A two-component dark matter model with extended seesaw mechanism

Francesco Costa

in collaboration with: Sarif Khan and Jinsu Kim

arXiv: 2209.13653

DISCRETE 2022, 08.11.2022

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Missing pieces in the SM

- The nature of Dark Matter
- Small neutrino masses

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Features of the model

- Two components DM, WIMP W_D and FIMP S_3.
- Gravitational waves from First Order Phase Transition (FOPT)

Gauge Group	Baryon Fields			Lepton Fields				Scalar Fields	
	$Q^i_L = (u^i_L, d^i_L)^T$	u^i_R	d^i_R	$L^i_L = (\nu^i_L, e^i_L)^T$	e^i_R	N^i_L	S^i_L	ϕ_h	ϕ_D
$SU(2)_L$	2	1	1	2	1	1	1	2	1
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	0	1/2	0
$U(1)_D$	0	0	0	0	0	0	0	0	1

Table 1. Particle contents and their corresponding charges under gauge groups.

Gauge Group	Baryon Fields			Lepton Fields				Scalar Fields	
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N_L^i	S_L^i	ϕ_h	ϕ_D
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Field content and symmetries

Gauge Group	Baryon Fields			Lepton Fields				Scalar Fields	
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FIMP

N^3, S^3

Gauge Group	Baryon Fields			Lepton Fields				Scalar Fields	
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N_L^i	S_L^i	ϕ_h	ϕ_D
$SU(2)_L$	2	1	1	2	1	1	1	2	1
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	0	1/2	0
$U(1)_D$	0	0	0	0	0	0	0	0	1

Table 1. Particle contents and their corresponding charges under gauge groups.

Neutrino Lagrangian,

$$\mathcal{L}_{NM} = -\frac{1}{2} \begin{pmatrix} \nu_L & S_L & N_L \end{pmatrix} \begin{pmatrix} 0 & 0 & M_D^T \\ 0 & \mu & M_S^T \\ M_D & M_S & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ S_L \\ N_L \end{pmatrix} + \text{h.c.}$$

Mass Hierarchy,

$$M_R > M_S > M_D \gg \mu \,, \qquad \mu < M_S^T M_R^{-1} M_S \,.$$

Neutrino mass matrices,

$$\begin{aligned} m_\nu &\simeq M_D^T (M_S^T)^{-1} \mu M_S^{-1} M_D \,, \\ m_S &\simeq -M_S^T M_R^{-1} M_S \,, \\ m_N &\simeq M_R \,. \end{aligned}$$

FIMP mass

$$\begin{pmatrix} S_m^3 \\ N_m^3 \end{pmatrix} \simeq \begin{pmatrix} 1 & \frac{M'^{33}_{SN}}{M'^{33}_R} \\ -\frac{M'^{33}_{SN}}{M'^{33}_R} & 1 \end{pmatrix} \begin{pmatrix} S_L^3 \\ N_L^3 \end{pmatrix}$$

Manimala Mitra et al. In: *Nucl. Phys. B* 856 (2012). arXiv: 1108.0004.

Dirac matrix,

$$M^D = \begin{pmatrix} m_D^{e1} & m_D^{\mu 1} & m_D^{\tau 1} \\ m_D^{e2\,R} + i m_D^{e2\,I} & m_D^{\mu 2\,R} + i m_D^{\mu 2\,I} & m_D^{\tau 2\,R} + i m_D^{\tau 2\,I} \end{pmatrix},$$

with

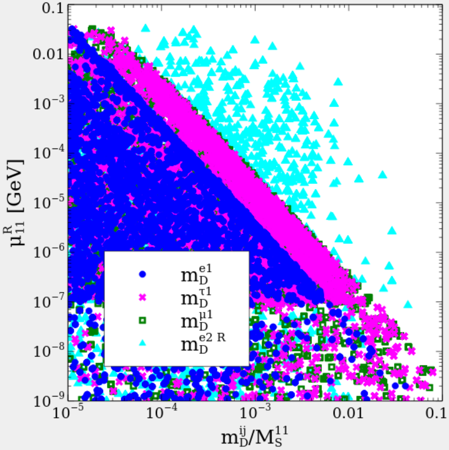
$$m_D^{ij} = y_{ij} v/\sqrt{2}$$

neutrino sector,

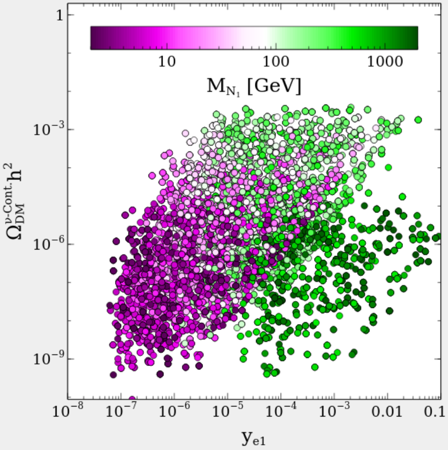
$$\mathcal{L} \supset \sum_{i=e,\mu,\tau,j=1,2} \bar{L}_i M_{ij}^D N_j + \text{h.c.}$$

