FLASY 2022 | 9th Workshop on Flavour Symmetries and Consequences in Accelerators and Cosmology

June 27 - July 1, 2022
IST Congress Centre, Instituto Superior Técnico
Lisbon, Portugal

Organised by Centro de Física Teórica de Partículas (CFTP)

Sterile Neutrino Portals to Majorana Dark Matter

Arsenii Titov

Departament de Física Teòrica, Universitat de València
IFIC, Universitat de València & CSIC

Based on **arXiv:2203.01946** with
L. Coito, C. Faubel, J. Herrero-García, A. Santamaria

VNIVERSITAT DE VALÈNCIA

IFIC INSTITUT DE FÍSICA CORPUSCULAR

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Outline

- Motivation for the sterile neutrino portal to dark matter (DM)
- The effective field theory (EFT) approach to DM—sterile neutrino interactions: portal operators
- UV completions of the portal operators: genuine and non-genuine models
- Phenomenology
- Conclusions

Motivation for the sterile neutrino portal

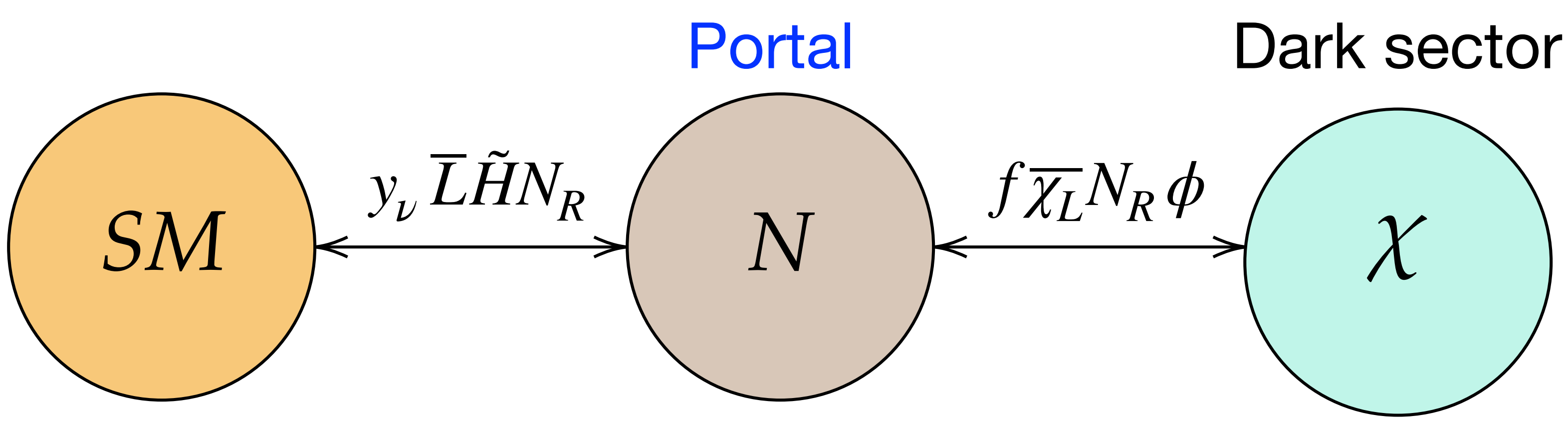
Most compelling pieces of evidence for physics beyond the SM:

- neutrino masses
- dark matter (DM)

These hint to the existence of SM gauge singlets:

- sterile neutrino(s) N
- DM particle χ

Sterile neutrino portal:



Pospelov, Ritz, Voloshin, 0711.4866; Escudero, Rius, Sanz, 1607.02373;
Batell et al., 1704.08708, 1709.07001; Bandyopadhyay et al., 1807.05122;
Blennow et al., 1903.00006; etc.

Effective field theory approach

The SM + 2 chiral fermions N_R and $\chi_L \sim (\mathbf{1},\mathbf{1})_0$ under $(SU(3)_C, SU(2)_L)_Y$
In addition, $\chi_L \to -\chi_L$ under a stabilising Z_2 symmetry

$$\mathscr{L}_4 = \mathscr{L}_{\rm SM} + \overline{N_R} i\gamma^\mu \partial_\mu N_R + \overline{\chi_L} i\gamma^\mu \partial_\mu \chi_L - \left[\frac{1}{2} m_N \overline{N_R^c} N_R + \frac{1}{2} m_\chi \overline{\chi_L} \chi_L^c + y_\nu \overline{L} \tilde{H} N_R + \text{H.c.}\right]$$

Assume that χ interacts with N via 4-fermion operators:

$$\mathscr{L}_6 = \frac{c_1}{\Lambda^2}\mathscr{O}_1 + \left[\frac{c_2}{\Lambda^2}\mathscr{O}_2 + \frac{c_3}{\Lambda^2}\mathscr{O}_3 + \text{H.c.}\right]$$

$$\mathscr{O}_1 = (\overline{N_R}\chi_L)(\overline{\chi_L}N_R) = -\frac{1}{2}(\overline{N_R}\gamma_\mu N_R)(\overline{\chi_L}\gamma^\mu \chi_L)$$

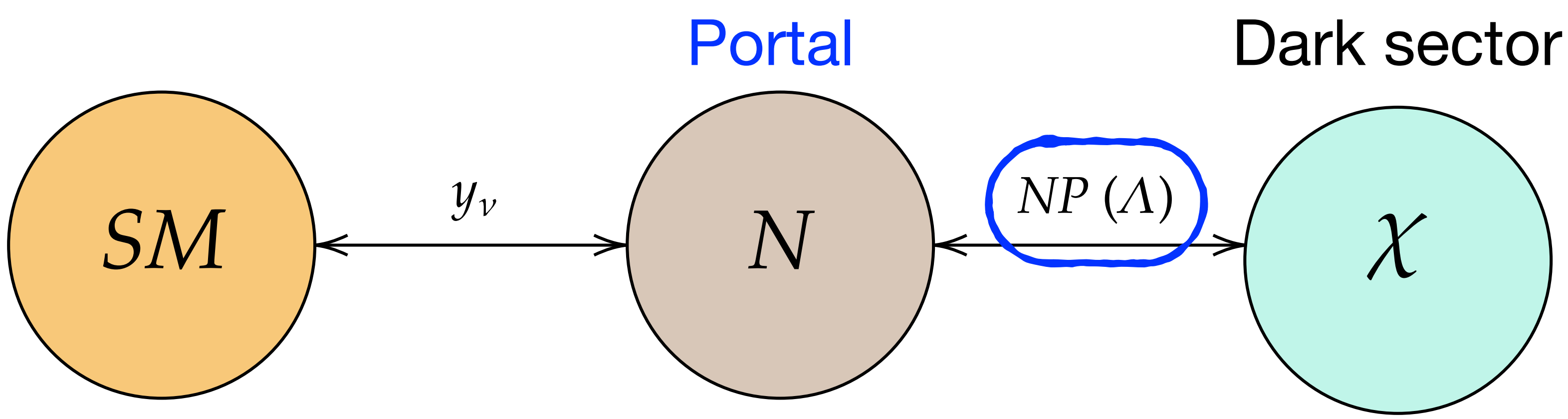
$$\mathscr{O}_2 = (\overline{N_R}\chi_L)(\overline{N_R}\chi_L) = -\frac{1}{2}(\overline{N_R}N_R^c)(\overline{\chi_L^c}\chi_L)$$

$$\mathscr{O}_3 = (\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L) = -\frac{1}{2}(\overline{N_R^c}\gamma_\mu \chi_L)(\overline{\chi_L^c}\gamma^\mu N_R)$$

