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Evaporation Barrier for Dark Matter in Celestial Bodies

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The minimum testable dark matter (DM) mass for almost all DM signatures in celestial bodies is determined by the rate at which DM evaporates. DM evaporation has previously been calculated assuming a competition between the gravitational potential of the object, and thermal kicks from the celestial-body matter. We point out a new effect, where mediators with a range larger than the interparticle spacing induce a force proportional to the density gradient of celestial objects, forming an *evaporation barrier* for the DM. This effect can be so significant that evaporation does not occur even for sub-MeV DM, in stark contrast to previous calculations. This opens up a wide range of new light DM searches, many orders of magnitude in DM mass below the sensitivity of direct detection.

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Dark matter (DM) incident on celestial bodies provides a wealth of opportunities for its discovery. One of our most powerful probes of DM comes from direct detection, which tests the rate at which incoming DM scatters with Standard Model (SM) detectors on the celestial body closest to us – Earth. Direct detection experiments have increasingly constrained GeV-scale DM [1, 2]. However, as the DM mass becomes lighter, its momentum decreases, decreasing the probability it produces a recoil above detector thresholds, and therefore weakening the sensitivity of direct detection. This has motivated a range of novel techniques and detectors to push to lower thresholds, and test the DM-SM scattering rate on the Earth at sub-GeV masses [3–19].

Another promising avenue to test the DM-SM scattering rate at sub-GeV DM masses is to perform new searches with a range of celestial objects. The general idea is that DM can scatter, lose energy, and become gravitationally captured by celestial bodies, and consequently produce detectable signals. However, for sizable DM signals to appear in the capturing object, the DM must not evaporate, *i.e.* thermal upscatterings of the DM particles to the escape velocity must be sufficiently infrequent, so that a significant amount of DM can build up over time. The lower mass limit for which this condition is met, *i.e. the evaporation mass*, varies for each object and is effectively a limiting threshold for how low the DM mass can be tested [20]. Recently it was pointed out that objects such as exoplanets [21], Jupiter [22], brown dwarfs [21, 23], neutron stars, and white dwarfs [23–61] are all objects which can probe sub-GeV DM, due to their relatively cool cores and high densities. Other objects such as the Sun and Earth allow for a range of powerful new searches [62–84], however they do not have as low evaporation masses in previous calculations [20].

In this paper, we show that the evaporation mass for DM in all celestial bodies can be dramatically lower than previously calculated, for a wide range of DM model parameters. This is due to an additional effect that we call the *evaporation barrier*. If the dark sector contains a SM-DM mediator with range larger than the interparticle spacing of the celestial object, the DM will feel an additional force proportional to the celestial-body SM density gradient. This new force can dominate over other effects and allow very light DM particles to be retained in celestial bodies.

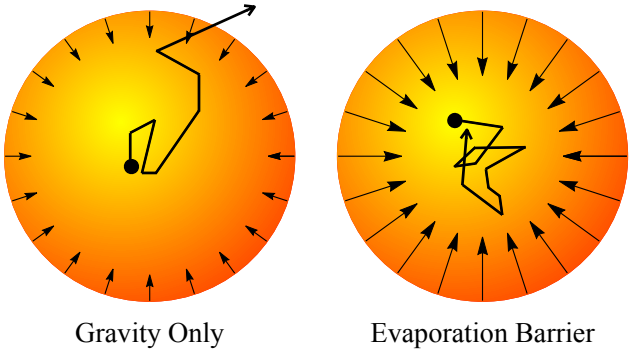

FIG. 1. Schematic representation of the evaporation barrier. **Left:** Gravity only (previous assumption). Evaporation of upscattered light DM particles is not suppressed. **Right:** The evaporation barrier blocks evaporation (this work).

The evaporation barrier arises in a wide range of DM parameter space, and is generic in the presence of any attractive long-range force, including models for axions [85], scalars [86], and new gauge bosons [87]. We will show that the barrier can be so efficient that even extremely feebly-coupled fields can prevent evaporation. This means that even when a DM-SM contact interaction dominates the scattering processes for capture and evaporation, the mere existence of otherwise decoupled light fields can be what determines the evaporation rate. As the fundamental nature of DM is completely unknown, considering the effects of a broader range of interaction types better spans the realm of possibilities that can be mapped to new DM searches with celestial bodies.

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The Evaporation Barrier. — A fairly generic assumption is that DM can interact with the SM fermions through a dark sector mediator of mass m_ϕ. Inside a celestial object with SM particle number density $n_{\rm SM}(\mathbf{r})$, this interaction leads to a potential energy for the DM

$$\phi_{\rm barrier}(\mathbf{r}) = -g_{\rm SM} g_\chi \int_V d^3\mathbf{r}' \, \frac{n_{\rm SM}(\mathbf{r}')\, e^{-m_\phi|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}\,, \quad (1)$$

where V is the volume of the object, and $g_{\rm SM}$ and g_χ are the mediator couplings to SM nucleons and fermionic DM respectively. The effect of this potential becomes relevant once the range of the interaction $r_Y = 1/m_\phi$ becomes larger than the interparticle spacing in the considered object *i.e.* $m_\phi \lesssim$ keV.

The attractive potential has a simple scaling when its range r_Y is such that the SM density varies slowly within the interaction volume. For longer mediator ranges, the field becomes Coulomb-like on the scale of the whole object, and the full solution has to be used (see App. I). The simple scaling applies for the objects we consider as long as $m_\phi \gtrsim 10^{-13}$ eV. In this case, the potential can be approximated as $\sim 1/r$ on scales below r_Y, and is effectively sourced by the number of particles $N_{\rm eff} \simeq n_{\rm SM}(r) r_Y^3$ within that range,

$$\phi_{\rm barrier}(r) \simeq -\frac{g_{\rm SM}\, g_\chi N_{\rm eff}}{r_Y} \simeq -\frac{g_{\rm SM}\, g_\chi n_{\rm SM}(r)}{m_\phi^2}\,, \quad (2)$$

where spherical symmetry is assumed such that $\mathbf{r}$ is written as r. We reproduce this heuristic result in an analytic derivation in App. I. For scalar mediators coupled to fermions, or for vector mediators that couple to DM and SM fermions with opposite charge, this potential will generically lead to an attractive force that scales as the density gradient of the celestial body. We call this potential well an evaporation barrier because it serves to pull the DM towards the celestial-body core, preventing DM evaporation.

The evaporation barrier may exist not only due to SM-DM interactions, but also DM self-interactions. Indeed, DM particles accumulated over time can themselves source a field with an analogous scaling relation $\phi(r) \simeq g_\chi^2 n_\chi(r)/m_\phi^2$. While the contribution to the evaporation barrier from self-interactions can be comparable to Eq. (2) in some cases, we neglect it in this work and focus only on the DM-SM interaction evaporation barrier contributions.

For our purposes of demonstrating the effect of the evaporation barrier, we will assume that contact interactions drive the dynamics other than the evaporation barrier. Such a setup is by no means required; the barrier is a generic feature of attractive long-range forces.

New Dark Matter Distributions. — To calculate DM evaporation under the presence of the evaporation barrier, we need the DM distribution in celestial objects. We will first address the framework for contact interactions, and discuss alterations due to additional long-range forces shortly. For contact interactions, the distribution is obtained from the Boltzmann Collisional Equation, of which two approximate solutions have been found in the limiting cases of short and long mean free paths. For a mean free path that is short compared to the scale of temperature variations, local thermal equilibrium (LTE) can be assumed. For the celestial objects considered, this occurs when the cross-section is above $\sim 10^{-37}$ cm$^2 - 10^{-34}$ cm^2. In this case, the radial profile is obtained from [20, 88]

$$\frac{dn_\chi(r)}{dr} + n_\chi(r)\left[(\kappa+1)\,\frac{d\log T(r)}{dr} + \frac{f(r)}{T(r)}\right] = 0\,. \quad (3)$$

Here $n_\chi(r)$ is the DM number density, $\kappa \simeq -1/[2(1 + m_\chi/m_{\rm SM})^{3/2}]$ is a thermal diffusion coefficient with m_χ the DM mass and $m_{\rm SM}$ the SM target mass [88], $T(r)$ is the local temperature of the celestial object, and $f(r)$ denotes the total external force, which is where the long-range force enters alongside gravity [88]. Solving this equation for $n_\chi(r)$ provides the DM radial profile in equilibrium, which corresponds to the equilibrium distribution found in Refs. [20, 88]:

$$n_\chi^{\rm LTE}(r) = N_0^{\rm LTE}\left[\frac{T(r)}{T(0)}\right]^{3/2-\alpha} \exp\left[-\int_0^R \frac{f(r)}{T(r)} dr\right], \quad (4)$$

where $N_0^{\rm LTE}$ is a constant that normalizes the volume integral of $n_\chi^{\rm LTE}(r)$ to the total number of DM particles in the object N_χ, and where $\alpha \simeq \kappa + 5/2$ [88]. We include our new effect as an additional potential energy alongside the gravitational potential energy $\phi_{\rm grav}$,

$$\phi_{\rm tot}(r) = \phi_{\rm grav}(r) + \phi_{\rm barrier}(r), \quad (5)$$

such that the net external force due to gravity and the evaporation barrier is

$$f(r) = -\nabla\phi_{\rm tot}(r). \quad (6)$$

By contrast, for long mean free paths, an isothermal distribution $n_\chi^{\rm iso}(r)$ becomes an increasingly good approximation for the DM number density distribution [89],

$$n_\chi^{\rm iso}(r) = N_0^{\rm iso} \exp\left[-\frac{\phi_{\rm tot}(r)}{T_\chi}\right], \quad (7)$$

where $N_0^{\rm iso}$ is a constant that normalizes the volume integral of $n_\chi^{\rm iso}(r)$ to N_χ. In this isothermal approximation, the temperature of the DM particles T_χ is obtained from requiring no net energy flow between the DM and SM baths in a steady state. In practice, T_χ will be an intermediate value between the central temperature of the celestial body and the temperature at the maximal orbital radius of the DM particles r_χ. This is approximated by

$$r_\chi \simeq \left(\frac{3\,T(0)}{2\pi\, G\, \rho(0)\, m_\chi}\right)^{1/2} \quad (8)$$

when only the gravitational force is present, where G is the gravitational constant and $\rho(0)$ is the SM density at the core of the object. The correction to this orbital radius due to the additional long-range force does not significantly impact our evaporation rate estimates, as it only shifts the relative weight between the LTE and isothermal distributions within a narrow range of DM-SM cross-sections.

The parameter that differentiates between the isothermal and the LTE regime is the Knudsen number $K = l(0)/r_\chi$, which relates the mean free path at the core $l(0)$ to the length-scale of the DM distribution. Here $l(0) = (\sum_i n_i(0)\sigma_{i\chi})^{-1}$ with i running over the constituent species of the celestial-body material, and $\sigma_{i\chi}$ the DM-SM scattering rate. The expression that approximately connects both regimes is [90, 91]

$$n_\chi(r) = f(K)\, n_\chi^{\rm LTE}(r) + [1 - f(K)]\, n_\chi^{\rm iso}(r), \qquad (9)$$

where $f(K) = 1 - (1 + (K_0/K)^2)^{-1}$ with $K_0 \approx 0.4$ [20] for the Sun; we will use the same value as an approximation for all objects. For the full formalism to describe DM distributions for short-range DM in the Sun, Earth, Jupiter, Brown Dwarfs, and Exoplanets, see Ref. [88].

New Dark Matter Evaporation Results.— An analytic formula for the evaporation rate is [92],

$$\Gamma_{\rm evap} = 4\pi \int_0^R r^2\, s(r)\, n_\chi(r) \left(\sum_i \xi_i(r) n_i(r) \sigma_{i\chi}\right) dr \ , \qquad (10)$$

where in the short mean free path regime, the DM velocity distribution is Maxwellian with $\bar{v} = \sqrt{8T(r)/(\pi m_\chi)}$, where $\bar{r}$ is the mean DM radius, and $\xi_i(r) = \bar{v}(r)\hat{\phi}e^{-\hat{\phi}}$, $s(r) = e^{-\tau(r)}\eta(r)$, where the opacity is given by [92]

$$\tau(r) = \int_r^R ds\, l(s)^{-1} = \sum_i \int_r^R ds\, n_i(s)\sigma_{i\chi}\,, \qquad (11)$$

where $l(r)$ is the mean free path of the DM particle, and the trajectory correction is [92]

$$\eta(r) = \frac{7}{10}\, e^{\frac{3\tau(r)}{2\hat{\phi}(r)}}\, \min\left(1, \tau^{-1}(r)\right)\ . \qquad (12)$$

Here $\hat{\phi}(r) = \phi_{\rm tot}(r)/T(r)$ is the ratio of the escape energy and temperature at radius r. The trajectory correction is derived assuming isotropic DM-SM scattering, and using the Chapman-Enskog expansion [92]. Eq. (10) also approximates the evaporation mass value well in the long mean free path regime [92].

