On the Dark Matter Candidate in the NMSSM

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4th December, 2020

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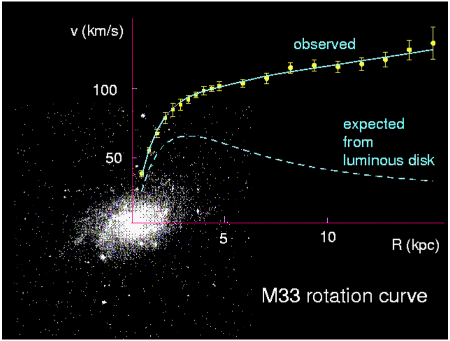
Evidences of Dark Matter



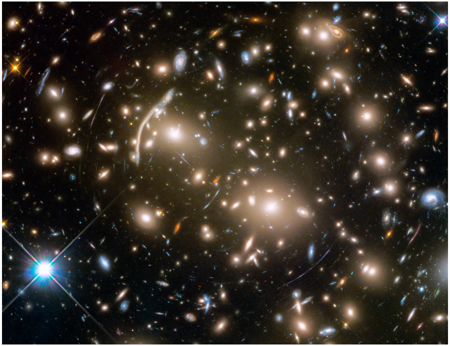


Figure 1: Common evidence of dark matter.
Left: Rotation curves of spiral galaxies [1].
Right: Gravitational lensing effect observed from Galaxy cluster Abell 370, figure taken from
`https://hubblesite.org/contents/articles/gravitational-lensing`

Basic Properties of Dark Matter

A list of plausible properties of dark matter reads:

- Electrically neutral.
- Massive.
- Long-lived.
- Non-baryonic.

Cosmological constraint [2; 3]:

$$0.094 < \left[\Omega_{\rm DM} h^2 \equiv \frac{\rho_{\rm DM}}{\rho_{\rm crit}} h^2\right] < 0.136 \quad \Rightarrow 3.71\rho_{\rm crit} < \rho_{\rm DM} < 5.36\rho_{\rm crit}.$$

The Boltzmann Equation

Evolution of phase-space distribution $f(x^\mu, p^\mu)$ is governed by the Boltzmann equation

$$\hat{\mathbf{L}}[f] = \hat{\mathbf{C}}[f]. \tag{1.1}$$

- $\hat{\mathbf{L}}$ describes the change in number density per phase-space volume.
- $\hat{\mathbf{C}}$ contains information about non-conserving particle number processes.

In FLW model[1], the Boltzmann equation for species χ reads

$$\dot{n}_\chi + 3Hn_\chi = -\langle \sigma_\chi v_{\text{Møl}} \rangle \left[n_\chi^2 - (n_\chi^{\text{eq}})^2 \right]$$

$$\Rightarrow \frac{x}{Y_\chi^{\text{eq}}} \frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{\Gamma_\chi}{H} \left[\left(\frac{Y_\chi}{Y^{\text{eq}}} \right)^2 - 1 \right], \quad Y_\chi = \frac{n_\chi}{s}$$

[1] FLW cosmology assume that the universe is homogeneous and isotropic universe.

Freeze-out Mechanism & Freeze-out Approximation

$$\frac{x}{Y_\chi^{\mathrm{eq}}}\frac{\mathrm{d}Y_\chi}{\mathrm{d}x} = -\frac{\Gamma_\chi}{H}\left[\left(\frac{Y_\chi}{Y^{\mathrm{eq}}}\right)^2 - 1\right]. \tag{1.2}$$

- $\Gamma_\chi \gtrsim H$: the collection of particles of the given species evolves while remain in thermal equilibrium.
- $\Gamma_\chi \lesssim H$: The abundance of the species χ remains nearly constant of after decoupling from thermal bath $\Rightarrow$ **freeze-out**

Based on solving x_f at which $\Gamma_\chi(x_f) = H(x_f)$, the **freeze-out approximation** implies

$$\frac{1}{Y_\chi(T)} = \frac{1}{Y_\chi^f} + \left(\frac{\pi}{45G}\right)^{1/2}\int_T^{T_f} g_*^{1/2}\left\langle \sigma_\chi v_{\text{Møl}}\right\rangle \mathrm{d}T, \tag{1.3}$$

$$\Rightarrow \Omega_\chi h^2 \approx 2.8282\times 10^8 \times m_\chi \times Y(T=T_0) \tag{1.4}$$

