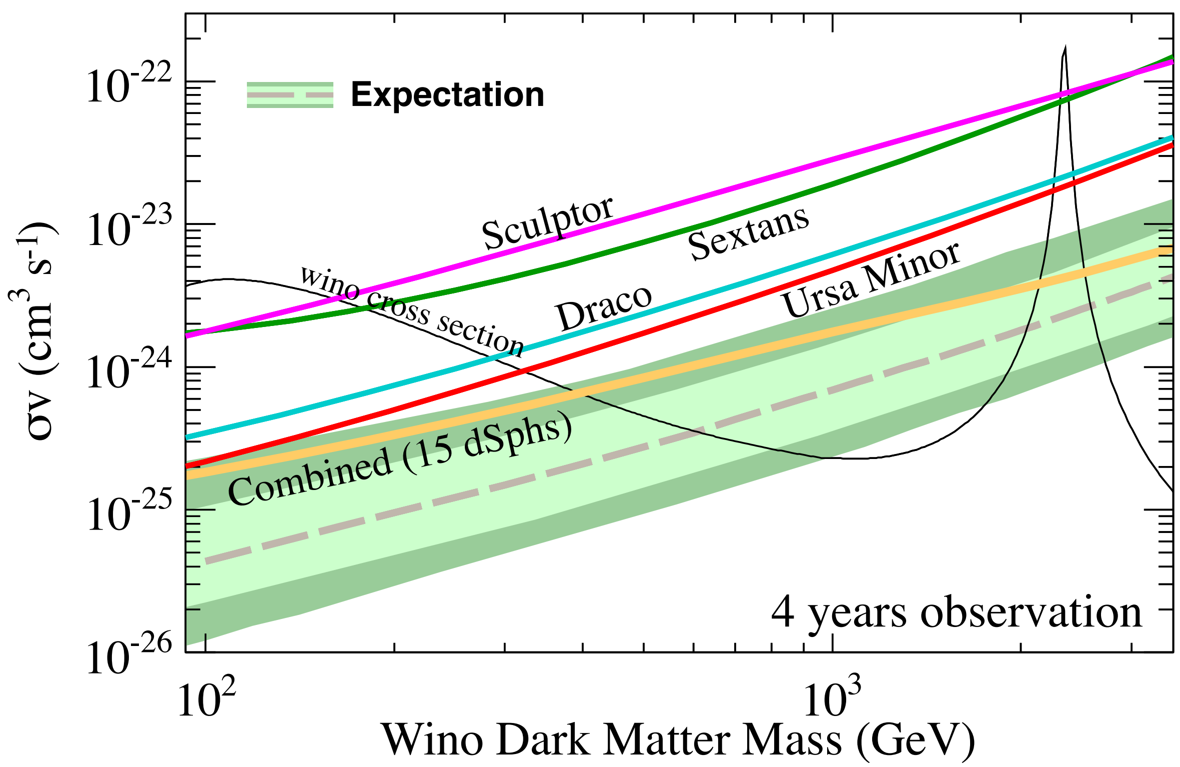
Dwarf spheroidal galaxies (dSphs)

Uncertainty from DM distribution is relatively small.

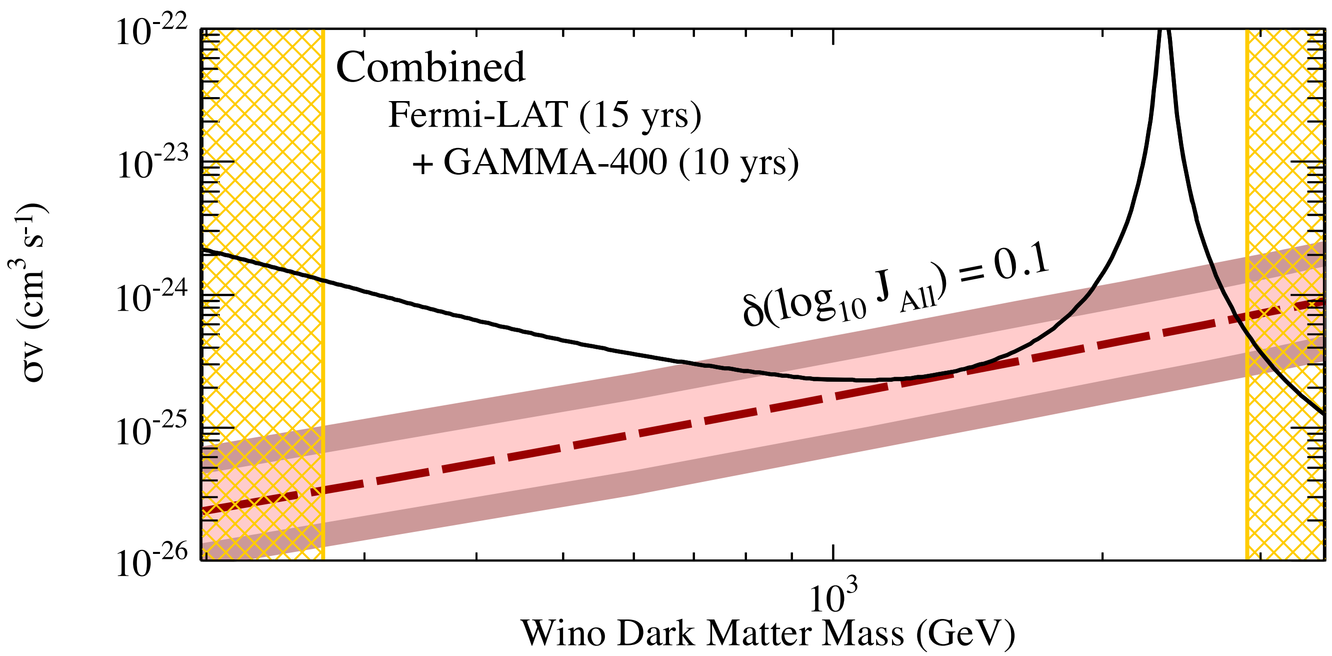
→ Gives a robust bound.