3 operators

These operators form part of the basis of $D = 6$ operators derived in Duch, Grzadkowski, Wudka, 1412.0520

Effective field theory approach



Sterile neutrino portal operators:

If $L(N_R) = +1$ and $L(\chi_L) = 0$

$$\mathcal{O}_1 = (\overline{N_R}\chi_L)(\overline{\chi_L}N_R) = -\frac{1}{2}(\overline{N_R}\gamma_\mu N_R)(\overline{\chi_L}\gamma^\mu \chi_L)$$ LNC (always)

$$\mathcal{O}_2 = (\overline{N_R}\chi_L)(\overline{N_R}\chi_L) = -\frac{1}{2}(\overline{N_R}N_R^c)(\overline{\chi_L^c}\chi_L)$$ LNV $(\Delta L = -2)$

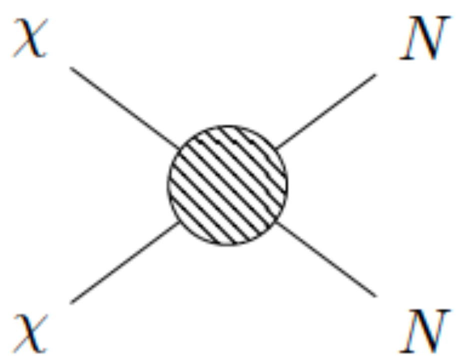
$$\mathcal{O}_3 = (\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L) = -\frac{1}{2}(\overline{N_R^c}\gamma_\mu \chi_L)(\overline{\chi_L^c}\gamma^\mu N_R)$$ LNV $(\Delta L = +2)$

We assume: $m_N < m_\chi < \Lambda < \mathcal{O}(100)$ TeV

$$m_\nu = \frac{y_\nu^2 \mathrm{v}^2}{2m_N} \approx 0.05 \text{ eV} \;\Rightarrow\; y_\nu \lesssim 10^{-6} \text{ for } m_N \lesssim 1 \text{ TeV}$$

DM annihilations into sterile neutrinos

The DM relic abundance is set by the freeze-out of annihilations $\chi\chi \to NN$



$$\sigma \mathrm{v} = a + b\frac{\mathrm{v}^2}{4} + \mathcal{O}\left(\mathrm{v}^4\right)$$

For the freeze-in production of DM in the renormalisable neutrino portal see talks by C. Cosme and B. Fu

$$a = \frac{m_\chi^2}{16\pi\Lambda^4}\sqrt{1-r_N^2}\left[\left(c_1 r_N + 2\mathrm{Re}c_2 + 4\mathrm{Re}c_3\right)^2 + 4\left(\mathrm{Im}c_2 - 2\mathrm{Im}c_3\right)^2\left(1-r_N^2\right)\right], \quad r_N \equiv \frac{m_N}{m_\chi}$$

$a = 0$ if $c_2 = -2c_3^*$ and either $c_1 = 0$ or $m_N = 0$

(the contribution of $\mathcal{O}_1$ to s-wave is chirality suppressed)

In the limit $m_N \to 0$:

$$a = \frac{m_\chi^2}{4\pi\Lambda^4}\left[|c_2|^2 + 4|c_3|^2 + 4\,\mathrm{Re}\left(c_2 c_3\right)\right]$$

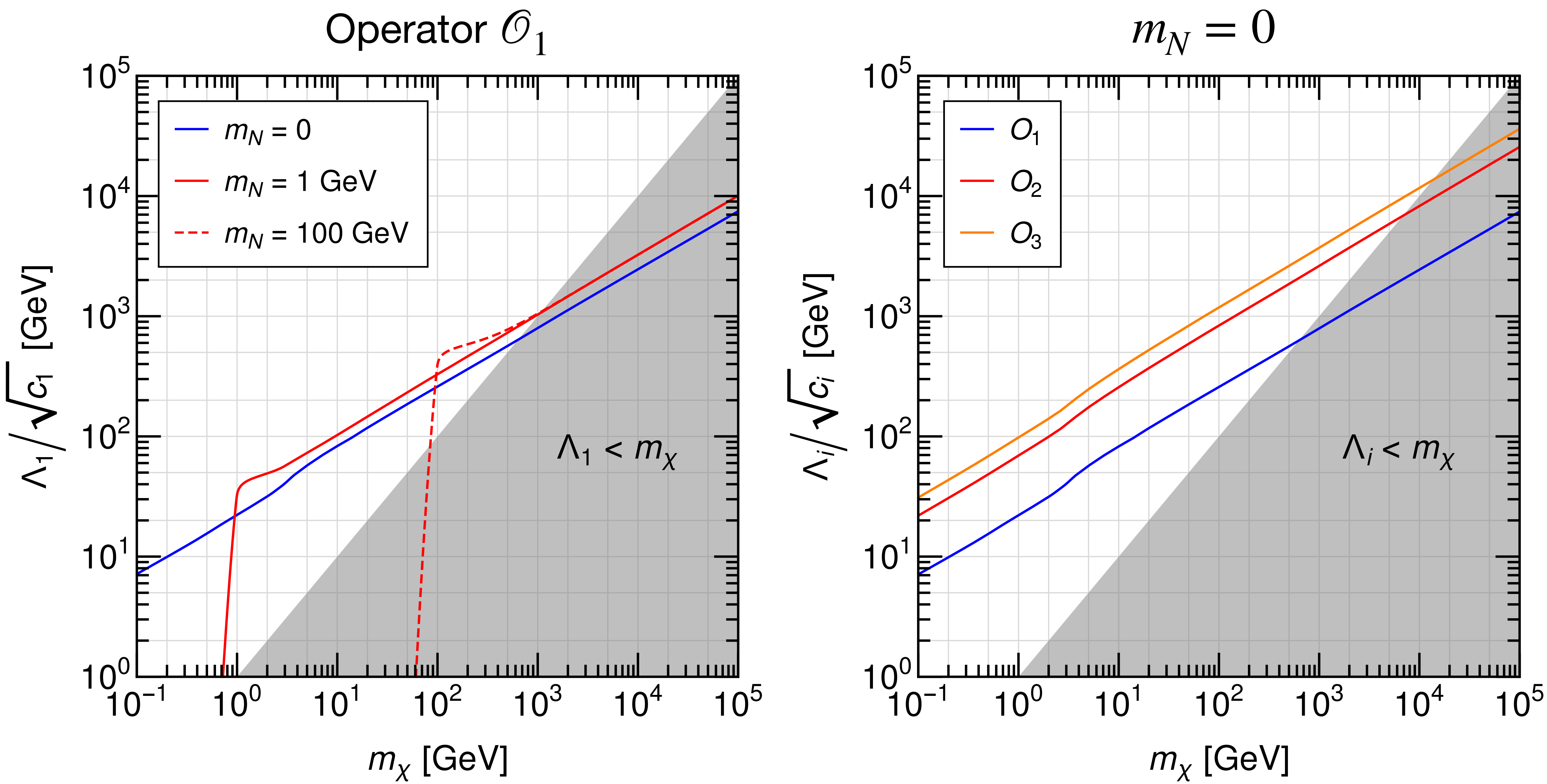
$$b = \frac{m_\chi^2}{12\pi\Lambda^4}\left[c_1^2 + 3|c_2|^2 + 12|c_3|^2 - 12\,\mathrm{Re}\left(c_2 c_3\right)\right]$$

