

Unconventional Materials for Light Dark Matter Detection

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We propose the use of several unconventional materials as detectors for dark matter with mass beneath the MeV scale. These include the transition-metal dichalcogenide TiSe_2 hosting a low-energy plasmon in the charge-density-wave phase, Sr_2RuO_4 containing a low-energy acoustic demon mode, and hole-doped diamond with tunable optical and acoustic plasmon frequencies. We perform first-principles density functional theory computations of their loss functions at nonvanishing momenta and establish their reach into light dark matter parameter space. We show that due to intense low-energy plasmon modes—of different microscopic origin in each—the reach of detectors based on these materials could surpass existing proposals by several orders of magnitude for both dark matter scattering and absorption on electrons. The anisotropic response of these materials, which enables directional detection, renders them exceptionally strong detector candidates, motivating the design and fabrication of future devices.

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The identity of dark matter (DM) in our Universe remains one of the most pressing open questions of modern day physics. The absence of experimental evidence for DM at the electroweak scale, despite years of focus on this regime, has brought lighter DM with mass beneath the GeV scale into the limelight. Indeed, new theoretical frameworks incorporating such light DM have been proposed in recent years (see Ref. [1] for a recent review), along with new experimental avenues with which to detect DM in the sub-GeV and even sub-MeV mass range [2–22]. Much progress has been made by interdisciplinary work sitting at the interface of particle physics, condensed matter physics, materials science, and quantum sensing.

Here, we propose several unconventional materials that can serve as excellent targets for light DM detection. Their common feature is a strong low-energy response in the tens to hundreds of meV energy-deposit regime. Kinematically, nonrelativistic Galactic DM of mass m_χ has a typical velocity $v \sim 10^{-3}$ in natural units. When scattering with a target detector, DM can deposit energy of order its kinetic energy $\sim m_\chi v^2$, corresponding to energy deposits of $\sim 10^{-6} m_\chi$, or when absorbed by the detector, it can deposit

its entire mass energy m_χ in the system. Consequently, materials with strong responses at energies ~ 1 –100 meV are exceptionally sensitive to DM masses at the keV (for scattering) or meV (for absorption) mass scales.

We highlight a set of low-energy collective excitations in condensed matter systems, which behave as emergent bosonic quasiparticles from far- to mid-infrared energies (~ 10 –100 meV) and originate from collective charge dynamics induced by symmetry breaking, nondegenerate multiband response, and charge doping. Furthermore, the anisotropic response of these excitations enables angular modulation of the DM scattering rate, thereby improving discrimination against isotropic backgrounds and enhancing detection prospects. Within this framework, we identify three paradigmatic realizations, each synthesizable at scale, which can serve as excellent targets for light DM detection: (i) TiSe_2 —here, a low-energy plasmon mode at few tens of meV appears when a system enters the charge-density-wave (CDW) phase below $T = 200$ K [23–25]; (ii) Sr_2RuO_4 —here, a gapless acoustic plasmon (i.e., a demon mode) emerges as a neutral collective mode generated by out-of-phase charge oscillations between distinct electronic bands [26]; and (iii) hole-doped diamond (HDD)—here, a distinct class of infrared plasmons, which are highly tunable with doping, arises due to oscillations of the valence manifold [27]. We show that the strong low-energy response of these example materials makes them significantly more sensitive than current existing proposals for both DM-electron scattering and absorption. In the former two cases, the

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intrinsic anisotropy of their response enables directional sensitivity through daily modulation, making them promising platforms for DM detection.

Unconventional-material loss functions—We consider spin-independent interactions between DM and the electrons in our unconventional target materials. Following the methodology of Refs. [28–31], the rate of such interactions [see Eqs. (1) and (3)] is determined by the loss function $\mathcal{W}(\omega, \mathbf{q}) \equiv \text{Im}\{-1/\epsilon_L(\omega, \mathbf{q})\}$, where $\epsilon_L(\omega, \mathbf{q}) = \hat{\mathbf{q}} \cdot \vec{\epsilon}(\omega, \mathbf{q}) \cdot \hat{\mathbf{q}}$ is the longitudinal component of the dielectric tensor for deposited energy ω and momentum $\mathbf{q}$ of magnitude $|\mathbf{q}| = q$. The loss encodes the linear response of the material, including many-body effects, and in this Letter is extracted from *ab initio* density functional theory (DFT) calculations at the random-phase-approximation level. This gives a simple, calculable and measurable way to assess DM interaction rates in any material of interest.

