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Exoplanets as Sub-GeV Dark Matter Detectors

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(Received 8 October 2020; revised 28 November 2020; accepted 15 March 2021; published 22 April 2021)

We present exoplanets as new targets to discover dark matter (DM). Throughout the Milky Way, DM can scatter, become captured, deposit annihilation energy, and increase the heat flow within exoplanets. We estimate upcoming infrared telescope sensitivity to this scenario, finding actionable discovery or exclusion searches. We find that DM with masses above about an MeV can be probed with exoplanets, with DM-proton and DM-electron scattering cross sections down to about 10^{-37} cm^2, stronger than existing limits by up to six orders of magnitude. Supporting evidence of a DM origin can be identified through DM-induced exoplanet heating correlated with galactic position, and hence DM density. This provides new motivation to measure the temperature of the billions of brown dwarfs, rogue planets, and gas giants peppered throughout our Galaxy.

DOI: 10.1103/PhysRevLett.126.161101

Introduction.—Are we alone in the Universe? This question has driven wide-reaching interest in discovering a planet like our own. Regardless of whether or not we ever find alien life, the scientific advances from finding and understanding other planets will be enormous. From a particle physics perspective, new celestial bodies provide a vast playground to discover new physics.

Astrophysical systems have already been broadly used to probe new physics, including investigating the effects of gravitationally captured dark matter (DM). If there is sufficient gravitational force, deposited DM kinetic energy can noticeably increase the temperature of the system. Regardless of gravitational strength, DM annihilation can also induce heating. This has been investigated in the context of neutron stars and white dwarfs [1–41]. Alternatively, the DM-related heat flow in other moons and planets has been considered, including Earth [42–44], Uranus [45,46], Neptune, and Jupiter [46,47], Mars [44], Earth's Luna [48,49], as well as hot Jupiters [46].

We explore the potential to discover DM using exoplanets—planets outside our solar system. We will use the term "exoplanets" to refer to the broader class of all extrasolar planets (including rogue planets), as well as brown dwarfs, which exist at the planet-star boundary. The general setup of this idea is as follows: particle DM in the galactic halo can scatter with exoplanets, lose energy, and become gravitationally captured by the exoplanet. The captured DM accumulates and may annihilate, releasing its mass energy to heat exoplanets. Assuming that the annihilation rate is in equilibrium with the scattering rate (see the Supplemental Material [50]), the annihilation heat measured by upcoming infrared telescopes allows for a new probe of the DM scattering rate.

We will show that this leads to new sensitivities to scattering cross sections between about $10^{-37} - 10^{-25}$ cm^2 in the sub-GeV mass range. This range of elastic interactions is expected in models with thermally produced sub-GeV DM, see, e.g., Refs. [51,52]. This cross section range is bounded by sufficiently weak DM interactions for DM to drift to the core and accumulate, and sufficiently strong DM interactions to produce a detectable DM heat flux. This requires the annihilation rates to be larger than a lower bound provided by the capture and annihilation equilibration condition. For, e.g., $2 \to 2$ annihilation, we will show that the thermally averaged cross section must be greater than about 10^{-37}–10^{-34} cm^3/s depending on the target, such that both s- and p-wave annihilation can be probed (see Supplemental Material [50] for more details). The lower DM-mass sensitivity is truncated by DM evaporating from the exoplanet (and therefore not annihilating to produce any heat), with sensitivity extending down to about 4 MeV (30 MeV) for brown dwarfs (Jupiters). While higher DM masses can also be probed with exoplanets, we will focus on the MeV – GeV mass range, as this features a new cross section range that has not been probed by direct detection or other experiments.

There are many advantages of using exoplanets to search for DM over other celestial bodies. These include the following:

A rapidly accelerating research program: Until 1992, we did not even know if exoplanets existed. Almost all exoplanets we now know were only discovered in the last decade, with the majority found in the last five years [53]. The exoplanet program is clearly rapidly growing (see the Supplemental Material [50] for details of many new experiments). This provides ample motivation to consider new ways this exploding research area can be used to probe new physics.

Enormous number of expected exoplanets: It is estimated that there is at least one planet per star in our Galaxy, and about one cold planet per star [54]. This means that there should be about 300 billion exoplanets awaiting discovery. While of course these will not all be immediately found, even a small percentage of this number leads to an enormous statistical advantage for understanding potential signals. It also allows ample room for growth with new discoveries and possible surprises in observations. To date, there are 4324 confirmed exoplanets, and an additional 5695 candidates are currently under investigation [53].

