Imprints of Non-thermal Wino Dark Matter on Small-Scale Structure

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Aug.29th @TeVPA

Mass Spectrum of sparticles in our paper

We take the Pure Gravity Mediation Model [M. Ibe and T. T. Yanagida, PLB, 2012]
motivated by the recent discovery of the 125 GeV Higgs-like particle by ATLAS and CMS collaboration in LHC.

In the Pure Gravity Mediation Model,
gaugino masses are given by the Anomaly Mediated Supersymmetry Breaking (AMSB), and proportional to the beta function of the corresponding gauge couplings inverse-squared.

$$M_i = -b_i \frac{g_i^2}{(4\pi)^2} m_{3/2}, \quad (b_1, b_2, b_3) = (33/5, 1, -3),$$

➡ $M_1 : M_2 : M_3 \simeq 2.8 : 1 : 8.3$ ➡ wino LSP

G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, LHEP, 1998

The other sparticles and heavy Higgsses have the masses of the order of the gravitno mass $m_{3/2} = O(100)\,\mathrm{TeV}$
via the tree-level interactions in Supergravity. (Fine tuning of 10^{-3}-10^{-5} is needed for Higgs mass.)
Large μ term leads to significant corrections to the gaugino masses,

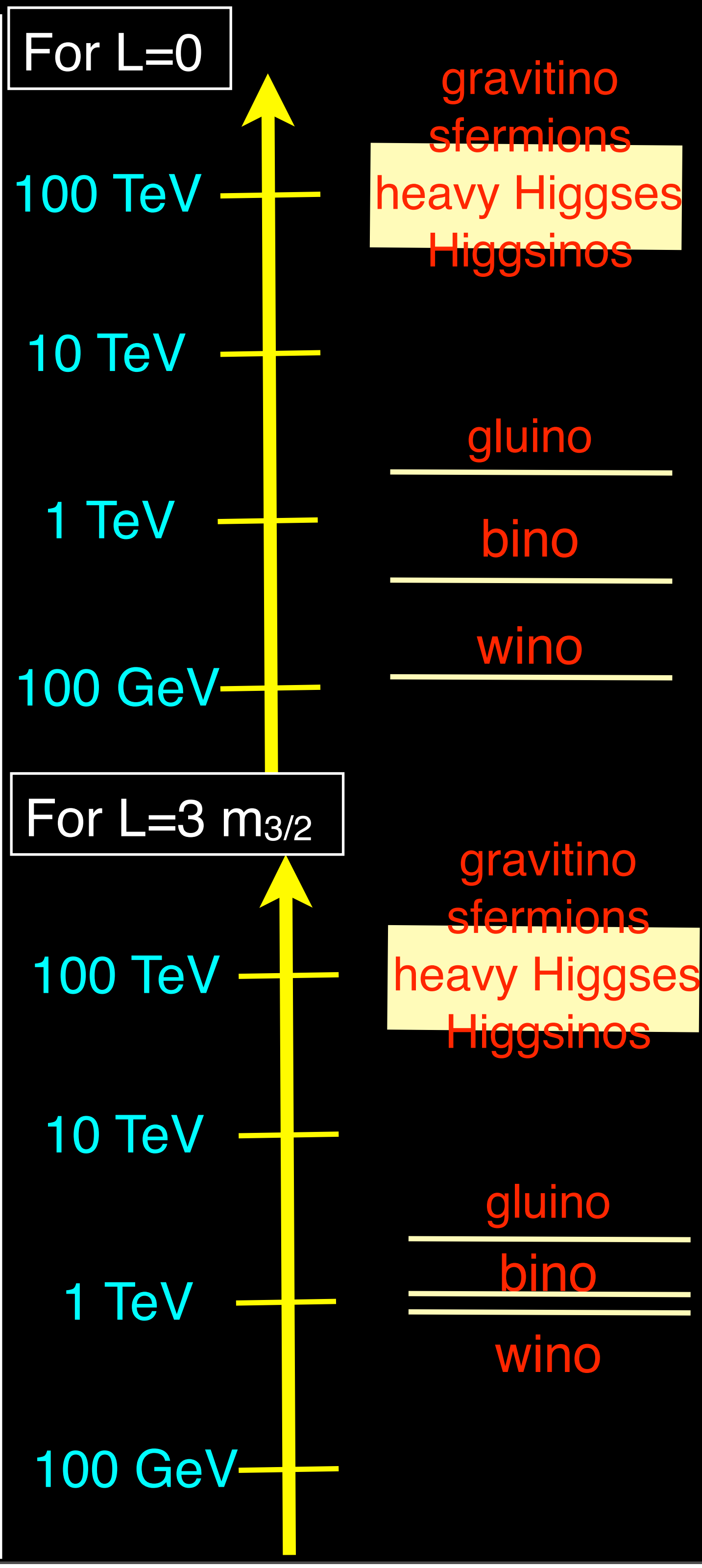
$$L = \mu \sin 2\beta \frac{m_A^2}{|\mu|^2 - m_A^2} \ln \frac{|\mu|^2}{m_A^2}$$

$$m_{\tilde{g}} \simeq 2.5 \times (1 - 0.13\,\delta_{32} - 0.04\,\delta_{\mathrm{SUSY}}) \times 10^{-2}\, m_{3/2}$$

$$m_{\tilde{w}} \simeq 3.0 \times (1 - 0.04\,\delta_{32} + 0.02\,\delta_{\mathrm{SUSY}}) \times 10^{-3}\, (m_{3/2} + L)$$

$$m_{\tilde{b}} \simeq 9.6 \times (1 + 0.01\,\delta_{\mathrm{SUSY}}) \times 10^{-3}\, (m_{3/2} + L/11)$$

$$\delta_{32,\tilde{g}} = \ln[(m_{3/2} + L)/100\,\mathrm{TeV}], \quad \delta_{32,\tilde{w}} = \ln[(m_{3/2} + L)/100\,\mathrm{TeV}]$$



Mass degeneracy of winos

Winos are weak SU(2) triplet $(\tilde{w}^+, \tilde{w}^0, \tilde{w}^-)$ and constitute vector multiplet with Standard Model (SM) W bosons. (W^+, W^0, W^-)

Charged winos $\tilde{w}^\pm$ have the same mass with neutral wino $\tilde{w}^0$ unless the weak SU(2) symmetry is not spontaneously broken.

MSSM have global $SU(2)_L \times SU(2)_R$
(in the limit of $U(1)_Y$ gauge coupling $g' \to 0$ and Yukawa couplings $y \to 0$)
$\Phi = \begin{pmatrix} H_d & H_u \end{pmatrix}$: 2×2 chiral multiplet matrix $\Phi \to U_L \Phi U_R^\dagger$
which is broken to $SU(2)_V$ for tanβ=1, $U(1)_{Cartan}$ otherwise at the spontaneous electro-weak symmetry breaking.
This custodial symmetry also prevents large mass splitting between charged winos and neutral wino. $\Delta m_{\tilde{w}} \equiv m_{\tilde{w}^\pm} - m_{\tilde{w}^0}$

With large μ term, the mass splitting at tree-level is given by,

$$\Delta m_{\tilde{w}}|_{\rm tree} = \frac{m_W^4 \sin^2 2\beta}{(M_1 - M_2)\mu^2} \tan^2\theta_W + 2\frac{m_W^4 M_2 \sin 2\beta}{(M_1-M_2)\mu^3}\tan^2\theta_W + \frac{m_W^6 \sin^3 2\beta}{(M_1-M_2)^2\mu^3}\tan^2\theta_W(\tan^2\theta_W - 1) + O(\frac{1}{\mu^4})$$

T. Gherghetta, G. F. Giudice and J. D. Wells, Nucl.Phys, 1999
J. L. Feng, T.Moroi, L. Randall, M. Strassler and S. Su, PRL, 1999

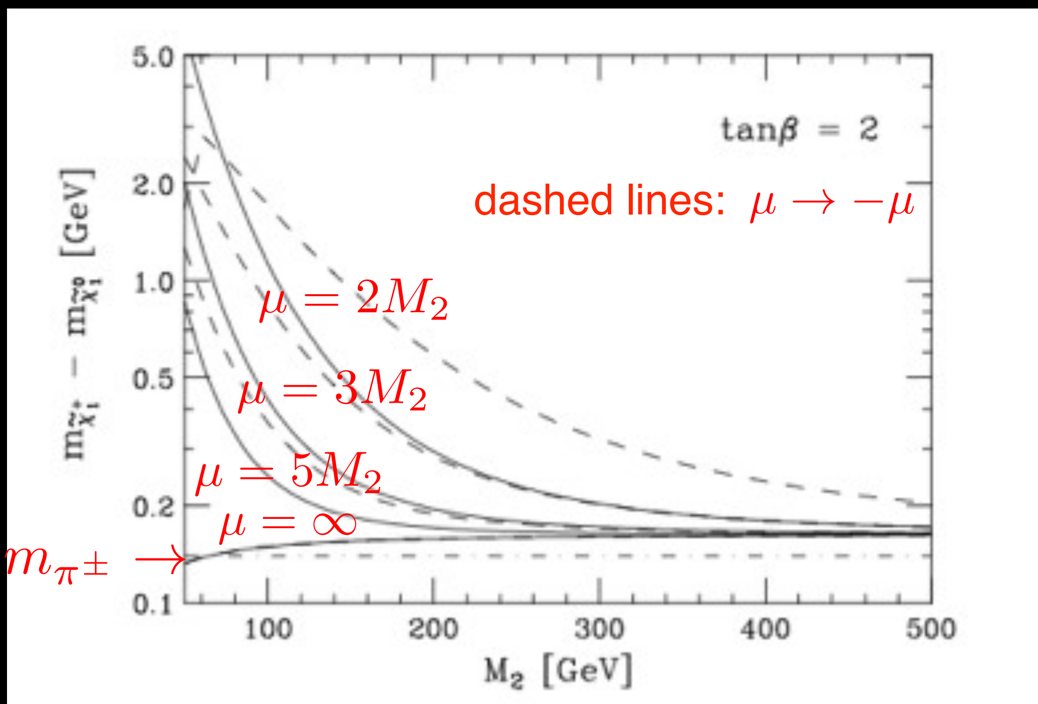
1-loop contribution from gauge boson-gaugino diagrams is given by,

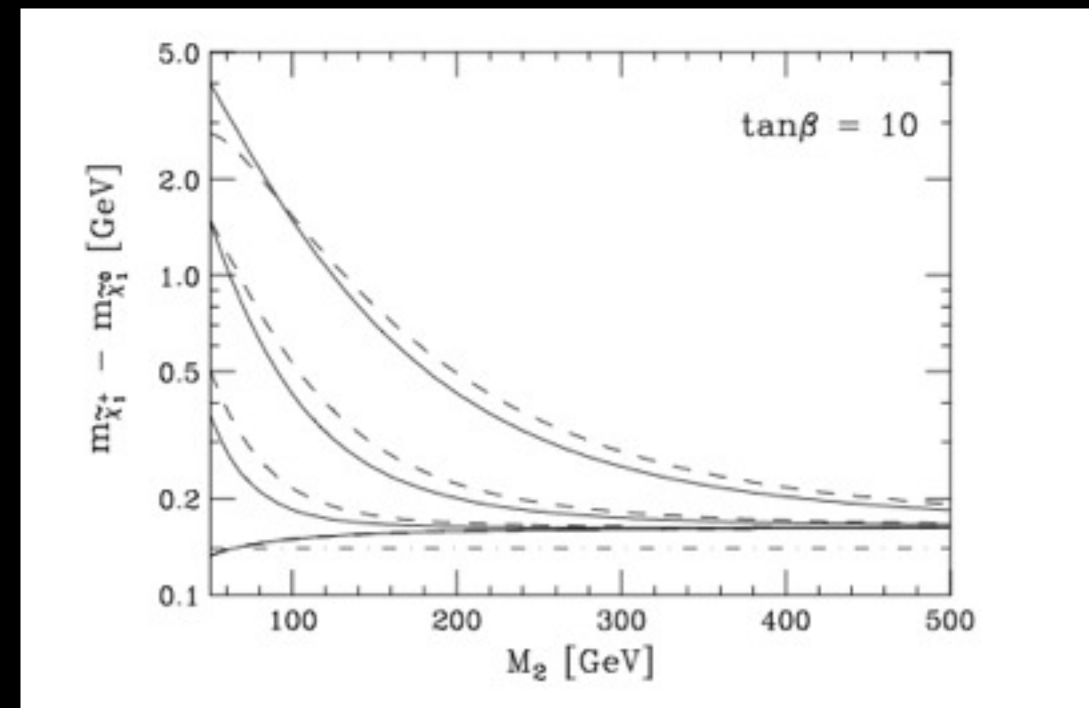
$$\Delta m_{\tilde{w}}|_{\rm 1-loop} = \frac{\alpha_2}{4\pi} M_2 \left(f\left(\frac{m_W}{M_2}\right) - \cos^2\theta_W f\left(\frac{m_Z}{M_2}\right) - \sin^2\theta_W f\left(\frac{0}{M_2}\right)\right), \quad f(r) \equiv \int_0^1 dx 2(1+x)\ln(x^2 + (1-x)r^2).$$

These contributions vanish in the custodial symmetry limit, $g' \to 0$ and $\tan\beta \to 1$.

Mass degeneracy of winos

The mass splitting is very small $\Delta m_{\tilde{w}} \simeq 160 - 170\,\mathrm{MeV}$
compared with the wino mass $m_{\tilde{w}} \simeq 100 - 1000\,\mathrm{GeV}$ in large μ limit.