Here, we present the loss functions and characteristics of our selected materials, which highlight their potential as DM detectors. The loss functions of the materials are presented in Fig. 1: panels (a)–(c) show DFT-computed loss functions in a representative direction, highlighting the low-energy excitations; panels (d)–(f) present the loss along two crystal directions conveying the anisotropy of their response. All computed loss functions along

with additional computational details are provided in Supplemental Material (SM) [32]. We note that the theoretical DFT-based loss functions of Sr_2RuO_4 and HDD have not been discussed in the literature thus far, and the response for TiSe_2 in the whole Brillouin zone (BZ) has been missing [36]. (For details concerning material synthesis and experimental considerations, see End Matter.)

TiSe_2 is a transition-metal dichalcogenide with a trigonal layered structure, which supports a second-order phase transition to CDW at around 200 K [37]. In this CDW phase, TiSe_2 undergoes a periodic lattice distortion that breaks the symmetry of the original cell and allows for the gap opening [23,25]. With this, the concentration of charge carriers and corresponding decay channels drop [38], decreasing the plasmon frequency to ~ 47 meV and increasing its intensity [23,24]. The interband excitations over the CDW gap form an additional interband plasmon at energies ~ 600 meV. We compute the loss function at $T = 30$ K along the $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ directions. The response along $\hat{\mathbf{x}}$ is shown in Fig. 1(a), while Fig. 1(d) compares responses along both directions at momenta $q = 10, 200, 600$ eV. As is evident in Fig. 1(a), our modeling produces the in-plane bulk plasmon as a sharp peak at energy of ~ 66 meV, and the interband plasmon as slightly broader and weaker feature at energies ~ 700 meV. Note that the response is anisotropic, in line

