Dark Matter Production in Hidden Vector Sector

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Outline

- Introduction
- Model
- Boltzmann Equations
- Conclusions

Energy density

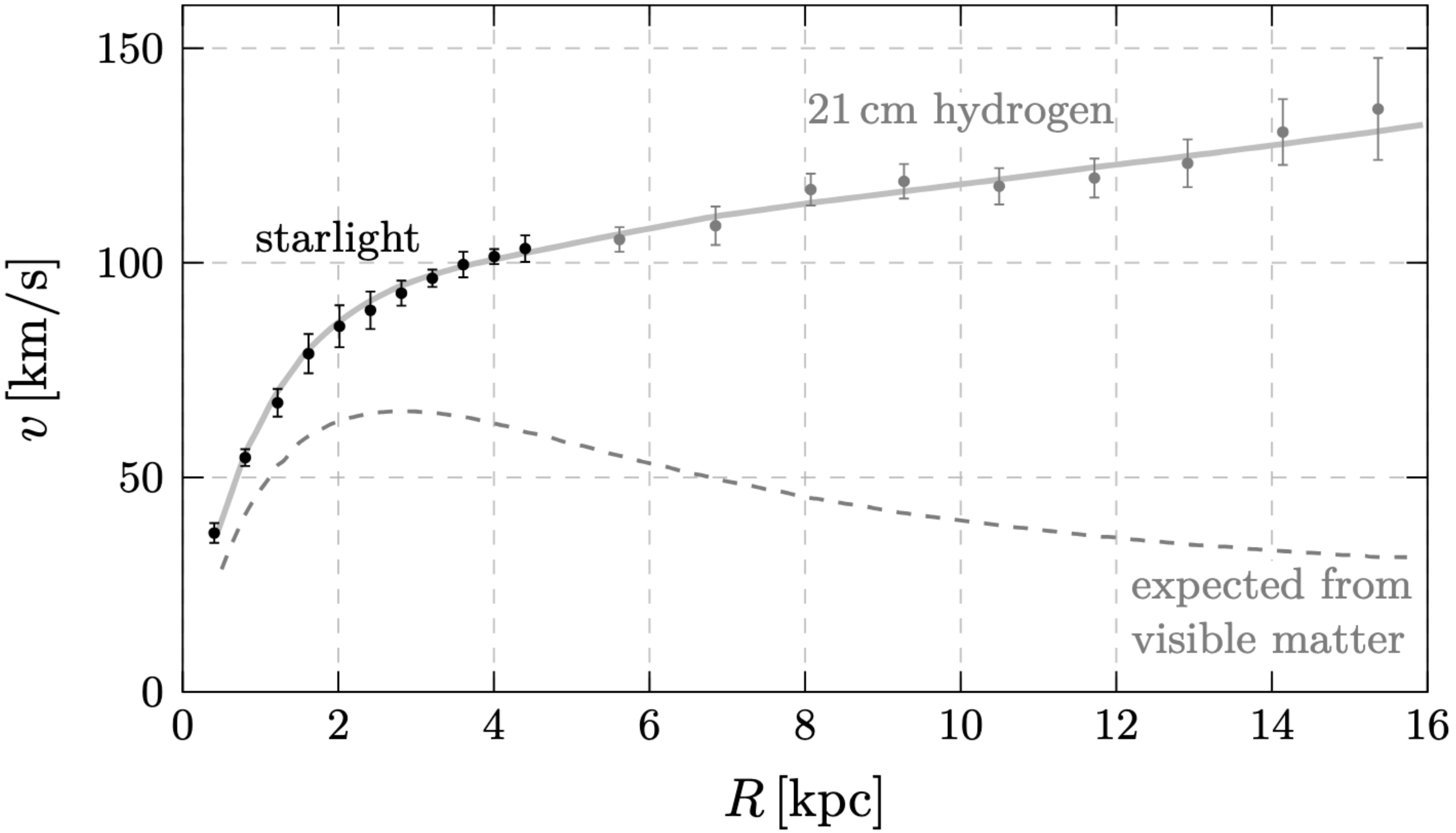
$$\Omega_r + \Omega_m + \Omega_\Lambda + \Omega_k = 1$$

