Searches for FIMP Dark Matter at the LHC

based on **JCAP 1407 (2014) 015**

and work in progress with

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CP[3] Origins
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Particle dark matter

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

1. Very little is known about its matter content and 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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<u>Alternative paradigm:</u> the dark matter is a **Feebly Interacting Massive Particle** (FIMP).

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

FIMPs have very weak renormalizable interactions with SM particles and never enter in thermal equilibrium. Their abundance is produced via *thermal freeze-in*. No signatures of these particles in *direct/indirect* searches. FIMPs may <u>induce exotic collider signatures</u>.

Long-lived particles at the LHC

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$$c\tau(\tilde{\tau}) \approx 100\ \mu\mathrm{m} \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{\tau}}}\right)^5 \left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4$$

Specific collider signatures depend on the stau lifetime (1601.01326):

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Specific collider signatures depend on the stau lifetime (1601.01326):

- opposite solitary displaced leptons: **100 μm** $\lesssim$ ***cτ*** $\lesssim$ **5 cm** [CMS-B2G-12-024]
- disappearing/kinked tracks: ***cτ*** ≈ ***O*(50cm)** [CMS-EXO-12-034, CERN-PH-EP-2013-155]
- heavy stable charged particle searches: ***cτ*** ≈ **1-3 m** [CMS-EXO-12-026, CERN-PH-EP-2014-252]

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- The next-to-lightest odd particle (NLOP) is the portal to the dark sector: its decay width might be directly related to the cosmological dark matter abundance and/or the dark matter mass
- LHC production cross-section of the NLOP might be sizeable
- NLOP lifetime/decay modes/collider specific signatures depend on the mass spectrum of the model

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interesting phenomenology within radiative neutrino mass models, which can naturally implement the FIMP dark matter paradigm

Scotogenic model

Lagrangian invariant under a Z_2 symmetry

Ernest Ma (2006)

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

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

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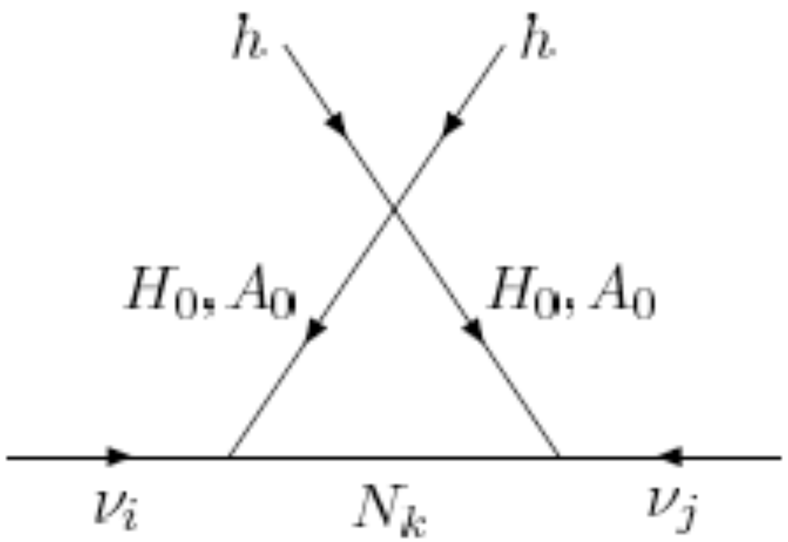
The dark sector mass spectrum:

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

Radiative neutrino mass generation

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



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

2 massive neutrinos

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

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

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

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

Lepton flavour violation

Constraints from charged lepton flavour violation:

$$\mathrm{B}(\mu \to e\,\gamma) < 4.2 \times 10^{-13}$$

MEG upper limit

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

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

FIMP dark matter

1. *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:

$$\boxed{\begin{array}{c}\Gamma(H_2 \to N_1\, L) \lesssim H(T \sim M_{H_2}) \\[1em] m_{H_2} \sim 100 \text{ GeV} \Longrightarrow y_1 \lesssim 10^{-8}\end{array}}$$

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

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

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

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

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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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thermal freeze-in:

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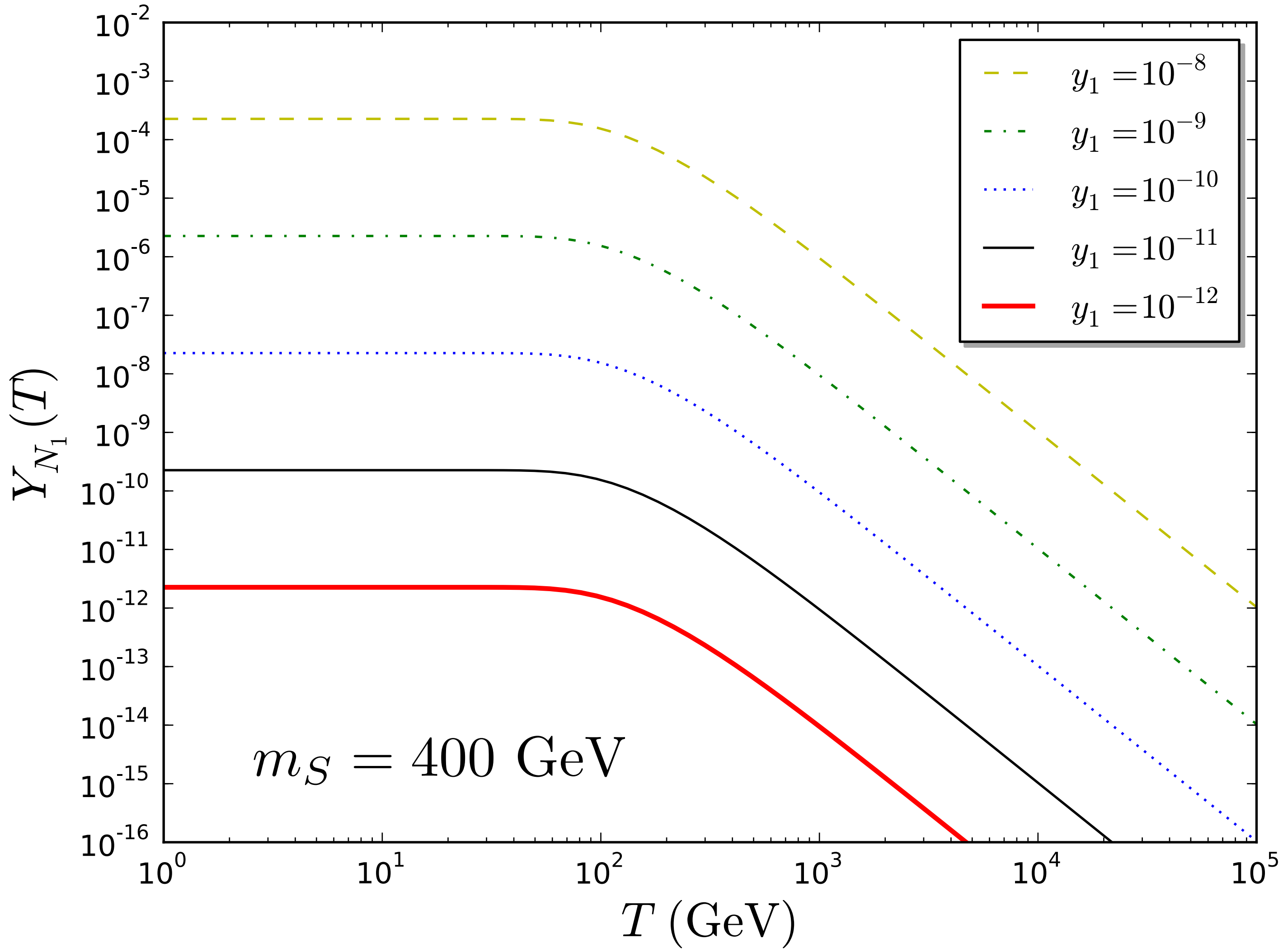
Dark matter abundance:

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

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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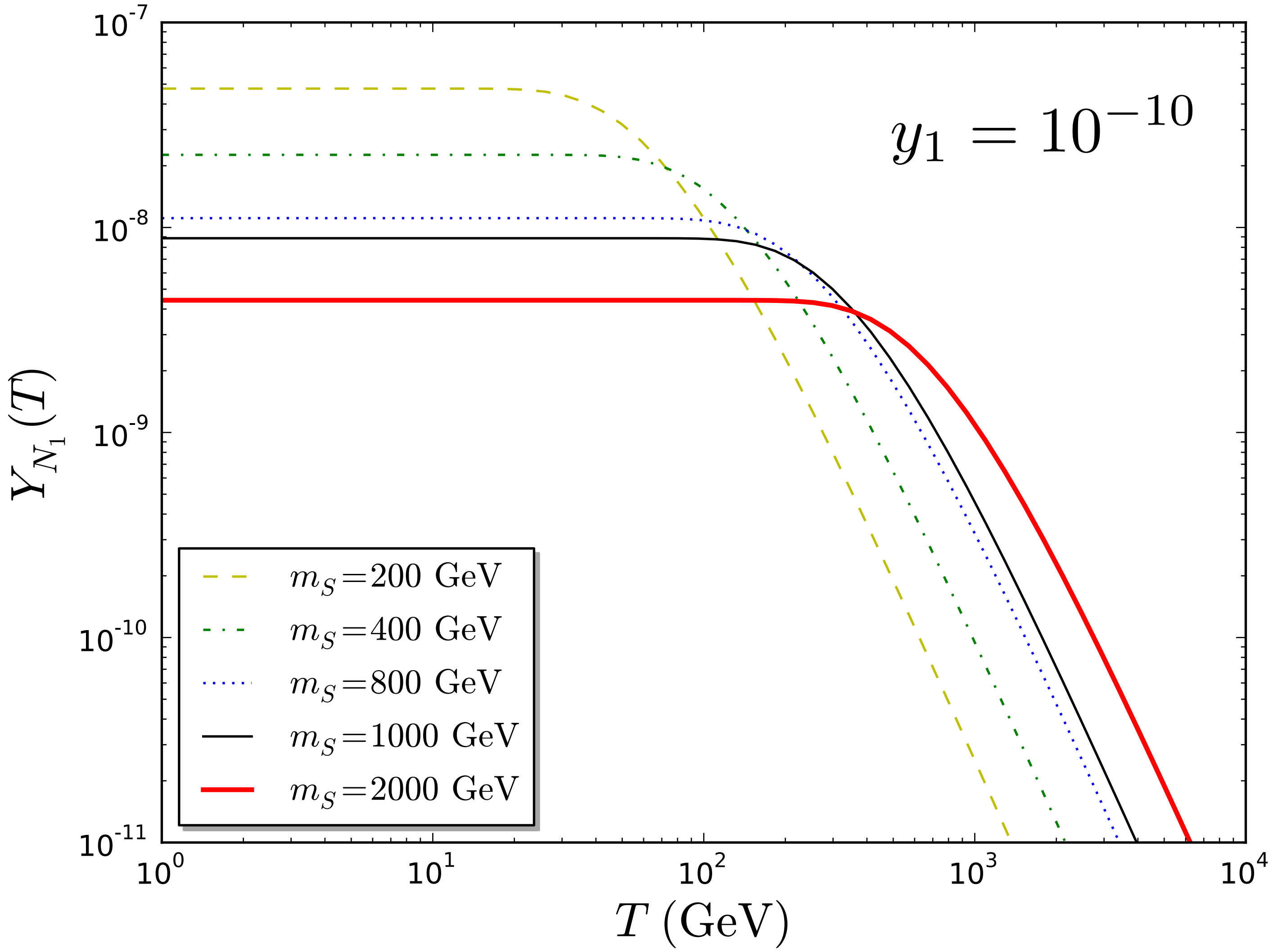