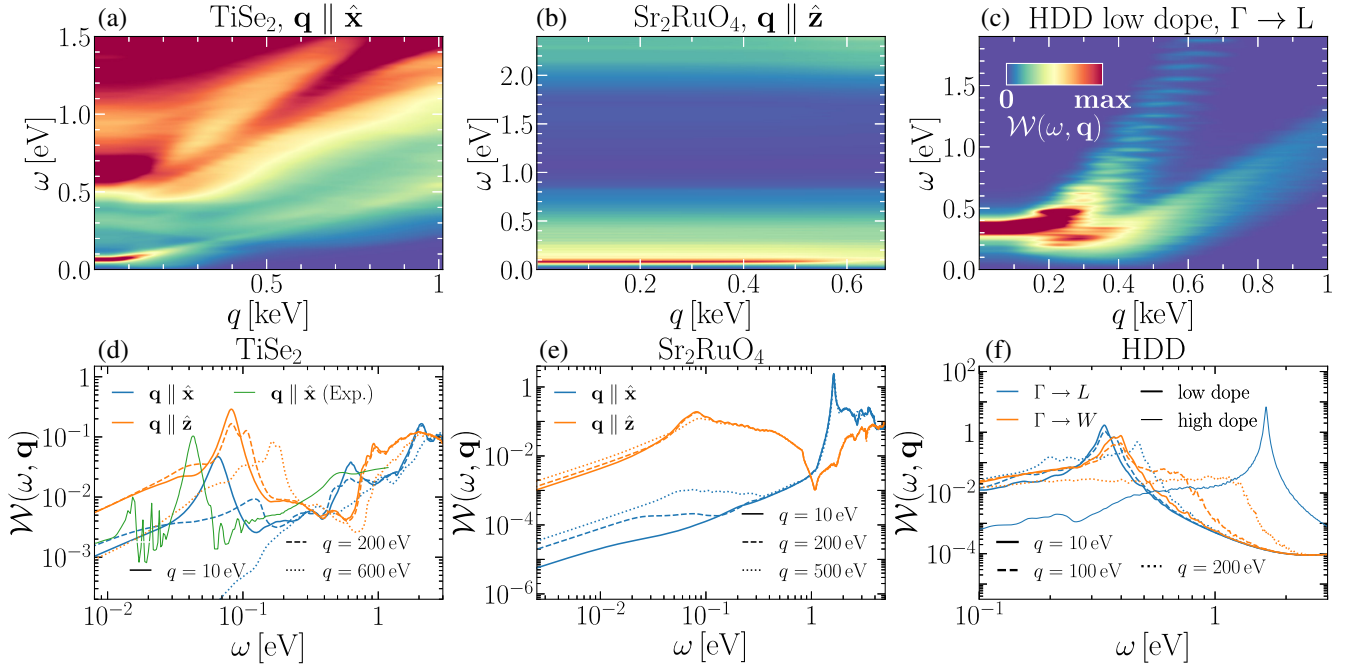


FIG. 1. Loss functions. Momenta are given in units where $1 \text{ keV} = 0.507 \text{ \AA}^{-1}$. Panels (a)–(c) display the DFT-calculated loss function along a representative crystal direction, while panels (d)–(f) compare responses in two selected directions, shown in blue and orange, across several momenta q , indicated by different line styles. TiSe_2 : panel (a) presents the loss function along $\hat{\mathbf{x}}$. Panel (d) compares responses along $\hat{\mathbf{x}}$ (blue) and $\hat{\mathbf{z}}$ (orange) for several q values. The green curve delineates the experimentally measured zero-momentum response at $T = 10$ K in the xy plane [23], to be compared with the solid blue DFT curve at low momenta in the $\hat{\mathbf{x}}$ direction. Sr_2RuO_4 : panel (b) shows the loss along $\hat{\mathbf{z}}$, and panel (e) compares the $\hat{\mathbf{x}}$ (blue) and $\hat{\mathbf{z}}$ (orange) responses. HDD: panel (c) presents the response along $\Gamma \rightarrow L$ with low doping ($n_h = 4.52 \times 10^{19} \text{ cm}^{-3}$), while panel (f) compares the loss along $\Gamma \rightarrow L$ (blue) and $\Gamma \rightarrow W$ (orange). Thick (thin) lines correspond to the low (high) doping $n_h = 4.52 \times 10^{19} \text{ cm}^{-3}$ ($n_h = 4.52 \times 10^{21} \text{ cm}^{-3}$).

with the anisotropy of the experimentally reported band structure [39] and resistivity [37].

In Fig. 1(d), we show our DFT-computed loss function for TiSe_2 at various fixed momenta and in different directions, along with optical measurements of the zero-momentum response [23]. Since the response is expected to be independent of q (but not of $\hat{\mathbf{q}}$) at momenta much smaller than the inverse lattice spacing, one can compare our $q = 10$ eV DFT-based calculation to the experimental optical data. Two key differences emerge: the measured plasmon frequency is slightly lower in the optical data, and additional phonon excitations appear there that are absent from our DFT result. These minor discrepancies are expected, considering the difficulty of simulating the right CDW gap and therefore the screening properties in TiSe_2 [36]. We will later show that these differences induce only $\mathcal{O}(1)$ corrections to the projected DM scattering sensitivity.

The second material we propose is Sr_2RuO_4 , which is a layered perovskite with a body-centered tetragonal structural that falls in the category of strange metals. Sr_2RuO_4 exhibits various unconventional features beyond what is expected for a Fermi liquid, such as linear temperature dependence of resistivity and unconventional superconductivity below 1.5 K [40]. Recently, a rich electronic response was observed in Sr_2RuO_4 , showing a low-energy acoustic demon mode in addition to a bulk plasmonic mode at 1.6 eV [26,41]. We compute the loss function of Sr_2RuO_4 along the $\hat{\mathbf{x}}$ and $\hat{\mathbf{z}}$ directions, with the loss function along the $\hat{\mathbf{z}}$ direction presented in Fig. 1(b) and the loss functions along both directions at momenta $q = 10, 200, 500$ eV presented in Fig. 1(e). The low-energy mode is prominent along the $\hat{\mathbf{z}}$ direction, manifesting itself as a broad peak in the loss function at energies $\sim 80\text{--}800$ meV. Furthermore, we find that this mode is suppressed along the $\hat{\mathbf{x}}$ axis, producing a large anisotropy in the response. The bulk plasmon is most prominent along the $\hat{\mathbf{x}}$ direction, which exhibits a sharp peak around 1.6 eV. The obtained anisotropic electronic response of Sr_2RuO_4 agrees very well with the experimental excitation spectrum probed by electron energy loss spectroscopy [41].