9×10^{-5}

0.68 0.005

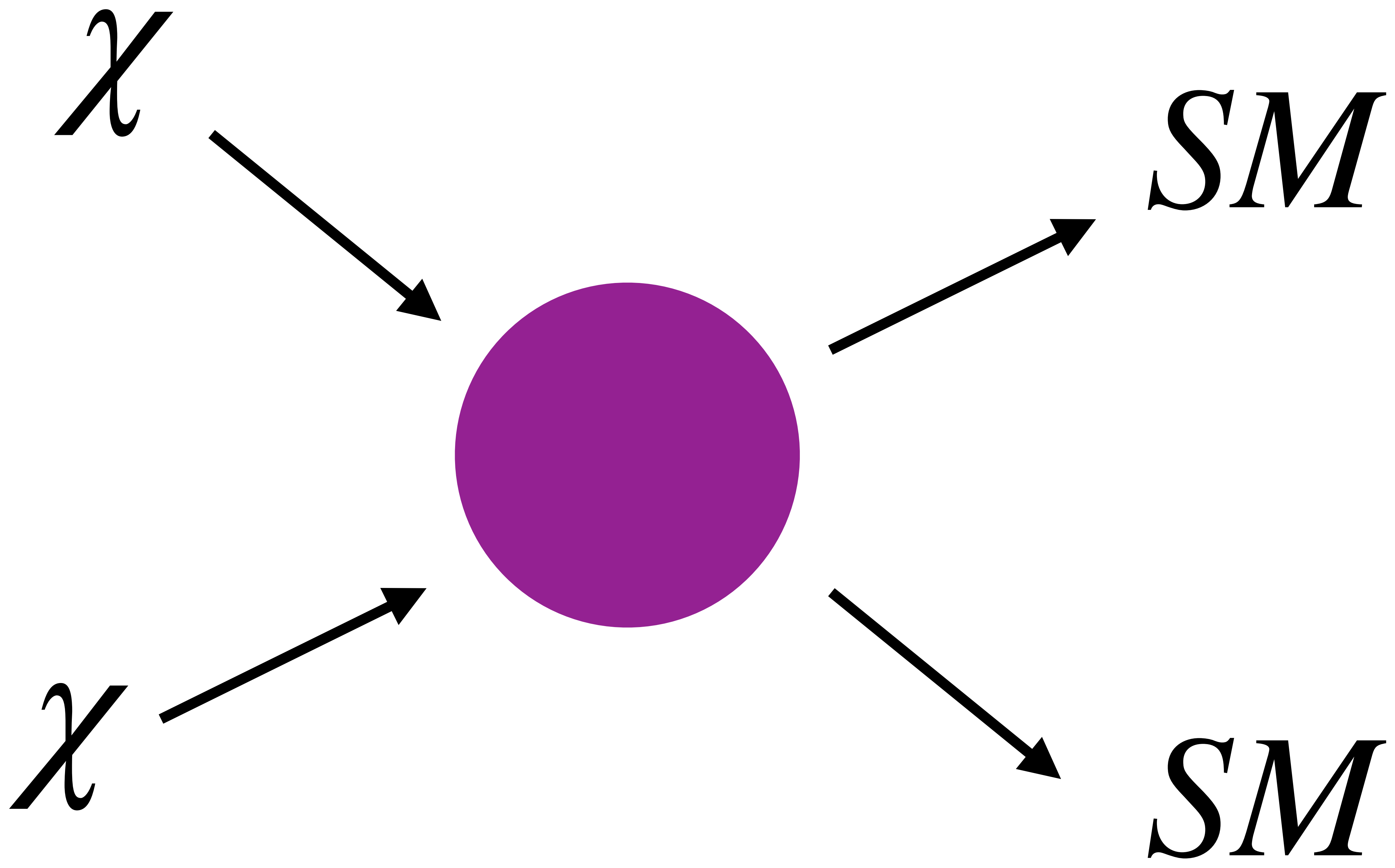
$$\Omega_b + \Omega_c$$

0.05 0.27



Rotation curve of M33 (Cosmology Daniel Baumann)

How could we describe it?



+

Boltzmann
Equations

Model

The extension has a $SU(2)_\chi$ symmetry

$$\mathscr{L} = \mathscr{L}^{SM} - \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + (D_\mu \phi)^\dagger (D^\mu \phi) - \lambda_m \phi^\dagger \phi H^\dagger H - \mu_\phi^2 \phi^\dagger \phi - \lambda_\phi (\phi^\dagger \phi)^2$$

Spontaneous Symmetry Breaking

$$\phi = \exp\left(i\tau \cdot \frac{\xi}{v_\phi} \right) \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} \left(v_\phi + \eta' \right) \end{pmatrix}$$

