FIMP Realization of the Scotogenic Model

in collaboration with
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Outline

- **Features of the scotogenic model**

- **FIMP fermionic dark matter**

  - **production via *thermal freeze-in***

  - **production via *superWIMP* mechanism**

- **Summary**

Dark matter

Strong empirical evidence of the existence of a “dark sector” beyond the Standard Model:

1. Very little is known about its matter content or its interactions

2. 85% of the matter content of the universe is in the form of a new particle which must have a long lifetime (longer than the age of the universe), as indicated by the non-observation of its decay products in cosmic ray experiments

3. No undeniable evidence up to now of dark matter detection from direct and indirect searches

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Weakly Interacting Massive Particles (WIMPs) are natural dark matter candidates: the relic density is of the same order as the observed dark matter abundance (*WIMP miracle*).

WIMP models generally give rise to signals in *direct* and *indirect* detection experiments as well as in *collider* searches.

Hall, Jedamzik, March-Russell, West (2010)

Alternative scenario: the dark matter is a **Feebly Interacting Massive Particle** (FIMP).

FIMPs have very weak interactions with SM particles and never enter in thermal equilibrium. Their abundance is produced via *thermal freeze-in*. No possibility to detect these particles in *direct/indirect* searches. FIMPs yield new types of collider signatures.

Scotogenic model

Ernest Ma (2006)

Lagrangian invariant under a Z_2 symmetry

$$\mathcal{L} \supset \left[Y^{\nu}_{\alpha i} \left(\overline{\nu}_{\alpha L}\, H_2^0 - \overline{\ell}_{\alpha L}\, H^+\right) N_i + \text{H.c.}\right] + \frac{1}{2} M_j\, \overline{N}_j\, N_j^C$$

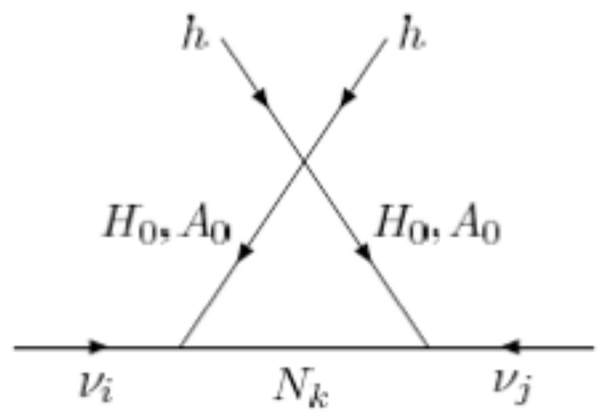
$$\begin{aligned} V(H_1, H_2) = & -\mu_1^2 \left(H_1^\dagger H_1\right) + \lambda_1 \left(H_1^\dagger H_1\right)^2 + \mu_2^2 \left(H_2^\dagger H_2\right) + \lambda_2 \left(H_2^\dagger H_2\right)^2 \\ & + \lambda_3 \left(H_1^\dagger H_1\right)\left(H_2^\dagger H_2\right) + \lambda_4 \left(H_1^\dagger H_2\right)\left(H_2^\dagger H_1\right) \\ & + \frac{\lambda_5}{2}\left[\left(H_1^\dagger H_2\right)^2 + \text{H.c.}\right] \end{aligned}$$

The dark sector mass spectrum:

- 3 Majorana fermions with masses $M_1 < M_2 < M_3$
- 1 CP-even neutral scalar H^0 with mass $m^2_{H^0} = \mu_2^2 + v^2\,(\lambda_3 + \lambda_4 + \lambda_5)/2$
- 1 CP-odd neutral scalar A^0 with mass $m^2_{A^0} = \mu_2^2 + v^2\,(\lambda_3 + \lambda_4 - \lambda_5)/2$
- 2 charged scalars $H^\pm$ with masses $m^2_{H^\pm} = \mu_2^2 + v^2\,\lambda_3/2$

The lightest Z_2-odd particle is stable and provides a dark matter candidate

Scotogenic model



Majorana mass term for active neutrinos is generated at 1-loop

$$(\mathcal{M}_\nu)_{\alpha\beta} = \sum_k \frac{Y^\nu_{\alpha k}\, Y^\nu_{\beta k}}{16\,\pi^2}\, M_k \left[\frac{m^2_{H^0}}{m^2_{H^0}-M_k^2}\log\left(\frac{m^2_{H^0}}{M_k^2}\right) - \frac{m^2_{A^0}}{m^2_{A^0}-M_k^2}\log\left(\frac{m^2_{A^0}}{M_k^2}\right)\right]$$

$$\overset{\lambda_5 \ll 1}{=} \frac{\lambda_5\, v^2}{16\,\pi^2}\sum_k Y^\nu_{\alpha k}\, Y^\nu_{\beta k}\,\frac{M_k}{m_0^2-M_k^2}\left(1-\frac{M_k^2}{m_0^2-M_k^2}\log\left(\frac{m_0^2}{M_k^2}\right)\right)$$

Case in which only $N_{2,3}$ contribute to neutrino mass generation

$$(\mathcal{M}_\nu)_{\alpha\beta} \simeq \frac{\lambda_5\, v^2}{16\,\pi^2}\sum_k \frac{Y^\nu_{\alpha k} Y^\nu_{\beta k}}{M_i}\left(\ln\frac{M_i^2}{m_0^2}-1\right)$$