The third candidate is HDD. When doped beyond the insulator-metal transition (e.g., with boron atoms), diamond exhibits metallic features such as superconductivity at $T_c = 4$ K [42] and strong plasmonic response [27]. Unlike conventional metals, the plasmon frequency in HDD can be tuned by variation of charge carrier density [27,43]. (See also Ref. [44] with focus on doped silicon.) We compute the HDD loss function for two hole dopings n_h in several directions: at $n_h = 4.52 \times 10^{19} \text{ cm}^{-3}$ along $\Gamma \rightarrow \text{L, X, W, K}$, and at $n_h = 4.52 \times 10^{21} \text{ cm}^{-3}$ along $\Gamma \rightarrow \text{L, X}$. In Fig. 1(c) we present the loss function for the lower doping along the $\Gamma \rightarrow \text{L}$ direction and in Fig. 1(f) along the $\Gamma \rightarrow \text{L, W}$ directions for momenta $q = 10, 100, 200$ eV. Our computed response consists of

an optical plasmon mode centered around ~ 350 meV, along with an acoustic plasmon feature at ~ 200 meV. The former establishes the relatively strong low-energy response whereas the latter substantially enhances the response at momenta $q > 100$ eV. Both plasmon dispersion relations vary with momenta direction, with larger variations in the acoustic branch. We discuss the integrated effect of the acoustic plasmon in our analysis in SM [32]. A low-energy electronic response between 100–200 meV was recently observed in boron-doped diamond by using electron energy loss and near-field infrared spectroscopies [27] and agrees reasonably well with our theoretical results.

Figure 1(f) compares the response of HDD along two directions and at various momenta. Comparing the response in the $\Gamma \rightarrow \text{L}$ direction at $q = 10$ eV for two different dopings, we find that the optical plasmon shifts from $\omega_p \sim 0.35$ eV to $\omega_p \sim 1.6$ eV following the typical plasmon to doping density scaling relation $\omega_p \propto n_h^{1/2}$ [43]. This scaling relation is expected to hold up to the metal-insulator critical point below which the plasmon mode is suppressed [27,45].

Dark matter interaction rates—For DM-electron scattering via a scalar or vector mediator, the DM-electron interaction rate is given by [28,29]

$$R(t) = \frac{1}{\rho_T} \frac{\rho_\chi}{m_\chi} \frac{\pi \bar{\sigma}_e}{\mu_{e\chi}^2} \int d^3\mathbf{v} f(\mathbf{v}, t) \Gamma(\mathbf{v}), \quad (1)$$

$$\Gamma(\mathbf{v}) = \int \frac{d^3q}{(2\pi)^3} |\mathcal{F}(q)|^2 \frac{q^2}{2\pi\alpha} \mathcal{W}[\omega_{\mathbf{q}}(\mathbf{v}), \mathbf{q}]. \quad (2)$$

Here, $q = |\mathbf{q}|$, ρ_T (ρ_χ) is the target (DM) energy density, $\alpha \simeq 1/137$ is the fine-structure constant, and m_χ , m_ϕ , m_e are the DM, mediator, and electron masses, respectively. $\mu_{e\chi}$ is the DM-electron reduced mass, and the DM-electron interaction is described by the potential $V(q) = g_e g_\chi / (q^2 + m_\phi^2)$, where g_e and g_χ are the mediator couplings to electrons and DM, respectively. Using a reference momentum transfer $q_0 = \alpha m_e$, we define a reference cross section $\bar{\sigma}_e = \mu_{e\chi}^2 |V(q_0)|^2 / \pi$. The form factor $|\mathcal{F}(q)|^2 = |V(q)/V(q_0)|^2$ interpolates between $(q_0/q)^4$ for light mediators and unity for heavy mediators. $f(\mathbf{v}, t)$ denotes the DM velocity distribution in the lab frame, $\mathbf{v}$ is the initial DM velocity, with the corresponding energy transfer determined kinematically as $\omega_{\mathbf{q}}(\mathbf{v}) = \mathbf{q} \cdot \mathbf{v} - q^2/(2m_\chi)$. We take $\rho_\chi = 0.3 \text{ GeV}/\text{cm}^3$ and use the Standard Halo Model [46] for $f(\mathbf{v}, t)$ with $v_0 = 220 \text{ km/s}$, $v_e = 230 \text{ km/s}$, and $v_{\text{esc}} = 540 \text{ km/s}$. In addition to accounting for the motion of the Earth in the Galactic plane, the modeling accounts for the rotation of the Earth around its axis, which leads to a daily modulation of the DM scattering rate for detectors with anisotropic responses.