DM relic abundance

$$\langle \sigma \mathrm{v} \rangle = a + \frac{3}{2} b\, x^{-1} + \mathcal{O}\left(x^{-2}\right) \qquad x = m_\chi / T$$

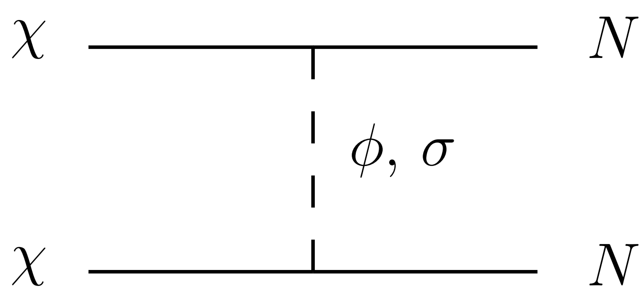
$$\langle \sigma \mathrm{v} \rangle \approx 2.2\ (4.4) \times 10^{-26}\ \text{cm}^3/\text{s} \quad \text{if} \quad a \neq 0\ (a = 0)$$

More precise values of $\langle \sigma \mathrm{v} \rangle$:
Steigman, Dasgupta, Beacom, 1204.3622
Bringmann et al., 2007.03696

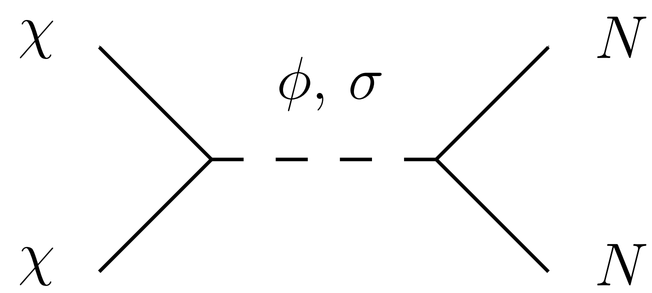


UV completions of the portal operators

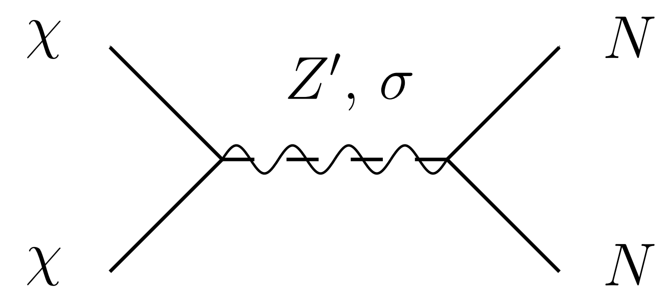
Models A



Models B



Models C



Model	Dark sector particles	Z_2	$U(1)_{B-L}$
A1	Majorana fermion χ	1	0
	real scalar ϕ	1	0
A2	Majorana fermion χ	1	0
	complex scalar σ	1	-1

Model	Dark sector particles	Z_2	$U(1)_{B-L}$
B1	Majorana fermion χ	1	0
	real scalar ϕ	0	0
B2	chiral fermion χ_L	1	$+1$
	complex scalar σ	0	$+2$

Model	Dark sector particles	Z_2	$U(1)_{B-L}$
C1	Majorana fermion χ	1	0
	massive vector boson Z'	0	0
C2	chiral fermion χ_L	1	$+1$
	complex scalar σ	0	$+2$
	gauge boson Z'	0	0

Relevant couplings

A1 : $f \overline{N_R} \chi_L \phi$

A2 : $f \overline{N_R} \chi_L \sigma$

B1 : $f \overline{N_R^c} N_R \phi + g \overline{\chi_L^c} \chi_L \phi$

B2 : $f \overline{N_R^c} N_R \sigma + g \overline{\chi_L} \chi_L^c \sigma$

$m_N\,, m_\chi \sim \mathrm{v}_\sigma$

C1 : $g_N \overline{N_R} \gamma^\mu N_R Z'_\mu + g_\chi \overline{\chi_L} \gamma^\mu \chi_L Z'_\mu$

C2 : gauged B2

$D_\mu = D_\mu^{\mathrm{SM}} - i g' Q_{B-L} Z'_\mu$

Matching of UV models onto the EFT

		Portals			Self-ints		Ints w/ SM		
		$(\overline{N_R}\chi_L)(\overline{\chi_L}N_R)$	$(\overline{N_R}\chi_L)(\overline{N_R}\chi_L)$	$(\overline{N_R^c}N_R)(\overline{\chi_L^c}\chi_L)$	$(\overline{N_R^c}N_R)(\overline{N_R}N_R^c)$	$(\overline{\chi_L^c}\chi_L)(\overline{\chi_L}\chi_L^c)$	$(\overline{N_R^c}N_R)(H^\dagger H)$	$(\overline{\chi_L^c}\chi_L)(H^\dagger H)$	
	Model	c_1/Λ^2	c_2/Λ^2	c_3/Λ^2	c_4/Λ^2	c_5/Λ^2	c_{NH}/Λ	$c_{\chi H}/\Lambda$	
Genuine models	A1	$\frac{\lvert f\rvert^2}{m_\phi^2}$	$\frac{f^2}{2m_\phi^2}$	✗	✗	✗	✗	✗	
	A2a	$\frac{f^2}{m_g^2}$	✗	✗	✗	✗	✗	✗	$m_N = 0$
	A2b	$\frac{f^2}{m_g^2}$	✗	✗	✗	✗	✗	✗	$m_N \neq 0$
	A2c	$\frac{f^2}{m_\sigma^2}$	$-\frac{f^2\mu_\sigma^2}{2m_\sigma^4}$	✗	✗	✗	✗	✗	m_N @ 1 loop
Non-genuine models	B1	✗	$-\frac{2f^*g}{m_\phi^2}$	$\frac{fg}{m_\phi^2}$	$\frac{\lvert f\rvert^2}{m_\phi^2}$	$\frac{\lvert g\rvert^2}{m_\phi^2}$	$\frac{f\mu_{\phi H}}{m_\phi^2}$	$\frac{g\mu_{\phi H}}{m_\phi^2}$	
	B2	✗	$-\frac{fg}{m_s^2}$	$\frac{fg}{2m_s^2}$	$\frac{f^2}{2m_s^2}$	$\frac{g^2}{2m_s^2}$	$\frac{f\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	$\frac{g\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	global $B-L$
	C1	$\frac{2g_Ng_\chi}{m_{Z'}^2}$	✗	✗	$-\frac{g_N^2}{m_{Z'}^2}$	$-\frac{g_\chi^2}{m_{Z'}^2}$	✗	✗	
	C2	$\frac{2g'^2Q_NQ_\chi}{m_{Z'}^2}$	$-\frac{fg}{m_s^2}$	$\frac{fg}{2m_s^2}$	$\frac{f^2}{2m_s^2}-\frac{g'^2Q_N^2}{m_{Z'}^2}$	$\frac{g^2}{2m_s^2}-\frac{g'^2Q_\chi^2}{m_{Z'}^2}$	$\frac{f\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	$\frac{g\lambda_{\sigma H}v_\sigma}{\sqrt{2}m_s^2}$	gauged $B-L$

