FIMP Realization of the Scotogenic Model

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Outline

- Neutrino masses and mixing
- WIMP and FIMP dark matter
- Scotogenic model
- FIMP dark matter
  - *thermal freeze-in* contribution
  - *superWIMP* contribution
- FIMP decay to dark matter (*direct* and *indirect* detection)
- Summary

Neutrino masses and mixing

Compelling experimental evidence of physics beyond the Standard Model

atmospheric neutrinos:

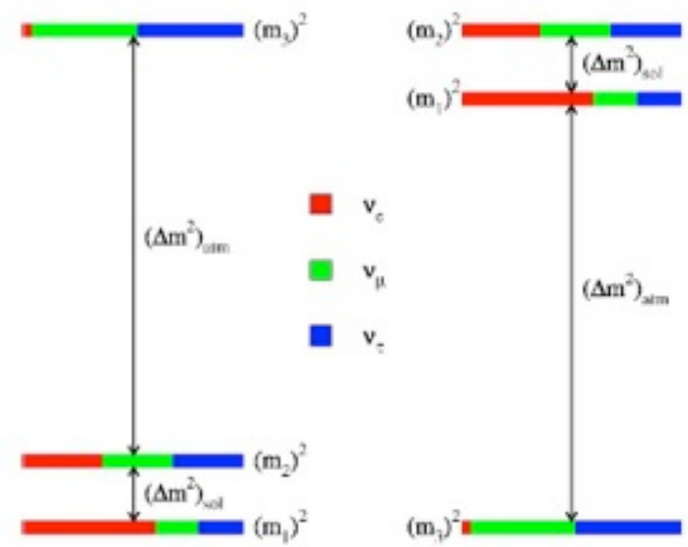
Super-Kamiokande: $|\Delta m_A^2| \sim O(10^{-3}\ eV^2)$ and $\theta_{23} \cong \pi/4$

solar neutrinos:

SNO, SK and KamLAND: $\Delta m_S^2 \sim O(10^{-5}\ eV^2)$ and $\theta_{12} \cong \arcsin(\sqrt{0.3})$

reactor and accelerator neutrinos:

Daya Bay, RENO, T2K, MINOS, Double CHOOZ: $\theta_{13} \neq 0$ at 10σ, $\theta_{13} \sim 0.15$



1. at least two massive neutrinos ν_j with masses $m_j \neq 0$
2. existence of neutrino mixing:

$$\nu_{\ell L}(x) = \sum_j (U_{\rm PMNS})_{\ell j}\, \nu_{jL}(x), \quad \ell = e, \mu, \tau$$

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \mathrm{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

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

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Weakly Interactive 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 signal 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 Interactive Massive Particle** (FIMP).

FIMPs have very weak renormalizable 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 collider signatures

Scotogenic model

Ernest Ma (2006)

Lagrangian invariant under a Z_2 symmetry

$$\mathcal{L} \supset \left[Y^{\nu}_{\alpha i}\left(\overline{\nu}_{\alpha L}\, H^0_2 - \overline{\ell}_{\alpha L}\, H^+\right) N_i + \text{H.c.}\right] + \frac{1}{2}\, M_j\, \overline{N}_j\, N^C_j$$

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

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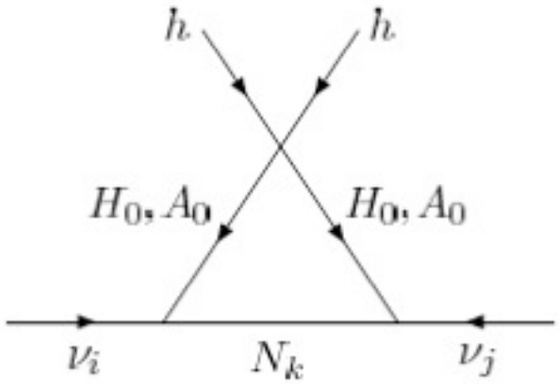
The dark sector mass spectrum:

- 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

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

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

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

$$\mathrm{B}(\mu \to e\,\gamma) \quad = \quad \frac{3\alpha_{\mathrm{em}}}{64\,\pi\,\left(G_F\,m_{H^\pm}^2\right)^2}\left|Y^\nu_{\mu k}\,Y^{\nu\,*}_{ek}\,F_2\left(\frac{M_k^2}{m_{H^\pm}^2}\right)\right|^2$$

$$\approx \quad 10^{-15}\left(\frac{100\,\mathrm{GeV}}{m_H^\pm}\right)^4\left|\frac{y_{2,3}}{10^{-2}}\right|^4\left(\frac{F_2(M_{2,3}^2/m_{H^\pm}^2)}{3\times 10^{-3}}\right)^2$$

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

FIMP dark matter

1. *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:

$$\Gamma(H_2 \to N_1\, L) \lesssim H(T \sim M_{H_2})$$

$$m_{H_2} \sim 100 \text{ GeV} \Longrightarrow y_1 \lesssim 10^{-8}$$

$N_{2,3}$ 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>

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

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

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

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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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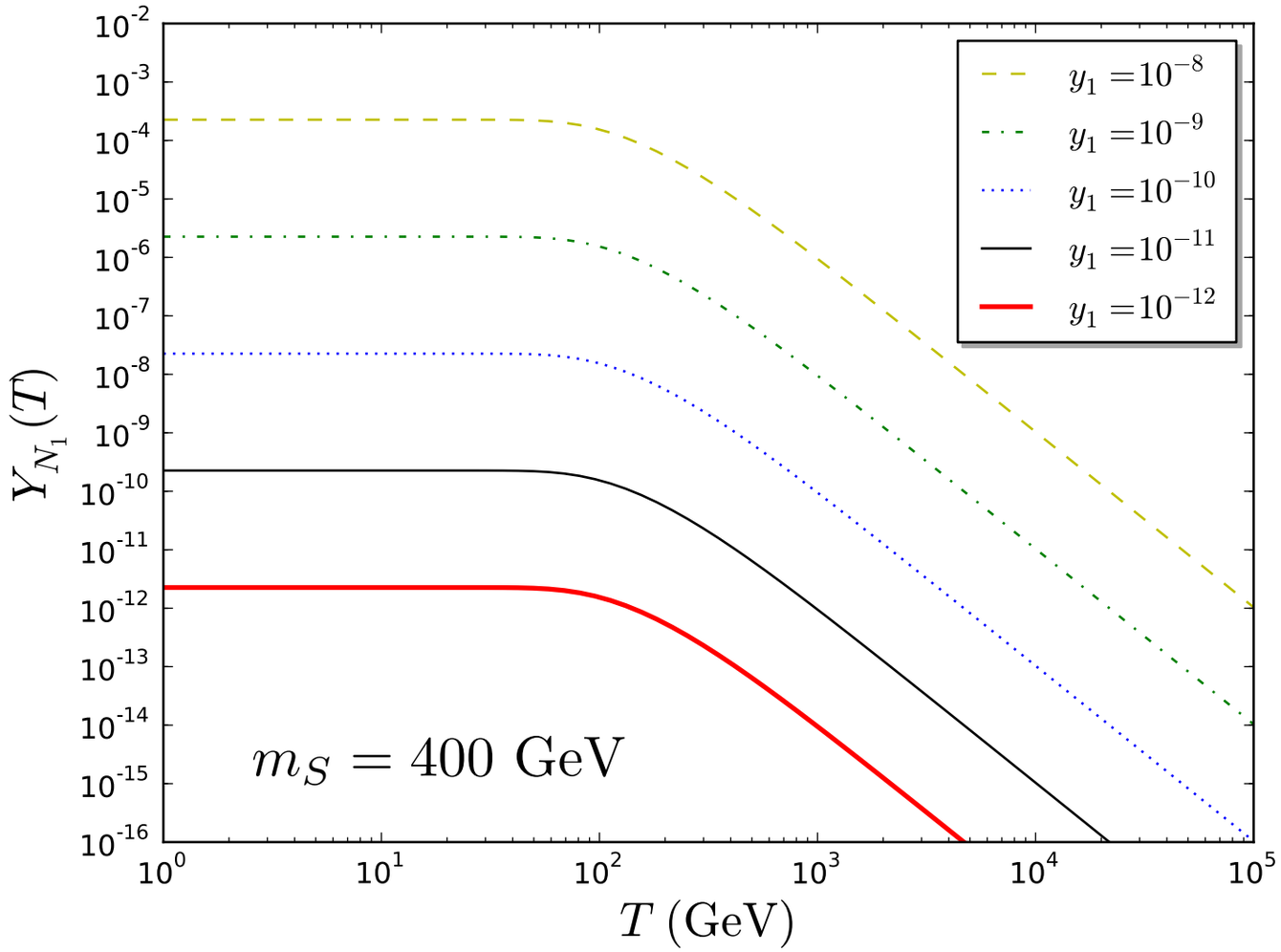
Dark matter abundance:

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

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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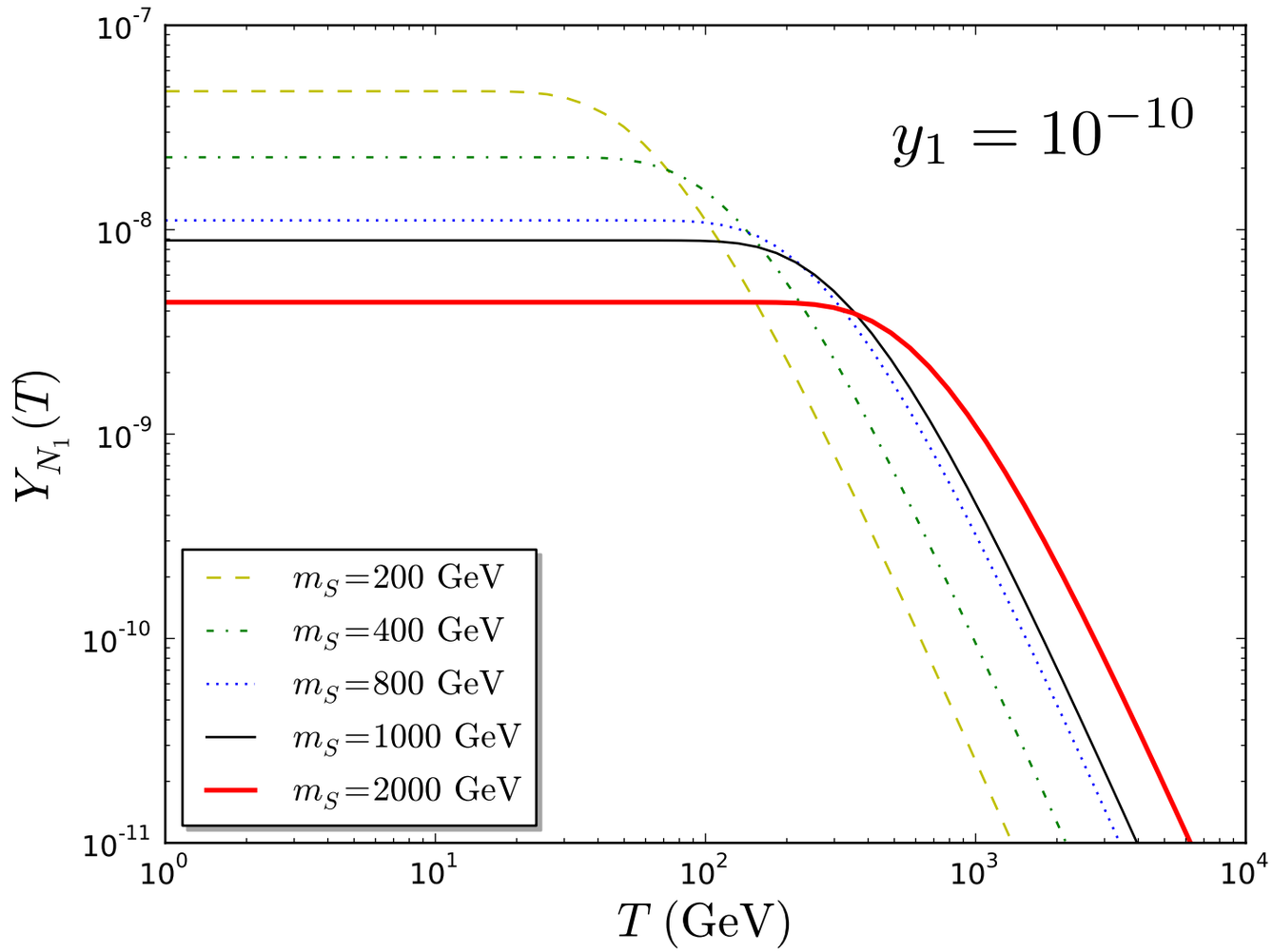