We also consider DM absorption, using the kinetically mixed dark-photon benchmark $\mathcal{L} \supset -(\kappa/2)F^{\mu\nu}F'_{\mu\nu}$, where κ is the kinetic mixing parameter and $F_{\mu\nu}(F'_{\mu\nu})$ is the photon (dark-photon) field strength. The dark-photon absorption rate per unit detector volume per DM particle is given by [30,47]

$$\Gamma_{\text{abs}} = \kappa^2 m_\chi \mathcal{W}(m_\chi, m_\chi \mathbf{v}). \quad (3)$$

For Galactic light DM, the transferred momentum in an absorption process can be approximated to zero since $|\mathbf{v}| \sim 10^{-3}$ and consequently $m_\chi |\mathbf{v}|$ is much smaller than the BZ boundary (typically $\sim \text{keV}$).

Results—We now present the reach into DM parameter space of the unconventional target materials proposed in this Letter: TiSe_2 , Sr_2RuO_4 , and HDD. We consider the detection prospects for an isotropic signal and for the ability to detect a directional daily modulation signal. Details regarding our data handling and statistical analysis

are provided in End Matter. Our projections are done at the 95% confidence level (CL) [48], assuming no background, a kg-yr exposure, and a detection sensitivity to energy deposits $\omega \in [10 \text{ meV}, 10 \text{ eV}]$.

Our results for DM-electron scattering are shown in Figs. 2(a) and 2(b), corresponding to the cases of a light and heavy mediator, respectively. Solid colored curves indicate the projected isotropic reach. For TiSe_2 , the shaded blue band indicates the impact of the uncertainty in the modeling of the material response: the boundary of the blue shaded region uses experimental optical data of the loss function at zero momentum [23], extrapolated to non-vanishing momenta via the fitting procedure of Ref. [49], for comparison to our full DFT results. (Full details of the fitting procedure are provided in SM [32] for completeness.) We find $\mathcal{O}(1)$ differences in the scattering rate for this material between the two methods, exhibiting remarkable agreement. Dashed curves delineate the anisotropic reach of these materials, indicating their directional