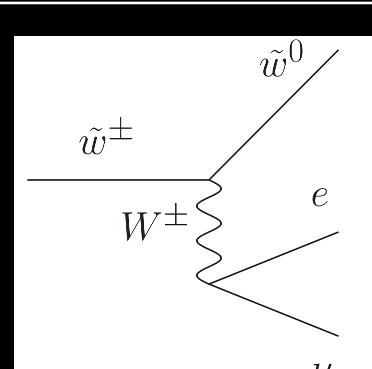




T. Gherghetta, G. F. Giudice and J. D. Wells, Nucl.Phys, 1999

This small mass splitting leads to phase space suppression of the leptonic three body decay of the charged wino. The charged wino decays into the neutral wino and the charged pion with relatively long lifetime

$$\tau \simeq 1.2 \times 10^{-10} s \times \left(\frac{160\,\mathrm{MeV}}{\Delta m_{\tilde{w}}}\right)^3 \left(1 - \frac{m_{\pi^\pm}}{\Delta m_{\tilde{w}}^2}\right)^{-1/2}.$$



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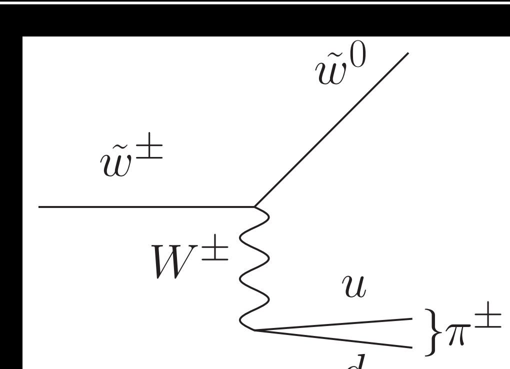
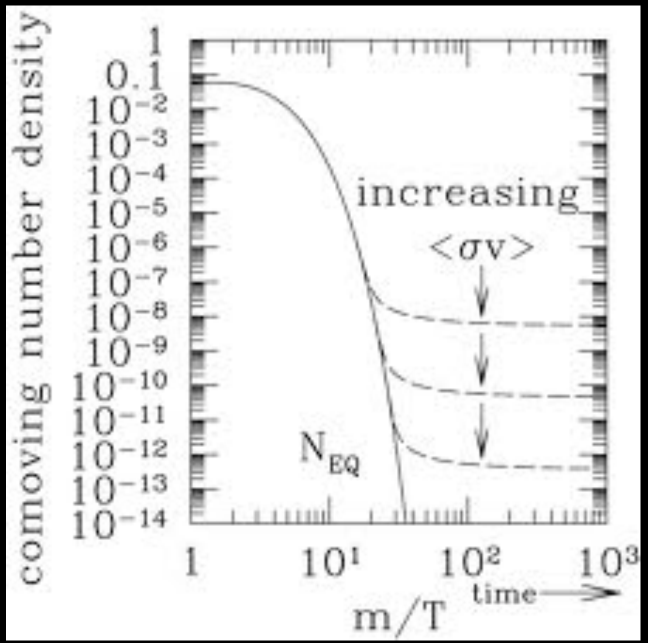
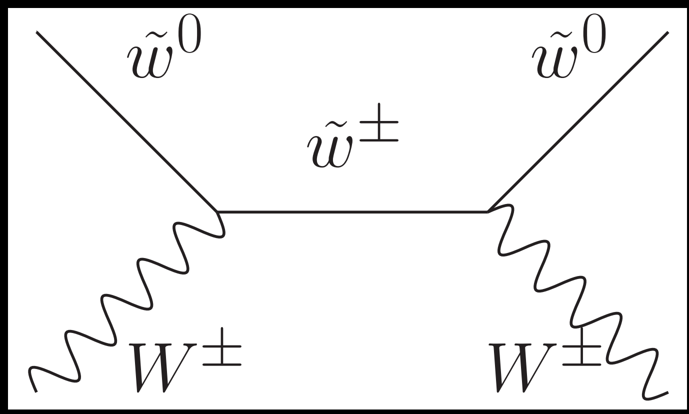


Thermal relic of wino



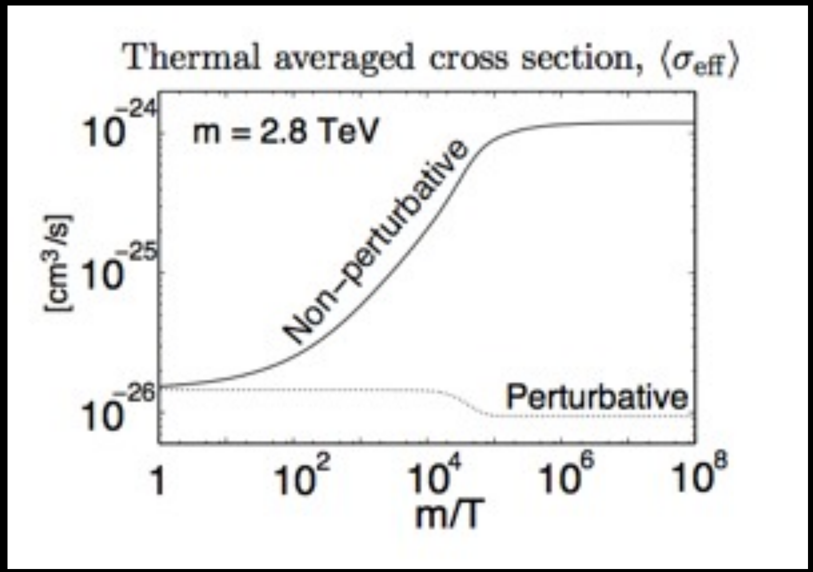
The annihilation cross section of non-relativistic neutral wino is too large to explain the observed relic abundance of dark matter

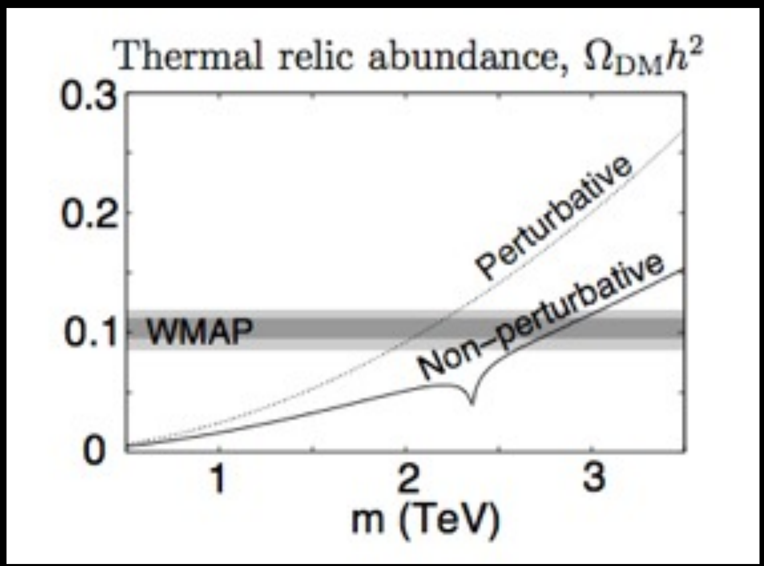
From standard Lee-Weinberg formula,
$\sigma v = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \simeq 3 \times 10^{-9}\,\mathrm{GeV}^{-2}$
is required.



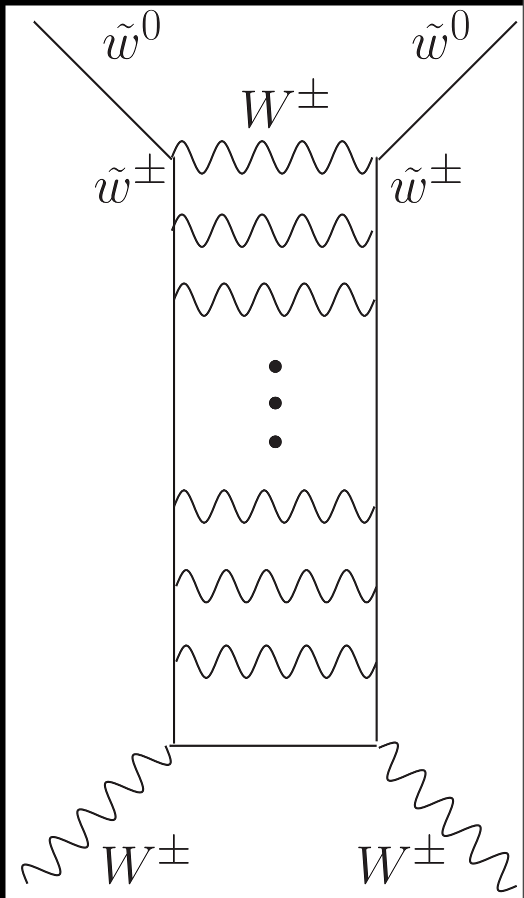
$$\sigma v = \frac{2\pi\alpha_2^2}{m_{\tilde{w}}^2} \simeq 3 \times 10^{-9}\,\mathrm{GeV} \times \left(\frac{1000\,\mathrm{GeV}}{m_{\tilde{w}}}\right)^2$$

Furthermore, the annihilation cross section of non-relativistic neutral wino is affected by the surrounding relic charged wino (coannihilation) and non-perturbative effect due to exchange of gauge bosons in initial state (Sommerfeld Enhancement).





For thermal wino dark matter, $m_{\tilde{w}} \simeq 2.9\mathrm{TeV}$ is required.



J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami, PLB, 2007

Non-thermal relic of wino

For wino dark matter with $m_{\tilde{w}} \lesssim 2.9\mathrm{TeV}$, we need to late time production mechanism (after the chemical decoupling of thermal winos) in order to explain the present dark matter density.

One of such mechanisms is late time decays (after the chemical decoupling of winos) of long-lived particles such as the moduli and the gravitino.
The relic abundance of wino dark matter (with mass of $\bar{m}_{\rm wino} \sim 100 - 1000\,\mathrm{GeV}$)
is determined by the

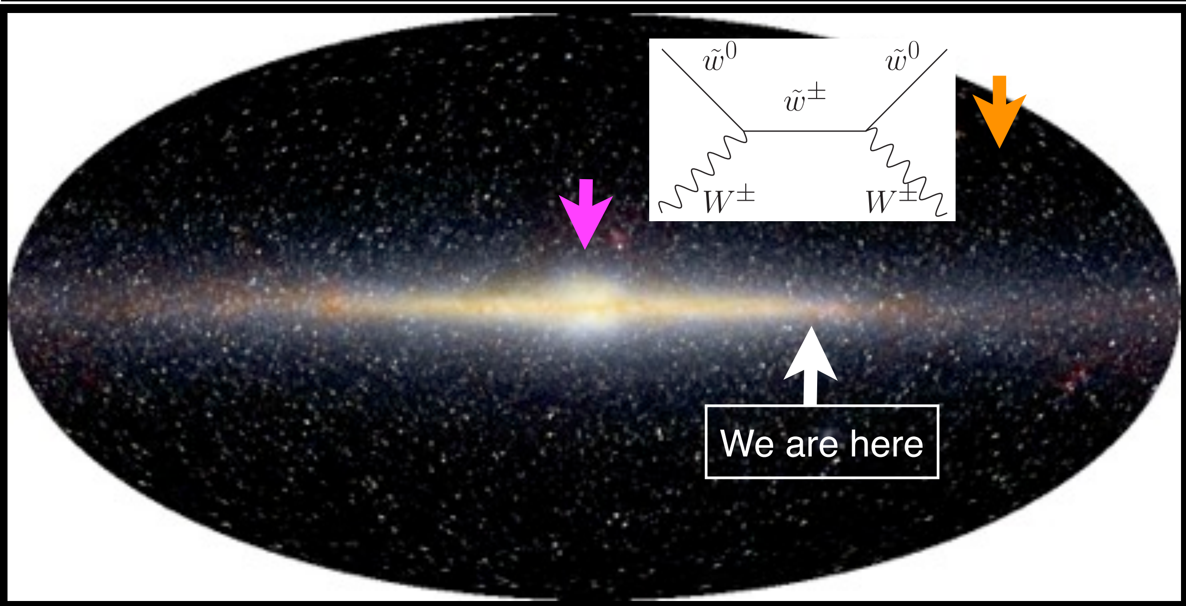
T. Moroi and L. Randall, Nucl.Phys, 2000

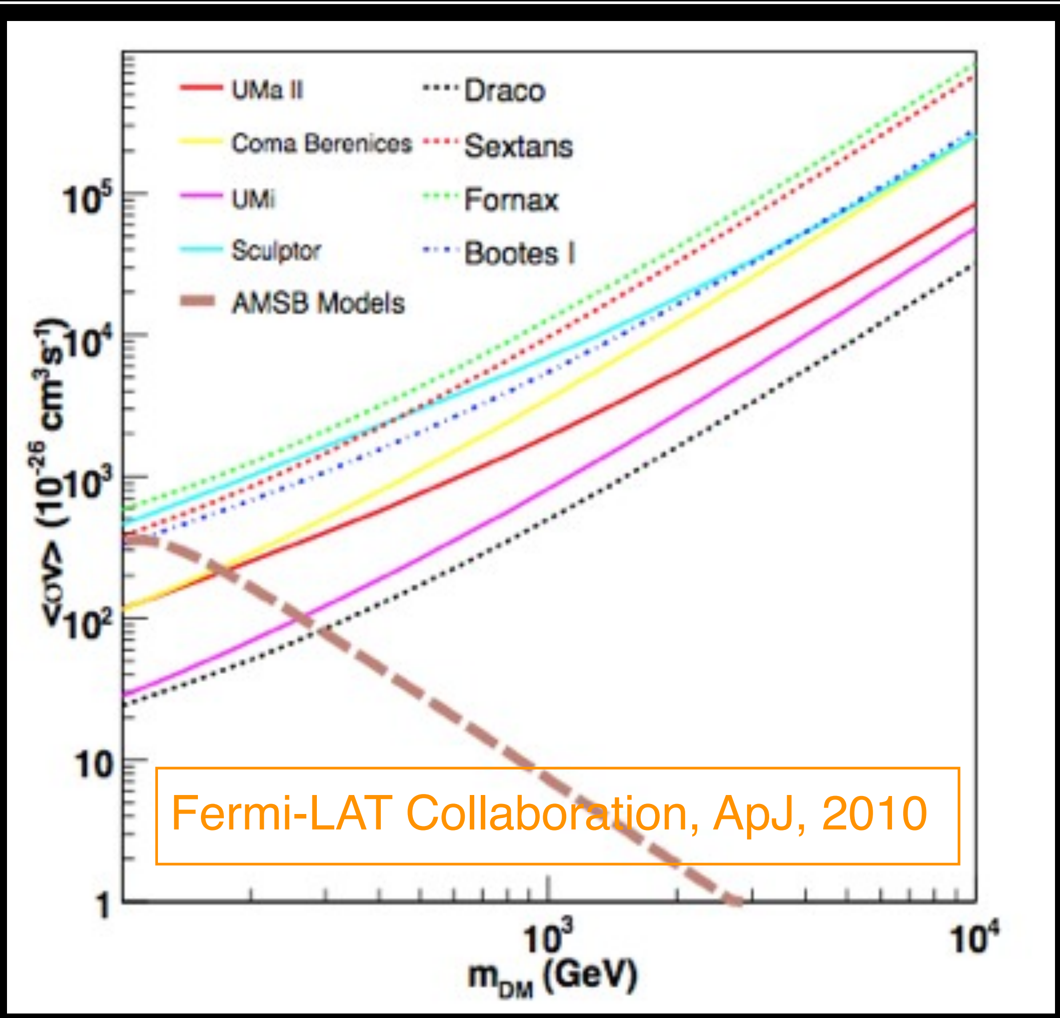
Branching ratio of the moduli decay into the wino, $\bar{N}_{\rm wino} (\sim 10^{-4} - 10^{-2})$
for the moduli decay and
Reheating temperature $T_{\rm RH} \sim 10^{9} - 10^{10}\mathrm{GeV}$ for the gravitino decay.
In this talk, we focus on the case of the gravitino decay.

$$\Omega_{\rm wino}^{\rm NT} h^2 \simeq 0.16 \times \left(\frac{m_{\tilde{w}}}{300\,\mathrm{GeV}}\right) \left(\frac{T_{\rm RH}}{10^{10}\,\mathrm{GeV}}\right)$$

Indirect detection

Wino dark matter annihilates into W boson pairs $\tilde{w}^0 + \tilde{w}^0 \to W^\pm + W^\pm$.
By the cascade decay of the W bosons, charged particles ($\bar{e}$, $\bar{p}$) and high-energy photon (γ) are produced and propagate to us.
Since the annihilation rate is proportional to the square of the dark matter density,
$\Gamma_{\rm ann} \propto \rho_{\rm dm}^2$, $\rho_{\rm dm} = \dfrac{\rho_s r_s^3}{r(r_s + r)^2}$: Navarro-Frenk-White (NFW) profile,
we have two main targets: Galactic center and Milky-Way dwarf spheroidals (dSphs)