For a given capture and annihilation cross-section, the evaporation mass is thus approximately defined as the threshold value $m_{\rm evap}$ for which [92]

$$\Gamma_{\rm evap}(m_{\rm evap}) \lesssim t_{\rm eq}^{-1}, \qquad (13)$$

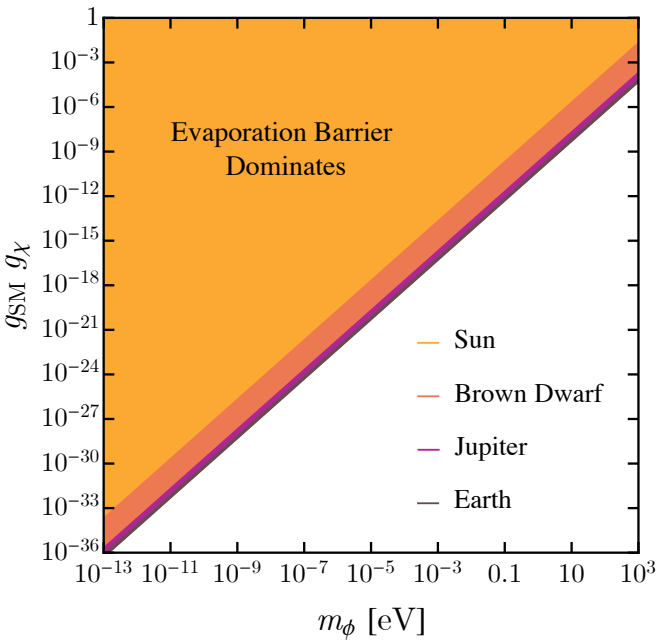

FIG. 2. Mediator masses m_ϕ and corresponding minimum coupling values $g_{\rm SM} g_\chi$ for which the DM evaporation mass is substantially reduced compared to the gravity-only case for each object.

where $t_{\rm eq} \simeq (\Gamma_{\rm cap}\Gamma_{\rm ann})^{1/2}$ is the equilibrium timescale, and $\Gamma_{\rm cap}$ is the capture rate, which we obtain following Ref. [88]. While the capture rate in Eq. (5) of Ref. [88] only applies in the strong interaction regime, we use the same capture equation even when entering the optically thin regime, and even when the SM target mass is smaller than the DM mass. This choice is made as a simplifying and conservative assumption; in any case, the evaporation rate is only logarithmically sensitive to the capture rate, so the precise value is not very important. As we are assuming the long-range force is decoupled compared to contact interactions, and we furthermore restrict our range to shorter than the celestial-body size, we can neglect long-range capture effects [93, 94]. The annihilation rate is [92]

$$\Gamma_{\rm ann} = 4\pi \langle \sigma_{\rm ann} v_{\rm rel} \rangle \int_0^R r^2\, n_\chi(r)^2\, dr. \qquad (14)$$

Regardless of the mean free path regime, the presence of long-range forces has important effects to reduce evaporation. First, it increases the required escape energy. Second, it increases the optical depth that any evaporating particle must traverse, since the distribution of DM becomes more concentrated at the center.

Figure 2 shows where the evaporation barrier is significant for four objects: the Sun, Earth, Jupiter, and a benchmark 50 Jupiter mass and 10 Gyr Brown Dwarf. In the shaded region, the evaporation barrier dominates, such that the DM evaporation mass will be severely decreased. Importantly, note the wide range of parameter

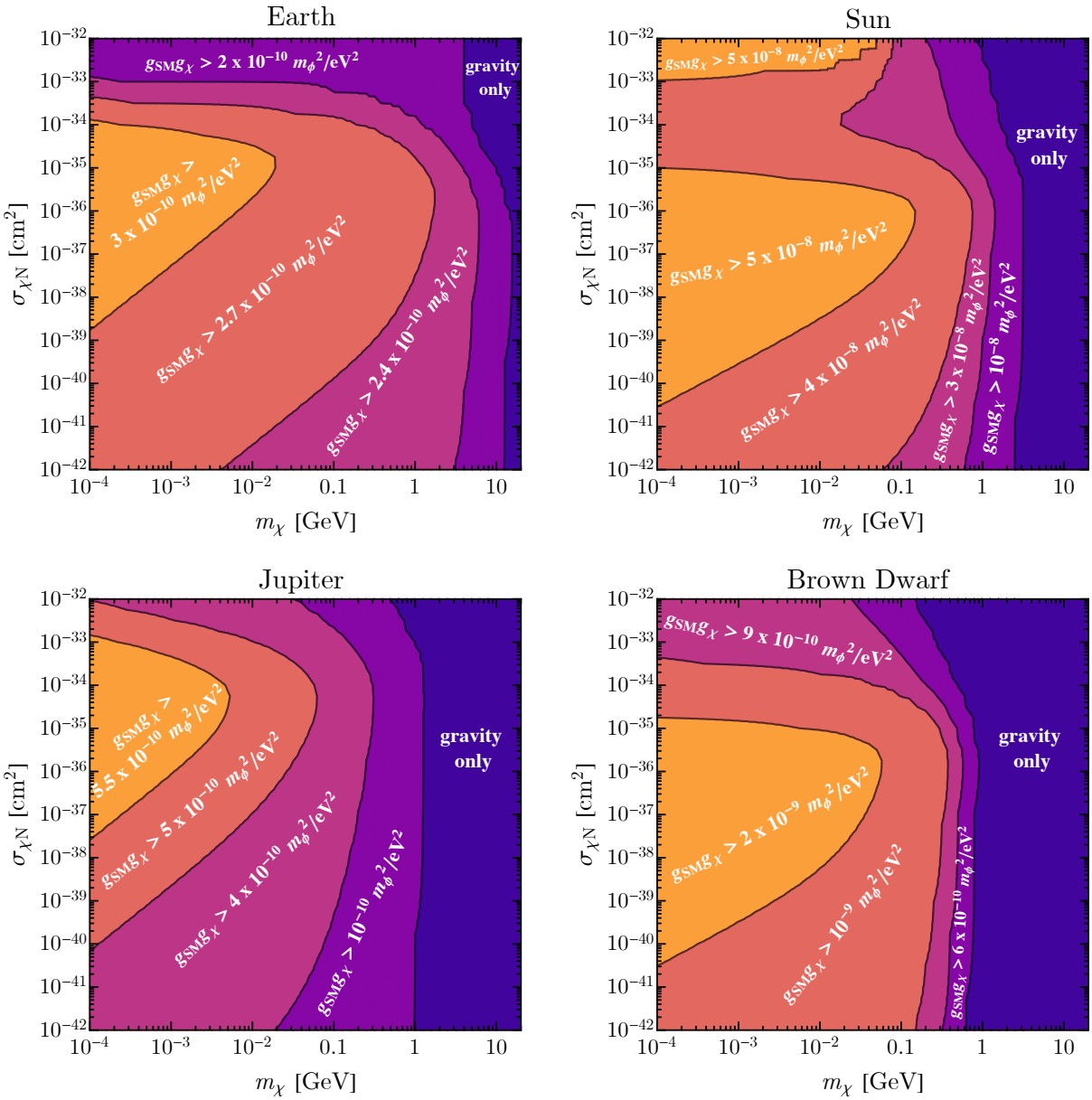

FIG. 3. DM evaporation mass contours for example celestial objects assuming an annihilation cross-section $\langle \sigma_{\rm ann} v_{\rm rel} \rangle = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$, and spin-independent DM-SM scattering $\sigma_{\chi N}$. The contour edges are defined by the minimum DM mass m_χ for which a combination of the mediator coupling to DM g_χ and SM nucleons $g_{\rm SM}$, and the mediator mass m_ϕ, lead to DM particles being retained in the celestial object. Right of the "gravity only" contour corresponds to the only parameter space where DM was retained in previous calculations; that region neglects the evaporation barrier.

space for which this is true. Couplings as small as about 10^{-36} or larger can have an effect, depending on the mass of the mediator. As the mediator mass increases, its range decreases, which decreases the sum of SM targets available for interactions. Therefore, larger couplings are required for the evaporation barrier to have a significant effect for shorter-range mediators. Depending on the DM model realization, the parameter space is subject to some constraints. We give examples in App. III. The evaporation barrier also exists for mediator masses $m_\phi \lesssim 10^{-13}$ eV, but requires use of the full solution, see App. I. We model the SM interior of these objects as per Ref. [88], although we do not include Earth's atmosphere.

Figure 3 shows DM evaporation contours with the evaporation barrier included. Regions that are shaded correspond to DM being retained in the celestial body (i.e. there is no significant evaporation), for the condition labeled on the contour. The previous classic DM evaporation framework of Ref. [20], widely used in the literature (see e.g. Ref. [95]) is shown as the

"gravity only" region. The regions below this in DM mass show the impact of the evaporation barrier – the DM evaporation mass can be extremely sensitive to even tiny couplings of the mediator. We discuss the behavior of these contours further in App. IV. In the case of a vector mediator, neglecting self-interactions, only DM of one charge will be retained, similar to an asymmetric DM scenario. However, this only leads to an $\mathcal{O}(1)$ increase in the evaporation mass. We re-iterate our simplifying assumptions in making these contours: no self-interaction effects, and we assume that the light mediator is de-coupled from the capture, annihilation, and evaporation scattering events, which are instead mediated by contact interactions. These assumptions are by no means required for the barrier to have an effect; they are only simplifying assumptions to explicitly demonstrate the impact of the barrier. We have also assumed only free particle interactions for scattering; for DM masses comparable to or lighter than the edge of our shown DM mass range of 100 keV, collective effects can also be relevant [96]. We expect however that qualitatively similar results would be obtained in that regime.

Implications and Outlook.— The fundamental particle model for DM is unfortunately *completely* unknown. In light of the span of vast possibilities for its nature, the community should perform DM searches in a manner as model-independent as possible. A wide range of celestial bodies have been shown to be excellent targets for DM detection, with their lower DM-mass reaches truncated by the evaporation process. We have shown for the first time that the DM mass at which DM evaporates in celestial objects is, in reality, severely model-dependent. Simple, widespread, and well-motivated extensions of the SM provide forces that can prevent lighter DM from evaporating, allowing sizable DM populations in celestial objects. This leads to sensitivities many orders of magnitude in DM mass below thresholds of other probes of the DM-SM scattering rate, such as direct detection experiments.

We have focused on the effects of the evaporation barrier for some of the most promising targets for DM searches: the Sun, the Earth, Jupiter, and Brown Dwarfs. For each case, we have found dramatic multi-order-of-magnitude reductions are possible for the DM evaporation mass, even for extremely feeble interactions. Our results open up new searches for sub-GeV and ultra-light DM in celestial objects, and significantly expand DM implications for existing searches. The implications include:

- Solar neutrino searches from DM annihilation at experiments such as Super-K [97, 98], IceCube [99, 100], Antares [101], should not cut their search sensitivity at the previously calculated DM evaporation mass of ~ 4 GeV for the Sun, which we have shown is a highly model-dependent value. Searches for neutrinos from DM annihilation in the Earth at SuperK [97], Antares [102], IceCube [103, 104] should not cut their sensitivity at the previously calculated ~ 10 GeV for the Earth. This opens substantial additional DM parameter space in neutrino searches.

- Searches for gamma rays from DM annihilation in the Sun [62, 67, 74, 76, 105], Brown Dwarfs [23, 106] and Jupiter [22] can likewise extend to at least sub-MeV DM mass, depending on the DM model.

- Searches for electron final states in the Sun [67, 68, 72, 107], or Jupiter [108] can be extended to at least sub-MeV DM masses.

- Exoplanet or brown dwarf heating [21] can extend to at least sub-MeV DM masses.

- Solar reflection constraints, as pointed out in Refs. [109–112], may now disappear for sufficiently coupled light mediators, and need reevaluation. Solar reflection is the idea that DM can scatter with the Sun, gain energy from the solar temperature, evaporate, and travel to Earth with higher energies, making sub-GeV DM sufficiently energetic to overcome direct detection thresholds. However, now that evaporation can be blocked by the barrier, DM may remain in the Sun and not be detectable by this method. This would remove the intrinsic component of Galactic DM expected from the Sun for sub-GeV DM, as usually shown as an irreducible constraint on the direct detection parameter space [113–115].

- The different DM distributions lead to new observables. For example, this may affect the solar abundance problem, which has not yet been solved, and presents a 6σ discrepancy between theory and experiment [116–125]. Further, DM effects on stellar evolution and astroseismology may also be different than previously studied [126–130]. In addition, this means that surface DM abundances can be different to previously calculated [88], but low-threshold direct detection of the thermalized DM population [19] may extend to lower DM masses.

We recommend that experimental collaborations, and theorists using data, analyze celestial-body data as low as experimental thresholds allow, rather than as low as one particular DM model's result for the DM evaporation mass. After all, the span of DM possibilities is vast, and in the end, anything could be realized by nature. Wherever DM is hiding, we don't want to miss it.

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Evaporation Barrier for Dark Matter in Celestial Bodies

Supplemental Material

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I. ANALYTIC SOLUTION FOR THE EVAPORATION BARRIER

The evaporation barrier is the potential energy a DM particle has due to the SM density $n_{\rm SM}$ of the celestial object. We express this as $\phi_{\rm barrier}(r) = g_\chi \phi(r)$, where the field $\phi(r)$ follows from the inhomogeneous time-independent Klein-Gordon equation

$$(\nabla^2 - m_\phi^2)\phi(\mathbf{r}) = g_{\rm SM}\, n_{\rm SM}(\mathbf{r}) \ , \tag{S1}$$

and $g_{\rm SM}$ and g_χ is the SM and DM coupling to new light sectors respectively. This coupling is in principle renormalized so that it accounts for potential loop-order corrections. Depending on the specific model realization, the field ϕ could be a scalar or the time-like component of a time-independent vector field. Since the evolution of the celestial bodies takes place on much slower timescales than the DM dynamics, this time-independence is justified. The set-up is analogous to the electrostatic solutions in classical electrodynamics, and we will refer to this regime as *static*. We proceed to derive an analytic solution for this equation given an arbitrary spherically-symmetric density profile. In particular, we will show below that, in the limit that the mediator mass m_ϕ is heavy compared to the inverse of the size R of the celestial object, this external potential becomes proportional to the local density of SM particles.