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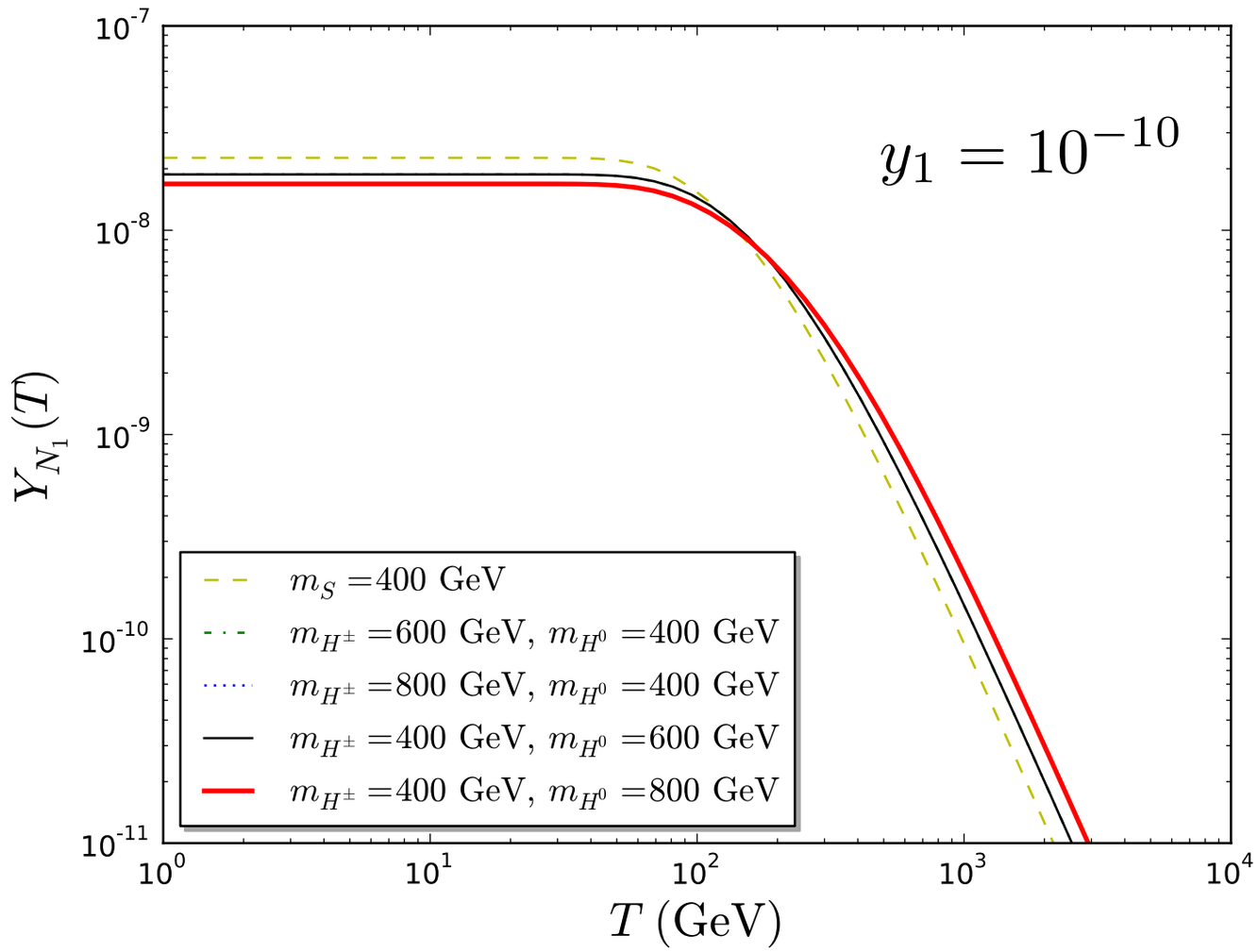

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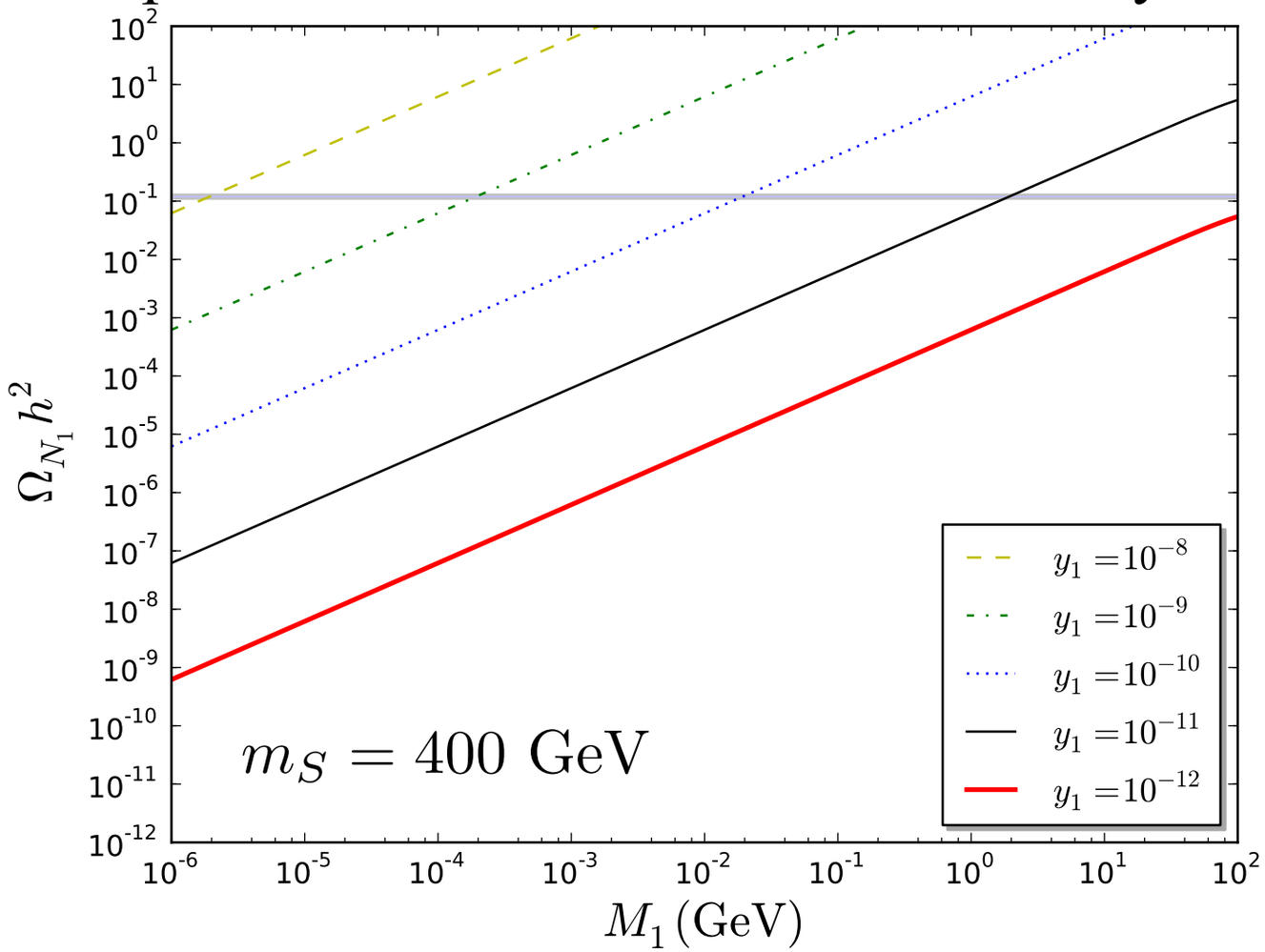
Thermal freeze-in mechanism