Spontaneous Symmetry Breaking

The result is

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}F_{\mu\nu} \cdot F^{\mu\nu} + \frac{1}{4}\left(\frac{\mathbf{g}_{\phi}\mathbf{v}_{\phi}}{\mathbf{2}}\right)^2 A_{\mu} \cdot A^{\mu} + \frac{1}{8}g_{\phi}^2 A_{\mu} \cdot A^{\mu}\eta'^2 + \frac{1}{4}g_{\phi}^2 v_{\phi} A_{\mu} \cdot A^{\mu}\eta'$$

$$+\frac{1}{2}(\partial_{\mu}\eta')^2 - \frac{\lambda_m}{2}(\eta' + v_{\phi})^2 H^{\dagger}H - \frac{\mu_{\phi}^{\mathbf{2}}}{\mathbf{2}}(\eta' + v_{\phi})^2 - \frac{\lambda_{\phi}}{4}(\eta' + v_{\phi})^4$$

Spontaneous Symmetry Breaking

In SM we have

$$H = \exp\left(i\tau \cdot \frac{\zeta}{v}\right)\left(\begin{array}{c} 0 \\ \frac{1}{\sqrt{2}}\left(v + h'\right) \end{array}\right)$$

Spontaneous Symmetry Breaking

Mass matrix is

$$M^2 = \begin{pmatrix} m_{h'}^2 & m_{h'\eta'}^2 \\ m_{h'\eta'}^2 & m_{\eta'}^2 \end{pmatrix}, \qquad \begin{pmatrix} h' \\ \eta' \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} h \\ \eta \end{pmatrix}$$