2 massive neutrinos

$$\approx 10^{-2}\mathrm{eV}\left(\frac{\lambda_5\, y^2_{2,3}}{10^{-11}}\right)\left(\frac{1\ \mathrm{TeV}}{M_{2,3}}\right)$$

$$\lambda_5 \lesssim 0.1 \quad \Longrightarrow \quad y_{2,3} \gtrsim 10^{-6}$$

For $y_1 \ll 10^{-6}$ N_1 gives no contribution to neutrino masses

Scotogenic model

Constraints from charged lepton flavour violation:

$$\mathrm{B}(\mu \to e\,\gamma) \quad < \quad 5.7 \times 10^{-13}$$

MEG 2013

$$\begin{aligned}\mathrm{B}(\mu \to e\,\gamma) \quad &= \quad \frac{3\alpha_{\rm em}}{64\,\pi\,\left(G_F\, m^2_{H^\pm}\right)^2}\left|Y^\nu_{\mu k}\, Y^{\nu\;*}_{ek}\, F_2\left(\frac{M_k^2}{m^2_{H^\pm}}\right)\right|^2 \\ &\approx \quad 10^{-15}\left(\frac{100\,\mathrm{GeV}}{m_H^\pm}\right)^4\left|\frac{y_{2,3}}{10^{-2}}\right|^4\left(\frac{F_2(M^2_{2,3}/m^2_{H^\pm})}{3\times 10^{-3}}\right)^2\end{aligned}$$

$y_{2,3} \gtrsim 0.1$ strongly disfavored for Z_2-odd particle masses at the EW scale

FIMP dark matter

1. *Thermal freeze-in* production mechanism: the dark matter particle never reaches thermal equilibrium in the early Universe

2. In the scotogenic model only the Majorana fermion singlets can behave as FIMP dark matter: equilibrium prevented if their Yukawa interactions are feeble

3. Production of fermion singlets via two-body (inverse-)decays of Z_2-odd scalars; $2 \leftrightarrow 2$ scatterings always subdominant

4. Out-of-equilibrium condition for N_1:

$$\boxed{\begin{gathered}\Gamma(H_2 \to N_1\, L) \lesssim H(T \sim m_{H_2}) \\ m_{H_2} \sim 100 \text{ GeV} \Longrightarrow y_1 \lesssim 10^{-8}\end{gathered}}$$

$N_{2,3}$ always in thermal equilibrium if they contribute to $\mathcal{M}_\nu$

$$H_2 \to N_{2,3}\, L \quad \text{or} \quad H_2\, L \to N_{2,3}$$

FIMP dark matter

Two *independent* contributions to DM abundance: from *thermal freeze-in* and late decays of next-to-lightest odd particle (*superWIMP* mechanism)

$$\Omega_{N_1}\, h^2 = \Omega^{freeze-in}\, h^2 + \Omega^{superWIMP}\, h^2$$

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<u>*Freeze-in* mechanism:</u>

Hall, Jedamzik, March-Russell, West (2010)

$$s\,T\,\frac{dY_{N_1}}{dT} = -\frac{\gamma_{N_1}(T)}{H(T)}$$

$$\gamma_{N_1}(T) = \sum_X \frac{g_X\, m_X^2\, T}{2\,\pi^2} K_1\,(m_X/T)\;\Gamma\,(X \to N_1\,\ell)$$

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Dominant contribution from scalar decays

$$\Gamma\left(H^0/A^0 \to N_1\,\nu_\alpha\right) \;\approx\; \frac{m_{H^0/A^0}\,\left|Y^\nu_{\alpha 1}\right|^2}{32\,\pi}$$

$$\Gamma\left(H^+ \to N_1\,\overline{\ell_\alpha}\right) \;\approx\; \frac{m_{H^+}\,\left|Y^\nu_{\alpha 1}\right|^2}{16\,\pi}$$

$N_{2,3}$ decays are subdominant

$$\Gamma(N_{2,3} \to N_1\,\overline{\nu_\alpha}\,\nu_\beta) \;\approx\; \frac{M_2^5}{3072\,\pi^3\,m_S^4}\left(\sum_\beta \left|Y^\nu_{\beta 1}\right|^2\right)\left(\sum_\alpha \left|Y^\nu_{\alpha 2,3}\right|^2\right)$$

