The Hubble tension and a renormalizable model of gauged neutrino self-interactions

Maximilian Berbig^{1,*}, Sudip Jana^{2,†} and Andreas Trautner^{2,‡}

¹*Bethe Center for Theoretical Physics und Physikalisches Institut der Universität Bonn,
Nussallee 12, 53115 Bonn, Germany*

²*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

(Received 21 May 2020; revised 22 July 2020; accepted 9 November 2020; published 3 December 2020)

We present a simple extension of the Standard Model that leads to renormalizable long-range vector-mediated neutrino self-interactions. This model can resolve the Hubble tension by delaying the onset of neutrino free-streaming during recombination, without conflicting with other measurements. The extended gauge, scalar, and neutrino sectors lead to observable signatures, including invisible Higgs and Z decays, thereby relating the Hubble tension to precision measurements at the LHC and future colliders. The model has a new neutrinophilic gauge boson with $m_{Z'} \sim \mathcal{O}(10 \text{ eV})$ and charged Higgses at a few 100 GeV. It requires hidden neutrinos with active-hidden mixing angles larger than 5×10^{-4} and masses in the range $1 \div 300 \text{ eV}$, which could also play a role for short baseline neutrino oscillation anomalies.

DOI: 10.1103/PhysRevD.102.115008

I. INTRODUCTION

There is convincing evidence that neutrinos played a substantial role during the epoch of big bang nucleosynthesis (BBN) at $T \sim \text{MeV}$, closely monitored by early element abundances. The lowest temperature scale indirectly probed for neutrinos is $T \sim \text{eV}$, where observations of the cosmic microwave background (CMB) fit well to a history of our universe that does not only comply with the cosmological standard model (ΛCDM), but also with the expectation of the Standard Model of particle physics (SM), including exactly three generations of neutrinos.

However, evidence is accumulating *not only* for a discrepancy between local measurements of today's Hubble rate H_0 [1–5] and therelike global determinations based on ΛCDM together with CMB [6], baryonic acoustic oscillations (BAO) and large scale structure (LSS) datasets [7–16], *but also* for an increasing tension in other parameters [17,18]. Resolving these discrepancies might require a modification of ΛCDM , preferentially, perhaps, shortly before the era of recombination [19,20]. Many new physics (NP) scenarios have been discussed, see [20–23]. Naturally, any consistent modification of ΛCDM must be in

compliance with a consistent modification of the Standard Model of particle physics (SM).

The positive correlation of H_0 and N_{eff} with the amplitude of the matter power spectrum σ_8 , as observed in CMB data [6], prohibits a resolution of the H_0 tension simply by increasing N_{eff} alone (LSS prefers low σ_8). However, a delay in the onset of neutrino free-streaming during recombination could achieve both: breaking the positive correlation of H_0 and σ_8 , while solving the Hubble tension (HT) at the cost of increasing ΔN_{eff} during recombination [24–29]. Taking into account an effective four-neutrino interaction $G_{\text{eff}}^{4\nu}(\bar{\nu}\nu)(\bar{\nu}\nu)$ a good, bimodal fit to CMB data is obtained with [28,29]

$$G_{\text{eff}}^{4\nu} \equiv \frac{g_{\text{eff}}^2}{m_{Z'}^2} \approx \begin{cases} (5 \text{ MeV})^{-2} & (\text{SI}), \text{ or} \\ (100 \text{ MeV})^{-2} & (\text{WI}). \end{cases} \quad (1)$$

The weakly interacting mode (WI) should be interpreted as an upper limit on $G_{\text{eff}}^{4\nu}$ such that cosmological parameters stay close to ΛCDM [24,25], without resolving above tensions. Therefore, we focus on the strongly interacting mode (SI), which considerably alters cosmology to resolve the tensions in H_0 and σ_8 while being consistent with local astronomical observations [28,29].

A valid alternative to heavy new physics would be to generate $G_{\text{eff}}^{4\nu}$ by the exchange of a light mediator. However, it is basically excluded to have very light mediators that recouple during recombination [30,31] and the same is true for light mediators which are thermalized during BBN [32]. Nonetheless, six orders of magnitude in temperature between BBN and CMB are enough to establish a mass

*berbig@physik.uni-bonn.de

†sudip.jana@mpi-hd.mpg.de

‡trautner@mpi-hd.mpg.de

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](#). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

FIG. 1. Thermally averaged four-neutrino interaction rate relative to the Hubble rate as a function of Temperature for $m_{Z'} = 25$ eV and two different values of the Z' width.

scale, say after a phase transition, and subsequently integrate it out to obtain a decoupling behavior of neutrinos during CMB resembling (1). In this way, neutrinos *recouple* by the new interactions only after BBN, and fall out of equilibrium during recombination, see Fig. 1.

Here we provide arguably the simplest renormalizable and phenomenologically viable extension of the SM that leads to vector mediated four-neutrino interactions of above characteristic. We first outline the parameter space suitable to address the HT, then present our model and discuss its phenomenology.

II. RELEVANT PARAMETER REGION

The effective four-neutrino interaction strength in our model is

$$G_{\text{eff}}^{4\nu} \equiv \frac{g_{\text{eff}}^2}{m_{Z'}^2} \equiv \frac{g_X^2 \epsilon_m^4}{m_{Z'}^2}, \quad (2)$$

where g_X is the gauge coupling of a new $U(1)_X$ symmetry, $\epsilon_m \ll 1$ a mixing between active and hidden ($U(1)_X$ charged) neutrinos, and $m_{Z'}$ the mass of the new gauge boson after $U(1)_X$ breaking. Equating the resulting thermally averaged interaction rate with the Hubble rate, $G_{\text{eff}}^{4\nu} 2T^5 \approx T^2/M_{\text{Pl}}$, confirms $T_{\text{dec.}} \approx 0.5$ eV.

On the other hand, for a range of temperatures $T \gg m_{Z'}$, while ϵ_m is relevant, the new gauge boson will be effectively massless, inducing a long-range four-neutrino interaction with thermally averaged rate $\Gamma \sim g_{\text{eff}}^4 T$. Requiring this interaction not to thermalize neutrinos prior to BBN, but before recombination, demands

$$2 \times 10^{-7} \lesssim g_X \epsilon_m^2 \lesssim 5 \times 10^{-6}. \quad (3)$$

Knowing g_{eff} and $G_{\text{eff}}^{4\nu}$ we can compute

$$1 \lesssim m_{Z'} \lesssim 25 \text{ eV} \quad (\text{SI}). \quad (4)$$

Parametrizing $m_{Z'} = g_X \bar{v}$ we can furthermore constrain the effective $U(1)_X$ -breaking vacuum expectation value (VEV)

$$\bar{v} := \frac{m_{Z'}}{g_X} \approx \epsilon_m^2 \times 5 \text{ MeV} \quad (\text{SI}). \quad (5)$$

Fig. 1 illustrates this particular re- and decoupling behavior, computed exactly within our model. Equation (5) implies a hierarchy between the relevant scales in the model of

$$\xi := \bar{v}/v_h \approx \epsilon_m^2 \times 2 \times 10^{-5} \quad (\text{SI}), \quad (6)$$

where $v_h = 246$ GeV is the SM Higgs VEV.