Much larger surface area than neutron stars: The other key proposed search using upcoming infrared telescopes on DM-heated astrophysical bodies is with old, cold neutron stars [25]. However, while neutron stars are much more dense, and allow for higher heating rates in part due to enhancements from kinetic heating, exoplanets and brown dwarfs are much larger. A typical neutron star has a radius of about 10 km, while exoplanets of interest have radii of about 50 000–200 000 km. This means that exoplanet temperatures can be measured much further into the galactic center (GC) and therefore can provide a DM-density dependent heating signal. Exoplanets can also be imaged to much higher significance, and with less exposure time.

Easier to find than neutron stars: The infrared neutron star search requires that a sufficiently cold neutron star candidate at a distance $\lesssim$100 pc from Earth is found [25]. While pulsars have been found at distances of $\sim$100 pc [189], it is possible that a sufficiently cold and sufficiently close-by neutron star may not be found, or cannot be measured with sufficient exposure time. On the other hand, exoplanets outnumber neutron stars in our galaxy by at least about a factor of a thousand [190], and are already known to exist in close enough proximity for DM searches.

Low temperatures: Lastly, exoplanets can be very cold, as they do not undergo nuclear fusion, and can exist very far in large orbits from any host star to which they may be bound. They can even go rogue, floating free from any parent star. As the low temperatures allow for a clearer signal over background for DM heating, exoplanets are advantageous over nuclear-fusing stars. Furthermore, their low core temperatures in part prevent DM evaporation compared to evaporation in these stars, providing new sensitivity to MeV DM.

In this work, we exploit all these features to identify new searches for DM in exoplanets. We establish two different searches: one for distant exoplanets and one for local exoplanets. The distant exoplanet searches will require that the exoplanets be rogue (or brown dwarfs), such that their detection is not obscured.

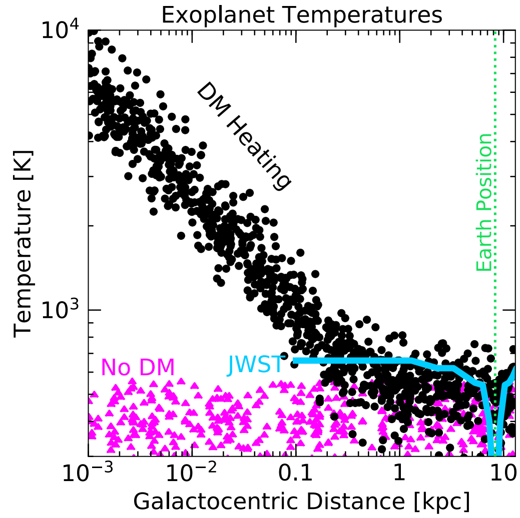

FIG. 1. Mock temperature distribution of old example exoplanets with 20–50 Jupiter masses over Galactocentric distances. Black dots are DM-heated exoplanets, magenta triangles are the same set of planets, without DM heating. JWST is the estimated minimum telescope sensitivity (see text).

Figure 1 demonstrates these searches and shows an example distribution of exoplanets with masses of about 20–50 Jupiters with and without DM heating. Distant exoplanets can be used to map the Galactic DM density, given sufficient telescope sensitivity. This is seen by the uptick of many hot exoplanets, scaling with the DM density. As well as searching for DM signals, local exoplanets can be used to test the hypothesis that DM contributes to internal heat of the gas giants in our own solar system, which are not well understood [46,47]. DM-heated exoplanets can be potentially measured when the infrared telescope James Webb Space Telescope (JWST) comes online. Both our suggested searches target new DM parameter space, probing the DM-proton and DM-electron scattering cross sections to unprecedented sensitivities.

Dark heat flow in exoplanets.—The total heat flow of the exoplanet $\Gamma_{\rm heat}^{\rm tot}$ can be determined by combining potential heat power sources, including internal heat $\Gamma_{\rm heat}^{\rm int}$, external heat $\Gamma_{\rm heat}^{\rm ext}$, and DM heat $\Gamma_{\rm heat}^{\rm DM}$:

$$\Gamma_{\rm heat}^{\rm tot} = \Gamma_{\rm heat}^{\rm ext} + \Gamma_{\rm heat}^{\rm int} + \Gamma_{\rm heat}^{\rm DM} = 4\pi R^2 \sigma_{\rm SB} T^4 \epsilon, \qquad (1)$$

where R is the exoplanet radius, T is the exoplanet temperature, $\sigma_{\rm SB}$ is the Stefan-Boltzmann constant, and ϵ is the emissivity (which is a measure of planetary heat radiation efficiency, ranging from 0 to 1). External heating is negligible for wide-orbit or free-floating planets.