In spherical coordinates, we impose as boundary conditions $\frac{d\phi}{dr}|_{r=0} = 0$ and $\phi(r > R) = \phi(R)(R/r)\exp(-m_\phi(r-R))$. The central field value $\phi(0)$, as well as the value at the boundary $\phi(R)$, are determined below from requiring continuity and differentiability. Writing Eq. (S1) explicitly in spherical coordinates, and introducing the change of variables $\psi(r) = r\,\phi(r)$, we get

$$\frac{d^2\psi}{dr^2} - m_\phi^2 \psi(r) = g_{\rm SM}\, r\, n_{\rm SM}(r) \ . \tag{S2}$$

In terms of the auxiliary field ψ, the boundary conditions read $\psi(0) = 0$ and $\psi'(0) = \phi(0)$. The solution to the above equation, for the boundary conditions we have imposed here, is

$$\psi_{\rm int}(r) = \psi_1(r) + g_{\rm SM} \int_0^r \psi_2(r-s)\ n_{\rm SM}(s)\, s\, ds \, , \tag{S3}$$

where ψ_1 is the solution to the homogeneous problem (*i.e.* Eq. (S2) without the source term) with boundary conditions $\psi_1(0) = 0$ and $\psi_1'(0) = \phi(0)$, while similarly $\psi_2(r)$ is the solution to the homogeneous problem but with boundary conditions $\psi_2(0) = 0$ and $\psi_2'(0) = 1$. These are

$$\psi_1(r) = \phi(0)\sinh(m_\phi r) \ , \tag{S4}$$

and

$$\psi_2(r) = \sinh(m_\phi r) \ . \tag{S5}$$

The solution for the interior of the celestial object must be smoothly connected to the solution outside, which will simply scale as $\phi_{\rm ext}(r) = \phi(R)(R/r)\exp\left(m_\phi(R-r)\right)$. Both $\phi(0)$ and $\phi(R)$ are then determined from this boundary condition. Switching back to $\phi(r) = \psi(r)/r$, this leads to a system of linear equations for the pair $(\phi(0), \phi(R))$ of the form

$$\begin{bmatrix} \sinh(m_\phi R) & -m_\phi R \\ \cosh(m_\phi R) & m_\phi R \end{bmatrix} \begin{bmatrix} \phi(0) \\ \phi(R) \end{bmatrix} = \begin{bmatrix} a \\ b \end{bmatrix}$$

where a and b are given by

$$a = -g_{\rm SM} \int_0^R \sinh\left(m_\phi(R-s)\right)\; s\, n_{\rm SM}(s)\, ds\,, \tag{S6}$$

$$\begin{aligned} b &= -g_{\rm SM} \frac{d}{dr}\left[\int_0^r \sinh\left(m_\phi(r-s)\right)\; s\, n_{\rm SM}(s)\, ds\right]_{r=R} \\ &= -g_{\rm SM} \int_0^R \cosh\left(m_\phi(R-s)\right)\; s\, n_{\rm SM}(s)\, ds\,. \end{aligned} \tag{S7}$$

The system above is non-singular and can be easily solved by inverting the coefficient matrix, which yields a solution for $\phi(0)$ of the form

$$\phi(0) = -g_{\rm SM} \int_0^R \exp(-m_\phi s)\; s\; n_{\rm SM}(s)\; ds\,. \tag{S8}$$

The formal solution to Eq. (S1) with the boundary conditions we imposed thus reads

$$\phi_{\rm int}(r) = \phi(0)\left(\frac{\sinh(m_\phi r)}{m_\phi r}\right) + g_{\rm SM}\int_0^r \frac{\sinh\left(m_\phi(r-s)\right)}{m_\phi r} s\; n_{\rm SM}(s)\; ds\,, \tag{S9}$$

and

$$\phi_{\rm ext}(r) = \phi(R)\left(\frac{R}{r}\right)\exp\left(-m_\phi(r-R)\right)\,. \tag{S10}$$

In the limit that the range of the interaction is short compared to the length scale of density variation, *i.e.* $m_\phi^{-1} \ll n_{\rm SM}(r)/n'_{\rm SM}(r)$ across the celestial object, a simple scaling relation for the field can be obtained. This can be seen upon expanding the hyperbolic functions in Eq. (S9):

$$\begin{aligned} \phi_{\rm int}(r) = &-g_{\rm SM}\int_r^R \frac{\exp(m_\phi(r-s))}{2m_\phi r}\, s\, n_{\rm SM}(s)\; ds \\ &- g_{\rm SM}\int_0^r \frac{\exp(-m_\phi(r-s))}{2m_\phi r}\, s\, n_{\rm SM}(s)\, ds \\ &+ g_{\rm SM}\int_0^R \frac{\exp(-m_\phi(r+s))}{2m_\phi r}\, s\, n_{\rm SM}(s)\, ds\,. \end{aligned} \tag{S11}$$

When the above condition is met, it is also the case that $m_\phi R \gg 1$, implying that the last term above becomes subdominant. By contrast, the first two terms are well-approximated by integrating over a domain width δr around $s = r$, where the exponential functions peak. Since the density varies slowly over the domain of integration, this yields

$$\int_r^{r+\delta r} \frac{\exp(m_\phi(r-s))}{2m_\phi r}\, s\, n_{\rm SM}(s)\, ds \simeq \frac{1}{2m_\phi} n_{\rm SM}(r)\delta r + \mathcal{O}(\delta r^2)\,, \tag{S12}$$

$$\int_{r-\delta r}^r \frac{\exp(-m_\phi(r-s))}{2m_\phi r}\, s\, n_{\rm SM}(s)\, ds \simeq \frac{1}{2m_\phi} n_{\rm SM}(r)\delta r + \mathcal{O}(\delta r^2)\,. \tag{S13}$$

Combining the above expressions and approximating the domain width by $\delta r \simeq m_\phi^{-1}$, we arrive at

$$\phi_{\rm int}(r) \simeq -\frac{g_{\rm SM} n_{\rm SM}(r)}{m_\phi^2} \ . \tag{S14}$$

The evaporation barrier, *i.e.* the potential energy that a dark matter particle has from this additional field in the celestial object, is then obtained from the product $\phi_{\rm barrier}(r) = g_\chi \phi(r)$. This is the same scaling we estimated based on heuristic arguments in Eq. (2) in the main text. Although our analytic solution given by Eqs. (S9) and (S10) is valid for any finite mediator mass, the simplified form in Eq. (S14) will hold for mediator masses $m_\phi \gtrsim 10^{-13}$ eV for the celestial objects considered here. In the context of stellar cooling, Ref. [131] uses a similar scaling to Eq. (S14) in their estimates of stellar cooling limits with additional mediators that shift the mass of the radiated dark particles; our Eqs. (S9) and (S10) provide the generalized forms.

II. DARK MATTER EFFECTIVE POTENTIAL FROM LIGHT DEGREES OF FREEDOM

We now show how light fields sourced by celestial objects translate into an effective potential for the DM which, within a certain range of parameters, can prevent the evaporation of DM below the canonical mass values commonly assumed. We consider two benchmark cases, in which the DM has either a scalar or vector portal to the SM. Specific models that could generate such portals are discussed in App. III below. The central point we discuss here is that, in both cases, the fields sourced by celestial objects modify the dispersion relation of DM particles. In the low energy limit, this translates into a potential that increases the escape energy required for DM to evaporate.

If the DM is coupled to the SM via a real scalar ϕ with coupling strength g_χ, the in-medium field inside the celestial object shifts the mass to an effective value

$$m_\chi^* = m_\chi + g_\chi \, \phi(\mathbf{r}) \ . \tag{S15}$$

Conservation of energy then implies that a DM particle with initial momentum $\mathbf{p}$ must be boosted to a momentum $\mathbf{p}'$ while transiting through due to the field sourced by the baryons, according to the relation

$$\mathbf{p}^2 + m_\chi^2 = \mathbf{p}'^2 + m_\chi^{*\,2} \ . \tag{S16}$$

In the limit that the effective mass shift is small compared to the bare DM mass $|g_\chi \phi(\mathbf{r})| \ll m_\chi$, the above expression can be expanded so that the kinetic energy change is expressed in terms of a non-relativistic potential

$$\frac{p^2 - p'^2}{2m_\chi} \simeq g_\chi \, \phi(\mathbf{r}) \equiv \phi_{\rm barrier}(\mathbf{r}) \ . \tag{S17}$$

See *e.g.* Refs. [132–134] for a similar discussion in the context of composite DM searches.

Similarly, the time-like component of a vector field $V_0(\mathbf{r})$ in the static limit also acquires an expectation value. However, the field shifts the total energy of the DM particle instead of its mass

$$\sqrt{\mathbf{p}^2 + m_\chi^2} = \sqrt{\mathbf{p}'^2 + m_\chi^2} - g_\chi \, V_0(\mathbf{r}) \ . \tag{S18}$$

As before, as long as $|g_\chi V_0(\mathbf{r})| \ll m_\chi$ and the DM particles are non-relativistic, both sides can be expanded to obtain

$$\frac{p^2 - p'^2}{2m_\chi} \simeq g_\chi V_0(\mathbf{r}) \equiv \phi_{\rm barrier}(\mathbf{r}) \, . \tag{S19}$$

In this non-relativistic limit, vector fields yield an effective potential for DM particles of the same functional form as the scalar case for the celestial objects we consider. Note that for stronger interactions, the above treatment becomes non-trivial, and each case has to be treated separately in a quantum field theory framework. However, the field sourced by celestial objects is proportional to both the coupling and number density of SM carriers. Since large couplings are quite constrained by experiments, such a relativistic regime would be inaccessible to most celestial objects unless they have extreme densities to compensate for the small coupling, such as white dwarfs and neutron stars.

III. PARTICLE MODEL REALIZATIONS FOR THE EVAPORATION BARRIER

As detailed in the previous section, both scalar and vector portals can generate an additional potential within celestial objects that prevents light DM from evaporating. Here, we discuss some well-motivated models for which this effect can be prominent, given existing constraints on new light mediators within the SM sector. In all cases, we assume that the DM is a Dirac fermion χ, although Majorana fermions or bosonic DM scenarios could be explored as well.

- *Light Scalar Mediators:* A real light scalar generically mediates an attractive force between SM nucleons and the DM, with interactions of the form

$$\mathcal{L} \supset (g_\chi \bar{\chi}\chi + g_n \bar{n}n)\,\phi - \frac{1}{2}m_\phi^2\phi^2. \tag{S20}$$

  The coupling to nucleons can be realized through a coupling of the scalar to the top quark or a colored vector-like generation [135]. Alternatively, one could consider a similar construction for a leptophilic scalar mediator that couples the DM to the electron field [136], though the leptophilic scenario is more constrained by BBN and stellar cooling. Overall, models with such light particles have been considered extensively in the literature, and are a well-motivated field of SM extensions. For example, they have been considered in the context of nuclear decay observations [137, 138], or the neutron lifetime anomaly [139].

  If self-interactions of the mediator were included for such scalar mediator models, quartic self-couplings could induce in-medium mass corrections of the order $\delta m_\phi^2 \sim \lambda g_{\rm SM}^2 n_{\rm SM}^2/m_\phi^4$. If the self-interaction is chosen to be repulsive, this could potentially weaken the evaporation barrier for ultralight mediators unless the self-coupling λ is small at tree-level. In addition, thermal corrections to the scalar mass are possible but are of order $\delta m_\phi^2 \sim g_{\rm SM} n_{\rm SM}/T$, and are therefore negligible for the parameter space considered.

- *Axion-like particles:* A particularly compelling candidate for a light particle is the axion, which is introduced as a solution to the strong CP-problem [140, 141]. The relevant coupling to the QCD sector arises from the axion-gluon interaction

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}\,, \tag{S21}$$

  where a is the axion field, f_a the axion decay constant $G^a_{\mu\nu}$ the gluon field tensors, and α_s the strong coupling constant. It has been discussed in Refs. [85, 142] that in the presence of CP-violation, which can either be the effect of an imperfect Peccei-Quinn symmetry or transferred from the electroweak sector of the SM, a CP-odd g_{aNN} coupling can arise leading to a non-derivative axion-nucleon interaction. The expected coupling strength needed to have a sizable effect on evaporation is compatible with the commonly assumed mass and coupling range of common axion scenarios [143, 144], as discussed in Ref. [142]. Similarly, the axion may couple to DM with dark sector coupling g_χ, which is only weakly constrained from the phenomenological perspective. The relevant interaction Lagrangian is thus analogous to the above scenario

$$\mathcal{L} \supset g_{aNN}a\bar{N}N + g_\chi a\,\bar{\chi}\chi - \frac{1}{2}m_a a^2\,. \tag{S22}$$

  The axion is expected to induce a long-range force between the DM and SM particles when its mass is light, as is commonly assumed in the literature. The parameter space for this long-range interaction is analogous to the one shown in Fig. 1.

