II Beyond WIMPs

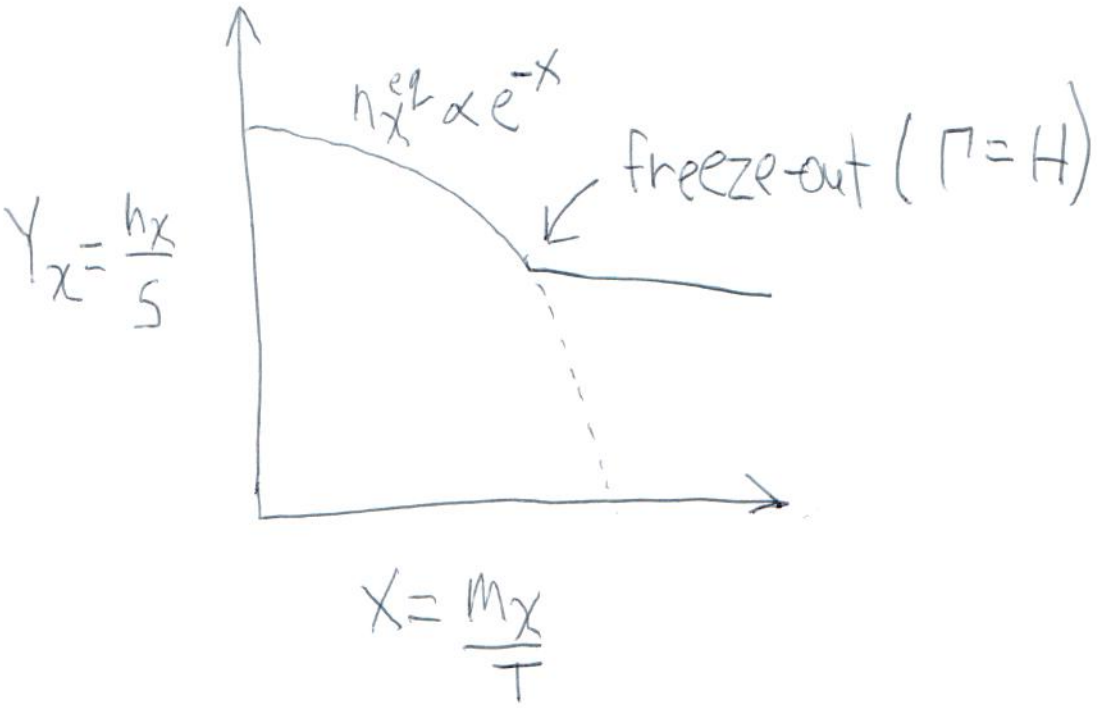
PLAN

I $2 \to 2$ Zoology

II Thermal Relics Beyond $2 \to 2$

III Non-Thermal DM

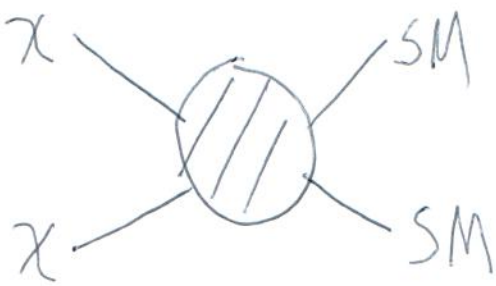
thermal relic



(I) 2→2 Zoology

WIMP

$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - (n_\chi^{eq})^2\right)$$



$n\langle\sigma v\rangle \approx H$

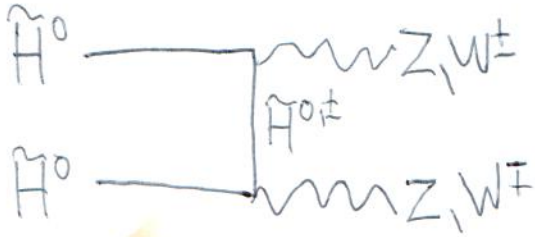
$$\Omega_\chi \sim \frac{1}{T_{eq} \cdot M_{pl} \langle\sigma v\rangle}$$

$$\langle\sigma v\rangle \sim \frac{1}{T_{eq} \cdot M_{pl}}$$

$$\boxed{m_\chi \sim \alpha_W \sqrt{T_{eq} \cdot M_{pl}}}$$

ex) $\tilde{H} = (1,2)_{\pm\frac{1}{2}}$ $\quad m_{\tilde{H}} \approx 1.1\ \text{TeV}$

