Lecture 15

DM candidates

No such candidates in the SM \( \rightarrow \) DM data. Require an extension of the SM

Among the candidates \( \rightarrow \) neutralino is the most natural

\[\text{stable} \quad \text{abundance} \quad \text{is in the right ballpark} \]

Other candidates require an adjustment of parameters to fit the DM observations

the zoo is huge! Only the most popular candidates are considered!

\( \text{LSP} \rightarrow \text{neutralino} \)

\( \text{SUSY} \rightarrow \text{fermions (e.g.)}, \text{bosons (e.g.)} \rightarrow \text{Higgs (e.g.)} \)

\( \text{SUSY} \) must be broken \( \rightarrow M_{\text{SUSY}} \) arbitrary!

negative SUSY searches \( \rightarrow (M_S \geq 100 \text{ GeV}) \rightarrow \) opportunities for the LHC

SUSY extensions \( \rightarrow B, L, \) numbers violation

R-parity \( \rightarrow \) forbids baryon and lepton number violation at low energies

\( \rightarrow \) even/odd particles

\[\begin{pmatrix} +1 \\ -1 \end{pmatrix} \]

SUSY particles \( \rightarrow \) SUSY particles \( \rightarrow \) sparticles and \( \rightarrow \) neutralinos

\( \text{slightly constrained by the LHC data!} \)

participates in weak interactions

detection methods

\[\text{neutralino} \rightarrow \text{neutralino} \quad \text{and gravitino!} \]

LSP in a wide range of parameters

\( \text{LSP is absolutely stable!} \)

MSSM: \( M_{\text{SUSY}} \approx 1 \text{ TeV} \)

\( \text{SUSY} \rightarrow \text{weakly decays} \rightarrow \text{final state particles} \)

\( \rightarrow \) LSP

\( \text{LSP is a candidate for DM!} \)

\( \text{LSP in a wide range of parameters!} \)

\( \text{LSP is stable!} \)

\( \text{neutralino} \rightarrow \text{neutralino} \rightarrow \text{neutralino, neutrino, and gravitino!} \)

\( \text{automatically satisfies to DM data!} \)
$X$ is neutral Majorana fermion (a linear combination of $\bar{\psi}, \bar{\chi}, \bar{\phi}, \bar{\psi}, \bar{\chi}, \bar{\phi}$)

$\frac{\Delta X}{\Delta \psi} \propto \frac{M_{SM}}{\Delta \psi}$ doublet.

$g_X = 2$, $g_X(h) \sim 100$

$T_f \propto \frac{M_X}{25}$, $\delta X \approx 0.8 \times 10^{-7}$ \left(\frac{M_X}{100 \text{ GeV}}\right)^2$ for $\Delta \psi = 1/30$

For $100 \text{ GeV} < M_X < 37 \text{ TeV}$ \Rightarrow $0.001 \leq \delta X \leq 10$

Let us refine this estimate further.

**Assumption:** neutralino is the only particle ($M_{\phi} \gg M_X$) associated with creation/annihilation.

**Neutrino pair creation/annihilation** \rightarrow **Boltzmann equation**

$$\frac{d\rho_X}{dt} + 3H \rho_X = - \langle \sigma_{\text{อนุรักษ์}} \cdot v \rangle \left( n_X^2 - n_{\text{อนุรักษ์}}^2 \right) \quad (\text{\textcircled{1}})$$

Kinetic and angular averaged, with equilibrium distribution.

**Thermal eq. density**

**The annihilation probability of a $X$ per unit time**

$$T_{\text{อนุรักษ์}} = \frac{\langle \sigma_{\text{อนุรักษ์}} \cdot v \rangle}{n_X} \rightarrow \text{ann. rate} \int \frac{d(n_X \cdot a^2)}{dt} \frac{\delta_{\text{อนุรักษ์}}}{\text{อนุรักษ์}} \int_{\text{อนุรักษ์}}$$

**in thermal eq. The creation rate**

$$\int \frac{d(n_X \cdot a^2)}{dt} \frac{\delta_{\text{อนุรักษ์}}}{\text{อนุรักษ์}} \rightarrow \int \langle \sigma_{\text{อนุรักษ์}} \cdot v \rangle n_X^2 \cdot a^2 \rightarrow \text{e.g. distributions over momenta}

$$\langle \sigma_{\text{อนุรักษ์}} \cdot s \rangle = \int dp_1 dp_2 \int_{\text{อนุรักษ์}} F_{\text{อนุรักษ์}}(p_1) F_{\text{อนุรักษ์}}(p_2) v \cdot s_{\text{อนุรักษ์}} \int F_1(p_1) = 1$$

Introducing $\Delta X = \frac{n_X}{S}, \Delta_{\text{อนุรักษ์}} = \frac{n_{\text{อนุรักษ์}}}{S}$, where the entropy $S = \frac{2 \pi^2}{45} g_X T^3$