Parameter space compatible with the observed relic density



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

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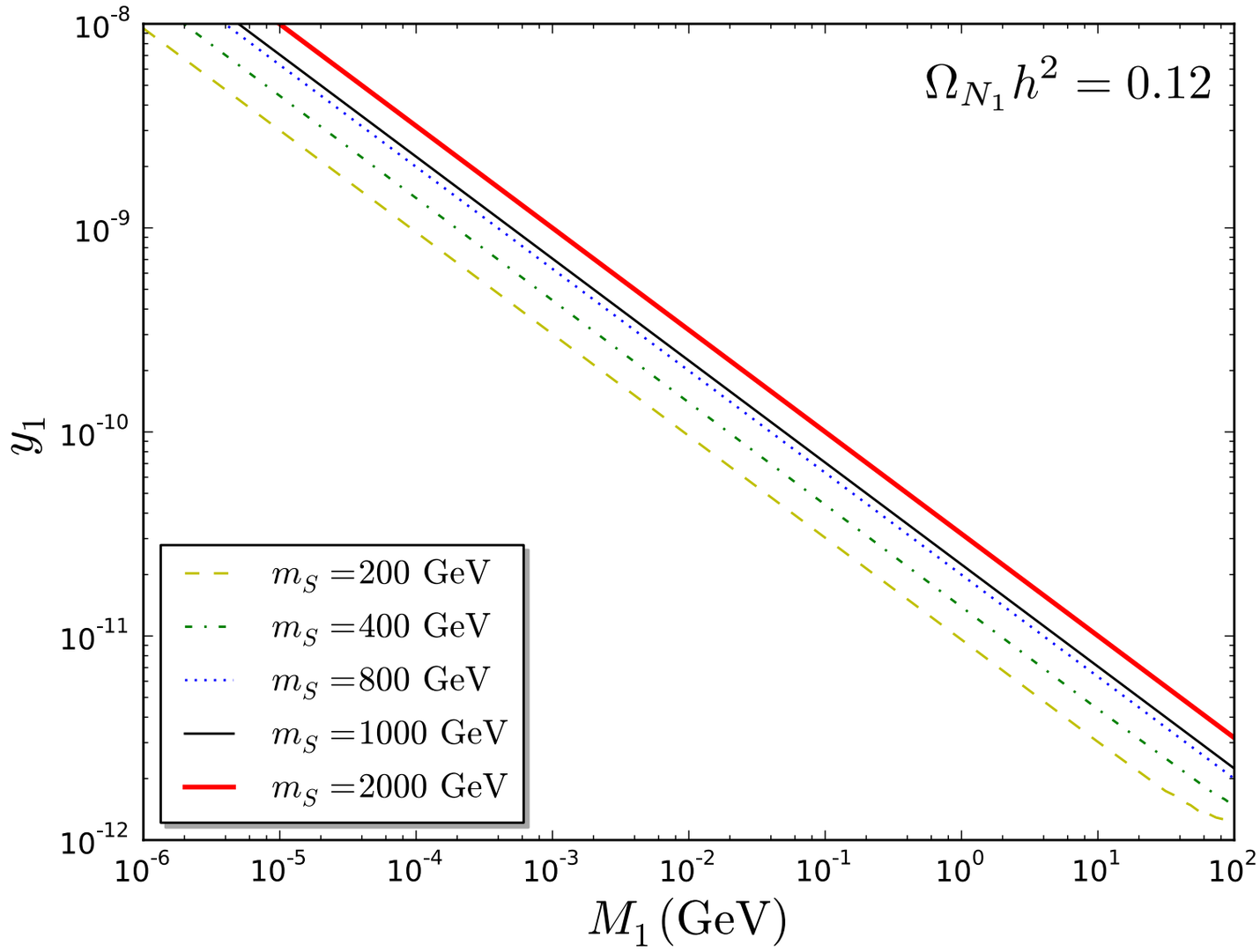

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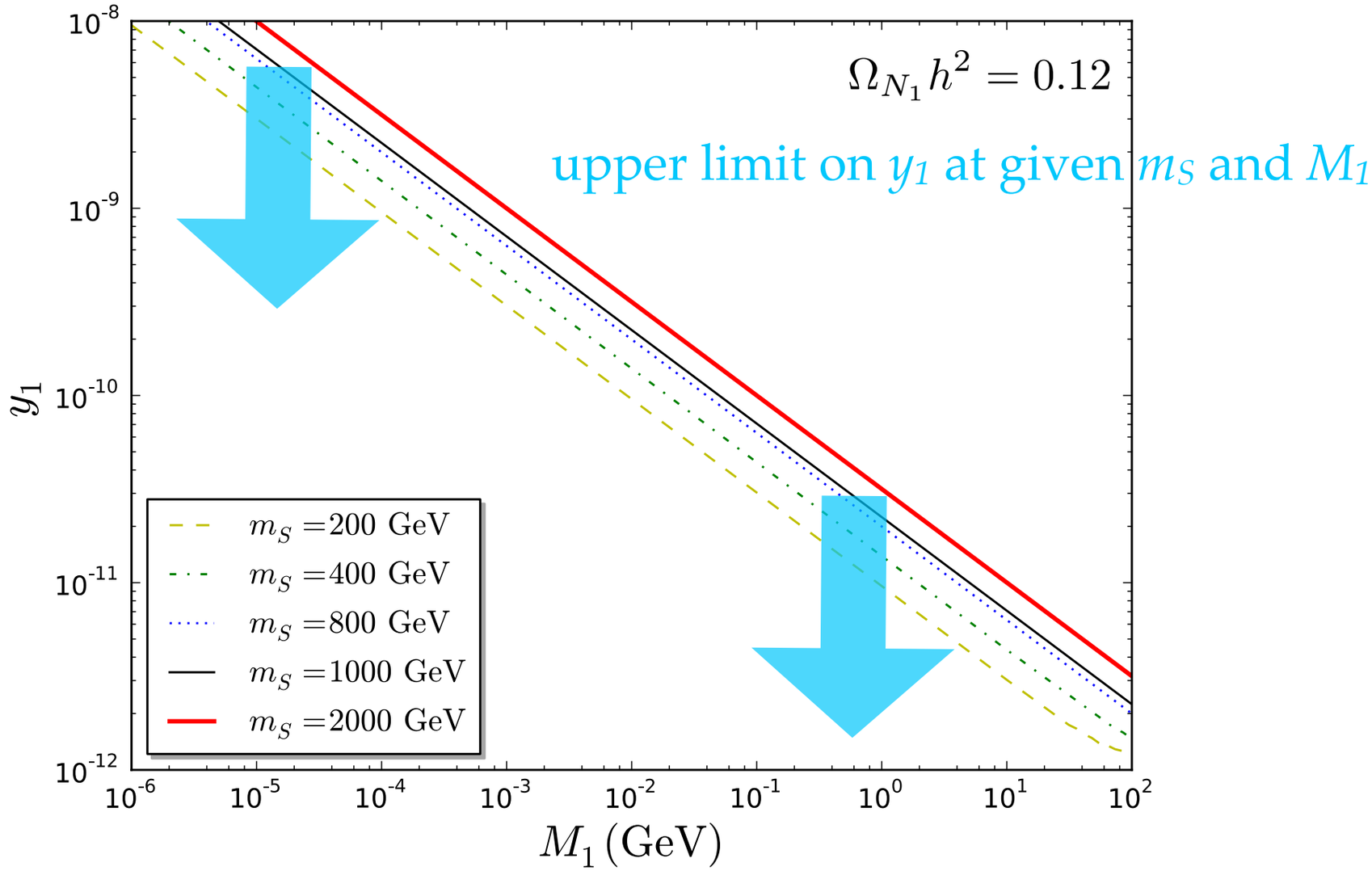