III. MODEL

Next to the new $U(1)_X$ gauge symmetry we introduce a pair of SM-neutral chiral fermions $N_{1,2}$ and two new scalars Φ, S with charges shown in Table I [33]. New interactions for SM-leptons are

$$\mathcal{L}_{\text{new}} = -y \bar{L} \tilde{\Phi} N_1 - M N_1 N_2 + \text{H.c.}, \quad (7)$$

where $\tilde{\Phi} := i\sigma_2 \Phi^*$, y is a Yukawa coupling, and M has mass-dimension one. We treat the one generation case here, but consider three generations of SM leptons and multiple generations of hidden fermions below.

We consider the most general scalar potential consistent with all symmetries,

$$V = V_H + V_\Phi + V_S + V_{H\Phi} + V_{HS} + V_{\Phi S} + V_3, \quad (8)$$

with

$$V_\Sigma := \mu_\Sigma^2 \Sigma^\dagger \Sigma + \lambda_\Sigma (\Sigma^\dagger \Sigma)^2 \quad (\Sigma = H, \Phi, S), \quad (9)$$

$$V_{H\Phi} := \lambda_3 (H^\dagger H) (\Phi^\dagger \Phi) + \lambda_4 (H^\dagger \Phi) (\Phi^\dagger H), \quad (10)$$

$$V_{DS} := \lambda_{DS} (D^\dagger D) (S^* S) \quad (D = H, \Phi), \quad (11)$$

$$V_3 := -\sqrt{2} \mu (H^\dagger \Phi) S^* + \text{H.c.} \quad (12)$$

TABLE I. New fields and their charges under Lorentz, SM gauge, new $U(1)_X$ gauge symmetry as well as under global Lepton number (S = Scalar, RH = right-handed Weyl fermion, V = vector).

Field	Φ	N_1	N_2	S	X_μ
Lorentz	S	RH	RH	S	V
$SU(2)_L \times U(1)_Y$	$(2, -\frac{1}{2})$	$\emptyset$	$\emptyset$	$\emptyset$	$\emptyset$
$U(1)_X$	+1	+1	-1	+1	0
$U(1)_L$	0	+1	-1	0	0

The scalars are decomposed as $S = \frac{1}{\sqrt{2}}(s + ia_s)$,

$$H = \begin{pmatrix} h^+ \\ \frac{1}{\sqrt{2}}(h + ia_h) \end{pmatrix}, \quad \text{and} \quad \Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(\phi + ia_\phi) \end{pmatrix}. \quad (13)$$

We choose parameters such that all neutral scalars obtain VEVs $v_\sigma := \langle \sigma \rangle$ for $\sigma = h, \phi, s$, and assume CP conservation in the scalar sector. v_h spontaneously breaks EW-symmetry, v_s breaks $U(1)_X$, and v_ϕ breaks both. Fixing the HT requires $v_h \gg v_s, v_\phi$, cf. (6), and we expand all of our expressions to leading order in that hierarchy.

The photon is exactly the same massless combination of EW bosons as in the SM, mixed by the electroweak angle $c_W := m_W/m_Z$ [37]. By contrast, the very SM-like Z boson contains a miniscule admixture of the new gauge boson X ,

$$Z_\mu = c_X(c_W W_\mu^3 - s_W B_\mu) + s_X X_\mu, \quad (14)$$

with an angle [38]

$$s_X \approx -2c_W \frac{g_X}{g_2} \left(\frac{v_\phi}{v_h} \right)^2 \ll 1 \quad \text{and} \quad c_X \approx 1. \quad (15)$$

Masses of the neutral gauge bosons up to $\mathcal{O}(\xi^2)$ are

$$m_Z \approx \frac{g_2 v_h}{2c_W} \quad \text{and} \quad m_{Z'} \approx g_X \bar{v} := g_X \sqrt{v_\phi^2 + v_s^2}. \quad (16)$$

The neutrino mass matrix in the gauge basis $(\nu, \bar{N}_1, \bar{N}_2)$ is

$$M_\nu = \begin{pmatrix} 0 & -yv_\phi/\sqrt{2} & 0 \\ -yv_\phi/\sqrt{2} & 0 & M \\ 0 & M & 0 \end{pmatrix}. \quad (17)$$

Upon 13-rotating by an angle ε_m ,

$$\tan \varepsilon_m := (yv_\phi)/(\sqrt{2}M), \quad (18)$$

M_ν reveals an *exact* zero eigenvalue, corresponding to approximately massless active neutrinos, and a Dirac neutrino N with $M_N := \sqrt{M^2 + y^2 v_\phi^2/2}$. The massless active neutrinos mix with $\bar{N}_2$ proportional to s_{ε_m} generating (2). Defining $\tan \gamma := v_\phi/v_s$, one can show that

$$M = (y/\sqrt{2})\varepsilon_m s_\gamma (G_{\text{eff}}^{4\nu})^{-1/2} \ll 5 \text{ MeV}. \quad (19)$$

Owing to constraints discussed below the parameter range one should have in mind is $2 \times 10^{-5} \lesssim y \lesssim 6 \times 10^{-3}$, $\varepsilon_m \lesssim 0.05$ and $s_\gamma \lesssim 0.2$. $M_N \approx M$ then turns out to be in the range $1 \div 300 \text{ eV}$.

Non-zero active neutrino masses are required by neutrino oscillation phenomenology, and also for a successful resolution of the Hubble tension with self-interacting neutrinos [28,29]. The mass generation for active neutrinos $m_\nu \ll yv_\phi$ can be realized as a small perturbation to the diagonalization of M_ν . In particular, our mechanism is compatible with an effective Majorana mass in $[M_\nu]_{11}$, and, therefore, with any type of mass generation mechanism that gives rise to the Weinberg operator [39]. Another minimal possibility in the present model would be to populate $[M_\nu]_{33}$ like in the inverse seesaw mechanism [40–42]. Also Dirac masses are possible but require additional fermions. This shows that, ultimately, any of the commonly considered neutrino mass generation mechanisms is compatible with our model.

IV. PHENOMENOLOGY

The scalar sector of the model corresponds to 2HDM + scalar singlet. However, both of the new scalars are charged under the hidden neutrino-specific $U(1)_X$ which considerably alters phenomenology with respect to earlier works [43–48]. Masses of the physical scalars, to leading order in $\xi \equiv \bar{v}/v_h$, are [49]

$$m_H^2 = 2\lambda_H v_h^2, \quad m_\Phi^2 = m_A^2 = \frac{2v_h \mu}{s_{2\gamma}}, \quad (20)$$

$$m_{\Phi^\pm}^2 = \frac{v_h \mu}{t_\gamma} - \frac{\lambda_4}{2} v_h^2, \quad (21)$$

$$m_{h_s}^2 \approx \xi^2 v_h^2 \left(2\lambda_S - \frac{\lambda_{HS}^2}{2\lambda_H} \right) + \mathcal{O}(\gamma\mu/v_h). \quad (22)$$

The neutral scalar mass matrix is diagonalized by three orthogonal rotations $O = R(\theta_{13})R(\theta_{12})R(\theta_{23})$, such that

$$O^T M_{\text{n.s.}}^2 O = \text{diag}(m_{h_s}^2, m_H^2, m_\Phi^2). \quad (23)$$

The mixing angles, to leading order in ξ , are given by

$$s_{12} \equiv s_{S\Phi} = s_\gamma, \quad s_{13} \equiv s_{HS} = \xi \frac{pt_\gamma + q}{2v_h \lambda_H}, \quad (24)$$

$$s_{23} \equiv s_{\Phi H} = \xi s_\gamma \frac{\mu(pt_\gamma + q) - 2\lambda_H v_h p}{2\lambda_H v_h (\lambda_H v_h s_{2\gamma} - \mu)}, \quad (25)$$

where we use $\lambda_{34} := \lambda_3 + \lambda_4$ and

$$p := \lambda_{34} v_H s_\gamma - \mu c_\gamma, \quad q := \lambda_{HS} v_H c_\gamma - \mu s_\gamma. \quad (26)$$

For the parameter region envisaged to resolve the Hubble tension, there are two new light bosonic fields: next to Z' there is a scalar h_s with mass in the keV range.

