Minimal Realization of Light Thermal Dark Matter

Johannes Herms,[1,*] Sudip Jana,[1,†] Vishnu P. K.,[2,‡] and Shaikh Saad[3,§]
[1]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[2]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[3]*Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland*

(Received 24 March 2022; accepted 4 August 2022; published 25 August 2022)

We propose a minimal UV-complete model for kinematically forbidden dark matter (DM) leading to a sub-GeV thermal relic. Our crucial realization is that the two-Higgs-doublet model can provide a light mediator through which the DM can annihilate into standard model leptons, avoiding indirect detection constraints. The DM mass is predicted to be very close to the mass of the leptons, which can potentially be identified from DM annihilation into gamma rays. Because of the sizable couplings to muons required to reproduce the DM relic abundance, this framework naturally favors a resolution to the $(g-2)_\mu$ anomaly. Furthermore, by embedding this setup to the Zee model, we show that the phenomenon of neutrino oscillations is inherently connected to the observed relic abundance of DM. All new physics involved in our framework lies at or below the electroweak scale, making it testable at upcoming colliders, beam-dump experiments, and future sub-GeV gamma-ray telescopes.

DOI: 10.1103/PhysRevLett.129.091803

Introduction.—Dark matter (DM) is a central part of our understanding of the cosmos, and identifying its nature is a key goal of contemporary cosmology, astrophysics, and particle physics. A prime candidate for DM is thermal relic particles—a new neutral, long-lived particle species that was in thermal equilibrium with the particles of the standard model (SM) in the early Universe before the connecting interactions froze out when it reached the DM abundance we observe today.

This weakly interacting massive particle (WIMP) DM scenario motivated great experimental efforts to identify these particles. Traditionally, the focus has been on electroweak-scale (EW-scale) WIMPs (see, e.g., Refs. [1,2]) since these are expected in many theories beyond the standard model and can naturally decouple at the correct abundance. With the experimental program to search for EW-scale DM particles well underway, and at the same time, the degree of confidence in new physics at the EW-scale waning in the face of the success of the SM at the LHC, thermal relics at smaller masses have become a focus of attention. This trend in DM studies is supported by connections to low-energy anomalies in particle physics, in particular, the $(g-2)_\mu$ tension [3], and can relate to neutrino physics; see, e.g., Ref. [4].

Thermal DM in the mass range MeV $\lesssim m_{\rm DM} \lesssim 10$ GeV requires a few general conditions. It typically requires a stabilizing symmetry to suppress decay, in contrast to lighter, keV-scale DM candidates like sterile neutrinos [5–7]. Equilibration with the SM in the early Universe then proceeds via annihilation. The annihilation products cannot be much heavier than the DM candidate, necessitating a coupling to light SM particles. In contrast to heavier WIMPs, successful sub-GeV freeze-out DM generically requires the existence of a new light mediator to enable a sufficiently large annihilation rate [8]. For this reason, many models in the literature propose to extend the gauge symmetry [11] of the theory by a $U(1)_D$, with a dark photon that can mediate between the dark and visible sectors (see, for instance, Refs. [9,12–14]).

In contrast to these previous DM theories that include new gauge sectors (e.g., [9,12–14]) or multifermionic extensions (e.g., [12,15,16]), this Letter presents a minimal, ultraviolet-complete (UV) model of sub-GeV thermal DM. Our proposal is based on the crucial fact that adding a second Higgs doublet [17] to the SM allows for a light scalar [18] that can couple to the light SM degrees of freedom and DM particles. Specifically, we work in the two-Higgs-doublet model (2HDM) framework, where DM annihilates into SM leptons via a light mediator emerging from the 2HDM. The simplest DM candidate is a real scalar stabilized by a $\mathbb{Z}_2$ symmetry that can easily reproduce the observed relic abundance via the 2HDM portal (see, e.g., Refs. [19–23] for related work on EW-scale WIMPs).

After taking into account constraints on DM annihilation today and during the epoch of cosmic microwave background (CMB) decoupling, the DM mass is required to be in the "forbidden" regime [13,16,24], where it is just slightly lighter than the SM particle it annihilates into. This makes for a predictive and positively identifiable framework, motivating in particular searches for sub-GeV gamma-ray lines close to SM lepton masses. Furthermore, the favored parameter space implies a positive shift for muon $g-2$ with the proper sign and strength to account for the measurement at Fermilab [3].

A simple extension of this setup by a charged scalar generates nonzero neutrino masses via one-loop quantum corrections. Within this framework, the same Yukawa couplings reproducing the correct DM relic abundance also participate in neutrino mass generation while remaining consistent with lepton flavor violation (LFV) constraints.

To demonstrate the versatility of the light 2HDM scalar portal, we also entertain the scenario of fermionic DM (see also Refs. [25–27]). A singlet fermion (Dirac or Majorana) DM can annihilate into SM leptons via a singlet scalar that mixes with the light scalar arising from the 2HDM.

In the following, before presenting minimal models for scalar and fermionic sub-GeV DM, we first recapitulate the thermal freeze-out mechanism for DM production. We present constraints from DM relic density, $(g-2)_\mu$, flavor violation, and DM indirect detection. Before concluding, we briefly demonstrate how neutrino masses can be naturally incorporated into the light-2HDM scenario.