$\tilde{W} = (1,3)_0$ $\quad m_{\tilde{W}} \approx 3\ \text{TeV}$

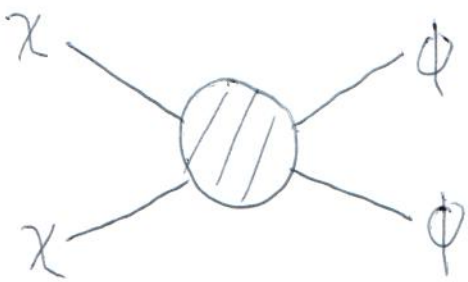


"Minimal DM" hep-ph/0512090

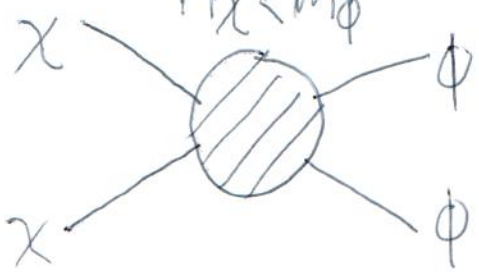
Dark Sector

$2 \to 2$ Variations

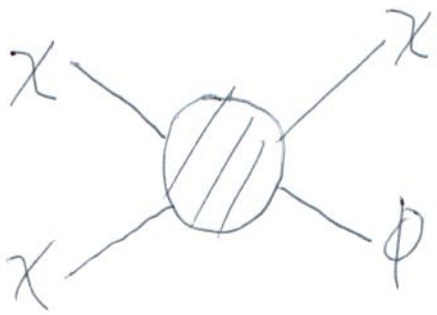
WIMP



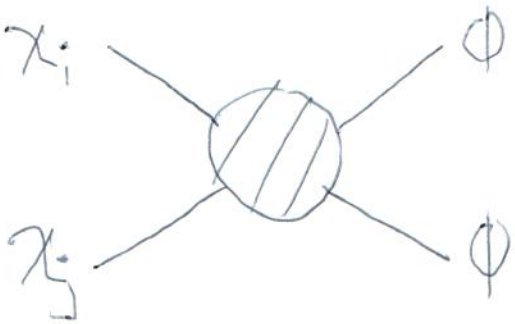
Forbidden $m_\chi < m_\phi$



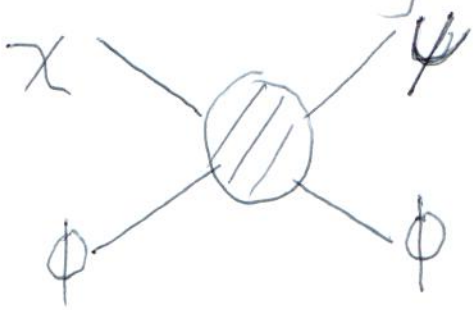
semi-annihilation



Coannihilations

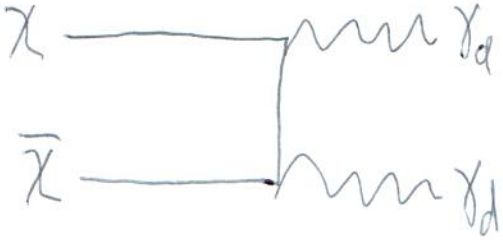


Coscattering



WIMP w/ dark annihilations

$G_d = U(1)_d$



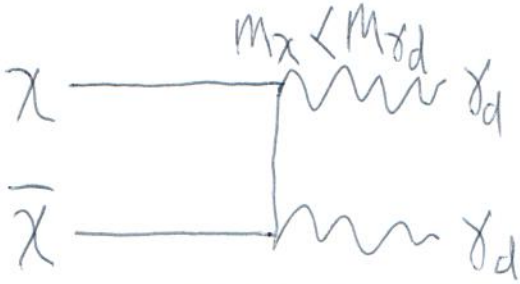
$$\langle \sigma v \rangle \simeq \frac{\pi \alpha_d^2}{m_\chi^2} \sim \frac{1}{T_{eq} \cdot M_{Pl}}$$

$$m_\chi \sim \alpha_d \sqrt{T_{eq} \cdot M_{Pl}} \sim \left(\frac{\alpha_d}{\alpha_W}\right) \times 1\ \text{TeV}$$