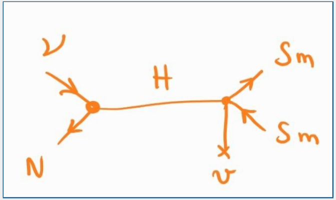
Active neutrino mass

$$(M_D/M_S)^2 \mu < 10^{-11} \text{ GeV}$$

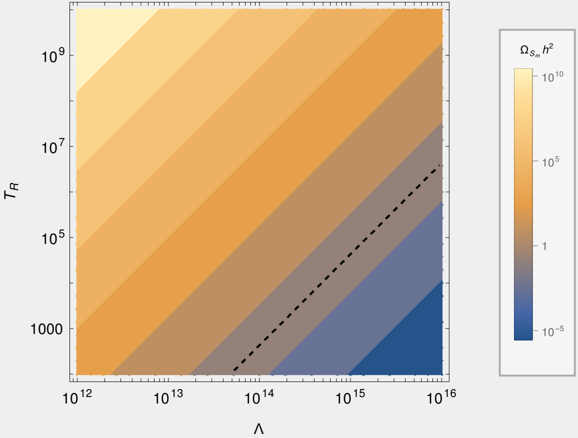


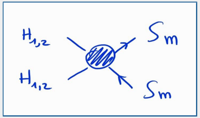
Taking into account **neutrino oscillation** and **LFV** data





Regime: only κ coupling is active

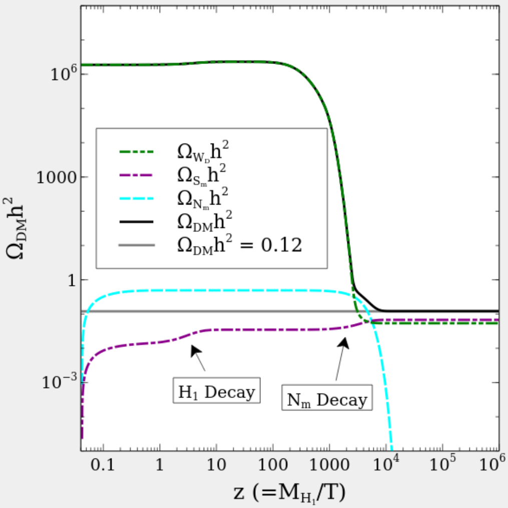




$$Y_{S_m} = \int_{T_{\rm end}}^{T_R} \frac{1}{SHT} \left(\frac{4\kappa}{\Lambda}\right)^2 \frac{1}{16\pi^5}\, \mathrm{T}^6,$$

Lawrence J. Hall et al. In: *JHEP* 03 (2010). arXiv: 0911.1120.

DM Production II



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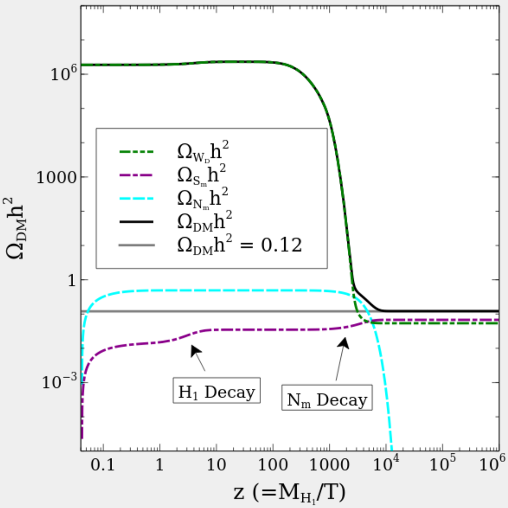
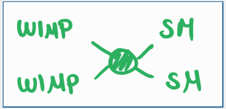
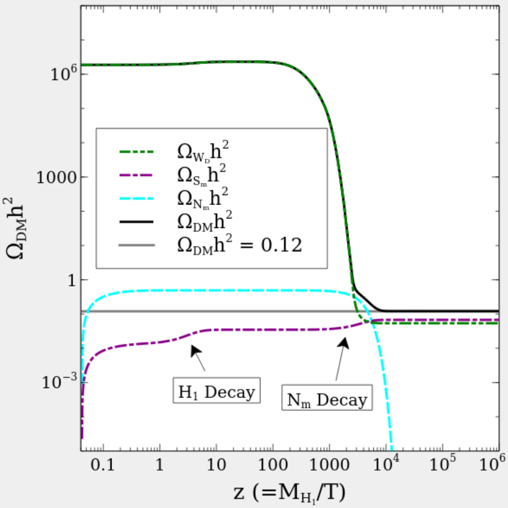
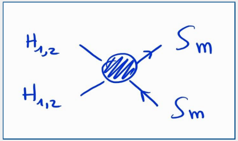
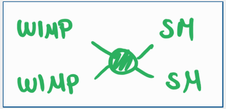