Forbidden DM.—The relic density of thermal DM is calculated by tracing its evolution in the early Universe. If the decay of DM into SM particles is precluded by symmetry, the leading number-changing term in the Boltzmann equation stems from annihilations of pairs of DM particles

$$\frac{dn_{\rm DM}}{dt} + 3Hn_\chi = \zeta\langle\sigma v\rangle(n_{\rm DM}^2 - n_{\rm DM}^{\rm eq2}), \tag{1}$$

where $n_{\rm DM}$ is the total DM number density, H is the Hubble expansion rate, and $\langle\sigma v\rangle$ is the thermally averaged cross section of DM annihilation ($\zeta = (1/2)1$ for (non)self-conjugate DM particles). In the freeze-out scenario, the relic density is determined by the time (or the corresponding SM bath temperature, $T_{\rm fo}$) when the annihilation rate drops below the Hubble rate

$$\zeta\langle\sigma v\rangle n_{\rm DM}^{\rm eq} = H. \tag{2}$$

It is often sufficient to work in the instantaneous freeze-out approximation, where the comoving DM density (denoted in terms of the abundance $Y \equiv n/s$, with s the SM entropy density) stays constant after freeze-out

$$Y_{\rm DM}^{\rm today} = Y_{\rm DM}^{\rm eq}(T_{\rm fo}). \tag{3}$$

This is to be compared to the observed DM density $\Omega_{\rm DM}h^2 = 0.12$ [28],

$$Y_{\rm DM}^{\rm obs} = \frac{n_{\rm DM}}{s_0} = \Omega_{\rm DM}\frac{\rho_C}{m_{\rm DM}s_0} = 4.35\times10^{-10}\left(\frac{m_{\rm DM}}{\rm GeV}\right)^{-1}. \tag{4}$$

Requiring freeze-out at the correct temperature to reproduce the observed relic abundance determines $\langle\sigma v\rangle$.

The generic implication of the WIMP scenario is DM annihilation, with $\langle\sigma v\rangle_{\rm fo} \sim {\rm pb}\,c$ at $T_{\rm fo} \sim m_{\rm DM}/20$. For sub-GeV DM, this can be a problem, since $\langle\sigma v\rangle_{\rm CMB\ epoch} = \langle\sigma v\rangle_{\rm fo}$ results in excessive energy injection into the SM plasma during CMB decoupling for $m_{\rm DM} \lesssim 10$ GeV [28,29].

In this Letter, we consider the "forbidden DM" scenario [13,16], where the DM particles $\chi\chi$ are slightly lighter than the bath particles $l_1\bar{l}_2$ they annihilate into. The leading annihilation rate $\langle\sigma v\rangle_{\chi\chi\to l_1\bar{l}_2} \simeq (1/2\zeta)\langle\sigma v\rangle_{l_1\bar{l}_2\to\chi\chi}e^{-2\Delta x}$ is then Boltzmann suppressed [30], where n_{l_i} denote the number density of l_i particles plus antiparticles and $n_{\rm DM}$ denotes the total DM number density, while $\Delta \equiv (m_{l_1} + m_{l_2} - 2m_{\rm DM})/2m_{\rm DM}$ and $x = m_{\rm DM}/T$. Tree-level DM annihilation is strongly suppressed at low temperature for $\Delta > 0$, evading CMB and cosmic ray probes. Radiative annihilation, however, is not forbidden, and gamma-ray line signals at energies just below SM particle masses can be a powerful and specific probe of the present scenario, as discussed later in the text.

Models.—We present a minimal scenario for forbidden DM. Our UV-complete model is a simple extension of the 2HDM [17] by a scalar singlet S, which qualifies as a DM candidate. The stability of DM is ensured by a discrete $\mathcal{Z}_2$ symmetry, under which only the DM transforms nontrivially. In the Higgs basis, when only one neutral Higgs acquires a nonzero vacuum expectation value, the Higgs doublets can be parametrized as

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+\phi_1^0+iG^0) \end{pmatrix}, \quad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\phi_2^0+iA) \end{pmatrix}. \tag{5}$$

Here, G^+ and G^0 are the Goldstone modes, whereas H^+ and $\{\phi_1^0, \phi_2^0, A\}$ are the physical Higgs bosons. The vacuum expectation value $v \simeq 246$ GeV of H_1 governs EW symmetry breaking. In the Higgs basis the most general scalar potential for the model can be written as

$$\begin{aligned} V = {}& \sum_{i=1}^{2}\left(\mu_i^2 + \sum_{i=1}^{2}\frac{\lambda_i}{2}H_i^\dagger H_i\right)H_i^\dagger H_i + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) \\ & + \lambda_4(H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{\frac{\mu_S^2}{2} + \frac{\lambda_S}{4!}S^2 + \sum_{i=1}^{2}\frac{\kappa_i}{2}H_i^\dagger H_i\right\}S^2 \\ & + \Bigg\{\Bigg(-\mu_{12}^2 + \frac{\lambda_5}{2}H_1^\dagger H_2 \\ & + \sum_{i=1}^{2}\lambda_{i+5}H_i^\dagger H_i + \frac{\kappa_{12}}{2}S^2\Bigg)H_1^\dagger H_2 + {\rm H.c.}\Bigg\}. \end{aligned} \tag{6}$$

We work in the alignment limit [17,31–33], where the SM Higgs $\phi_1^0 \approx h$ decouples from the new CP-even Higgs