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SuperWIMP mechanism

Feng, Rajaraman, Takayama 2003

N_2 is the NLOP

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

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N_2 decays after the *freeze-out* time

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

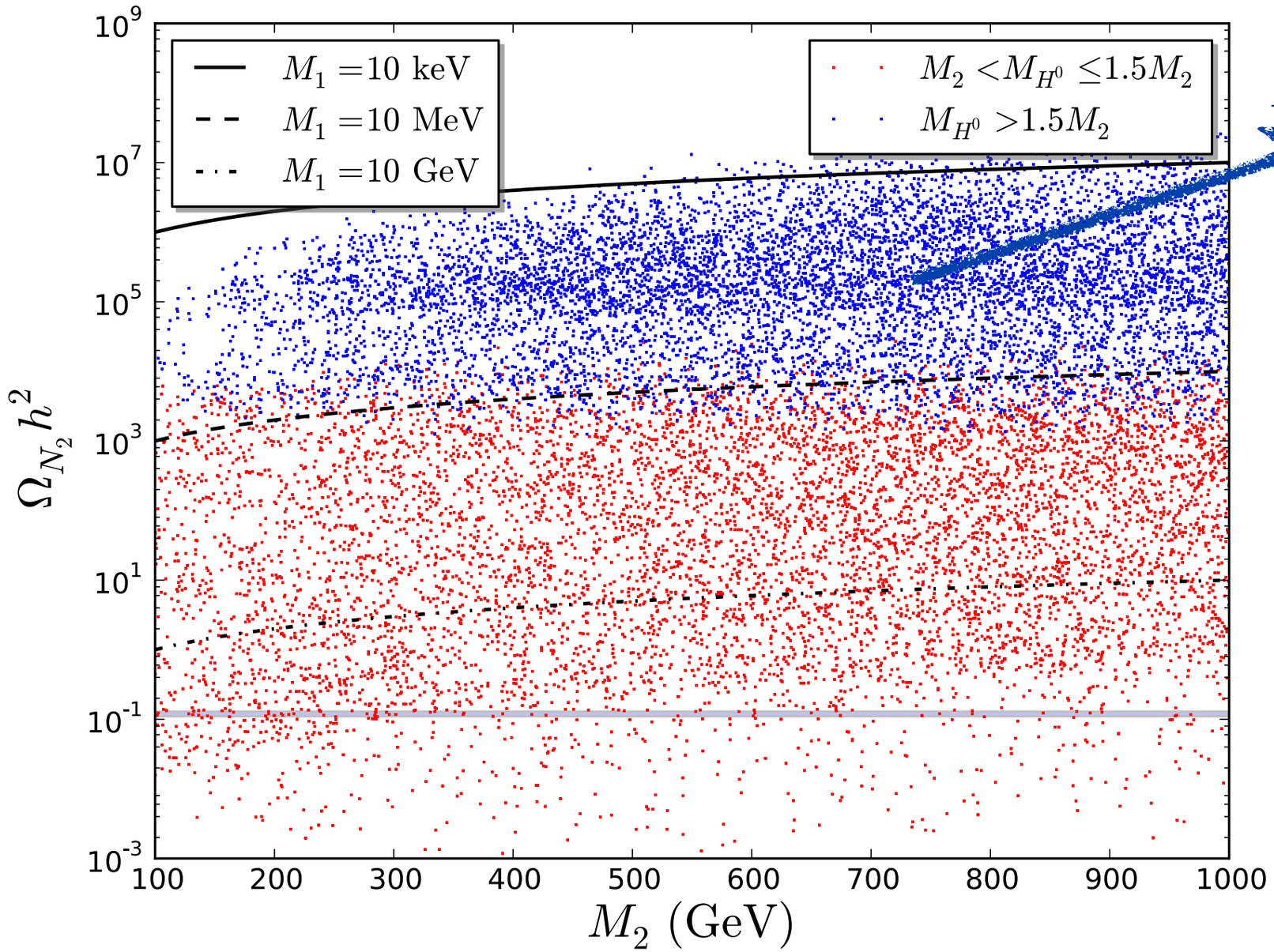
$$y_1\, y_2 \;\lesssim\; 2 \times 10^{-6} \left(\frac{m_S}{1\,\mathrm{TeV}}\right) \left(\frac{1\,\mathrm{TeV}}{M_2}\right)^{3/2}$$