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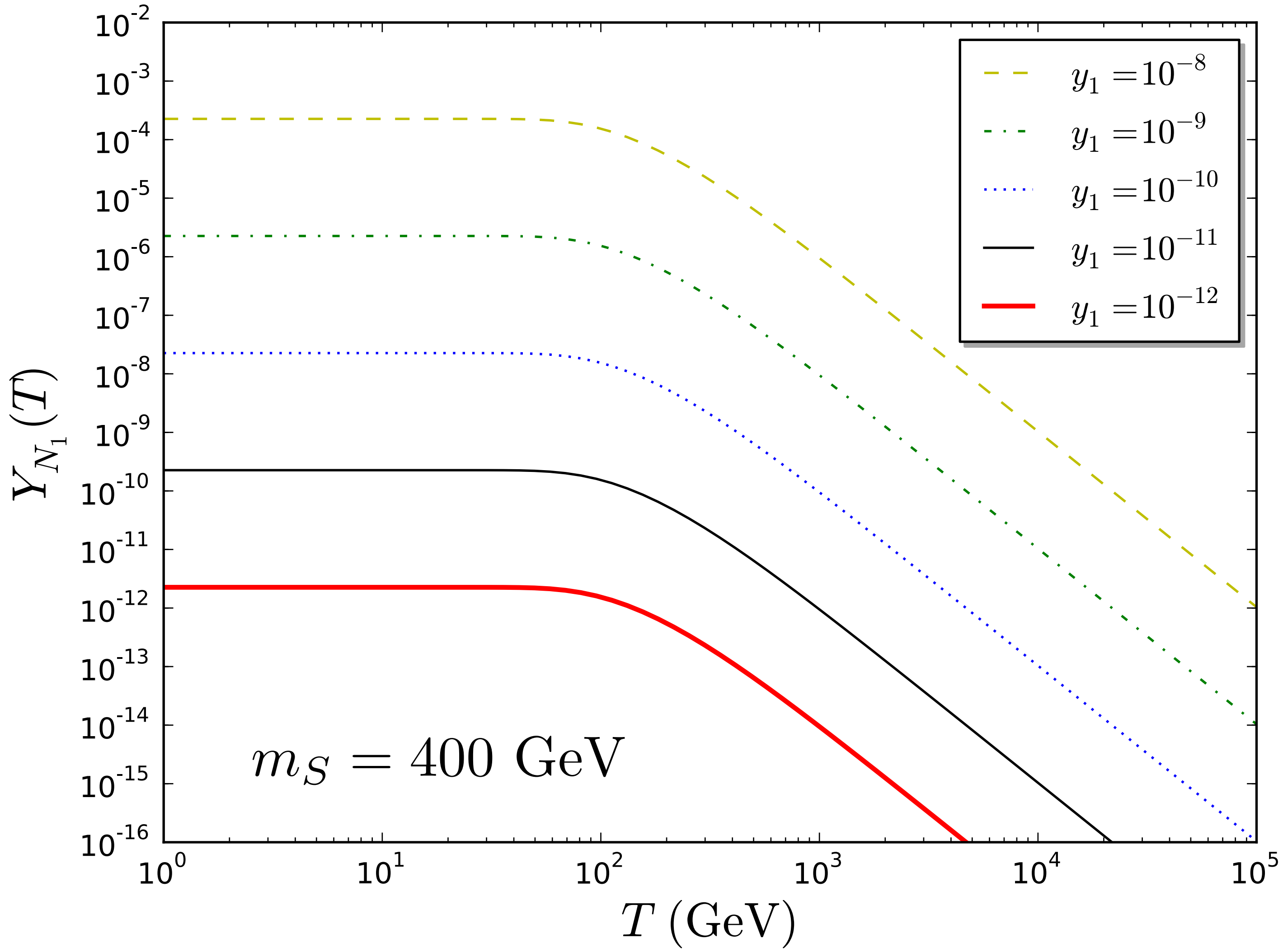
Dark matter abundance:

$$\boxed{\Omega_{N_1}\, h^2 \;=\; 2.744 \times 10^8\, \frac{M_1}{\mathrm{GeV}}\, Y_{N_1}(T_0)}$$

Thermal freeze-in mechanism



$$\frac{dY_{N_1}}{dT} \approx -5\times 10^3\,\mathrm{GeV}^3 \left(\frac{m_S}{1\ \mathrm{TeV}}\right)^2 \left(\frac{y_1}{10^{-8}}\right)^2 T^{-4} \qquad \text{at} \quad T \gg m_S$$

$$Y_{N_1}\,(T \lesssim m_S) \approx 10^{-4} \left(\frac{1\ \mathrm{TeV}}{m_S}\right) \left(\frac{y_1}{10^{-8}}\right)^2$$

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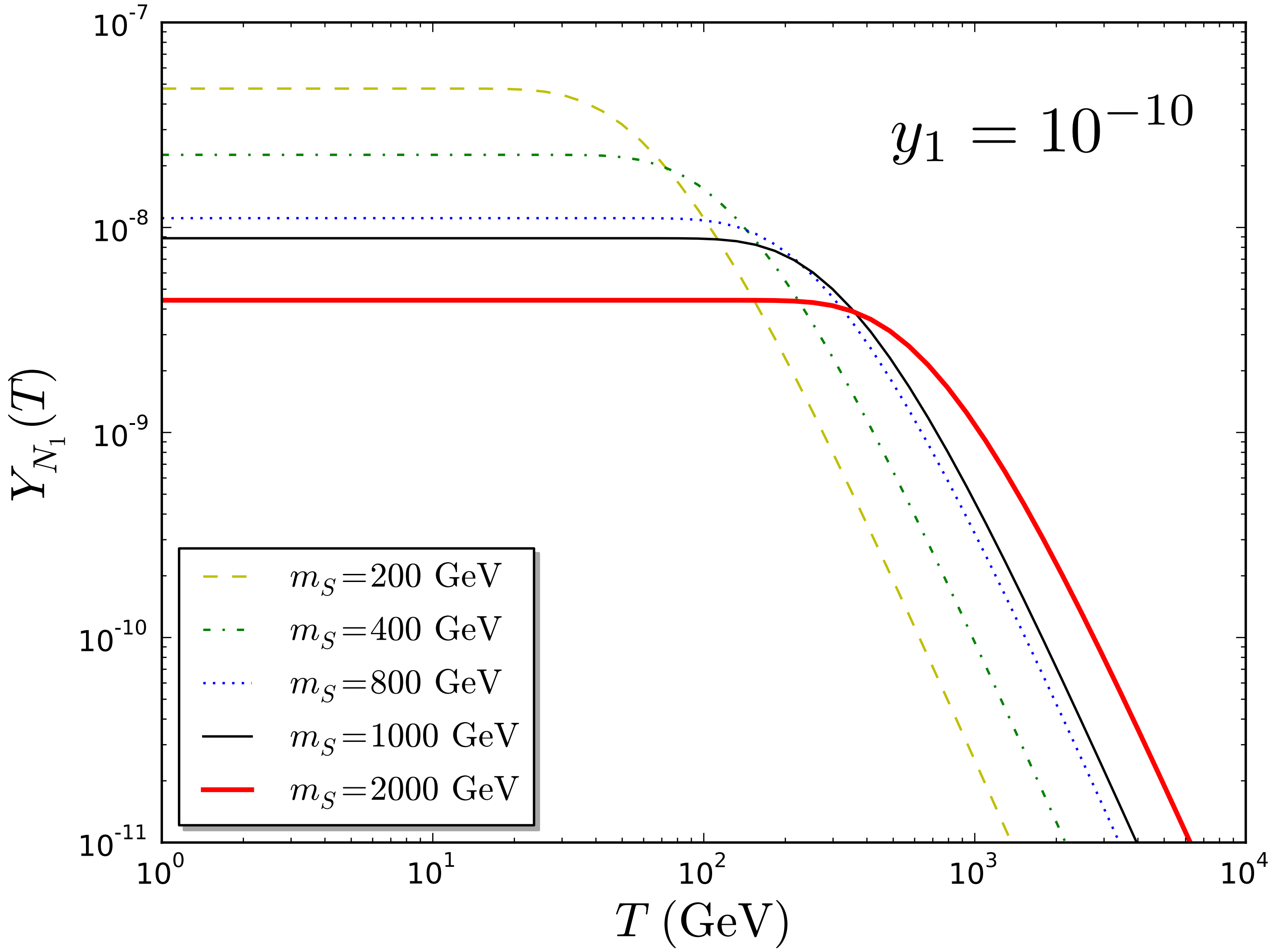

