Superheavy neutralinos as dark matter particles

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Thermal relics

- Two types of cosmic relics: Thermal and non-thermal.
- Thermal relics are held in thermal equilibrium until they decouple.
- Present aboundance Ω_X of thermal relic particle X scales $\approx$

$$\Omega_X \propto 1/\sigma_{\text{ann}}.$$

Unitarity induces upper limit on thermal M_X

- Unitarity of S-matrix restricts annihilations into l'th partial wave of particles with relative velocity $v_{\rm rel}$ as

$$\sigma_{\rm ann}^{(l)} \leq (2l+1)4\pi/(v_{\rm rel} M_X^2)$$

- Non-relativistic point-particles: $l > 1$ suppressed
- Observed $\Omega_{\rm CDM} h^2 = 0.105 \Rightarrow$

$$M_X \lesssim 100\ TeV.$$

Superheavy dark matter as a non-thermal relic

- Non-thermal relics: not produced in thermal equilibrium with the rest of the universe.
- Examples: monopoles, axions, cosmic strings and superheavy dark matter (SHDM).
- Original motivation for SHDM: secondaries produced in SHDM decays could explanain ultra-high energy cosmic rays.

The generality of superheavy dark matter

- Gravitational interactions at the end of inflation generate correct DM abundance,

$$\Omega_X \sim 1,$$

for any stable X with

$$m_X \sim 10^{13}\ GeV,$$

and reheating temperature $T_R \sim 10^9$ GeV.
(Chung, Kolb and Riotto, 1998)
- Generality of production mechanism and its
- Independence from the details of concrete particle physics model
- $\Rightarrow$ SHDM attractive DM candidate.

Perturbative superheavy dark matter (SHDM)

- Most SHDM candidates: no tree-level interactions with standard model (SM) particles.
- Possibility: Having a SHDM particle with SM-like couplings to the weak gauge bosons.
- Problem: longitudinal part of gauge bosons couples

$$\propto g \frac{M_X}{m_Z}$$

to a particle X

Perturbative superheavy dark matter (SHDM)

- $\Rightarrow$ weak interactions become (generically) strong for $M_X \gg m_Z \Rightarrow$ non-perturbativity.
- $\Rightarrow$ Upper limit of $M_X \sim \mathrm{TeV}$ for particles coupling with SM strength to weak gauge bosons.
- Exception: softly broken supersymmetry (SUSY), in particular the minimal supersymmetric extension of the SM (MSSM).

Superheavy supersymmetry is perturbative

- Conlusion: Superheavy MSSM becomes perturbative, and we can hence calculate the properties of SHDM.
- $\Rightarrow$ We suggest superheavy MSSM, $M_{\mathrm{SUSY}} \gtrsim 10^{11}$ GeV as concrete model for SHDM with SM weak interactions.
- Can be falsified by discovery of low-scale/split SUSY at the LHC. If not: superheavy DM may be the unique opportunity to connect SUSY to the physical world.

Neutralino as superheavy LSP

- Neutralino mass matrix M_χ in the $(\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0)$ basis

$$\begin{pmatrix} M_1 & 0 & -c_\beta m_Z s_W & m_Z s_W s_\beta \\ 0 & M_2 & c_W c_\beta m_Z & -c_W m_Z s_\beta \\ -c_\beta m_Z s_W & c_W c_\beta m_Z & 0 & -\mu \\ m_Z s_W s_\beta & -c_W m_Z s_\beta & -\mu & 0 \end{pmatrix}$$

- Gives mass eigenvalues

$$\{M_1, M_2, -\mu, \mu\} + \mathcal{O}(m_Z/M_{\text{SUSY}})^2.$$

- $M_{\text{SUSY}} >> m_Z \Rightarrow$ Pure Bino, Wino or Higgsino.

Elastic scattering on fermions and the energy relaxation time

- Energy relaxation time τ_{rel}: The inverse of the number of reactions per unit time. $\tau_{\text{rel}} > t_H$ the neutralinos exit kinetic equilibrium with the rest of the universe, i.e. reactions like

$$\nu\chi \to \nu\chi$$

becomes ineffective, due to the expansion of the universe.

- For $T << m_{\text{weak}}$ (ω kinetic energy of neutralino χ):

$$\omega \ll m_Z \ll m_\chi, \tag{1}$$

$$\Rightarrow \omega m_\chi^2 + m_Z^2 m_\chi + \omega^2 m_\chi + m_Z^3 \approx \omega m_\chi^2 + m_Z^2 m_\chi. \tag{2}$$

- We moreover assume no mass degeneration:

$$|\mu - M_1|, \, |\mu - M_2|, \, |M_2 - M_1| \gg m_Z \, .$$

Energy relaxation times

- Bino case ($M_1 < M_2, |\mu|$):

$$\tau_{\rm rel} \propto \frac{M_1 \left(M_{\tilde{\nu}}^2 - M_1^2\right)^2 \left(\mu^2 - M_1^2\right)^2}{T^6 \left(c_{2\beta} M_{\tilde{\nu}}^2 + \mu^2 - 2c_\beta^2 M_1^2\right)^2}.$$

- Higgsino case ($0 < \mu < M_1, M_2$):

$$\tau_{\rm rel} \propto \frac{\mu^3 \left(\mu - M_1\right)^2 \left(\mu - M_2\right)^2}{T^6 \left(M_1 c_W^2 + M_2 s_W^2 - \mu\right)^2}.$$

Elastic neutralino-neutralino scattering, $\chi\chi \to \chi\chi$

- Both Bino and Higgsino cases: *h*-exchange dominant:

$$|\mathcal{M}_{h\text{-exch}}|^2 = \mathcal{O}(m_Z/M_{SUSY})^0,$$

- Other 7 channels suppressed: $|\mathcal{M}|^2 \leq \mathcal{O}(m_Z/M_{SUSY})^4$.

Elastic neutralino-neutralino scattering, total cross sections

- $\sigma_{\chi\chi\to\chi\chi} = \sigma_{h-\text{exchange}}$
- Bino case:

$$\sigma \propto \frac{m_Z^4 M_1^2 \left(\mu \sin(2\beta) + M_1\right)^4}{M_h^4 \left(\mu^2 - M_1^2\right)^4}.$$

- Higgsino case:

$$\sigma \propto \frac{\mu^2 m_Z^4 \left(M_1 c_W^2 + M_2 s_W^2 - \mu\right)^4}{M_h^4 \left(\mu - M_1\right)^4 \left(\mu - M_2\right)^4}.$$

Neutralino annihilations, $\chi\chi \rightarrow \ldots$

- Bino case, dominated by channels

$$\chi, \chi \rightarrow ZH,\ hA,\ AH, \text{ and } W^{\pm}H^{\mp}.$$

- Here $|\mathcal{M}|^2 = \mathcal{O}(m_Z/M_{SUSY})^0$,
- Other channels suppressed by powers of $m_Z/M_{\rm SUSY}(\lesssim 10^{-9})$.
- In the Higgsino case, additional dominant channels:

$$\chi, \chi \rightarrow ZZ,\ W^+W^- \text{ and } Zh.$$

- I.e. all bosonic channels, except h, H and Z, A, are dominant.

Applications in another coming article:

Next step: Investigate properties of DM structures (differences to standard neutralinos) and detection prospects.