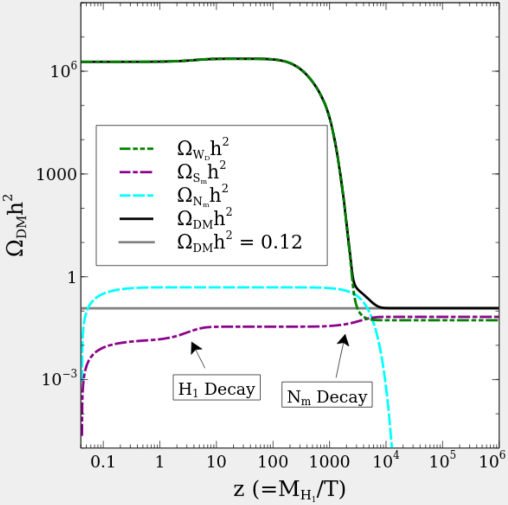


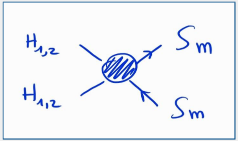

$\Omega_{W_D}h^2$
$\Omega_{S_m}h^2$
$\Omega_{N_m}h^2$
$\Omega_{DM}h^2$
$\Omega_{DM}h^2 = 0.12$
H_1 Decay
N_m Decay
10^6
1000
1
10^{-3}
$\Omega_{DM}h^2$
0.1
1
10
100
1000
10^4
10^5
10^6
z (=M_{H_1}/T)

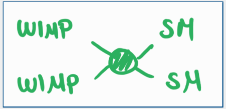

$H_{1,2}$
$H_{1,2}$
S_m
S_m

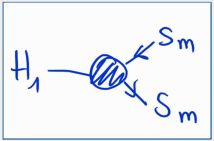

WIMP
WIMP
SM
SM

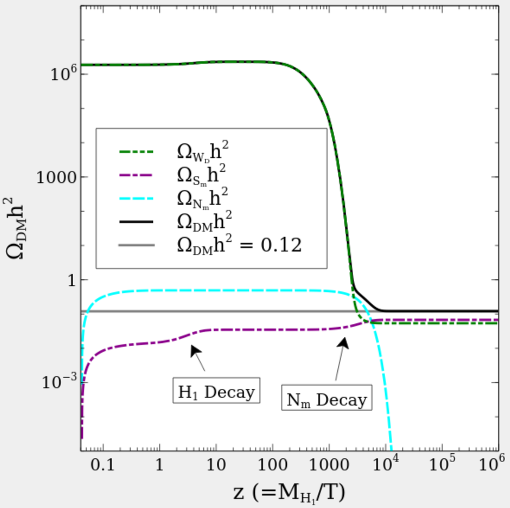
DM Production II







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$\Omega_{S_m}h^2$
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H_1 Decay
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10^6
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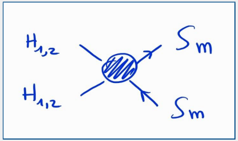
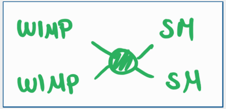
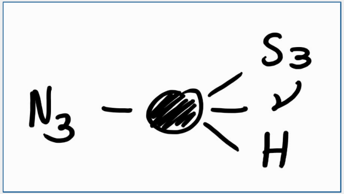
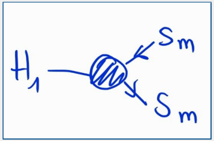
10^6
z (=M_{H_1}/T)