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Supersymmetry

According to [4], the most general continuous symmetry group in nature is

SuperPoincaré $\times$ Internal symmetries

SuperPoincaré generators include of P^μ, $M^{\mu\nu}$ and $Q, \overline{Q}$

$$\begin{cases} Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle \\ Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle \end{cases} \Longrightarrow$$

Supersymmetry
between fermions and bosons

Highlights

- Each particle has a corresponding superpartner with different spin.

lepton $\leftrightarrow$ slepton	gauge boson $\leftrightarrow$ gaugino
quark $\leftrightarrow$ squark	Higgs boson $\leftrightarrow$ higgsino

- Offer candidates for Dark Matter particles.

Supersymmetric Extension of the Standard Model

Minimal Supersymmetric Standard Model (MSSM)

- Keep the minimum number of superfields compared to SM.
- Fine-tuning μ-problem.

Next-to-Minimal Supersymmetric Standard Model (NMSSM)

- Adding one Higgs singlet $\hat{S}$ to MSSM particle content.
- Consider $\mathbb{Z}_3$ symmetry $\Rightarrow$ Scale-independent coupling constants in superpotential.
- Dynamically generate μ via electroweak symmetry breaking, thus solves the MSSM μ-problem.

NMSSM Lightest Neutralino as a Dark Matter Candidate

R-Parity

R-parity is a $\mathbb{Z}_2$ symmetry defined as $P_R \equiv (-1)^{3(B-L)+2s}$.

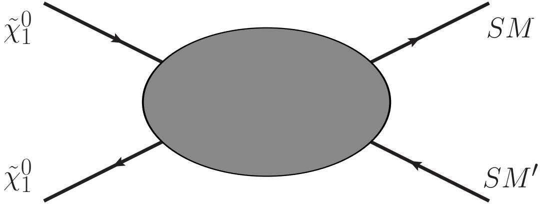
- R-parity conservation forbids couplings that violate baryon number and lepton number.
- SM particles have even R-parity; the superpartners have odd R-parity.
- **The Lightest Supersymmetric Particle (LSP)** in a R-parity preserved models cannot decay.

Neutralinos

Neutralinos in the NMSSM are mass eigenstates of neutral gauginos $\tilde{B}, \tilde{W}^3$ and neutral Higgsinos $\tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}$.

- If lightest neutralino $\tilde{\chi}_1^0$ is a LSP $\Longrightarrow$ DM candidate.

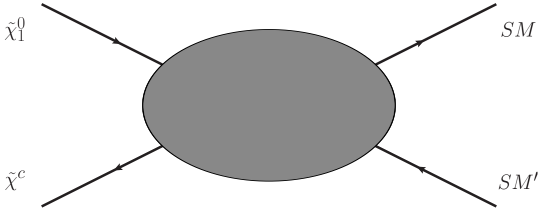
Neutralino Annihilations at Tree-level



Tree-level neutralino annihilation processes

- Fermionic final states.
- Weak gauge boson pair final states.
- One weak gauge boson + one Higgs boson.
- Higgs boson pair final states.
  - s-channel with exchanged Higgs bosons or Z boson.
  - t-channel and u-channel with exchanged sfermions, neutralinos or charginos.

Neutralino Annihilations at Tree-level



Tree-level neutralino annihilation processes

- Fermionic final states.
- Weak gauge boson pair final states.
- One weak gauge boson + one Higgs boson.
- Higgs boson pair final states.
  - s-channel with exchanged charged Higgs bosons or W boson.
  - t-channel and u-channel with exchanged sfermions, neutralinos or charginos.

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Input parameters

The mass spectrum is generated using **NMSSMCALC**, with the parameter point taken therein.

$m_{\tilde{\chi}_1^0} = 190.7491\,(\mathrm{GeV})$	
$M_{h_1} = 87.2381\,(\mathrm{GeV})$	$M_{h_2} = 125.0445\,(\mathrm{GeV})$
$M_{h_3} = 700.044\,(\mathrm{GeV})$	$M_{h_4} = 895.9974\,(\mathrm{GeV})$
$M_{h_5} = 897.8033\,(\mathrm{GeV})$	

Table 1: Some values taken from NMSSM mass spectrum with the given parameter point.