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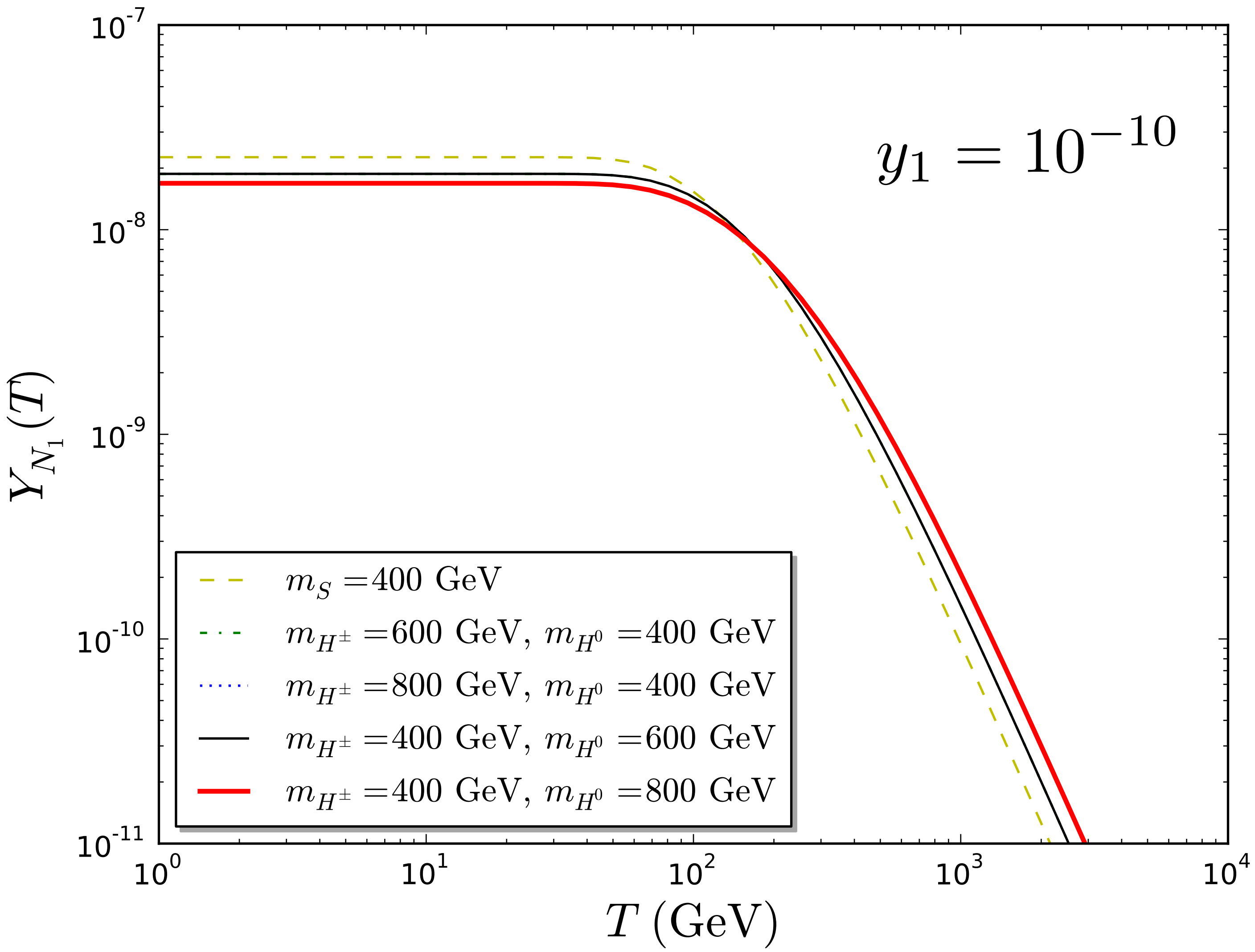