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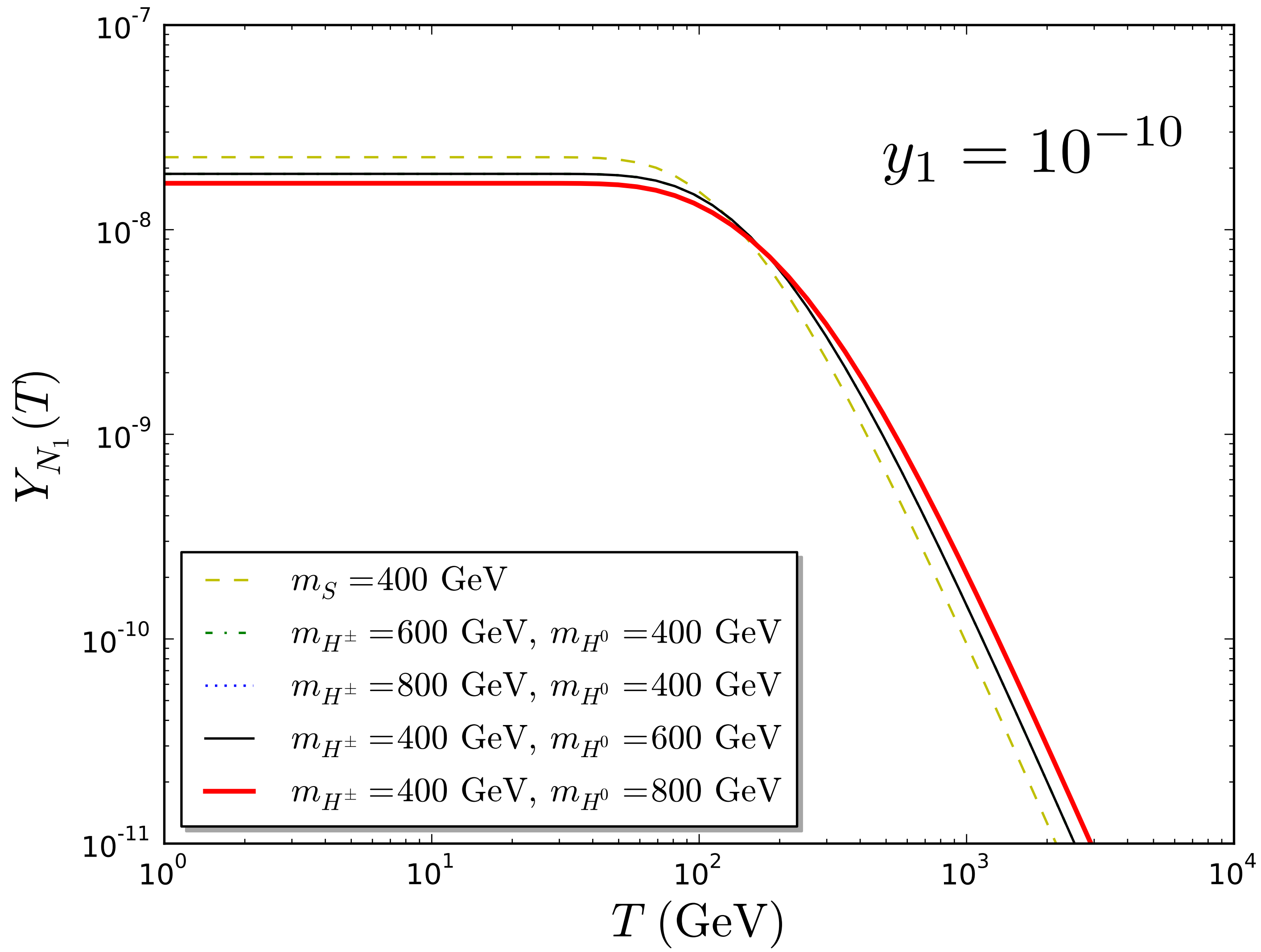

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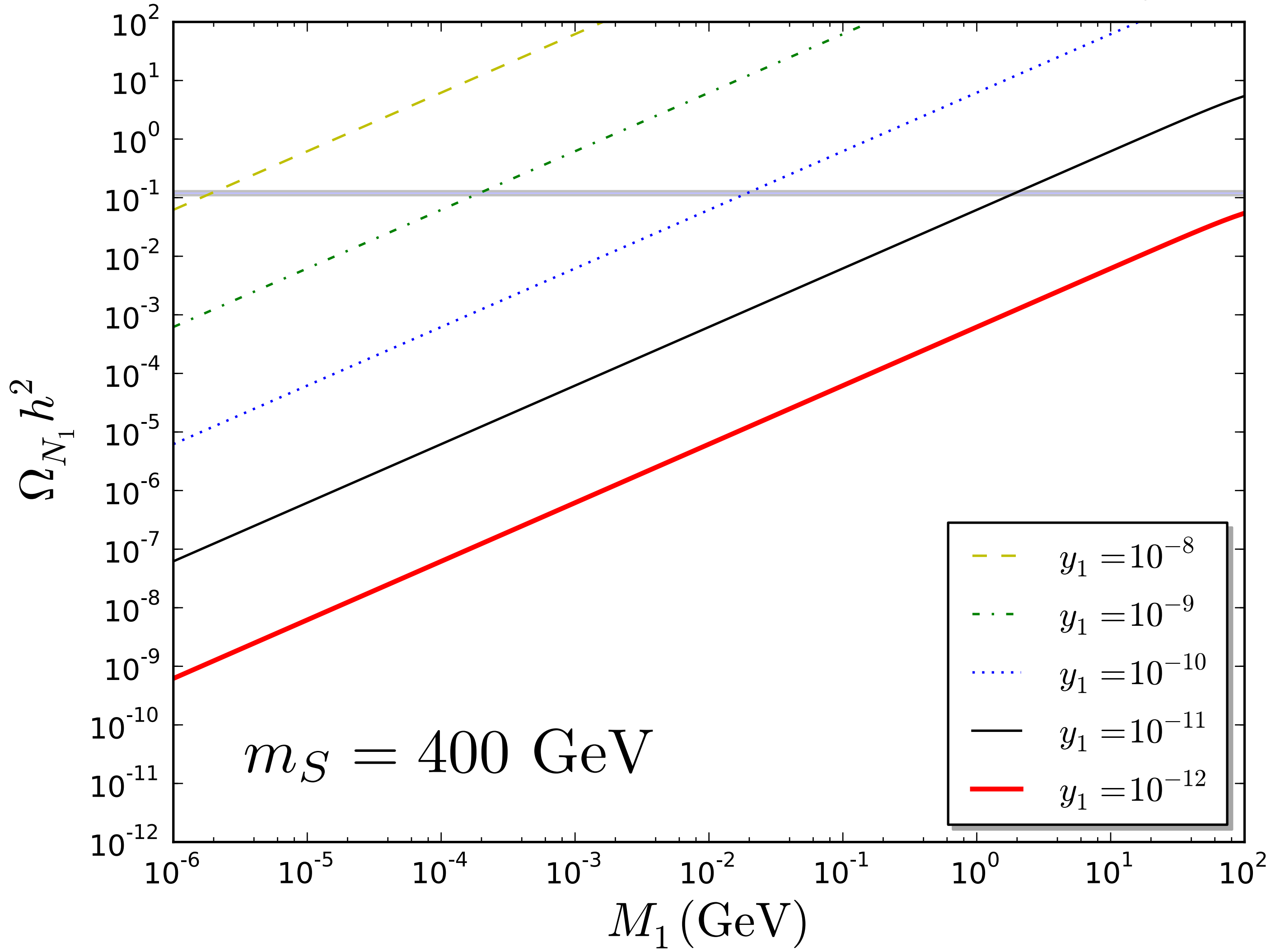
Thermal freeze-in mechanism

Parameter space compatible with the observed relic density



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

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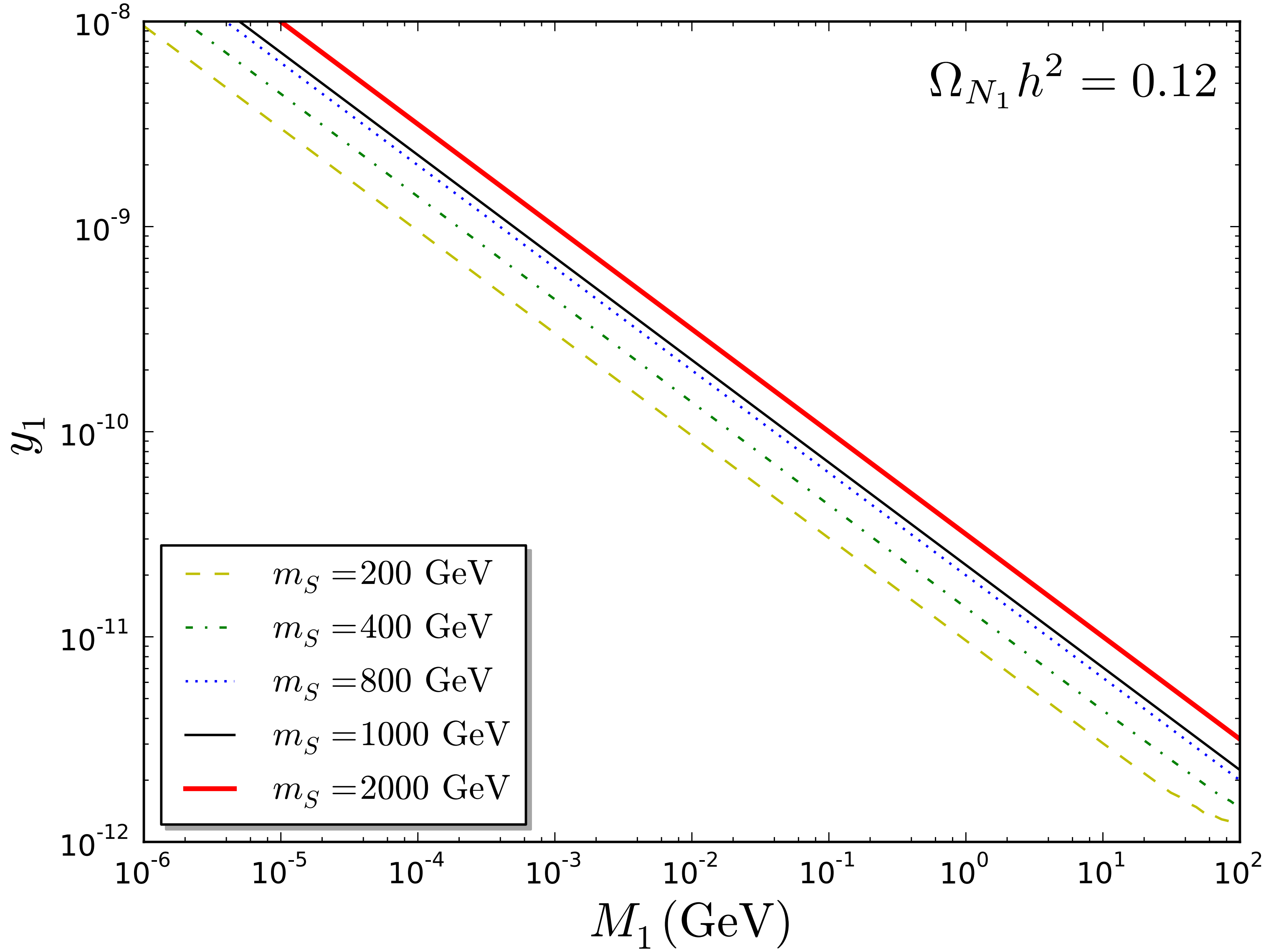