We compute the internal heat flow for our range of benchmark brown dwarfs and Jupiters without DM. As the minimum temperature for heavy brown dwarfs (with $55M_{\rm jup}$) and benchmark Jupiters (with $M_{\rm jup}$) after about 10 Gyr is about 750 and 80 K, respectively, we can determine the internal heat flow required to produce these temperatures,

$$\Gamma_{\rm heat}^{\rm int} = 4\pi R^2 \sigma_{\rm SB} T^4 \epsilon, \tag{2}$$

which corresponds to about 1.1×10^9 TW and 1.4×10^5 TW for benchmark brown dwarfs and Jupiters, respectively. This serves as our non-DM baseline for comparing with a potential DM signal.

The additional DM heating source occurs if DM scatters on exoplanet particles, becomes captured, and annihilates. This produces heat that can be absorbed by the exoplanet. We assume that the DM scattering and annihilation processes are in equilibrium (see the Supplemental Material [50]). The DM heat flow depends on how many external DM particles are captured from the incoming DM flux reservoir. The maximal, i.e., geometric capture rate of DM is given by [191]

$$C_{\rm max} = \pi R^2 n_\chi(r) v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_d(r)^2}\right) \xi[v_p, v_d(r)], \tag{3}$$

where $n_\chi(r)$ is the DM number density at distance r from the GC, the average speed in the DM rest frame v_0 is related to the velocity dispersion $v_d(r)$ as $v_0 = \sqrt{8/(3\pi)}v_d(r)$ at distance r from the GC, and R is the exoplanet radius. The factor $1 + 3v_{\rm esc}^2/2v_d^2$ is the result of gravitational focusing, with $v_{\rm esc}^2 = 2G_N M/R$ being the escape velocity, M the exoplanet mass, and G_N the gravitational constant. The motion of the planet with velocity v_p with respect to the DM halo is taken into account by $\xi[v_p, v_d(r)]$. In the scenarios we are interested in, the DM velocity, the planetary velocity and the escape velocities are of similar order and the function $\xi[v_d(r), v_p] \sim 1$. The circular velocities $v_c(r)$ in the galaxy are related to the DM velocity dispersion by $v_d(r) = \sqrt{3/2}v_c(r)$. We extract the circular velocities at different radii in the Milky Way by combining the data for the gas, bulge, and disk components, as well as the analytic expressions for DM contributions to the total velocity from Ref. [192]. For the DM density, we consider an Navarro-Frenk-White (NFW) profile [55], a generalized Navarro-Frenk-White (gNFW) profile, and a Burkert profile [193], with the local DM density 0.42 $\mathrm{GeV/cm^3}$ [194], see the Supplemental Material [50] for more details.

The heat power produced by DM is given by the product of the DM mass m_χ, the fraction of the captured DM particles that have passed through the object f, and the maximal capture rate, such that

$$\Gamma_{\rm heat}^{\rm DM} = m_\chi f C_{\rm max}. \tag{4}$$

Using $n_\chi(r) = \rho_\chi(r)/m_\chi$, $\xi[v_d(r), v_p] \sim 1$, and combining with Eq. (3), the DM heat power is

$$\Gamma_{\rm heat}^{\rm DM} = f\pi R^2 \rho_\chi(r) v_0 \left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_d(r)^2}\right). \tag{5}$$

Searches and infrared telescope sensitivity.—Exoplanets may first be identified by, e.g., Doppler spectroscopy or gravitational lensing. Once their location is found, infrared telescopes such as JWST may be able to measure their temperature. The general sensitivity of JWST to exoplanet heating can be found by considering the spectral flux density,

$$f_\nu = \pi B(\nu, T) \times \frac{4\pi R^2}{4\pi d^2}, \tag{6}$$

where d is the distance from the telescope to the exoplanet, R is the radius of the exoplanet, and

$$B(\nu, T) = \frac{2\nu^3 \epsilon}{\exp(\frac{2\pi\nu}{k_b T}) - 1}, \tag{7}$$

where ν is the wavelength, T is the temperature, k_b is the Boltzmann constant, and ϵ is the atmospheric emissivity. We use $\epsilon = 1$ which provides the usual blackbody spectral flux density, and is the most conservative case. Deviations from a blackbody occur for $\epsilon < 1$; see the Supplemental Material [50] for emissivity impact on telescope sensitivity.

