A testable hidden-sector model for Dark Matter and neutrino masses

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May 5, 2020

In collaboration with Mathias Pierre:
published in JHEP02 (2020) 068, 1912.06661

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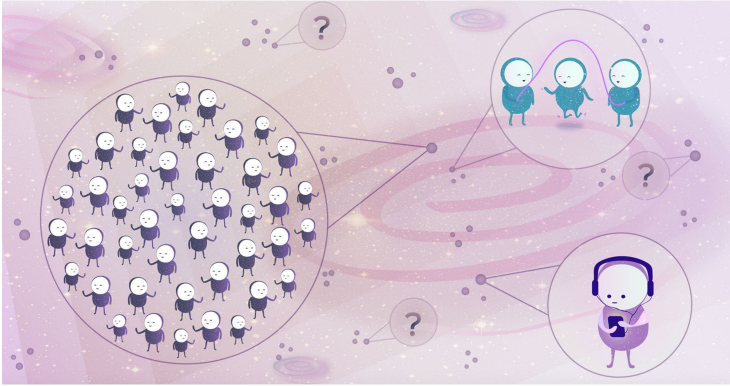
Open questions of the SM

- Experimentally observed non-vanishing **neutrino masses**
- measured fermion masses and mixings are very different: **flavour puzzle**
- Need for a **Dark Matter** candidate
- Higgs boson found but it is very light: **hierarchy problem**

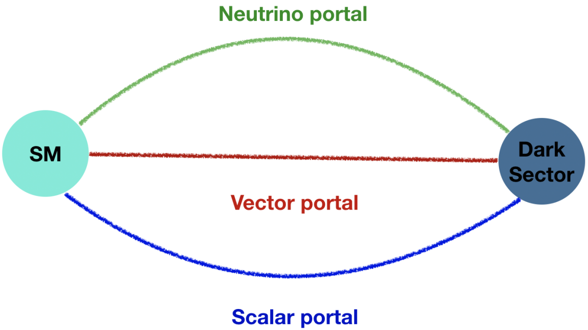
non-observation of new physics particles might imply that the new physics sector interacts only very weakly with visible sector & particles not directly charged under SM group

Hidden sectors [Essig et al. 1311.0029]

does not exclude that the new sector has a **rich structure** itself & mass scales possibly well below the weak scale



$\epsilon F^{\mu\nu} F'_{\mu\nu}$	vector portal
$\lambda H^2 S^2 + \mu H^2 S$	scalar portal
$y(\bar{L}\tilde{H})N$	neutrino portal



Hidden sector model for neutrino masses and DM [JG, Pierre '19]

- introduce dark $U(1)'$ under which the particle in the hidden sector are charged
- hidden sector contains right-handed neutrinos which give mass to the SM neutrinos via an extended seesaw mechanism
- simplest, interesting anomaly-free version of the theory: additional chiral fermions need to be introduced
- find viable DM candidate, one massless state which contributes to the effective relativistic degrees-of-freedom in the early Universe

Hidden sector model for neutrino masses and DM [JG, Pierre '19]

	$U(1)'$ breaking	ESS		DM candidate		massless f.
Field	Φ	N_R	N'_R	χ_R	χ_L	ω_L
$U(1)'$	1	0	1	5	4	4
Multiplicity	1	3	3	1	1	1

SM particles neutral under $U(1)'$

$$\mathcal{L}_{\text{fermions}} = -y_\nu^\alpha \overline{L_L^\alpha} \widetilde{H} N_R - \frac{\mu_N}{2} \overline{N_R^c} N_R - y_N \Phi^* \overline{N_R^c} N'_R - y_\chi \Phi \overline{\chi}_R \chi_L + \text{h.c.}$$

DM and sterile neutrino mass have the **same** origin!

Hidden sector model for neutrino masses and DM [JG, Pierre '19]

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fermion mass matrix $(\nu_L^c, N_R, N'_R, \chi_L^c, \chi_R)$:

$$M = \left(\begin{array}{ccc|cc} 0 & y_\nu \widetilde{H} & 0 & 0 & 0 \\ y_\nu^T \widetilde{H}^\dagger & \mu_N & y_N \Phi & 0 & \\ 0 & y'_N \Phi^* & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & y_\chi \Phi^* \\ 0 & 0 & 0 & y_\chi^T \Phi & 0 \end{array}\right)$$

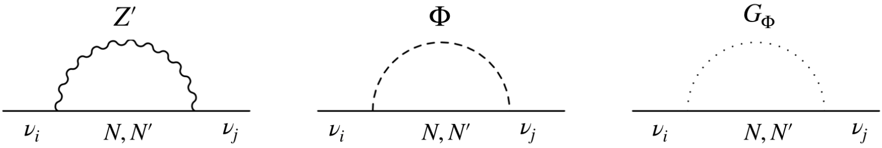
Extended Seesaw [Barry, Rodejohann, Zhang ’11, Dev, Pilaftsis ’12]

neutrino mass matrix (ν_L^c, N_R, N_R'):

$$M_\nu = \begin{pmatrix} 0 & y_\nu \widetilde{H} & 0 \\ y_\nu^T \widetilde{H}^\dagger & \mu_N & y_N \Phi \\ 0 & y_N' \Phi^* & 0 \end{pmatrix}$$

massless neutrinos at tree level!