$H_{1,2}$
$H_{1,2}$
S_m
S_m

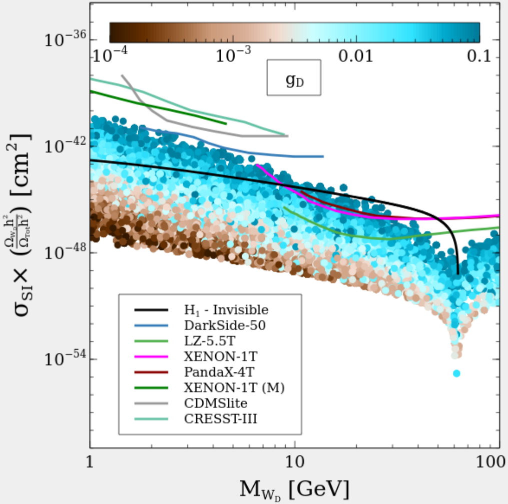

WIMP
WIMP
SM
SM


N_3
S_3
H

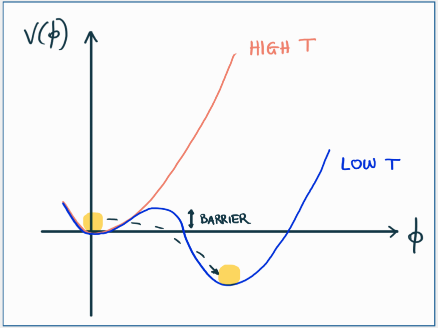

H_1
S_m
S_m

Constraints:

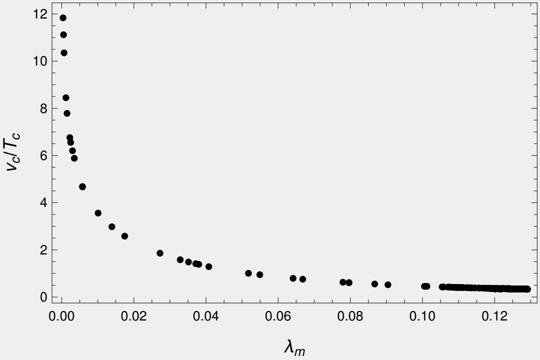
- DM relic density
- Direct detection
- Indirect detection
- Higgs invisible decay
- Higgs signal strength



The one-loop scalar effective potential



$$\lambda_m \equiv \lambda_h - \lambda_{hD}^2/(4\lambda_D)$$

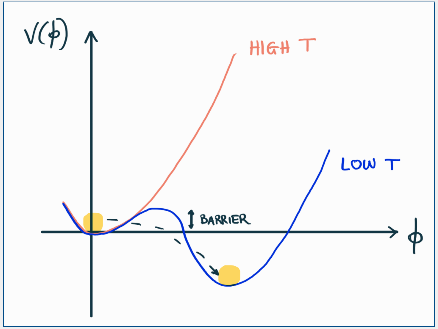


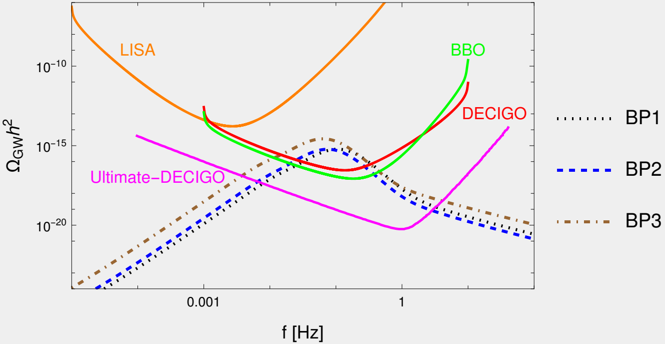
Including only the thermal correction to the potential $\longrightarrow$ strong FOPT

Marcela Carena et al. In: *JHEP* 08 (2020). arXiv: 1911.10206.

GW Production II

The one-loop scalar effective potential





$$\Omega_{\rm GW}h^2 \simeq \Omega_{\rm col}h^2 + \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

Thank You!