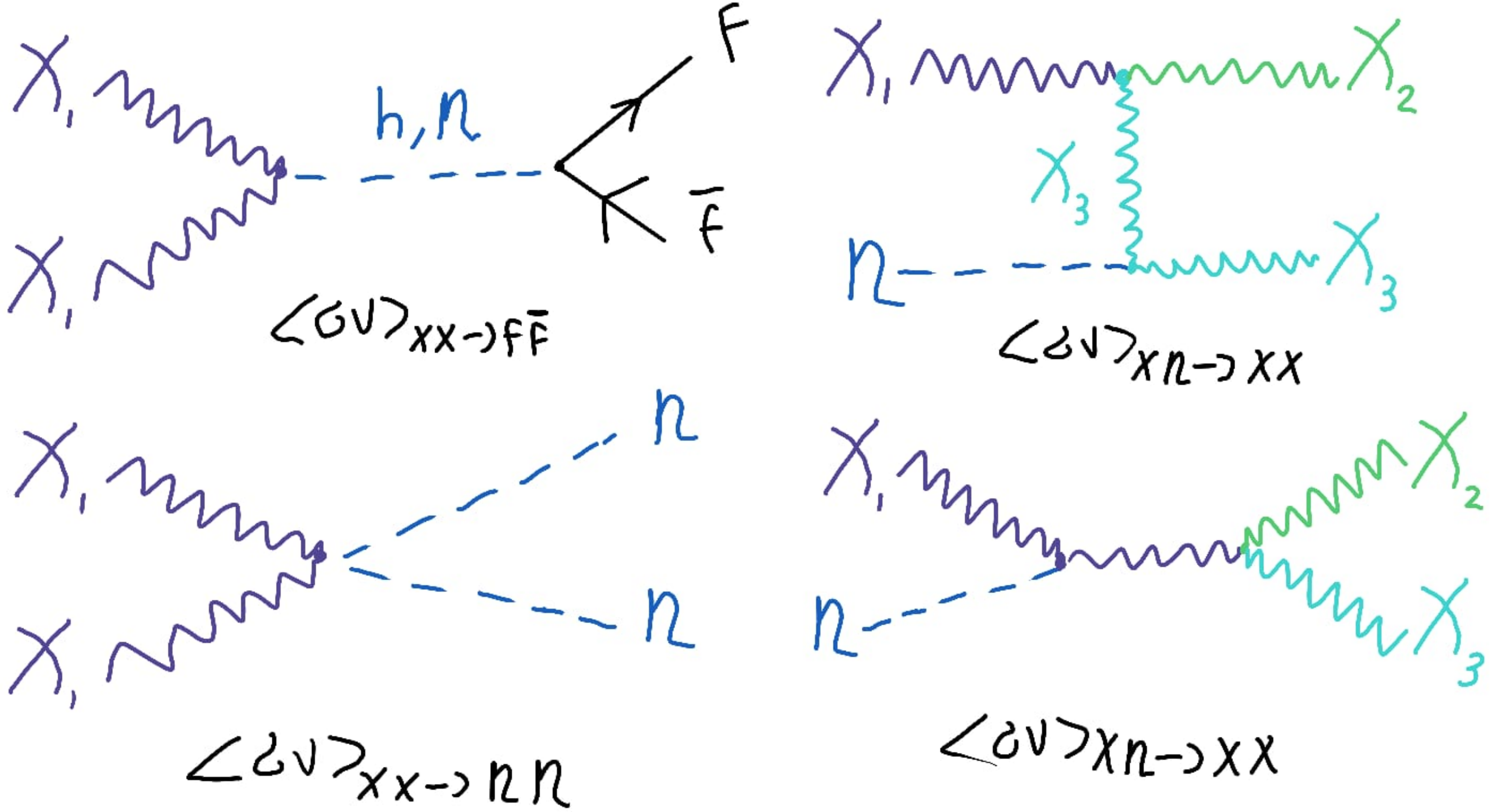
Spontaneous Symmetry Breaking

The final lagrangian is

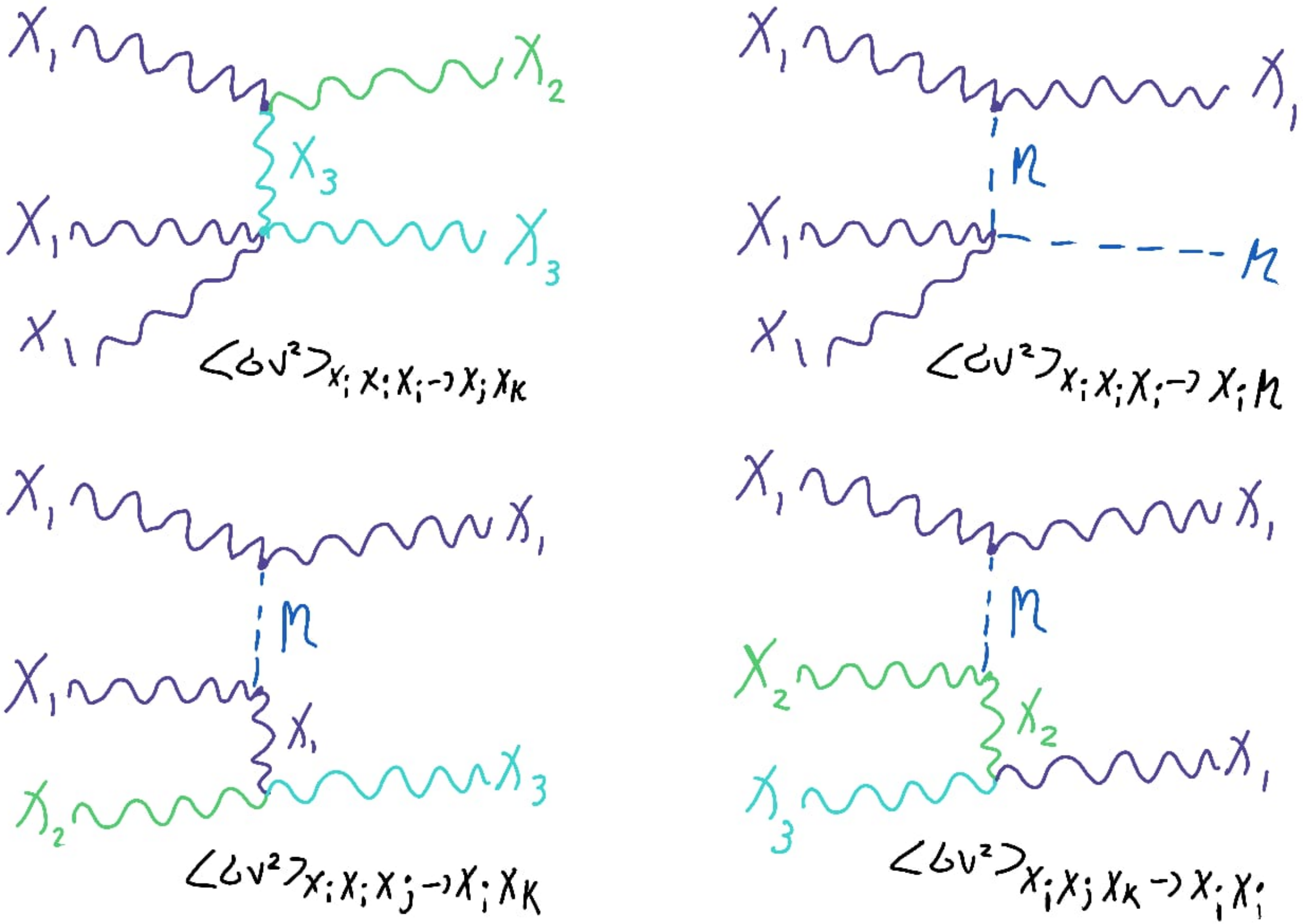
$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu} \cdot F^{\mu\nu} + \frac{1}{8}(g_\phi v_\phi)^2 A_\mu \cdot A^\mu + \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_\eta^2 \eta^2 - \frac{1}{2}m_h^2 h^2$$

$$+A_\mu \cdot A^\mu \left[\kappa_\eta \eta^2 + \kappa_h h^2 + \kappa_{h\eta} \eta h + 2v_\phi \xi_\eta^\phi \eta + 2v_\phi \xi_h^\phi h\right] + \ldots$$