  Note that in the case of the axion the quartic self-coupling is naturally small, since it scales as $\lambda_a \sim m_a^2/f_a^2$ [145], where f_a is typically required to be above $\sim 10^{12}$ GeV. Thus in-medium mass corrections are negligible in this scenario.

- *New $U(1)$ gauge bosons:* Numerous BSM theories have considered baryon and lepton numbers or a combination of these as new gauge symmetries that are spontaneously broken [146–149]. To illustrate the applicability of this scenario, we consider a new $U(1)_B$ gauge interaction which can be parametrized at the nucleon level as

$$\mathcal{L} \supset (g_\chi \bar{\chi}\gamma^\mu\chi + g_n \bar{n}\gamma^\mu n)\,V_\mu - \frac{1}{2}m_V^2 V_\mu V^\mu, \tag{S23}$$

  where the time-like component acquires a non-zero expectation value inside the celestial object in the static limit. For the above model, additional field content is generally needed to ensure it is anomaly-free [146, 150, 151], and gauge invariant [151–153] which we avoid detailing here. Theories with additional gauged quantum numbers have been considered extensively in a number of outstanding problems such as the $(g-2)_\mu$ anomaly [154, 155], flavour violating decays [156–158], DM [159–164] and neutrino mass generation [165, 166].

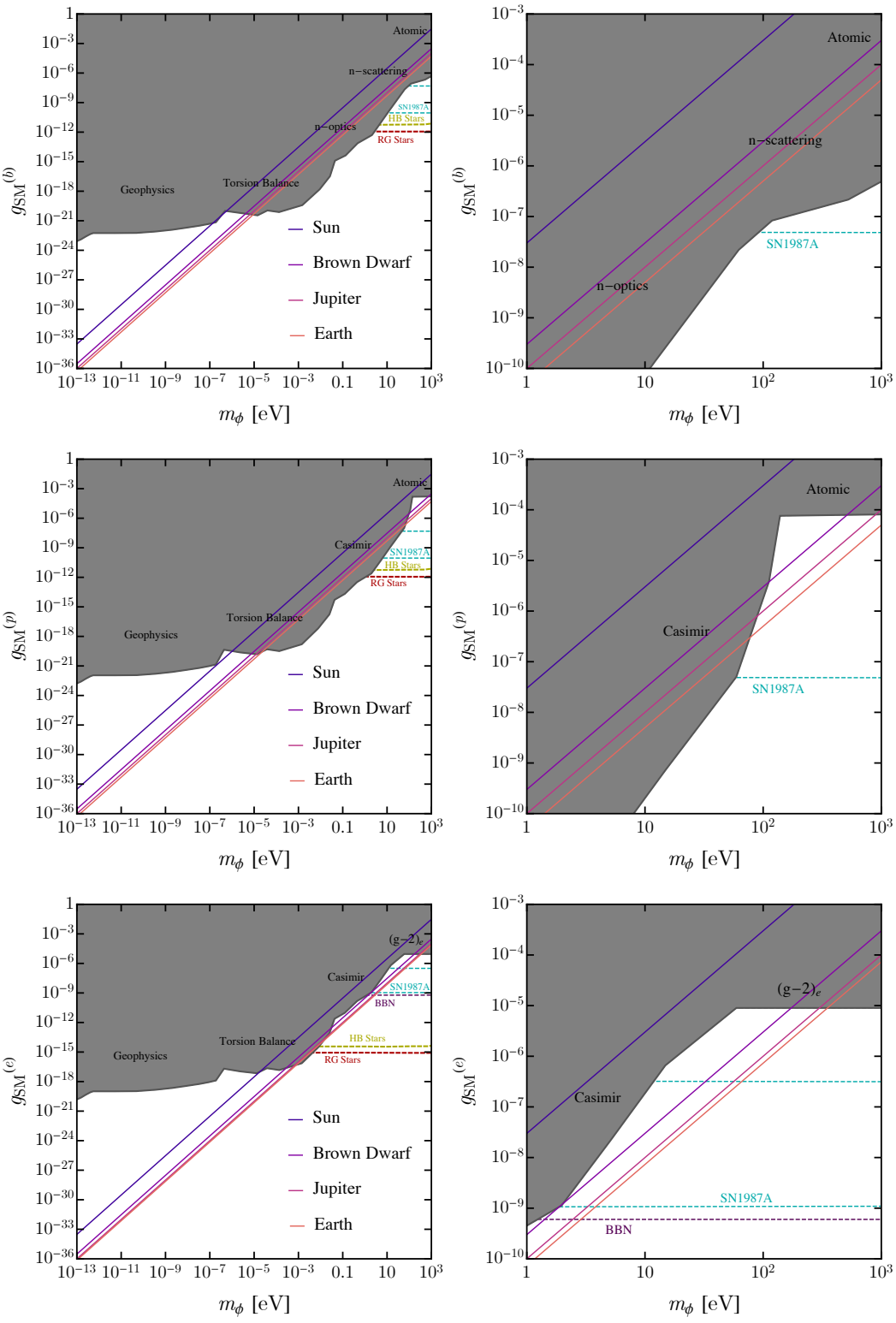

FIG. S1. Constraints on long-range mediators with equal coupling to protons and neutrons (**top row**), proton-only coupling (**middle row**), and electron-only coupling (**bottom row**); see text for constraint details. Overlaid we show minimum coupling values $g_{\rm SM}$ (assuming $g_\chi = 1$) for which the resulting evaporation barrier dominates in each celestial object, and therefore reduces the DM evaporation mass. The right column is simply a zoom in on the high mediator mass region of the left column.

Figure S1 illustrates the minimum coupling $g_{\rm SM}$ for which evaporation barrier effects dominate in each celestial object, compared to existing experimental constraints. To facilitate straightforward comparison, we have set the DM coupling $g_\chi = 1$. We show three coupling cases on each row: equal proton and neutron couplings, proton couplings, or electron couplings. These couplings are partly constrained by experiments including torsion balance [167–172], casimir-type searches [173–177], atomic and nuclear measurements [178, 179] and geophysical data [180]. For isospin-invariant couplings, there are additional constraints from neutron optics and neutron-xenon scattering experiments [181–185]. For proton-only couplings, we have rescaled the limits by a factor $Z/A \simeq 1/2$ and neglected the mass difference between neutrons and protons. Similarly, for electron-only couplings, we have included $(g-2)_e$ constraints [186] and rescaled other applicable limits form $5^{\rm th}$ force searches by a factor $m_e/m_N \simeq 1/1836$. We also show astrophysical constraints for scalar mediators based on stellar cooling of RG and HB stars [187], and SN1987A [188, 189], as well as cosmological constraints based on BBN deuterium abundances for leptophilic mediators [135, 190]. For vector mediators, these limits are in general weaker in the light mass end than the scalar bounds shown in Fig. S1. While we show astrophysical bounds as dashed lines for completeness, it is important to keep in mind that they are highly model dependent, and can disappear under a similar mechanism to the evaporation barrier, as discussed in Ref. [131]. In addition to the previous limits, black hole superradiance places coupling-independent constraints on light bosonic particles in mass windows below $\lesssim 10^{-11}$ eV [191–194]. However, these limits crucially depend on black hole spin measurements [195], for which there is not a consensus [196]. Simple model building [196] and back-reaction effects [197], for example, can entirely lift these constraints in some cases.

Overall, we emphasise that while data from BBN and CMB have potential to constrain light dark sectors, a crucial required assumption is that those sectors are thermalized during the relevant epochs. Several scenarios avoid those bounds all together. One possibility is that the dark sector never enters thermal and kinetic equilibrium with the SM, and the DM abundance is produced non-thermally. Another possibility is that a late-time phase transition makes light degrees of freedom light only at late times [198]. Or as a third option, thermalization can only take place after a late-time phase transition [136]. In all these scenarios dark sectors with light particles are consistent with cosmological observations.

Finally, we also comment on constraints arising from DM self-interactions, which can generically arise in some of these models. Observations of the Bullet Cluster and halo shapes have led to claimed limits on DM self-couplings through light mediators of order $g_\chi \lesssim 10^{-4}\ (m_\chi/{\rm MeV})^{3/4}$ for velocities that would be relevant for captured DM in celestial objects [135]. However, we emphasize that these bounds are not robust, due to their dependence on how observations of the astrophysical probe are performed [199–203], and a lack of systematic error bars. They also depend on the DM model assumptions [135]. In any case, even taking these bounds at face value, ample viable parameter space exists where the evaporation barrier present in celestial objects could trap light DM.

IV. BEHAVIOUR OF EVAPORATION CONTOURS

A. Dependence on Cross Section and DM Mass

There are several factors that lead to evaporation or retention of DM in celestial objects. First, higher or lower ambient temperatures lead to larger or smaller thermal kicks imparted to the DM. Second, the size of the DM-SM scattering rate determines how frequently the DM receives thermal kicks from the ambient SM temperature, and it is also relevant for keeping the DM trapped by down-scattering the thermally kicked DM. Third, the amount of celestial-body overburden available to keep the DM trapped is relevant – if there are too few SM particles standing between the DM and the surface for a given interaction rate, the DM will not be retained. Fourth, the lighter the DM is, the easier it is for it to escape the gravitational well. These features appear in our Fig. 3 in the main text. The lowest evaporation masses occur in the two extremes: either the strong interaction limit, or weak interaction limit. In the strong limit, DM is thermally kicked often, but it is also quickly down-scattered again, due to the large optical depth between the DM and the surface. In the weak limit, DM receives very few thermal kicks, so the few down-scatters do not matter given DM is not excited much in the first place. The highest evaporation masses usually occur at the cross sections roughly where DM interactions switch from the weak to the strong interaction regime. This cross section is about 5×10^{-36} cm^2, 10^{-36} cm^2, 10^{-35} cm^2, and 2×10^{-36} cm^2 for the Earth, Sun, Jupiter, and our benchmark Brown Dwarf, respectively. In this case, the interaction is not so strong that the thermally kicked DM can be scattered back down and remain trapped, but it is not so weak that the thermal kicks happen so infrequently that evaporation occurs less often.

The optimal celestial-body radius for evaporation within the celestial object varies strongly as a function of the DM-SM scattering rate. In fact, for high cross sections, the DM evaporation occurs only in a very thin shell towards the celestial-body surface [20]. For smaller cross sections, evaporation optimally occurs closer to the core [20].

Our additional evaporation barrier effect serves to re-enforce gravity, offering an additional potential that also pulls

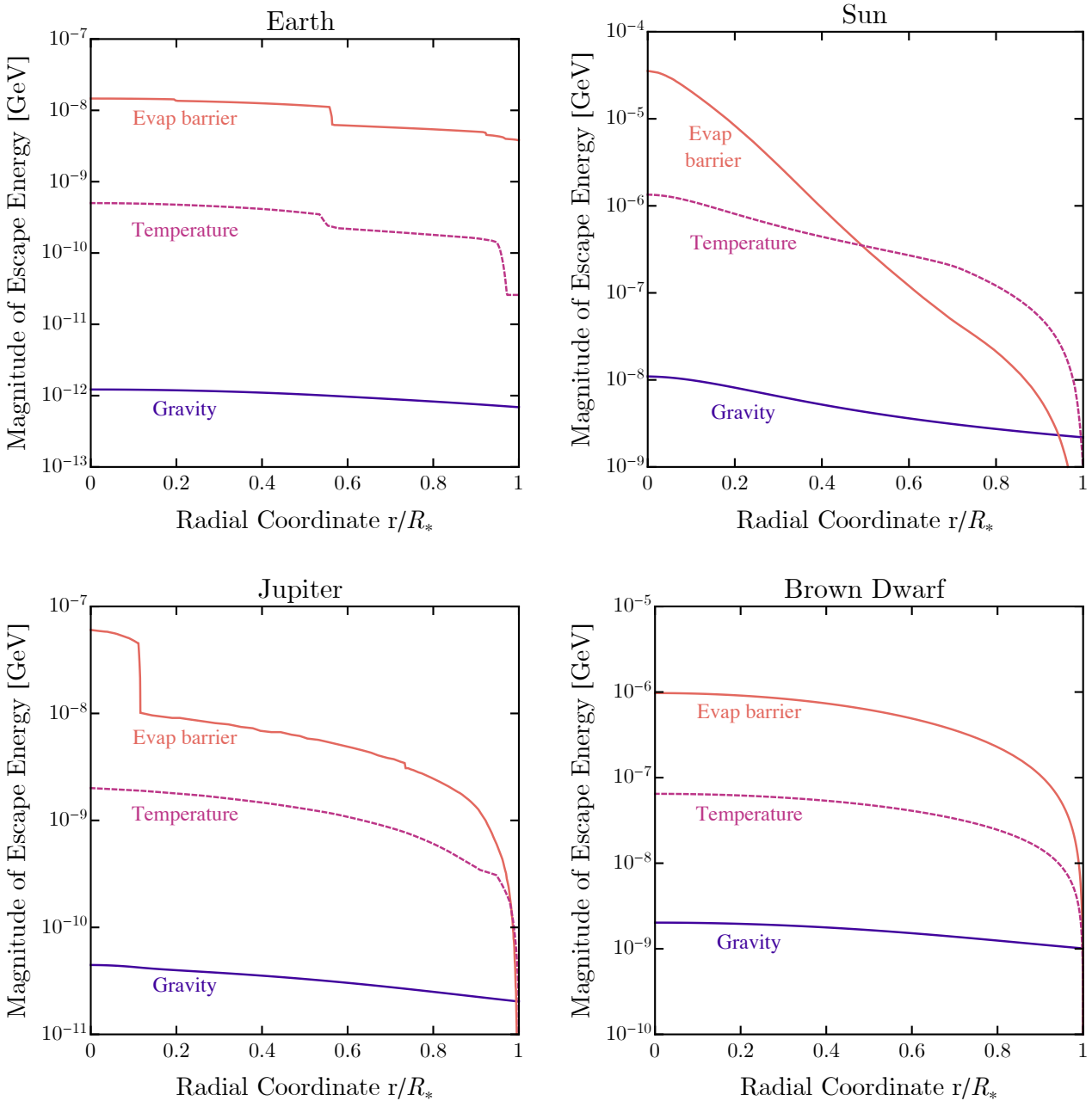

FIG. S2. Magnitude of the total energy needed to escape from radius r for a 1 MeV DM particle due to gravity (solid) and the evaporation barrier (solid), for each celestial object as labeled. Here we have chosen the new long-range force couplings such that $\phi_{\rm barrier} \gg \phi_{\rm grav}$ at the core of the object. For comparison, we include the temperature (dashed) as a function of radius r which is a measure of the local evaporation efficiency.

the DM particles towards the core. The shape of the curves we see in Fig. 3 of the main text is dominantly for the reasons we just outlined above, though there are some interesting effects we observe which do not occur in the gravity only case, which we now discuss below.