To prevent possible reservations about these light states straightaway, let us discuss their coupling to the SM. The only way in which h_S couples to fermions other than neutrinos is via mixing with the SM Higgs. Operators involving h_S linearly can be written as $\mathcal{O}_{h_S} = c_{S\Phi} s_{HS} \times \mathcal{O}_{H \rightarrow h_S}^{\text{SM}}$. Hence, couplings to fermions are suppressed by their Yukawa couplings and there are no new flavor changing effects. Reference [50] collects bounds on this scenario. Besides BBN, discussed below, the strongest constraint arises from SN1987A burst duration and requires $(c_{S\Phi} s_{HS})^2 \lesssim 10^{-12}$. Parametrically, $(c_{S\Phi} s_{HS})^2 \sim \xi^2 \sim \epsilon_m^4 \times 10^{-10}$, avoiding the bound for $\epsilon_m \lesssim 0.1$.

The dominant coupling of Z' to SM fermions other than neutrinos is by $Z - Z'$ mixing. Given (15), Z' couples to the SM neutral current with strength $2g_X(v_\phi/v_h)^2 = 2g_X \xi^2 s_\gamma^2$. For momentum transfer below $m_{Z'}$ this gives rise to new four-Fermi (NSI) operators of effective strengths

$$(G_{\text{eff}}^{(2\nu)(2f\neq\nu)})/G_F = -2\sqrt{2}\epsilon_m^2 s_\gamma^2, \quad \text{and} \quad (27a)$$

$$(G_{\text{eff}}^{(4f\neq\nu)})/G_F = 4\sqrt{2}\xi^2 s_\gamma^4 \approx \epsilon_m^4 s_\gamma^4 \times 2 \times 10^{-9}. \quad (27b)$$

Such feeble effects are currently not constrained by experiment.

We note that the vector mixing of (15) can be modified by gauge-kinetic mixing of the $U(1)$ field strengths $\mathcal{L}_\chi = -(s_\chi/2)B^{\mu\nu}X_{\mu\nu}$ [51,52]. This shifts the Z' coupling to the SM neutral current by a negligible amount proportional to $\chi\mathcal{O}(m_{Z'}^2/m_Z^2)$ [53,54] (given $m_{Z'} \ll m_Z, \chi \ll 1$). More important is the introduction of a coupling of Z' to the electromagnetic current scaling as $c_W c_X \chi$. Experimental constraints on this are collected in [55,56] and our model could, in principle, saturate these limits. Therefore, we stress that $\chi \neq 0$ would neither affect our solution to the HT, nor the H and Z decay rates in Eqs. (30) and (31) below (to leading order), which are fixed by Goldstone boson equivalence.

We thus focus on effects directly involving neutrinos. For $T \lesssim v_\phi$, neutrino mixing is active. As required by direct-search bounds [57–60] and PMNS unitarity [61] (as extracted from [62]) we assume [34,35]

$$\epsilon_m^{(e)} \leq 0.050, \quad \epsilon_m^{(\mu)} \leq 0.021, \quad \epsilon_m^{(\tau)} \leq 0.075, \quad (28)$$

for mixing with e, μ, τ flavors. These are the most conservative bounds in the mass range set by Eq. (19), and often larger mixings can be allowed, especially for light masses and non- e flavors. For $M \lesssim 10$ eV oscillation experiments become important, requiring a dedicated analysis, see e.g., [63], nonetheless still allowing (28). Since nothing in our resolution of the HT is required to depend on flavor, we adopt $\epsilon_m \sim 5 \times 10^{-2}$ as a universal benchmark value.

Couplings of neutrinos to Z' at low T are given by $g_X \epsilon_m^2$ with a strength set by (3). This gives rise to the four-fermion

operators (2, 27), but also to the possibility of Z' emission off neutrinos. Eq. (3) together with $g_X \lesssim 1$ implies a *lower* bound $\epsilon_m \gtrsim 5 \times 10^{-4}$. This fuels the intuition that this model is testable.

Constraints on neutrinos directly interacting with light mediators are collected in [21,64–71]. The strongest laboratory constraints arise from meson [64,72–81] and nuclear double-beta decays [82–86]. However, even the most stringent bounds for the least favorable flavor structure cannot exclude $g_{\text{eff}} \lesssim 10^{-5}$ for light $m_{Z'}$. While most experiments constrain light scalar (majoron) emission, the present study emphasizes the need to reanalyze those also for light vectors. The most important constraint is SN1987A neutrino propagation through the cosmic neutrino background (CνB) [87]. The exact bound depends on the neutrino masses and rank of y , but even the most pessimistic assumptions allow $g_{\text{eff}} \lesssim 5 \times 10^{-4}$ for $m_{Z'} < 60$ eV.

The $\bar{\nu}\nu \leftrightarrow \bar{\nu}\nu$ scattering cross section via Z' exchange is approximated by

$$\sigma^{(4\nu)}(s) = \frac{g_X^4 \epsilon_m^8}{12\pi} \frac{s}{(m_{Z'}^2 - s)^2 + m_{Z'}^2 \Gamma_{Z'}^2}. \quad (29)$$

To generate Fig. 1 we include the t -channel and use Maxwell-Boltzmann thermal averaging [88], while noting that a more refined analysis should employ Fermi-Dirac statistics [89,90]. For $m_{Z'} > 2M_N$, Z' decays to $\bar{N}_1 N_1$, $\bar{N}_2 N_2$, $\bar{\nu} N_2 (\nu \bar{N}_2)$ and $\bar{\nu}\nu$, while for $m_{Z'} \lesssim M_N$ only the last channel is accessible. The respective total widths are $\Gamma_{Z'}/m_{Z'} \approx 10^{-7}$ or 10^{-12} , corresponding to Z' lifetimes from micro- to tens of picoseconds. We show thermally averaged rates (dashed) obtained by dimensional analysis for $T \gg v_\phi$. For $T \ll m_{Z'}$ we reproduce the scaling of the effective operator (1). Obviously, before recombination $\Gamma_{4\nu}(T)$ differs from the effective theory. This would not qualitatively change the conclusions of [24–29], which are based on the (non-)free-streaming nature of neutrinos, see also [91]. Nonetheless, this motivates a dedicated cosmological analysis to tell if our specific temperature dependence could be discriminated from the effective model.

Finally, we discuss the coupling of neutrinos to h_S . For massless active neutrinos and conserved lepton number, diagonalization of (17) is exact in s_{ϵ_m} . This prevents a quadratic coupling of neutrinos to h_S . Hence, SM neutrinos couple to h_S only in association with hidden neutrinos, or suppressed by their tiny mass (e.g., $[M_\nu]_{11} \sim m_\nu$ produces such a coupling). In both cases effects are unobservably small, also because of the vastly suppressed coupling of h_S to matter targets.