- Can couple to SM through kinetic mixing

Forbidden DM

- D'Agnolo + JTR 1505.07107
- Griest + Seckel 1991



$$\langle \sigma v \rangle_{\chi\bar{\chi}} \sim \frac{1}{T_{eq} \cdot M_{pl}}$$

- thermal average: (hep-ph/0310123 app. A)

$$\langle \sigma v \rangle_{\chi\bar{\chi}} = \frac{1}{(n_\chi^{eq})^2} \int d\vec{p}_\chi d\vec{p}_{\bar{\chi}} f_\chi f_{\bar{\chi}} \int d\vec{p}_{\gamma_{d1}} d\vec{p}_{\gamma_{d2}} |M|^2 \times (2\pi)^4 \delta^4(p_\chi + p_{\bar{\chi}} - p_{\gamma_{d1}} - p_{\gamma_{d2}})$$

$$d\vec{p}_i = \frac{d^3 p_i}{2E_i (2\pi)^3}$$

- trick: detailed balance

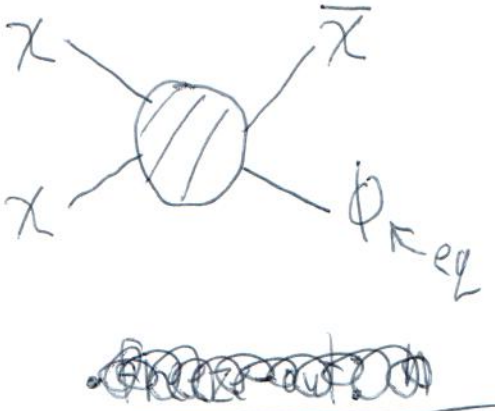
$$(n_\chi^{eq})^2 \langle \sigma v \rangle_{\chi\bar{\chi}} = (n_{\gamma_d}^{eq})^2 \langle \sigma v \rangle_{\gamma_d \gamma_d} \sim \frac{\alpha_d^2}{m_\chi^2}$$

$$\langle \sigma v \rangle_{\chi\bar{\chi}} \sim e^{-2\delta m/T} \frac{\alpha_d^2}{m_\chi^2} \qquad \delta m = m_{\gamma_d} - m_\chi$$

$$\boxed{m_\chi \sim e^{-\delta m / T_{FO}} \alpha_d \sqrt{T_{eq} \cdot M_{pl}}} \ll \text{TeV}$$

Semi-annihilations — D'Eramo, Thaler 1003.5912

- vanilla annihilations respect a Z_2: $\chi \to -\chi$
- Z_3 stabilized DM: $\chi \to e^{\frac{2\pi i}{3}} \chi$, $\bar{\chi} \to e^{\frac{4\pi i}{3}} \bar{\chi}$

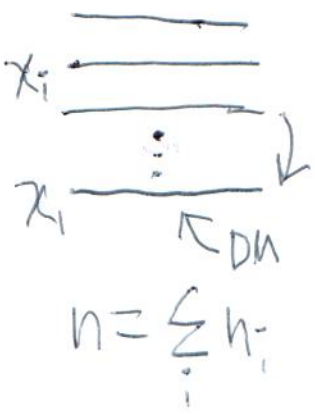


$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\chi}\left(n_\chi^2 - n_\chi n_\chi^{eq}\right)$$

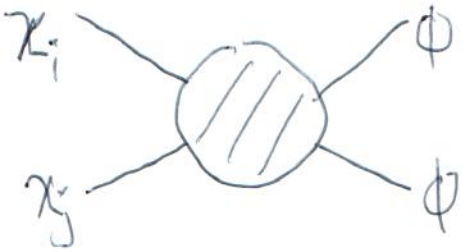
$$\langle\sigma v\rangle_{\chi\chi} \sim \frac{1}{T_{eq} \cdot M_{pl}}$$

[illegible]