B. Comparison of Escape Energy to Temperature in Celestial Objects

Figure S2 compares the magnitude of the escape energy due to the gravitational field or new long-range force (which traces the SM density profile of the object), to the temperature, for each celestial object. For concreteness,

we have set the DM mass to 1 MeV, which lies below the evaporation mass for these objects when considering only the gravitational force. For the Earth, Jupiter, or the Brown Dwarf, we see that when the long-range force dominates at the core of the object, it also dominates at the surface. Given that at high cross-sections the DM evaporation occurs in a very thin shell at the surface [20], this means that even at high cross sections the new long-range force will dominate in these objects and prevent DM evaporation. However, this is not true for the Sun. In this case, due to the shape of the solar SM density profile traced by the new long-range force, compared to the solar temperature profile, we see that while the new long-range force can dominate at the core, it will not dominate at radii closer to the solar surface unless the coupling is significantly stronger compared to the other cases. This means that, for sub-GeV DM masses in the Sun, while the new long-range force blocks evaporation for lower cross sections (which have evaporation shells closer to the core), it will not generically block evaporation at higher cross sections (which have evaporation shells closer to the surface). This is exactly what we observe for the Sun in our main text Fig. 3, where at high cross sections the reduction in the DM evaporation mass is not as prominent compared to lower cross sections.

Comparing instead just the gravitational escape energy and the temperature in Fig. S2, we note that temperature is roughly dominating everywhere over gravity for all the objects. For this reason, without including our evaporation barrier, DM below about 250 MeV with spin-independent dominated capture and evaporation interactions was previously claimed to evaporate in all celestial objects [95]. We have however shown that whether or not DM below about 250 MeV evaporates is highly-model dependent. In addition, note that the fitting procedure for brown dwarf core temperatures in Ref. [95] extrapolates results of Ref. [204] that go to 3 Gyr, resulting in higher brown dwarf core temperatures compared to core temperatures at 10 Gyr [21] where an analytic brown dwarf evolution model is used [205]. This overall leads to higher DM evaporation mass estimates for brown dwarfs in Ref. [95] even in the gravity only case.

[1] J. Aalbers *et al.*, "A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics," (2022), arXiv:2203.02309 [physics.ins-det].

[2] J. Aalbers *et al.* (LZ), "First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment," (2022), arXiv:2207.03764 [hep-ex].

[3] Yonit Hochberg, Yonatan F. Kahn, Rebecca K. Leane, Surjeet Rajendran, Ken Van Tilburg, Tien-Tien Yu, and Kathryn M. Zurek, "New approaches to dark matter detection," Nature Rev. Phys. **4**, 637–641 (2022).

[4] Yonit Hochberg, Yue Zhao, and Kathryn M. Zurek, "Superconducting Detectors for Superlight Dark Matter," Phys. Rev. Lett. **116**, 011301 (2016), arXiv:1504.07237 [hep-ph].

[5] Yonit Hochberg, Matt Pyle, Yue Zhao, and Kathryn M. Zurek, "Detecting Superlight Dark Matter with Fermi-Degenerate Materials," JHEP **08**, 057 (2016), arXiv:1512.04533 [hep-ph].

[6] Yonit Hochberg, Yonatan Kahn, Noah Kurinsky, Benjamin V. Lehmann, To Chin Yu, and Karl K. Berggren, "Determining Dark-Matter Electron Scattering Rates from the Dielectric Function," Phys. Rev. Lett. **127**, 151802 (2021), arXiv:2101.08263 [hep-ph].

[7] Yonit Hochberg, Eric David Kramer, Noah Kurinsky, and Benjamin V. Lehmann, "Directional Detection of Light Dark Matter in Superconductors," (2021), arXiv:2109.04473 [hep-ph].

[8] Yonit Hochberg, Ilya Charaev, Sae-Woo Nam, Varun Verma, Marco Colangelo, and Karl K. Berggren, "Detecting Sub-GeV Dark Matter with Superconducting Nanowires," Phys. Rev. Lett. **123**, 151802 (2019), arXiv:1903.05101 [hep-ph].

[9] Jeff Chiles *et al.*, "New Constraints on Dark Photon Dark Matter with Superconducting Nanowire Detectors in an Optical Haloscope," Phys. Rev. Lett. **128**, 231802 (2022), arXiv:2110.01582 [hep-ex].

[10] Katelin Schutz and Kathryn M. Zurek, "Detectability of Light Dark Matter with Superfluid Helium," Phys. Rev. Lett. **117**, 121302 (2016), arXiv:1604.08206 [hep-ph].

[11] Simon Knapen, Tongyan Lin, and Kathryn M. Zurek, "Light Dark Matter in Superfluid Helium: Detection with Multi-excitation Production," Phys. Rev. D **95**, 056019 (2017), arXiv:1611.06228 [hep-ph].

[12] Andrea Caputo, Angelo Esposito, and Antonio D. Polosa, "Sub-MeV Dark Matter and the Goldstone Modes of Superfluid Helium," Phys. Rev. D **100**, 116007 (2019), arXiv:1907.10635 [hep-ph].

[13] Sinead Griffin, Simon Knapen, Tongyan Lin, and Kathryn M. Zurek, "Directional Detection of Light Dark Matter with Polar Materials," Phys. Rev. D **98**, 115034 (2018), arXiv:1807.10291 [hep-ph].

[14] Simon Knapen, Tongyan Lin, Matt Pyle, and Kathryn M. Zurek, "Detection of Light Dark Matter With Optical Phonons in Polar Materials," Phys. Lett. B **785**, 386–390 (2018), arXiv:1712.06598 [hep-ph].

[15] Yonit Hochberg, Yonatan Kahn, Mariangela Lisanti, Kathryn M. Zurek, Adolfo G. Grushin, Roni Ilan, Sinéad M. Griffin, Zhen-Fei Liu, Sophie F. Weber, and Jeffrey B. Neaton, "Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials," Phys. Rev. D **97**, 015004 (2018), arXiv:1708.08929 [hep-ph].

[16] R. Matthias Geilhufe, Bart Olsthoorn, Alfredo Ferella, Timo Koski, Felix Kahlhoefer, Jan Conrad, and Alexander V. Balatsky, "Materials Informatics for Dark Matter Detection," Phys. Status Solidi RRL **12**, 1800293 (2018), arXiv:1806.06040 [cond-mat.mtrl-sci].

[17] R. Matthias Geilhufe, Felix Kahlhoefer, and Martin Wolfgang Winkler, "Dirac Materials for Sub-MeV Dark Matter

Detection: New Targets and Improved Formalism," Phys. Rev. D **101**, 055005 (2020), arXiv:1910.02091 [hep-ph].
[18] Ahmet Coskuner, Andrea Mitridate, Andres Olivares, and Kathryn M. Zurek, "Directional Dark Matter Detection in Anisotropic Dirac Materials," Phys. Rev. D **103**, 016006 (2021), arXiv:1909.09170 [hep-ph].
[19] Anirban Das, Noah Kurinsky, and Rebecca K. Leane, "Dark Matter Induced Power in Quantum Devices," (2022), arXiv:2210.09313 [hep-ph].
[20] Andrew Gould and Georg Raffelt, "Thermal Conduction by Massive Particles," Astrophys. J. **352**, 654 (1990).
[21] Rebecca K. Leane and Juri Smirnov, "Exoplanets as Sub-GeV Dark Matter Detectors," Phys. Rev. Lett. **126**, 161101 (2021), arXiv:2010.00015 [hep-ph].
[22] Rebecca K. Leane and Tim Linden, "First Analysis of Jupiter in Gamma Rays and a New Search for Dark Matter," (2021), arXiv:2104.02068 [astro-ph.HE].
[23] Rebecca K. Leane, Tim Linden, Payel Mukhopadhyay, and Natalia Toro, "Celestial-Body Focused Dark Matter Annihilation Throughout the Galaxy," Phys. Rev. D **103**, 075030 (2021), arXiv:2101.12213 [astro-ph.HE].
[24] I. Goldman and S. Nussinov, "Weakly Interacting Massive Particles and Neutron Stars," Phys. Rev. D **40**, 3221–3230 (1989).
[25] Andrew Gould, Bruce T. Draine, Roger W. Romani, and Shmuel Nussinov, "Neutron Stars: Graveyard of Charged Dark Matter," Phys. Lett. B **238**, 337–343 (1990).
[26] Chris Kouvaris, "WIMP Annihilation and Cooling of Neutron Stars," Phys. Rev. D **77**, 023006 (2008), arXiv:0708.2362 [astro-ph].
[27] Gianfranco Bertone and Malcolm Fairbairn, "Compact Stars as Dark Matter Probes," Phys. Rev. D **77**, 043515 (2008), arXiv:0709.1485 [astro-ph].
[28] Arnaud de Lavallaz and Malcolm Fairbairn, "Neutron Stars as Dark Matter Probes," Phys. Rev. D **81**, 123521 (2010), arXiv:1004.0629 [astro-ph.GA].
[29] Chris Kouvaris and Peter Tinyakov, "Can Neutron stars constrain Dark Matter?" Phys. Rev. D **82**, 063531 (2010), arXiv:1004.0586 [astro-ph.GA].
[30] Samuel D. McDermott, Hai-Bo Yu, and Kathryn M. Zurek, "Constraints on Scalar Asymmetric Dark Matter from Black Hole Formation in Neutron Stars," Phys. Rev. **D85**, 023519 (2012), arXiv:1103.5472 [hep-ph].
[31] Chris Kouvaris and Peter Tinyakov, "Excluding Light Asymmetric Bosonic Dark Matter," Phys. Rev. Lett. **107**, 091301 (2011), arXiv:1104.0382 [astro-ph.CO].
[32] Tolga Guver, Arif Emre Erkoca, Mary Hall Reno, and Ina Sarcevic, "On the capture of dark matter by neutron stars," JCAP **1405**, 013 (2014), arXiv:1201.2400 [hep-ph].
[33] Joseph Bramante, Keita Fukushima, and Jason Kumar, "Constraints on bosonic dark matter from observation of old neutron stars," Phys. Rev. **D87**, 055012 (2013), arXiv:1301.0036 [hep-ph].
[34] Nicole F. Bell, Andrew Melatos, and Kalliopi Petraki, "Realistic neutron star constraints on bosonic asymmetric dark matter," Phys. Rev. **D87**, 123507 (2013), arXiv:1301.6811 [hep-ph].
[35] Joseph Bramante, Keita Fukushima, Jason Kumar, and Elan Stopnitzky, "Bounds on self-interacting fermion dark matter from observations of old neutron stars," Phys. Rev. **D89**, 015010 (2014), arXiv:1310.3509 [hep-ph].
[36] Bridget Bertoni, Ann E. Nelson, and Sanjay Reddy, "Dark Matter Thermalization in Neutron Stars," Phys. Rev. D **88**, 123505 (2013), arXiv:1309.1721 [hep-ph].
[37] Chris Kouvaris and Peter Tinyakov, "Constraining Asymmetric Dark Matter through observations of compact stars," Phys. Rev. **D83**, 083512 (2011), arXiv:1012.2039 [astro-ph.HE].
[38] Matthew McCullough and Malcolm Fairbairn, "Capture of Inelastic Dark Matter in White Dwarves," Phys. Rev. D **81**, 083520 (2010), arXiv:1001.2737 [hep-ph].
[39] M. Angeles Perez-Garcia and Joseph Silk, "Constraining decaying dark matter with neutron stars," Phys. Lett. **B744**, 13–17 (2015), arXiv:1403.6111 [astro-ph.SR].
[40] Joseph Bramante, "Dark matter ignition of type Ia supernovae," Phys. Rev. Lett. **115**, 141301 (2015), arXiv:1505.07464 [hep-ph].
[41] Peter W. Graham, Surjeet Rajendran, and Jaime Varela, "Dark Matter Triggers of Supernovae," Phys. Rev. **D92**, 063007 (2015), arXiv:1505.04444 [hep-ph].
[42] Marina Cermeno, M.Angeles Perez-Garcia, and Joseph Silk, "Light dark matter scattering in outer neutron star crusts," Phys. Rev. **D94**, 063001 (2016), arXiv:1607.06815 [astro-ph.HE].
[43] Peter W. Graham, Ryan Janish, Vijay Narayan, Surjeet Rajendran, and Paul Riggins, "White Dwarfs as Dark Matter Detectors," Phys. Rev. **D98**, 115027 (2018), arXiv:1805.07381 [hep-ph].
[44] Javier F. Acevedo and Joseph Bramante, "Supernovae Sparked By Dark Matter in White Dwarfs," Phys. Rev. **D100**, 043020 (2019), arXiv:1904.11993 [hep-ph].
[45] Ryan Janish, Vijay Narayan, and Paul Riggins, "Type Ia supernovae from dark matter core collapse," Phys. Rev. **D100**, 035008 (2019), arXiv:1905.00395 [hep-ph].
[46] Rebecca Krall and Matthew Reece, "Last Electroweak WIMP Standing: Pseudo-Dirac Higgsino Status and Compact Stars as Future Probes," Chin. Phys. **C42**, 043105 (2018), arXiv:1705.04843 [hep-ph].
[47] David McKeen, Ann E. Nelson, Sanjay Reddy, and Dake Zhou, "Neutron stars exclude light dark baryons," Phys. Rev. Lett. **121**, 061802 (2018), arXiv:1802.08244 [hep-ph].
[48] Masha Baryakhtar, Joseph Bramante, Shirley Weishi Li, Tim Linden, and Nirmal Raj, "Dark Kinetic Heating of Neutron Stars and An Infrared Window On WIMPs, SIMPs, and Pure Higgsinos," Phys. Rev. Lett. **119**, 131801 (2017), arXiv:1704.01577 [hep-ph].
[49] Nirmal Raj, Philip Tanedo, and Hai-Bo Yu, "Neutron stars at the dark matter direct detection frontier," Phys. Rev.