Interactions



Interactions



Boltzmann Equations

$$\frac{dn_1}{dt} + 3Hn_1 = \text{Production and Annihilation terms}$$

Boltzmann Equations

$$\frac{dn_1}{dt} + 3Hn_1 = 2\langle\sigma v\rangle_{SMSM\to ii}\, n_{SM}^2 - 2\langle\sigma v\rangle_{ii\to SMSM}\, n_1^2 + \dots$$

Boltzmann Equations

$$\frac{dn_1}{dt} + 3Hn_1 = 2\langle \sigma v \rangle_{ii \to SMSM} (n_{eq}^2 - n_1^2) + \ldots$$

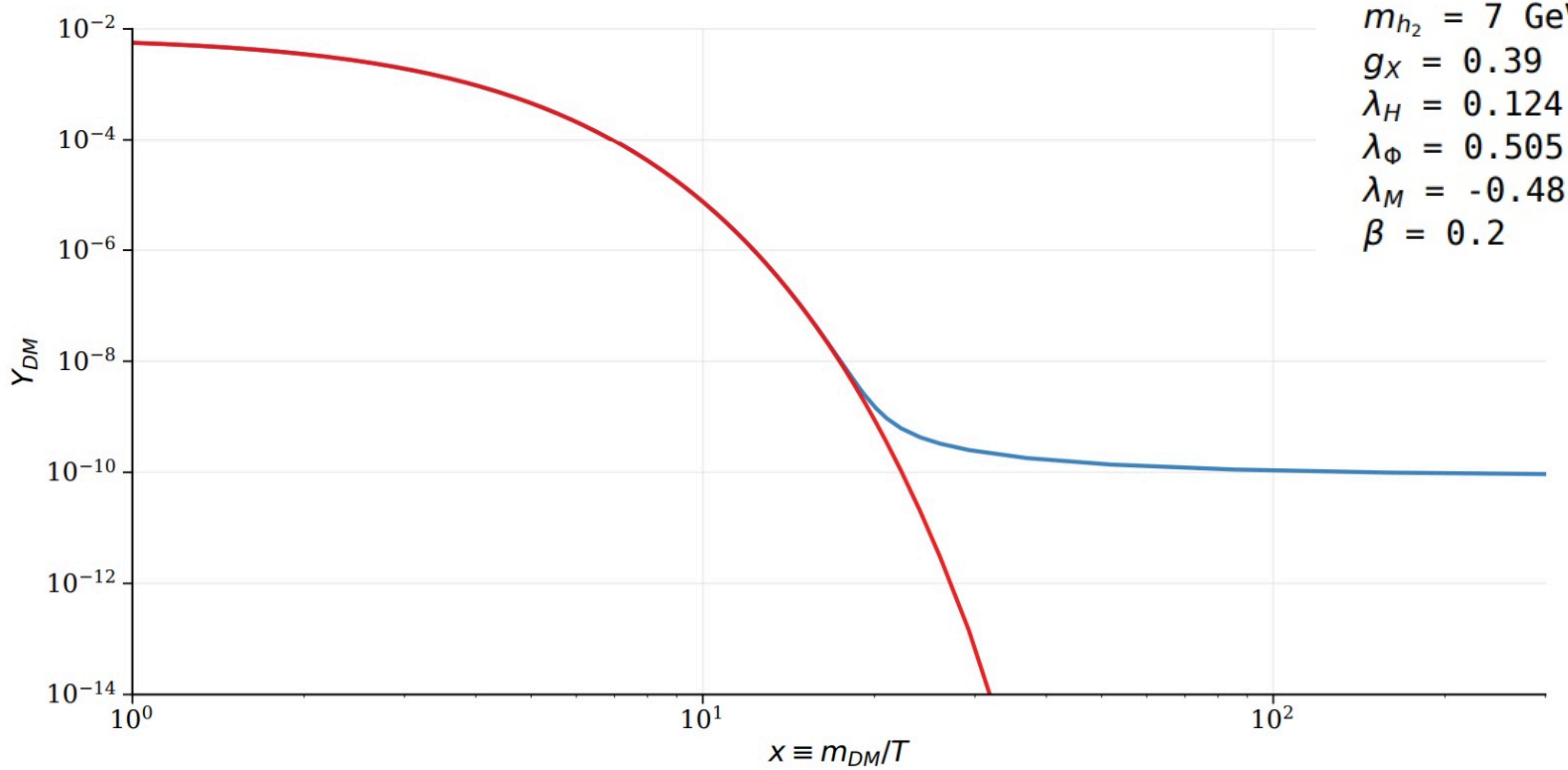
Boltzmann Equations

We new variables: $N \equiv n_1 + n_2 + n_3 = 3n_1, \quad Y \equiv N/s, \quad x \equiv \frac{m_\chi}{T}$

$$\frac{1}{1 - \frac{x}{3g_{eff}\frac{\partial g_{eff}}{\partial x}}}\frac{\partial Y}{\partial x} = \frac{1}{H(x)x}\left(\frac{2}{3}s\langle\sigma v\rangle_{ii\to SMSM}\left(Y_{eq}^2 - Y^2\right) + \dots\right)$$