($\phi_2^0 \approx H$). The masses of the physical scalar states in this limit are

$$m_h^2 = \lambda_1 v^2, \qquad m_H^2 = \mu_2^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5), \quad (7)$$

$$m_A^2 = m_H^2 - v^2\lambda_5, \qquad m_{H^\pm}^2 = m_H^2 - \frac{v^2}{2}(\lambda_4 + \lambda_5), \quad (8)$$

$$m_S^2 = \mu_S^2 + \frac{\kappa_1}{2} v^2, \quad (9)$$

From the above mass relations, it is clear that H can be made light independently from A and $H^\pm$ by appropriately choosing values for quartic couplings λ_4 and λ_5. For example, if we set $m_A, m_{H^\pm} \simeq 110$ GeV, this will imply that $\lambda_4 = \lambda_5 \simeq -0.2$ (here we have neglected the small mass of H scalar). The emergence of this light state from the 2HDM is the key to realizing light thermal DM.

In our analysis, both for simplicity and possible connections to muon and neutrino properties, we consider the second doublet to be predominantly leptophilic, with negligible coupling to quarks. The Yukawa part of the Lagrangian then reads

$$-\mathcal{L}_Y \supset \tilde{Y}_l \bar{\psi}_L H_1 \psi_R + Y_l \bar{\psi}_L H_2 \psi_R + \text{H.c.} \quad (10)$$

In the alignment limit, the former Yukawa coupling is responsible for generating the masses of the charged leptons, i.e., $\tilde{Y}_l = \text{diag}(m_e, m_\mu, m_\tau)/v$, while Y_l determines the DM phenomenology. We focus on the minimal scalar DM scenario, where annihilation proceeds via the s-channel process DMDM $\to H^* \to l_i^+ l_j^-$. The structure of Y_l needs to ensure only kinematically forbidden channels receive significant couplings. In particular, forbidden DM annihilating to $\mu\mu$, $\mu\tau$, and $\tau\tau$ is phenomenologically possible. The forbidden ee channel is precluded by thermal DM of $m_{\text{DM}} \lesssim m_e$ being too light [34], while $e\mu$ or $e\tau$ are constrained by lepton flavor violation [16].

We also consider fermionic forbidden DM based on the light 2HDM mediated scenario. In this case, the scalar mediator needs to have an admixture of an additional light singlet scalar to couple to a pair of DM fermions. The full model description is given in Appendix II. Although annihilation proceeds through a similar s-channel process as before, it is velocity-suppressed in the fermionic DM case and CMB bounds allow for general nonforbidden DM masses and Yukawa structures Y_l. For the purposes of this Letter, however, we restrict ourselves to forbidden mass spectra.

Results and phenomenological implications.—Our model incorporates new physics below the electroweak scale, making it very predictive. Figure 1 shows relic abundance predictions, contrasted with constraints from laboratory experiments and late time DM annihilation. The panels show the values of the Yukawa couplings $Y_{\mu\mu,\mu\tau,\tau\tau}$ that reproduce the observed relic abundance in the three leptophilic forbidden DM regimes $m_{\text{DM}} \lesssim \{m_\mu, (m_\mu + m_\tau)/2, m_\tau\}$ (left to right) for both the scalar