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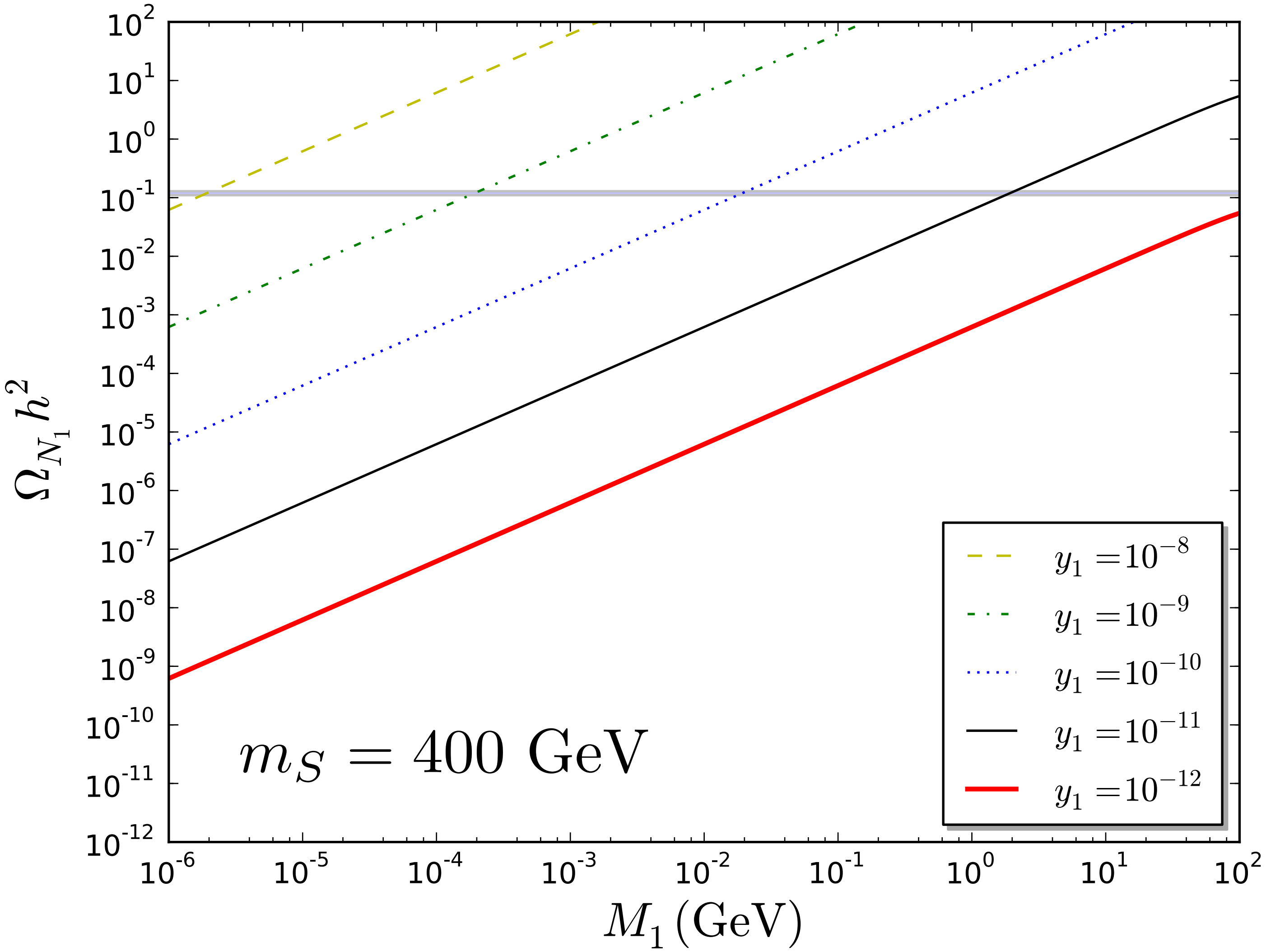
Thermal freeze-in mechanism

Parameter space compatible with the observed relic density



$$\Omega_{N_1} h^2 \quad \approx 0.3 \left(\frac{M_1}{0.1\,\mathrm{GeV}}\right) \left(\frac{1\,\mathrm{TeV}}{m_S}\right) \left(\frac{y_1}{10^{-10}}\right)^2$$

Thermal freeze-in mechanism

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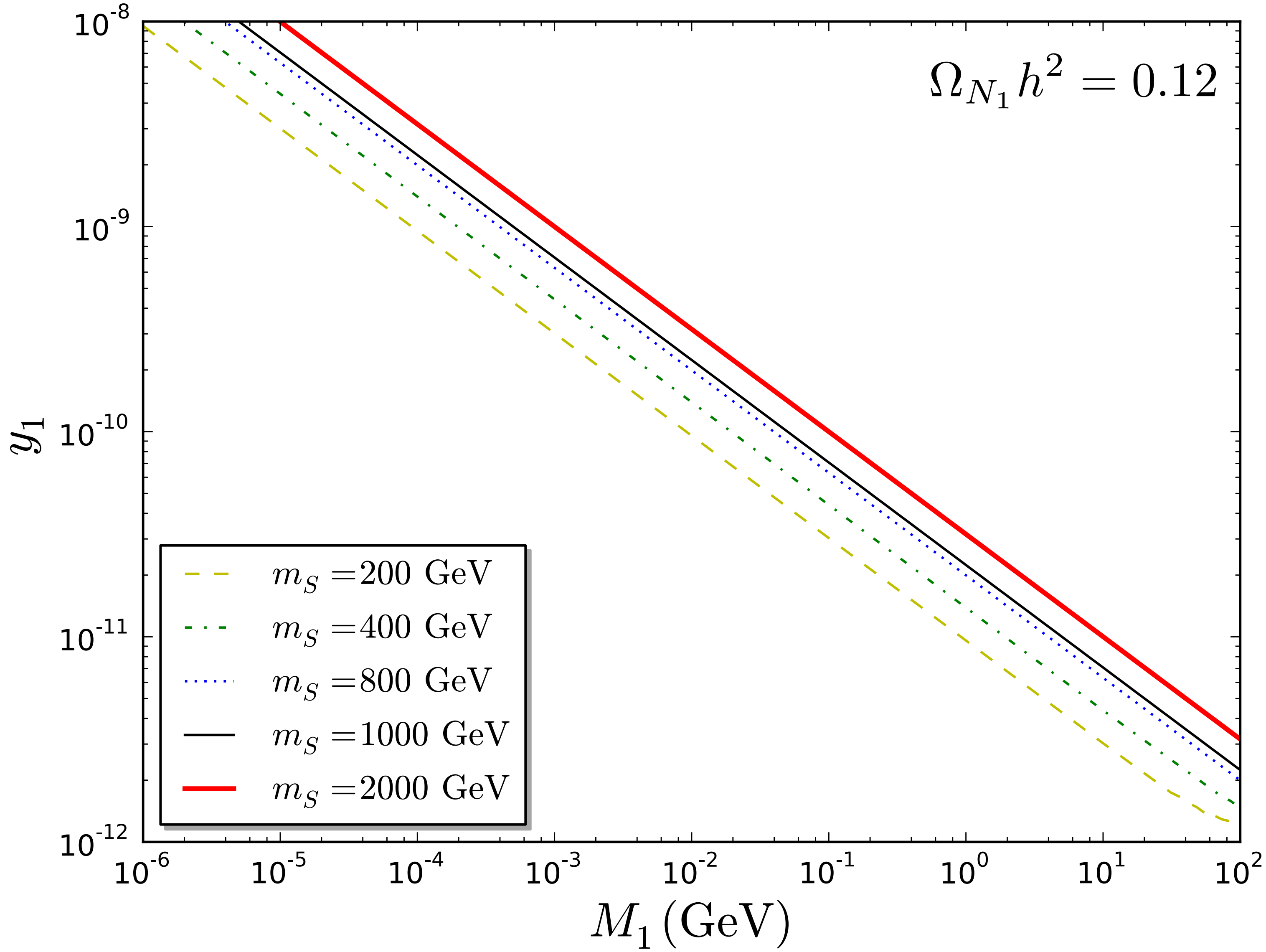