Also modification of Z decays to neutrinos are unobservably small. Even if N mixes with ν , the invisible Z width is unaltered for $M_N \ll m_Z$ [57]. The vertex $Z\bar{N}\nu$ also leads to N production from neutrino upscattering on matter targets, suppressed by ϵ_m compared to G_F . N decays invisibly leaving an unaccompanied recoil as signature.

Any consistent model of strong neutrino self-interactions requires a modification of the SM scalar sector. These are among the most visible effects of this model. The necessary modifications imply new invisible decays of SM Z and Higgs. To leading order in ξ , rates of the most prominent decays are

$$\Gamma_{H \rightarrow h_s h_s} = \frac{v_h^2}{32\pi m_H} \left[\lambda_{HS} c_\gamma^2 + \lambda_{34} s_\gamma^2 - \frac{\mu s_{2\gamma}}{v_h} \right]^2, \quad (30)$$

$$\Gamma_{H \rightarrow Z' Z'} = \Gamma_{H \rightarrow h_s h_s}, \quad \Gamma_{Z \rightarrow Z' h_s} = \frac{m_Z g_2^2 s_\gamma^4}{192\pi c_W^2}, \quad (31)$$

and to leading order in ξ and γ (the exact expression in γ is known)

$$\Gamma_{H \rightarrow ZZ'} \stackrel{\gamma \ll 1}{=} \frac{g_2^2}{c_W^2} \frac{(m_H^2 - m_{Z'}^2)^3}{m_H^3 m_{Z'}^2} \frac{\xi^2 s_\gamma^4}{16\pi} \left(1 + \frac{\lambda_{HS}}{4\lambda_H} \right)^2. \quad (32)$$

$\Gamma_{H \rightarrow \text{inv.}} \leq 1.3 \text{ MeV}$ [92–94] and $\Gamma_{Z \rightarrow \text{inv.}}^{\text{new}} \leq 2.0 \text{ MeV}$ [95] constrain the parameters as shown in Fig. 2. $\Gamma_{Z \rightarrow Z' h_s}$ requires $\gamma \lesssim 0.4$. $\Gamma_{H \rightarrow \text{inv.}}$, without fine tuning, demands

FIG. 2. Allowed region (blank) in the $\tan \gamma - (\mu/v_h)$ plane. The region is independent of any other free parameters as long as $\lambda_{HS}, \lambda_{34} \ll \mathcal{O}(10^{-2})$ (for definiteness, we have chosen scalar potential parameters as $\lambda_{HS} = 0.001$, $\lambda_3 = 0.002$, $\lambda_4 = 0.003$, $\lambda_\Phi = 0.3$, $\lambda_S = 0.4$, $\lambda_{\Phi S} = 0.5$). The Hubble tension can be resolved in the entire allowed region. We show equilines of the corresponding hidden neutrino mass M for benchmark parameters $\epsilon_m = 0.05$, $g_X = 2 \times 10^{-3}$, and $y = 6 \times 10^{-5}$ (6×10^{-3}). In the orange region $M < m_\nu$ (for $y = 6 \times 10^{-5}$) which is inconsistent with our assumptions.

$\lambda_{HS}, \lambda_{34}, (\mu s_{2\gamma}/v_h) \lesssim \mathcal{O}(10^{-2})$. $\Gamma_{H \rightarrow ZZ'}$ then is merely a rare Higgs decay with $\text{BR}(H \rightarrow ZZ') \approx 10^{-8} \epsilon_m^4 s_\gamma^4$.

The model without S is excluded by $\Gamma_{Z \rightarrow Z' h_s}$, which would be given by (31) with $\gamma \rightarrow \pi/4$. The constraints on γ further limit the allowed mass range of M , cf. Eq. (19), and we show corresponding values of M in Fig. 2.

Charged scalars $\Phi^\pm$ couple to $\ell^\pm$ and N via (7). Constraints on y arise from $\ell_1 \rightarrow \ell_2 \gamma$ and measured lepton magnetic moments, both mediated by a loop of $\Phi^\pm$ and N . Exact constraints are given in [34]. Here it suffices to note that certainly $y \lesssim \mathcal{O}(1)$ for all flavors, as much tighter constraints are found below.

The coupling of $\Phi^\pm$ to quarks is suppressed by $s_\gamma \xi$ and standard LHC searches [96,97] do not apply. At LEP, $\Phi^\pm$ could have been pair-produced via s -channel γ/Z or t -channel N , or singly-produced associated with charged and neutral leptons. $\Phi^\pm$ dominantly decays to $N_\alpha \bar{\ell}_\beta$ with BRs set by y . N further decays to neutrinos via Z' . The final state for $\Phi^\pm$ hence is $\ell_\beta^\pm + \text{MET}$. LEP limits on $\Phi^\pm$ pair-production [98] and a reinterpreted LEP selectron search [99–102] imply a lower bound $m_{\Phi^\pm} > 100 \text{ GeV}$ [103].

Regarding electroweak precision, there are no new tree-level contributions to $\rho \equiv \alpha T$. We follow [106] for one-loop corrections. T is always enhanced compared to the SM, staying in the allowed interval $T = 0.09 \pm 0.13$ [107] for $|m_{\Phi^\pm} - m_\Phi| \lesssim 120 \text{ GeV}$.

V. BBN

The bound on $\Delta N_{\text{eff}}^{\text{BBN}}$ during BBN [32] prohibits any of the new light species, Z' , N , or h_s , to be in thermal equilibrium with the SM during BBN. Ultimately, a thermal QFT analysis seems worthwhile to fully explore the early universe cosmology of this model for $T \gg v_\phi$. The coupled Boltzmann equations then should be solved to track abundances precisely, but this is beyond the scope of this paper. Nonetheless, an order of magnitude estimate suffices to clarify that there are parameters for which BBN proceeds as usual.

While $m_{Z'}$ is fixed by (4), M_N is limited by (19), and $m_{h_s} \approx \xi v_h \sqrt{2\lambda_S} \approx 7 \epsilon_m^2 \sqrt{\lambda_S} \text{ MeV}$. Hence, neither of these states can simply be pushed beyond the MeV scale to avoid BBN constraints. Instead, we discuss the possibility that all of them are sufficiently weakly coupled to the SM such that a thermal abundance is not retained. While all of the new fields thermalize with the SM at EW temperatures, this changes once the heavy scalars freeze out. The abundance of new light states is subsequently diluted by reheating in the SM. We thus focus on temperatures around BBN.

