THE SURFACE DENSITIES OF DISK BROWN DWARFS IN JWST SURVEYS

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ABSTRACT

We present predictions for the surface density of ultracool dwarfs (with spectral types M8–T8) for a host of deep fields that are likely to be observed with the James Webb Space Telescope. Based on simple thin and thick/thin disk (exponential) models, we show that the typical distance modulus is \( \mu \approx 9.8 \) mag, which at high Galactic latitude is \( 5 \log(2 \, z_{\text{gal}}) - 5 \). Since this is a property of the density distribution of an exponential disk, it is independent of spectral type or stellar sample. Using the published estimates of the ultracool dwarf luminosity function, we show that their number counts typically peak around \( J \sim 24 \) mag with a total surface density of \( \Sigma \sim 0.3 \) arcmin\(^{-2} \), but with a strong dependence on galactic coordinate and spectral type. Owing to the exponential shape of the disk, the ultracool dwarfs are very rare at faint magnitudes (\( J \geq 27 \) mag), with typical densities of \( \Sigma \sim 0.005 \) arcmin\(^{-2} \) (or \( \sim 20\% \) of the total contribution within the field). Therefore, in very narrow and deep fields, we predict there are only a few ultracool dwarfs, and hence these stars are likely not a severe contaminant in searches for high-redshift galaxies. Furthermore, the ultracool dwarfs are expected to be considerably brighter than the high-redshift galaxies, so samples near the faint end of the high-redshift galaxy population will be the purest. We present the star-count formalism in a simplified way so that observers may easily predict the number of stars for their conditions (field, depth, wavelength, etc.).

Key words: brown dwarfs – galaxies: high-redshift – Galaxy: disk – Galaxy: structure – stars: low-mass

Supporting material: tar.gz file

1. INTRODUCTION

Number–magnitude counts have a long tradition of providing a simple but effective tool for probing the distribution of stars within the Milky Way and the large-scale structure of the universe (such as the visual star-gauging of Herschel 1785). The application of photography to astronomical research in the late 1800s provided a means of obtaining permanent records of celestial objects, leading to systematic surveys such as the Plan of Areas (Kapteyn 2006) and the star-count analyses (Seares et al. 1925; Bok 1937). Additionally, photography also opened the way for surveys of the distribution of extragalactic nebulae, notably the Lick survey by Shane & Wirtanen (1954) and the Abell (1958) catalog of galaxy clusters, derived from the wide-field Schmidt plates of the first Palomar Observatory Sky Survey.

Photography captured images of the sky for posterity, but visual inspection of plates can only yield a qualitative understanding. The development of scanning densitometers in the 1970s provided the first means of quantifying photographic data for statistical analyses. When combined with deep imaging with 4 m telescopes, photography yielded the first reliable color–magnitude diagrams for field stars and galaxies fainter than \( \sim 20 \) mag (Kron 1980), and automated scans of the wide-field Schmidt plate mapped the stellar distribution at bright magnitudes (e.g., Hewett et al. 1981; Gilmore et al. 1985), but see Reid (1993, p. 37) and Chincarini (2013) for a more extensive discussion of those developments. In more recent years, these investigations have given way to direct digital imaging, whether through narrow pencil-beam surveys, as exemplified by the Hubble Deep Field (HDF; Williams et al. 1996) and its successors, or through near all-sky surveys, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000).

By and large, stars and galaxies occupy distinct domains in imaging surveys. At high galactic latitudes, stars are typically bright (\( V \sim 20 \) mag), while galaxies dominate at fainter magnitudes (\( v \gtrsim 25 \) mag). However rare objects often challenge conventional models and highlight shortcomings in current theories. For example, Gilmore (1981) showed that rare, faint stars can significantly contaminate samples of distant objects. In recent years, the focus has moved to significantly higher redshifts, with the deepest surveys, aided partly by gravitational lensing, reaching beyond \( z \sim 10 \) (Coe et al. 2013; Ellis et al. 2013). At those redshifts, the Lyman break moves upward of \( \lambda \sim 1 \) \( \mu \)m and galaxies have extremely red colors at near-infrared wavelengths. As Wilkins et al. (2015) have pointed out, very high-redshift galaxies and ultracool dwarfs often have similar near-infrared colors. In this paper, we consider the likely surface density of MLT dwarfs (Kirkpatrick et al. 1999; Cushing et al. 2011) and their potential to bias studies of high-redshift galaxies.

This paper is organized as follows: in Section 2 we give a brief discussion of stellar populations in the Milky Way, the relevant properties of ultracool dwarfs, and our choice of representative deep fields. In Section 3 we detail the star-count formalism. In Section 4 we discuss these results in the context of deep fields with the Hubble Space Telescope (HST) and the James Webb Space Telescope (JWST). Finally, in Section 5 we conclude with a brief summary, reviewing the key points. Throughout this paper, we take care to explicitly state the magnitude system to avoid confusion between Vega-based (often used in the Galactic and stellar community) and AB-based (the de facto standard in extragalactic work) magnitudes.