WIMP Solution

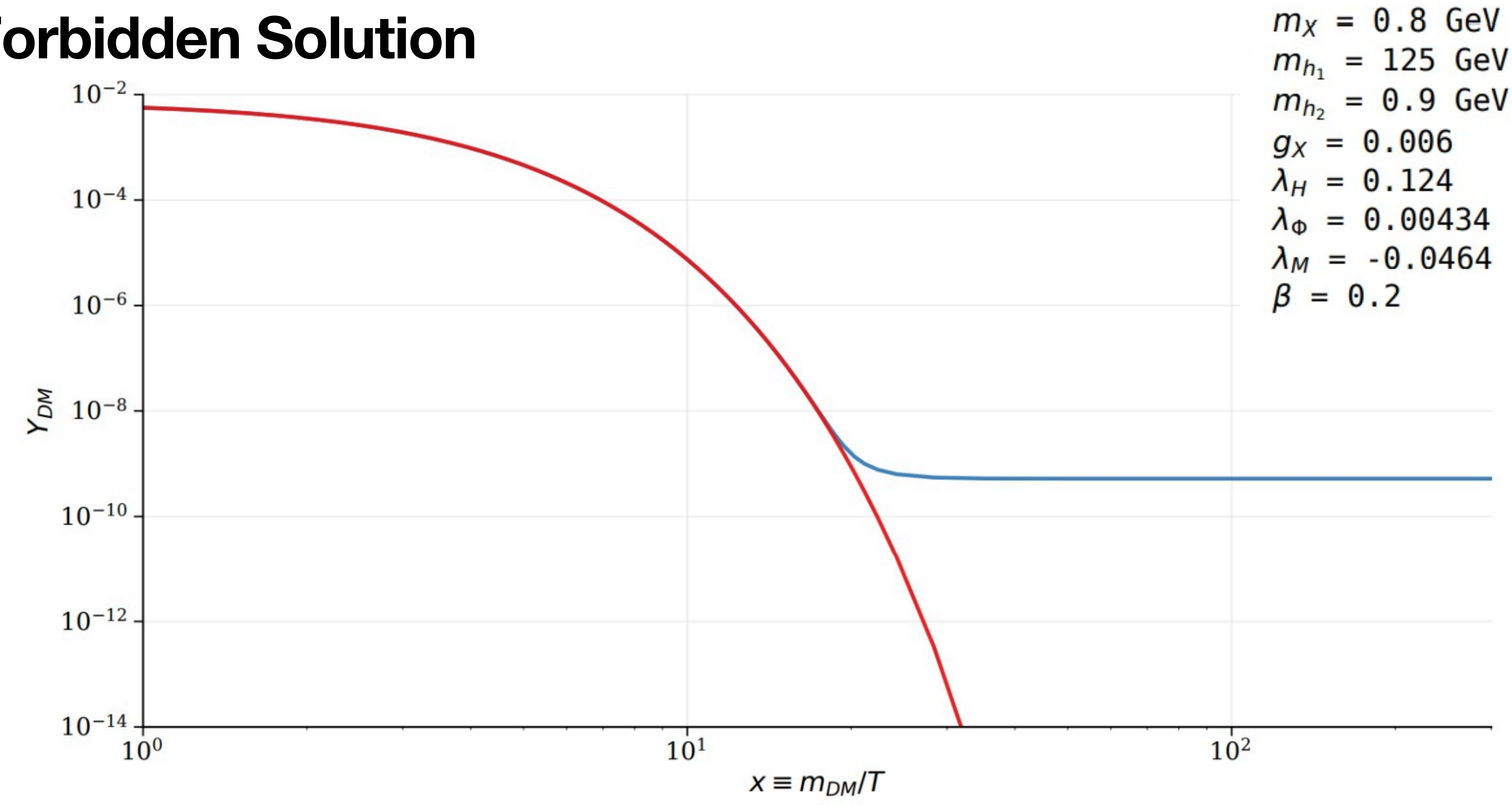
m_X = 5 GeV
m_{h_1} = 125 GeV
m_{h_2} = 7 GeV
g_X = 0.39
λ_H = 0.124
λ_Φ = 0.505
λ_M = -0.481
β = 0.2