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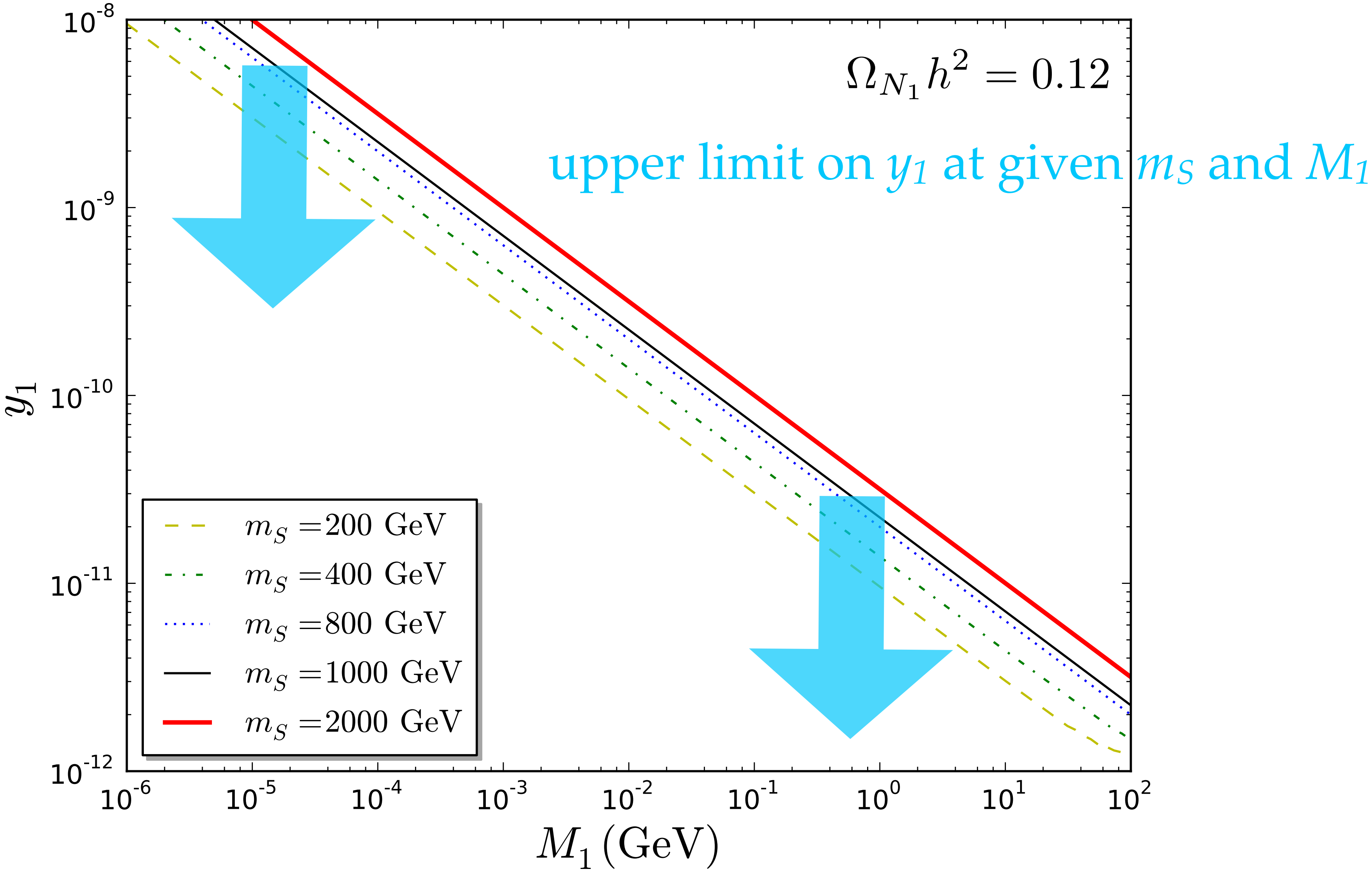

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Charged scalar NLOP

mass spectrum: $M_1 < m_{H^\pm} < m_{H^0,\, A^0} < M_{2,3}$

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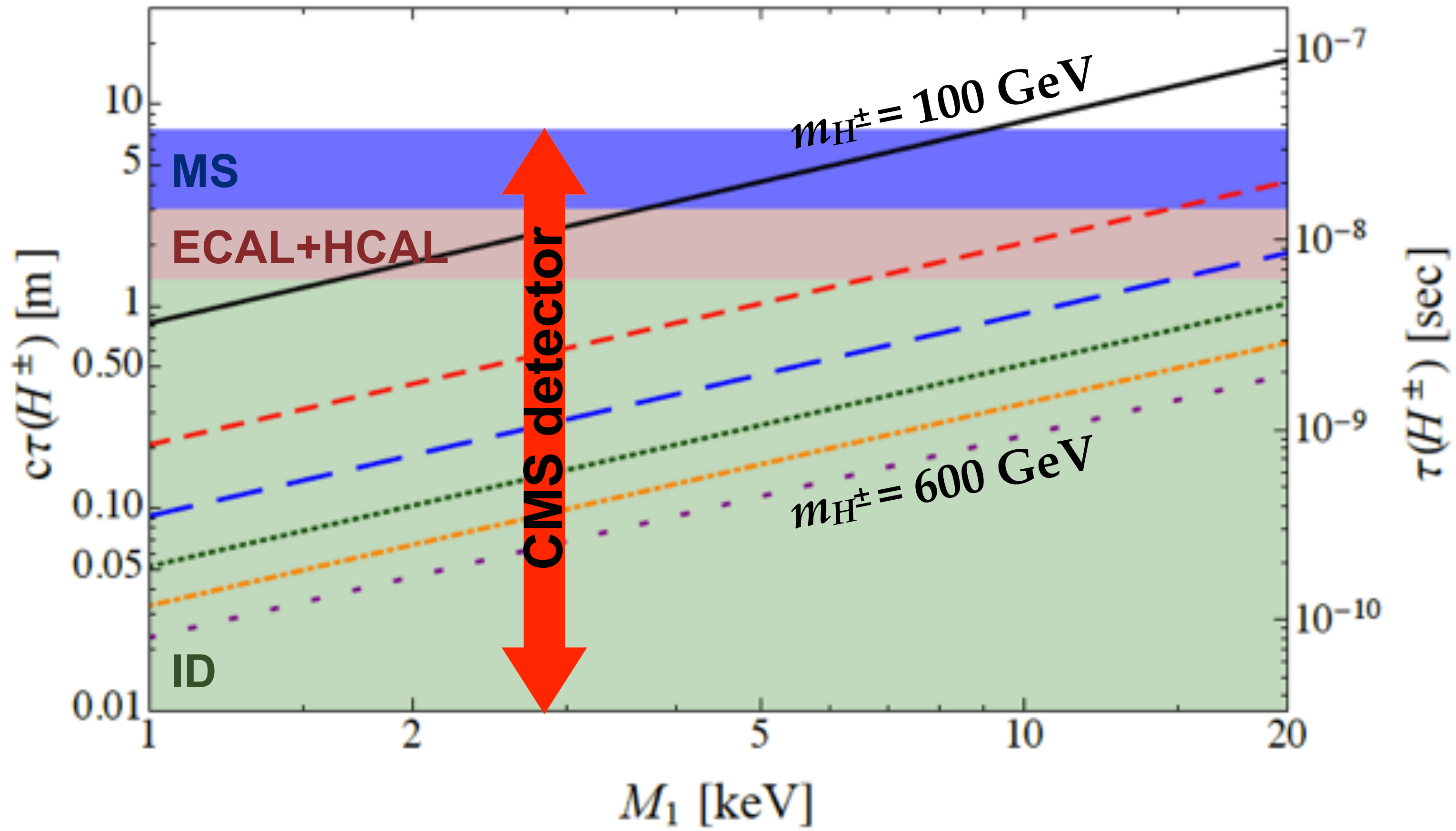
- dark matter abundance via *freeze-in*
- for $m_{H^\pm} \gtrsim 100$ GeV the NLOP is either stable or decays within the detector
- the life-time/decay-length of the NLOP depends on the initial velocity and the dark matter mass



$$c\tau(H^\pm) \;\approx\; 8.3\,\mathrm{m}\left(\frac{M_1}{10\ \mathrm{keV}}\right)\left(\frac{100\ \mathrm{GeV}}{m_{H^\pm}}\right)^2$$

$$\tau(H^\pm) \;\approx\; 2.8\times 10^{-8}\,\mathrm{sec}\left(\frac{M_1}{10\ \mathrm{keV}}\right)\left(\frac{100\ \mathrm{GeV}}{m_{H^\pm}}\right)^2$$