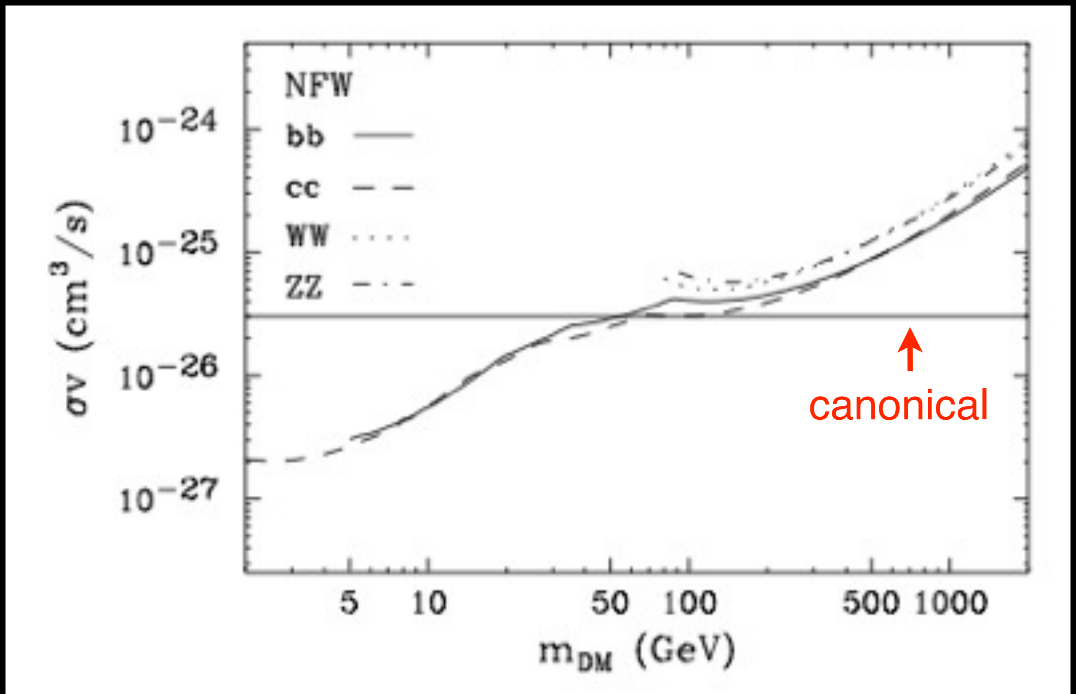
For γ-ray search, until recently, dSphs (especially, Draco due to its large core) gives the most stringent constraint on the wino mass.

Wino mass should be larger than 300 GeV, while there are both theoretical (possibility of the other profile than NFW) and observational (small number of the sample stellar velocities) ambiguities in the determination of the dark matter profile.

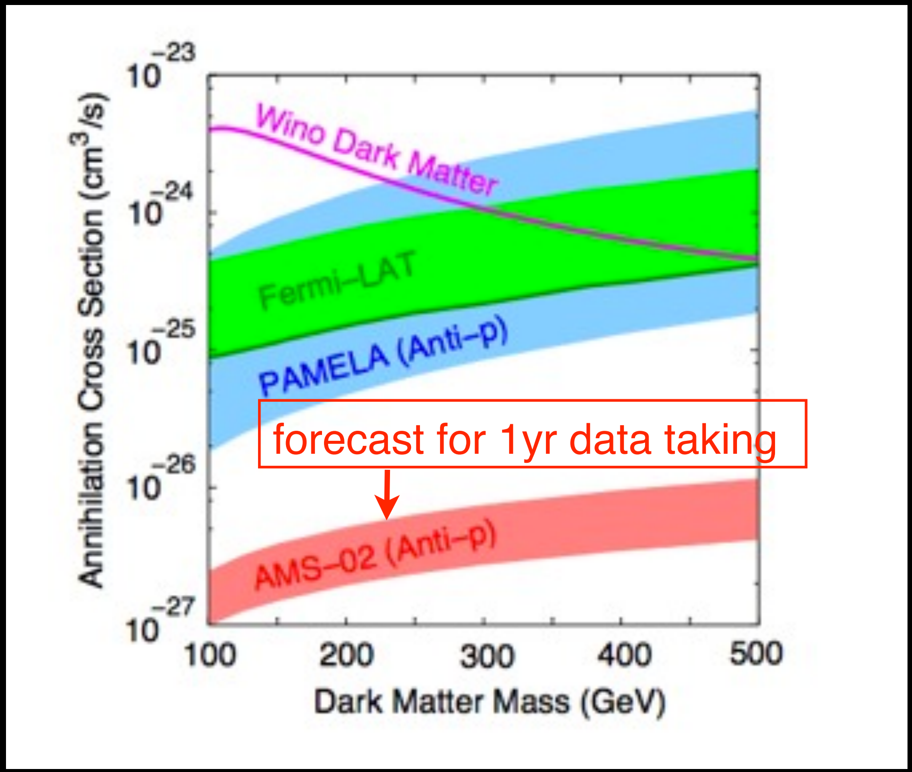
Indirect detection

Recently, Dan Hooper *et al.* uses the data from Galactic center of the Fermi Gamma-Ray Space Telescope (FGST) and set very stringent constraints on the annihilation cross section of the dark matter. The limits almost reach the canonical value of the annihilation cross section $\sigma v = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$.

D. Hooper, C. Kelso and F. S. Queiroz, ASP, 2013



Charged particles ($\bar{e}$, $\bar{p}$) are affected by the Galactic magnetic field and interstellar medium (ISM). Thus, there are ambiguities in the propagation model as well as in the determination of the dark matter profile.



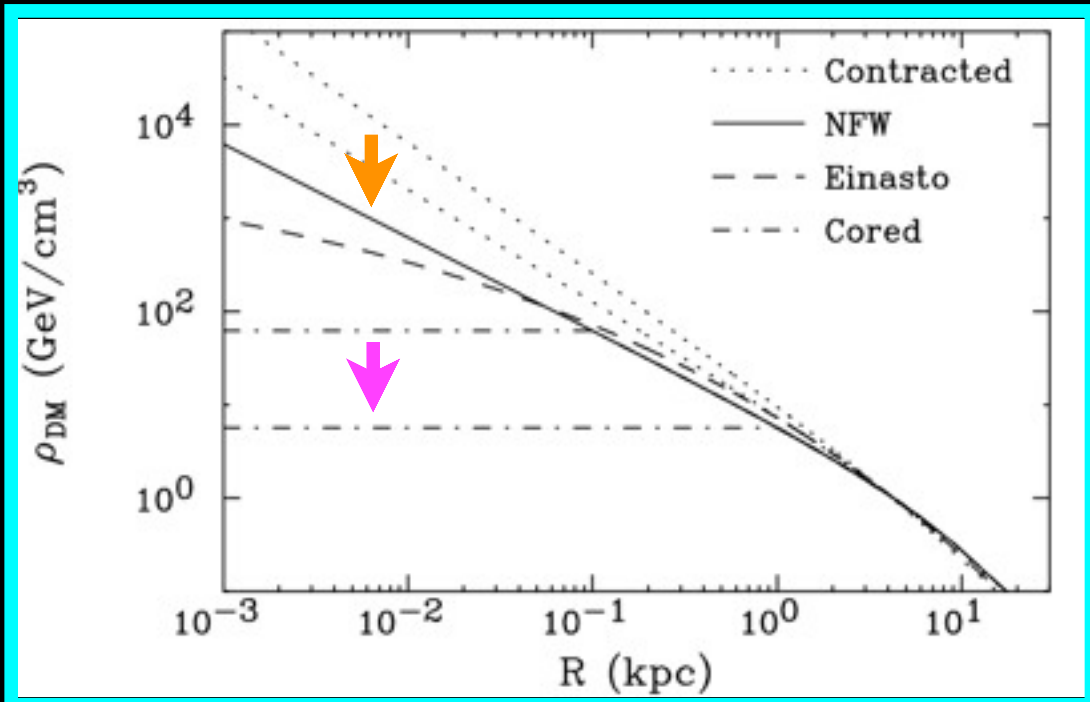
At present, wino dark matter should be heavier than 300-1000 GeV with ambiguities.

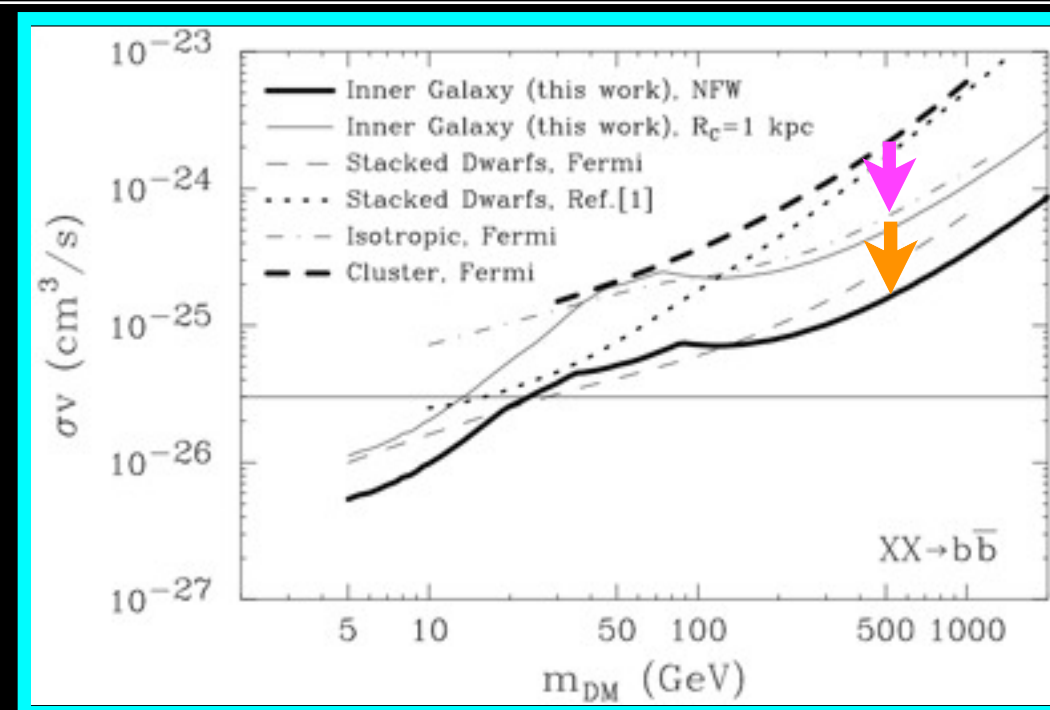
By astrophysical observations, we may determine the mass of the wino dark matter.
If future astrophysical observations would tell us that the dark matter should be wino with mass of e.g. 1.0 TeV, it would be non-thermally produced.

M. Ibe, S. Matsumoto, T.Yanagida, PRD, 2012

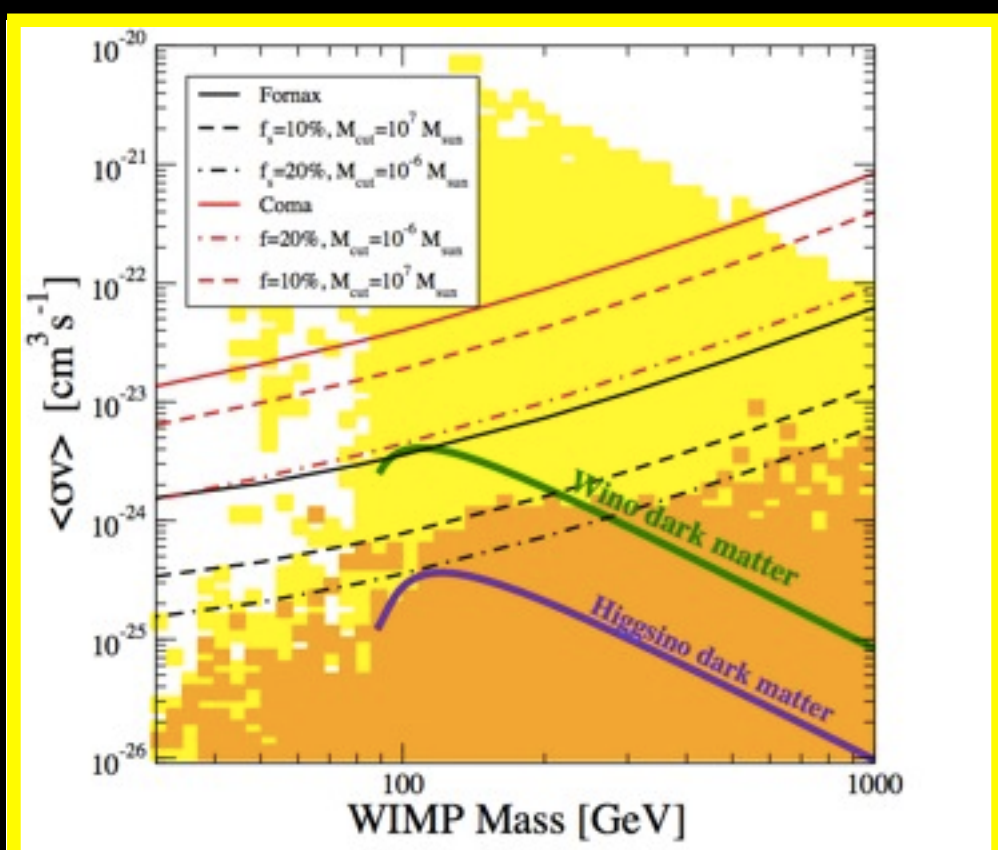
Boost Factor

The (constraint on) annihilation cross section obtained from the indirect search suffers from the astrophysical uncertainty,
e.g. density profile of dark matter, existence of substructure.





D. Hooper, C. Kelso and F. S. Queiroz, ASP, 2013

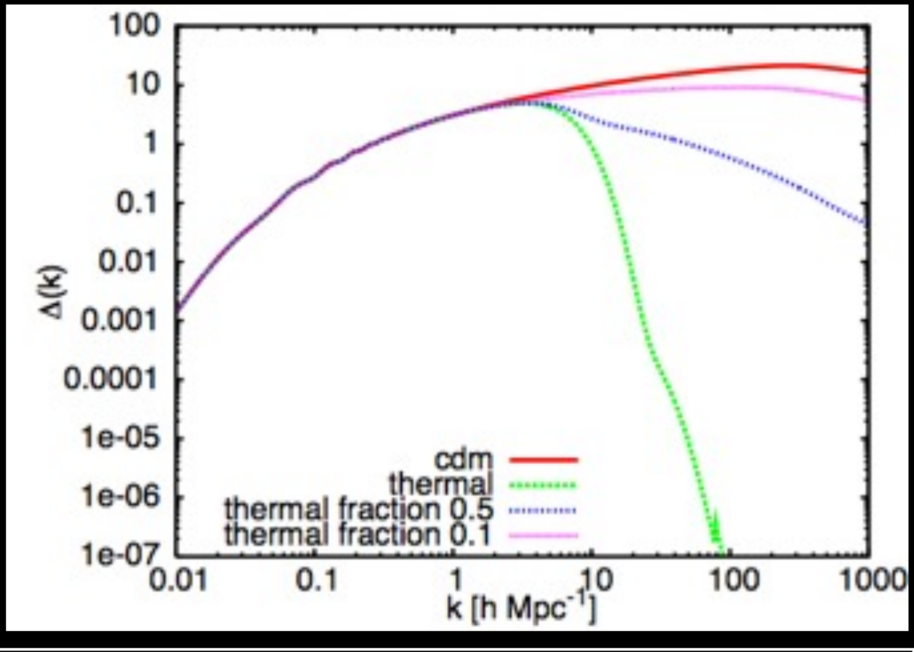


Fermi-LAT Collaboration, JCAP, 2010

The simulations of the structure formation is basically based on the ΛCDM cosmology.
First of all, is wino dark matter always cold dark matter?