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



$M_1/M_2 \lesssim 10^{-4}$

SuperWIMP mechanism

NLOP is one of the odd scalars

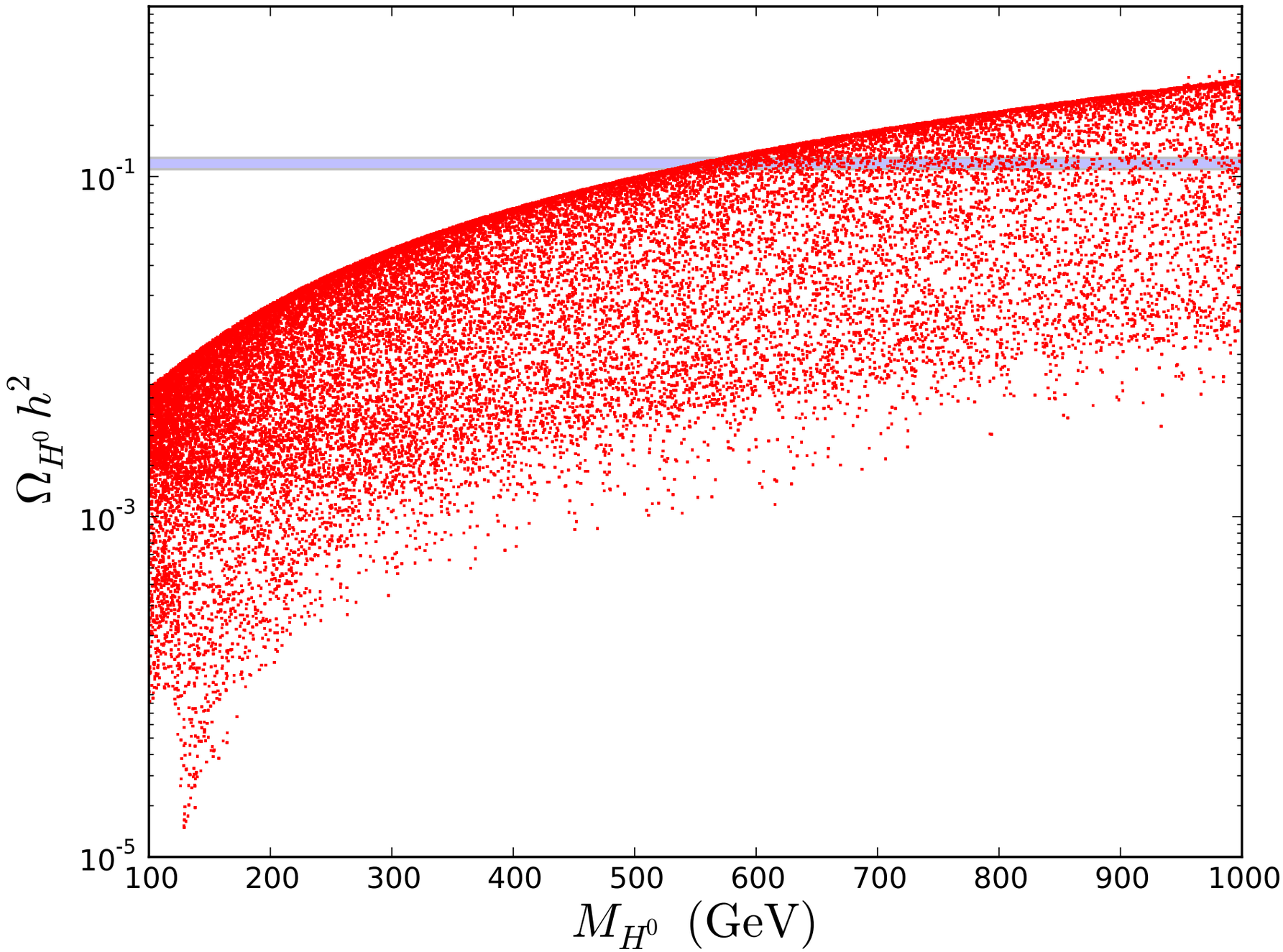
$$\Omega_{N_1}^{superWIMP}\, h^2 \;=\; \frac{M_1}{m_S}\, \Omega_{NLOP}^{freeze-out}\, h^2$$

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



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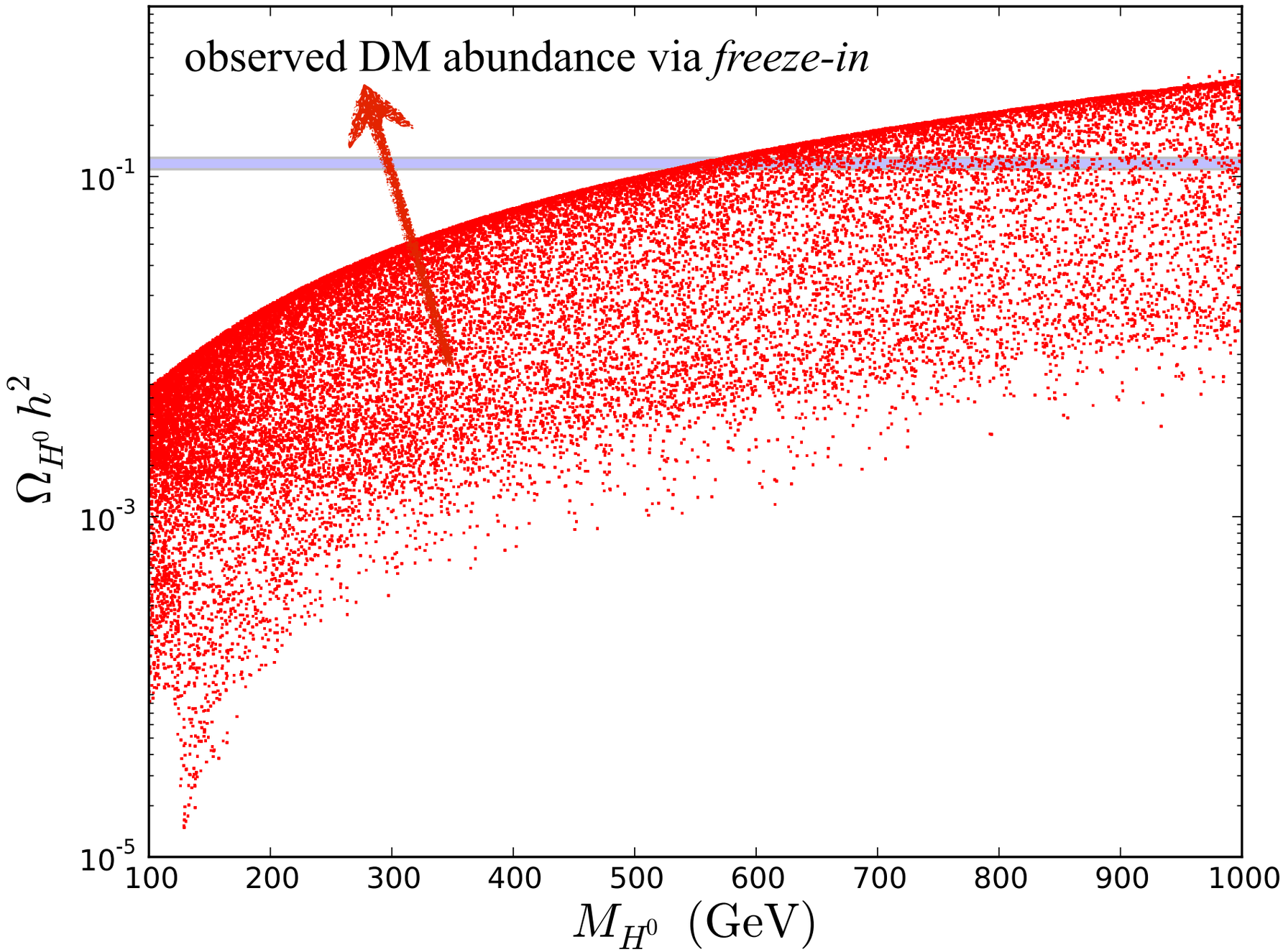