Models' features

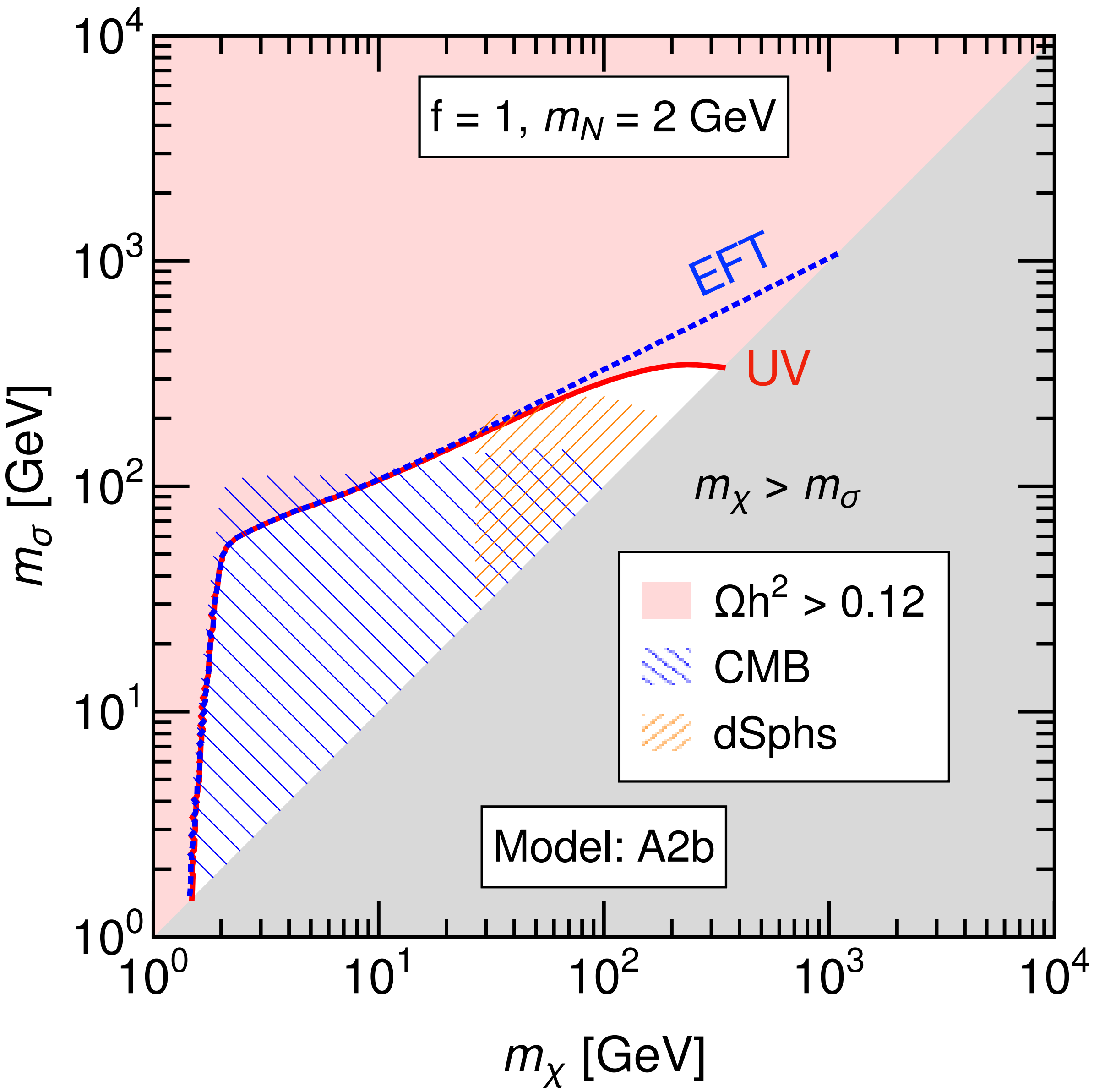
Feature \ Model	A1	A2a ($m_N = 0$)	A2b ($m_N \neq 0$)	A2c (m_N @ 1 loop)	B1	B2	C1	C2
	Genuine models				Non-genuine models			
s-wave $\langle \sigma v \rangle_{\chi\chi \to NN}$	✓	✗	✓	✓	*	✗	✓	✓
DD @ tree level	✗	✗	✗	✗	✓	✓	✗	✓
Self-interactions	✗	✗	✗	✗	✓	✓	✓	✓

* p-wave if $g \in \mathbb{R}$

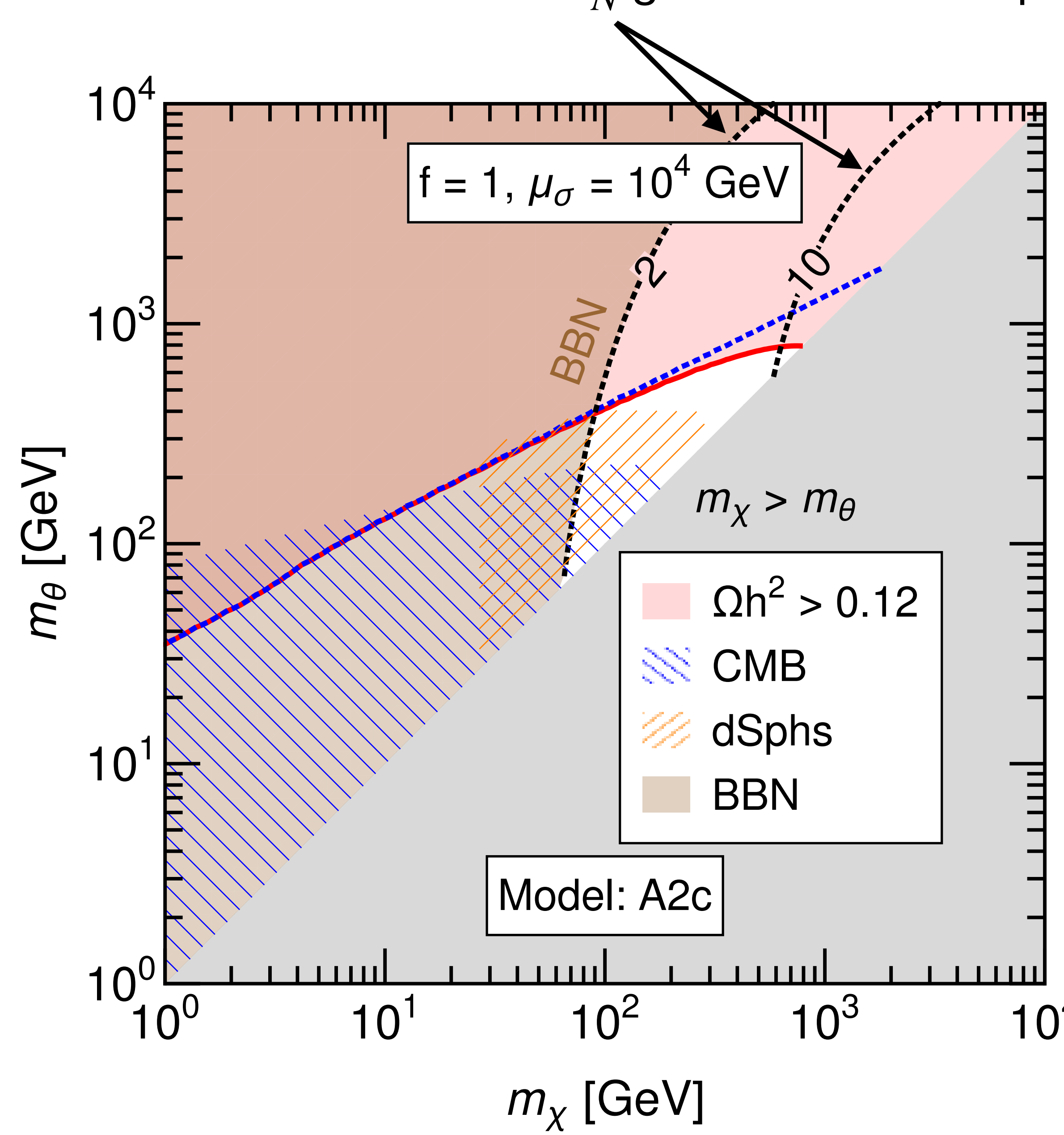
- Model A1 (w/ real scalar ϕ) Escudero, Rius, Sanz, 1607.02373
  Batell, Han, Shams Es Haghi, 1704.08708
  Bandyopadhyay et al., 1807.05122
- Model B2 (global $B - L$) Escudero, Rius, Sanz, 1606.01258
- Model C2 (gauged $B - L$) Escudero, Witte, Rius, 1806.02823