Non-thermal wino production by decays of the Gravitino

Non-thermal winos produced by the decay of the gravitino are relativistic at the time of the decay. If the winos do not loose their energy, they have non-negligible velocity at the time of the matter-radiation equality and succeeding structure formation era to leave the imprints on the matter power spectra. In other word, they may be warm dark matter.



The momentum of the winos at the time of the gravitino decay is proportional to the gravitino mass. However, the decay temperature is proportional to the gravitino mass to the power of 3/2 to lead the smaller comoving wino momentum for heavier gravitino.

$$T_d \simeq 3.8\,\mathrm{MeV} \times \left(\frac{m_{3/2}}{100\,\mathrm{TeV}}\right)^{3/2}$$

$$p_{\mathrm{w,\,typical}}(t_0) \simeq 2.1 \times 10^{-6}\,\mathrm{GeV} \times \left(\frac{m_{3/2}}{100\,\mathrm{TeV}}\right)^{-1/2}$$

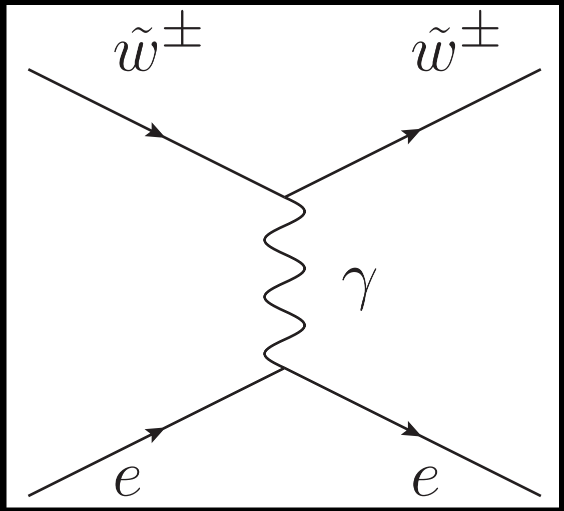
This is a somewhat direct search of the mass spectrum other than wino mass.

However, winos (especially charged winos) interact with the thermal background and loose their energy. The energy loss rate of the charged winos via the Coulomb scattering with electrons/positrons takes the form;

$$-\frac{dE_{\tilde{w}^\pm}}{dt} = \frac{\pi\alpha^2 T^2}{3}\Lambda\left(1 - \frac{m_{\tilde{w}}^2}{2E_{\tilde{w}^\pm}^2}\ln\left(\frac{E_{\tilde{w}^\pm}+p_{\tilde{w}^\pm}}{E_{\tilde{w}^\pm}-p_{\tilde{w}^\pm}}\right)\right)$$

where $\Lambda \sim O(1)$ is the Coulomb Logarithm.

M. H. Reno and D. Seckel, PRD, 1988

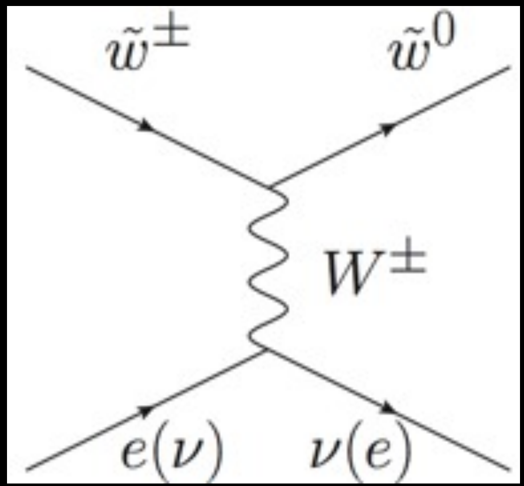


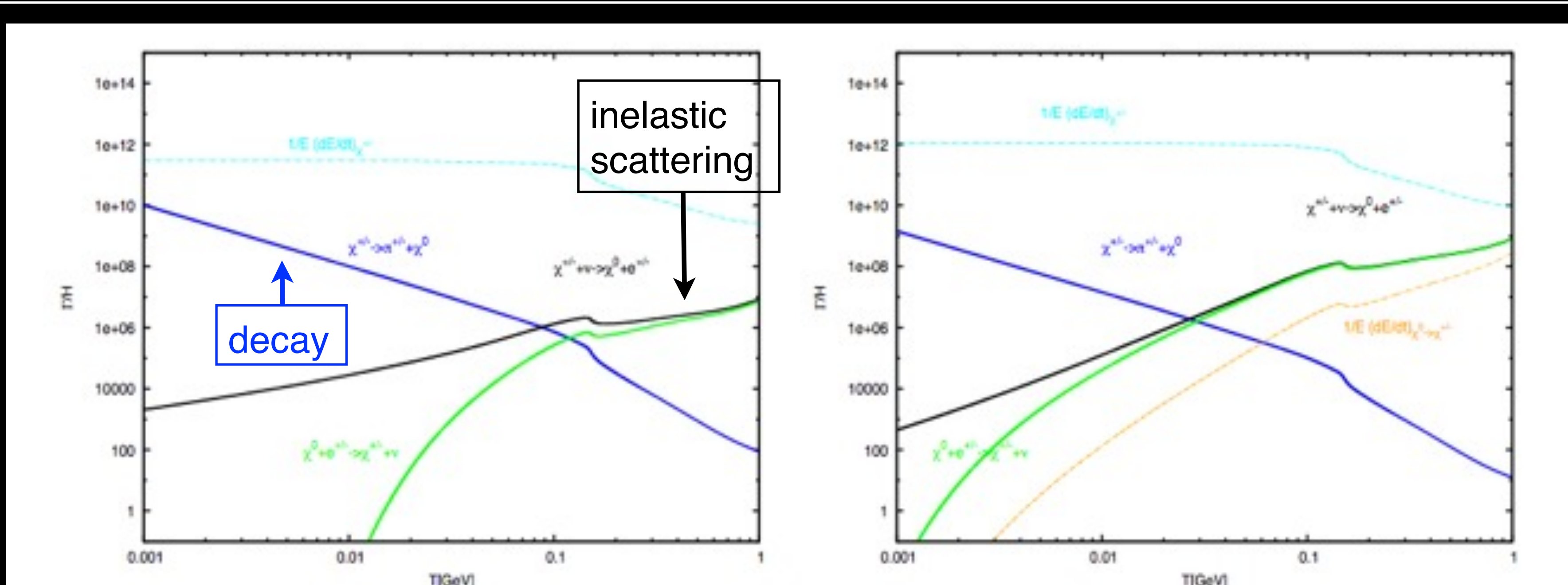
energy loss of the Charged winos

The relatively long lifetime of the charged winos allows the charged winos to lose their non-thermal energy and be in kinetic equilibrium with the thermal background before they decay into neutral winos.
The energy loss in one lifetime of charged winos is given by,

$$\frac{\Delta E_{\tilde{w}^\pm}}{E_{\tilde{w}^\pm}}\bigg|_{1-\mathrm{lifetime}} \simeq 97\Lambda\left(1-\frac{m_\pi^2}{\Delta m_{\tilde{w}}^2}\right)^{-1/2}\left(\frac{T}{1\,\mathrm{MeV}}\right)^2\left(\frac{160\,\mathrm{MeV}}{\Delta m_{\tilde{w}}}\right)^3\left(\frac{100\,\mathrm{GeV}}{m_{\tilde{w}}}\right)\left(1-\frac{m_{\tilde{w}}^2}{2E_{\tilde{w}^\pm}^2}\ln\left(\frac{E_{\tilde{w}^\pm}+p_{\tilde{w}^\pm}}{E_{\tilde{w}^\pm}-p_{\tilde{w}^\pm}}\right)\right).$$

Charged winos could also turn into neutral winos via the inelastic scattering with leptons. But, the inelastic scattering is subdominant at the cosmic temperature of interest.





(a) Case 1: $m_\chi = 103.5$ GeV, $T_R = 100$ MeV, $E/m_\chi = 1.005$. (b) Case 2: $m_\chi = 103.5$ GeV, $T_R = 100$ MeV, $E/m_\chi = 10$.

G. Arcadi and P. Ullio, PRD, 2011

2/3 of all the winos produced by the gravitino decay are charged winos, which decay into cold neutral winos after energy loss.

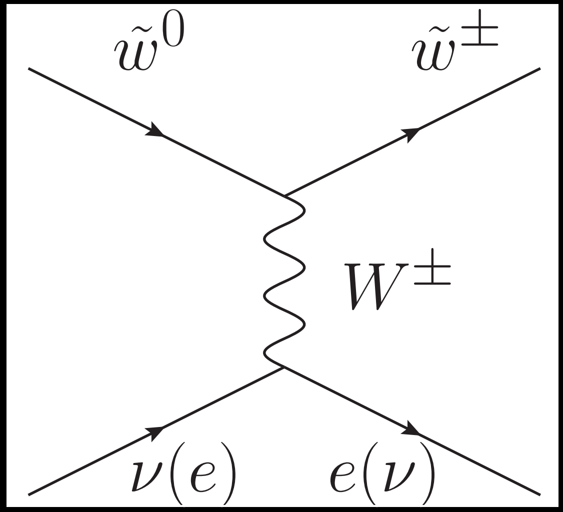
energy loss of the Neutral winos

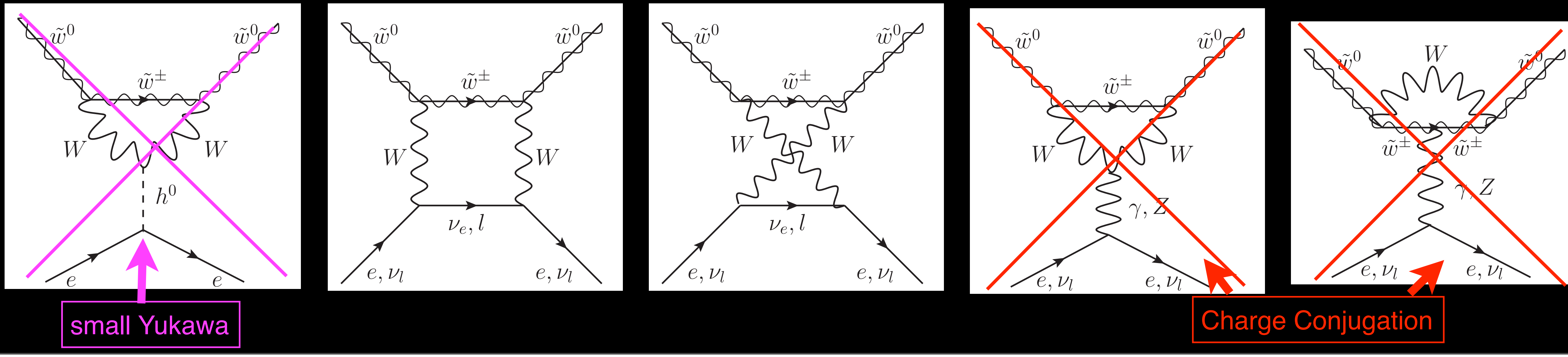
Neutral winos themselves do not have energy loss process at the tree level in the pure wino limit with heavy sfermions. Neutral winos, however, turn into charged winos via the inelastic scattering with the thermal background. Once neutral winos turn into charged winos, they loose their energy immediately and decay into cold neutral winos.
The inelastic scattering rate is given by, J. Hisano, K. Kohri and M. M. Nojiri, PLB, 2001

$$\Gamma_{\tilde{w}^0,\,\mathrm{inelastic}} = \frac{8}{\pi^3} G_F^2 T^5 \frac{(E_{\tilde{w}^0}+p_{\tilde{w}^0})^4}{m_{\tilde{w}}^2 E_{\tilde{w}^0} p_{\tilde{w}^0}} \left(6 + 2\frac{m_{\tilde{w}}}{E_{\tilde{w}^0}+p_{\tilde{w}^0}} \frac{\Delta m_{\tilde{w}}}{T}\right) \exp\left(-\frac{m_{\tilde{w}}}{E_{\tilde{w}^0}+p_{\tilde{w}^0}} \frac{\Delta m_{\tilde{w}}}{T}\right).$$

The last factor represents the kinematical suppression of the inelastic scattering (Boltzmann suppression)

The Boltzmann suppression means a sudden drop of the inelastic scattering rate as the Universe cools down. The elastic energy loss process may become dominant at the low temperature. The external 4-momentum of the thermal back ground particle is smaller than the wino mass and weak boson mass.
$O(E_{\tilde{w}} T / m_{\tilde{w}}) \ll m_{\tilde{w}}, m_W$ ➡ effective Lagrangian approach





energy loss of the Neutral winos

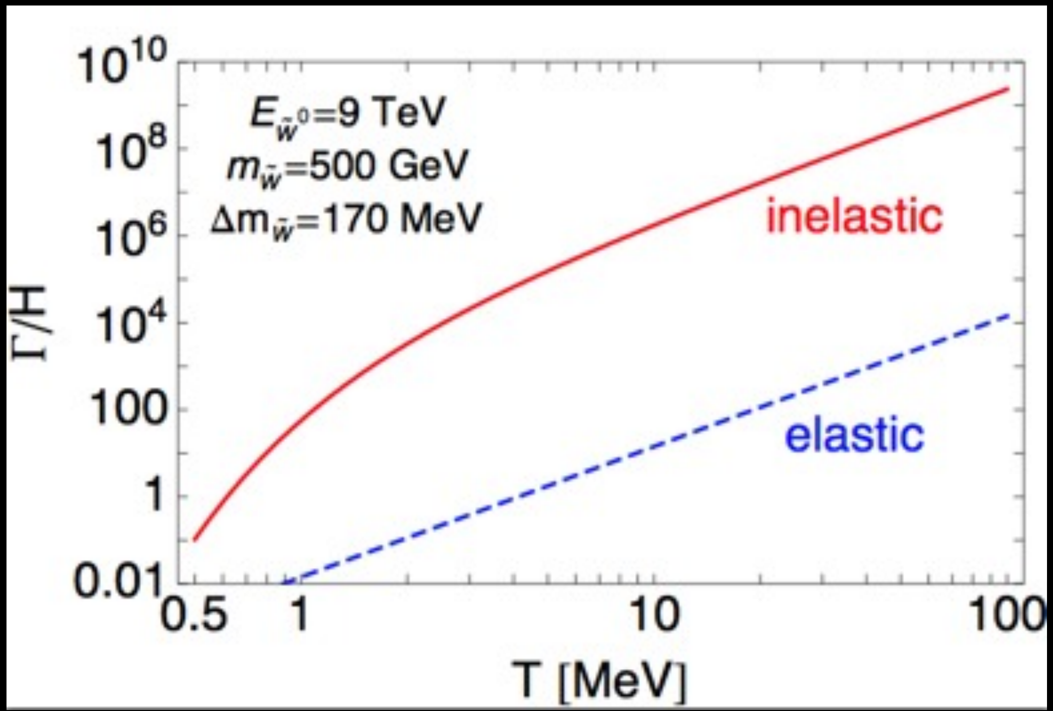
The effective Lagrangian takes a form in terms of the 4-component fermion,