Figure 2 shows the expected exoplanet temperature as a function of Galactocentric distance, for DM-heating arising due to several different DM profiles as labeled. We distinguish between Jovian exoplanets with masses between $1 - 14M_{\rm jup}$ and brown dwarfs with masses in the range of $14 - 55M_{\rm jup}$. All exoplanets shown have a radius of $R_{\rm jup}$, as they are expected to converge to this radius after 10 Gy. The shaded region for a given DM profile represents the range of heating possibilities for the indicated mass range, with the heaviest (lightest) exoplanets lying at the upper (lower) boundary. The shape of the curves over galactic distances is due to an interplay of the DM density and velocity profiles, and the effective capture radius of the exoplanet.

We show in Fig. 2 the optimal JWST sensitivity, which is found using Eq. (6) with the benchmark dwarf/Jupiter radius of $R_{\rm jup}$. As different JWST instrument filters are optimized for different flux densities/temperatures, we use several different filters while scanning over the minimal temperature measurable, to obtain the optimal sensitivity. This is calculated using the near-infrared imager and slitless spectrograph in imaging mode for temperatures above about 500 K, and the mid-infrared instrument in imaging or medium-resolution spectroscopy mode for temperatures from about 100–500 K. The dashed line is for JWST to obtain about 10^5 seconds of exposure to achieve a

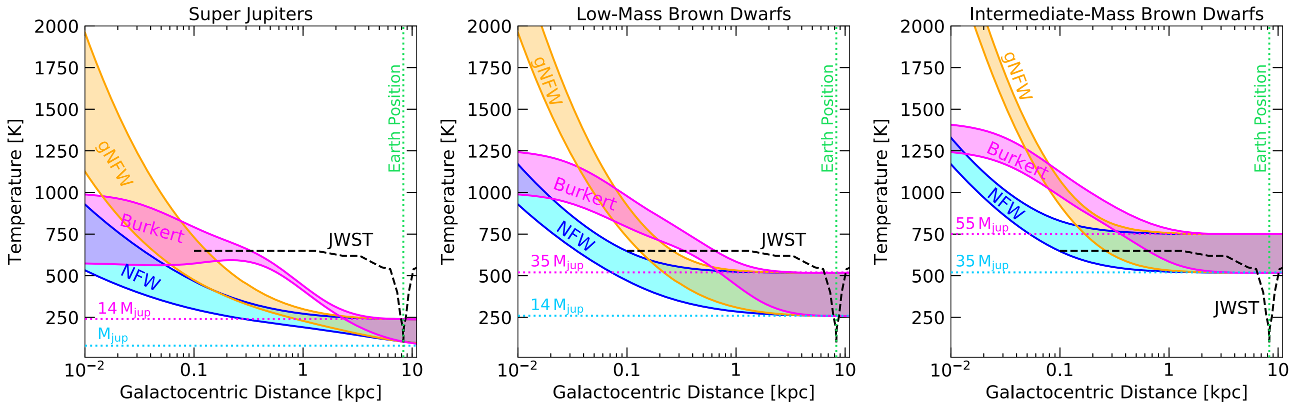

FIG. 2. Exoplanet temperatures over Galactocentric distances, with variations due to DM for labeled density profiles. Each panel represents our classification of different exoplanet types: super Jupiters ($M_{\rm jup} - 14M_{\rm jup}$), low-mass brown dwarfs ($14 - 35M_{\rm jup}$), and intermediate-mass brown dwarfs ($35 - 55M_{\rm jup}$). Any exoplanet within the indicated mass range will have temperatures between these lines in the shaded region. The dotted lines show the range of minimum temperatures for a 10 Giga-year-old exoplanet without DM. Black dashed line is the optimal minimum JWST sensitivity (temperatures above this line can be detected), see text.

signal-to-noise ratio (SNR) of 2. 10 SNR can be achieved at about 10^6 seconds of exposure at most of the temperatures shown. Note however that these exposure times are for the minimum temperatures on the dashed line; higher temperatures generally require less exposure time. Significantly less time is required to achieve 10 SNR in the local region; see Supplemental Material for more detailed JWST sensitivity estimates, including estimates of dust extinction and stellar crowding, which conservatively limit the expected JWST sensitivity to distances larger than 0.1 kpc from the GC.