Forbidden Solution

$$\frac{1}{1-\frac{x}{3g_{\text{eff}}}\frac{\partial g_{\text{eff}}}{\partial x}}\frac{\partial Y}{\partial x}=\frac{1}{H(x)x}\left[\mathbf{6\frac{n_{h_{2_{eq}}}^{2}}{s(x)}\langle\sigma v\rangle_{h_2h_2\rightarrow ii}\left(-Y^2+Y_{eq}^2\right)}+\frac{2}{3}\langle\sigma v\rangle_{ii\rightarrow SMSM}s(x)\left(-Y^2+Y_{eq}^2\right)+\ldots\right]$$

Forbidden Solution

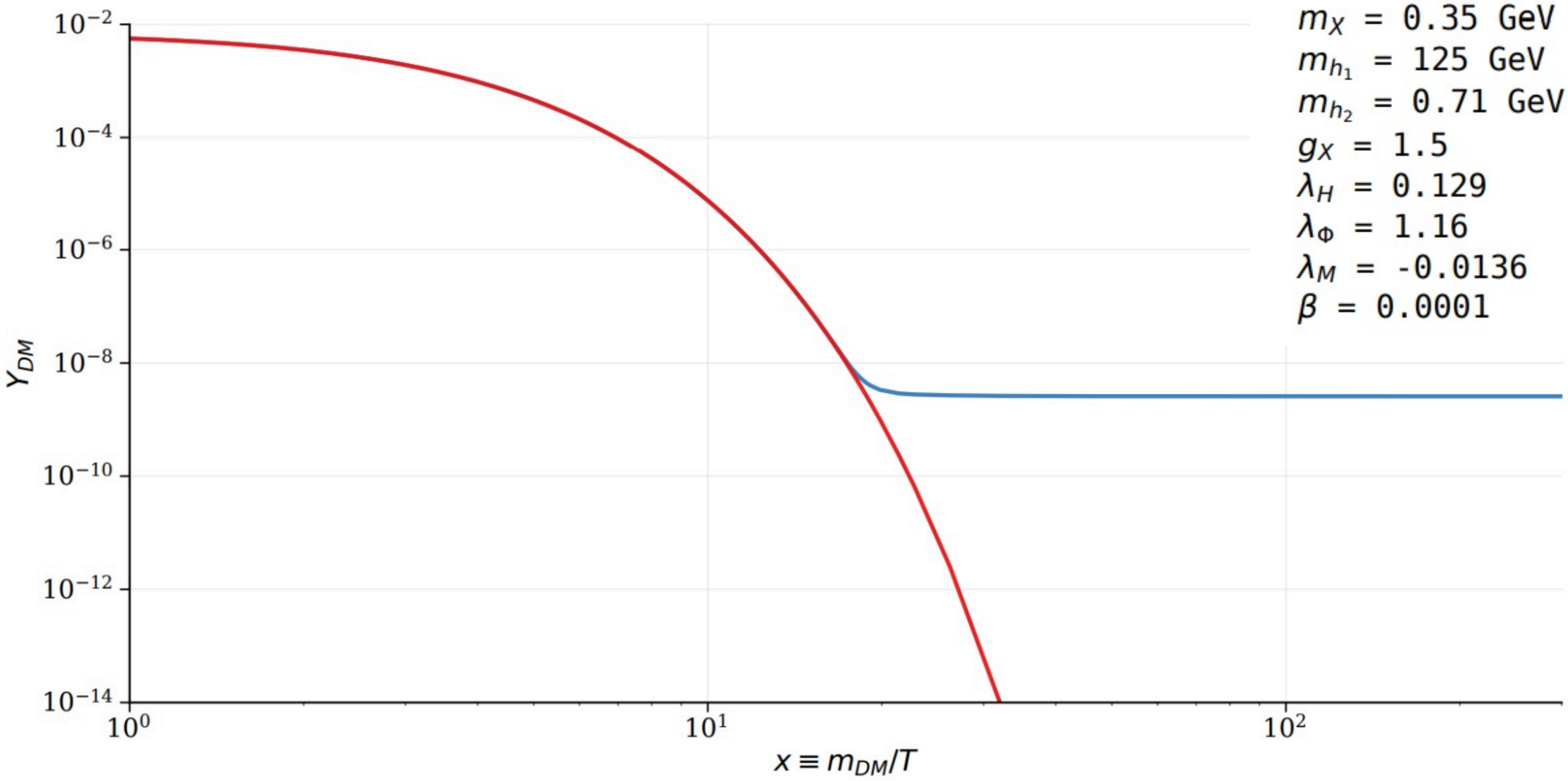


SIMP Solution

$$\frac{1}{1-\frac{x}{3g_{\rm eff}}\frac{\partial g_{\rm eff}}{\partial x}}\frac{\partial Y}{\partial x}=\frac{1}{H*x}\left[6\frac{n^2_{h_{2eq}}}{s}\langle\sigma v\rangle_{h_2h_2\to ii}\left(-Y^2+Y_{eq}\right)+\frac{2}{3}\langle\sigma v\rangle_{ii\to SMSM}\left(-Y^2+Y^2_{eq}\right)\right.$$