The coupling of Z' to the SM, as well as active-hidden neutrino mixing ϵ_m , is only effective after the $U(1)_X$ breaking phase transition [108]. This warrants that Z' does not thermalize with the SM between EW and BBN. Regarding h_s , the most relevant processes for thermalization

are $e^+e^- \leftrightarrow h_S h_S$, $e^-\gamma \leftrightarrow e^- h_S$, and $\nu\bar{\nu} \leftrightarrow h_S h_S$. None of them reaches thermal equilibrium due to the highly suppressed couplings of h_S . The leading process thermalizing N 's with the SM is $e^+e^-(\nu\bar{\nu}) \leftrightarrow N\bar{N}$ via t -channel $\Phi^\pm$ (Φ, A) exchange, which scales as $\Gamma \sim (y/m_{\Phi^{(\pm)}})^4 T^5$. Requiring this to be absent after QCD (EW) epoques demands $y \lesssim 6 \times 10^{-3(5)} (m_{\Phi^{(\pm)}}/100 \text{ GeV})$. Together with above bounds on ε_m and $\gamma \lesssim 0.2$ this implies $M \lesssim 300(3) \text{ eV}$. Consistency of our analysis requires $m_\nu \ll yv_\phi \ll M$, implying $y \gg 2 \times 10^{-5} (m_\nu/0.05 \text{ eV})$ and a lower bound on γ , shown in orange in Fig. 2 for $m_\nu = 0.05 \text{ eV}$ [109]. Noteworthy, this limits M_N to values which can resolve short baseline neutrino anomalies: *Either* in the well-known way with eV-scale states, see, e.g., [63,110], which however is already in considerable tension with other experiments [63] and certainly requires specific assumptions on the flavor dependence of the mixing angle ε_m . *Or*, by realizing the novel “decaying sterile neutrino solution” for $M_N \sim \mathcal{O}(100) \text{ eV}$ [111,112], which requires the assumption $\varepsilon_m^e \gg \varepsilon_m^\mu$ [111].

Finally, we note that despite bearing some danger for BBN, the new states can also be a virtue: To resolve the HT with self-interacting neutrinos, N_{eff} must be enhanced to $\Delta N_{\text{eff}}^{\text{CMB}} \approx 1$ during recombination [28,29], requiring some energy injection in the dark sector after BBN. The thermalization of N, h_S, Z' with n flavors of active neutrinos after BBN produces entropy [113] which is released back to the neutrino background after the new states decay, before recombination. This would heat the neutrinos to $T'_\nu \approx [1 + 30/7n]^{1/12} T_\nu$ resulting in $\Delta N_{\text{eff}}^{\text{CMB}} \approx 1.03, 0.93, 0.74$ for $n = 3, 2, 1$. Regarding the decays of the light states to neutrinos, we note that h_S decays to $\bar{N}_1 \nu$ and $\bar{N}_1 N_2$, but in absence of L -violation not to $\bar{\nu} N_2$, $\bar{N}_{1(2)} N_{1(2)}$ or $\bar{\nu} \nu$ (or all processes barred), with $\Gamma_{h_S} \propto y^2 s_\gamma^2 \cdot \tau_{h_S}$, therefore, is extremely dependent on the exact parameters ranging from milli- to picoseconds. Two-body decays $N \rightarrow Z' \nu$ contribute, provided $M_N > m_{Z'} + m_\nu$. For $M_N < m_{Z'} + m_\nu$, on the other hand, only three-body decays $N \rightarrow (2\nu)\bar{\nu}$ are possible with lifetime $\tau_N \sim (8\pi)^{-3} M_N^5 G_{\text{eff}}^{4\nu^2} \varepsilon_m^{-2}$. Depending on the exact parameters, a population of N , thus, *could* but doesn't have to decay before recombination.

VI. DISCUSSION

We have presented a consistent (renormalizable and phenomenologically viable) model that leads to vector-mediated neutrino self-interactions. In a narrow region of parameter space these interactions have the right strength to resolve the tensions between local and global determinations of H_0 and σ_8 [114]. To consistently implement such interactions in the SM, we had to introduce a second Higgs doublet and a new Dirac fermion, both charged under a new $U(1)_X$ gauge symmetry. Phenomenological consistency

required the introduction of the $U(1)_X$ charged SM singlet scalar S .

There are several new states, all with very lepton-specific couplings: h_S with mass of $\mathcal{O}(10 \text{ keV})$, as well as Φ , pseudo-scalar A and the charged scalars $\Phi^\pm$ all with masses of $\mathcal{O}(100 \text{ GeV})$. The new, naturally neutrinophilic fore carrier has a mass of $m_{Z'} \sim \mathcal{O}(10 \text{ eV})$, and the new hidden neutrinos masses in the range $M_N \sim 1 \div 300 \text{ eV}$ and mixing angles $\varepsilon_m > 5 \times 10^{-4}$. The allowed parameter space can be narrowed down by more precise measurements of Higgs $\rightarrow \text{inv.}$ and searches for leptophilic charged Higgses at the HL-LHC and future colliders such as ILC, CLIC, or FCC-he/hh. Other testable signatures include non-standard neutrino matter interactions with maximal strength $G_{\text{eff}}^{(2\nu)(2f \neq \nu)} \sim \mathcal{O}(10^{-4}) G_F$, as well as distortions of short baseline neutrino oscillations.

That our model works without specifying the mechanism of neutrino mass generation may feel like a drawback to some. We think this is a virtue, as it renders this scenario compatible with all standard neutrino mass generation mechanisms.

The least appealing feature of our model, perhaps, is the introduction of several new scales (v_ϕ, v_s, μ, M), and some hierarchies among them. We have nothing to say here about this or any other hierarchy problem but simply accepted this fact for the reason that we are convinced that this is the simplest renormalizable model in which *active* neutrinos pick up gauged self-interactions. Stabilizing these hierarchies against radiative corrections might require smaller scalar quartic cross-couplings than the direct constraints discussed above. Suchlike would not contradict any of our findings.

Finally, our analysis also shows that “model independent” considerations are actually not always valid in concrete models. On the contrary, only complete models allow to directly relate early universe cosmology, like the Hubble tension, to physics testable in laboratories.

ACKNOWLEDGMENTS

We would like to thank V. Brdar, L. Graf, and M. E. Krauss for useful conversations as well as O. Fischer, A. Ghoshal, M. Ratz, and S. Vogl for comments on the manuscript. In particular we thank S. Vogl for pointing out the entropy production in the hidden sector re- and decoupling dynamics. This work benefited from using the computer codes SARAH [115], FeynArts/FormCalc [116,117], and PackageX [118].

Note added.—During the completion of this work, Ref. [119] appeared on the arXiv which discusses a different UV complete model for self-interacting neutrinos.