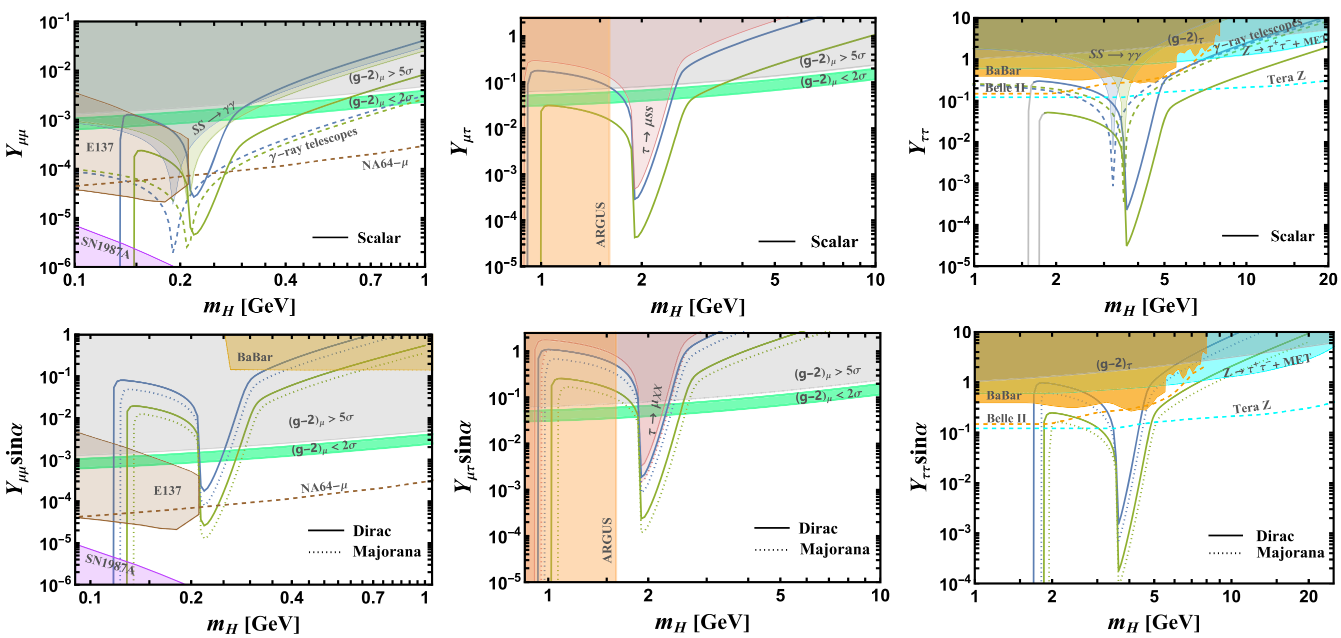

FIG. 1. Predictions and constraints on scalar (top) and fermionic forbidden DM (bottom) for DM annihilations into $\mu^+\mu^-$ (left), $\mu + \tau$ (center), and $\tau^+\tau^-$ (right). The different colored contours represent the DM relic density $\Omega h^2 = 0.12$ for different values of relative mass splitting: $\Delta = 0.1$ (blue), and $\Delta = 0.001$ (green). The green band indicates the $(g-2)_\mu$ 2σ preferred range. The other shaded regions are exclusion bounds as described in the text, with dashed lines indicating future sensitivities. For the scalar (fermion) DM scenario, we set $\kappa_{ij} = 10^{-3}$ ($Y_\chi \cos\alpha = 0.1$).

(top row) and fermionic (bottom row) DM scenarios and different mass splittings, as function of the mediator mass. The $\Delta = 10^{-3} \sim 0$ line (green) indicates the lowest achievable couplings in the forbidden DM scenario. Larger $\Delta = 0.1$ (blue) results in a larger Boltzmann suppression, implying larger couplings. The smallest couplings $y \sim 10^{-5}$ are reached close to the s-channel resonance for $m_H \gtrsim 2m_{\mathrm{DM}}$. Toward low m_H, "secluded" annihilation [9] into mediator pairs determines the relic abundance, which becomes independent of the coupling to leptons [35].

DM indirect detection constraints on tree-level DM annihilation are avoided in the forbidden DM scenario. We point out that loop-level annihilation into two photons is a generic probe of forbidden DM coupled to SM fermions. The kinematic suppression of the two-fermion final state can be lifted by joining them into a loop that radiates two photons instead. PLANCK bounds [28,29] on $\langle \sigma v \rangle_{SS\to\gamma\gamma}$ (see Supplemental Material [36] for cross section formula) during CMB decoupling are shown in Fig. 1 as blue and green shaded regions. Galactic gamma-ray lines at energies just below the lepton masses are a specific prediction of the present scenario, which could be probed at future MeV gamma-ray missions like the AMEGO and e-ASTROGAM proposals [38–40] (dashed lines). In the fermionic DM scenario, annihilation is velocity suppressed, rendering this detection channel ineffective.

Requiring a light mediator has nontrivial consequences on the scalar mass spectrum. A lower bound on the mass of the CP-odd scalar A is obtained from Z decay width measurements, $m_A \geq m_Z - m_H \simeq 90$ GeV [41,42]. A lower bound on the charged scalar mass, $m_{H^+} \simeq 100$ GeV [43] is set by the Large Electron-Positron Collider experiment, while slepton searches at the LHC [44–46] are less stringent (see discussion in Ref. [43]). The mass splitting $m_H \ll m_A, m_{H^+}$ affects electroweak precision observables, in particular the T parameter. However a light m_H with mass splitting $\mathcal{O}(100)$ GeV to $m_A \sim m_{H^+}$ is allowed [18], which can potentially explain the W boson mass shift [47,48] as observed by the Collider Detector at Fermilab collaboration [49]. Because of the alignment limit (no mixing of the SM Higgs h and CP-even scalar H) and the absence of massive cubic scalar couplings involving the SM Higgs, the predictions for Higgs observables do not deviate from the SM and are hence unconstrained by LHC Higgs searches. For our analysis, we set $m_A, m_{H^+} \simeq 110$ GeV and vary the light CP-even scalar mass from the $\mathcal{O}(\mathrm{MeV})$ to the $\mathcal{O}(\mathrm{GeV})$ range. This unrestricted parametric space of the 2HDM has received little attention in the literature.

The light leptophilic charged scalar $\mathcal{O}(100)$ GeV can result in large nonstandard neutrino interactions [43] and generate Glashow-like resonance features in the ultrahigh energy neutrino event spectrum of future neutrino telescopes [50–52]. The hierarchical scalar mass spectrum predicts the novel same-sign di-lepton signature $pp \to H^\pm H^\pm jj \to l^\pm_\alpha l^\pm_\beta jj + \not{E}_T$ at the LHC [18]. This can be a good test of our model, but the detailed exploration is beyond the scope of this study.

In the following, we discuss phenomenological implications of a light scalar coupling to SM leptons and DM. Constraints are shown as bordered shaded regions in Fig. 1. Light scalars coupled to charged leptons contribute to the lepton anomalous magnetic moments. For coupling to the muon or muon and tauon, the loop corrections mediated by the light CP-even scalar H always contribute positively to $(g-2)_\mu$. In Fig. 1, we show the parameters consistent with the $(g-2)_\mu$ measurement at Fermilab [3] as a green band. The gray shaded regions above this band indicate the parameter space where the $(g-2)_\mu$ discrepancy is larger than 5σ, or $(g-2)_\tau$ is larger than the 2σ constraint determined by [53].