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SuperWIMP mechanism

Feng, Rajaraman, Takayama 2003

N_2 is the NLOP

$$\boxed{\Omega_{N_1}^{superWIMP}\, h^2 \;=\; \frac{M_1}{M_2}\, \Omega_{NLOP}^{freeze-out}\, h^2}$$

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Feng, Rajaraman, Takayama 2003

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$$\boxed{\Omega_{N_1}^{superWIMP}\,h^2 \;=\; \frac{M_1}{M_2}\,\Omega_{NLOP}^{freeze-out}\,h^2}$$

N_2 decays after the *freeze-out* time

$$\Gamma(N_2 \to N_1\,\nu\,\overline{\nu}) \;\lesssim\; H(T \simeq M_2/20)$$

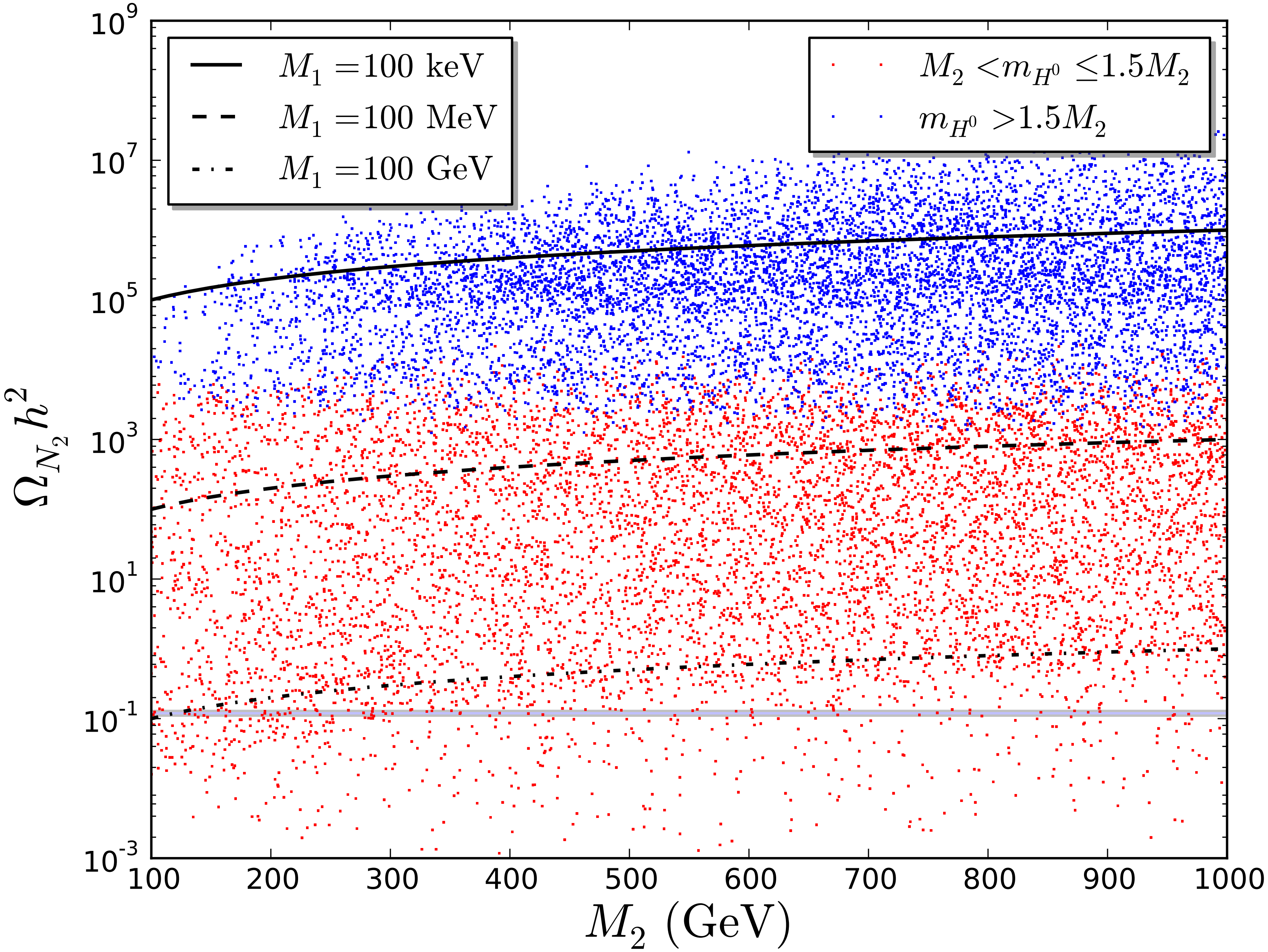
$$y_1\,y_2 \;\lesssim\; 2\times 10^{-6}\left(\frac{m_S}{1\,\mathrm{TeV}}\right)\left(\frac{1\,\mathrm{TeV}}{M_2}\right)^{3/2}$$