Models A2

$\langle \sigma v \rangle_{\chi\chi \to NN}$ is s-wave



Contours of constant m_N generated @ 1 loop

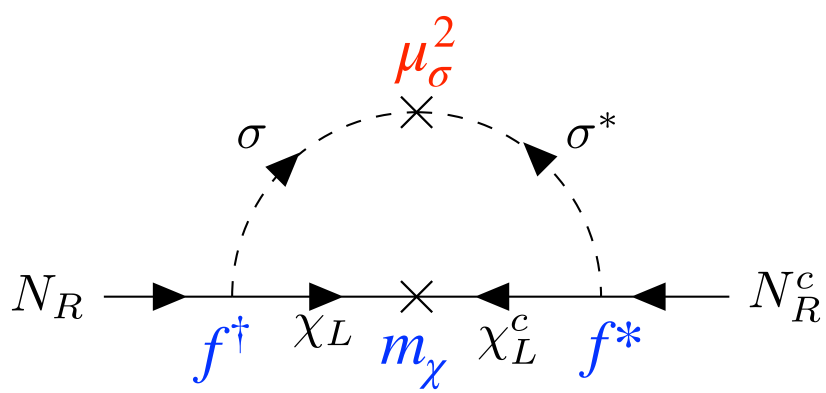


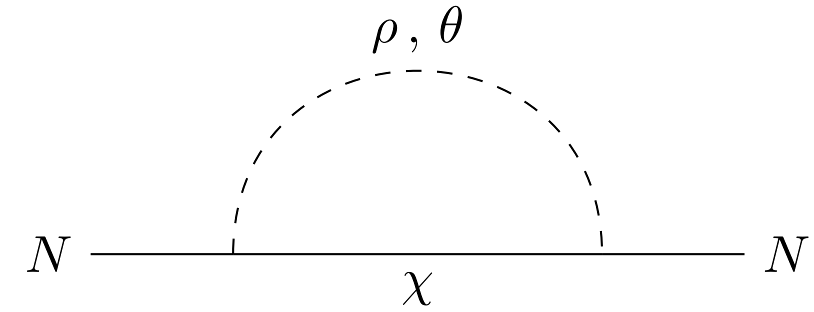
Indirect detection constraints from Batell, Han, Shams Es Haghi, 1704.08708

Generation of m_N in Model A2c

$$-\mathscr{L}_{\text{A2c}} \supset \frac{1}{2} m_\chi \overline{\chi_L} \chi_L^c + \frac{1}{2}\mu_\sigma^2\,\sigma^2 + f\,\overline{N_R}\chi_L\sigma + \text{H.c.} \qquad L(\sigma) = +1$$

soft breaking of L





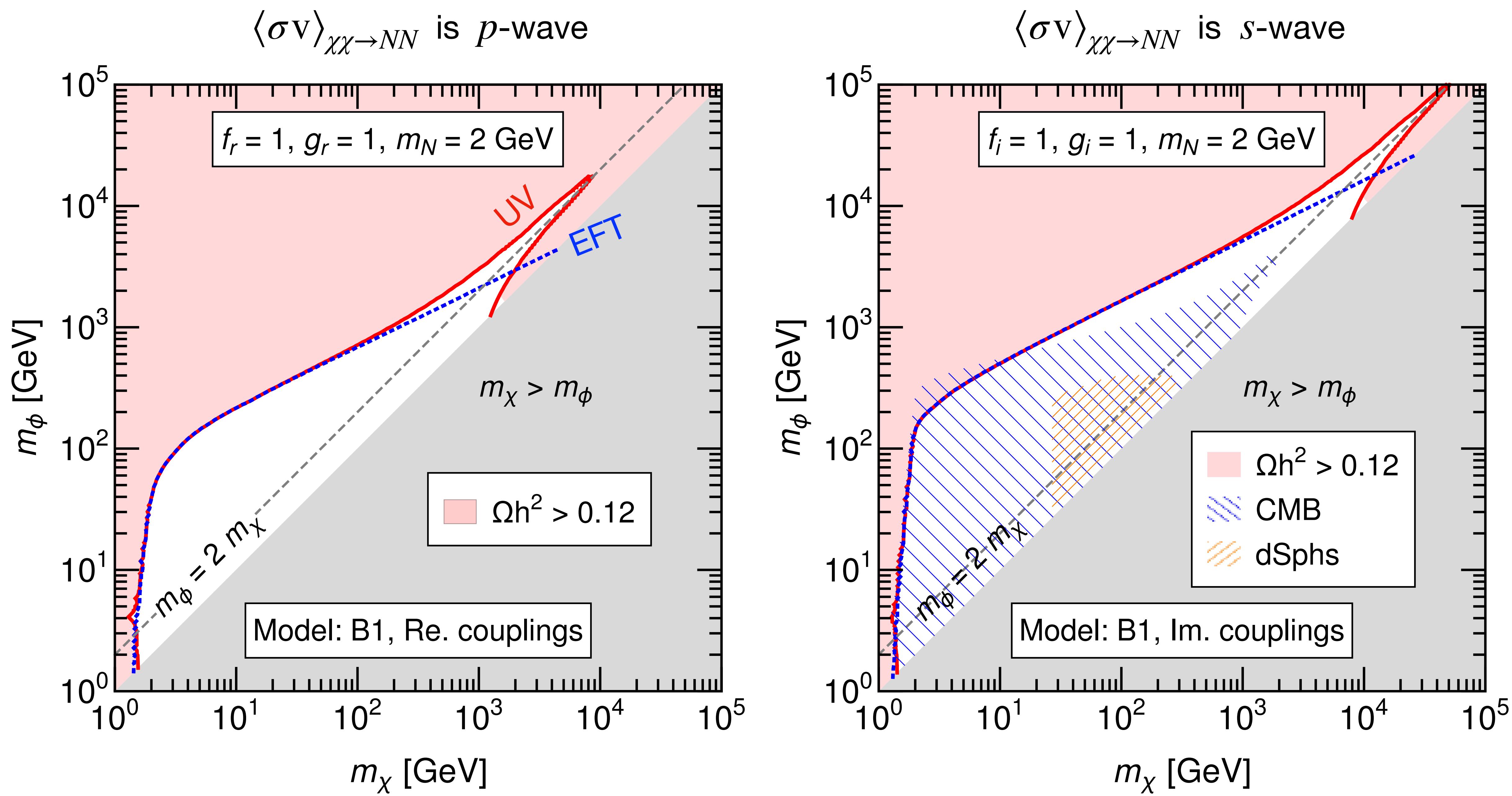
Scotogenic-like mass:

$$\left(m_N\right)_{ij} = \sum_{k=1}^{n_\chi} \frac{f_{ik}^* f_{jk}^* m_{\chi_k}}{32\pi^2} F\left(m_\rho^2, m_\theta^2, m_{\chi_k}^2\right) \approx \frac{\mu_\sigma^2}{16\pi^2 m_\sigma^2} \sum_{k=1}^{n_\chi} f_{ik}^* f_{jk}^* m_{\chi_k}$$

for $m_{\chi_k} \ll m_\rho, m_\theta$ and $m_\rho \simeq m_\theta \simeq m_\sigma$

$$F(x,y,z) = \frac{x}{x-z}\log\left(\frac{x}{z}\right) - \frac{y}{y-z}\log\left(\frac{y}{z}\right)$$

Model B1



Indirect detection constraints from Batell, Han, Shams Es Haghi, 1704.08708

Conclusions

- The sterile neutrino portal to dark matter constitutes a viable option
- If dark sector particles are heavier than N and χ, DM—sterile neutrino interactions can be parameterised by 4-fermion operators:
  3 portal operators "$NN\chi\chi$" (for 1 generation of N and χ)
- Genuine models (generating at $D \leq 6$ only portal operators) involve t-channel scalars charged under a stabilising Z_2 symmetry; non-genuine models contain s-channel scalars/vector bosons neutral under Z_2
- Indirect detection experiments constrain the parameter space of the models, except for the cases when $\langle \sigma \mathrm{v} \rangle_{\chi\chi \to NN}$ is p-wave
- In Model A2c, characterised by soft breaking of L in the scalar potential, finite m_N is generated at 1 loop

Back-up

Models A

Model A1: real scalar ϕ charged under Z_2

$$\mathscr{L}_{\rm A1} = \mathscr{L}_4 + \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - V(\phi, H) - \left[f \overline{N_R} \chi_L \phi + \text{H.c.}\right]$$

$$V(\phi, H) = \frac{1}{2} m_\phi^2 \phi^2 + \lambda_{\phi H} \phi^2 |H|^2 + \lambda_\phi \phi^4$$

Model A2: complex scalar $\sigma = \left(\rho + i\theta\right)/\sqrt{2}$ charged under Z_2 and $U(1)_L$

$$L(N_R) = L(\sigma) = +1$$

$$\mathscr{L}_{\rm A2} = \mathscr{L}_4 + (\partial_\mu \sigma)^* (\partial^\mu \sigma) - V(\sigma, H) - \left[f \overline{N_R} \chi_L \sigma + \text{H.c.}\right]$$

$$V(\sigma, H) = m_\sigma^2 |\sigma|^2 + \lambda_{\sigma H} |\sigma|^2 |H|^2 + \lambda_\sigma |\sigma|^4$$

- A2a: $m_N = 0$ in $\mathscr{L}_4 \Rightarrow U(1)_L$ is unbroken
- A2b: $m_N \neq 0$ in $\mathscr{L}_4$
- A2c: $m_N = 0$ in $\mathscr{L}_4$ and $V(\sigma, H) \to V(\sigma, H) - \left[\frac{1}{2}\mu_\sigma^2 \sigma^2 + \text{H.c.}\right] \Rightarrow U(1)_L$ is softly broken

Models B

Model B1: real scalar ϕ neutral under Z_2

$$\mathscr{L}_{\rm B1} = \mathscr{L}_4 + \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - V(\phi, H) - \left[f \overline{N_R^c} N_R \phi + g \overline{\chi_L^c} \chi_L \phi + \text{H.c.}\right]$$

$$V(\phi, H) = \frac{1}{2} m_\phi^2 \phi^2 + \mu_\phi \phi^3 + \lambda_\phi \phi^4 + \mu_{\phi H} \phi |H|^2 + \lambda_{\phi H} \phi^2 |H|^2$$

Model B2: complex scalar σ neutral under Z_2, but charged under global $U(1)_{B-L}$

$$L(N_R) = L(\chi_L^c) = 1 \quad \text{and} \quad L(\sigma) = -2$$

$$\mathscr{L}_{\rm B2} = \mathscr{L}_4|_{m_N = m_\chi = 0} + (\partial_\mu \sigma)^* (\partial^\mu \sigma) - V(\sigma, H) - \left[f \overline{N_R^c} N_R \sigma + g \overline{\chi_L} \chi_L^c \sigma + \text{H.c.}\right]$$

$$V(\sigma, H) = m_\sigma^2 |\sigma|^2 + \lambda_{\sigma H} |\sigma|^2 |H|^2 + \lambda_\sigma |\sigma|^4$$

Model B2 has been studied in detail in Escudero, Rius, Sanz, 1606.01258

Models C

Model C1: massive vector boson Z'_μ neutral under Z_2 (effective model)

$$\mathscr{L}_{\rm C1} = \mathscr{L}_4 - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{1}{2} m_{Z'}^2 Z'_\mu Z'^\mu + g_N \overline{N_R} \gamma^\mu N_R Z'_\mu + g_\chi \overline{\chi_L} \gamma^\mu \chi_L Z'_\mu$$

In general, kinetic mixing $\epsilon Z'_{\mu\nu} Z^{\mu\nu}$ and mass mixing $\delta m^2 Z'_\mu Z^\mu$ are also allowed

Model C2: gauged $U(1)_{B-L}$ (anomaly free with 2 N_R and 1 χ_L)

	Q	u_R	d_R	L	e_R	$N_R^{1,2}$	χ_L	σ
$U(1)_{B-L}$	$+1/3$	$+1/3$	$+1/3$	-1	-1	-1	$+1$	$+2$

$$\mathscr{L}_{\rm C2} = \mathscr{L}_{\rm B2} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu}$$

$$D_\mu = D_\mu^{\rm SM} - i g' Q_{B-L} Z'_\mu$$

Model C2 has been studied in detail in Escudero, Witte, Rius, 1806.02823

More on Model B2

We can parameterise the complex scalar as

$$\sigma = \frac{1}{\sqrt{2}} \left(v_\sigma + s\right) e^{iJ/v_\sigma} \,. \tag{38}$$