New scalars lighter than a few hundred MeV can be produced in astrophysical settings. Their contribution to supernova cooling is constrained by the neutrino observation of SN1987A [54]. Recently, Ref. [55] studied the impact of new light particles interacting with muons on SN1987A (see also Ref. [56]), which we recast to the purple-shaded region in Fig. 1.

At collider or beam dump experiments, the light scalar can be produced in association with the leptons it couples to. Null results from the electron beam dump experiment E137 [57] constrain the $H\mu^+\mu^-$ coupling [15] (brown in Fig. 1). Dark photon searches at *BABAR* [58] provide a stringent constraint on a light scalar with coupling to the muons through the $e^+e^- \to \mu^+\mu^- H$ process [15,25], with $H \to \mu^+\mu^-$. We recast this result for the case $\mathrm{BR}(H \to \mu^+\mu^-) < 1$ (light-yellow in Fig. 1). The *BABAR* collaboration also searches for events with a high energy monophoton and large missing energy [59], which puts limits on the $H\tau^+\tau^-$ coupling [16,60,61] (yellow in Fig. 1). The dashed yellow line indicates the corresponding projected sensitivity of Belle-II [16,61,62].

The $Y_{\tau\tau}$ coupling is also constrained by Z decay [16,60], where the associated production and subsequent dark decay of H can contribute to the measured $Z \to \tau^+\tau^-$ width [42] (cyan in Fig. 1). Finally, τ decays are modified in the $\mu\tau$-coupled case. The search for LFV two-body τ decay at ARGUS [63] requires $m_H > m_\tau - m_\mu$ to forbid $\tau \to \mu H$ decay (orange in Fig. 1). Similarly, the decay $\tau \to \mu SS$ would contribute to the measured width $\Gamma(\tau \to \mu \bar{\nu}_\mu \nu_\tau)$ [42], requiring $m_{\mathrm{DM}} > (m_\tau - m_\mu)/2$ or equivalently $\Delta < 0.126$ (light pink in Fig. 1).

In the future, muon beam dump experiments may be used to probe for a light scalar coupled to muons and DM by performing a muon missing energy search. The corresponding projected sensitivity from the muon beam experiment NA64-μ [16,60,64] is shown in Fig. 1 as a brown dashed line. Future Z factories based on e^+e^- colliders look for exotic decay modes of Z bosons. The projected sensitivity from these experiments [16,65–68] is shown in Fig. 1 as a cyan dashed line.

Overall, the light 2HDM-mediated forbidden DM scenario shares many implications with previous phenomenological models [16], but makes further predictions for the scalar sector around the EW scale. From the DM side, radiative annihilation is a very informative probe of forbidden DM annihilating into SM particles, which in particular could identify $\mu\mu$-coupled scalar DM in the $(g-2)_\mu$-favored part of parameter space.

Neutrino mass.—The simplest radiative neutrino mass model—the Zee model [69]—uses two-Higgs doublets. Adding a singly charged scalar $\eta^\pm$ to our setup to complete the loop diagram that provides neutrino mass, the same Yukawa couplings responsible for providing the correct DM relic abundance explain neutrino masses.

The Yukawa couplings given in Eq. (10) are supplemented by

$$-\mathcal{L}_Y \supset f_{ij} L_i \epsilon L_j \eta^+ + \text{H.c.}, \tag{11}$$

where ϵ is the Levi-Civita tensor, and f_{ij} is antisymmetric in flavor indices. Equations (10) and (11), together with the following cubic term,

$$-V \supset \mu H_1 \epsilon H_2 \eta^- + \text{H.c.}, \tag{12}$$

lead to nonzero neutrino mass given by

$$M_\nu = a_0 (f m_E Y_l - Y_l^T m_E f), \tag{13}$$

$$a_0 = \frac{\sin 2\omega}{16\pi^2} \ln\left(\frac{m_{h^+}^2}{m_{H^+}^2}\right); \qquad \sin 2\omega = \frac{\sqrt{2} v \mu}{m_{h^+}^2 - m_{H^+}^2}, \tag{14}$$

where m_E is the diagonal charged lepton mass matrix, ω is the mixing angle between the singly charged scalars, and h^+ and H^+ represent mass eigenstates [70].

DM annihilation imposes strong restrictions on the texture of Y_l. To satisfy neutrino oscillation data, Y_l is required to have significant off-diagonal entries, which are constrained by LFV processes. This rules out the $\mu\mu$-coupled forbidden DM scenario, where sizable nonzero entries with the tau lepton are ruled out by nonobservation of $\tau \to \ell H$ [63]. To generate viable neutrino masses and mixings, we hence consider a Yukawa texture with zero 2×2 block in the 1–2 sector.