Upper limit on N_2 lifetime from BBN: $\tau < 1$ sec

$$y_1\,y_2 \;\gtrsim\; 3\times 10^{-12}\left(\frac{m_S}{1\,\mathrm{TeV}}\right)^2\left(\frac{1\,\mathrm{TeV}}{M_2}\right)^{5/2}$$

Bound very restrictive for high values of the dark matter mass

SuperWIMP mechanism



SuperWIMP mechanism

NLOP is one of the odd scalars

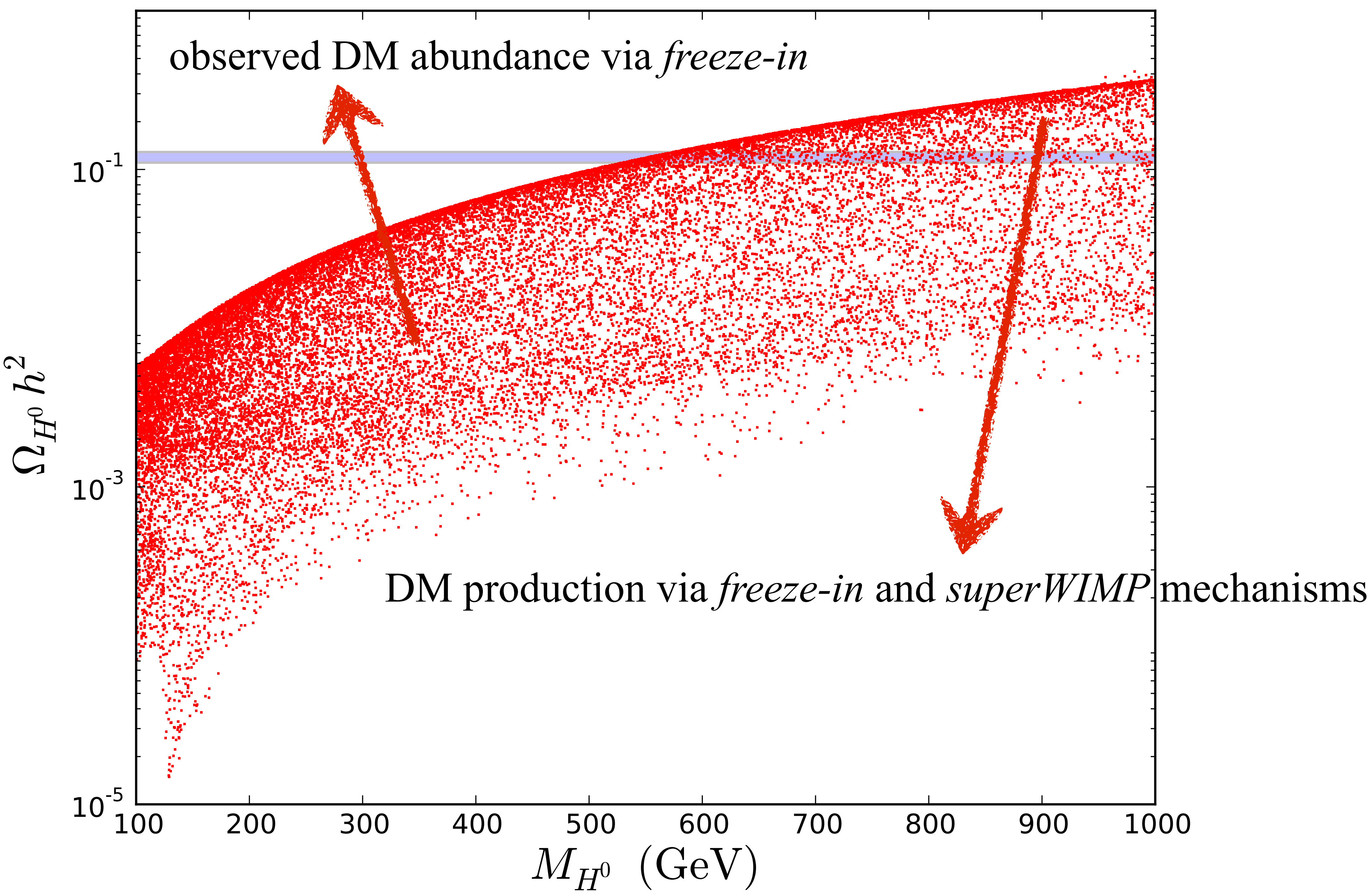
$$\boxed{\Omega_{N_1}^{superWIMP}\, h^2 \;=\; \frac{M_1}{m_S}\, \Omega_{NLOP}^{freeze-out}\, h^2}$$

Decays after the *freeze-out* but before BBN

$$10^{-13}\left(\frac{1\,\mathrm{TeV}}{m_S}\right)^{1/2} \lesssim\; y_1 \;\lesssim\; 10^{-8}\left(\frac{m_S}{1\,\mathrm{TeV}}\right)^{1/2}$$