Coannihilations — Griest + Seckel 1991



$$n = \sum_i n_i$$



$$\langle\sigma v\rangle_{eff} = \sum_{ij} \frac{n_i^{eq} n_j^{eq}}{(n_i^{eq})^2} \langle\sigma_{ij} v\rangle$$

$$\dot{n} + 3Hn = -\langle\sigma v\rangle_{eff}\left(n^2 - n_{eq}^2\right)$$

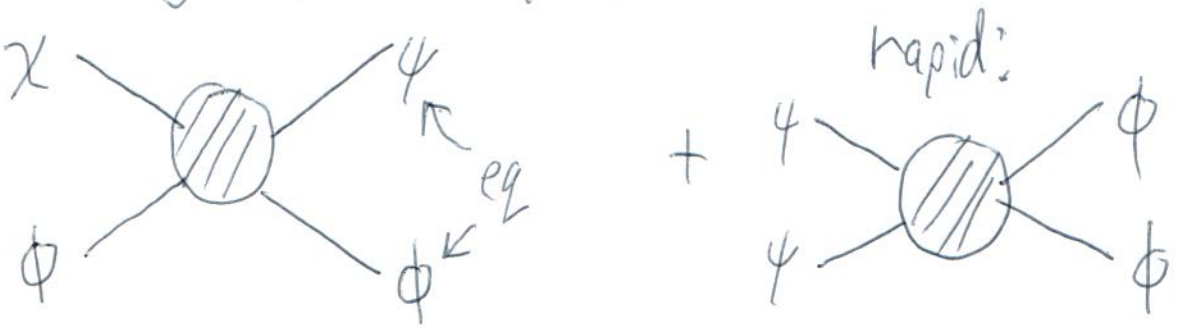
$$\langle\sigma v\rangle_{eff} \sim \frac{1}{T_{eq} \cdot M_{pl}}$$