To be consistent with DM phenomenology, we fix $y_{\mu\tau} = 5 \times 10^{-4}$ and require $m_H \sim 2$ GeV (cf. Fig. 1, upper-middle plot). We then perform a fit to the neutrino sector and provide a benchmark,

$$Y_l = 10^{-4} \begin{pmatrix} 0 & 0 & 3.494 \times 10^{-4} \\ 0 & 0 & 5 \\ -10^{-3} & -0.382 & 0.542 \end{pmatrix}, \tag{15}$$

$$a_0 \cdot f = 10^{-7} \begin{pmatrix} 0 & 2.135 & 0 \\ -2.135 & 0 & 2.266 \\ 0 & -2.266 & 0 \end{pmatrix}. \tag{16}$$

Neutrino observables associated with this fit yield,

$$\Delta m_{21}^2 = 7.486 \times 10^{-5}\,\text{eV}^2, \quad \Delta m_{31}^2 = 2.511 \times 10^{-3}\,\text{eV}^2,$$
$$\theta_{12} = 34.551°, \quad \theta_{23} = 47.830°, \quad \theta_{13} = 8.545°,$$

in good agreement with neutrino oscillation data [71].

The mandatory nonzero off-diagonal elements in Eq. (15) lead to LFV processes, the most dangerous of which are light scalar mediated $\mu \to e\gamma, \tau \to e\gamma$, and $\tau \to \mu\gamma$ at one loop, which we compute following [72]. While the rates of the former two can be easily suppressed, the branching ratio of $\mu \to e\gamma$ is typically close to the current limit [73] or within the reach of future experiments such as MEG-II [74].

Conclusions.—This Letter proposes a minimal realization of light dark matter, enabled by a light scalar mediator that can arise in the 2HDM. We focus on forbidden DM annihilating to SM leptons, which predicts the DM mass to be close to the μ or τ masses. Stringent CMB constraints on sub-GeV DM are avoided, while we have identified Galactic gamma-ray lines at energies just below m_μ, m_τ from radiative annihilation as a specific probe of forbidden DM coupled to leptons. A distinctive trademark is that all new physics states appear at or below the EW scale; in particular, a CP-odd and charged scalars are predicted to have masses of order 100 GeV. Furthermore, a leptophilic-like 2HDM of this type can shed light on the $(g-2)_\mu$ anomaly, and—when embedded within the Zee model—the couplings that determine the relic abundance become intimately linked to neutrino oscillations. This minimal kinematically forbidden scenario is very predictive and in particular testable at future beam-dump experiments, colliders, and sub-GeV gamma-ray telescopes. However, the light 2HDM portal to dark matter is rather general and provides a simple way of linking light dark sectors to the standard model that may well have wider application.

The work of V. P. K is in part supported by US Department of Energy Grant No. DE-SC 0016013. We acknowledge the use of the FEYNCALC package [75].

*herms@mpi-hd.mpg.de
†Corresponding author.
sudip.jana@mpi-hd.mpg.de
‡vipadma@okstate.edu
§shaikh.saad@unibas.ch

[1] G. Bertone and D. Hooper, History of dark matter, Rev. Mod. Phys. 90, 045002 (2018).
[2] B. W. Lee and S. Weinberg, Cosmological Lower Bound on Heavy Neutrino Masses, Phys. Rev. Lett. 39, 165 (1977).

[3] B. Abi *et al.* (Muon $g-2$ Collaboration), Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm, Phys. Rev. Lett. **126**, 141801 (2021).

[4] S. Jana, Vishnu P. K., W. Rodejohann, and S. Saad, Dark matter assisted lepton anomalous magnetic moments and neutrino masses, Phys. Rev. D **102**, 075003 (2020).

[5] S. Dodelson and L. M. Widrow, Sterile-Neutrinos as Dark Matter, Phys. Rev. Lett. **72**, 17 (1994).

[6] B. M. Roach, K. C. Y. Ng, K. Perez, J. F. Beacom, S. Horiuchi, R. Krivonos, and D. R. Wik, NuSTAR tests of sterile-neutrino dark matter: New galactic bulge observations and combined impact, Phys. Rev. D **101**, 103011 (2020).

[7] S. Heeba, F. Kahlhoefer, and P. Stöcker, Freeze-in production of decaying dark matter in five steps, J. Cosmol. Astropart. Phys. 11 (2018) 048.

[8] This is true also in scenarios where DM does not annihilate directly to SM particles, such as secluded DM [9] or to a lesser extent SIMP DM [10], where the heat produced in DM annihilation is ultimately transferred to the SM bath.

[9] M. Pospelov, A. Ritz, and M. B. Voloshin, Secluded WIMP dark matter, Phys. Lett. B **662**, 53 (2008).

[10] Y. Hochberg, E. Kuflik, and H. Murayama, SIMP spectroscopy, J. High Energy Phys. 05 (2016) 090.

[11] T. A. Chowdhury and S. Saad, Non-Abelian vector dark matter and lepton $g-2$, J. Cosmol. Astropart. Phys. 10 (2021) 014.

[12] C. Boehm and P. Fayet, Scalar dark matter candidates, Nucl. Phys. **B683**, 219 (2004).

[13] R. T. D'Agnolo and J. T. Ruderman, Light Dark Matter from Forbidden Channels, Phys. Rev. Lett. **115**, 061301 (2015).

[14] H. M. Lee and M.-S. Seo, Communication with SIMP dark mesons via Z' -portal, Phys. Lett. B **748**, 316 (2015).

[15] B. Batell, A. Freitas, A. Ismail, and D. Mckeen, Flavor-specific scalar mediators, Phys. Rev. D **98**, 055026 (2018).

[16] R. T. D'Agnolo, D. Liu, J. T. Ruderman, and P.-J. Wang, Forbidden dark matter annihilations into standard model particles, J. High Energy Phys. 06 (2021) 103.