Indirect search (triplet)

Current constraint



Future prospects

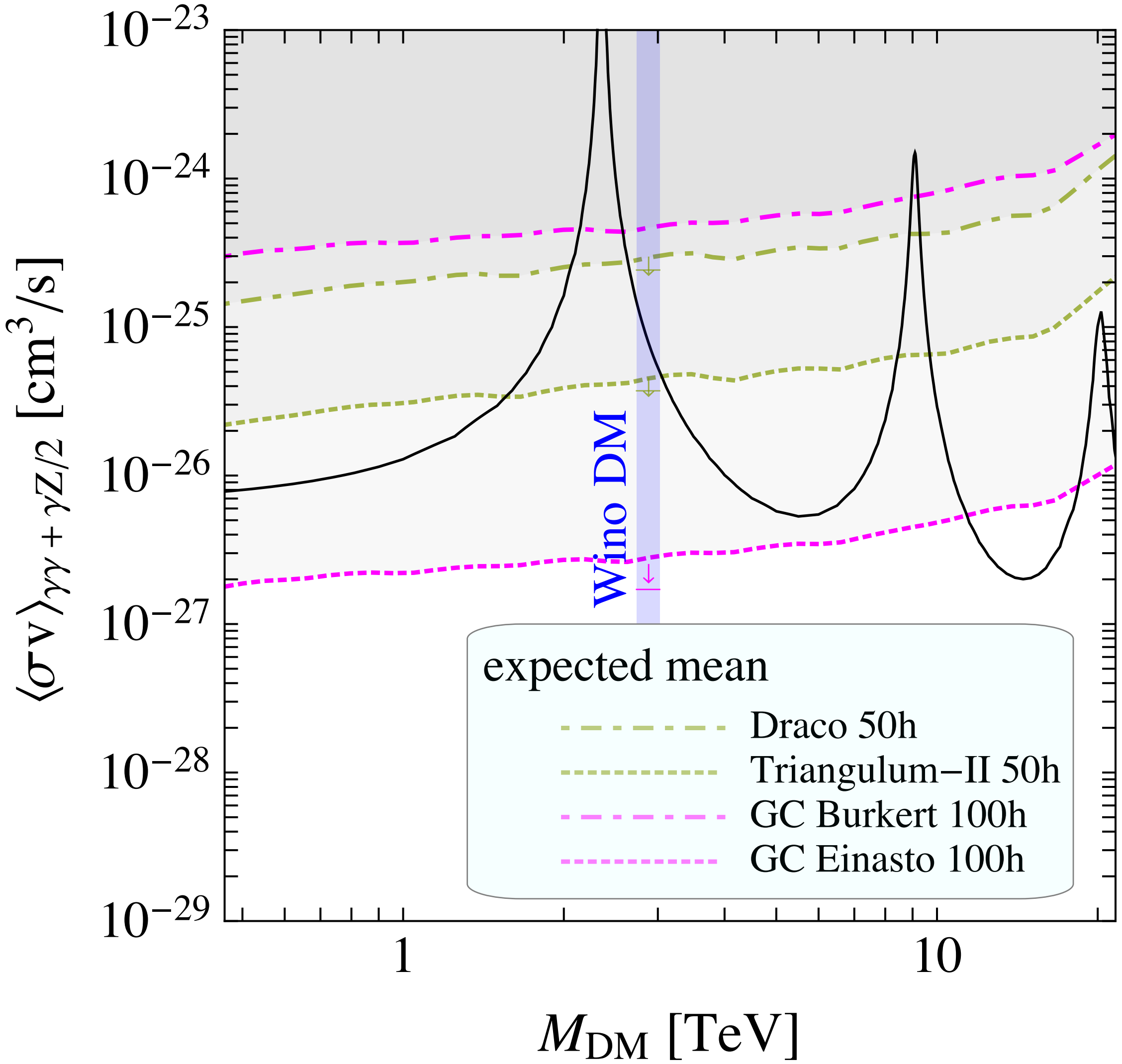


Triplet case can be tested in future experiments.