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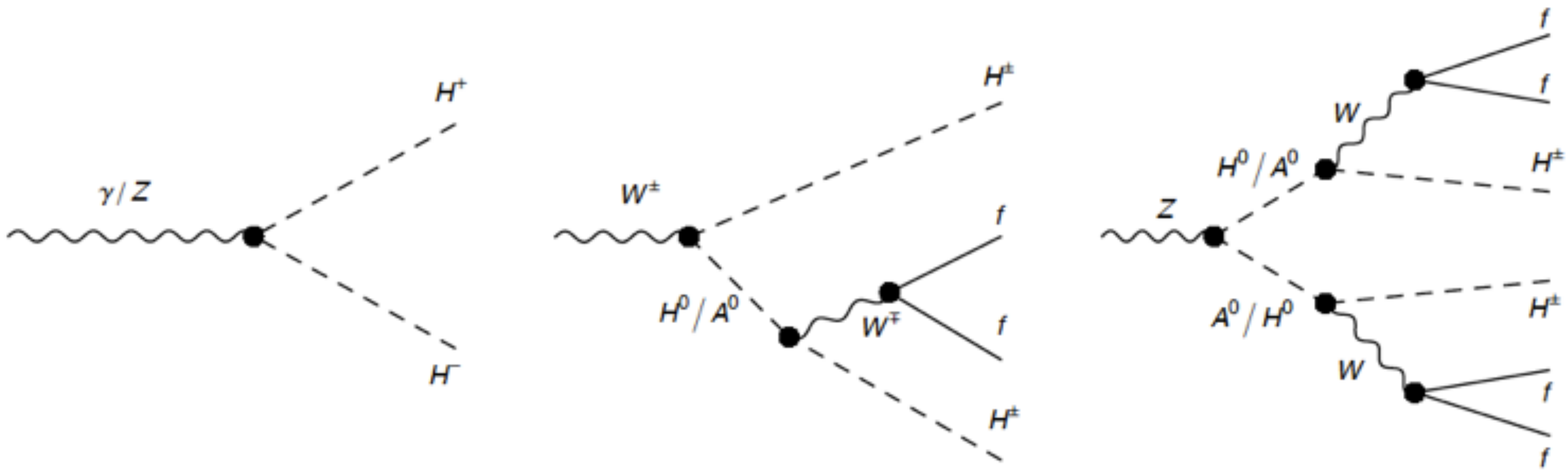
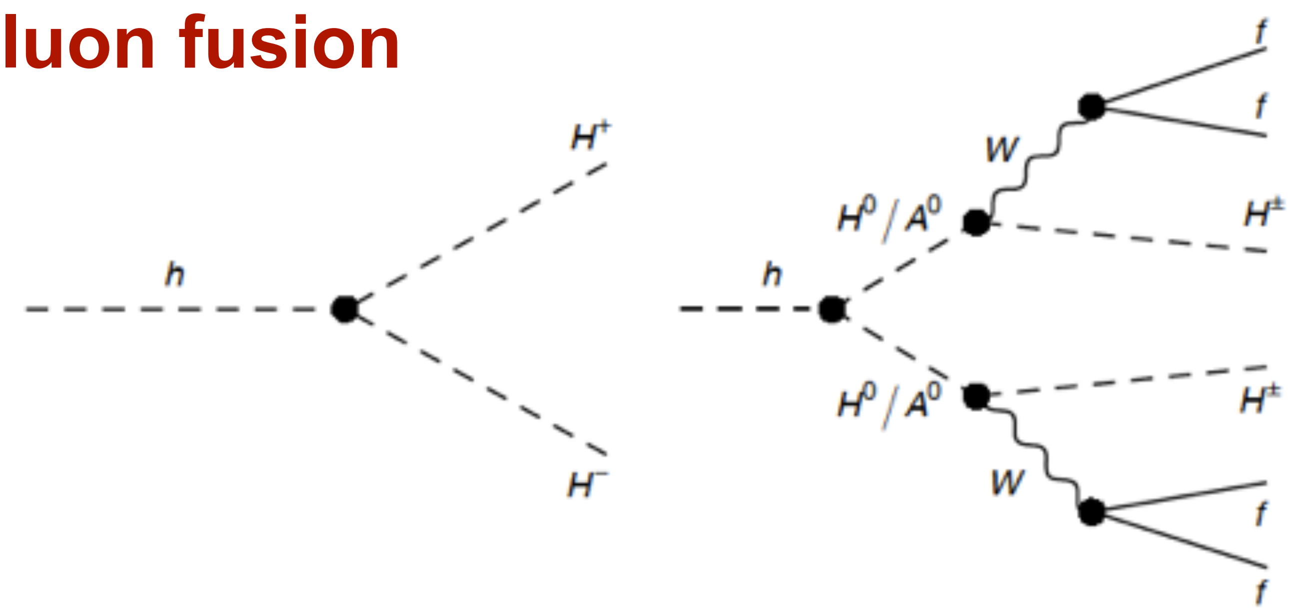
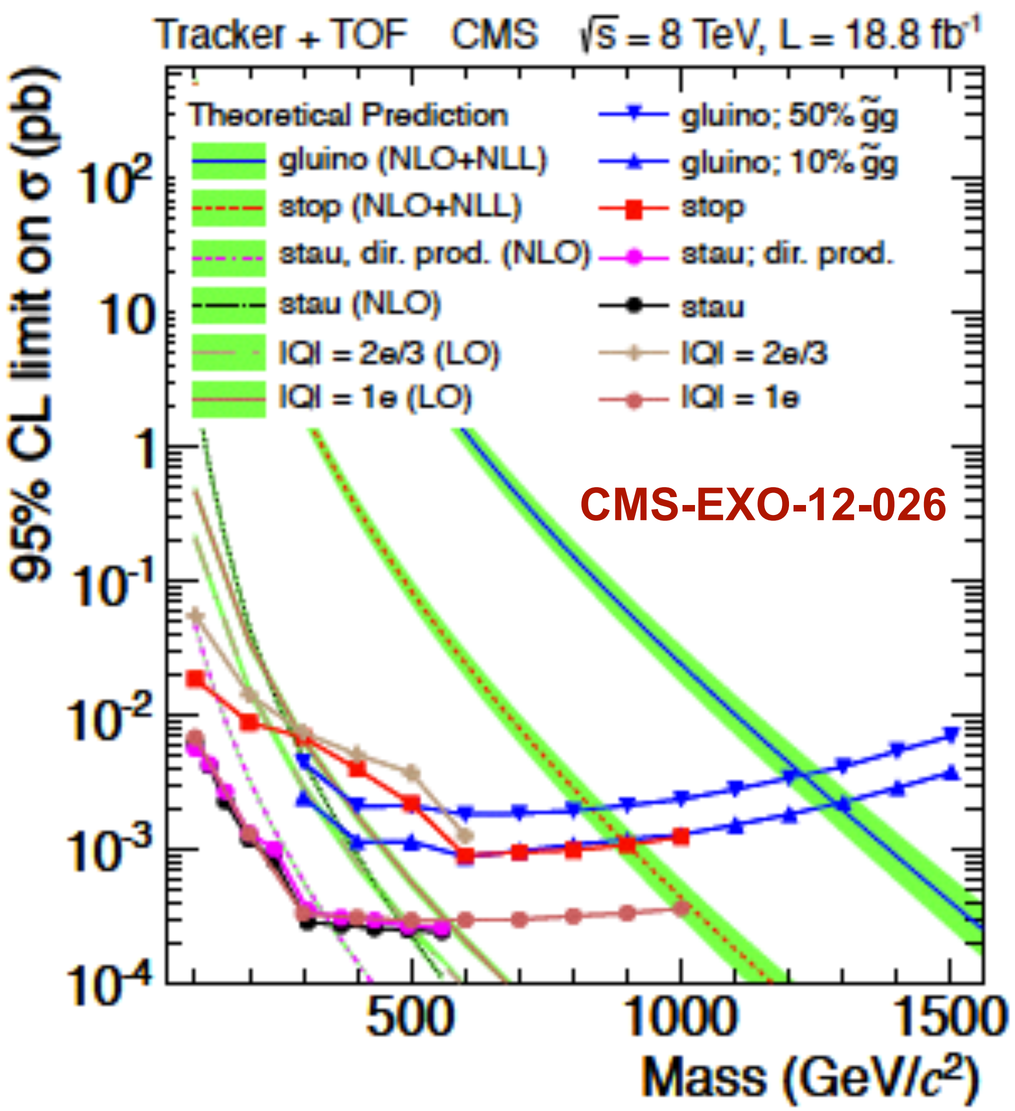
Drell-Yan



Higgs-mediated gluon fusion



Charged track analysis



We recast Tracker + Time-of-Flight analysis of CMS on metastable singly-charged particles:

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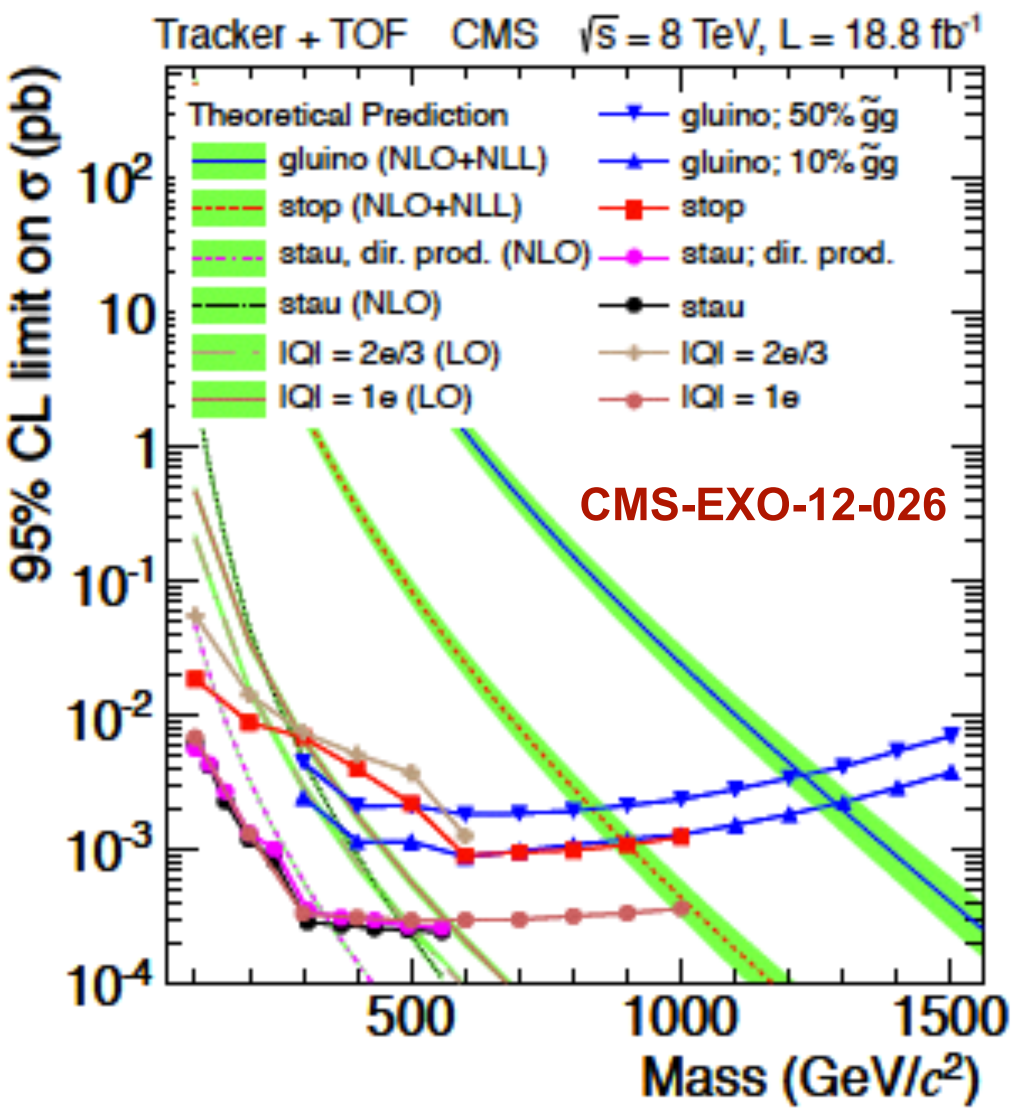