ex) $\tilde{B}/\tilde{H}$, $\tilde{B}/\tilde{W}$

"Well-Tempered Neutralino" hep-ph/0601041

Coscattering

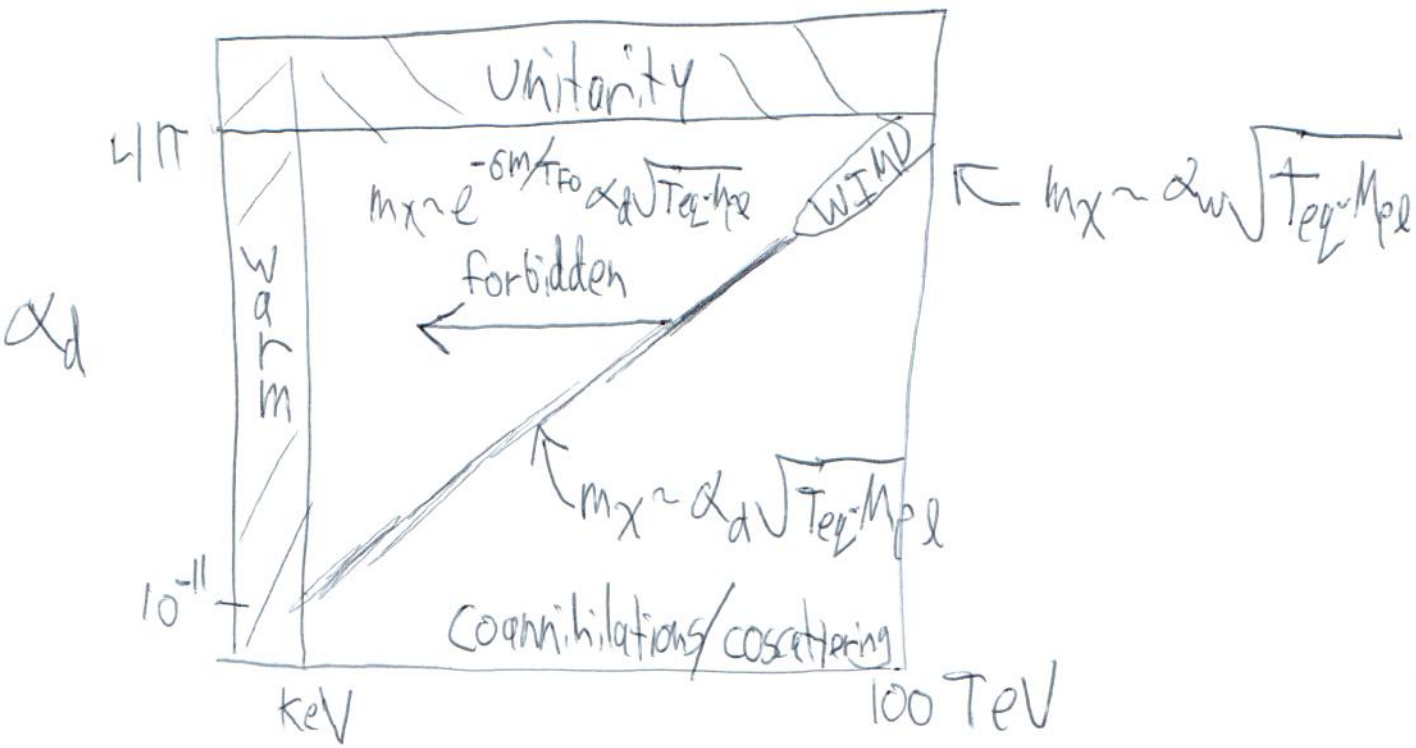
- D'Agnolo, Pappadopulo, JTR 1705.08450



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v\rangle_{\chi\phi}\left(n_\chi n_\phi^{eq} - n_\chi^{eq} n_\phi^{eq}\right)$$

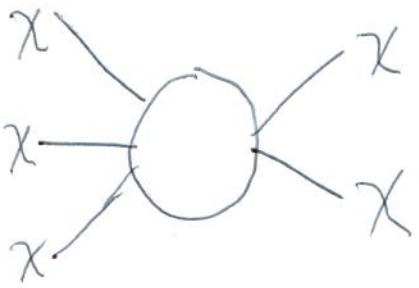
freeze-out: $n_\phi^{eq}\langle\sigma v\rangle_{\chi\phi} = H$

Phase Diagram



II Thermal Relics Beyond 2→2

SIMPs 1402.5143



$$\dot{n}_\chi + 3Hn_\chi = -\langle\sigma v^2\rangle_{3\chi}\left(n_\chi^3 - n_\chi^2 n_\chi^{eq}\right)$$

Freeze-out: $n_\chi^2 \langle\sigma v^2\rangle \approx H$

$$\Omega_\chi h^2 \sim \frac{m_\chi Y_\chi}{T_{eq}} = \frac{m_\chi h_\chi}{s T_{eq}} = \frac{m_\chi H^{1/2}}{s T_{eq} \langle\sigma v^2\rangle^{1/2}}$$

$$H \sim \frac{T^2}{M_{pl}} \qquad s \sim T^3 \qquad T \sim m$$

$$\Omega_\chi \sim \frac{1}{m_\chi T_{eq} M_{pl}^{1/2} \langle\sigma v^2\rangle^{1/2}}$$

$$\langle\sigma v^2\rangle \sim \frac{\alpha_d^3}{m_\chi^5} \Rightarrow \boxed{m_\chi \sim \alpha_d \left(T_{eq}^2 M_{pl}\right)^{1/3}}$$

~ 100 MeV

Asymmetric DM

0901.4117

- primordial baryon asymmetry: $n_B - n_{\bar{B}}$

$$\Omega_b h^2 = \left(\frac{s_0}{\rho_c h^{-2}}\right)\left(\frac{n_B - n_{\bar{B}}}{s}\right) m_p$$

- DM asymmetry? $n_X - n_{\bar{X}}$

$$\Omega_{DM} h^2 = \left(\frac{s_0}{\rho_c h^{-2}}\right)\left(\frac{n_X + n_{\bar{X}}}{s}\right) m_X = \Omega_b h^2 \left(\frac{n_X - n_{\bar{X}}}{n_B - n_{\bar{B}}}\right)\left(\frac{m_X}{m_p}\right)$$

$$\frac{\Omega_{DM}}{\Omega_b} \simeq 5.3$$

- mechanisms
  - dark phase transition
  - out-of-equil. decay
  - $B-L \Leftrightarrow X$ transfer

ex) $\mathcal{L} \supset \frac{\bar{X}^2 (LH)^2}{M^4}$ sets: $n_X - n_{\bar{X}} = C(n_B - n_{\bar{B}})$

$C = \frac{-12}{49}$

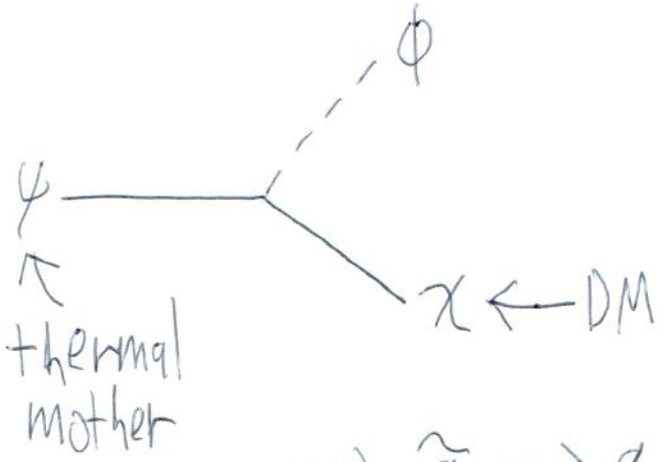
$$\Gamma = n\langle\sigma v\rangle \sim \frac{T^9}{M^8}$$

$$\frac{\Gamma}{H} \propto T^7$$ "UV dominated"