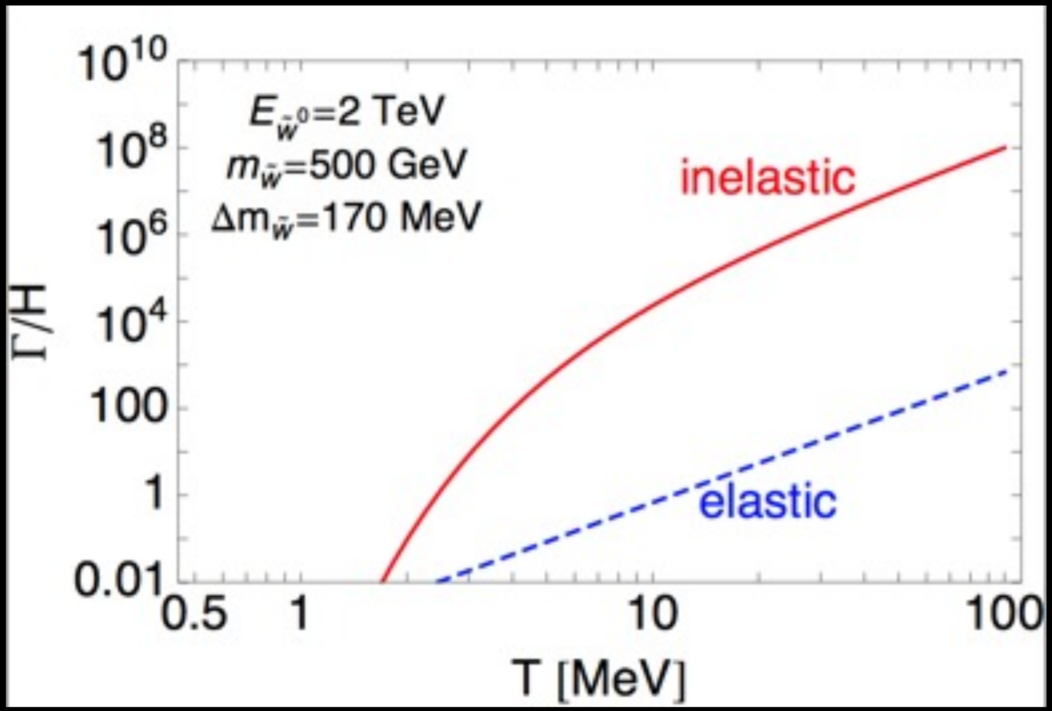
$$\mathcal{L}_{\rm int}^{\rm eff} = \sum_{f=e,\nu_e,\nu_\mu,\nu_\tau} \frac{1}{2} g_{\rm loop}\left(\frac{m_W^2}{m_{\tilde{w}}^2}\right) G_F^2 m_W^2 \, \bar{\tilde{w}}^0 \gamma_\mu \gamma_5 \tilde{w}^0 \, \bar{f}\gamma^\mu P_L f$$

with $g_{\rm loop}(x) = \frac{1}{3\pi^2}\left(\frac{\sqrt{x}}{\sqrt{1-x/4}}(8-x-x^2)\arctan\left(\frac{2\sqrt{1-x/4}}{\sqrt{x}}\right) - x\,(2-(3+x)\ln x)\right)$.

By using this effective Lagrangian, we calculate the elastic scattering rate.

$$\Gamma_{\tilde{w}^0,\,\rm elastic} = \frac{135}{\pi^3}\zeta(5) g_{\rm loop}^2 \left(\frac{m_W^2}{m_{\tilde{w}}^2}\right) G_F^4 T^5 m_W^4 \frac{E_{\tilde{w}^0}^2}{m_{\tilde{w}}^2}\left(1+\frac{p_{\tilde{w}^0}^2}{E_{\tilde{w}^0}^2}\right)$$





The elastic scattering is subdominant for the relevant parameter region of our study. We care about only the energy loss via the inelastic scattering.

Boltzmann equation of the ``warm'' winos

The above observations make the Boltzmann equations of the ``warm'' winos short and clear. It is a closed differential equation for the phase space density of the ``warm'' winos with source term by the gravitino decay (a factor of 1/3 represents the fact that only the neutral winos can be ``warm'') and damping term by the inelastic scattering.

$$\frac{\partial}{\partial t} f_{\rm w}(p_{\rm w}, t) - H p_{\rm w} \frac{\partial}{\partial p_{\rm w}} f_{\rm w}(p_{\rm w}, t) = \frac{1}{3} \frac{d\Gamma_{3/2}}{d^3 p_{\rm w}} \frac{a(t_0)^3}{a(t)^3} e^{-\Gamma_{3/2} t} - \Gamma_{\tilde{w}^0,\,{\rm inelastic}} f_{\rm w}(p_{\rm w}, t)$$

Here, $p_{\rm w}$ is the physical momentum of the ``warm'' winos and we normalize the phase space density $f_{\rm w}(p_{\rm w},t)$ by the present number density of the dark matter (Thus, $f_{\rm w}(p_{\rm w},t)$ has a dimension of mass^{-3}).

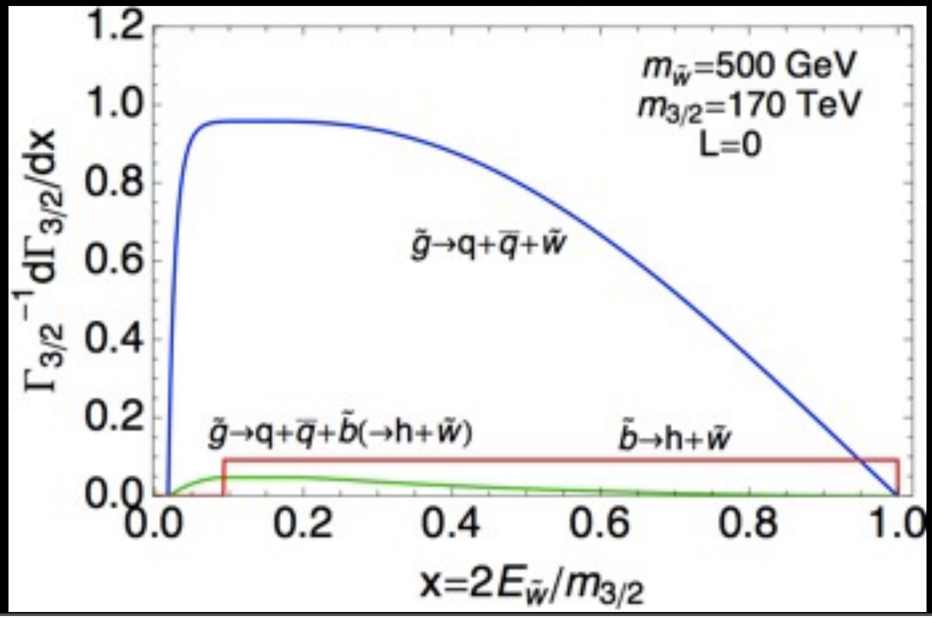
The energy spectrum of the winos at the gravitino decay $\frac{d\Gamma_{3/2}}{dE_{\rm w}} \left(= \frac{4\pi p_{\rm w}^2}{(2\pi)^3} \frac{E_{\rm w}}{p_{\rm w}} \frac{d\Gamma_{3/2}}{d^3 p_{\rm w}} \right)$ is obtained by the direct calculation.

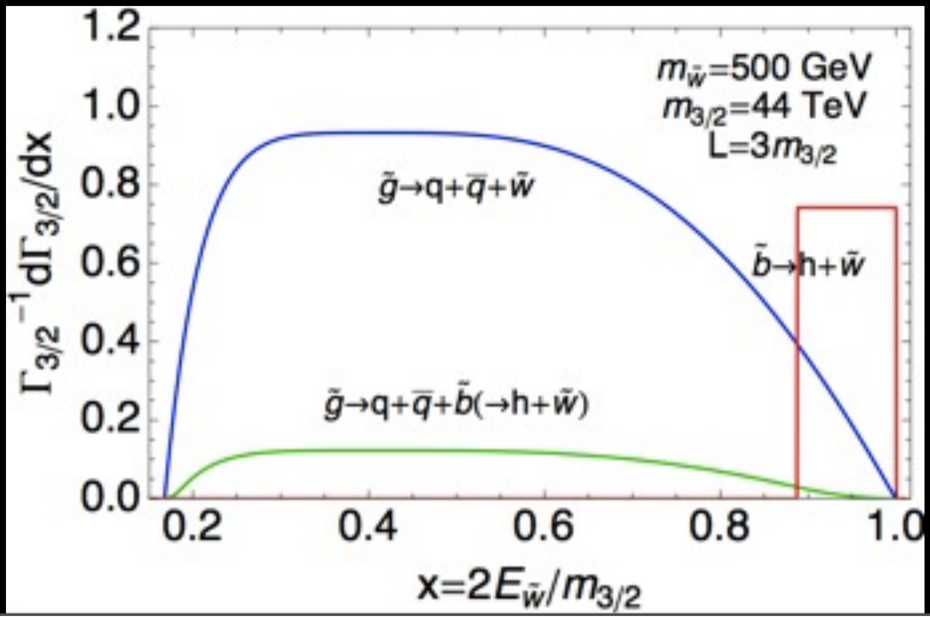
It is a superposition of three continuum spectra by the cascade decays ($\tilde{G} \to \tilde{g} \to \tilde{w}$, $\tilde{G} \to \tilde{g} \to \tilde{b} \to \tilde{w}$, $\tilde{G} \to \tilde{b} \to \tilde{w}$) and one line spectrum by the direct decay ($\tilde{G} \to \tilde{w}$).

$$\frac{1}{\Gamma_{3/2}} \frac{d\Gamma_{3/2}}{dE_{\tilde{w}}} = \frac{8}{12} \left\{ \frac{Br_{\tilde{g}\to\tilde{w}}}{\Gamma_{\tilde{g}\to\tilde{w}}} \frac{d\Gamma_{\tilde{g}\to\tilde{w}}}{dE_{\tilde{w}}} \right\} + \frac{8}{12} \left\{ \int dE_{\tilde{b}} \frac{Br_{\tilde{g}\to\tilde{b}}}{\Gamma_{\tilde{g}\to\tilde{b}}} \frac{d\Gamma_{\tilde{g}\to\tilde{b}}}{dE_{\tilde{b}}} \frac{1}{\Gamma_{\tilde{b}\to\tilde{w}}} \frac{d\Gamma_{\tilde{b}\to\tilde{w}}}{dE_{\tilde{w}}} \right\} + \frac{1}{12} \left\{ \frac{1}{\Gamma_{\tilde{b}\to\tilde{w}}} \frac{d\Gamma_{\tilde{b}\to\tilde{w}}}{dE_{\tilde{w}}} \right\} + \frac{3}{12} \delta(E_{\tilde{w}} - m_{3/2}/2)$$

Sample Spectrum

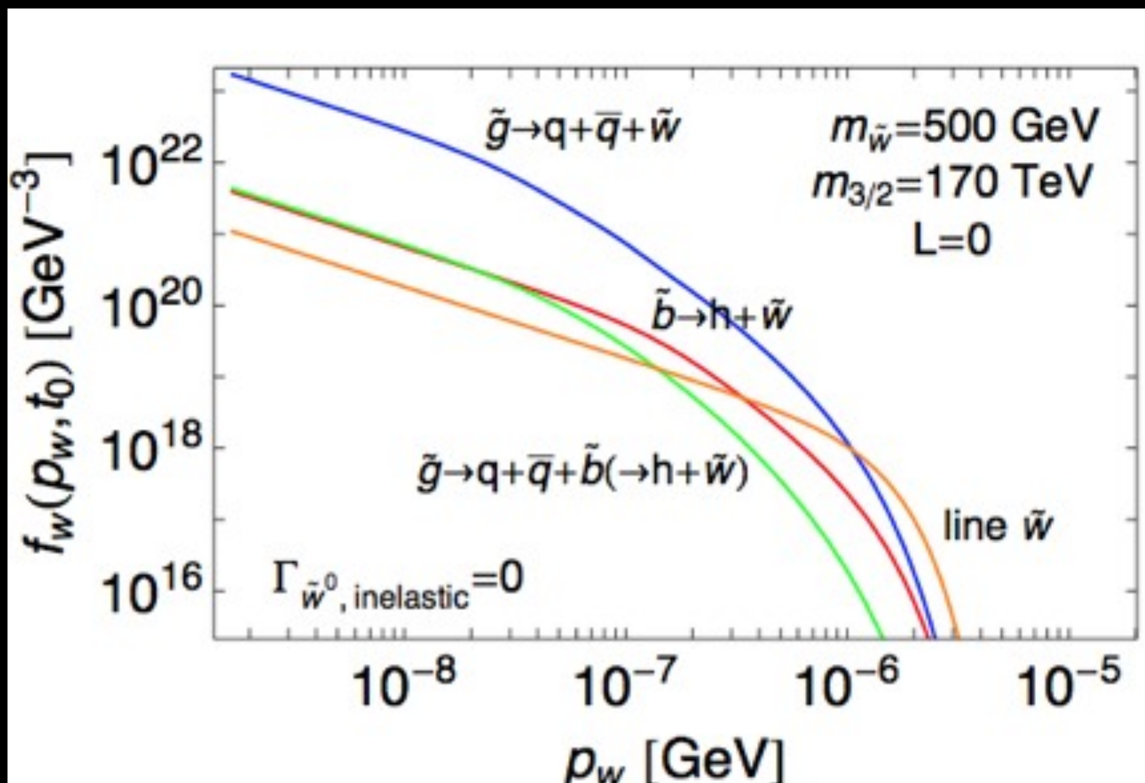
Non-thermal winos are more energetic for $L=3m_{3/2}$, since the wino mass is closer to the the gluino mass.

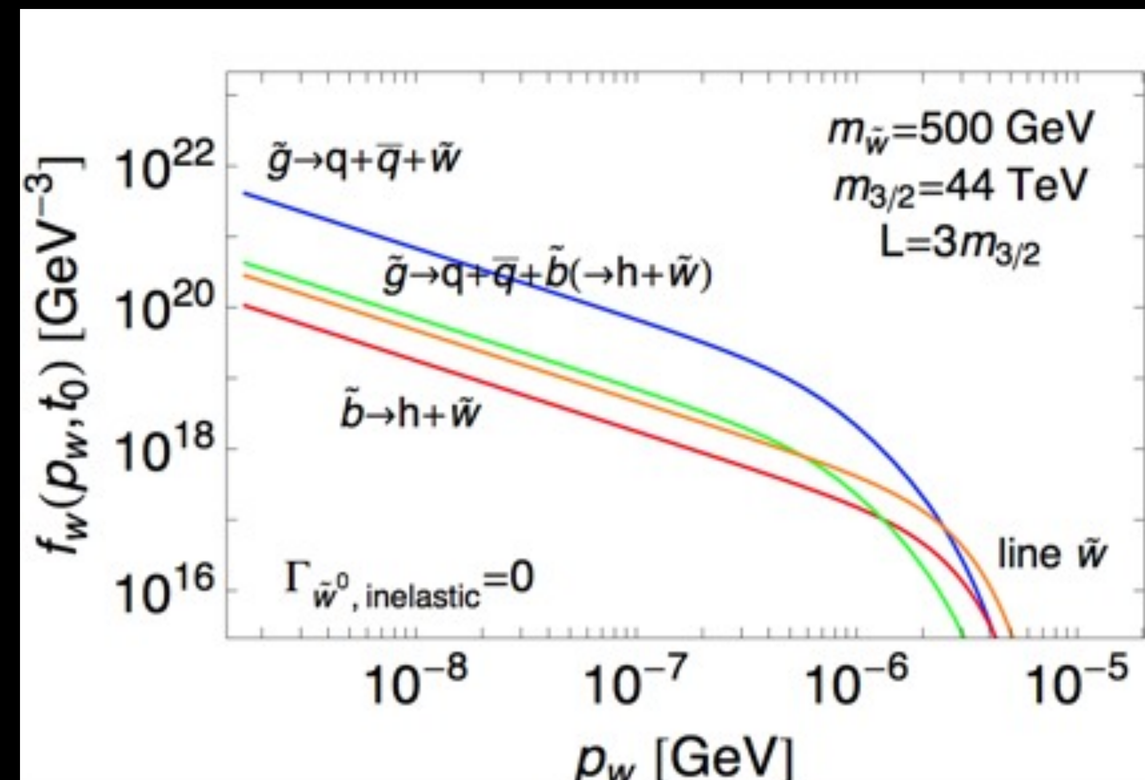




Present momentum distribution w/o inelastic scattering

First of all, we turn off the inelastic scattering term $\Gamma_{\tilde{w}^0,\,\mathrm{inelastic}} = 0$ for trial.
In that case, the present-day spectrum is a superposition of $\dfrac{d\Gamma_{3/2}}{d^3 p_{\mathrm{w}}}$ weighted by the number density of the gravitino.