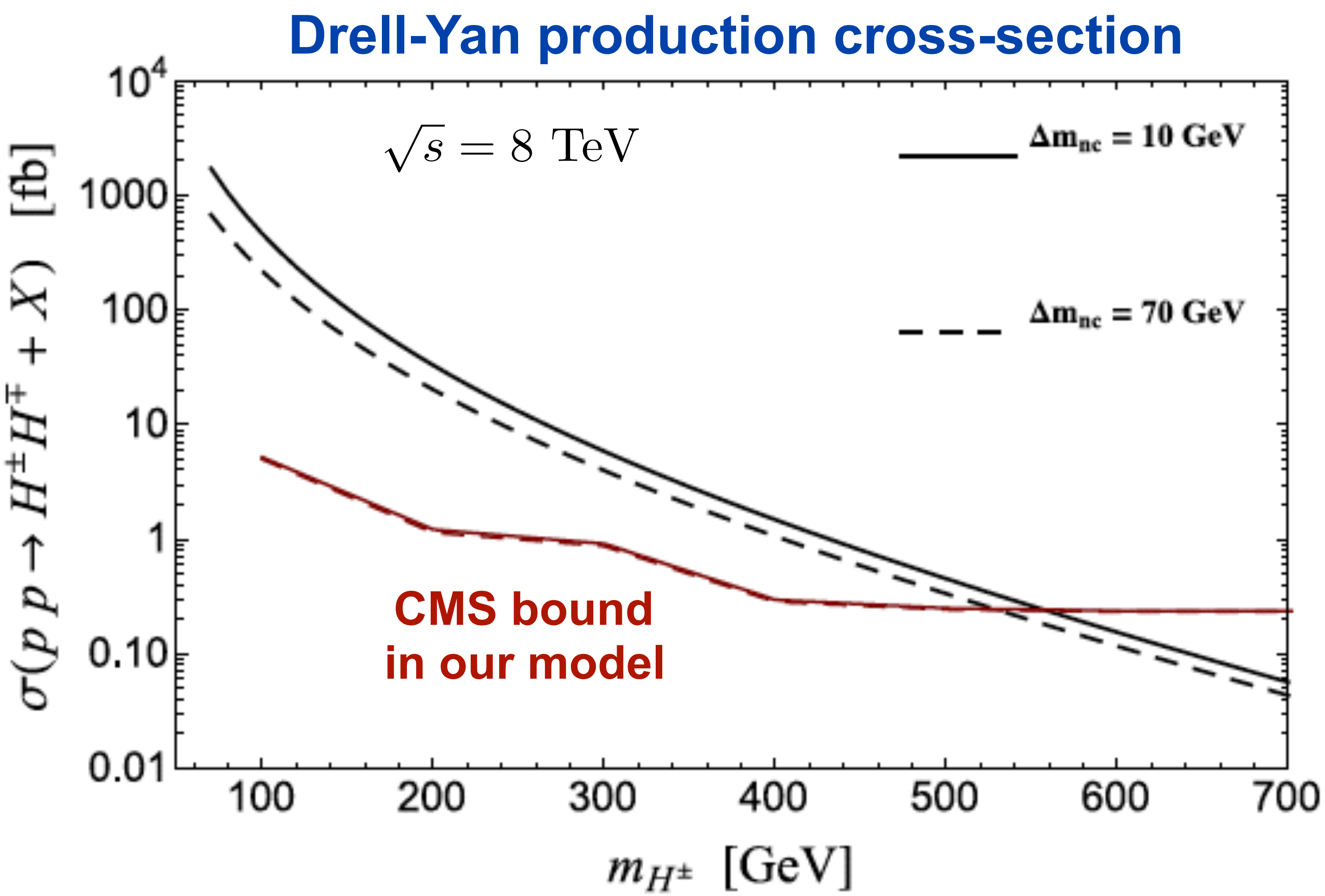

We recast Tracker + Time-of-Flight analysis of CMS on metastable singly-charged particles:

$$m_{H^\pm} \gtrsim 560\ (530)\ \text{GeV} \quad \text{for} \quad \Delta m_{\rm nc} = 10\ (70)\ \text{GeV}$$

bound for stable heavy singly-charged particles

Charged track analysis

in-flight decays of the NLOP

Survival probability of ***H*±** after depends on the distance ***x***:

$$P^{\rm sur}_{H^\pm}(x) \;=\; \exp\left(-\,\frac{x}{\beta\gamma\, c\tau(H^\pm)}\right)$$

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Excluded cross-section:

$$\sigma(p\,p \to H^+\,H^- \,+\, X) \;\lesssim\; \sigma_{ex} \;\equiv\; \frac{N_{ex}}{L\times\mathcal{A}_{\rm scot}}$$

L: integrated luminosity 18.8 fb^{-1}

N_{ex} : # excluded events for stau pair production (CMS-EXO-12-026)
tracker+TOF analysis (tracks reconstructed in the ID and MS)

$A_{\rm scot}$: signal acceptance computed via a Monte Carlo technique (CMS-EXO-13-006)

$$\mathcal{A}_{\rm scot} = \frac{1}{N}\sum_{i=1}^{N} P^{\rm on}(k_i^1, k_i^2, \Gamma_{H^\pm}) \times P^{\rm off}(m_{\rm thr}, k_i^1, k_i^2) \qquad k_i = (\beta_i, \eta_i, p_{Ti})$$

contains information of ***H*^±**—lifetime/probability of the track passing through the muon spectrometer

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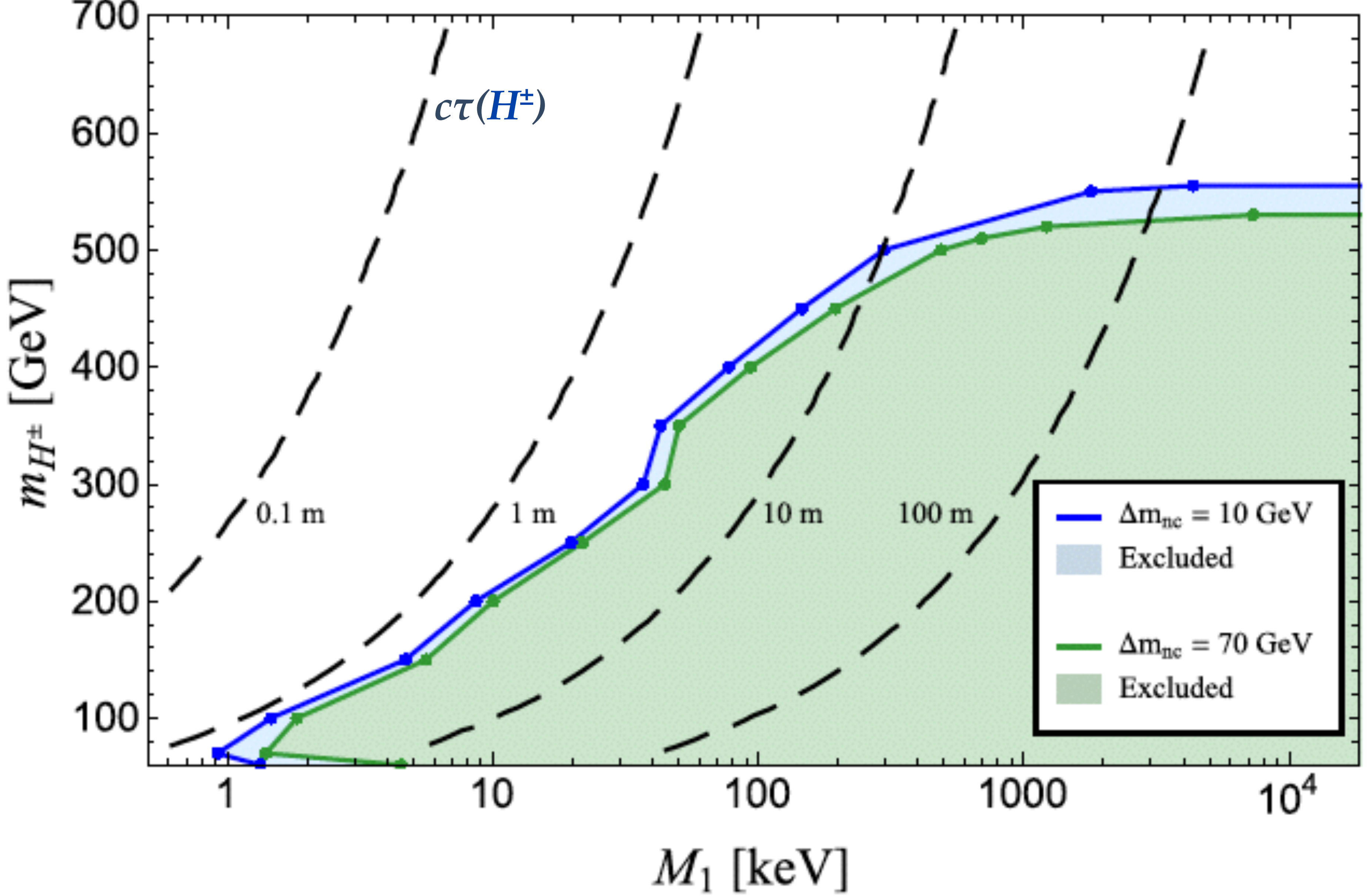
95% CL excluded regions



Fermion NLOP

mass spectrum: $M_1 < M_2 < m_{H^\pm, H^0, A^0} < M_3$

- Prompt decays (*y₂>>y₁*):

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N_2 decay-length exceeds the detector size

Constraints from regular searches of final states with large transverse missing energy

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collider signature: two charged leptons and large missing energy

We apply ATLAS constraints from searches for SUSY simplified models with light sleptons and weakly decaying charginos (1403.5294) $\tilde{\chi}_1^\pm \to (\tilde{\ell}^\pm \nu \text{ or } \ell^\pm \tilde{\nu}) \to \ell^\pm \nu \tilde{\chi}_1^0$

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- reconstruction of τ's challenging
- only e and μ in the final state
- use CheckMATE to recast analysis of ATLAS
  1403.5294
- for BR($H^\pm \to N_2 \tau$) $\gtrsim$ 0.3 dilepton production cross-section reduced: all the parameter space is allowed