D97, 043006 (2018), arXiv:1707.09442 [hep-ph].
[50] Nicole F. Bell, Giorgio Busoni, and Sandra Robles, "Heating up Neutron Stars with Inelastic Dark Matter," JCAP **1809**, 018 (2018), arXiv:1807.02840 [hep-ph].
[51] Chian-Shu Chen and Yen-Hsun Lin, "Reheating neutron stars with the annihilation of self-interacting dark matter," JHEP **08**, 069 (2018), arXiv:1804.03409 [hep-ph].
[52] Raghuveer Garani, Yoann Genolini, and Thomas Hambye, "New Analysis of Neutron Star Constraints on Asymmetric Dark Matter," JCAP **05**, 035 (2019), arXiv:1812.08773 [hep-ph].
[53] Basudeb Dasgupta, Aritra Gupta, and Anupam Ray, "Dark matter capture in celestial objects: Improved treatment of multiple scattering and updated constraints from white dwarfs," JCAP **08**, 018 (2019), arXiv:1906.04204 [hep-ph].
[54] Koichi Hamaguchi, Natsumi Nagata, and Keisuke Yanagi, "Dark Matter Heating vs. Rotochemical Heating in Old Neutron Stars," Phys. Lett. **B795**, 484–489 (2019), arXiv:1905.02991 [hep-ph].
[55] Daniel A. Camargo, Farinaldo S. Queiroz, and Riccardo Sturani, "Detecting Dark Matter with Neutron Star Spectroscopy," JCAP **1909**, 051 (2019), arXiv:1901.05474 [hep-ph].
[56] Nicole F. Bell, Giorgio Busoni, and Sandra Robles, "Capture of Leptophilic Dark Matter in Neutron Stars," JCAP **1906**, 054 (2019), arXiv:1904.09803 [hep-ph].
[57] Javier F. Acevedo, Joseph Bramante, Rebecca K. Leane, and Nirmal Raj, "Warming Nuclear Pasta with Dark Matter: Kinetic and Annihilation Heating of Neutron Star Crusts," JCAP **03**, 038 (2020), arXiv:1911.06334 [hep-ph].
[58] Aniket Joglekar, Nirmal Raj, Philip Tanedo, and Hai-Bo Yu, "Relativistic capture of dark matter by electrons in neutron stars," (2019), arXiv:1911.13293 [hep-ph].
[59] Aniket Joglekar, Nirmal Raj, Philip Tanedo, and Hai-Bo Yu, "Kinetic Heating from Contact Interactions with Relativistic Targets: Electrons Capture Dark Matter in Neutron Stars," (2020), arXiv:2004.09539 [hep-ph].
[60] Nicole F. Bell, Giorgio Busoni, Sandra Robles, and Michael Virgato, "Improved Treatment of Dark Matter Capture in Neutron Stars," (2020), arXiv:2004.14888 [hep-ph].
[61] Raghuveer Garani, Aritra Gupta, and Nirmal Raj, "Observing the thermalization of dark matter in neutron stars," (2020), arXiv:2009.10728 [hep-ph].
[62] Brian Batell, Maxim Pospelov, Adam Ritz, and Yanwen Shang, "Solar Gamma Rays Powered by Secluded Dark Matter," Phys. Rev. D **81**, 075004 (2010), arXiv:0910.1567 [hep-ph].
[63] Maxim Pospelov, Adam Ritz, and Mikhail B. Voloshin, "Secluded WIMP Dark Matter," Phys. Lett. B **662**, 53–61 (2008), arXiv:0711.4866 [hep-ph].
[64] Maxim Pospelov and Adam Ritz, "Astrophysical Signatures of Secluded Dark Matter," Phys. Lett. B **671**, 391–397 (2009), arXiv:0810.1502 [hep-ph].
[65] Ira Z. Rothstein, Thomas Schwetz, and Jure Zupan, "Phenomenology of Dark Matter annihilation into a long-lived intermediate state," JCAP **07**, 018 (2009), arXiv:0903.3116 [astro-ph.HE].
[66] Fang Chen, James M. Cline, and Andrew R. Frey, "Nonabelian dark matter: Models and constraints," Phys. Rev. D **80**, 083516 (2009), arXiv:0907.4746 [hep-ph].
[67] Philip Schuster, Natalia Toro, and Itay Yavin, "Terrestrial and Solar Limits on Long-Lived Particles in a Dark Sector," Phys. Rev. D **81**, 016002 (2010), arXiv:0910.1602 [hep-ph].
[68] Philip Schuster, Natalia Toro, Neal Weiner, and Itay Yavin, "High Energy Electron Signals from Dark Matter Annihilation in the Sun," Phys. Rev. D **82**, 115012 (2010), arXiv:0910.1839 [hep-ph].
[69] Nicole F Bell and Kalliopi Petraki, "Enhanced neutrino signals from dark matter annihilation in the sun via metastable mediators," Journal of Cosmology and Astroparticle Physics **2011**, 003–003 (2011).
[70] Jonathan L. Feng, Jordan Smolinsky, and Philip Tanedo, "Dark Photons from the Center of the Earth: Smoking-Gun Signals of Dark Matter," Phys. Rev. D **93**, 015014 (2016), [Erratum: Phys.Rev.D 96, 099901 (2017)], arXiv:1509.07525 [hep-ph].
[71] Chris Kouvaris and Peter Tinyakov, "Can Neutron stars constrain Dark Matter?" Phys. Rev. D **82**, 063531 (2010), arXiv:1004.0586 [astro-ph.GA].
[72] Jonathan L. Feng, Jordan Smolinsky, and Philip Tanedo, "Detecting dark matter through dark photons from the Sun: Charged particle signatures," Phys. Rev. D **93**, 115036 (2016), [Erratum: Phys.Rev.D 96, 099903 (2017)], arXiv:1602.01465 [hep-ph].
[73] Rouzbeh Allahverdi, Yu Gao, Bradley Knockel, and Shashank Shalgar, "Indirect Signals from Solar Dark Matter Annihilation to Long-lived Right-handed Neutrinos," Phys. Rev. D **95**, 075001 (2017), arXiv:1612.03110 [hep-ph].
[74] Rebecca K. Leane, Kenny C. Y. Ng, and John F. Beacom, "Powerful Solar Signatures of Long-Lived Dark Mediators," Phys. Rev. D **95**, 123016 (2017), arXiv:1703.04629 [astro-ph.HE].
[75] Chiara Arina, Mihailo Backović, Jan Heisig, and Michele Lucente, "Solar γ rays as a complementary probe of dark matter," Phys. Rev. D **96**, 063010 (2017), arXiv:1703.08087 [astro-ph.HE].
[76] A. Albert *et al.* (HAWC), "Constraints on Spin-Dependent Dark Matter Scattering with Long-Lived Mediators from TeV Observations of the Sun with HAWC," Phys. Rev. **D98**, 123012 (2018), arXiv:1808.05624 [hep-ph].
[77] A. Albert *et al.* (HAWC), "First HAWC Observations of the Sun Constrain Steady TeV Gamma-Ray Emission," Phys. Rev. D **98**, 123011 (2018), arXiv:1808.05620 [astro-ph.HE].
[78] M. U. Nisa, J. F. Beacom, S. Y. BenZvi, R. K. Leane, T. Linden, K. C. Y. Ng, A. H. G. Peter, and B. Zhou, "The Sun at GeV–TeV Energies: A New Laboratory for Astroparticle Physics," (2019), arXiv:1903.06349 [astro-ph.HE].
[79] Carl Niblaeus, Ankit Beniwal, and Joakim Edsjo, "Neutrinos and gamma rays from long-lived mediator decays in the Sun," JCAP **11**, 011 (2019), arXiv:1903.11363 [astro-ph.HE].
[80] A. Cuoco, P. De La Torre Luque, F. Gargano, M. Gustafsson, F. Loparco, M.N. Mazziotta, and D. Serini, "A search for