III Non-Thermal DM

FIMP: χ is kinetically/chemically decoupled

- initial condition? ex) $n_\chi(T_{RH}) = 0$



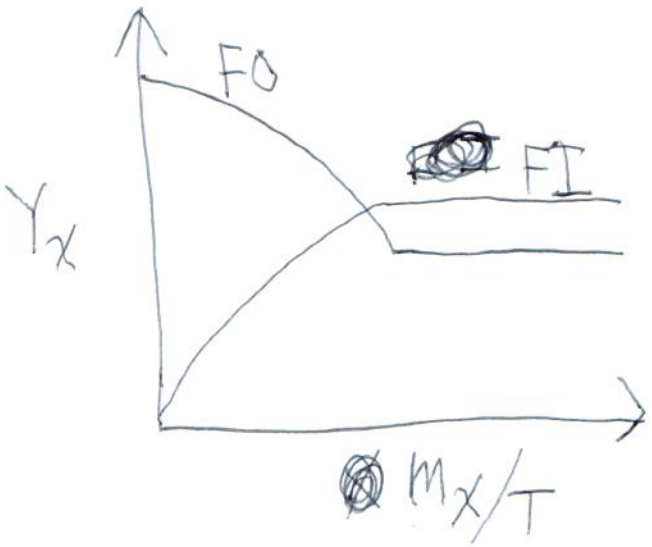
$\Gamma_\psi < H(T = m_\psi)$

ex) $\tilde{q} \to q \tilde{G}$

A) freeze-in: χ produced when $n_\psi = n_\psi^{eq}$

B) Super-WIMP: χ produced after ψ freezes-out

A) Freeze-In 09.11.20



$\dot{n}_\chi + 3Hn_\chi = n_\psi^{eq} \langle \Gamma_\psi \rangle$

$$\langle \Gamma_\psi \rangle = \frac{K_1(m_\psi/T)}{K_2(m_\psi/T)} \Gamma_\psi$$

$$\hookrightarrow \begin{cases} \frac{m_\psi}{2T} & T >> m_\psi \\ 1 & T << m_\psi \end{cases}$$

$$Y_\chi \simeq \int \frac{dT}{T} Y_\psi^{eq} \frac{\langle \Gamma_\psi \rangle}{H}$$

- for $T << m_\psi$, suppressed by $Y_\psi^{eq} \propto e^{-m_\psi/T}$
- for $T >> m_\psi$, $\frac{\langle \Gamma_\psi \rangle}{H} \propto T^{-3}$

• dominant production: $T \sim m_\psi$

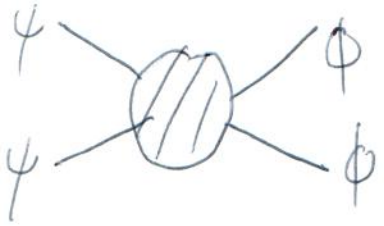
$$Y_\chi \sim \frac{\Gamma_\psi}{H(T=m_\psi)} \sim \frac{\Gamma \, M_{pl}}{m_\psi^2}$$

$$m_\chi \gtrsim T_{eq} \Rightarrow \frac{\Gamma_{eq} \cdot m_\psi}{\alpha_d \cdot M_{pl}}$$

$$\Omega \sim \frac{m_\chi Y_\chi}{T_{eq}} \sim \frac{m_\chi \Gamma \cdot M_{pl}}{m_\psi^2 T_{eq}}$$

B) Super WIMP hep-ph/0302215

1) ψ freezes out



2) ψ decays to DM

$Y_\chi = Y_\psi$ $\quad \Omega_\chi = m_\chi Y_\chi = m_\chi Y_\psi$

$$\Omega_\chi = \frac{m_\chi}{m_\psi} \Omega_\psi^{FO}$$

Dark Mechanisms