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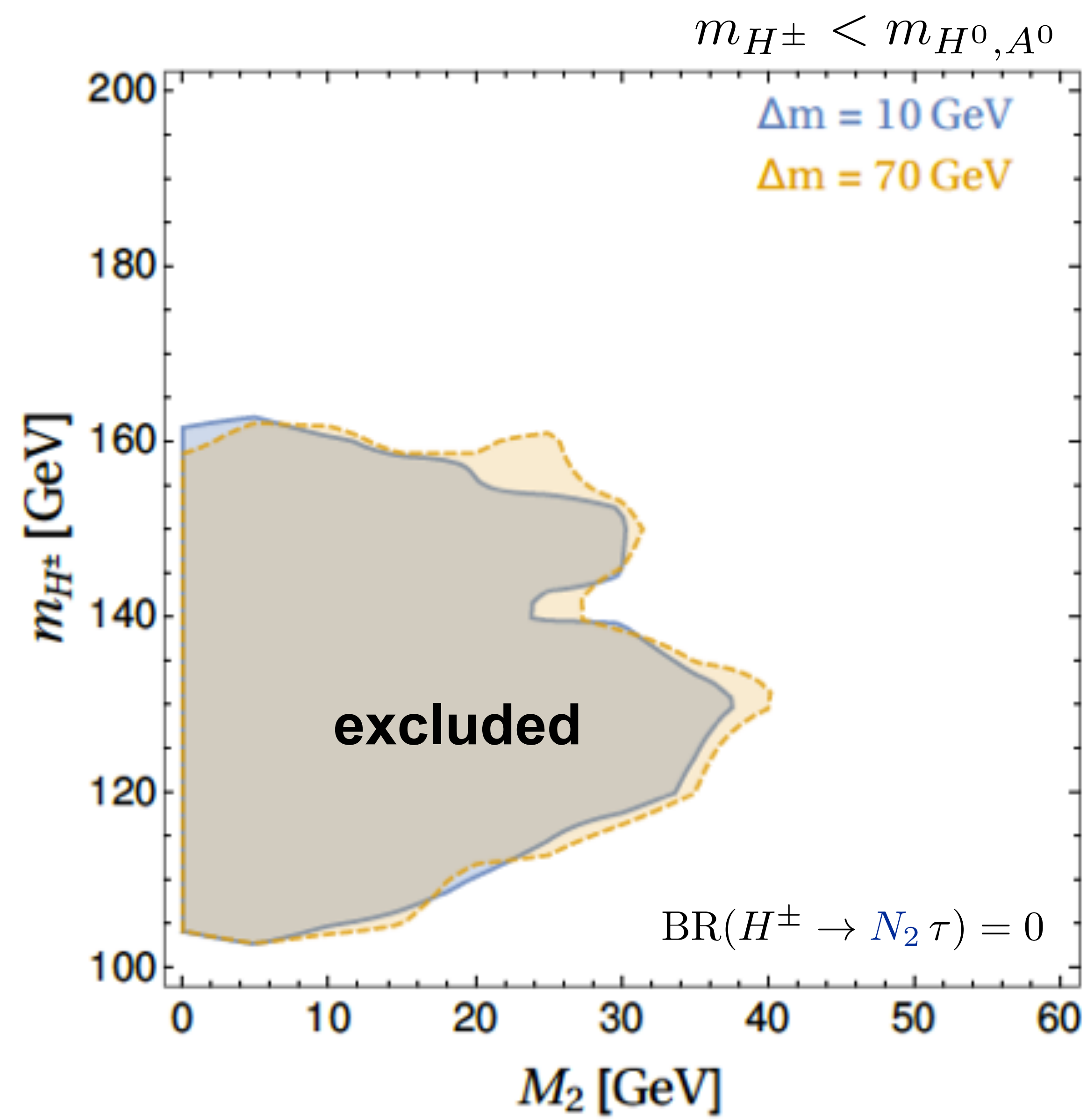

most optimistic scenario

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- Again N_2 is stable on collider scales
- N_3 decay rate suppressed by neutrino Yukawa couplings: $N_3 \to \ell_\alpha \bar{\ell}_\beta N_2$

$$c\tau(N_3) \approx 0.02\text{cm}\frac{10\text{ GeV}}{M_3}\frac{(10^{-2})^4}{|Y^\nu_{\alpha 2}|^2|Y^\nu_{\beta 3}|^2}\frac{m^4_{H^\pm}}{M_3^4}$$

Fermion NLOP

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$

- Direct connection to the neutrino sector

- Again N_2 is stable on collider scales

- N_3 decay rate suppressed by neutrino Yukawa couplings: $N_3 \to \ell_\alpha \bar{\ell}_\beta N_2$

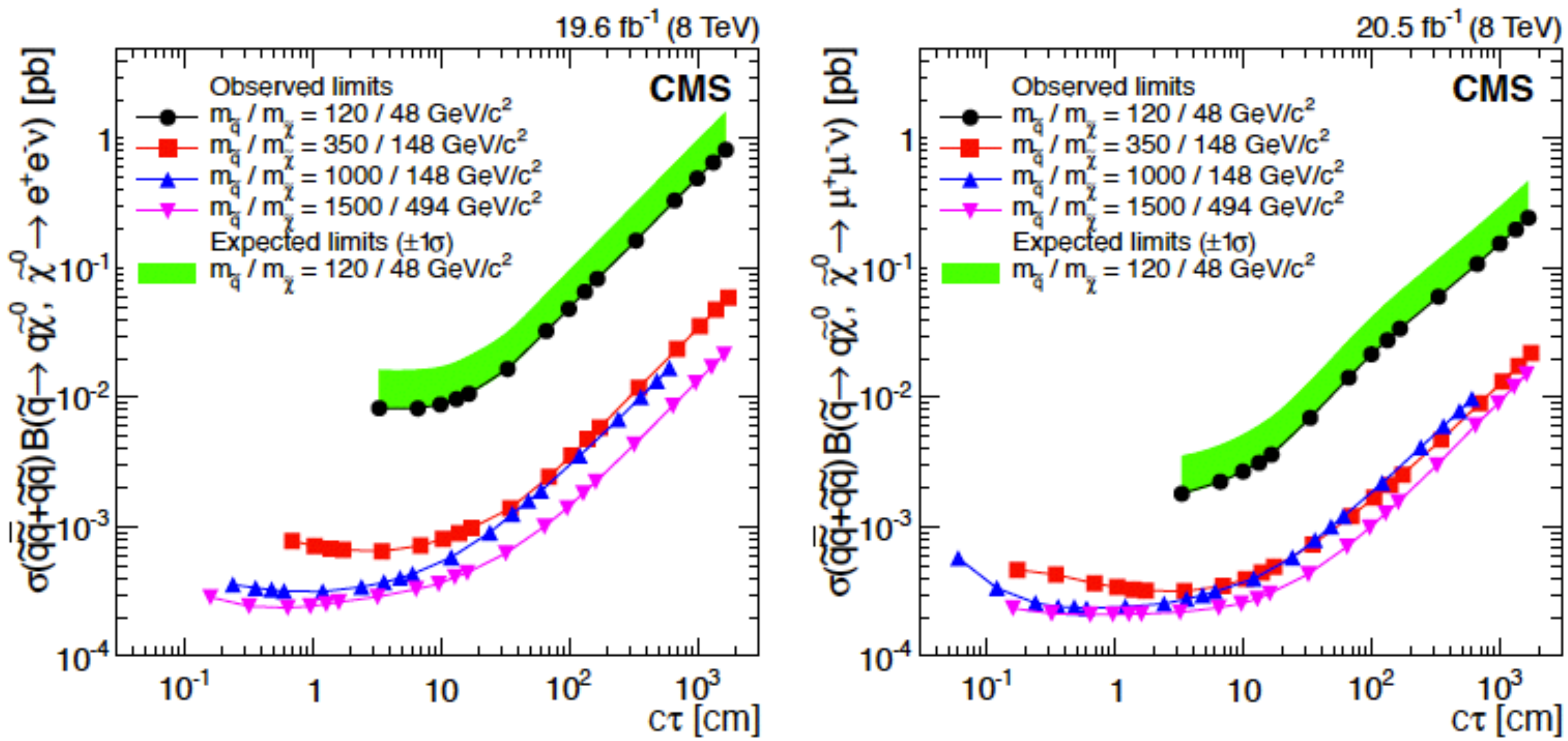
$$c\tau(N_3) \approx 0.02\text{cm} \frac{10 \text{ GeV}}{M_3} \frac{(10^{-2})^4}{|Y^\nu_{\alpha 2}|^2 |Y^\nu_{\beta 3}|^2} \frac{m^4_{H^\pm}}{M^4_3}$$

collider signature: displaced dileptons

Displaced dilepton pairs can be searched for very efficiently at the LHC. We focus on the search of displaced muon pairs in CMS-EXO-12-037