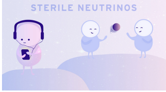
$\rightarrow$ **loop-level** generation of neutrino masses

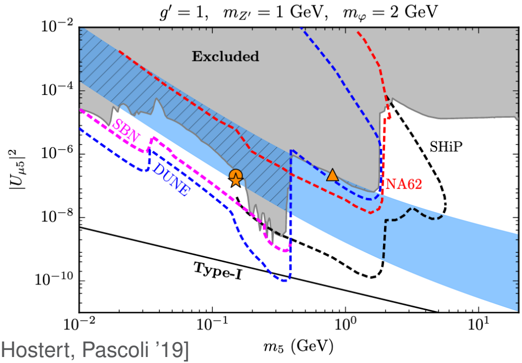


Neutrino phenomenology

same neutrino sector as in [Ballett, Hostert, Pascoli '19]
(see also [Bertuzzo, Jana, Machado, Zukanovich Funchal '18] for similar model)

active-sterile mixing angle:
$U_{\alpha,i} = \frac{m_D}{\sqrt{2} M_R}$



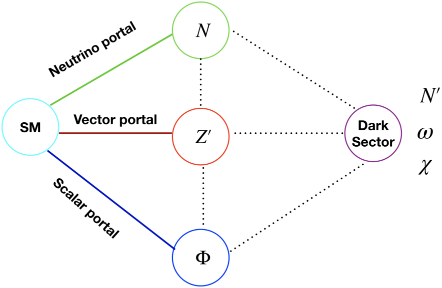


[figure from Ballett, Hostert, Pascoli '19]

Dark sector phenomenology [JG, Pierre '19]

three portals to the SM

- Neutrino portal: active-sterile mixing
- Scalar portal: mixing with Higgs
- Vector portal: kinetic mixing



Dark sector phenomenology [JG, Pierre '19]

- dominant annihilation channel $\bar{\chi}\chi \to \omega\omega$:

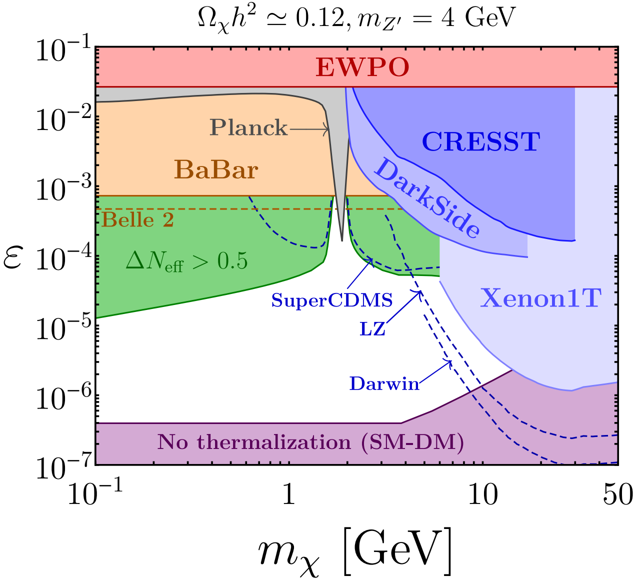
  correct relic abundance: $g_{Z'} \sim 10^{-1} - 10^{-2}$ for $m_{Z'} \sim 1 - 50$ GeV

- massless fermion contributes to N_{eff}

$$\Delta N_{\text{eff}} = \left(\frac{43}{4}\right)^{4/3} \left(\frac{g_\star^\omega(T_{\text{FO}})}{2}\right)^{4/3} \left(\frac{1}{g_\star^{\text{SM}}(T_{\text{FO}})}\right)^{4/3}$$

  typical value $\Delta N_{\text{eff}} \sim 0.03 - 0.2$

Results [JG, Pierre ’19]



Summary and Conclusions

- constructed a hidden sector below the weak scale under which sterile neutrinos are charged
- need for additional particles leads to interesting phenomenology
- model presents three testable portals to the SM
- sterile neutrinos, scalar and gauge boson with GeV masses
- DM candidate at GeV scale, massless fermion which contributes to $N_{\rm eff}$

Thank you for your attention!