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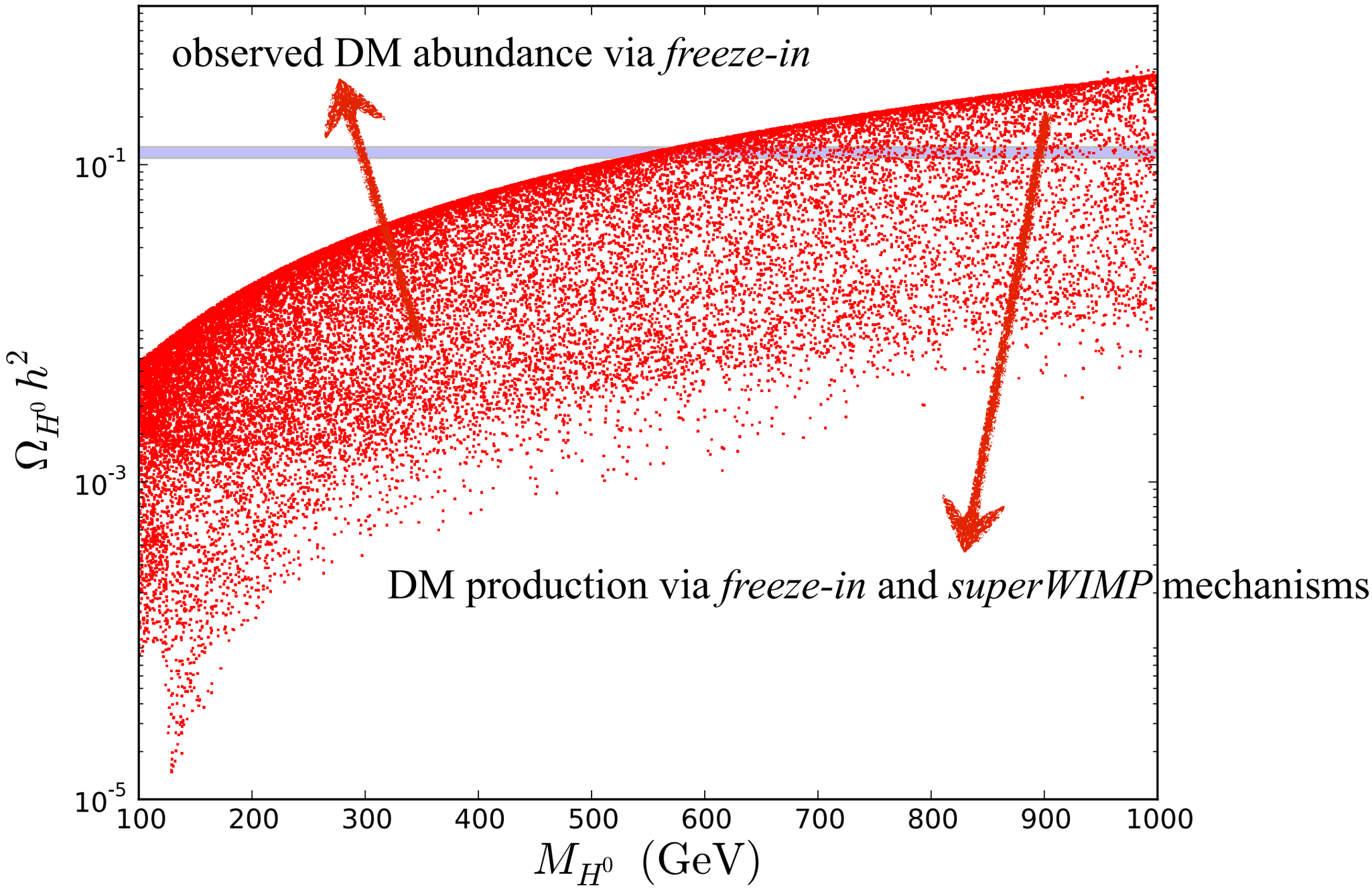