[17] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Theory and phenomenology of two-Higgs-doublet models, Phys. Rep. **516**, 1 (2012).

[18] S. Jana, Vishnu P. K., and S. Saad, Resolving electron and muon $g-2$ within the 2HDM, Phys. Rev. D **101**, 115037 (2020).

[19] Y. Bai, V. Barger, L. L. Everett, and G. Shaughnessy, Two-Higgs-doublet-portal dark-matter model: LHC data and Fermi-LAT 135 GeV line, Phys. Rev. D **88**, 015008 (2013).

[20] A. Berlin, S. Gori, T. Lin, and L.-T. Wang, Pseudoscalar portal dark matter, Phys. Rev. D **92**, 015005 (2015).

[21] N. R. Shah, The Higgs and WIMP DM lamp posts for new weak scale physics: EFT perspectives and the NMSSM, Nucl. Part. Phys. Proc. **303–305**, 92 (2018).

[22] G. Arcadi, A. Djouadi, and M. Raidal, Dark Matter through the Higgs portal, Phys. Rep. **842**, 1 (2020).

[23] M. E. Cabrera, J. A. Casas, A. Delgado, and S. Robles, 2HDM singlet portal to dark matter, J. High Energy Phys. 01 (2021) 123.

[24] K. Griest and D. Seckel, Three exceptions in the calculation of relic abundances, Phys. Rev. D **43**, 3191 (1991).

[25] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Muon anomalous magnetic moment through the leptonic Higgs portal, Phys. Rev. D **95**, 075003 (2017).

[26] S. Okawa and Y. Omura, Light mass window of lepton portal dark matter, J. High Energy Phys. 02 (2021) 231.

[27] L.-B. Jia, Dark leptophilic scalar with the updated muon $g-2$ anomaly, Eur. Phys. J. C **82**, 321 (2022).

[28] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. **641**, A6 (2020); **652**, C4(E) (2021).

[29] T. R. Slatyer, Indirect dark matter signatures in the cosmic dark ages. I. Generalizing the bound on s-wave dark matter annihilation from Planck results, Phys. Rev. D **93**, 023527 (2016).

[30] In the models we consider, DM freeze-out can also be determined by forbidden annihilations into two mediator particles, provided the mediator remains in equilibrium with the SM bath. We have verified that this is ensured by $\phi \leftrightarrow \nu\bar{\nu}, \gamma\gamma$ processes for the relevant values of mediator-lepton couplings.

[31] K. S. Babu and S. Jana, Enhanced di-Higgs production in the two Higgs doublet model, J. High Energy Phys. 02 (2019) 193.

[32] J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang, and S. Kraml, Scrutinizing the alignment limit in two-Higgs-doublet models: $m_h = 125$ GeV, Phys. Rev. D **92**, 075004 (2015).

[33] P. S. Bhupal Dev and A. Pilaftsis, Maximally symmetric two Higgs doublet model with natural standard model alignment, J. High Energy Phys. 12 (2014) 024; 11 (2015) 147(E).

[34] C. Boehm, M. J. Dolan, and C. McCabe, A lower bound on the mass of cold thermal dark matter from Planck, J. Cosmol. Astropart. Phys. 08 (2013) 041.

[35] The secluded parameter space is ruled out by indirect detection constraints on $SS \to HH \to 4\gamma$ in the case of scalar DM annihilating to $\tau\tau$ (drawn with solid gray vertical lines in the plot). In the other cases shown, the correct relic abundance is reached in the forbidden secluded regime.

[36] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.129.091803, which includes Ref. [37], for the velocity averaged s-wave annihilation cross section of scalar DM into two photons and the model details of the fermionic dark matter scenario.

[37] L. Resnick, M. K. Sundaresan, and P. J. S. Watson, Is there a light scalar boson?, Phys. Rev. D **8**, 172 (1973).

[38] R. Caputo *et al.* (AMEGO Collaboration), All-sky medium energy gamma-ray observatory: Exploring the extreme multimessenger universe, arXiv:1907.07558.

[39] M. Tavani *et al.* (e-ASTROGAM Collaboration), Science with e-ASTROGAM: A space mission for MeV–GeV gamma-ray astrophysics, J. High Energy Astrophys. **19**, 1 (2018).

[40] R. Bartels, D. Gaggero, and C. Weniger, Prospects for indirect dark matter searches with MeV photons, J. Cosmol. Astropart. Phys. 05 (2017) 001.

[41] LEP, ALEPH, DELPHI, L3, OPAL, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavor Group, t. S. Electroweak Collaborations, A Combination of preliminary electroweak measurements and constraints on the standard model, arXiv:hep-ex/0312023.

[42] M. Tanabashi *et al.* (Particle Data Group Collaboration), Review of particle physics, Phys. Rev. D **98**, 030001 (2018).

[43] 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.

[44] A. M. Sirunyan *et al.* (CMS Collaboration), Search for supersymmetry in events with a τ lepton pair and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 11 (2018) 151.

[45] G. Aad *et al.* (ATLAS Collaboration), Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, J. High Energy Phys. 10 (2014) 096.

[46] A. M. Sirunyan *et al.* (CMS Collaboration), Search for supersymmetric partners of electrons and muons in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **790**, 140 (2019).

[47] K. S. Babu, S. Jana, and V. P. K., Correlating W-boson mass shift with muon $g-2$ in the 2HDM, arXiv:2204.05303.