dark matter cosmic-ray electrons and positrons from the Sun with the Fermi Large Area Telescope," Phys. Rev. D **101**, 022002 (2020), arXiv:1912.09373 [astro-ph.HE].
[81] Davide Serini, Francesco Loparco, and Mario Nicola Mazziotta (Fermi-LAT), "Constraints on dark matter scattering with long-lived mediators using gamma-rays from the Sun," PoS **ICRC2019**, 544 (2020).
[82] Javier F. Acevedo, Joseph Bramante, Alan Goodman, Joachim Kopp, and Toby Opferkuch, "Dark Matter, Destroyer of Worlds: Neutrino, Thermal, and Existential Signatures from Black Holes in the Sun and Earth," JCAP **04**, 026 (2021), arXiv:2012.09176 [hep-ph].
[83] M.N. Mazziotta, F. Loparco, D. Serini, A. Cuoco, P. De La Torre Luque, F. Gargano, and M. Gustafsson, "Search for dark matter signatures in the gamma-ray emission towards the Sun with the Fermi Large Area Telescope," Phys. Rev. D **102**, 022003 (2020), arXiv:2006.04114 [astro-ph.HE].
[84] Nicole F. Bell, James B. Dent, and Isaac W. Sanderson, "Solar Gamma Ray Constraints on Dark Matter Annihilation to Secluded Mediators," (2021), arXiv:2103.16794 [hep-ph].
[85] Shohei Okawa, Maxim Pospelov, and Adam Ritz, "Long-range axion forces and hadronic CP violation," Phys. Rev. D **105**, 075003 (2022), arXiv:2111.08040 [hep-ph].
[86] S. Dimopoulos and G. F. Giudice, "Macroscopic forces from supersymmetry," Phys. Lett. B **379**, 105–114 (1996), arXiv:hep-ph/9602350.
[87] Pierre Fayet, "A NEW LONG RANGE FORCE?" Phys. Lett. B **171**, 261–266 (1986).
[88] Rebecca K. Leane and Juri Smirnov, "Floating Dark Matter in Celestial Bodies," (2022), arXiv:2209.09834 [hep-ph].
[89] D. N. Spergel and W. H. Press, "Effect of hypothetical, weakly interacting, massive particles on energy transport in the solar interior," Astrophys. J. **294**, 663–673 (1985).
[90] A. Bottino, G. Fiorentini, N. Fornengo, B. Ricci, S. Scopel, and F. L. Villante, "Does solar physics provide constraints to weakly interacting massive particles?" Phys. Rev. D **66**, 053005 (2002), arXiv:hep-ph/0206211.
[91] Pat Scott, Malcolm Fairbairn, and Joakim Edsjo, "Dark stars at the Galactic centre - the main sequence," Mon. Not. Roy. Astron. Soc. **394**, 82 (2009), arXiv:0809.1871 [astro-ph].
[92] Andrew Gould, "Evaporation of WIMPs with Arbitrary Cross Sections," Astrophys. J. **356**, 302 (1990).
[93] Jing Chen, Zheng-Liang Liang, Yue-Liang Wu, and Yu-Feng Zhou, "Long-range self-interacting dark matter in the Sun," JCAP **12**, 021 (2015), arXiv:1505.04031 [hep-ph].
[94] Cristian Gaidau and Jessie Shelton, "Singularities in the gravitational capture of dark matter through long-range interactions," JCAP **01**, 016 (2022), arXiv:2110.02234 [hep-ph].
[95] Raghuveer Garani and Sergio Palomares-Ruiz, "Evaporation of dark matter from celestial bodies," JCAP **05**, 042 (2022), arXiv:2104.12757 [hep-ph].
[96] William DeRocco, Marios Galanis, and Robert Lasenby, "Dark matter scattering in astrophysical media: collective effects," JCAP **05**, 015 (2022), arXiv:2201.05167 [hep-ph].
[97] S. Desai *et al.* (Super-Kamiokande), "Search for dark matter WIMPs using upward through-going muons in Super-Kamiokande," Phys. Rev. D **70**, 083523 (2004), [Erratum: Phys.Rev.D 70, 109901 (2004)], arXiv:hep-ex/0404025.
[98] K. Choi *et al.* (Super-Kamiokande), "Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by Super-Kamiokande," Phys. Rev. Lett. **114**, 141301 (2015), arXiv:1503.04858 [hep-ex].
[99] M. G. Aartsen *et al.* (IceCube), "Search for dark matter annihilations in the Sun with the 79-string IceCube detector," Phys. Rev. Lett. **110**, 131302 (2013), arXiv:1212.4097 [astro-ph.HE].
[100] M. G. Aartsen *et al.* (IceCube), "Improved limits on dark matter annihilation in the Sun with the 79-string IceCube detector and implications for supersymmetry," JCAP **04**, 022 (2016), arXiv:1601.00653 [hep-ph].
[101] S. Adrian-Martinez *et al.* (ANTARES), "Limits on Dark Matter Annihilation in the Sun using the ANTARES Neutrino Telescope," Phys. Lett. B **759**, 69–74 (2016), arXiv:1603.02228 [astro-ph.HE].
[102] A. Albert *et al.* (ANTARES), "Search for Dark Matter Annihilation in the Earth using the ANTARES Neutrino Telescope," Phys. Dark Univ. **16**, 41–48 (2017), arXiv:1612.06792 [hep-ex].
[103] M. G. Aartsen *et al.* (IceCube), "First search for dark matter annihilations in the Earth with the IceCube Detector," Eur. Phys. J. C **77**, 82 (2017), arXiv:1609.01492 [astro-ph.HE].
[104] Rasha Abbasi *et al.* (IceCube), "Search for dark matter annihilation in the center of the Earth with 8 years of IceCube data," PoS **ICRC2019**, 541 (2020), arXiv:1908.07255 [astro-ph.HE].
[105] Patrick Meade, Shmuel Nussinov, Michele Papucci, and Tomer Volansky, "Searches for Long Lived Neutral Particles," JHEP **06**, 029 (2010), arXiv:0910.4160 [hep-ph].
[106] Pooja Bhattacharjee, Francesca Calore, and Pasquale Dario Serpico, "Gamma-ray flux limits from brown dwarfs: Implications for dark matter annihilating into long-lived mediators," (2022), arXiv:2211.08067 [astro-ph.HE].
[107] M. Ajello *et al.* (Fermi LAT), "Constraints on dark matter models from a Fermi LAT search for high-energy cosmic-ray electrons from the Sun," Phys. Rev. D **84**, 032007 (2011), arXiv:1107.4272 [astro-ph.HE].
[108] Lingfeng Li and JiJi Fan, "Jupiter missions as probes of dark matter," JHEP **10**, 186 (2022), arXiv:2207.13709 [hep-ph].
[109] Chris Kouvaris, "Probing Light Dark Matter via Evaporation from the Sun," Phys. Rev. D **92**, 075001 (2015), arXiv:1506.04316 [hep-ph].
[110] Haipeng An, Maxim Pospelov, Josef Pradler, and Adam Ritz, "Directly Detecting MeV-scale Dark Matter via Solar Reflection," Phys. Rev. Lett. **120**, 141801 (2018), [Erratum: Phys.Rev.Lett. 121, 259903 (2018)], arXiv:1708.03642 [hep-ph].
[111] Timon Emken, Chris Kouvaris, and Niklas Grønlund Nielsen, "The Sun as a sub-GeV Dark Matter Accelerator," Phys. Rev. D **97**, 063007 (2018), arXiv:1709.06573 [hep-ph].
[112] Haipeng An, Haoming Nie, Maxim Pospelov, Josef Pradler, and Adam Ritz, "Solar reflection of dark matter," Phys.

Rev. D **104**, 103026 (2021), arXiv:2108.10332 [hep-ph].
[113] Liron Barak *et al.* (SENSEI), "SENSEI: Direct-Detection Results on sub-GeV Dark Matter from a New Skipper-CCD," Phys. Rev. Lett. **125**, 171802 (2020), arXiv:2004.11378 [astro-ph.CO].
[114] Peizhi Du, Daniel Egaña Ugrinovic, Rouven Essig, and Mukul Sholapurkar, "Doped Semiconductor Devices for sub-MeV Dark Matter Detection," (2022), arXiv:2212.04504 [hep-ph].
[115] Rouven Essig, Graham K. Giovanetti, Noah Kurinsky, Dan McKinsey, Karthik Ramanathan, Kelly Stifter, and Tien-Tien Yu, "Snowmass2021 Cosmic Frontier: The landscape of low-threshold dark matter direct detection in the next decade," in *2022 Snowmass Summer Study* (2022) arXiv:2203.08297 [hep-ph].
[116] Martin Asplund, Nicolas Grevesse, A. Jacques Sauval, and Pat Scott, "The chemical composition of the sun," Annual Review of Astronomy and Astrophysics **47**, 481–522 (2009).
[117] Aldo M. Serenelli, Sarbani Basu, Jason W. Ferguson, and Martin Asplund, "New solar composition: The problem with solar models revisited," **705**, L123–L127 (2009).
[118] Maria Bergemann and Aldo Serenelli, "Solar abundance problem," in *Determination of Atmospheric Parameters of B-, A-, F- and G-Type Stars* (Springer International Publishing, 2014) pp. 245–258.
[119] Mads T. Frandsen and Subir Sarkar, "Asymmetric dark matter and the Sun," Phys. Rev. Lett. **105**, 011301 (2010), arXiv:1003.4505 [hep-ph].
[120] Marco Taoso, Fabio Iocco, Georges Meynet, Gianfranco Bertone, and Patrick Eggenberger, "Effect of low mass dark matter particles on the Sun," Phys. Rev. D **82**, 083509 (2010), arXiv:1005.5711 [astro-ph.CO].
[121] Daniel T. Cumberbatch, Joyce. A. Guzik, Joseph Silk, L. Scott Watson, and Stephen M. West, "Light WIMPs in the Sun: Constraints from Helioseismology," Phys. Rev. D **82**, 103503 (2010), arXiv:1005.5102 [astro-ph.SR].
[122] Aaron C. Vincent, Pat Scott, and Aldo Serenelli, "Possible Indication of Momentum-Dependent Asymmetric Dark Matter in the Sun," Phys. Rev. Lett. **114**, 081302 (2015), arXiv:1411.6626 [hep-ph].
[123] Aaron C. Vincent, Aldo Serenelli, and Pat Scott, "Generalised form factor dark matter in the Sun," JCAP **08**, 040 (2015), arXiv:1504.04378 [hep-ph].
[124] Aaron C. Vincent, Pat Scott, and Aldo Serenelli, "Updated constraints on velocity and momentum-dependent asymmetric dark matter," JCAP **11**, 007 (2016), arXiv:1605.06502 [hep-ph].
[125] Hannah Banks, Siyam Ansari, Aaron C. Vincent, and Pat Scott, "Simulation of energy transport by dark matter scattering in stars," (2021), arXiv:2111.06895 [hep-ph].
[126] Fabio Iocco, Marco Taoso, Florent Leclercq, and Georges Meynet, "Main sequence stars with asymmetric dark matter," Phys. Rev. Lett. **108**, 061301 (2012).
[127] Lopes, Jose and Lopes, Ildio, "Dark matter capture and annihilation in stars: Impact on the red giant branch tip," A&A **651**, A101 (2021).
[128] Troy J Raen, Héctor Martínez-Rodríguez, Travis J Hurst, Andrew R Zentner, Carles Badenes, and Rachel Tao, "The effects of asymmetric dark matter on stellar evolution – I. Spin-dependent scattering," Monthly Notices of the Royal Astronomical Society **503**, 5611–5623 (2021), https://academic.oup.com/mnras/article-pdf/503/4/5611/37057230/stab865.pdf.
[129] José Lopes and Ilídio Lopes, "Asymmetric dark matter imprint on low-mass main-sequence stars in the milky way nuclear star cluster," The Astrophysical Journal **879**, 50 (2019).
[130] Joao Rato, Jose Lopes, and Ildio Lopes, "On asymmetric dark matter constraints from the asteroseismology of a subgiant star," Mon. Not. Roy. Astron. Soc. **507**, 3434–3443 (2021), arXiv:2109.12671 [astro-ph.SR].
[131] William DeRocco, Peter W. Graham, and Surjeet Rajendran, "Exploring the robustness of stellar cooling constraints on light particles," Phys. Rev. D **102**, 075015 (2020), arXiv:2006.15112 [hep-ph].
[132] Javier F. Acevedo, Joseph Bramante, and Alan Goodman, "Nuclear fusion inside dark matter," Phys. Rev. D **103**, 123022 (2021), arXiv:2012.10998 [hep-ph].
[133] Javier F. Acevedo, Joseph Bramante, and Alan Goodman, "Accelerating composite dark matter discovery with nuclear recoils and the Migdal effect," Phys. Rev. D **105**, 023012 (2022), arXiv:2108.10889 [hep-ph].
[134] Javier F. Acevedo, Amit Bhoonah, and Joseph Bramante, "Diffuse x-ray and gamma-ray limits on boson stars that interact with nuclei," JCAP **12**, 031 (2022), arXiv:2209.00017 [hep-ph].
[135] Simon Knapen, Tongyan Lin, and Kathryn M. Zurek, "Light Dark Matter: Models and Constraints," Phys. Rev. D **96**, 115021 (2017), arXiv:1709.07882 [hep-ph].
[136] Aditya Parikh, Juri Smirnov, Weishuang Linda Xu, and Bei Zhou, "Scalar Co-SIMP Dark Matter: Models and Sensitivities," (2023), arXiv:2302.00008 [hep-ph].
[137] Jonathan L. Feng, Bartosz Fornal, Iftah Galon, Susan Gardner, Jordan Smolinsky, Tim M. P. Tait, and Philip Tanedo, "Particle physics models for the 17 MeV anomaly in beryllium nuclear decays," Phys. Rev. D **95**, 035017 (2017), arXiv:1608.03591 [hep-ph].
[138] Bartosz Fornal, "Is There a Sign of New Physics in Beryllium Transitions?" Int. J. Mod. Phys. A **32**, 1730020 (2017), arXiv:1707.09749 [hep-ph].
[139] Bartosz Fornal and Benjamin Grinstein, "Dark particle interpretation of the neutron decay anomaly," J. Phys. Conf. Ser. **1308**, 012010 (2019).
[140] R. D. Peccei and Helen R. Quinn, "CP Conservation in the Presence of Instantons," Phys. Rev. Lett. **38**, 1440–1443 (1977).
[141] C. B. Adams *et al.*, "Axion Dark Matter," in *2022 Snowmass Summer Study* (2022) arXiv:2203.14923 [hep-ex].
[142] Francesco Bigazzi, Aldo L. Cotrone, Matti Järvinen, and Elias Kiritsis, "Non-derivative Axionic Couplings to Nucleons at large and small N," JHEP **01**, 100 (2020), arXiv:1906.12132 [hep-ph].

[143] Mikhail A. Shifman, A. I. Vainshtein, and Valentin I. Zakharov, "Can Confinement Ensure Natural CP Invariance of Strong Interactions?" Nucl. Phys. B **166**, 493–506 (1980).

[144] Michael Dine, Willy Fischler, and Mark Srednicki, "A Simple Solution to the Strong CP Problem with a Harmless Axion," Phys. Lett. B **104**, 199–202 (1981).

[145] Giovanni Grilli di Cortona, Edward Hardy, Javier Pardo Vega, and Giovanni Villadoro, "The QCD axion, precisely," JHEP **01**, 034 (2016), arXiv:1511.02867 [hep-ph].

[146] Pavel Fileviez Perez and Mark B. Wise, "Baryon and lepton number as local gauge symmetries," Phys. Rev. D **82**, 011901 (2010), [Erratum: Phys.Rev.D 82, 079901 (2010)], arXiv:1002.1754 [hep-ph].

[147] Nicole F. Bell, Yi Cai, Rebecca K. Leane, and Anibal D. Medina, "Leptophilic dark matter with Z' interactions," Phys. Rev. D **90**, 035027 (2014), arXiv:1407.3001 [hep-ph].

[148] Sean Tulin, "New weakly-coupled forces hidden in low-energy QCD," Phys. Rev. D **89**, 114008 (2014), arXiv:1404.4370 [hep-ph].

[149] Bogdan A. Dobrescu and Claudia Frugiuele, "Hidden GeV-scale interactions of quarks," Phys. Rev. Lett. **113**, 061801 (2014), arXiv:1404.3947 [hep-ph].

[150] Michael Duerr, Pavel Fileviez Perez, and Mark B. Wise, "Gauge Theory for Baryon and Lepton Numbers with Leptoquarks," Phys. Rev. Lett. **110**, 231801 (2013), arXiv:1304.0576 [hep-ph].

[151] Michael Duerr, Pavel Fileviez Perez, and Juri Smirnov, "Baryonic Higgs at the LHC," JHEP **09**, 093 (2017), arXiv:1704.03811 [hep-ph].

[152] Boris Kors and Pran Nath, "A Stueckelberg extension of the standard model," Phys. Lett. B **586**, 366–372 (2004), arXiv:hep-ph/0402047.

