Non-perturbative Effect on Thermal Relic Abundance of Dark Matter

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I. Dark Matter (DM) abundance

From recent cosmological observation

$\Omega_{DM} = 0.20\ (+\ 0.02 - 0.04)$

Existence of non-baryonic (cold) DM

What is the dark matter?

No candidate in the SM ⇒ **Beyond SM Physics**

Many scenarios providing the dark matter:
MSSM (LSP), UED (LKP), LHT (LTP)

In these models,

Thermal relic abundance of the DM is important prediction!!

Because thermal scenario is most natural one to produce the DM abundance.

II. Thermal Relic Scenario

The dark matter density per comoving volume was fixed due to the expansion of the universe at a certain temperature. The relics are now observed as the dark matter abundance. Its amount is quantitatively calculated by the Boltzmann eq.

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left[n^2 - n_{\rm th}^2 \right]$$

Important quantity is

$\langle \sigma v \rangle$ **: Thermally averaged annihilation cross section of DM**

(or effective thermally averaged annihilation cross section,
if coannihilation processes are efficient)

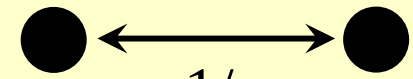
Usually, the cross section is calculated by a perturbative method.

If the DM is non-singlet under $SU(2)_L$ gauge interaction
(e.g. Wino- or Higgsino-like neutralino in MSSM)
and heavy compared to the weak gauge bosons,
then the non-perturbative effect (Sommerfeld enhancement)
has to be included to calculate the abundance correctly.

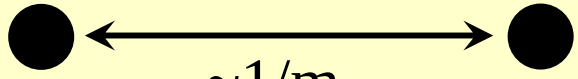
III. Sommerfeld enhancement

= Long-distance force induced from the gauge boson exchange.
(It has been found in inelastic reactions between non-relativistic charged particles.)

Annihilation



The long range force



Therefore, the weak gauge boson exchange becomes
a long-distance force for such kind of heavy DMs ($m >> m_W$)

Due to the force, the wave function of incident dark matters are modified from the plane waves.

If attractive force exists,

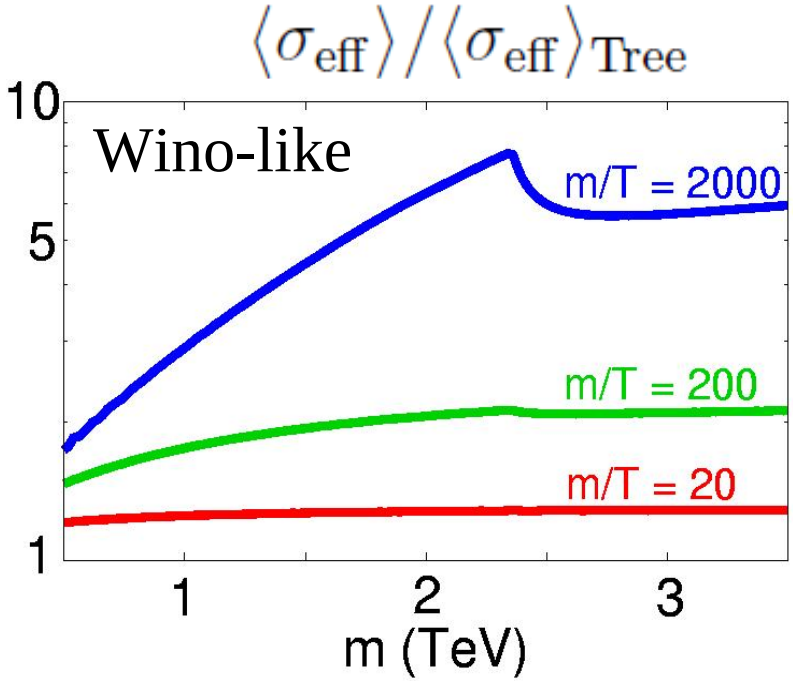
The overlap between the wave functions is increased.

It leads to

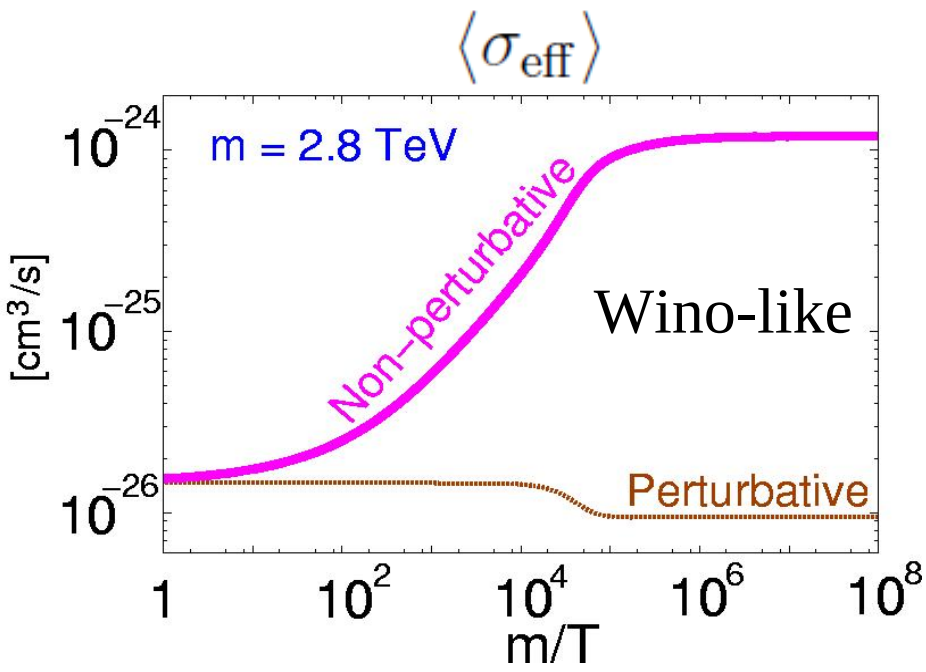
Enhancement of the annihilation cross section!!

