

Graukho production $\sigma \sim \frac{1}{F^2} \frac{m_{3/2}^2}{M_p^2}$ $\Lambda_{3/2} + 3 H \Lambda_{3/2} \approx \frac{T_R^6}{M_p^2}$

$\Omega_{3/2} \sim \frac{T_R^4}{M_p^2} \Rightarrow$ bound on T_R .
 Never in equilibrium
 Freeze-in num. density builds up over time.

NLSP decay $\Gamma \sim \frac{m_{NLSP}^5}{F^2} \Rightarrow \Omega_{3/2} = \Omega_{1/2} \left(\frac{m_{3/2}}{m_{1/2}} \right)$

Wary about BBN \rightarrow destruction of Li etc.

Co-annihilation 9704361

One of 3 exceptional cases for relic abundance calc. (Griest + Seckel)
 (50% splitting)
 States nearly in mass to DM with strong couplings to DM or themselves can alter relic abundance.

e.g. higgsinos / winos / staus is generic.

$\chi_1, \chi_2 \rightarrow SM SM$ could be large
 (χ_2 next other stau state eg squark, chargino, Neutralino)

or $(\chi_2 \chi_2 \rightarrow SM SM) + (\chi_1 SM \rightarrow \chi_2 SM)$

either help deplete χ_1 .

Susy states $\chi_1 \dots \chi_N$
 \uparrow
 DM

$$\sigma_{ij} = \sum_{\substack{X \\ SM \text{ fields}}} \sigma(\chi_i \chi_j \rightarrow X)$$

$$\sigma'_{ij} = \sum_{\substack{X \\ \neq Y}} (\chi_i X \rightarrow \chi_j Y)$$

$$\Gamma_{ij} = \sum_X \Gamma(\chi_i \rightarrow \chi_j X)$$

Full BE:
$$\frac{dn_i}{dt} + 3Hn_i = - \sum_{j=1}^N \sum_{l=1}^N \langle \sigma_{ij} v_{ij} \rangle (n_i n_j - n_i^{eq} n_j^{eq})$$

$$- \sum_{j \neq i} \left[\langle \sigma'_{xij} v_{ij} \rangle (n_i n_x - n_i^{eq} n_x^{eq}) - \sigma'_{xji} (n_j n_x - n_j^{eq} n_x^{eq}) \right] \quad (2)$$

$$- \sum_{j \neq i} \left[\Gamma_{ij} (n_i - n_i^{eq}) - \Gamma_{ji} (n_j - n_j^{eq}) \right] \quad (3)$$

Ultimately any slow state decays down to 1 DM state Γ_{ii}
 So find WIMP abundance in $\sum_i n_i \equiv n$. (2) (3) $\rightarrow 0$ in sum.

$\sigma'_{xij} \sim \sigma_{ij}$ since $n_x \gg n_i$ so x_i dist. \sim thermal. $\Rightarrow \frac{n_i}{n} \sim \frac{n_i^{eq}}{n^{eq}}$

So
$$\frac{dn}{dt} + 3Hn = - \langle \sigma_{eff} v \rangle (n^2 - n^{eq2}) ; \langle \sigma_{eff} v \rangle = \sum_{i,j} \langle \sigma_{ij} v_{ij} \rangle \frac{n_i^{eq} n_j^{eq}}{n^{eq2}}$$

eg. Squark m_2 $\uparrow \uparrow \rightarrow X$, $\uparrow X \rightarrow X$, $XX \rightarrow X$
 DM m_1

Indices to calc, or codes: MicroMegas, DarkSUSY

$$\sigma_{22} \sim \frac{\alpha_s}{\alpha} \sigma_{12} \approx \sigma_{12} \sim \frac{\alpha_s}{\alpha} \sigma_{11}$$

HW
$$\sigma_{eff} v = \sigma_{11} \left(\frac{1 + \frac{\alpha_s}{\alpha} w}{1+w} \right)^2$$

$$w = \frac{g_2}{g_1} (1+\Delta)^{3/2} e^{-\Delta}$$

$$w = \frac{m_1}{T} \quad \Delta = \frac{m_2 - m_1}{m_1}$$

Estimate effect on relic abundance.

Forbidden channel

Namely you might think of all $XX \rightarrow XY$ processes with $m_X + m_Y < 2m_X$.

But $\alpha = m_{\nu/T} \sim 20-25 \Rightarrow k_B \sim T$ So fed of Boltzmann allows "forbidden" channel. Esp. important if forbidden channel has large σ -sec

Resonances

$$\Omega_{\nu X} \simeq m_X \quad \sigma \nu \sim \frac{\alpha^2 s}{(s-M^2)^2 + M^2 \Gamma^2} \quad \text{eg } A^0 \text{ pole funnel} \\ \text{Higgs funnel}$$

In sum CP nature of Majorana DM needs $XX \rightarrow A^0 \rightarrow$ heavy fermions.

Well tempering

Bino gives Ω_X too large. Wino, higgsino give Ω_X too small.

Because ν sensitive to mixing, coannihilation etc.

Lie on narrow bino/higgsino or bino/wino boundary.

$$|M_1| \simeq |M_2| \quad |M_1| \simeq |M_2|$$

Freeze-in

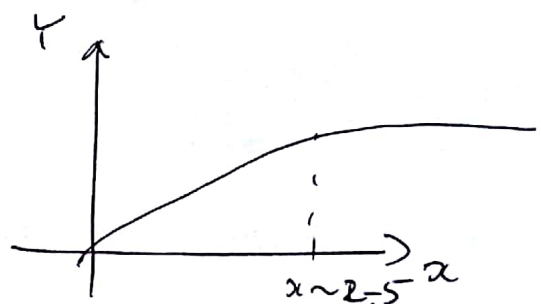
Path that was never in thermal equilibrium in early universe
very small couplings.

B.E. $\dot{n} + 3Hn = \langle \sigma v \rangle \Lambda_{SM}^2$

↑
 ignore $\chi\chi \rightarrow SM \gamma SM$
 since $\sigma_{\chi\chi}$ too small.

$2 \rightarrow 2$
 ie SM production

Abundance of χ grows w/ time



If $m_{SM} < m_{\chi}$ then $2 \rightarrow 2$ process proceeds until $T \lesssim m_{\chi}$

← dominated by IR
 ← cf freeze-out when $\alpha \sim 20$.

Then abundance fixed: freeze-in.

Example

$2 > \lambda (H)^2 S^2$
 ↑
 DM, scalar.

$R h^2 \approx 0.1 \times \left(\frac{\lambda}{10^{-11}}\right)^2 \left(\frac{M_S}{2 \text{ GeV}}\right)$

Very small couplings \rightarrow perhaps DM not stable just very long lived

\rightarrow Hard to see DM in other expts.