CMS displaced dileptons

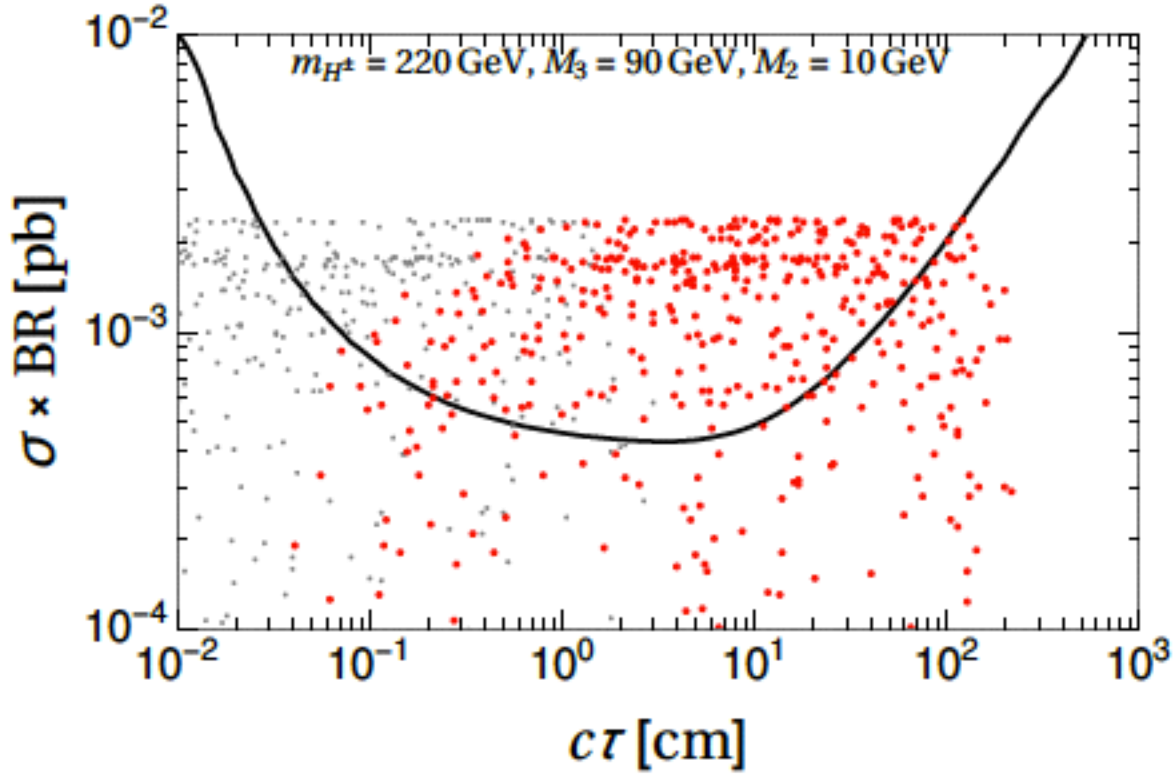
CMS-EXO-12-037



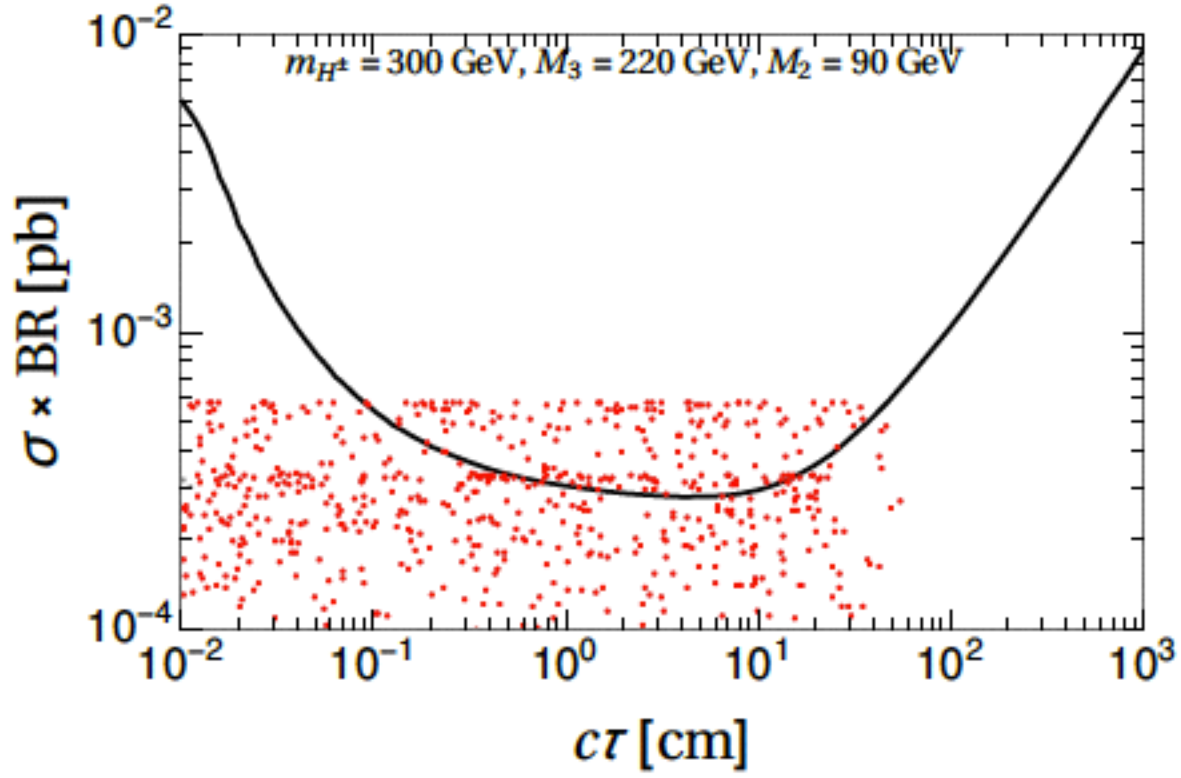
$$\tilde q \to q\,\tilde\chi^0, \quad \tilde\chi^0 \to \ell^+\ell^-\nu$$ in RPV-SUSY

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$



95% CL exclusion on displaced $\mu^+ \mu^-$ pair production



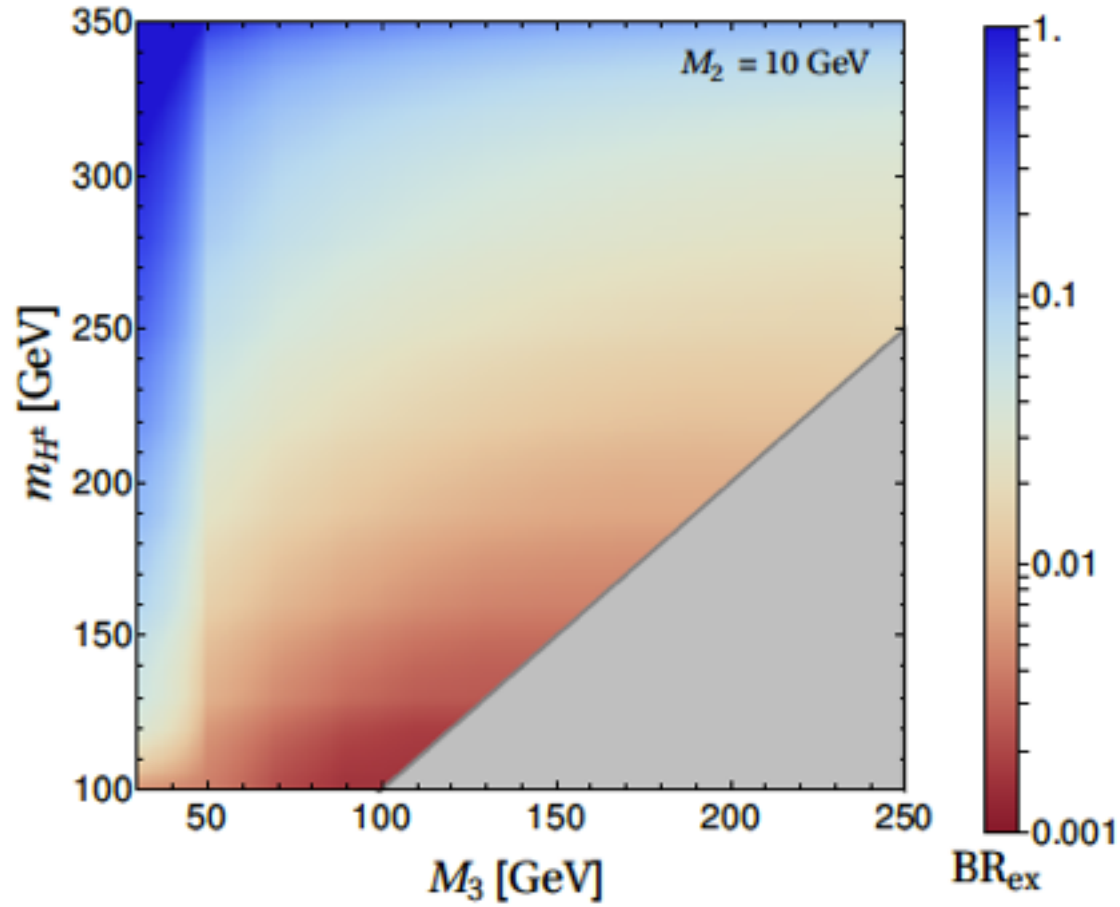
> All the points points reproduce light neutrino masses and mixing

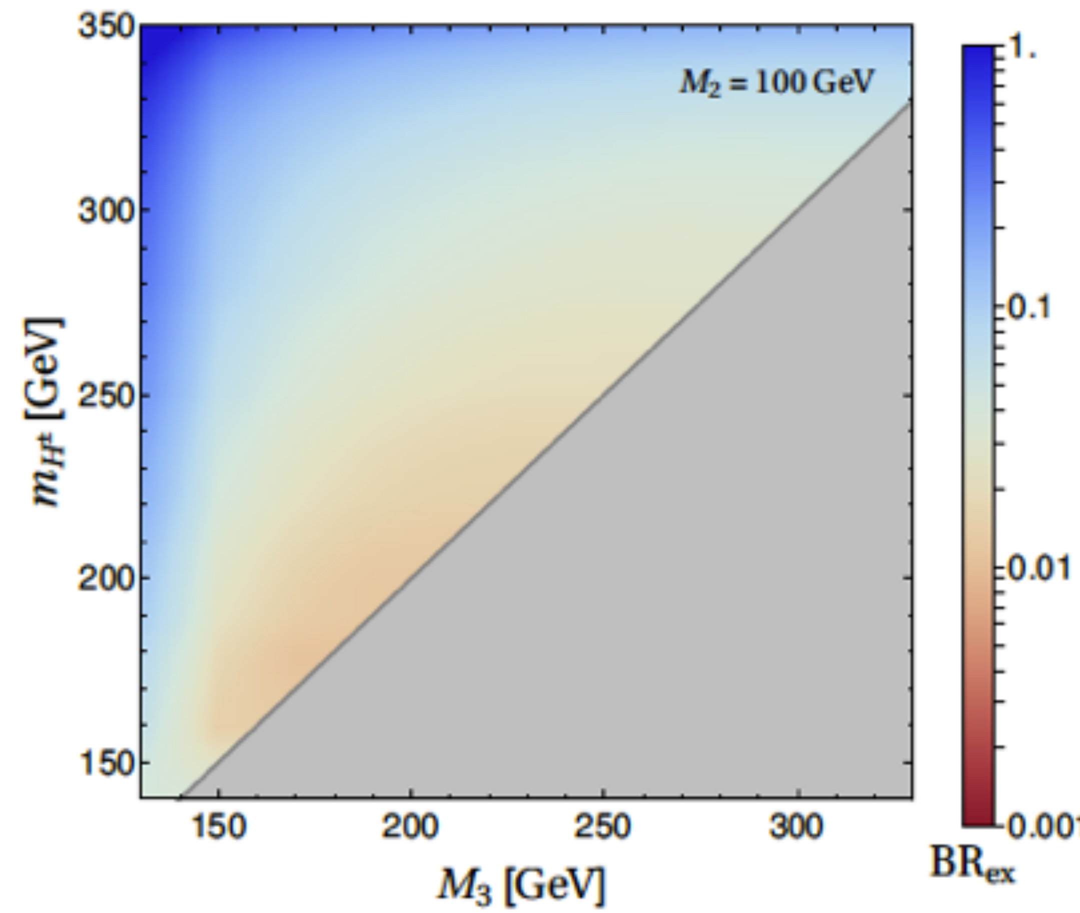
> Grey points are excluded by upper limit on $\mu \to e \gamma$

Fermion NLOP: displaced dileptons

mass spectrum: $M_1 < M_2 < M_3 < m_{H^\pm, H^0, A^0}$

95% CL excluded BR in displaced $\mu^+ \mu^-$





$$c\tau(N_3) = 10 \text{ cm}$$

Summary

★ Search program for long-lived particles at the LHC provides powerful tests of BSM physics

★ In the radiative neutrino mass model *only* one of the singlet fermions, N_1, can be out-of- equilibrium in the early Universe and can behave as a FIMP

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

★ The NLOP is the portal to the dark sector at the LHC

★ Different collider topologies are possible according to the mass spectrum:

- heavy meta-stable charged scalars
- displaced dileptons
- prompt decays to leptons + $\not{E}_T$