These bounds are always easily satisfied

SuperWIMP mechanism



Summary

1. **In the scotogenic model *only one* of the singlet fermions, N_1, can be out-of-equilibrium in the early universe and can behave as a FIMP**

2. **In this framework the dark matter can be either a FIMP (N_1) or a WIMP (H^0)**

3. **In the case of FIMP dark matter, the relic density receives two contributions: production via *freeze-in* and late decays of NLOP (*superWIMP* mechanism)**

4. **The *freeze-in* allows for dark matter masses from the keV to the TeV range**

5. **The *superWIMP* contribution is strongly affected by the nature of the NLOP**

6. In the case of WIMP (H^0) dark matter, non-thermal contribution from the late decays of the FIMP (N_1) affects the dark matter relic density. This scenario can be probed by direct and indirect detection experiments

FIMP decay into the dark matter

1. In this case the FIMP N_1 is not the lightest Z_2-odd particle

2. N_1 decays modify the regions where the dark matter constraint is satisfied

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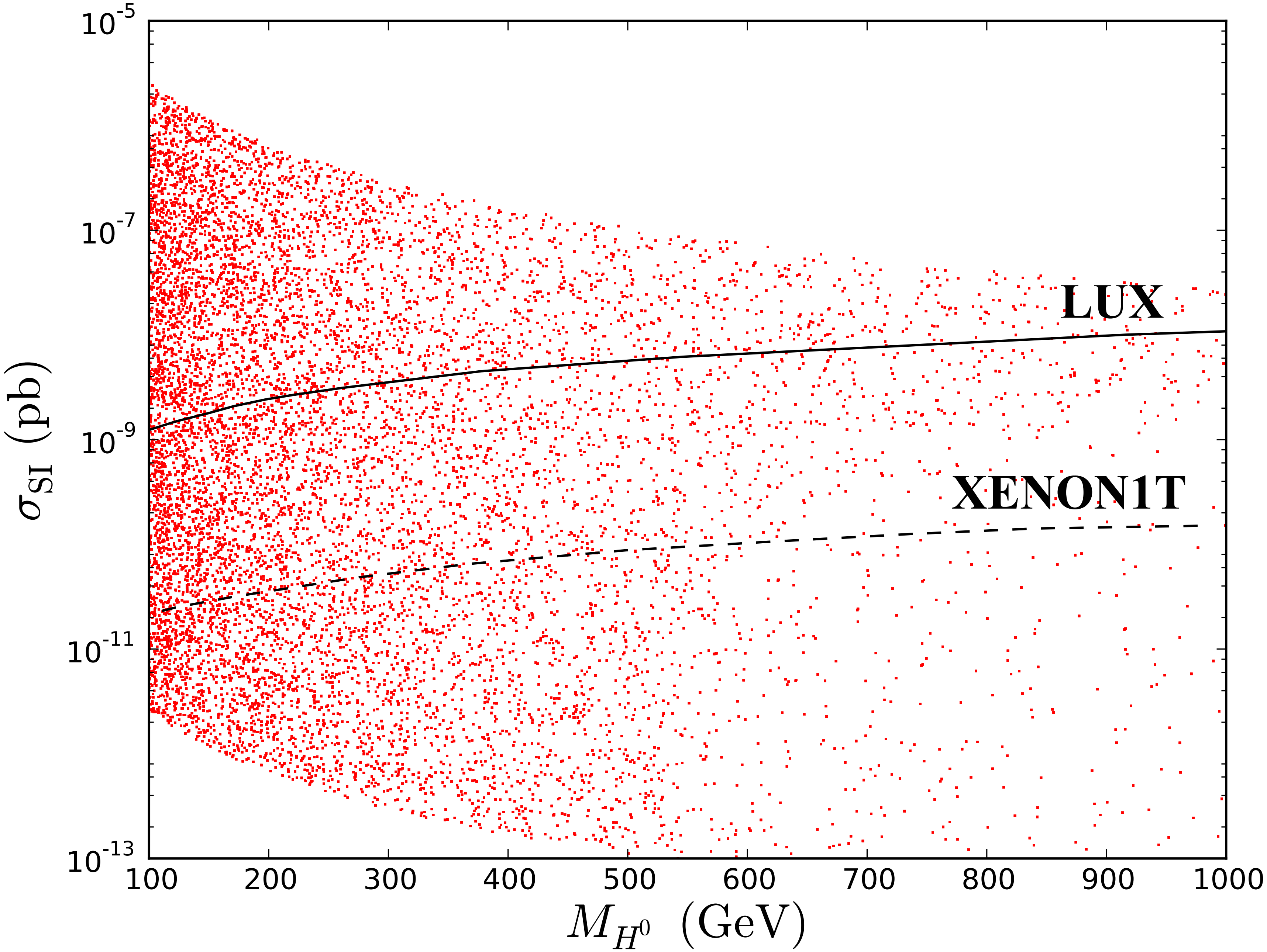
N_1 is produced via *freeze-in* $(H_2\,\ell \to N_1)$ and decays after DM *freeze-out*

$$\gamma_{N_1}(T) \;=\; \sum_X \frac{g_{N_1}\, m_{N_1}^2\, T}{2\,\pi^2}\, K_1\,(M_1/T)\;\Gamma\,(N_1 \to X\,\ell)\,,$$

$$\Omega_{H^0}^{N_1-decay} h^2 \quad \approx 0.1\,\left(\tfrac{m_S}{100\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{TeV}}{M_1}\right)\left(\frac{y_1}{2\times 10^{-12}}\right)^2 .$$

FIMP decay into the dark matter

Direct detection cross-section mediated by the Higgs exchange



FIMP decay into the dark matter

Indirect detection constraints