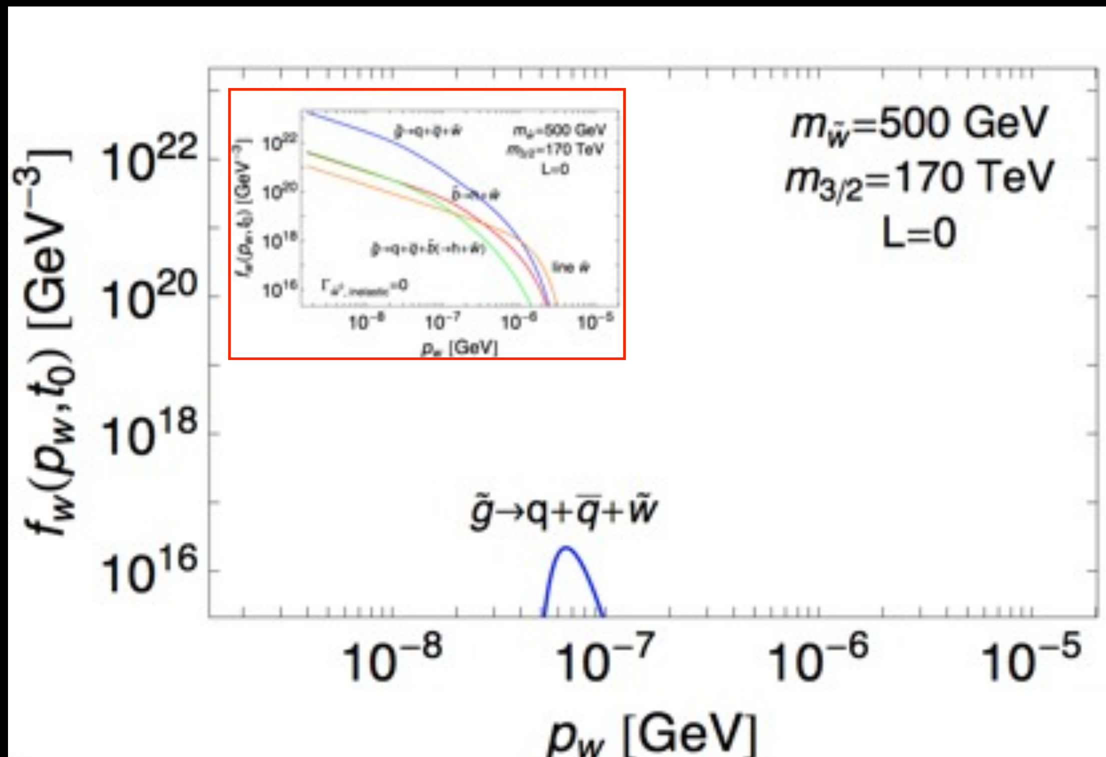
The cascade decay of $\tilde{G} \to \tilde{g} \to \tilde{w}$ is dominant.
The typical present-day momentum of the non-thermal wino is estimated as

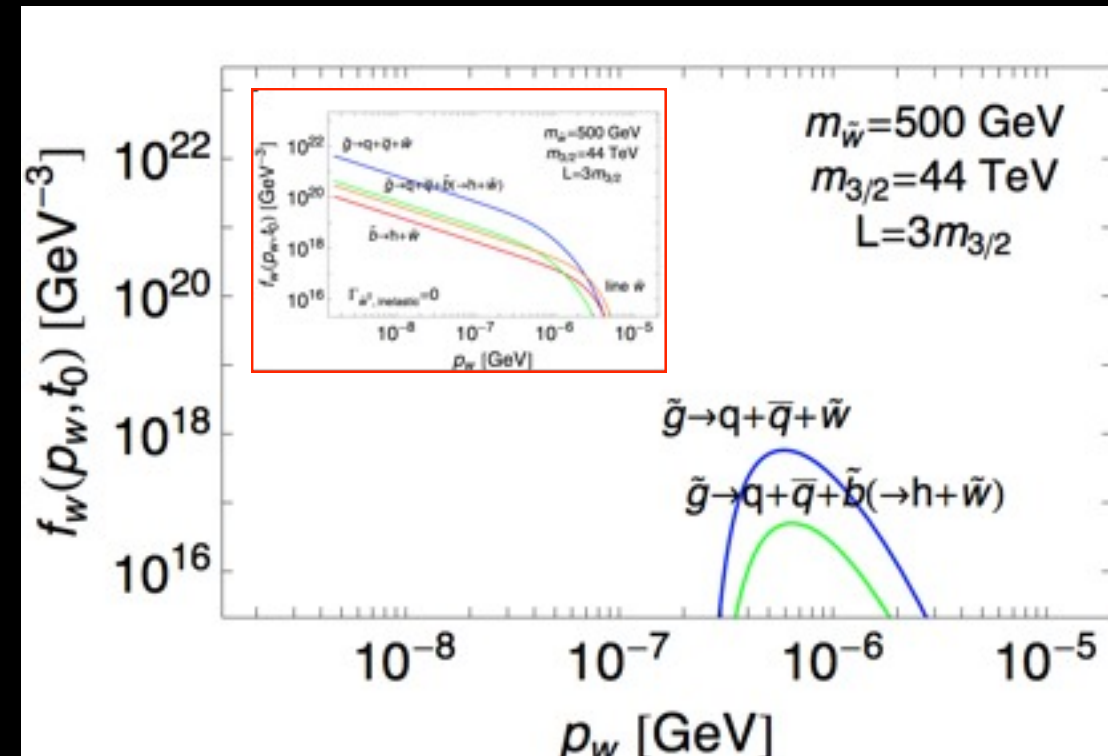
$$p_{\mathrm{w,\,typical}}(t_0) \simeq 2.1 \times 10^{-6}\,\mathrm{GeV} \times \left(\frac{m_{3/2}}{100\,\mathrm{TeV}}\right)^{-1/2} \times O(0.1).$$

The sudden drop at the high momentum comes from exponential decay of the number density of the gravitino at late times.

Present momentum distribution w/ inelastic scattering

Now, we switch on the inelastic scattering term $\Gamma_{\tilde{w}^0,\,\mathrm{inelastic}}$.





For $L=m_{3/2}$ (smaller gravitino mass for given wino mass), more neutral winos remain ``warm”, since the inelastic scattering rate is lower.
The low momentum winos are mainly produced when the cosmic temperature is high, and thus, the efficient inelastic scattering stops non-thermal winos.
The cascade decay of $\tilde{G} \to \tilde{g} \to \tilde{w}$ and $\tilde{G} \to \tilde{g} \to \tilde{b} \to \tilde{w}$ have a 3-body decay to lead to the winos with relatively low momentum at the gravitino decay. Only these less energetic winos may evade the inelastic scattering and remain ``warm”.
Almost all of the winos produced by the direct decay of the gravtino turn into ``cold” winos. This suggests the details of decay processes (e.g. mass spectrum of sparticles) may leave imprints in the ``warmness” of the wino dark matter.

Two indices (indicators) of ``warmness” of the dark matter

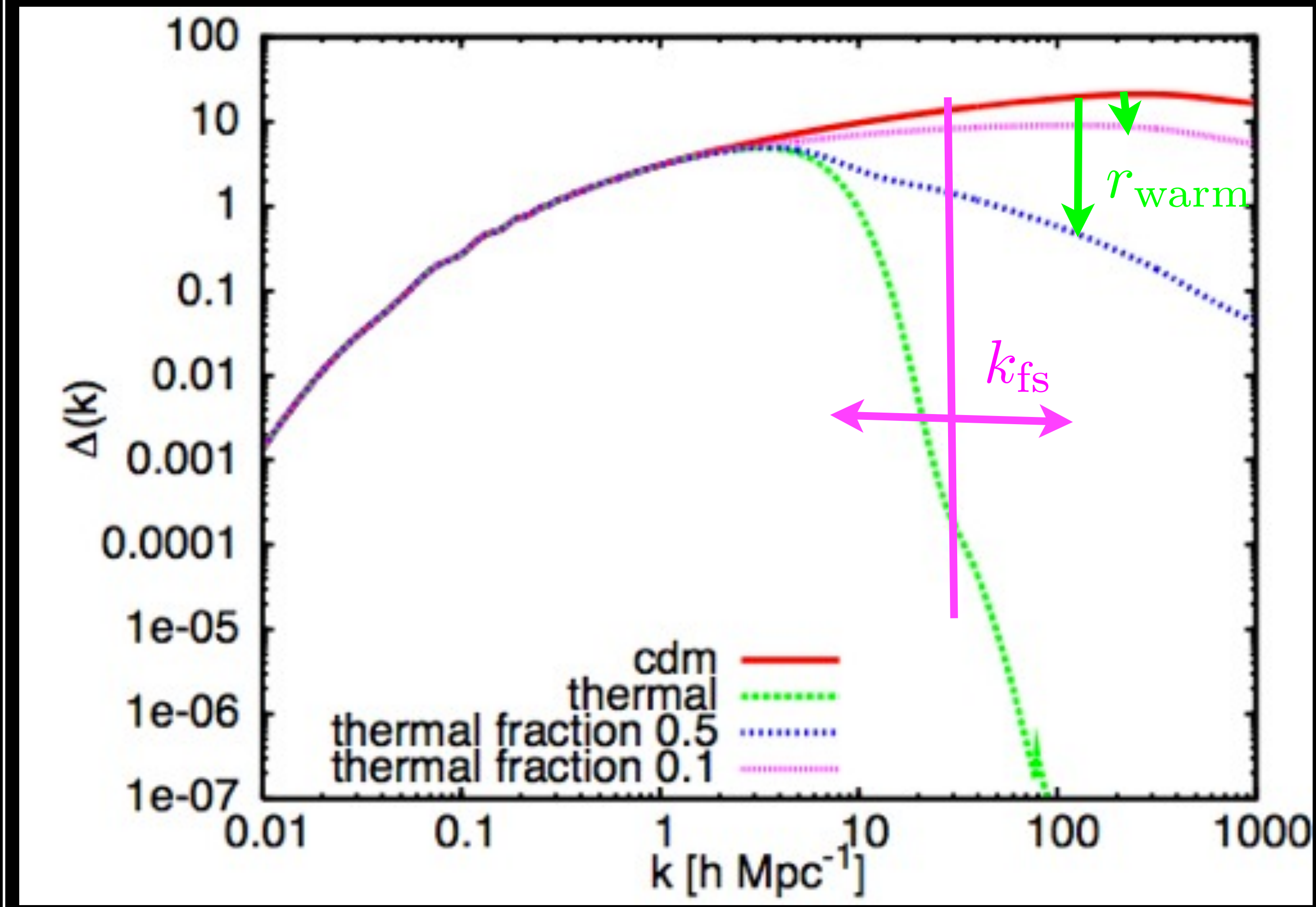
To make discussions quantitative, we introduce two indices (indicators) which represents how warm the dark matter is.

1. fraction of the warm component $r_{\rm warm}$
: determines the amplitude of reduction in the matter power spectrum.

2. Jeans scale at the matter-radiation equality

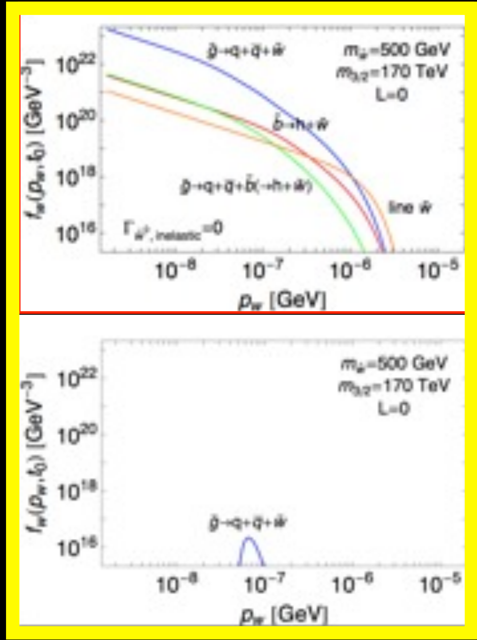
$$k_{\rm fs} = a\sqrt{\frac{4\pi G\rho_{\rm mat}}{\langle v^2\rangle}}\Bigg|_{a=a_{\rm eq}}$$

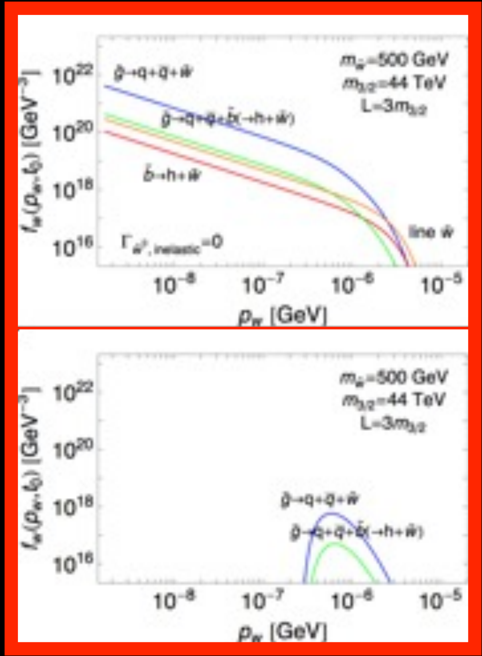
: determines the cut-off scale below which the matter power spectrum reduces.
$k_{\rm fs} = O(100)\,{\rm Mpc}^{-1}$ for conventional warm dark matter such as light gravitino.