- [1] A. G. Riess *et al.*, A 2.4% determination of the local value of the Hubble constant, *Astrophys. J.* **826**, 56 (2016).
- [2] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri, and D. Scolnic, Large magellanic cloud cepheid standards provide a 1% foundation for the determination of the hubble constant and stronger evidence for physics beyond Λ CDM, *Astrophys. J.* **876**, 85 (2019).
- [3] W. L. Freedman *et al.*, The Carnegie-Chicago Hubble Program. VIII. An independent determination of the Hubble constant based on the tip of the red giant branch, *Astrophys. J.* **882**, 34 (2019).
- [4] S. Birrer *et al.*, H0LiCOW—IX. Cosmographic analysis of the doubly imaged quasar SDSS 1206 + 4332 and a new measurement of the Hubble constant, *Mon. Not. R. Astron. Soc.* **484**, 4726 (2019).
- [5] K. C. Wong *et al.*, H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3σ tension between early and late-Universe probes, *Mon. Not. R. Astron. Soc.* **498**, 1420 (2020).
- [6] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020).
- [7] F. Khlinger *et al.*, KiDS-450: The tomographic weak lensing power spectrum and constraints on cosmological parameters, *Mon. Not. R. Astron. Soc.* **471**, 4412 (2017).
- [8] S. Joudaki *et al.*, KiDS-450 + 2dFLenS: Cosmological parameter constraints from weak gravitational lensing tomography and overlapping redshift-space galaxy clustering, *Mon. Not. R. Astron. Soc.* **474**, 4894 (2018).
- [9] S. Joudaki *et al.*, KiDS+VIKING-450 and DES-Y1 combined: Cosmology with cosmic shear, *Astron. Astrophys.* **638**, L1 (2020).
- [10] S. Alam *et al.* (BOSS Collaboration), The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Cosmological analysis of the DR12 galaxy sample, *Mon. Not. R. Astron. Soc.* **470**, 2617 (2017).
- [11] O. H. E. Philcox, M. M. Ivanov, M. Simonovi, and M. Zaldarriaga, Combining full-shape and BAO analyses of galaxy power spectra: A 1.6% CMB-independent constraint on H_0 , *J. Cosmol. Astropart. Phys.* **05** (2020) 032.
- [12] M. A. Troxel *et al.* (DES Collaboration), Dark Energy Survey Year 1 results: Cosmological constraints from cosmic shear, *Phys. Rev. D* **98**, 043528 (2018).
- [13] T. M. C. Abbott *et al.* (DES Collaboration), Dark energy survey year 1 results: A precise H_0 estimate from DES Y1, BAO, and D/H data, *Mon. Not. R. Astron. Soc.* **480**, 3879 (2018).
- [14] T. M. C. Abbott *et al.* (DES Collaboration), Dark energy survey year 1 results: Measurement of the baryon acoustic oscillation scale in the distribution of galaxies to redshift 1, *Mon. Not. R. Astron. Soc.* **483**, 4866 (2019).
- [15] C. Hikage *et al.* (HSC Collaboration), Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data, *Publ. Astron. Soc. Jpn.* **71**, 43 (2019).
- [16] M. H. Abdullah, A. Klypin, and G. Wilson, Cosmological constraint on Ω_m and σ_8 from cluster abundances using the GalWCat19 optical-spectroscopic SDSS catalog, *Astrophys. J.* **901**, 90 (2020).
- [17] E. Di Valentino, A. Melchiorri, and J. Silk, Planck evidence for a closed Universe and a possible crisis for cosmology, *Nat. Astron.* **4**, 196 (2020).
- [18] E. Di Valentino, A. Melchiorri, and J. Silk, Cosmic discordance: Planck and luminosity distance data exclude Λ CDM, *arXiv:2003.04935*.
- [19] N. Schneberg, J. Lesgourgues, and D. C. Hooper, The BAO + BBN take on the Hubble tension, *J. Cosmol. Astropart. Phys.* **10** (2019) 029.
- [20] L. Knox and M. Millea, The Hubble hunter's guide, *Phys. Rev. D* **101**, 043533 (2020).
- [21] M. Escudero and S. J. Witte, A CMB search for the neutrino mass mechanism and its relation to the H_0 tension, *Eur. Phys. J. C* **80**, 294 (2020).
- [22] J. Sakstein and M. Trodden, Early Dark Energy from Massive Neutrinos—A Natural Resolution of the Hubble Tension, *Phys. Rev. Lett.* **124**, 161301 (2020).
- [23] L. Verde, T. Treu, and A. G. Riess, Tensions between the early and the late universe, *Nat. Astron.* **3**, 891 (2019).
- [24] F.-Y. Cyr-Racine and K. Sigurdson, Limits on neutrino-neutrino scattering in the early universe, *Phys. Rev. D* **90**, 123533 (2014).
- [25] M. Archidiacono and S. Hannestad, Updated constraints on non-standard neutrino interactions from Planck, *J. Cosmol. Astropart. Phys.* **07** (2014) 046.
- [26] L. Lancaster, F.-Y. Cyr-Racine, L. Knox, and Z. Pan, A tale of two modes: Neutrino free-streaming in the early universe, *J. Cosmol. Astropart. Phys.* **07** (2017) 033.
- [27] I. M. Oldengott, T. Tram, C. Rampf, and Y. Y. Y. Wong, Interacting neutrinos in cosmology: Exact description and constraints, *J. Cosmol. Astropart. Phys.* **11** (2017) 027.
- [28] C. D. Kreisch, F.-Y. Cyr-Racine, and O. Dor, The neutrino puzzle: Anomalies, interactions, and cosmological tensions, *Phys. Rev. D* **101**, 123505 (2020).
- [29] M. Park, C. D. Kreisch, J. Dunkley, B. Hadzhiyska, and F.-Y. Cyr-Racine, Λ CDM or self-interacting neutrinos: How CMB data can tell the two models apart, *Phys. Rev. D* **100**, 063524 (2019).
- [30] F. Forastieri, M. Lattanzi, and P. Natoli, Constraints on secret neutrino interactions after Planck, *J. Cosmol. Astropart. Phys.* **07** (2015) 014.
- [31] F. Forastieri, M. Lattanzi, and P. Natoli, Cosmological constraints on neutrino self-interactions with a light mediator, *Phys. Rev. D* **100**, 103526 (2019).
- [32] B. D. Fields, K. A. Olive, T.-H. Yeh, and C. Young, Big-bang nucleosynthesis after Planck, *J. Cosmol. Astropart. Phys.* **03** (2020) 010.
- [33] A model similar to ours, albeit in a different parameter region has been investigated in [34–36]. However, baryons are neutral under our $U(1)_X$, implying the absence of large nonstandard neutrino-matter interactions.
- [34] Y. Farzan and J. Heeck, Neutrinophilic nonstandard interactions, *Phys. Rev. D* **94**, 053010 (2016).
- [35] Y. Farzan and M. Tortola, Neutrino oscillations and non-standard interactions, *Front. Phys.* **6**, 10 (2018).
- [36] P. B. Denton, Y. Farzan, and I. M. Shoemaker, Activating the fourth neutrino of the $3 + 1$ scheme, *Phys. Rev. D* **99**, 035003 (2019).
- [37] We use abbreviations $\sin \theta_i \equiv s_i$, $\cos \theta_i \equiv c_i$, and $\tan \theta_i \equiv t_i$ for all angles θ_i in this work.