[153] Daniel Feldman, Zuowei Liu, and Pran Nath, "The Stueckelberg Z-prime Extension with Kinetic Mixing and Milli-Charged Dark Matter From the Hidden Sector," Phys. Rev. D **75**, 115001 (2007), arXiv:hep-ph/0702123.

[154] Hye-Sung Lee, "Muon g−2 anomaly and dark leptonic gauge boson," Phys. Rev. D **90**, 091702 (2014), arXiv:1408.4256 [hep-ph].

[155] Wolfgang Altmannshofer, Chien-Yi Chen, P. S. Bhupal Dev, and Amarjit Soni, "Lepton flavor violating Z' explanation of the muon anomalous magnetic moment," Phys. Lett. B **762**, 389–398 (2016), arXiv:1607.06832 [hep-ph].

[156] Gautam Dutta, Anjan S. Joshipura, and K. B. Vijaykumar, "Leptonic flavor violations in the presence of an extra Z," Phys. Rev. D **50**, 2109–2115 (1994), arXiv:hep-ph/9405292.

[157] Julian Heeck and Werner Rodejohann, "Gauged $L_\mu - L_\tau$ Symmetry at the Electroweak Scale," Phys. Rev. D **84**, 075007 (2011), arXiv:1107.5238 [hep-ph].

[158] Wolfgang Altmannshofer, Marcela Carena, and Andreas Crivellin, "$L_\mu - L_\tau$ theory of Higgs flavor violation and $(g-2)_\mu$," Phys. Rev. D **94**, 095026 (2016), arXiv:1604.08221 [hep-ph].

[159] Michael Duerr and Pavel Fileviez Perez, "Baryonic Dark Matter," Phys. Lett. B **732**, 101–104 (2014), arXiv:1309.3970 [hep-ph].

[160] Pedro Schwaller, Tim M. P. Tait, and Roberto Vega-Morales, "Dark Matter and Vectorlike Leptons from Gauged Lepton Number," Phys. Rev. D **88**, 035001 (2013), arXiv:1305.1108 [hep-ph].

[161] Brian Batell, Patrick deNiverville, David McKeen, Maxim Pospelov, and Adam Ritz, "Leptophobic Dark Matter at Neutrino Factories," Phys. Rev. D **90**, 115014 (2014), arXiv:1405.7049 [hep-ph].

[162] Nicole F. Bell, Yi Cai, and Rebecca K. Leane, "Dark Forces in the Sky: Signals from Z' and the Dark Higgs," JCAP **08**, 001 (2016), arXiv:1605.09382 [hep-ph].

[163] Nicole F. Bell, Yi Cai, and Rebecca K. Leane, "Impact of mass generation for spin-1 mediator simplified models," JCAP **01**, 039 (2017), arXiv:1610.03063 [hep-ph].

[164] Nicole F. Bell, Yi Cai, James B. Dent, Rebecca K. Leane, and Thomas J. Weiler, "Enhancing Dark Matter Annihilation Rates with Dark Bremsstrahlung," Phys. Rev. **D96**, 023011 (2017), arXiv:1705.01105 [hep-ph].

[165] Manfred Lindner, Daniel Schmidt, and Thomas Schwetz, "Dark Matter and neutrino masses from global $U(1)_{B-L}$ symmetry breaking," Phys. Lett. B **705**, 324–330 (2011), arXiv:1105.4626 [hep-ph].

[166] Shinya Kanemura, Toshinori Matsui, and Hiroaki Sugiyama, "Neutrino mass and dark matter from gauged $U(1)_{B-L}$ breaking," Phys. Rev. D **90**, 013001 (2014), arXiv:1405.1935 [hep-ph].

[167] J. K. Hoskins, R. D. Newman, R. Spero, and J. Schultz, "Experimental tests of the gravitational inverse square law for mass separations from 2-cm to 105-cm," Phys. Rev. D **32**, 3084–3095 (1985).

[168] C. D. Hoyle, D. J. Kapner, Blayne R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt, and H. E. Swanson, "Sub-millimeter tests of the gravitational inverse-square law," Phys. Rev. D **70**, 042004 (2004), arXiv:hep-ph/0405262.

[169] E. G. Adelberger, Blayne R. Heckel, Seth A. Hoedl, C. D. Hoyle, D. J. Kapner, and A. Upadhye, "Particle Physics Implications of a Recent Test of the Gravitational Inverse Sqaure Law," Phys. Rev. Lett. **98**, 131104 (2007), arXiv:hep-ph/0611223.

[170] Stephan Schlamminger, K. Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger, "Test of the equivalence principle using a rotating torsion balance," Phys. Rev. Lett. **100**, 041101 (2008), arXiv:0712.0607 [gr-qc].

[171] A. O. Sushkov, W. J. Kim, D. A. R. Dalvit, and S. K. Lamoreaux, "New Experimental Limits on Non-Newtonian Forces in the Micrometer Range," Phys. Rev. Lett. **107**, 171101 (2011), arXiv:1108.2547 [quant-ph].

[172] Shan-Qing Yang, Bi-Fu Zhan, Qing-Lan Wang, Cheng-Gang Shao, Liang-Cheng Tu, Wen-Hai Tan, and Jun Luo, "Test of the Gravitational Inverse Square Law at Millimeter Ranges," Phys. Rev. Lett. **108**, 081101 (2012).

[173] S. K. Lamoreaux, "Demonstration of the Casimir force in the 0.6 to 6 micrometers range," Phys. Rev. Lett. **78**, 5–8 (1997), [Erratum: Phys.Rev.Lett. 81, 5475–5476 (1998)].

[174] J. M. Obrecht, R. J. Wild, M. Antezza, L. P. Pitaevskii, S. Stringari, and E. A. Cornell, "Measurement of the Temperature

Dependence of the Casimir-Polder Force," Phys. Rev. Lett. **98**, 063201 (2007), arXiv:physics/0608074.
[175] M. Masuda and M. Sasaki, "Limits on non-standard forces in the submicrometer range," Phys. Rev. Lett. **102**, 171101 (2009), arXiv:0904.1834 [hep-ex].
[176] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, "Advance and prospects in constraining the Yukawa-type corrections to Newtonian gravity from the Casimir effect," Phys. Rev. D **81**, 055003 (2010), arXiv:1002.2141 [hep-th].
[177] V. B. Bezerra, G. L. Klimchitskaya, V. M. Mostepanenko, and C. Romero, "Constraints on non-Newtonian gravity from measuring the Casimir force in a configuration with nanoscale rectangular corrugations," Phys. Rev. D **83**, 075004 (2011), arXiv:1103.0993 [hep-ph].
[178] Jun Xu, Bao-An Li, Lie-Wen Chen, and Hao Zheng, "Nuclear constraints on non-Newtonian gravity at femtometer scale," J. Phys. G **40**, 035107 (2013), arXiv:1203.2678 [astro-ph.SR].
[179] Jiro Murata and Saki Tanaka, "A review of short-range gravity experiments in the LHC era," Class. Quant. Grav. **32**, 033001 (2015), arXiv:1408.3588 [hep-ex].
[180] E. G. Adelberger, Blayne R. Heckel, and A. E. Nelson, "Tests of the gravitational inverse square law," Ann. Rev. Nucl. Part. Sci. **53**, 77–121 (2003), arXiv:hep-ph/0307284.
[181] H. Leeb and J. Schmiedmayer, "Constraint on hypothetical light interacting bosons from low-energy neutron experiments," Phys. Rev. Lett. **68**, 1472–1475 (1992).
[182] V. V. Nesvizhevsky and K. V. Protasov, "Constraints on nonNewtonian gravity from the experiment on neutron quantum states in the earth's gravitational field," Class. Quant. Grav. **21**, 4557–4566 (2004), arXiv:hep-ph/0401179.
[183] Geoffrey L. Greene and Vladimir P. Gudkov, "A Neutron interferometric method to provide improved constraints on non-Newtonian gravity at the nanometer scale," Phys. Rev. C **75**, 015501 (2007), arXiv:hep-ph/0608346.
[184] S. Baessler, V. V. Nesvizhevsky, K. V. Protasov, and A. Yu. Voronin, "A New constraint for the coupling of axion-like particles to matter via ultra-cold neutron gravitational experiments," Phys. Rev. D **75**, 075006 (2007), arXiv:hep-ph/0610339.
[185] V. V. Nesvizhevsky, G. Pignol, and K. V. Protasov, "Neutron scattering and extra short range interactions," Phys. Rev. D **77**, 034020 (2008), arXiv:0711.2298 [hep-ph].
[186] Yu-Sheng Liu, David McKeen, and Gerald A. Miller, "Electrophobic Scalar Boson and Muonic Puzzles," Phys. Rev. Lett. **117**, 101801 (2016), arXiv:1605.04612 [hep-ph].
[187] Edward Hardy and Robert Lasenby, "Stellar cooling bounds on new light particles: plasma mixing effects," JHEP **02**, 033 (2017), arXiv:1611.05852 [hep-ph].
[188] Ermal Rrapaj and Sanjay Reddy, "Nucleon-nucleon bremsstrahlung of dark gauge bosons and revised supernova constraints," Phys. Rev. C **94**, 045805 (2016), arXiv:1511.09136 [nucl-th].
[189] Jae Hyeok Chang, Rouven Essig, and Samuel D. McDermott, "Supernova 1987A Constraints on Sub-GeV Dark Sectors, Millicharged Particles, the QCD Axion, and an Axion-like Particle," JHEP **09**, 051 (2018), arXiv:1803.00993 [hep-ph].
[190] Richard H. Cyburt, Brian D. Fields, Keith A. Olive, and Tsung-Han Yeh, "Big Bang Nucleosynthesis: 2015," Rev. Mod. Phys. **88**, 015004 (2016), arXiv:1505.01076 [astro-ph.CO].
[191] Richard Brito, Vitor Cardoso, and Paolo Pani, "Superradiance: New Frontiers in Black Hole Physics," Lect. Notes Phys. **906**, pp.1–237 (2015), arXiv:1501.06570 [gr-qc].
[192] Vitor Cardoso, Óscar J. C. Dias, Gavin S. Hartnett, Matthew Middleton, Paolo Pani, and Jorge E. Santos, "Constraining the mass of dark photons and axion-like particles through black-hole superradiance," JCAP **03**, 043 (2018), arXiv:1801.01420 [gr-qc].
[193] Masha Baryakhtar, Robert Lasenby, and Mae Teo, "Black Hole Superradiance Signatures of Ultralight Vectors," Phys. Rev. D **96**, 035019 (2017), arXiv:1704.05081 [hep-ph].
[194] Masha Baryakhtar, Marios Galanis, Robert Lasenby, and Olivier Simon, "Black hole superradiance of self-interacting scalar fields," Phys. Rev. D **103**, 095019 (2021), arXiv:2011.11646 [hep-ph].
[195] Asimina Arvanitaki and Sergei Dubovsky, "Exploring the String Axiverse with Precision Black Hole Physics," Phys. Rev. D **83**, 044026 (2011), arXiv:1004.3558 [hep-th].
[196] Anubhav Mathur, Surjeet Rajendran, and Erwin H. Tanin, "Clockwork mechanism to remove superradiance limits," Phys. Rev. D **102**, 055015 (2020), arXiv:2004.12326 [hep-ph].
[197] Diego Blas and Samuel J. Witte, "Quenching Mechanisms of Photon Superradiance," Phys. Rev. D **102**, 123018 (2020), arXiv:2009.10075 [hep-ph].
[198] Gilly Elor, Robert McGehee, and Aaron Pierce, "Maximizing Direct Detection with Highly Interactive Particle Relic Dark Matter," Phys. Rev. Lett. **130**, 031803 (2023), arXiv:2112.03920 [hep-ph].
[199] Andrew Robertson, Richard Massey, and Vincent Eke, "What does the Bullet Cluster tell us about self-interacting dark matter?" Mon. Not. Roy. Astron. Soc. **465**, 569–587 (2017), arXiv:1605.04307 [astro-ph.CO].
[200] Andrew Robertson, Eric Huff, and Katarina Markovic, "Why weak lensing cluster shapes are insensitive to self-interacting dark matter," (2022), arXiv:2210.13474 [astro-ph.CO].
[201] P. Popesso, A. Biviano, H. Böhringer, and M. Romaniello, "RASS-SDSS galaxy cluster survey," Astronomy and Astrophysics **464**, 451–464 (2006).
[202] David Wittman, Nathan Golovich, and William A. Dawson, "The mismeasure of mergers: Revised limits on self-interacting dark matter in merging galaxy clusters," The Astrophysical Journal **869**, 104 (2018).
[203] Susmita Adhikari *et al.*, "Astrophysical Tests of Dark Matter Self-Interactions," (2022), arXiv:2207.10638 [astro-ph.CO].
[204] Bill Paxton, Lars Bildsten, Aaron Dotter, Falk Herwig, Pierre Lesaffre, and Frank Timmes, "Modules for Experiments

in Stellar Astrophysics (MESA)," Astrophys. J. Suppl. **192**, 3 (2011), arXiv:1009.1622 [astro-ph.SR].
[205] Sayantan Auddy, Shantanu Basu, and S. R. Valluri, "Analytic Models of Brown Dwarfs and the Substellar Mass Limit," Advances in Astronomy **2016**, 574327 (2016), arXiv:1607.04338 [astro-ph.SR].