Backup: Other seesaw mechanisms

- linear seesaw:

$$M = \begin{pmatrix} 0 & m_D & \epsilon \\ m_D^T & 0 & M_N \\ \epsilon & M_N^T & 0 \end{pmatrix}$$

$$m_\nu \sim \epsilon \frac{m_D}{M_N}$$

- inverse seesaw:

$$M = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix}$$

$$M_R \gg \mu$$

$$\rightarrow m_\nu \sim \mu \frac{m_D^2}{M_R^2}$$

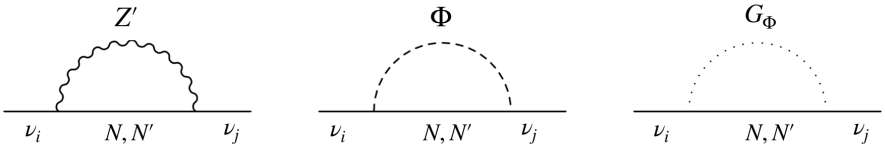
Backup: Neutrino masses

Extended Seesaw [Barry, Rodejohann, Zhang '11, Dev, Pilaftsis '12]

$$m_{ij} = \frac{1}{4\pi^2} N_F \sum_{k=4}^{5} \left[C_{ik} C_{jk} \frac{m_k^3}{m_Z^2} F(m_k^2, m_Z^2, m_h^2) + D_{ik} D_{jk} \frac{m_k^3}{m_{Z'}^2} F(m_k^2, m_{Z'}^2, m_\phi^2) \right]$$

$$C_{ik} \equiv \frac{g_{Z'}}{4c_W} \sum_{\alpha=e}^{\tau} U_{\alpha i}^* U_{\alpha k} \; , \qquad D_{ik} \equiv \frac{g_{Z'}}{2} U_{R' i}^* U_{R' k}$$

Extended Seesaw [Barry, Rodejohann, Zhang '11, Dev, Pilaftsis '12]



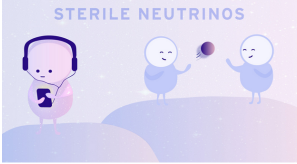
$M_R \gg m_{Z'}, m_\phi$

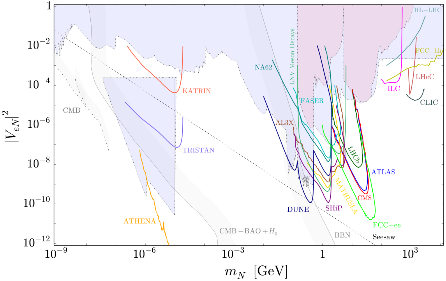
$$m_3 = N_F \frac{g_{Z'}^2 m_D^2 \mu_N}{16\pi^2 M_R^2} \left(3 + \frac{m_\phi^2}{m_{Z'}^2}\right)$$

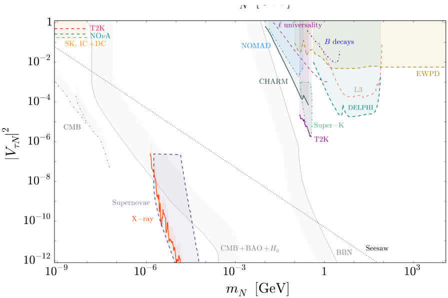
$M_R \ll m_{Z'}, m_\phi$

$$m_3 = N_F \frac{g_{Z'}^2 m_D^2 \mu_N}{16\pi^2 m_{Z'}^2} \left[3 \log\left(\frac{m_{Z'}^2}{M_R^2}\right) + \log\left(\frac{m_\phi^2}{M_R^2}\right) - 4\right]$$

constraints on mixing with electron and tau neutrinos [Bolton, Deppisch, Dev '19]







Backup: Portals [JG, Pierre '19]

gauge portal:

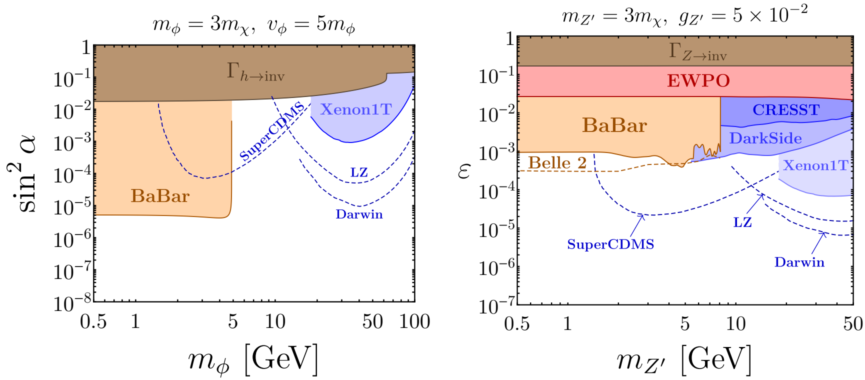
$$tan(2\zeta) = \frac{m_Z^2 s_W \sin 2\xi}{m_{Z'}^2 - m_Z^2}$$

$$\mathcal{L} \supset eA_\mu J^\mu_{\rm EM} + Z_{1\mu}\left[\frac{e}{s_W c_W} J^\mu_Z + g_{Z'}\varepsilon t_W J^\mu_{Z'}\right] + Z_{2\mu}\left[-e\varepsilon J^\mu_{\rm EM} + g_{Z'} J^\mu_{Z'}\right]$$