BACKUP SLIDES

SuperWIMP mechanism

Feng, Rajaraman, Takayama 2003

N_2 is the NLOP

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

SuperWIMP mechanism

Feng, Rajaraman, Takayama 2003

N_2 is the NLOP

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

N_2 decays after the *freeze-out* time

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

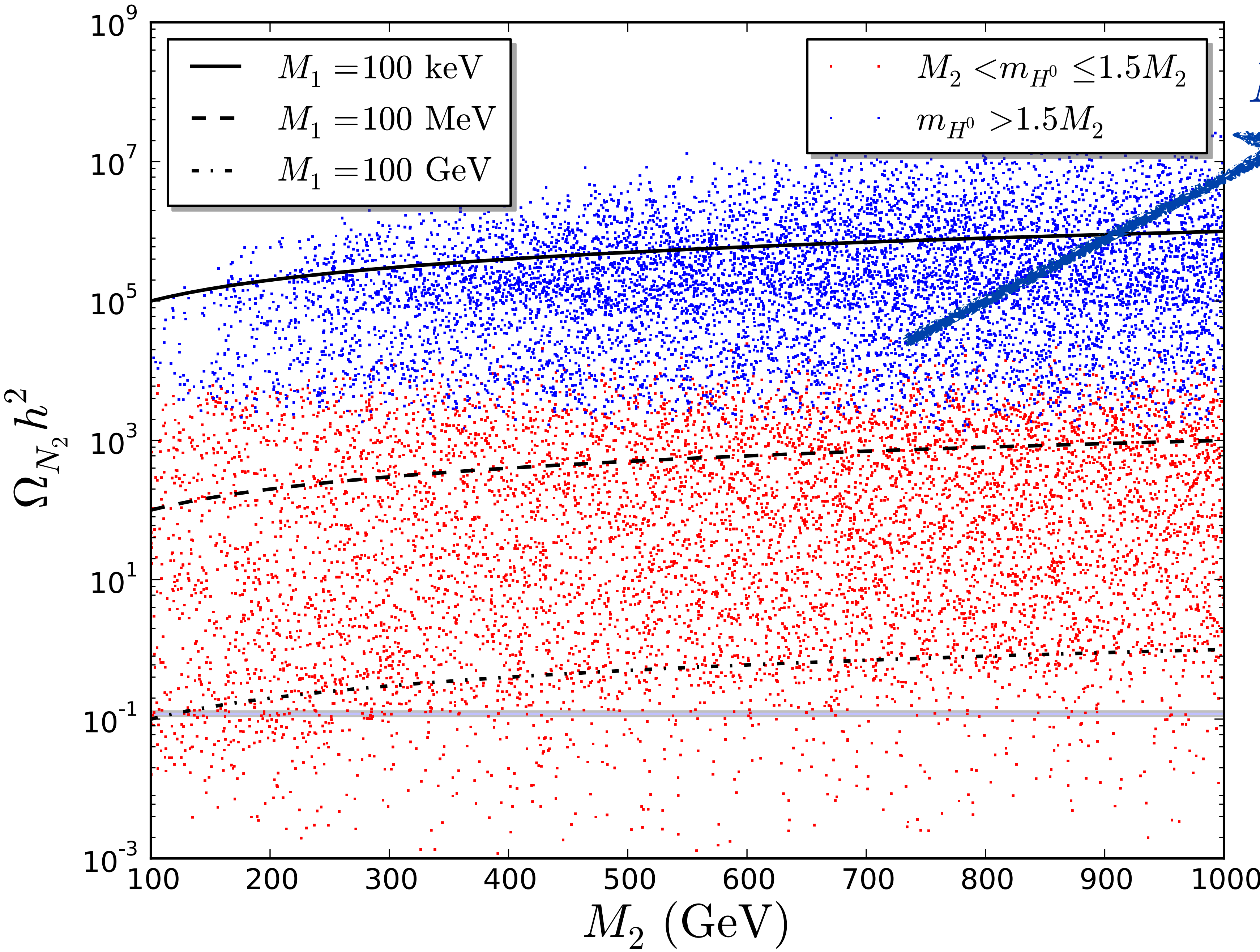
$$y_1\, y_2 \;\lesssim\; 2 \times 10^{-6} \left(\frac{m_S}{1\,\mathrm{TeV}}\right) \left(\frac{1\,\mathrm{TeV}}{M_2}\right)^{3/2}$$

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

<u>NLOP is one of the odd scalars</u>

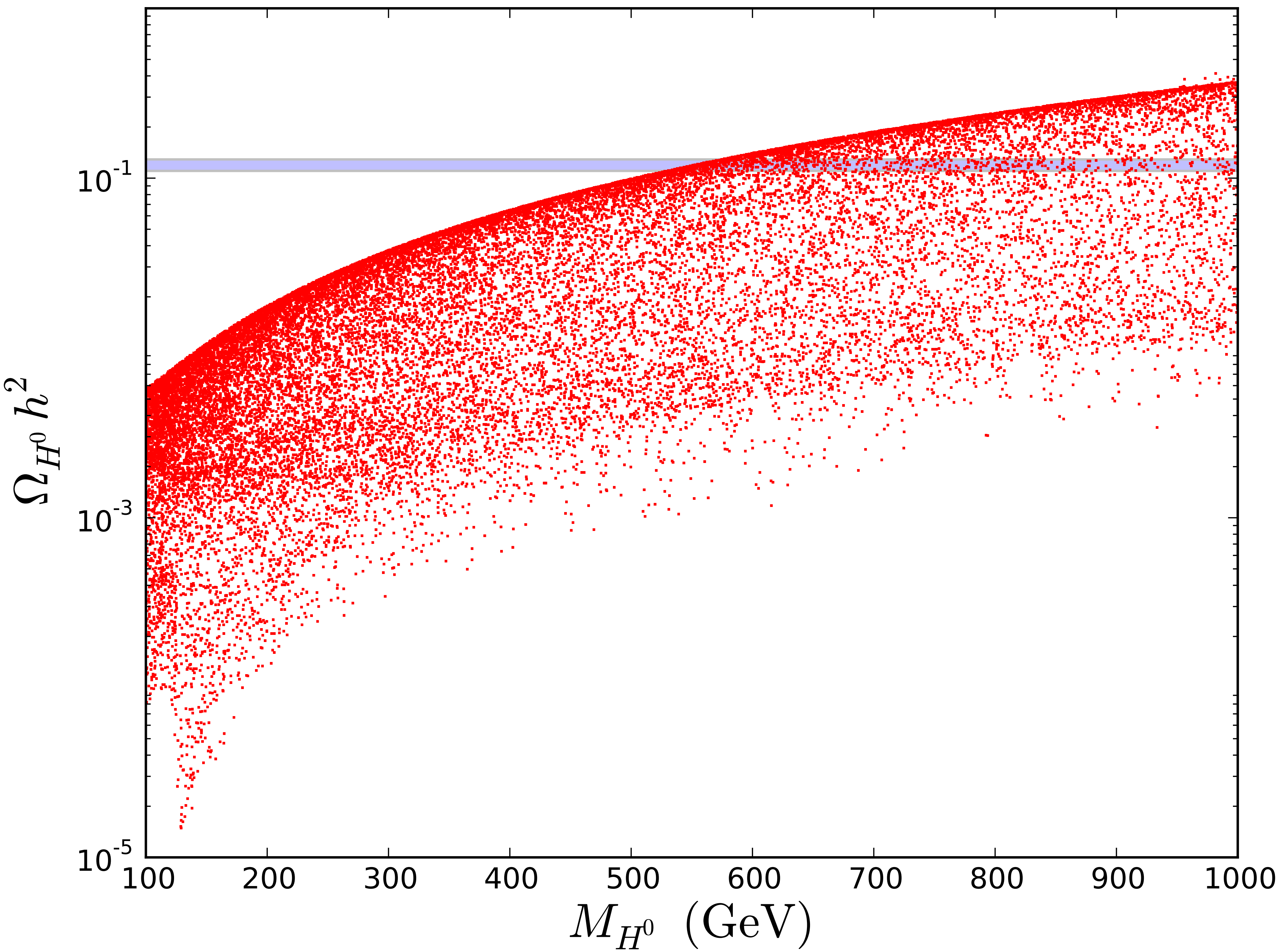
$$\boxed{\Omega_{N_1}^{superWIMP}\, h^2 \;=\; \frac{M_1}{m_S}\,\Omega_{NLOP}^{freeze-out}\, h^2}$$

Decays after the *freeze-out* but before BBN

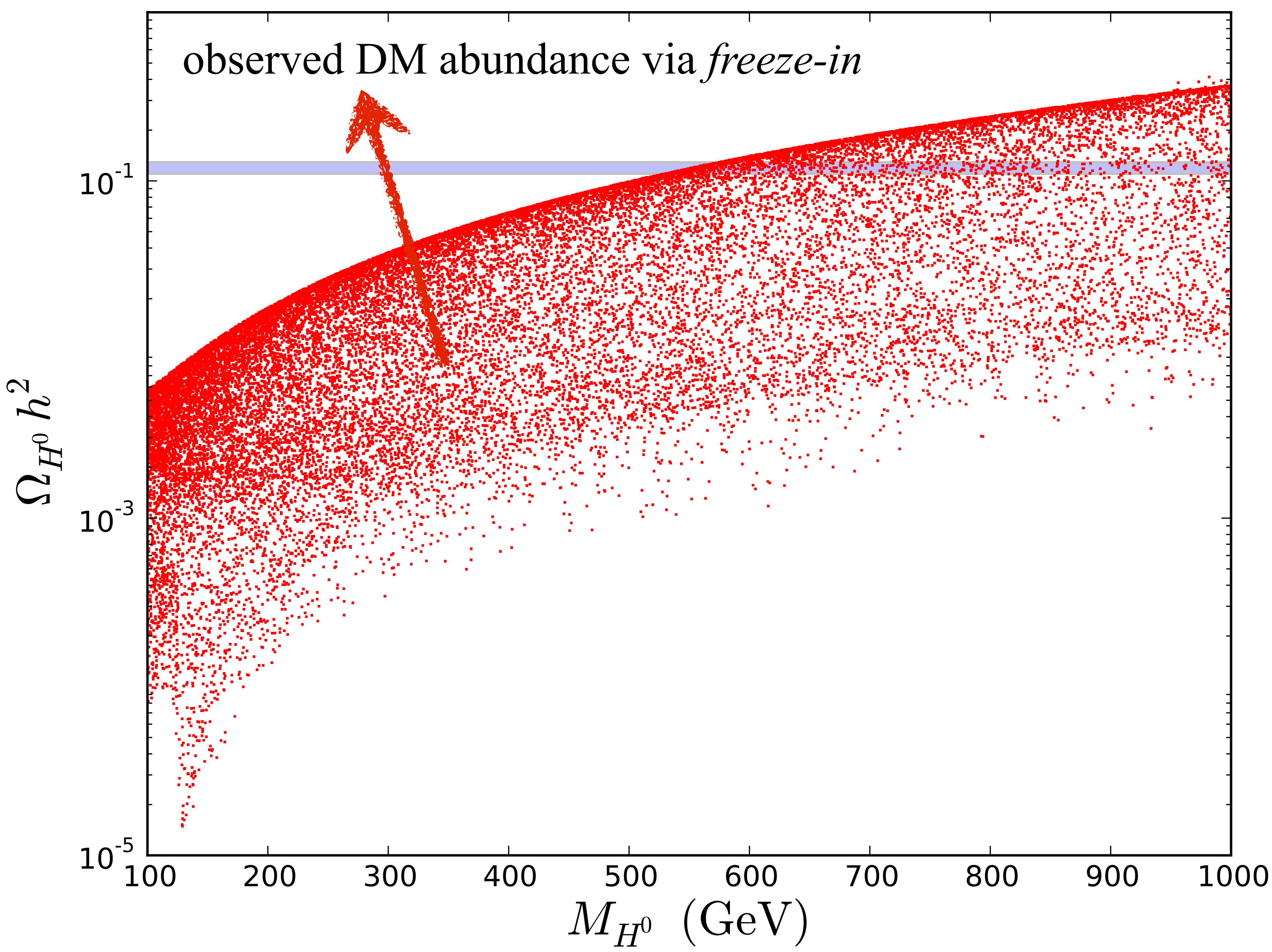
$$10^{-13}\left(\frac{1\,\mathrm{TeV}}{m_S}\right)^{1/2} \lesssim\; y_1 \;\lesssim\; 10^{-8}\left(\frac{m_S}{1\,\mathrm{TeV}}\right)^{1/2}$$

These bounds are always easily satisfied

SuperWIMP mechanism



SuperWIMP mechanism



SuperWIMP mechanism