The dotted lines in Fig. 2 show exoplanet temperatures without DM heating, for masses labeled, where intermediate masses would sit between these dotted lines. It is clear that different types of exoplanets are most useful as a DM heating targets in different regimes. The lower mass Jupiters are ideal for local searches, as DM heating can outperform their internal heat at the local position. For higher mass brown dwarfs, their internal heat is too high to reveal a DM heating signal at the local position. However, their larger masses are advantageous towards the GC due to gravitational focusing.

We therefore propose two search strategies: one for DM in local Jupiters, and another for all exoplanets towards the DM dense GC. As shown in Fig. 2, towards the GC exoplanets are increasingly heated by DM. This means that exoplanets can potentially be used to trace the DM density in our Galaxy. Given a large statistical sample, DM overdensities could also be revealed by too many hot exoplanets in a given region, which is additional motivation for the distant search. Note that at large distances the exoplanet must be a rogue planet or brown dwarf, since a parent star would obscure its resolution.

Dark matter parameter space.—We now consider the implications of DM-heated exoplanets for particle DM models. Limits from planetary heat flow often probe strongly interacting DM [42,44]. Exoplanets are instead ideal laboratories to study broader classes of sub-GeV DM models.

To relate the DM heat flow with scattering cross sections, we need to find the range of parameters for which a fraction f of the DM particles passing through the planet is gravitationally captured. Normalizing to the maximal DM capture rate [defined in Eq. (3)], we obtain the captured DM fraction

$$f = \frac{C_{\rm cap}}{C_{\rm max}} = \sum_{N=1}^{N_{\rm max}} f_N, \tag{8}$$

with the capture fraction for a given number of scatterings being

$$f_N = p(N,\tau)\left[1 - \kappa \exp\left(-\frac{3(v_N^2 - v_{\rm esc}^2)}{2v_d^2}\right)\right], \tag{9}$$

with

$$\kappa = \left(1 + \frac{3}{2}\frac{v_N^2}{v_d^2}\right)\left(1 + \frac{3}{2}\frac{v_{\rm esc}^2}{v_d^2}\right)^{-1}. \tag{10}$$

Here v_d is the velocity dispersion, $v_N = v_{\rm esc}(1 - \langle z\rangle\beta)^{-N/2}$ where the average scattering angle is $\langle z\rangle = 1/2$ [195], $\beta = 4m_\chi m_A/(m_\chi + m_A)^2$, and m_A is the mass of the target particle. The probability that the DM particle scatters N times is

$$p(N,\tau) = \frac{2}{\tau^2}\left(N_s + 1 - \frac{\Gamma(N_s + 2, \tau)}{N_s!}\right), \tag{11}$$

where $\Gamma(a,b)$ is the incomplete gamma function. This scattering probability is a function of the optical depth,

$\tau = \frac{3}{2}\sigma/\sigma_{\mathrm{sat}}$ where $\sigma_{\mathrm{sat}} = \pi R^2/N_{\mathrm{SM}}$ is the saturation cross section, R the planetary radius, N_{SM} is the target particle number, and σ is the DM-target cross section. To set sensitivity limits on DM scattering in Jupiters and brown dwarfs, we assume spheres of hydrogen with constant density. As gas giants are expected to be dominated by hydrogen, we expect a hydrogen sphere to be approximately representative. For example, Jupiter's composition is about 84% hydrogen and 16% helium [196].

Figure 3 shows our sensitivity estimates for Jupiter-like planets and brown dwarfs to the DM parameter space for spin-dependent DM-proton scattering (see Sec. V of the Supplemental Material [50] for spin-independent, additional velocity dependent, and electron scattering results). We show a "min" cross section for the object as labeled, which corresponds to effectively all the DM being captured, and planets being maximally heated, producing the most striking signal. We also show a "max" cross section, which corresponds to the smallest DM capture fraction (about 10%) that can be probed in the near future with JWST. This is likely the maximum cross section reach, as the temperatures corresponding to this lower scattering rate are approaching either the JWST minimum temperature detection threshold, or the expected background temperature, in most of the parameter space. The sensitivity curves become flat for brown dwarfs, as their larger escape velocity leads to the opacity limit being reached for some of the parameter space. Thus, increasing the DM capture cross section further in that region does not change the capture fraction.