FIMP decay into the dark matter

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

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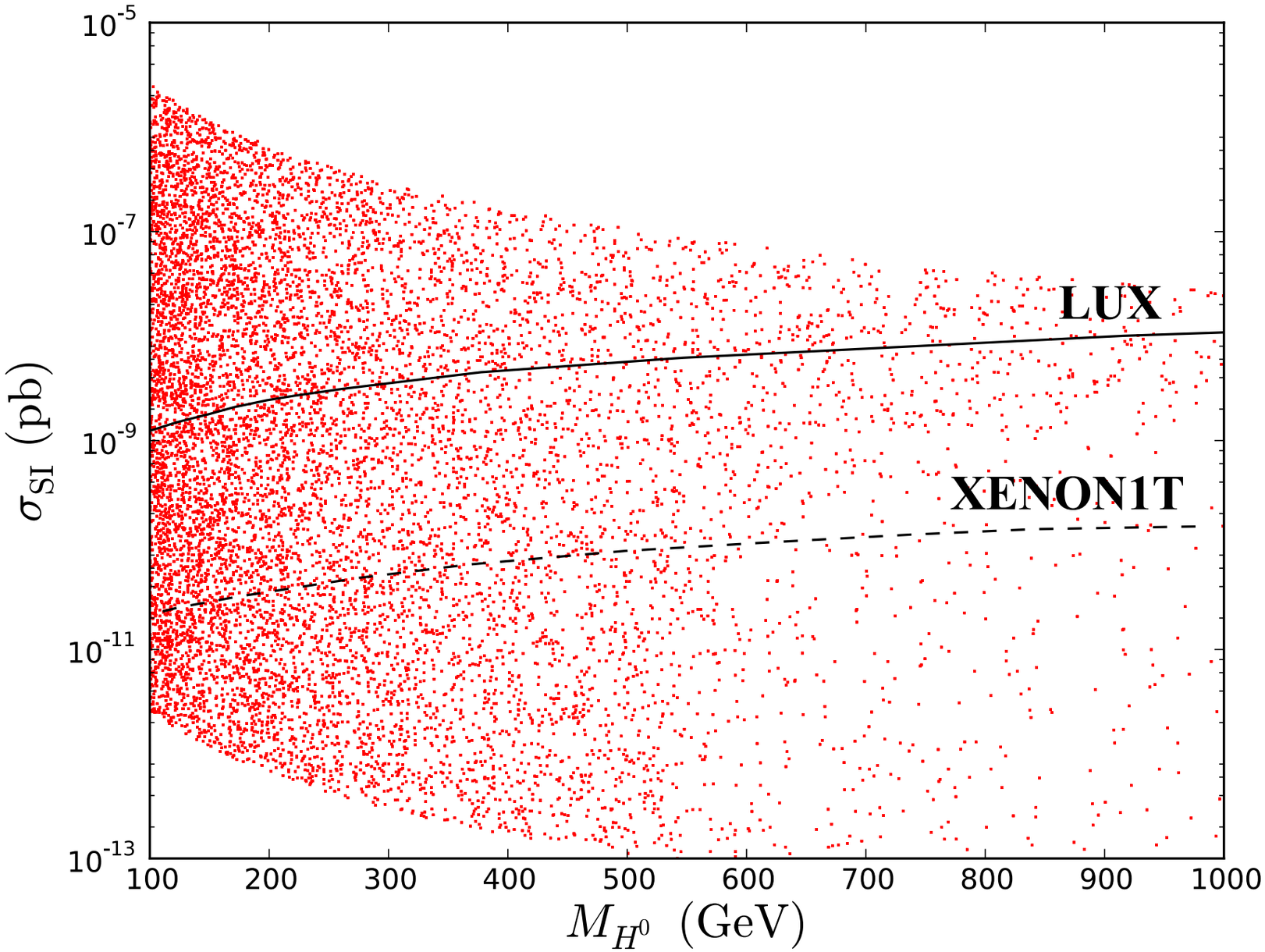
N_1 is produced via *freeze-in* $(H_2\, \ell \to N_1)$ and decays after DM *freeze-out*

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

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

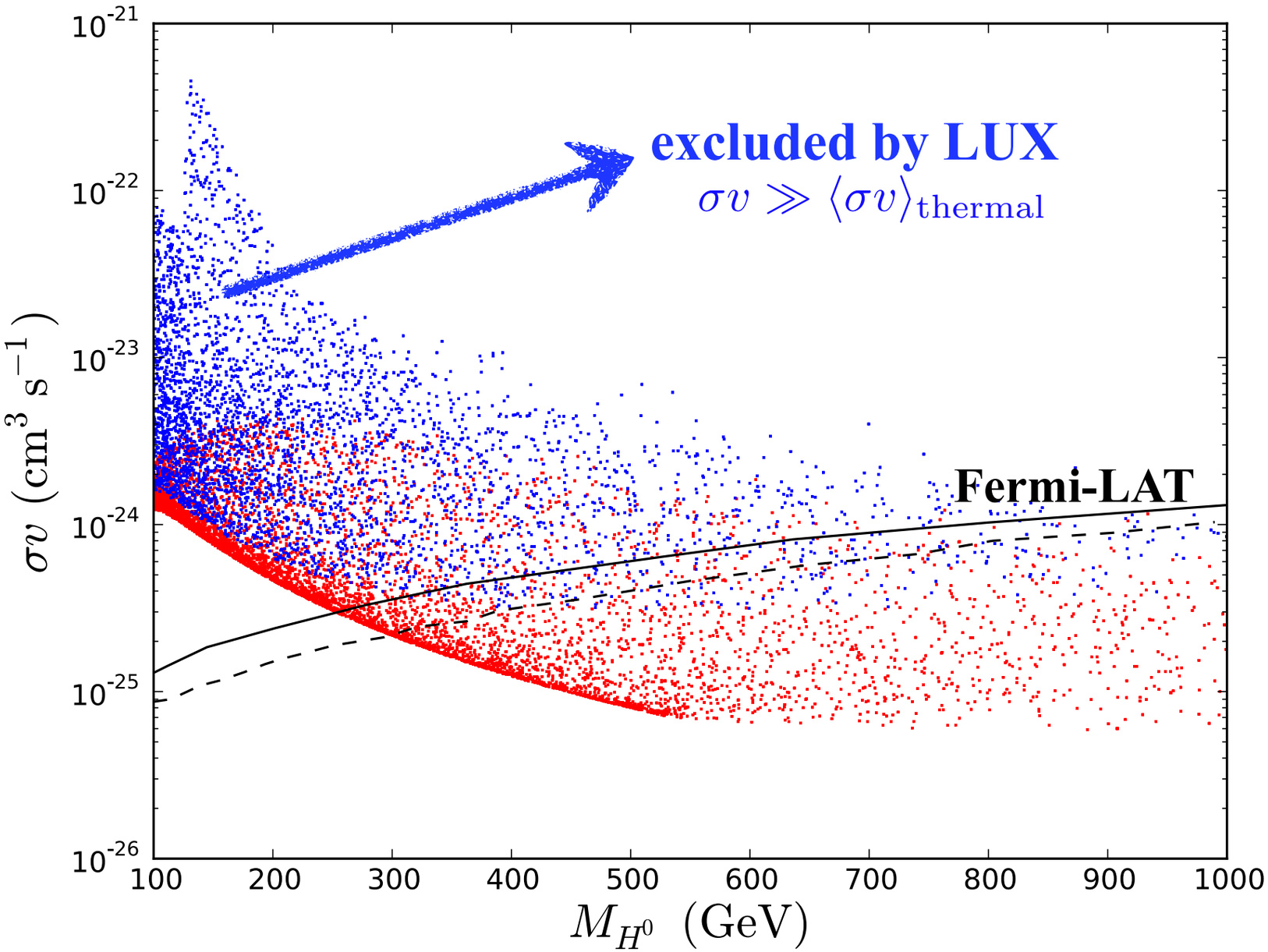
FIMP decay into the dark matter

Direct detection cross-section mediated by the Higgs exchange



FIMP decay into the dark matter

Indirect detection constraints



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