Then J corresponds to the (massless) Goldstone boson, the Majoron, and s is the radial excitation. In this parameterisation, J is not present in the potential and appears in the Lagrangian only through the kinetic term

$$\left(\partial_\mu \sigma\right)^* \left(\partial^\mu \sigma\right) = \frac{1}{2} \left(\partial s\right)^2 + \frac{1}{2} \left(\partial J\right)^2 + \frac{1}{v_\sigma} s \left(\partial J\right)^2 + \frac{1}{2 v_\sigma^2} s^2 \left(\partial J\right)^2 \,, \tag{39}$$

and the Yukawa interactions in Eq. (37). Further, we can rotate the fields carrying non-zero lepton number, namely, $\Psi = N_R,\, \chi_L^c,\, L$ and e_R, as

$$\Psi \to e^{-iJ/(2 v_\sigma)} \Psi \,, \tag{40}$$

and remove J from all Yukawa interactions. After this transformation, the kinetic terms for the fermions Ψ will induce

$$\mathcal{O}_{\Psi J} = (\overline{\Psi} \gamma^\mu \Psi)(\partial_\mu J) \qquad \text{with} \qquad \frac{c_{\Psi J}}{\Lambda} = \frac{1}{2 v_\sigma} \,. \tag{41}$$

In this way, the derivative nature of Goldstone boson's couplings is manifest. It is worth noting that, despite having $D = 5$, this operator is not related to integrating out a heavy mediator, but is a consequence of the non-linear field redefinition performed in Eq. (40).

More on Model B2

On top of the interactions given in Tab. 3, there is a $D = 6$ operator describing the Higgs–Majoron interaction (cf. Ref. [60]):

$$\mathcal{O}_{HJ} = |H|^2\,(\partial J)^2 \qquad \text{with} \qquad \frac{c_{HJ}}{\Lambda^2} = -\frac{\lambda_{\sigma H}}{m_s^2} = -\frac{\lambda_{\sigma H}}{2\lambda_\sigma v_\sigma^2}\,. \tag{42}$$

It is interesting to note that the $|H|^6$ operator is not generated at tree level due to a peculiar cancellation coming from the s^3 and $s^2|H|^2$ terms in the potential upon using the equation of motion for s and the relation between m_s and v_σ. (This had been previously noted in Ref. [61].) Finally, the parameters of the SM potential,

$$V_{\text{SM}} = m_H^2|H|^2 + \lambda_H|H|^4\,, \tag{43}$$

get shifted as

$$m_H^2 \to m_H^2 + \frac{1}{2}\lambda_{\sigma H} v_\sigma^2 \qquad \text{and} \qquad \lambda_H \to \lambda_H - \frac{\lambda_{\sigma H}^2}{4\lambda_\sigma}\,. \tag{44}$$

More on Model C2

Apart from the operators summarised in Tab. 3, we find the following four-fermion interactions:

$$\mathcal{O}_{\psi\psi} = (\overline{\psi}\gamma_\mu\psi)(\overline{\psi}\gamma^\mu\psi)\,, \tag{48}$$

$$\mathcal{O}_{N\psi} = (\overline{N_R}\gamma_\mu N_R)(\overline{\psi}\gamma^\mu\psi)\,, \tag{49}$$

$$\mathcal{O}_{\chi\psi} = (\overline{\chi_L}\gamma_\mu\chi_L)(\overline{\psi}\gamma^\mu\psi)\,, \tag{50}$$

where ψ stands for the SM fermions, *i.e.* $\psi = L,\ e_R,\ Q,\ u_R,\ d_R$. The corresponding Wilson coefficients read:

$$\frac{c_{\psi\psi}}{\Lambda^2} = -\frac{g'^2 Q_\psi^2}{2m_{Z'}^2}\,, \quad \frac{c_{N\psi}}{\Lambda^2} = -\frac{g'^2 Q_N Q_\psi}{m_{Z'}^2} \quad \text{and} \quad \frac{c_{\chi\psi}}{\Lambda^2} = -\frac{g'^2 Q_\chi Q_\psi}{m_{Z'}^2}\,. \tag{51}$$

Here Q_ψ, Q_N and Q_χ denote the $B-L$ charges of ψ, N_R and χ_L, respectively, see Tab. 4.

Annihilation cross sections

Model A2b (f real): $r_i \equiv m_i/m_\chi$

$$a = \frac{f^4}{16\pi m_\chi^2}\frac{r_N^2\sqrt{1-r_N^2}}{\left(1+r_\sigma^2-r_N^2\right)^2}$$

Model A2c (f real):

$$a = \frac{f^4}{64\pi m_\chi^2}\frac{\sqrt{1-r_N^2}\left(r_\rho^2-r_\theta^2-\left(2+r_\rho^2+r_\theta^2\right)r_N+2r_N^3\right)^2}{\left(1+r_\rho^2-r_N^2\right)^2\left(1+r_\theta^2-r_N^2\right)^2}$$

Model B1 (f and g complex):