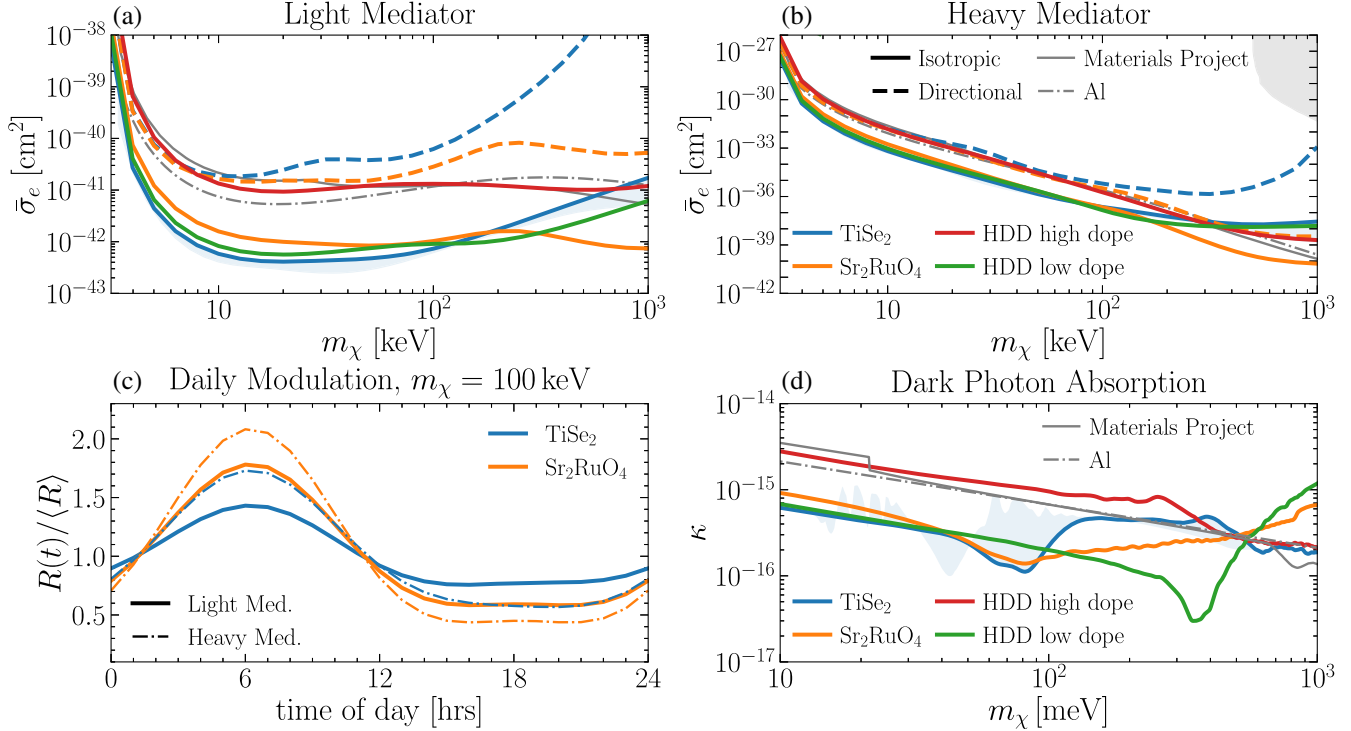


FIG. 2. DM reach. (a),(b) Scattering: projected reach of the candidate materials TiSe_2 , Sr_2RuO_4 , and HDD for spin-independent DM-electron scattering, assuming a light (a) or heavy (b) mediator. Solid (dashed thick) colored curves indicate projections for the isotropic (anisotropic) reach. The high (low) dope HDD curves correspond to hole doping of $n_h = 4.52 \times 10^{21} \text{ cm}^{-3}$ ($4.52 \times 10^{19} \text{ cm}^{-3}$). The shaded gray region indicates existing terrestrial constraints [50–52]. (c) Daily modulation: the daily modulation of the DM-target scattering rate resulting from the Earth’s rotation around its axis in the Galactic frame, shown for a DM mass $m_\chi = 100 \text{ keV}$ and a light (solid curves) or heavy (dot-dashed curves) mediator. (d) Absorption: projected reach for detection of a kinetically mixed dark photon. In panels (a),(b),(d), the boundary of the blue shaded region uses experimental optical data of the TiSe_2 loss function at zero momentum [23], extrapolated when relevant to nonvanishing momenta via a fitting procedure, for comparison with our full DFT results. The shaded blue band thus indicates the potential impact of discrepancies between our DFT results and the experimentally measured loss function, which we find to be at most $\mathcal{O}(1)$. In all panels we show results at 95% CL assuming a kg-yr exposure, no backgrounds, and energy-deposit acceptance in the range $\omega \in [10 \text{ meV}, 10 \text{ eV}]$. Thin gray curves delineate the best combined reach of the Materials Project dataset [49] and superconducting aluminum [5,6,9] for comparison.

discrimination power. Here, the “anisotropic reach” is defined by the cross section for which the null hypothesis of an isotropic event rate can be rejected at the 95% CL. For HDD we find modulations below the 1% level and therefore do not present its directional reach. Note that for the isotropic (anisotropic) reach, we find that a single orientation $\hat{\mathbf{z}}$ ($\hat{\mathbf{x}}$) provides the best reach across the entire presented DM mass range.

We learn that the proposed unconventional materials are capable of probing new regions of light DM parameter space, improving the reach well-beyond established benchmarks such as superconducting aluminum [5,6,9] and even the best materials found in the large material science dataset of the Materials Project [49] (where, e.g., LiMoO₂ [mp-19338 [53]] and C [mp-569304 [54]] have the best reach in the mass range considered here for scattering). TiSe₂ in particular outperforms both aluminum and the Materials Project database by up to 2 to 3 orders of magnitude, respectively, over several DM mass decades, with strong directional detection prospects.