Total Cross Section & Its Thermal Average

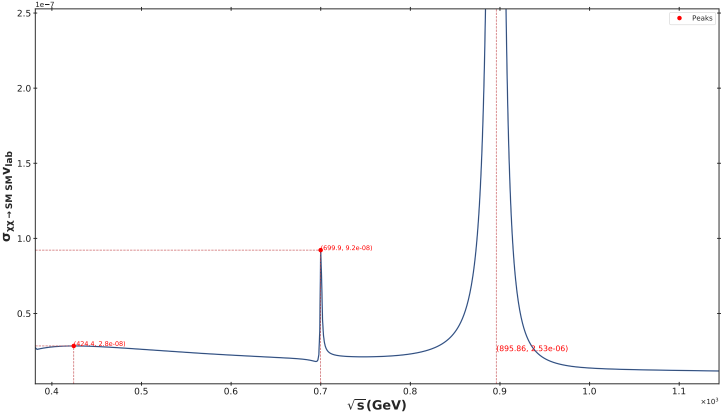

Figure 2: Total cross section of neutralino annihilation processes.

Numerical Results for Relic Abundance

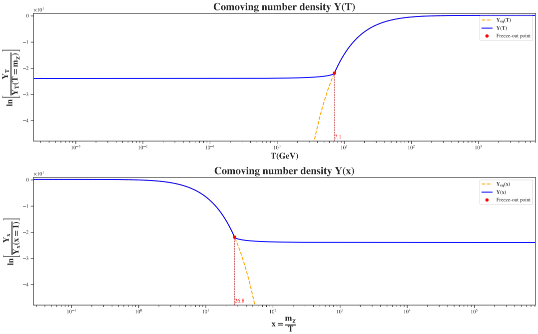

Figure 3: Solution of the comoving number density in the range (x_f, x_0).

- Neutralino relic density (without co-annihilations): $\mathbf{\Omega_{\tilde{\chi}_1^0} h^2 \approx 0.01259}$.
- Neutralino relic density (with co-annihilations): $\mathbf{\Omega_{\tilde{\chi}_1^0} h^2 \approx 0.00698}$.

Recall the cosmological constraint: $0.094 < \Omega_{\mathrm{DM}} h^2 < 0.136$.

Summary

Summary

- The lightest neutralino in the NMSSM is consider as a DM candidate in the calculations.
- The calculation of neutralino relic density used the freeze-out approximation with all annihilation processes up to tree-level.
- Co-annihilations should be taken into accounts for better description of abundances.

References I

[1] Lars Bergström. "Non-baryonic dark matter: observational evidence and detection methods".
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DOI: 10.1088/0034-4885/63/5/2r3.
arXiv: hep-ph/0002126 [hep-ph] (cit. on p. 4).

[2] Jan Hamann et al. "How robust are inflation model and dark matter constraints from cosmological data?"
In: 75.2, 023522 (Jan. 2007), p. 023522.
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arXiv: astro-ph/0611582 [astro-ph] (cit. on p. 5).

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[3] Max Tegmark et al.
"Cosmological constraints from the SDSS luminous red galaxies".
In: 74.12, 123507 (Dec. 2006), p. 123507.
DOI: 10.1103/PhysRevD.74.123507.
arXiv: astro-ph/0608632 [astro-ph] (cit. on p. 5).

[4] Sidney R. Coleman and J. Mandula.
"All Possible Symmetries of the S Matrix".
In: *Phys. Rev.* 159 (1967). Ed. by A. Zichichi, pp. 1251–1256.
DOI: 10.1103/PhysRev.159.1251 (cit. on p. 9).

Thank you

for

your attention!