$$\left.+\left(\frac{1}{9}\langle\sigma \mathbf{v}^2\rangle_{\mathbf{ijk}}+\frac{2}{9}\langle\sigma \mathbf{v}^2\rangle_{\mathbf{iij}}+\frac{1}{9}\langle\sigma \mathbf{v}^2\rangle_{\mathbf{iii}}\right)\mathbf{s}^2\left(-\mathbf{Y}^3+\mathbf{Y}^2\mathbf{Y}_{\mathbf{eq}}\right)+\cdots\right]$$

SIMP Solution



Conclusion

- Wimp: Predictive framework but strongly constrained by direct detection experiments.
- Forbidden: Provides a way to evade strict bounds by suppressing couplings to the SM.
- SIMP:Viable in the sub-GeV range, with relic density set by 3 to 2 processes and interesting self-interaction effects.
- Hidden vector sector: A unified setup provides all these scenarios, depending on the parameter space.

References

- Baumann, D. (2022). *Cosmology*. Cambridge University Press.
- Hambye, Hidden vector dark matter, JHEP 01 (2009) 028.
- Choi et al., Vector SIMP dark matter, JHEP 10 (2017) 162.

Thanks :)

Spontaneous Symmetry Breaking

The final lagrangian is

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}\cdot F^{\mu\nu} + \frac{1}{8}(g_\phi v_\phi)^2 A_\mu \cdot A^\mu + \frac{1}{2}(\partial_\mu \eta)^2 + \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_\eta^2\eta^2 - \frac{1}{2}m_h^2 h^2$$

$$+A_\mu \cdot A^\mu \left[\kappa_\eta \eta^2 + \kappa_h h^2 + \kappa_{h\eta}\eta h + 2v_\phi \xi_\eta^\phi \eta + 2v_\phi \xi_h^\phi h\right]$$

$$+\left(2W_\mu^+ W^{-\mu} + \frac{1}{\cos^2\theta_W} Z^\mu Z_\mu\right)\left[\kappa_\eta \eta^2 + \kappa_h h^2 + \kappa_{h\eta}\eta h + 2v\xi_\eta \eta + 2v\xi_h h\right]$$

$$-\lambda_\eta \eta^4 - \lambda_h h^4 - \lambda_1 \eta^2 h^2 - \lambda_2 h^3 \eta - \lambda_3 h\eta^3 - \rho_\eta \eta^3 - \rho_h h^3 - \rho_1 \eta^2 h - \rho_2 h^2 \eta$$

Boltzmann Equations

$$
\begin{aligned}
\frac{1}{1-\frac{x}{3g_{\text{eff}}}\frac{\partial g_{\text{eff}}}{\partial x}}\frac{\partial Y}{\partial x} = \frac{1}{H(x)x}\Bigg[& 6\frac{n_{h_{2eq}}^2}{s(x)}\langle\sigma v\rangle_{h_2h_2\to ii}\left(-Y^2+Y_{eq}\right) \\
&+n_{h_2}^0\frac{\langle\sigma v\rangle_{ih_2\to jk}}{3}\left(Y-\frac{Y^2}{Y_{eq}}\right) \\
&+\left(\frac{1}{9}\langle\sigma v^2\rangle_{ijk}+\frac{2}{9}\langle\sigma v^2\rangle_{iij}+\frac{1}{9}\langle\sigma v^2\rangle_{iii}\right)\frac{S(m_\chi,\alpha)^2}{x^5}\left(-Y^3+Y^2Y_{eq}\right) \\
&+\left(\frac{2}{9}\langle\sigma v^2\rangle_{iii}^{h_2}+\frac{4}{9}\langle\sigma v^2\rangle_{ijj}^{h_2}\right)\frac{S(m_\chi,\alpha)^2}{x^5}\left(-Y^3+YY_{eq}^2\right) \\
&+\frac{2}{3}\langle\sigma v\rangle_{ii\to SMSM}s(x)\left(-Y^2+Y_{eq}^2\right)\Bigg]
\end{aligned}
$$