IV. Thermally averaged annihilation cross section

Strategy: With the use of the Schrödinger equation describing the relative motion between DMs, the effect of the Sommerfeld enhancement is evaluated!!
(The equation can be derived from the 1st principle using the NR-Lagrangian.)



Mass dependence of the cross section normalized by the perturbative one



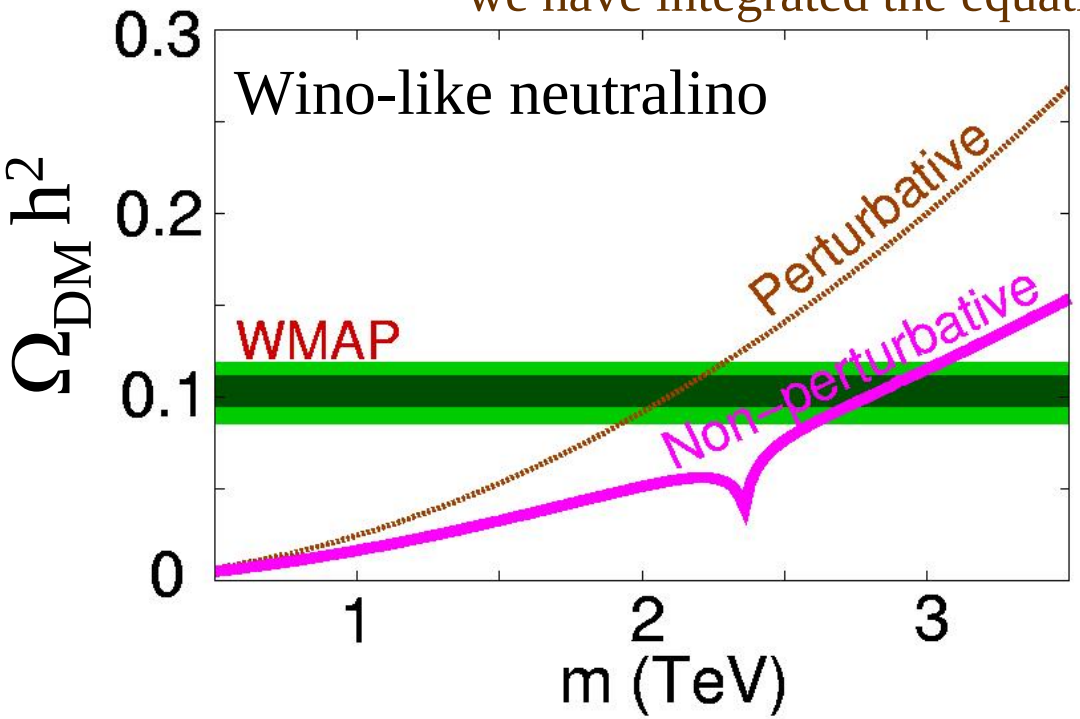
Temperature dependence with fixed m

The cross section is increased by 10 % at the freeze-out temperature, and the enhancement becomes more significant at smaller temperature!!

V. The DM mass consistent with WMAP

Once the annihilation cross section is obtained, we can calculate the DM abundance by solving the Boltzmann equation.

Since the cross section depends on the temperature in a non-trivial way, we have integrated the equation numerically.



The mass consistent with the WMAP is increased by 600 GeV,
→Wino-like neutralino DM with 2.7 TeV < m < 3.0 TeV is favored in the thermal relic scenario.

VI. Summary and discussion

Summary

1. We have pointed out that thermal relic density can be significantly affected by the non-perturbative effect when the DM is heavy $SU(2)_L$ charged one.
2. The non-perturbative effect has investigated quantitatively using the Wino -like neutralino DM as an example. We have shown that its mass consistent with the WMAP is increaded by about 600 GeV (2.7 TeV < m < 3.0 TeV).

Discussion

1. The non-perturbative effect can change relic abundances of other DM cand.
2. Higgsino-like neutralino: its $SU(2)_L$ charge is less that that of Wino-like neutralino DM, and the typical mass consistent with the observation is around 1 TeV. The effect on the abundance is expected to be 5-10 %.
3. When co-annihilation processes are efficient and the co-annihilating particle is charged, the non-perturbative effect can be important.