- [38] s_X can be modified by gauge-kinetic mixing, we comment on this below Eq. (27).
- [39] S. Weinberg, Baryon and Lepton Nonconserving Processes, *Phys. Rev. Lett.* **43**, 1566 (1979).
- [40] R. N. Mohapatra, New contributions to neutrinoless double-beta decay in supersymmetric theories, *Phys. Rev. D* **34**, 3457 (1986).
- [41] E. Bertuzzo, S. Jana, P. A. N. Machado, and R. Zukanovich Funchal, Neutrino masses and mixings dynamically generated by a light dark sector, *Phys. Lett. B* **791**, 210 (2019).
- [42] P. S. B. Dev and A. Pilaftsis, Minimal radiative neutrino mass mechanism for inverse seesaw models, *Phys. Rev. D* **86**, 113001 (2012).
- [43] S. Gabriel and S. Nandi, A new two Higgs doublet model, *Phys. Lett. B* **655**, 141 (2007).
- [44] S. Baek and T. Nomura, Dark matter physics in neutrino specific two Higgs doublet model, *J. High Energy Phys.* **03** (2017) 059.
- [45] E. Bertuzzo, P. A. N. Machado, Z. Tabrizi, and R. Zukanovich Funchal, A neutrinophilic 2HDM as a UV completion for the inverse Seesaw mechanism, *J. High Energy Phys.* **11** (2017) 004.
- [46] T. Nomura and H. Okada, Hidden $U(1)$ gauge symmetry realizing a neutrinophilic two-Higgs-doublet model with dark matter, *Phys. Rev. D* **97**, 075038 (2018).
- [47] S. Baek, A. Das, and T. Nomura, Scalar dark matter search from the extended ν THDM, *J. High Energy Phys.* **05** (2018) 205.
- [48] U. K. Dey, N. Nath, and S. Sadhukhan, Non-standard neutrino interactions in a modified ν 2HDM, *Phys. Rev. D* **98**, 055004 (2018).
- [49] We use tadpole conditions to trade $\mu_{H,\Phi,S}$ for other parameters. $m_{\Phi^\pm}^2, m_{h_S}^2 > 0$ imply constraints on the parameter space, see Fig. 2.
- [50] J. Beacham *et al.*, Physics beyond colliders at CERN: Beyond the standard model working group report, *J. Phys. G* **47**, 010501 (2020).
- [51] P. Galison and A. Manohar, Two Z's or not two Z's? *Phys. Lett.* **136B**, 279 (1984).
- [52] B. Holdom, Two $U(1)$'s and epsilon charge shifts, *Phys. Lett.* **166B**, 196 (1986).
- [53] M. Baumgart, C. Cheung, J. T. Ruderman, L.-T. Wang, and I. Yavin, Non-Abelian dark sectors and their collider signatures, *J. High Energy Phys.* **04** (2009) 014.
- [54] K. Babu, A. Friedland, P. Machado, and I. Mocioiu, Flavor gauge models below the Fermi scale, *J. High Energy Phys.* **12** (2017) 096.
- [55] J. Redondo, Atlas of solar hidden photon emission, *J. Cosmol. Astropart. Phys.* **07** (2015) 024.
- [56] T. Gherghetta, J. Kersten, K. Olive, and M. Pospelov, Evaluating the price of tiny kinetic mixing, *Phys. Rev. D* **100**, 095001 (2019).
- [57] A. de Gouvea and A. Kobach, Global constraints on a heavy neutrino, *Phys. Rev. D* **93**, 033005 (2016).
- [58] D. A. Bryman and R. Shrock, Improved constraints on sterile neutrinos in the MeV to GeV mass range, *Phys. Rev. D* **100**, 053006 (2019).
- [59] D. A. Bryman and R. Shrock, Constraints on sterile neutrinos in the MeV to GeV mass range, *Phys. Rev. D* **100**, 073011 (2019).
- [60] P. D. Bolton, F. F. Deppisch, and P. Bhupal Dev, Neutrinoless double beta decay versus other probes of heavy sterile neutrinos, *J. High Energy Phys.* **03** (2020) 170.
- [61] S. Antusch and O. Fischer, Non-unitarity of the leptonic mixing matrix: Present bounds and future sensitivities, *J. High Energy Phys.* **10** (2014) 094.
- [62] E. Fernandez-Martinez, J. Hernandez-Garcia, and J. Lopez-Pavon, Global constraints on heavy neutrino mixing, *J. High Energy Phys.* **08** (2016) 033.
- [63] M. Dentler, A. Hernandez-Cabezudo, J. Kopp, P. A. N. Machado, M. Maltoni, I. Martinez-Soler, and T. Schwetz, Updated global analysis of neutrino oscillations in the presence of eV-scale sterile neutrinos, *J. High Energy Phys.* **08** (2018) 010.
- [64] R. Laha, B. Dasgupta, and J. F. Beacom, Constraints on new neutrino interactions via light Abelian vector bosons, *Phys. Rev. D* **89**, 093025 (2014).
- [65] K. C. Y. Ng and J. F. Beacom, Cosmic neutrino cascades from secret neutrino interactions, *Phys. Rev. D* **90**, 065035 (2014); Erratum, *Phys. Rev. D* **90**, 089904 (2014).
- [66] K. Ioka and K. Murase, IceCube PeVEeV neutrinos and secret interactions of neutrinos, *Prog. Theor. Exp. Phys.* **2014**, 061E01 (2014).
- [67] M. Bustamante, C. A. Rosenstroem, S. Shalgar, and I. Tamborra, Bounds on secret neutrino interactions from high-energy astrophysical neutrinos, *Phys. Rev. D* **101**, 123024 (2020).
- [68] N. Blinov, K. J. Kelly, G. Z. Krnjaic, and S. D. McDermott, Constraining the Self-Interacting Neutrino Interpretation of the Hubble Tension, *Phys. Rev. Lett.* **123**, 191102 (2019).
- [69] V. Brdar, M. Lindner, S. Vogl, and X.-J. Xu, Revisiting neutrino self-interaction constraints from Z and τ decays, *Phys. Rev. D* **101**, 115001 (2020).
- [70] A. de Gouvea, P. B. Dev, B. Dutta, T. Ghosh, T. Han, and Y. Zhang, Leptonic scalars at the LHC, *J. High Energy Phys.* **07** (2020) 142.
- [71] K.-F. Lyu, E. Stamou, and L.-T. Wang, Self-interacting neutrinos: Solution to Hubble tension versus experimental constraints, *arXiv:2004.10868* [Phys. Rev. D (to be published)].
- [72] K. M. Belotsky, A. L. Sudarikov, and M. Yu. Khlopov, Constraint on anomalous 4ν interaction, *Yad. Fiz.* **64**, 1718 (2001) [*Phys. At. Nucl.* **64**, 1637 (2001)].
- [73] A. P. Lessa and O. L. G. Peres, Revising limits on neutrino-Majoron couplings, *Phys. Rev. D* **75**, 094001 (2007).
- [74] L. Fiorini (NA48/2 Collaboration), Testing LFV measuring the ratio $R(K)$ between the branching ratio of $K^\pm \rightarrow e^\pm \nu(\gamma)$ and $K^\pm \rightarrow \mu^\pm \nu(\gamma)$ in NA48/2 experiment: Measurement and perspectives, *Nucl. Phys. B, Proc. Suppl.* **169**, 205 (2007).
- [75] P. Bakhti and Y. Farzan, Constraining secret gauge interactions of neutrinos by meson decays, *Phys. Rev. D* **95**, 095008 (2017).
- [76] J. A. Dror, R. Lasenby, and M. Pospelov, New Constraints on Light Vectors Coupled to Anomalous Currents, *Phys. Rev. Lett.* **119**, 141803 (2017).
- [77] J. A. Dror, R. Lasenby, and M. Pospelov, Dark forces coupled to nonconserved currents, *Phys. Rev. D* **96**, 075036 (2017).