For the previous samples of the present momentum distributions

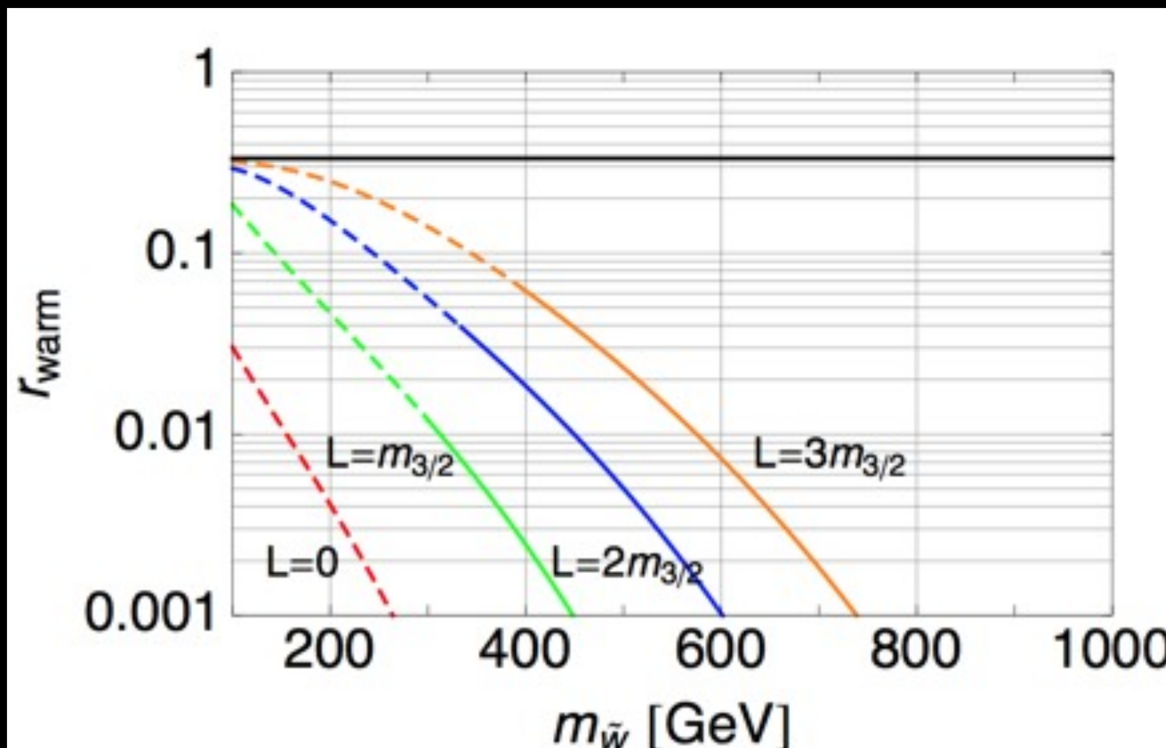
parameters	$r_{\rm warm}$	$k_{\rm fs}\,[{\rm Mpc}^{-1}]$
$m_{\tilde w} = 500\,{\rm GeV},\ m_{3/2} = 170\,{\rm TeV},\ L = 0$	$1.5\times10^{-7}\,(0.33)$	$4.5\times10^{7}\,(2.7\times10^{3})$
$m_{\tilde w} = 500\,{\rm GeV},\ m_{3/2} = 44\,{\rm TeV},\ L = 3m_{3/2}$	$0.016\,(0.33)$	$7.5\times10^{3}\,(1.2\times10^{3})$

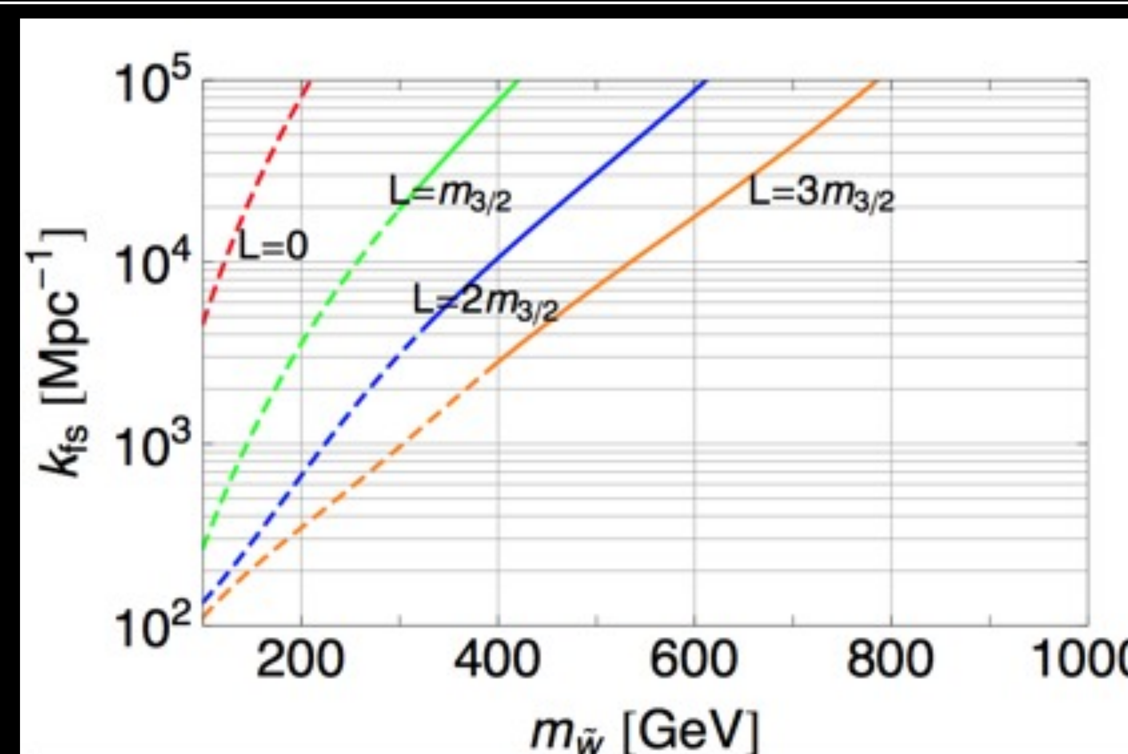




How warm the non-thermal wino dark matter is?

We calculate the two indices for several wino masses $m_{\tilde{w}} = 100 - 1000\,\mathrm{GeV}$
and several Higgsino threshold corrections $L = 0,\, m_{3/2},\, 2m_{3/2},\, 3m_{3/2}$.





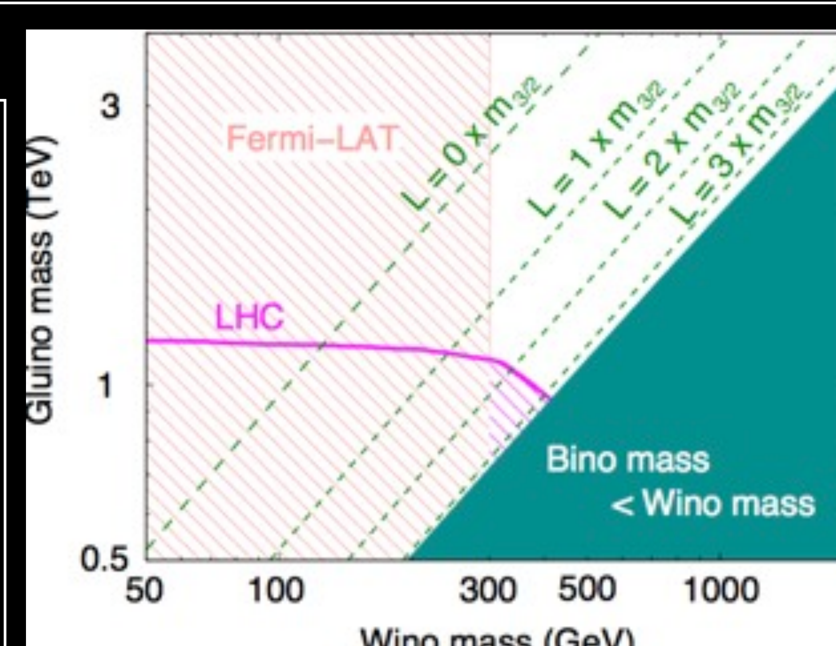
Here, we have shown the disfavored region from gravitino problem and collider/indirect search in dotted lines.

For successful BBN, $m_{3/2} > 30\,\mathrm{TeV}$

M. Kawasaki, K. Kohri, T. Moroi and A. Yotsuyanagi, PRD, 2008

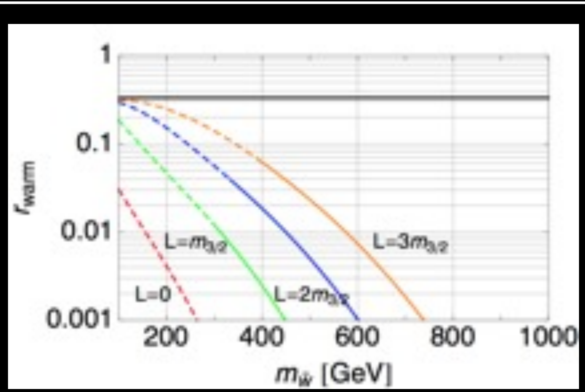
For collider search of wino LSP, see B. Bhattacherjee, B. Feldstein, M. Ibe, S. Matsumoto and T. T. Yanagida, arXiv:1207.5453

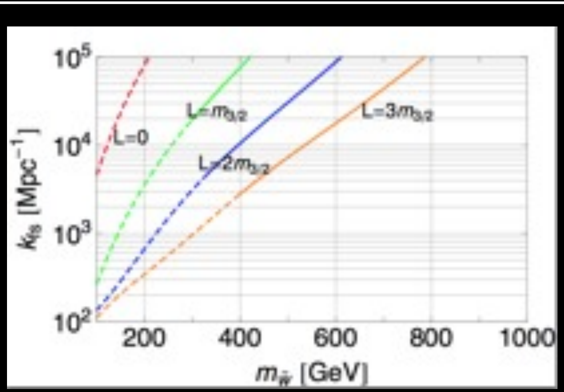
In heavier wino case, corresponding heavier gravitino decay in earlier Universe with higher temperature and leave more energetic winos. This results in more redshifted and inelastically scattered winos, that is, colder winos.
In larger Higgsino threshold correction (L) case, gravitino mass is lighter for a given wino mass to lead to less redshifted and inelastically scattered winos, that is, warmer winos.

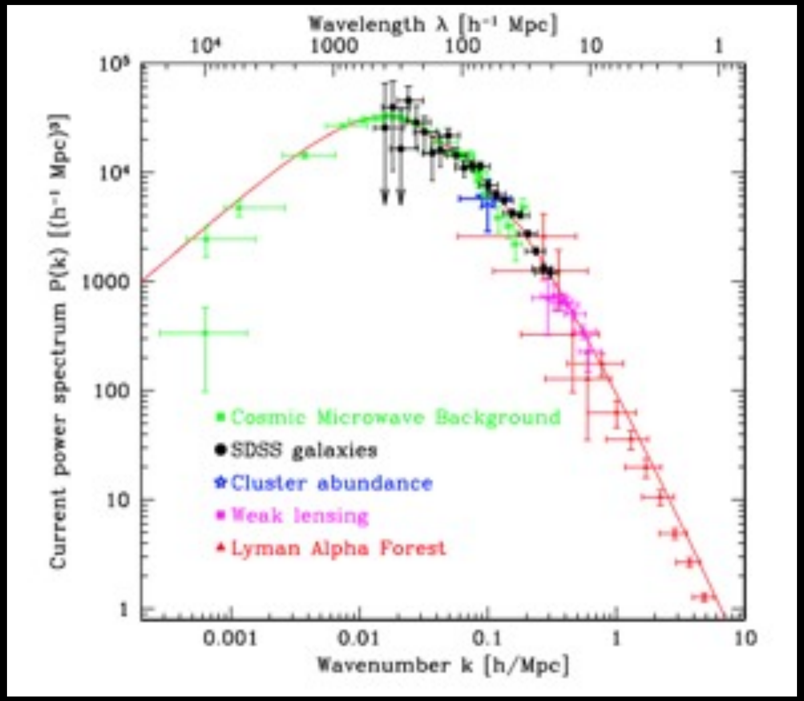


Can we see the ``warmness'' of the wino dark matter ?

The current astrophysical observations of CMB anisotropy, galaxy auto-correlation, ... can reach the matter fluctuation with $k \lesssim 100\, h\mathrm{Mpc}^{-1}$. In order to detect the imprints of the non-thermal wino dark matter, we should see matter fluctuations at smaller scales, e.g. $k \gtrsim O(1000)\, h\mathrm{Mpc}^{-1}$.

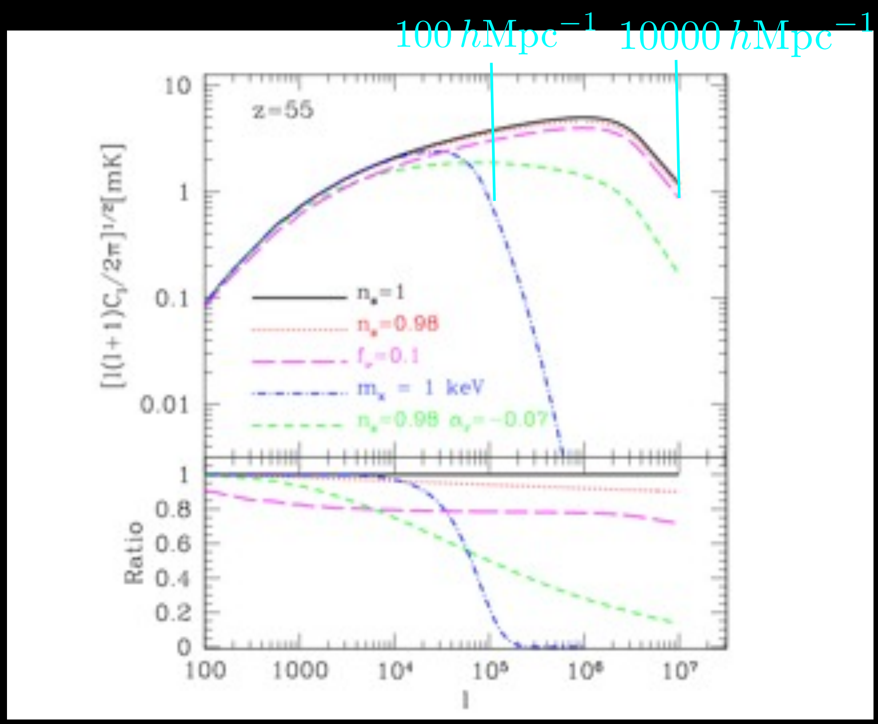






M. Tegmark *et al.* (Sloan Digital Sky Survey, SDSS collaboration), ApJ, 2003

We suggest that the future observations of the spatial fluctuations of the absorption lines of neutral hydrogen 21cm transition (hyperfine splitting of the 1S state) such as SKA and FFT. The spatial fluctuations of the 21cm brightness temperature at z=30-200 is a direct probe of the linear matter density fluctuations.



A. Loeb and M. Zaldarriaga, PRL, 2003

Our result highly motivates the search of the detectability of the mixed dark matter in the future 21cm line observation.