The daily modulation of the scattering rate in Sr₂RuO₄ and TiSe₂ is shown in Fig. 2(c), illustrated for a $m_\chi = 100$ keV DM signal for light (solid) and heavy (dot-dashed) mediators. The directionally dependent response is computed using a symmetry-aware angular interpolation of the DFT dielectric data, incorporating all crystallographically equivalent directions. The modulation arises from the Earth’s daily rotation, which continuously changes the DM wind orientation relative to the crystal axes. Sr₂RuO₄ and TiSe₂ exhibit especially large daily modulation signals due to their anisotropic low-energy plasmon features that are present along specific axes and suppressed along others. Unsurprisingly, the heavy mediator model exhibits larger modulations since it probes higher momentum transfers, where interaxis differences in the response are more pronounced. For instance, the in-plane and out-of-plane plasmonic responses in Sr₂RuO₄ are strongly disparate, and hence the corresponding modulation is the largest among the considered systems. Additionally, we find that despite substantial differences in the response across HDD doping levels, the shape and amplitude of the modulation remain nearly identical since the anisotropy of the response is preserved within the considered doping range.

Figure 2(d) shows the prospects for detection of absorption of kinetically mixed dark-photon DM. The shaded blue region delineates the difference between the projection of our DFT low momenta results for TiSe₂ and the use of fitted optical data [23]. The qualitative $\mathcal{O}(1)$ differences between the two absorption rates for this material are attributed to the known limitations of our DFT modeling, as discussed earlier. We learn that TiSe₂, Sr₂RuO₄, and HDD at low doping surpass the reach of the best candidates from the Materials Project [49] and of superconducting aluminum [5,6,9], consolidating their standing as exceptional candidate targets for DM searches across many mass scales.

Outlook—We have identified three classes of unconventional materials with low-energy collective excitations—transition-metal dichalcogenides with a CDW phase, multilayered perovskites, and doped multiband semiconductors—that provide enhanced sensitivity to dark matter scattering (absorption) at keV–MeV (meV–eV) masses. Focusing on candidate materials in each class—TiSe₂, Sr₂RuO₄, and HDD—we demonstrated that detectors based on these materials could surpass existing proposals by several orders of magnitude in isotropic searches, with TiSe₂ and Sr₂RuO₄ additionally exhibiting strong directional sensitivity. Our Letter utilizes the dielectric function formalism [28] along with state-of-the-art material science in order to identify materials with incredible prospects for DM detection and to establish their reach.

The proposed materials are experimentally accessible, with TiSe₂ in particular synthesizable on a large scale: milligram-size crystals are readily synthesized, and kg-scale targets are achievable on the timescale of months of furnace operation at minimal cost. The strong, anisotropic low-energy responses of the proposed materials open new avenues for designing detectors that improve sensitivity to light DM and enable a robust mechanism for background discrimination. Existing low-threshold readout technologies employed in other DM detection experiments can be applied to our proposed targets, enabling the construction of an end-to-end light DM experiment based on these materials.

Our results motivate the exploration of these and similar materials as the constituents of next-generation DM detectors, such as transition-metal dichalcogenides with low-energy plasmons [55] and cuprate perovskites [56]. Low-energy deposits in these materials should allow the detection of DM-nucleon interactions as well through phonon production [21], as will be explored in future work. More broadly, our Letter emphasizes that $\mathcal{O}(\text{meV})$ -scale collective modes in solid-state systems have yet to be comprehensively mapped out in the context of DM. Fundamental physics will gain much from an interdisciplinary cohesive effort that classifies and identifies relevant materials targeting light DM detection.

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Data availability—The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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End Matter

Material synthesis—All three materials considered in this Letter have been experimentally studied and are synthesizable in laboratory quantities [23–27]. To illustrate this, we briefly describe the scalable synthesis of TiSe_2 crystals using chemical vapor transport, following well-established procedures. TiSe_2 can be synthesized from elemental Ti and Se in sealed quartz ampules placed in a two-zone furnace. References [57–60] report gram-scale batches per ampule, with growth times of one to two weeks and stoichiometry controlled at the level of $\lesssim 1\%$ in Se content (this level of purity is necessary for preserving the CDW in the material response). We have performed an additional experimental test of these protocols at the Politano lab at L'Aquila using a single-ampule, one-week chemical vapor transport run. The run produced two millimeter-scale TiSe_2 crystals with a total mass of a few tens of milligrams, shown in Fig. 3, demonstrating that the growth protocol is both simple and robust. With an optimized setup utilizing a few tens of ampules in parallel, production rates of hundreds of grams per month are expected to be achievable at a total operational cost below US \$1000 per kilogram.