[48] T. A. Chowdhury, J. Heeck, S. Saad, and A. Thapa, W boson mass shift and muon magnetic moment in the Zee model, Phys. Rev. D **106**, 035004 (2022).

[49] T. Aaltonen *et al.* (CDF Collaboration), High-precision measurement of the W boson mass with the CDF II detector, Science **376**, 170 (2022).

[50] K. S. Babu, P. S. Bhupal Dev, S. Jana, and Y. Sui, Zee-Burst: A New Probe of Neutrino Nonstandard Interactions at IceCube, Phys. Rev. Lett. **124**, 041805 (2020).

[51] G.-y. Huang, S. Jana, M. Lindner, and W. Rodejohann, Probing new physics at future tau neutrino telescopes, J. Cosmol. Astropart. Phys. 02 (2022) 038.

[52] K. S. Babu, P. S. B. Dev, and S. Jana, Probing neutrino mass models through resonances at neutrino telescopes, Int. J. Mod. Phys. A **37**, 2230003 (2022).

[53] L. Beresford and J. Liu, New physics and tau $g-2$ using LHC heavy ion collisions, Phys. Rev. D **102**, 113008 (2020).

[54] K. Hirata, T. Kajita, M. Koshiba, M. Nakahata, Y. Oyama *et al.* (Kamiokande-II Collaboration), Observation of a Neutrino Burst from the Supernova SN 1987a, Phys. Rev. Lett. **58**, 1490 (1987).

[55] D. Croon, G. Elor, R. K. Leane, and S. D. McDermott, Supernova muons: New constraints on Z' bosons, axions and ALPs, J. High Energy Phys. 01 (2021) 107.

[56] A. Caputo, G. Raffelt, and E. Vitagliano, Muonic boson limits: Supernova redux, Phys. Rev. D **105**, 035022 (2022).

[57] J. D. Bjorken, S. Ecklund, W. R. Nelson, A. Abashian, C. Church, B. Lu, L. W. Mo, T. A. Nunamaker, and P. Rassmann, Search for neutral metastable penetrating particles produced in the SLAC beam dump, Phys. Rev. D **38**, 3375 (1988).

[58] J. P. Lees *et al.* (*BABAR* Collaboration), Search for a muonic dark force at *BABAR*, Phys. Rev. D **94**, 011102 (2016).

[59] J. P. Lees *et al.* (*BABAR* Collaboration), Search for Invisible Decays of a Dark Photon Produced in e^+e^- Collisions at *BABAR*, Phys. Rev. Lett. **119**, 131804 (2017).

[60] C.-Y. Chen, J. Kozaczuk, and Y.-M. Zhong, Exploring leptophilic dark matter with NA64-μ, J. High Energy Phys. 10 (2018) 154.

[61] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, Revised constraints and Belle II sensitivity for visible and invisible axion-like particles, J. High Energy Phys. 12 (2017) 094; 03 (2021) 190(E).

[62] T. Abe *et al.* (Belle-II Collaboration), Belle II Technical Design Report, arXiv:1011.0352.

[63] H. Albrecht *et al.* (ARGUS Collaboration), A search for lepton flavor violating decays tau—-> e alpha, tau—> mu alpha, Z. Phys. C **68**, 25 (1995).

[64] S. N. Gninenko, N. V. Krasnikov, and V. A. Matveev, Muon $g-2$ and searches for a new leptophobic sub-GeV dark boson in a missing-energy experiment at CERN, Phys. Rev. D **91**, 095015 (2015).

[65] J. Liu, L.-T. Wang, X.-P. Wang, and W. Xue, Exposing the dark sector with future Z factories, Phys. Rev. D **97**, 095044 (2018).

[66] M. Bicer *et al.* (TLEP Design Study Working Group Collaboration), First look at the physics case of TLEP, J. High Energy Phys. 01 (2014) 164.

[67] D. d'Enterria, Physics case of FCC-ee, Frascati Phys. Ser. **61**, 17 (2016).

[68] D. d'Enterria, Physics at the FCC-ee, in *Particle Physics at the Year of Light* (World Scientific, Singapore, 2017).

[69] A. Zee, A theory of lepton number violation, neutrino Majorana mass, and oscillation, Phys. Lett. **93B**, 389 (1980); **95B**, 461(E) (1980).

[70] For small mixing angle, which is typically required to provide tiny masses to neutrinos, the H^+-state can to good approximation be identified with the charged scalar from the 2HDM.

[71] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, The fate of hints: Updated global analysis of three-flavor neutrino oscillations, J. High Energy Phys. 09 (2020) 178.

[72] B. Dutta, S. Ghosh, and T. Li, Explaining $(g-2)_{\mu,e}$, the KOTO anomaly and the MiniBooNE excess in an extended Higgs model with sterile neutrinos, Phys. Rev. D **102**, 055017 (2020).

[73] P. A. Zyla *et al.* (Particle Data Group Collaboration), Review of particle physics, Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).

[74] A. M. Baldini *et al.* (MEG Collaboration), Search for the lepton flavour violating decay $\mu^+ \to e^+\gamma$ with the full dataset of the MEG experiment, Eur. Phys. J. C **76**, 434 (2016).

[75] V. Shtabovenko, R. Mertig, and F. Orellana, New Developments in FeynCalc 9.0, Comput. Phys. Commun. **207**, 432 (2016).