Lecture 14.3

- $X_f \leftrightarrow X_f$ in Early Universe
- Intro to Ind. Det.
THE DM THERMAL HISTORY IS POTENTIALLY IMPORTANT FOR DM STRUCTURE FORMATION, ESP FOR (COLD) "WIMPS" IN EARLY UNIVERSE, $\chi f \leftrightarrow \chi f$ (F THERMAL BATH)

KEEPS DM IN KINETIC EQ. EVEN AFTER CHEMICAL FREEZE-OUT (i.e. WHEN $\Gamma_{\chi\to X} < H$)

REASON IS THAT TARGET DENSITIES ARE VERY DIFF:

$\chi f \leftrightarrow \chi f \rightarrow \Gamma = \frac{m_{NR}}{T}$ - EXP. SUPPORTED

$\chi f \to \chi f \rightarrow \Gamma = \frac{m_{REL}}{T}$

TYPICALLY, FOR WIMP DM $\Gamma_{\chi f \to \chi f} \sim \frac{g_6^2 T^2}{\rho}$

HERE, TO ESTIMATE KINETIC DECOUPLING, WE NEED TO ACCOUNT FOR "INEFFICIENT" MOMENTUM TRANSFER:

$\hat{p}_f \sim T$ BUT FOR COLD RELICS $\frac{p^2}{2m} \sim T$

TYPICAL MOMENTUM TRANSFER IN KINETIC EQUILIBRIUM $\frac{\hat{p}_f}{\hat{p}} \sim \frac{1}{N}$

$\hat{p}_f $ " " SCATTERING TO ESTABLISH KINETIC EQUILIBRIUM $\frac{1}{1}$
So, here, we want to compare

\[ T^3 \cdot \frac{G_\nu T^2}{M_{\text{pl}}} \left( \frac{M_{\text{pl}}^2}{G_F^2} \right)^2 \sim \frac{T^2}{M_{\text{pl}}} \]

\[ M_{\text{rel}} \frac{1}{T_{\text{dec}}} \left( \frac{G_F^2}{M_{\text{pl}}} \right)^2 \]

So \( T_{\text{kd}} \sim \left( \frac{M_{\text{pl}}}{G_F^2} \right)^{1/4} \sim \left( \frac{100 \text{ GeV}}{1.8 \times 10^{-10} \text{ GeV}^{-4}} \right)^{1/4} \sim 10^{-6} \)

or \( T_{\text{kd}} \sim 30 \text{ MeV} \left( \frac{M_{\text{pl}}}{100 \text{ GeV}} \right)^{1/4} \)

What does this imply for structure formation?

Roughly, cutoff will be size of horizon at kinetic decoupling, so

\[ M_{\text{kd}} \sim \frac{4 \pi}{3} \left( \frac{1}{H(T_{\text{kd}})} \right)^3 \phi \left( T_{\text{kd}} \right) \]

\[ \sim 30 M_\odot \left( \frac{10 \text{ MeV}}{T_{\text{kd}}} \right)^3 \]

(More precisely: cutoff scale set by largest or free streaming \( T_{\text{kd}} \sim 0.1 \text{ GeV} \) vs. acoustic damping \( T_{\text{kd}} \sim 0.1 \text{ GeV} \))
So, for typical WIMPS, photot halos have mass \( \sim M_\odot \) (to \( \sim 10^{-6} M_\odot \))

**Important for indirect detection (boost factor)**

and for DM "small scale problems"

\[
\frac{dN}{dM} \sim M^{-2}
\]

Ways to probe? \( X\bar{q} \leftrightarrow qX \) same process as direct detection!

\( M_{\text{cut}} \) correlate with \( T_{\text{peak}} \)

**Caveat:** Usually \( T_{\text{peak}} < T_{\text{QCD}} \), so quark scattering secondary... \( \sim 200 \text{ MeV} \)

But if (model-dep.) quark-lepton universality holds, then correlation is expected.

And found (Cornell + Profumo, 2012) e.g.: SUSY, UED
INDIRECT DETECTION

KEY PROCESS: \( \chi \rightarrow SM \) IN LATE UNIVERSE
(also \( \chi \rightarrow SM \) DECAY)

KEY INGREDIENTS: (i) PRODUCTION RATES

(ii) ENERGY SPECTRUM

(iii) ANNIHILATION PRODUCTS

\[
\text{Rate for given particle in unit volume} = \left( \frac{\text{# DM pairs in unit volume}}{\text{dV}} \right) \times \left( \text{pair annihilation rate} \right) \times \left( \frac{\text{# of particles per ann. event}}{\text{event}} \right)
\]

\[
\int \frac{p_{\text{DM}}}{m_\chi^2} \text{d}V <T(x)\neq 0> M_\chi, \text{ANN FINAL STATE}
\]

TALKED ABOUT \(<\Delta\phi>, M_\chi; \text{ANN FINAL STATE}>
**ANNIHILATION FINAL STATE**

If DM is MAJORANA, \( \tilde{\tau} \tilde{\tau} \rightarrow \bar{f}f \) REQUIRES

**HELCILITY FLIP** \( \rightarrow \sqrt{M_f^2} \propto M_\tau^2 \) (exactly as for \( \tau \) decay!)

\[ \begin{array}{c}
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\text{So: NO LIGHT FERMIONS!} \\
\text{(f, f)}
\end{array}
\end{array} \]

If \( M_\tau \lesssim M_{top} \) AND \( \tau \) doesn't like \( W^+W^-ZZhh \)

\( \rightarrow \tilde{\tau} \tilde{\tau} \rightarrow b\bar{b}, \tau^+\tau^- \) DOMINANT

3x COLOR

\( \tau^+\tau^- \) can be boosted, e.g., with light \( \tau \) in SUSY.

\( \tilde{\tau} \rightarrow \tau \tilde{\nu} \) (true in \( \text{MSUGRA/CMSSM} \))

\( \ldots \) but killed by \( M_\tau \sim 125 \text{ GeV} \)

TOTALLY OPPOSITE FORUED, \( B(\tau) \propto \text{HYPERCHARGE} \)

\[ \begin{array}{c}
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B(\tau) \quad \nu_L \\
\text{F}
\end{array}
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\[ \left| M_f^2 \right| \sim \left| \langle \nu \rangle \right|^4 \]

\( U_L : |\nu| = 4 \)

\( e_R : |\nu| = 2 \)
In $SU(2)$ multiplets (e.g., higgsinos, winos in SUSY, everything is fixed by gauge interactions)

Winos: Final states: $W^+W^-$

$\tilde{\chi}^1_0$ = 3SM $\sim M_2$

$\sim 10^5$ MeV

Exactly structure we postulated!

$\langle \xi W \rangle \sim \frac{3/4 g_4}{16 \pi M_2^2}$

$\rightarrow$ includes $\tilde{\chi}^0_0$, $\tilde{\chi}^1_0$, $W^+$, $W^-$

$\lambda_{WW} h^2 \sim 0.1 \left( \frac{M_2}{2.2 \text{ TeV}} \right)^2$

Higgsinos: Final states: $W^+W^-$, $ZZ$

$\tilde{\chi}^0_0$ = $\tilde{\chi}^2_0$

$\tilde{\chi}^1_0$ = $\sim \mu$

$\langle \xi W \rangle \sim \frac{g_4^4}{512 \pi M_2^2} (21 + 3 \tan^2 \theta_W + 11 \tan^4 \theta_W)$

$\lambda_{WW} h^2 \sim 0.1 \left( \frac{\mu}{1 \text{ TeV}} \right)^2$