Backup Slides

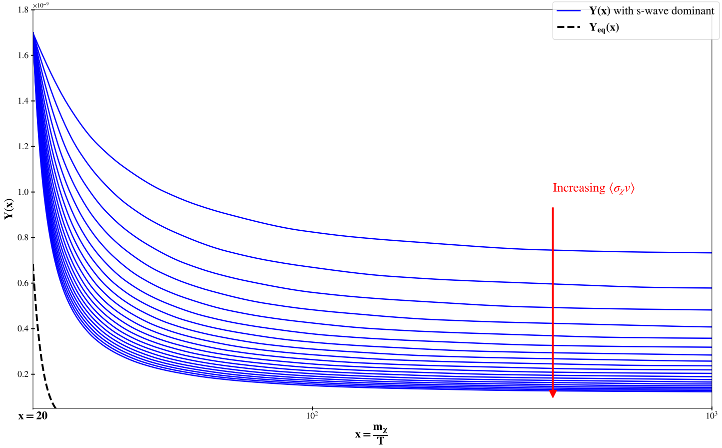


Figure 4: An illustration of $Y_\chi(x)$ when consider the lowest order of expansion over ϵ.

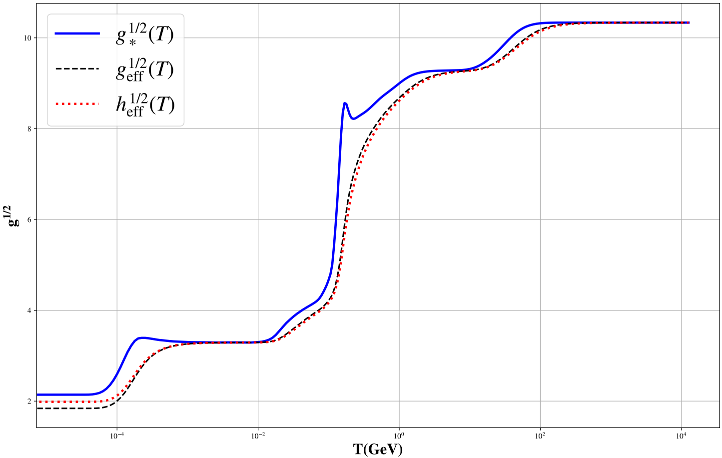


Figure 5: Degrees of freedom parameter with respect to temperature.

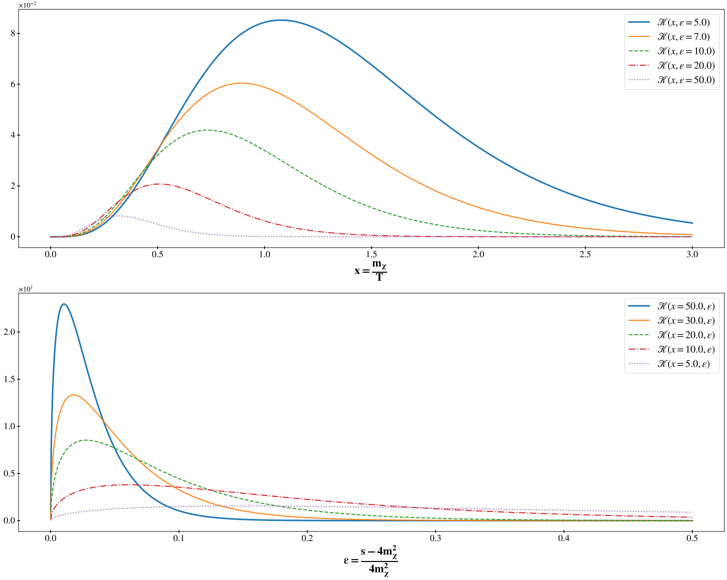


Figure 6: Plot of the thermal kernel $\mathscr{K}(x, \epsilon)$ with respect to x and ϵ.

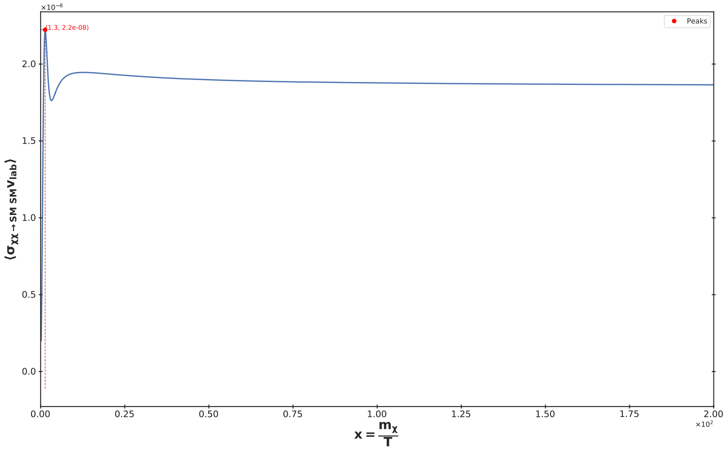


Figure 7: The thermal average of velocity-weighted total cross section in the range $x \in (0, 200)$.