Experimental considerations—Beyond material synthesis, a full detector concept based on the targets presented in this Letter will require coupling the material to a suitable low-threshold readout. The sub-eV plasmonic excitations produced by a DM interaction are expected to decay into electronic and phononic excitations, which may be measured calorimetrically or through

nonequilibrium charge collection at electrical contacts either at the surface or embedded in the material. A full demonstration of sensitivity in the lowest-energy region will also require dedicated sensor optimization. The same low thresholds that make these materials sensitive to light DM also require addressing thermal and infrared photons, radiogenic and surface backgrounds, and cosmogenic secondaries—motivating cryogenic operation, shielding, and ideally underground deployment. Crucially, the anisotropic response of the targets we propose serves as a strong discriminator between a DM signal and isotropic or stationary backgrounds.

Data handling—In order to obtain the full anisotropic response of the target materials, we take the directionally dependent DFT results of $\epsilon_n(\omega, q) = \hat{\mathbf{q}}_n \cdot \vec{\epsilon}(\omega, \mathbf{q} \parallel \hat{\mathbf{q}}_n) \cdot \hat{\mathbf{q}}_n$ for the directions $\hat{\mathbf{q}}_n$ we have computed, and utilize the crystal symmetries to determine all directions with equivalent responses, and consequently interpolate over the unit sphere using a von Mises–Fisher kernel [61]. This procedure ensures our loss function respects all crystal symmetries and aligns with data at all equivalent directions to $\hat{\mathbf{q}}_n$. We describe the interpolation scheme in more detail in SM [32].

Statistical analysis—Regarding DM scattering with electrons, our analysis considers both the detection prospects for an isotropic signal, as well as the projected ability to detect a directional daily modulation signal. For the former, we compute the projected reach at 95% CL of each target, assuming Poisson statistics and no background [48] (i.e., a three-event reach). We compare the daily-averaged scattering rate along each of the Cartesian directions and select the direction yielding the best experimental reach.

To determine the prospects to detect an anisotropic signal, we perform a two-bin analysis (AM vs PM) for each material to determine the significance of its respective daily modulation signals. The significance is calculated via Monte Carlo, where the DM-target scattering events are assumed to be distributed according to a Poisson distribution, with the different rates in AM and PM accounting for the daily modulation, and no directional backgrounds are assumed. Through this procedure, we discern the minimal number of scattering events required to observe a difference between the two bins at 95% CL, which we denote as $N_{\text{directional}}$. Since $N_{\text{directional}}$ depends on the rate modulation, it varies between the different materials and model parameters (e.g., m_χ , m_ϕ). We estimate the reach of experiments relying on a daily modulating signal to discern a DM signal using the $N_{\text{directional}}$ -event reach. Similarly to the isotropic

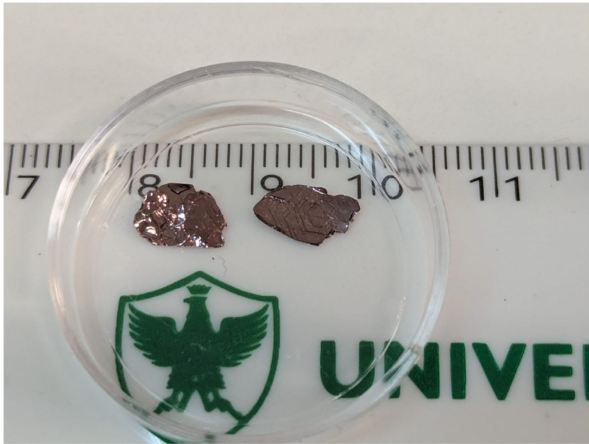


FIG. 3. Synthesized TiSe_2 samples. The two TiSe_2 milligram-scale flakes synthesized using chemical vapor transport in the Politano lab at L'Aquila.

case, we compare the $N_{\text{directional}}$ -event reach along each of the Cartesian directions, selecting the one with the best experimental prospects. Note that this yields a conservative reach since the required $N_{\text{directional}}$ events would be smaller for a more elaborate statistical test utilizing, e.g., a multibin analysis.

For the case of absorption, we take the loss function in Eq. (3) to be the angle-averaged loss function $\widehat{\mathcal{W}}(\omega, q) = (1/4\pi) \int d\Omega_{\mathbf{q}} \mathcal{W}(\omega, \mathbf{q})$, using the zero momentum limit, in order to establish the prospects of each material to probe the parameter space of kinetically mixed dark-photon DM.