- [78] P. Bakhti, Y. Farzan, and M. Rajaei, Secret interactions of neutrinos with light gauge boson at the DUNE near detector, *Phys. Rev. D* **99**, 055019 (2019).
- [79] J. A. Dror, R. Lasenby, and M. Pospelov, Light vectors coupled to bosonic currents, *Phys. Rev. D* **99**, 055016 (2019).
- [80] M. Bahraminasr, P. Bakhti, and M. Rajaei, Sensitivities to secret neutrino interaction at FASER ν , [arXiv:2003.09985](https://arxiv.org/abs/2003.09985).
- [81] J. A. Dror, Discovering leptonic forces using non-conserved currents, *Phys. Rev. D* **101**, 095013 (2020).
- [82] C. D. Carone, Double beta decay with vector majorons, *Phys. Lett. B* **308**, 85 (1993).
- [83] M. Agostini *et al.*, Results on $\beta\beta$ decay with emission of two neutrinos or Majorons in ^{76}Ge from GERDA Phase I, *Eur. Phys. J. C* **75**, 416 (2015).
- [84] K. Blum, Y. Nir, and M. Shavit, Neutrinoless double-beta decay with massive scalar emission, *Phys. Lett. B* **785**, 354 (2018).
- [85] T. Brune and H. Ps, Massive Majorons and constraints on the Majoron-neutrino coupling, *Phys. Rev. D* **99**, 096005 (2019).
- [86] F. F. Deppisch, L. Graf, W. Rodejohann, and X.-J. Xu, Neutrino self-interactions and double beta decay, *Phys. Rev. D* **102**, 051701 (2020).
- [87] E. W. Kolb and M. S. Turner, Supernova SN 1987a and the secret interactions of neutrinos, *Phys. Rev. D* **36**, 2895 (1987).
- [88] P. Gondolo and G. Gelmini, Cosmic abundances of stable particles: Improved analysis, *Nucl. Phys. B* **360**, 145 (1991).
- [89] G. Arcadi, O. Lebedev, S. Pokorski, and T. Toma, Real scalar dark matter: Relativistic treatment, *J. High Energy Phys.* **08** (2019) 050.
- [90] O. Lebedev and T. Toma, Relativistic freeze-in, *Phys. Lett. B* **798**, 134961 (2019).
- [91] N. Blinov and G. Marques-Tavares, Interacting radiation after Planck and its implications for the Hubble tension, *J. Cosmol. Astropart. Phys.* **09** (2020) 029.
- [92] M. Tanabashi *et al.* (Particle Data Group Collaboration), Review of particle physics, *Phys. Rev. D* **98**, 030001 (2018).
- [93] M. Cepeda *et al.*, Report from Working Group 2, CERN Yellow Rep. Monogr. **7**, 221 (2019), <http://cds.cern.ch/record/2650162?ln=de>.
- [94] ATLAS Collaboration, Search for invisible Higgs boson decays with vector boson fusion signatures with the ATLAS detector using an integrated luminosity of 139 fb $^{-1}$, <https://cds.cern.ch/record/2715447>.
- [95] M. Carena, A. de Gouvea, A. Freitas, and M. Schmitt, Invisible Z boson decays at e+ e- colliders, *Phys. Rev. D* **68**, 113007 (2003).
- [96] M. Aaboud *et al.* (ATLAS Collaboration), Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **11** (2018) 085.
- [97] A. M. Sirunyan *et al.* (CMS Collaboration), Search for a charged Higgs boson decaying into top and bottom quarks in events with electrons or muons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **01** (2020) 096.
- [98] G. Abbiendi *et al.* (ALEPH, DELPHI, L3, OPAL, and LEP Collaborations), Search for charged Higgs bosons: Combined results using LEP data, *Eur. Phys. J. C* **73**, 2463 (2013).
- [99] A. Heister *et al.* (ALEPH Collaboration), Search for scalar leptons in e+ e- collisions at center-of-mass energies up to 209-GeV, *Phys. Lett. B* **526**, 206 (2002).
- [100] G. Abbiendi *et al.* (OPAL Collaboration), Search for anomalous production of dilepton events with missing transverse momentum in e+ e- collisions at $s^{*}(1/2) = 183\text{-GeV}$ to 209-GeV, *Eur. Phys. J. C* **32**, 453 (2004).
- [101] P. Achard *et al.* (L3 Collaboration), Search for scalar leptons and scalar quarks at LEP, *Phys. Lett. B* **580**, 37 (2004).
- [102] J. Abdallah *et al.* (DELPHI Collaboration), Searches for supersymmetric particles in e+ e- collisions up to 208-GeV and interpretation of the results within the MSSM, *Eur. Phys. J. C* **31**, 421 (2003).
- [103] Sometimes $m_{\Phi^{\pm}} \gtrsim 275$ GeV is quoted based on [104]. However, this requires assumptions on $\Phi^{\pm}$ -BRs see [[105], Sec. 4.7] for details.
- [104] V. Khachatryan *et al.* (CMS Collaboration), Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV, *Eur. Phys. J. C* **74**, 3036 (2014).
- [105] K. S. Babu, P. S. B. Dev, S. Jana, and A. Thapa, Non-standard interactions in radiative neutrino mass models, *J. High Energy Phys.* **03** (2020) 006.
- [106] W. Grimus, L. Lavoura, O. M. Ogreid, and P. Osland, A Precision constraint on multi-Higgs-doublet models, *J. Phys. G* **35**, 075001 (2008).
- [107] M. Baak, J. Cth, J. Haller, A. Hoecker, R. Kogler, K. Mnig, M. Schott, and J. Stelzer (Gfitter Group Collaboration), The global electroweak fit at NNLO and prospects for the LHC and ILC, *Eur. Phys. J. C* **74**, 3046 (2014).
- [108] L. Vecchi, Light sterile neutrinos from a late phase transition, *Phys. Rev. D* **94**, 113015 (2016).
- [109] This is the minimal possible value of m_{ν} for at least one generation, as allowed by neutrino oscillation experiments.
- [110] S. Bser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens, A. Schukraft, and M. Wurm, Status of light sterile neutrino searches, *Prog. Part. Nucl. Phys.* **111**, 103736 (2020).
- [111] M. Dentler, I. Esteban, J. Kopp, and P. Machado, Decaying sterile neutrinos and the short baseline oscillation anomalies, *Phys. Rev. D* **101**, 115013 (2020).
- [112] A. de Gouvea, O. L. G. Peres, S. Prakash, and G. V. Stenico, On the decaying-sterile neutrino solution to the electron (anti)neutrino appearance anomalies, *J. High Energy Phys.* **07** (2020) 141.
- [113] R. S. L. Hansen and S. Vogl, Thermalizing Sterile Neutrino Dark Matter, *Phys. Rev. Lett.* **119**, 251305 (2017).
- [114] Our model is viable also in a different parameter space not discussed here: For $m_{Z'} \ll \text{eV}$ and $g_X \ll 10^{-7}$, active neutrinos recouple only after recombination, with crucial impacts on the CMB.
- [115] F. Staub, SARAH 4: A tool for (not only SUSY) model builders, *Comput. Phys. Commun.* **185**, 1773 (2014).

- [116] T. Hahn, Generating Feynman diagrams and amplitudes with FeynArts 3, *Comput. Phys. Commun.* **140**, 418 (2001).
- [117] T. Hahn and M. Perez-Victoria, Automatized one loop calculations in four-dimensions and D-dimensions, *Comput. Phys. Commun.* **118**, 153 (1999).
- [118] H. H. Patel, Package-X: A *Mathematica* package for the analytic calculation of one-loop integrals, *Comput. Phys. Commun.* **197**, 276 (2015).
- [119] H.-J. He, Y.-Z. Ma, and J. Zheng, Resolving Hubble tension by self-interacting neutrinos with Dirac Seesaw, *J. Cosmol. Astropart. Phys.* **11** (2020) 003.