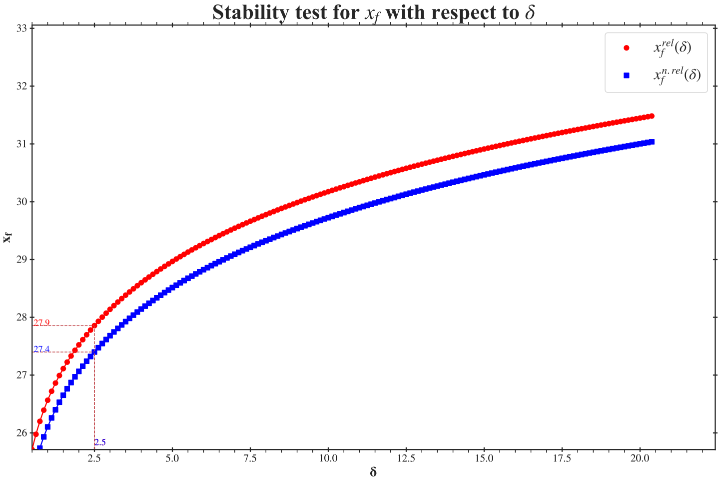
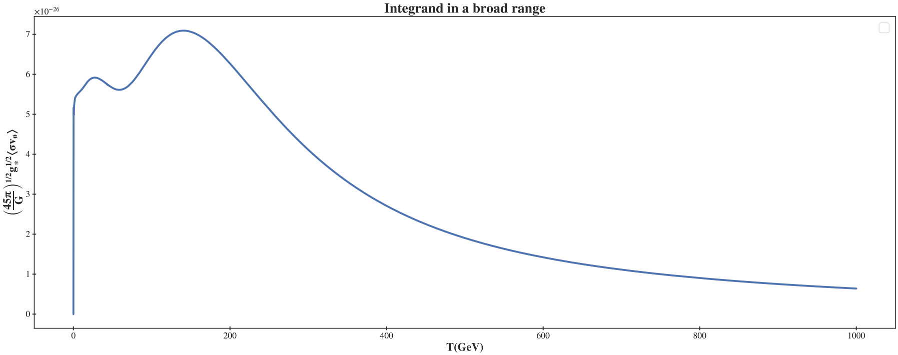
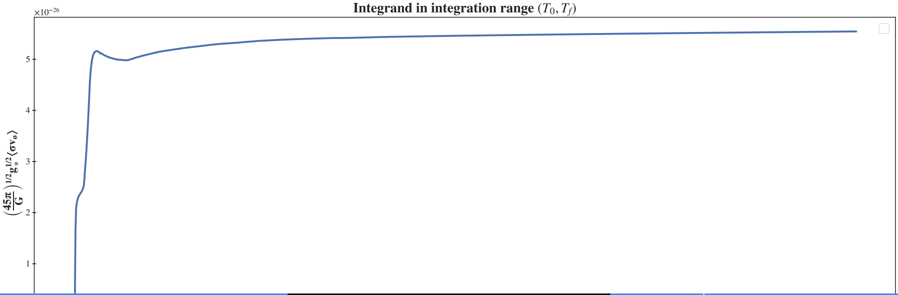


Figure 8: Solution of freeze-out point x_f.


Integrand in a broad range
×10⁻²⁶
$\left(\frac{45\pi}{G}\right)^{1/2} g_*^{1/2} \langle \sigma v_\varnothing \rangle$
0
1
2
3
4
5
6
7
0
200
400
600
800
1000
T(GeV)


Integrand in integration range (T_0, T_f)
×10⁻²⁶
$\left(\frac{45\pi}{G}\right)^{1/2} g_*^{1/2} \langle \sigma v_\varnothing \rangle$
1
2
3
4
5