Lagrangian

Neutrino sector,

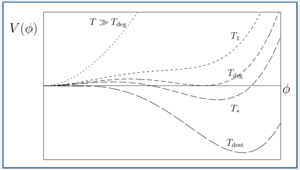
$$\mathcal{L}_N = \sum_{i=1,2} \frac{i}{2}\bar{N_L^i}\gamma^\mu D_\mu^N N_L^i + \sum_{i=1,2} \frac{i}{2}\bar{S_L^i}\gamma^\mu D_\mu^S S_L^i - \sum_{i,j=1,2} \mu_{ij} S_L^i S_L^j - \sum_{i,j=1,2} M_S^{ij} S_L^i N_L^j$$
$$- \sum_{i,j=1,2} M_R^{ij} N_L^i N_L^j - \sum_{i=e,\,\mu,\,\tau,j=1,2} y_{ij}\bar{L}_i\tilde{\phi}_h N_j + \text{h.c.}$$

Dark sector,

$$\mathcal{L}_{\rm DM} = \frac{i}{2}\bar{N_L^3}\gamma^\mu\partial_\mu N_L^3 + \frac{i}{2}\bar{S_L^3}\gamma^\mu\partial_\mu S_L^3 - \mu_{33}S_L^3S_L^3 - M_S^{33}S_L^3N_L^3 - M_R^{33}N_L^3N_L^3$$
$$+ \frac{\kappa}{\Lambda}S_L^3S_L^3(\phi_h^\dagger\phi_h) + \frac{\kappa'}{\Lambda}S_L^3S_L^3(\phi_D^\dagger\phi_D) + \frac{\xi}{\Lambda}N_L^3N_L^3(\phi_h^\dagger\phi_h) + \frac{\xi'}{\Lambda}N_L^3N_L^3(\phi_D^\dagger\phi_D)$$
$$+ \frac{\alpha}{\Lambda}N_L^3S_L^3(\phi_h^\dagger\phi_h) + \frac{\alpha'}{\Lambda}N_L^3S_L^3(\phi_D^\dagger\phi_D) + \text{h.c.}\,.$$

Phase Transition

Thermal Potential



The rate of tunneling per unit volume in a radiation dom. universe

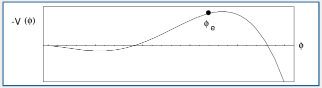
$$\Gamma = \Gamma_0 \exp\left\{-\frac{S_3(T)}{T}\right\}$$

For a spherical bubble

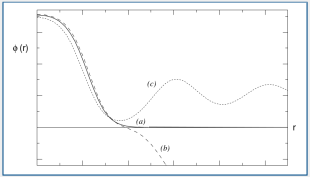
$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi_b}{dr}\right)^2 + V\left(\phi_b, T\right)\right]$$

Riccardo Apreda et al. arXiv: `gr-qc/0107033`.

Over/under shooting method



Bubble Profile



The temperature at which the transition starts

$$\int_0^{t_*} \frac{\Gamma}{H^3} dt \sim 1$$

GW Production

Collision of bubble walls, the sound wave in the plasma, and the magneto-hydrodynamic turbulence contributions to GW production

$$\Omega_{\rm GW}h^2 \simeq \Omega_{\rm col}h^2 + \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2 \,,$$

where

$$\Omega_{\rm col}h^2 = 1.67\times 10^{-5}\left(\frac{H_*}{\beta}\right)^2\left(\frac{\kappa_\phi\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{0.11v_w^3}{0.42+v_w^2}\right)\left(\frac{3.8\,(f/f_{\rm col})^{2.8}}{1+2.8\,(f/f_{\rm col})^{3.8}}\right)\,,$$

$$\Omega_{\rm sw}h^2 = 2.65\times 10^{-6}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w\,(f/f_{\rm sw})^3\left(\frac{7}{4+3\,(f/f_{\rm sw})^2}\right)^{\frac{7}{2}}\,,$$

and

$$\Omega_{\rm turb}h^2 = 3.35\times 10^{-4}\left(\frac{H_*}{\beta}\right)\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{\frac{1}{3}}\left(\frac{v_w\,(f/f_{\rm turb})^3}{[1+(f/f_{\rm turb})]^{\frac{11}{3}}\,(1+8\pi f/h_*)}\right)\,,$$

Chiara Caprini et al. In: *JCAP* 03 (2020), p. 024. arXiv: 1910.13125.

Benchmark Points

BP	v_D [TeV]	M_{H_2} [GeV]	$\sin\theta$	g_D $[10^{-4}]$	α	$\frac{\beta}{H_*}$	T_n [GeV]	$\frac{v_c}{T_c}$	$\frac{\Omega_{\rm WIMP}}{\Omega_{\rm Tot}}$	$\frac{\Omega_{\rm FIMP}}{\Omega_{\rm Tot}}$
1	3.37	2.21	0.082	3.1	0.238	13671	34.43	4.67	0.46	0.54
2	0.673	2.77	-0.076	19.7	0.139	6760.0	46.67	3.56	0.044	0.956
3	4.63	1.0	0.060	1.0	0.461	13820	21.58	6.76	0.87	0.13

Constraint II