$M_X \gtrsim 50 \text{ GeV}$ \Rightarrow $70 \leq \delta X \leq 106.75$

**Entropy conservation**

$$a^2 \cdot S = \text{constant} \rightarrow \frac{d\Delta X}{dt} = S \cdot \frac{dA_X}{dt} - 3H$$
\( \xi = \text{const} \Rightarrow T = \frac{M_X}{M_X} \Rightarrow \frac{dA_X}{d\xi} = \frac{\langle 0 \nu \rangle}{M_X} \cdot S \left( \frac{A_X^2 - \xi^2}{M_X^2} \right) \)

\( S(\tau) = \frac{2\tau}{45} \xi \tau^3 \), \( H(\tau) = \frac{\tau^2}{M_{PL}^2} \Rightarrow \)

\( M_{PL} = \sqrt{\frac{350}{8\pi^2}} \frac{M_X}{\xi} \)

\[ \frac{dA_X}{d\xi} = \langle 0 \nu \rangle \cdot \frac{\xi}{355} \frac{M_X}{M_{PL}} \cdot (A_X^2 - \xi^2) \]

in non-relativistic limit

\( \langle U \rangle = 2 \langle U_X^2 \rangle \)

\( \langle E_{\text{kin}} \rangle = \frac{M_X \langle U_X^2 \rangle}{2} = \frac{3}{2} T \Rightarrow \frac{3}{2} \times M_X \Rightarrow \)

\( \langle U_X^2 \rangle = 3 \xi \Rightarrow \langle U \rangle = 6 \xi \)

\( \Delta_X(\tau_f) \approx \Delta_X^{eq}(\tau_f) \) at \( \tau \ll \tau_f \Rightarrow \Delta_X^{eq}(\tau_f) \approx \Delta_X(\tau_f) \)

using \( \Delta_X(\tau = 0) \ll \Delta_X^{eq}(\tau_f) \) and integrating

\[ \Delta_X^{-1}(\tau = 0) = (a_0 \frac{x_f + 3a_1 X_f^2}{355 \frac{M_X}{M_{PL}}}) \]

\( D_X = \frac{M_X + n_x}{g} \approx \frac{1}{h^2} \cdot 0.9 \times 10^{-10} \frac{1}{x_f \sqrt{\xi}} \cdot \text{Gev}^2 \]

The freeze out temperature \( T_f \) can be obtained from (see previous lecture)

\[ \frac{1}{g_X g_0} \left( \frac{2\pi}{M_X T_f} \right)^{3/2} e^{M_X / T_f} = \frac{M_{PL}^3}{T_f^2} \Rightarrow \]

\[ x_f = \ln \left( \frac{3550 a_0}{8 \pi^2 \frac{g_X}{g_0} M_X M_{PL}} \right) \times (a_0 + 6a_1 x_f) \]

\( a_0 = a_0 + 6a_1 x_f \)

\( \) depend on dominant annihilation channel

II. Sneutrino \( \bar{\nu} \)

Weak interactions are the same as for \( \nu \).

\( \bar{\nu} + \text{nuclei} \rightarrow \bar{\nu} + \text{nuclei} \)

\( G_{\text{elastic}} \Rightarrow \text{exp. bounds} (2-3 \text{rd ord}) \)

\( \) But right sneutrinos are fine!

\( \Rightarrow 0 \) is ruled out!
Local SUSY $\rightarrow$ SilCRA

graviton $s = 2$

gravitino $s = \frac{3}{2}$

spontaneously broken SUSY $\rightarrow$ $M_{3/2} = \frac{\sqrt{8}F}{3M_{Pl}}$ $\sqrt{F} \sim M_{Susy}$

Phenomenologically, $1$ TeV $\leq \sqrt{F} \leq M_{Pl}$

$2 \times 10^{-6}$ eV $\leq M_{3/2} \leq M_{Pl}$ it can be stable for $M_{3/2} \leq 100$ GeV

The DM candidate?

(deflection is very difficult!)

IV Axioms $M_{Ax} = 10^{-5} - 10^{-6}$ eV $\rightarrow$ consistent with astrophysical data

Can serve as DM candidate (homogeneous axion field oscillating after the QCD epoch)

$\Rightarrow$ Superheavy relic particles

in thermal equilibrium $T \gg M_{Ax}$ $\rightarrow$ overproduced, bound $M_{Ax} \ll 100$ eV of these particles?

$\Rightarrow$ never been in thermal equilibrium!

"Wimpzillas" $\Rightarrow \chi \sim 0.2$ $\Rightarrow \frac{M_{Ax}}{M_{max}} = 2.5 + \frac{1}{2} \cdot \ln \left(\frac{M_{Ax}}{\langle 0 \rangle}\right)$ (production)

$\Rightarrow$ "fine-tuning" problem