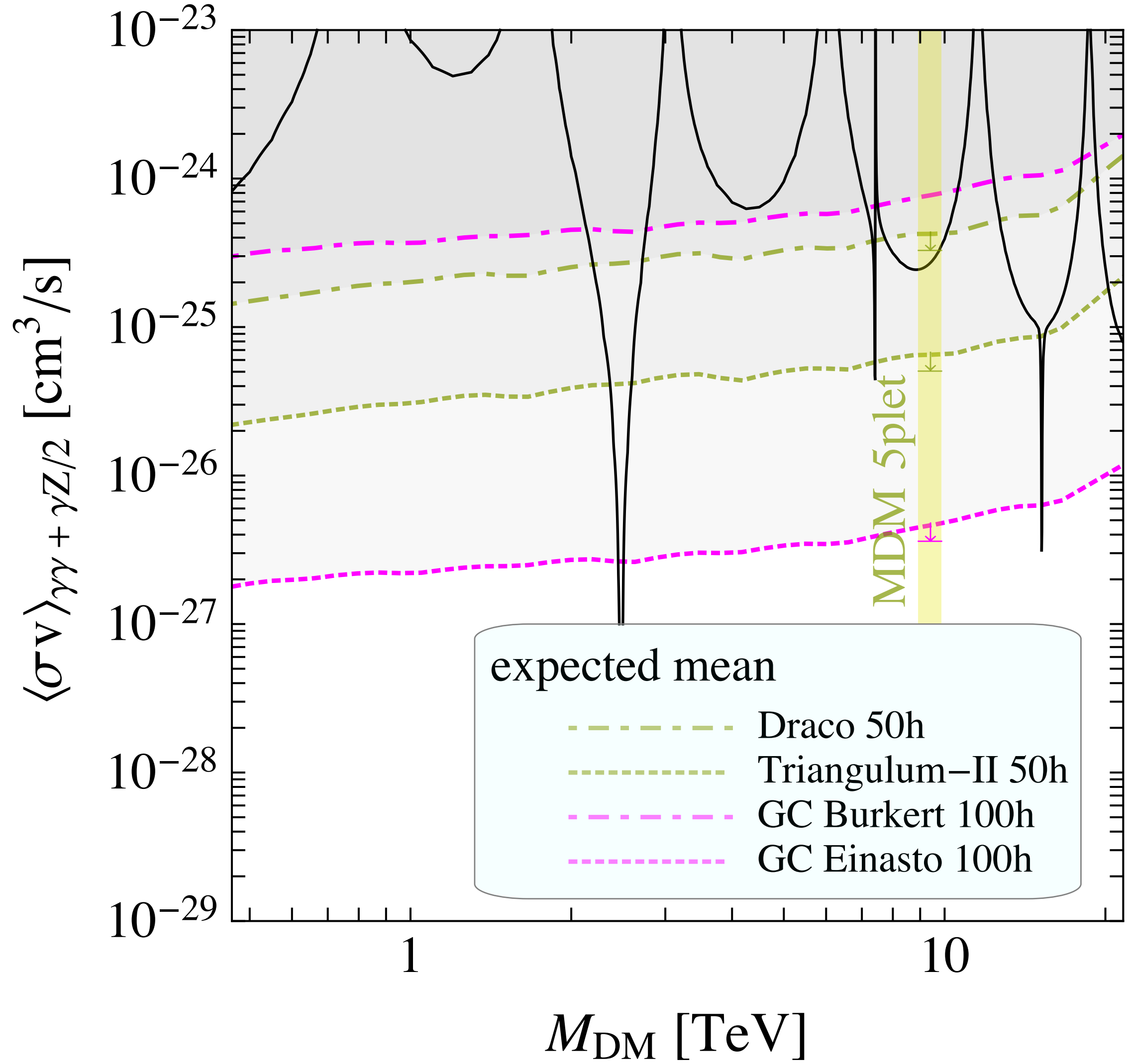
B. Bhattacherjee, M. Ibe, K. Ichikawa, S. Matsumoto, and K. Nishiyama, JHEP **1407**, 080 (2014).

CTA

Triplet case



Quintuplet case



Galactic Center γ-ray searches suffer from large uncertainty from DM density profile.

V. Lefranc, E. Moulin, P. Panci, F. Sala, and J. Silk, JCAP **1609**, 043 (2016).