These sensitivities do not depend on the DM density profile or value; sensitivity to the cross sections shown only requires that the DM heating is successfully detected. For

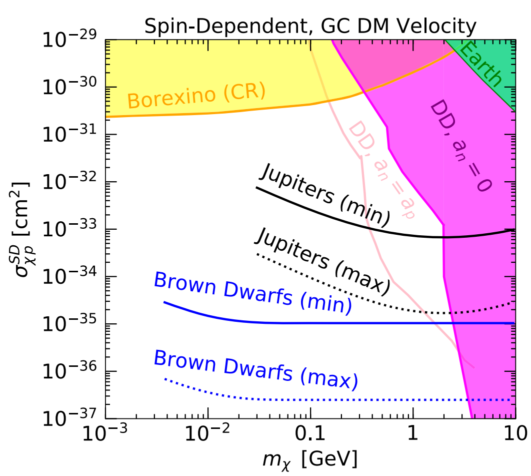

FIG. 3. Spin-dependent DM-nucleon scattering cross section sensitivity estimates for Jupiters and brown dwarfs, assuming a GC DM velocity. The solid (min) lines show cross sections assuming effectively that all DM is captured, and the dotted (max) lines show the maximum expected reach. Complementary constraints are also shown, see text.

more discussion of detection/search prospects, see the Supplemental Material [50]. We show the earth heat flow bounds from Ref. [44] for comparison, and direct detection (DD) bounds [56,57,197,198]. "DD, $a_n = 0$" corresponds to proton-only DD limits, while "DD, $a_n = a_p$" corresponds to equal proton/neutron coupling DD limits. Borexino shows limits from boosted DM from cosmic rays interactions [58–61]. Note that these limits have different assumptions; the direct detection limits do not require any minimum annihilation cross section.

Conclusions.—The exoplanet program is rapidly accelerating. Amongst the billions of new worlds in our Galaxy, many are waiting to reveal their surprises. Unexpected discoveries are inevitable, and numerous new telescopes with cutting-edge technology are ready to make them. For the first time, we have pointed out the broad applicability of exoplanets to be used as DM detectors, with actionable discovery or exclusion searches using new infrared telescopes. We target old, cold, Jupiter-like planets and brown dwarfs, which are advantageous due to their large sizes, densities, and low core temperatures.

Our first suggested search is for overheated local exoplanets. There are hundreds of known Jupiters in our local neighborhood, and Gaia is expected to identify tens of thousands of potential candidates in the next few years [93], providing a sample with great statistical power.

Our second suggested search is for overheated exoplanets, correlated with DM density, rising sharply in temperature towards the GC. The presence of DM overdensities or substructure may also be confirmed with exoplanets, with a pocket of even hotter DM-heated exoplanets. We conclude that, at an estimate, JWST may have sensitivity to exoplanet temperatures above about 650 K, for exoplanets all the way into about 0.1 kpc of the inner Galaxy (for more local searches, the minimum temperature sensitivity is lower).

We calculated the DM parameter space sensitivity to brown dwarfs and Jupiters that may have their temperature measured in the near future. We determined that DM with masses above about an MeV can be probed with exoplanets, with DM-proton scattering cross sections down to about 10^{-37} cm^2, stronger than existing limits by up to six orders of magnitude. We pointed out that this DM mass sensitivity is lighter than many other celestial body searches for DM heat flow. This is because brown dwarfs and Jupiters have large integrated column densities and low core temperatures, and so it is more difficult for light DM to evaporate in these systems.

We thank John Beacom, Joe Bramante, Chris Cappiello, Rouven Essig, Katie Freese, Savannah Jacklin, Shirley Li, Bruce Macintosh, Nirmal Raj, Anupam Ray, Pat Scott, Sara Seager, Aaron Vincent, and Ji Wang for helpful comments and discussions. R. K. L. was supported by the Office of High Energy Physics of the U.S. Department of Energy under Grants No. DE-SC00012567 and No. DE-SC0013999, as well as the NASA Fermi Guest Investigator

Program under Grant No. 80NSSC19K1515, and later at SLAC under Contract No. DE-AC02-76SF00515. J. S. is largely supported by a Feodor Lynen Fellowship from the Alexander von Humboldt foundation.

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