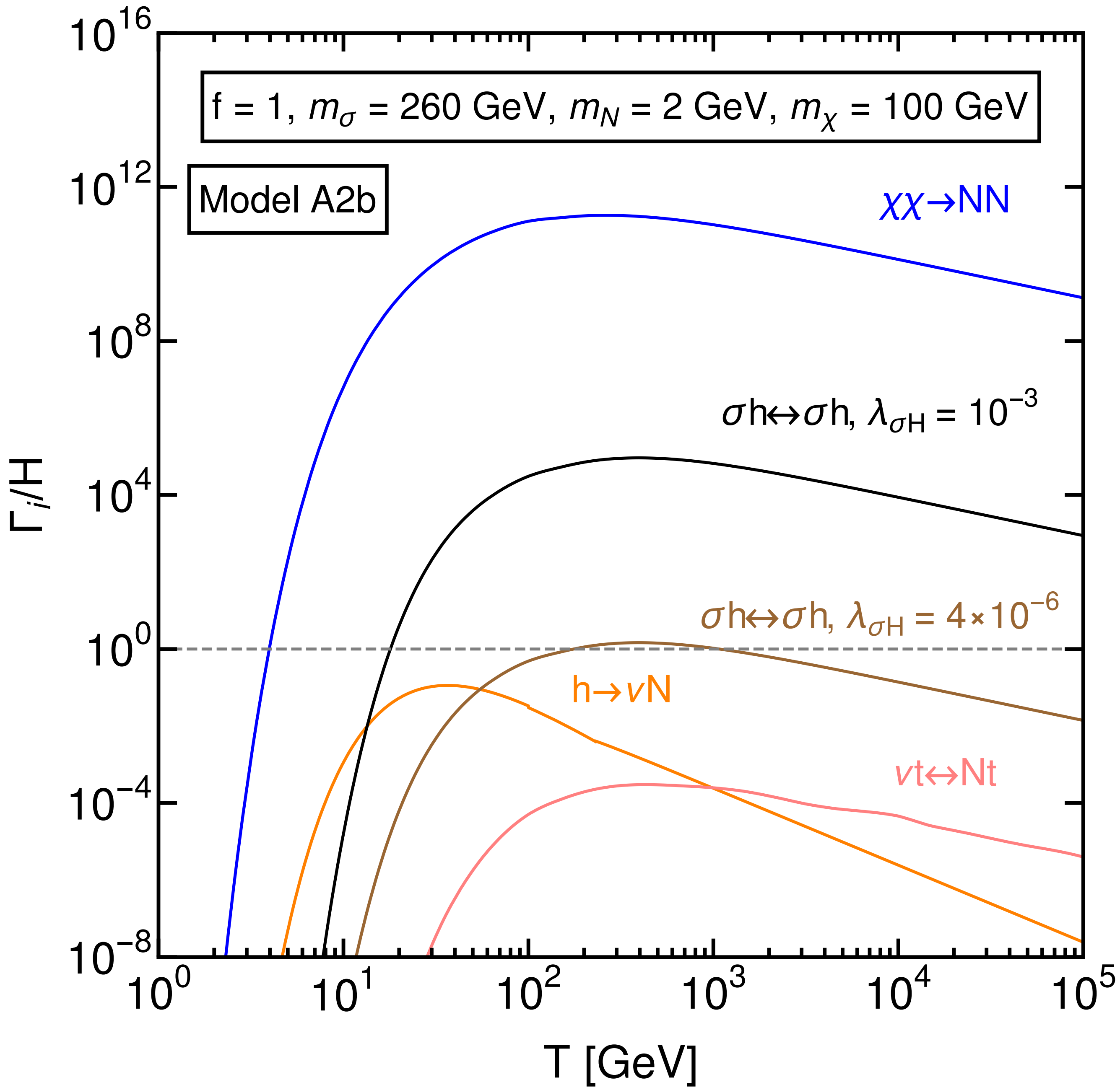
$$f = f_r + i f_i$$
$$g = g_r + i g_i$$

$$a = \frac{4g_i^2}{\pi m_\chi^2}\frac{\sqrt{1-r_N^2}}{\left(r_\phi^2-4\right)^2}\left[f_i^2+f_r^2\left(1-r_N^2\right)\right]$$

f and g real: $a=0$ $\quad b = \frac{4f_r^2 g_r^2}{\pi m_\chi^2}\frac{\left(1-r_N^2\right)^{3/2}}{\left(r_\phi^2-4\right)^2}$

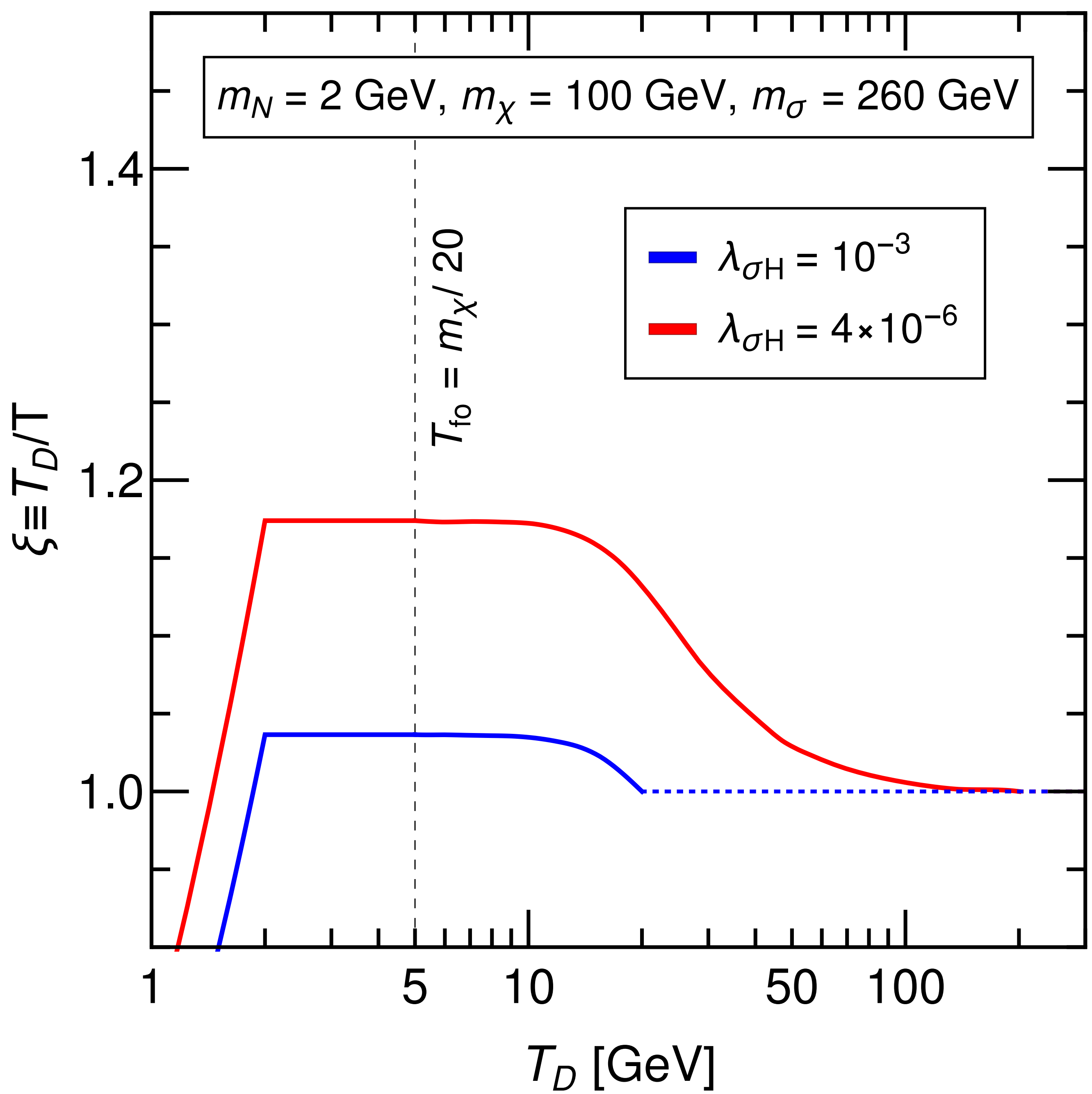
f and g complex: $a = \frac{4f_i^2 g_i^2}{\pi m_\chi^2}\frac{\sqrt{1-r_N^2}}{\left(r_\phi^2-4\right)^2}$

Thermal equilibrium



- Chemical freeze-out of $\chi\chi \to NN$
- $y_\nu \approx 5 \times 10^{-8}$ fixed by the seesaw relation assuming $m_\nu \approx 0.05$ eV
- Kinetic equilibrium with the SM is maintained (up to a certain T) by $\lambda_{\sigma H}|\sigma|^2|H|^2$ if $\lambda_{\sigma H} \gtrsim 10^{-6}$
- Kinetic equilibrium within the dark sector is ensured for $m_N \lesssim m_\chi/20$, when N is relativistic at DM freeze-out

Dark sector temperature



Assumption: entropy is conserved individually in the visible and dark sectors

Berlin, Hooper, Krnjaic, 1609.02555

$$\frac{s_D}{s_{\rm SM}} = \left.\frac{s_D}{s_{\rm SM}}\right|_{T=T_{\rm kd}}$$

$$s_{\rm SM} = \frac{2\pi^2}{45} g_*(T) T^3$$

$$s_D = \frac{\rho_D(T_D) + p_D(T_D)}{T_D}$$

$$\frac{\Omega h^2}{\left(\Omega h^2\right)_{\rm std}} \propto \xi \sqrt{\frac{g_*^{\rm eff}}{g_*}} \approx 1 \div 1.2$$

$$g_*^{\rm eff} = g_* + g_D \xi^4$$