Summary and Future direction

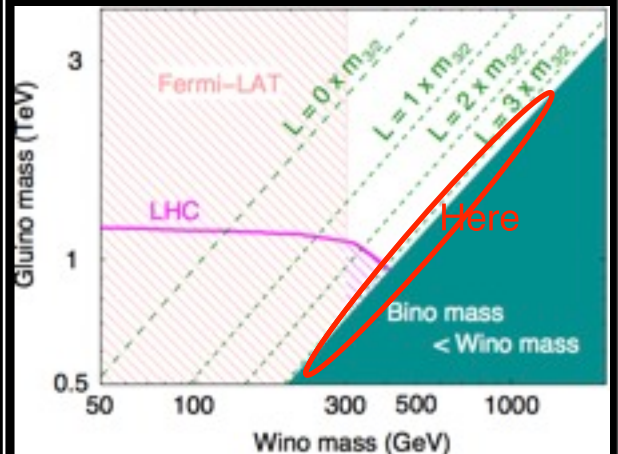
We study the cosmological implication of the wino dark matter. The wino dark matter with mass of $m_{\tilde{w}} \lesssim 2.9\mathrm{TeV}$ should be dominantly produced by the non-thermal process. In particular, we investigate the ``warmness'' of the non-thermal wino dark matter.

We take the Pure Gravity Mediation Model for the sparticle spectrum motivated by the recent discovery of the 125 GeV Higgs-like particle by ATLAS and CMS collaboration in

We clarify the energy loss mechanisms of the non-thermal winos via the interactions with the thermal background.
We find that due to the relatively long lifetime the charged winos go in kinetic equilibrium with the thermal background and then decay into neutral winos.
At the cosmic temperature of interest, the neutral winos mainly loose their energy via the inelastic scattering into the charged winos.

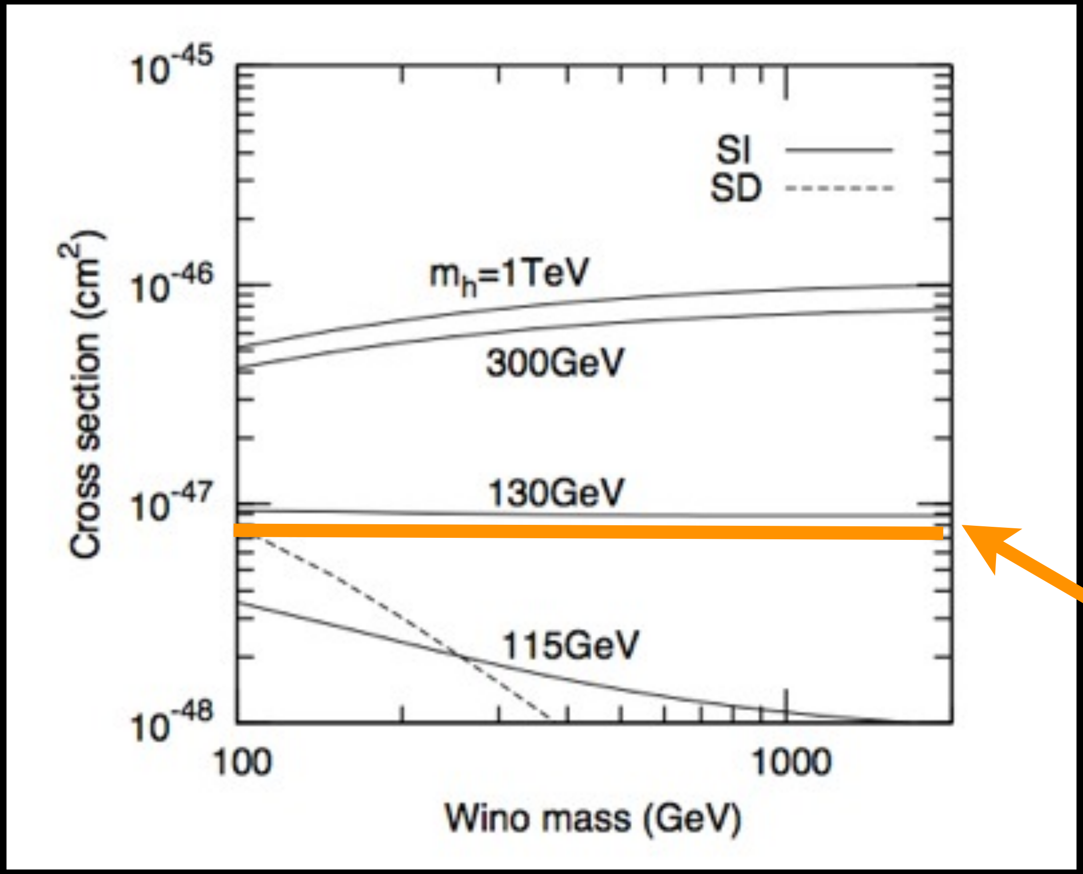
By following the ``warm'' momentum distribution numerically, we find the a sizable fraction of the wino dark matter remains ``warm'' for relatively light winos, $m_{\tilde{w}} \simeq 100 - 500\,\mathrm{GeV}$. Our result suggests that the wino dark matter may be mixed (Cold +Warm) dark matter to motivate the study of the detectability of the mixed dark matter in the future 21cm line observations.

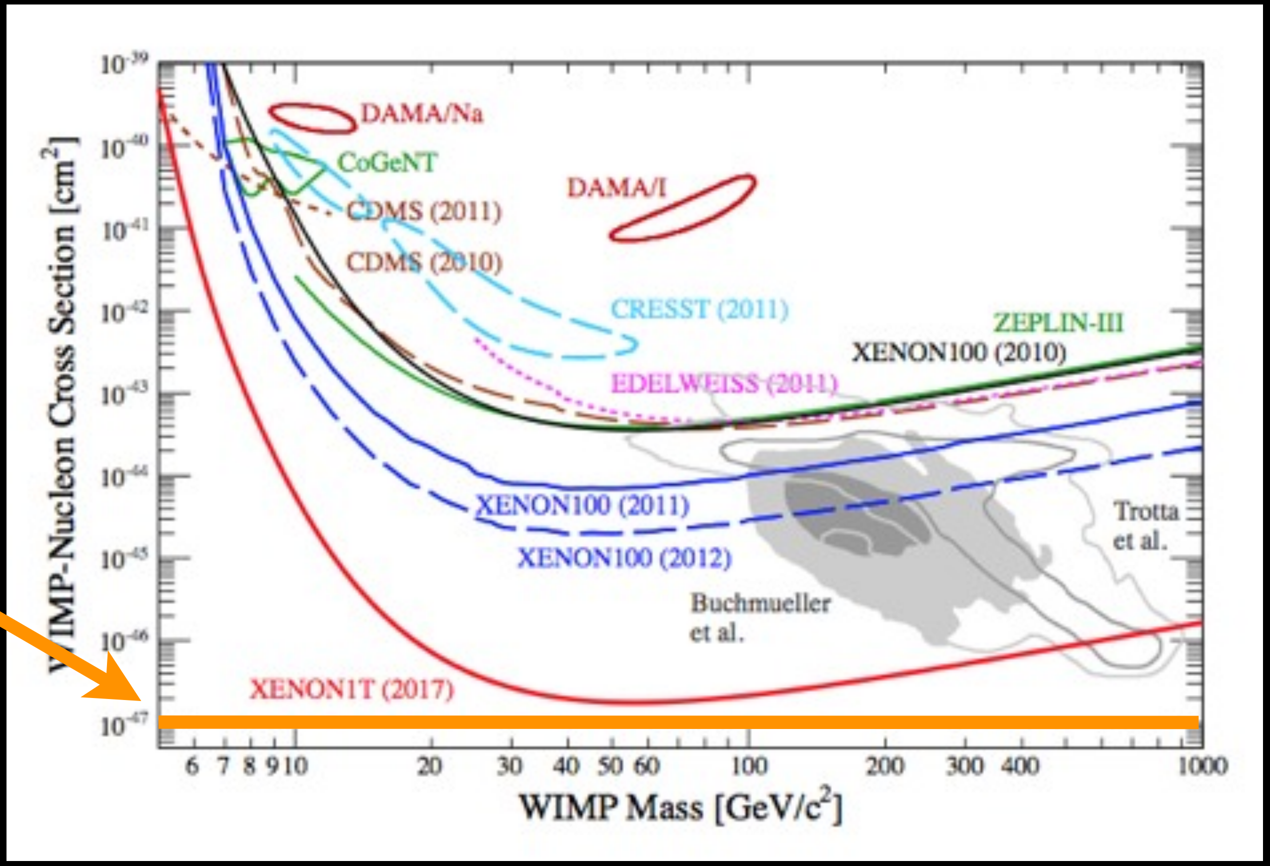
In the wino LSP case, the relatively long lifetime ensures the ``coldness'' of at least 2/3 of wino dark matters. The Higgsino LSP has the mass splitting of $\Delta m_{\tilde{h}} \simeq 1 - 10\,\mathrm{GeV}$ due to the Yukawa couplings and may leave more significant imprints than the wino LSP. The bino LSP with degenerate (co-annihilation) NLSP wino is also interesting and now in progress .



Direct detection

In the pure wino limit with heavy sfermions, wino dark matter does not interact with nucleons at tree-level. 1-loop effective Lagrangian approach gives the wino-nucleon Spin Dependent (SD)/Spin Independent (SI) cross section $\sigma_{\tilde{w}-n} \lesssim 10^{-47}\,\mathrm{cm}^2$, while the future experiment (XENON1T, 2017) can detect the dark matter whose wino-nucleon cross section is $\sigma_{\tilde{w}-n} \gtrsim 10^{-47}\,\mathrm{cm}^2$.



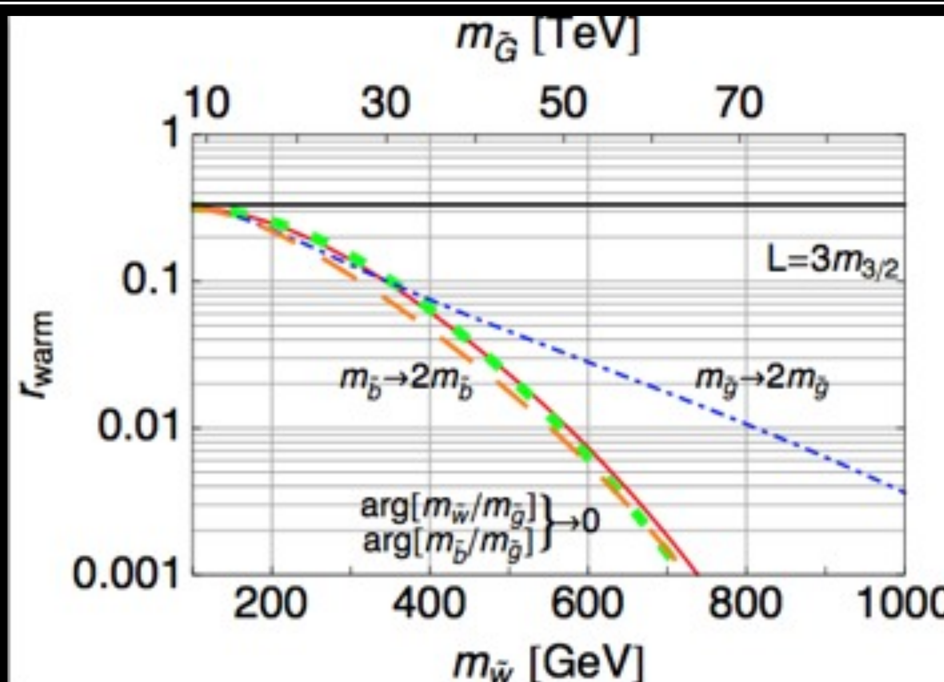


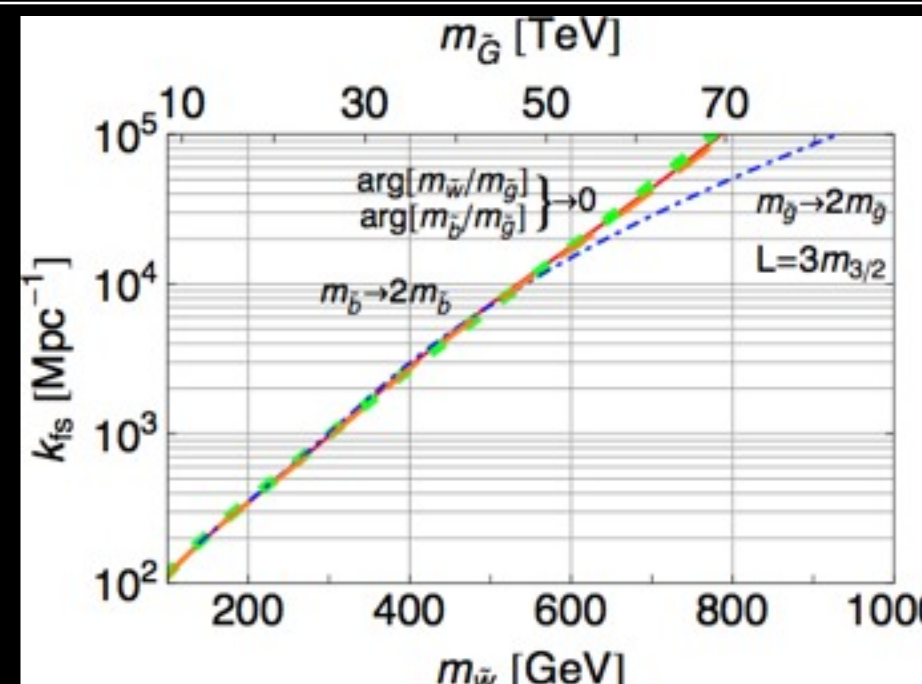
J. Hisano, K. Ishiwata and N. Nagata, PLB, 2010

P. R. Scovell and XENON1T collaboration, Proceedings of DM2012 at UCLA, 2012, arXiv:1206.6288

Imprints of the mass spectrum

In the end, we leave the Pure Gravity Mediation Model. We vary the relative phase between gaugino mass parameters, $\arg[m_{\tilde{w}}/m_{\tilde{g}}]$ and $\arg[m_{\tilde{b}}/m_{\tilde{g}}]$, bino mass $m_{\tilde{b}}$ and gluino mass $m_{\tilde{g}}$.





The relative phase between gaugino mass parameter does not change the results, since the relative phase is the subdominant effect in the decay rate.

$$\Gamma_{\tilde{g}\to\tilde{w}} = \frac{4g_2^2g_3^2}{3(16\pi)^3}\frac{m_{\tilde{g}}^6}{E_{\tilde{g}}m_{\rm squark}^4}\left((1-r_{\tilde{w}}^2)\left(1-7r_{\tilde{w}}^2-7r_{\tilde{w}}^4+r_{\tilde{w}}^6+2c_{\tilde{w}}(r_{\tilde{w}}+10r_{\tilde{w}}^3+r_{\tilde{w}}^5)\right)+24r_{\tilde{w}}^3(c_{\tilde{w}}-r_{\tilde{w}}c_{\tilde{w}}-r_{\tilde{w}}+c_{\tilde{w}}r_{\tilde{w}}^2)\ln r_{\tilde{w}}\right),$$

$c_{\tilde{w}} = \cos(\arg[m_{\tilde{w}}/m_{\tilde{g}}])$, $r_{\tilde{w}} = m_{\tilde{w}}/m_{\tilde{g}}$

The bino mass also does not affect the results, since the cascade decay of $\tilde{G}\to\tilde{b}\to\tilde{w}$ does not produce non-thermal winos which contribute to the ``warmness'' of the wino dark matter.

The gluino mass change the fraction of the warm component drastically. This is because in the dominant cascade decay of $\tilde{G}\to\tilde{g}\to\tilde{w}$, the wino carry away more energy from the gluino for closer gluino mass to given wino mass.

→ The ``warmness'' of the wino dark matter may remember the gluino mass.