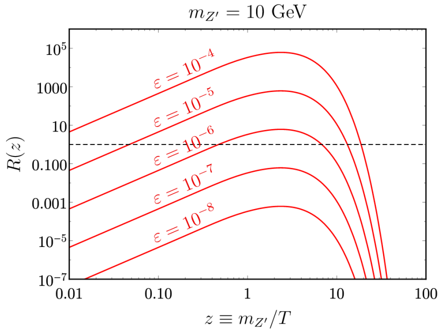
scalar portal:

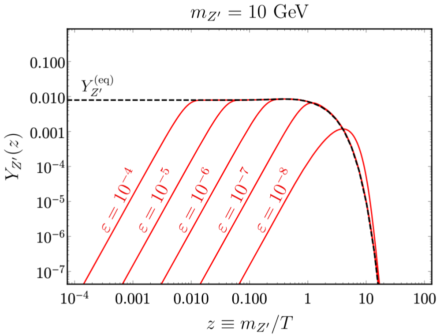
$$\tan(2\alpha) = \frac{\lambda_{\phi h} v_h v_\phi}{\lambda_\phi v_\phi^2 - \lambda_h v_h^2}$$

constraints on dark scalar and dark gauge boson



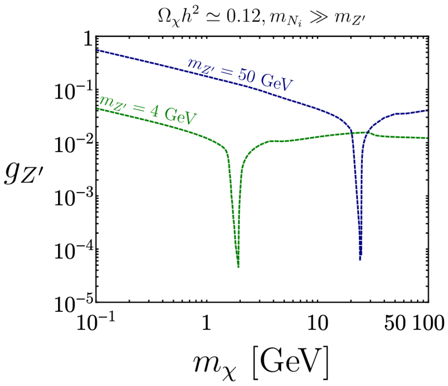
production of dark sector from inverse decays $\bar{\psi} + \psi \to Z'$



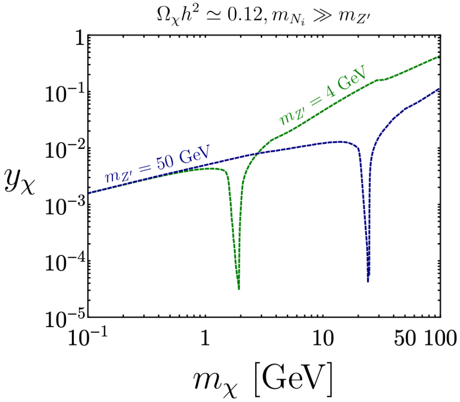


Backup: DM phenomenology [JG, Pierre '19]

$g_{Z'} > y_\chi$: dominant $\bar{\chi}\chi \to \omega\omega$

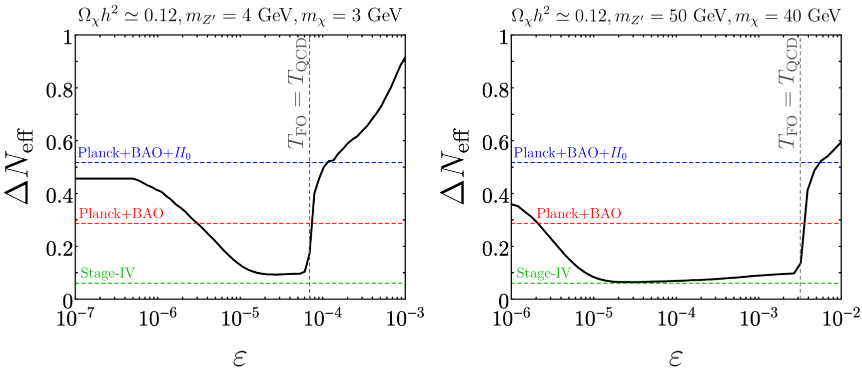


$g_{Z'} < y_\chi$: dominant $\bar{\chi}\chi \to \phi\phi, N_{4,5}N_{4,5}$



Backup: Massless fermion [JG, Pierre '19]

$$\Delta N_{\text{eff}} = \left(\frac{43}{4}\right)^{4/3} \left(\frac{g_\star^\omega(T_{\text{FO}})}{2}\right)^{4/3} \left(\frac{1}{g_\star^{\text{SM}}(T_{\text{FO}})}\right)^{4/3}$$



Backup: Results [JG, Pierre '19]