2. BACKGROUND

2.1. The Stellar Populations of the Milky Way

The resolved stellar constituents of nearby galaxies are generally categorized as members of distinct populations. Following Baade (1944) and Oort (1958), astellar population is
characterized as a collection of stars that have similar dynamical properties and share a common evolutionary scenario. Within the Milky Way, the main populations are the thin disk, the thick disk, the stellar halo, and the Galactic bulge/bar. The latter population is generally confined within the central regions of the Galaxy (although radial migration may lead to some local representation), and we therefore focus on the first two populations as representative of stars in the outer regions of the Galaxy in general and the solar neighborhood in particular. The main properties of these populations are well summarized by Freeman (2012, p. 137).

Considering the three local populations, the thin disk is the dominant baryonic component, with a total mass of $\sim 5 \times 10^9 M_\odot$, and encompassing the gas and dust contributing to the current star formation. The density distribution is generally well represented by a double exponential, with a radial scale length of $\sim 2.5-2.7$ kpc. Gas, dust, and young stars are closely confined to the Galactic midplane, with the vertical distribution increasing rapidly with age as the velocity increases due to scattering by massive objects such as molecular clouds (Spitzer & Schwarzschild 1951; Wielebn 1977). The oldest stars in the disk have ages as $\sim 8-10$ Gyr and are distributed in a disk with a scale height of $\sim 250$ pc (Juric et al. 2008).

The thick disk is a more extended component, again following a double-exponential distribution with a radial scale length that is similar to the thin disk. Originally identified within the Galaxy from star-count analyses by Gilmore & Reid (1983), the vertical distribution can be matched with a scale height of $\sim 800-900$ pc. The color–magnitude diagram clearly indicates that this is an old population ($\sim 10-12$ Gyr), with essentially no ongoing star formation. While the exact origin remains unclear, detailed spectroscopic analyses show that thick-disk stars have enhanced abundances of $\alpha$-elements (Bensby et al. 2013), indicating that the population formed rapidly, before SNe Ia could significantly enhance the iron abundance. The local density of thick-disk stars is $\sim 8\%-10\%$ that of the thin disk, with a likely total mass of $\sim (1-2) \times 10^9 M_\odot$.

### 2.2. Colors of the Ultracool Dwarf Population

Ultracool dwarfs have effective temperatures $T < 2500$ K and emergent spectra characterized by absorption from broad molecular and narrow resonance features (e.g., H$_2$O, FeH, TiO, CO, CH$_4$, Na, and K). Consequently, these low-mass stars have very red optical/near-infrared broadband colors, which are similar to galaxies at $z \sim 6$ (Yan et al. 2003; Ryan et al. 2005; Caballero et al. 2008; Wilkins et al. 2015). In Figure 1, we show the JWST/NIRCam broadband colors synthesized from the IRTF/SpEx library $^1$ as colored points. The colored lines show the tracks of power-law spectra with $f_{\lambda} \propto \lambda^{-\beta}$ with blue ($\beta = 2$), green ($\beta = 1$), and red ($\beta = 0$).

$^1$ As compiled by A. Burgasser and available at http://pono.ucsd.edu/~adam/brown dwarfs/spexprism/
Table 1

| Name          | $\alpha$ (h m s) | $\delta$ (° ′ ″) | $\ell$ (degree) | $b$ (degree) | $E_{B-V}$ (mag) |
|---------------|------------------|------------------|-----------------|--------------|-----------------|
| Abell 2744    | 00 14 21.2       | −30 23 50.1      | 8.8975          | −81.23860    | 0.012           |
| UKIDSS UDS    | 02 17 37.5       | −05 12 00.0      | 158.95220       | −51.54158    | 0.020           |
| Abell 370     | 02 39 52.9       | −01 34 36.5      | 173.00410       | −53.57030    | 0.028           |
| HUDF/GOODS-S  | 03 32 29.5       | −27 48 18.3      | 223.56903       | −54.43162    | 0.007           |
| MACS J0416−2403 | 04 16 08.9   | −24 04 28.7      | 221.08660       | −44.05440    | 0.036           |
| MACS J0717+3745 | 07 17 34.0 | +37 44 49.0      | 180.24429       | +21.04515    | 0.068           |
| COSMOS        | 10 00 27.9       | +02 12 03.5      | 236.82544       | +42.11648    | 0.016           |
| MACS J1149+2223 | 11 49 36.3  | +22 23 58.1      | 228.16350       | +75.19849    | 0.020           |
| HDFN/GOODS-N  | 12 36 54.9       | +62 14 18.9      | 125.86574       | +54.80702    | 0.011           |
| EGS           | 14 19 18.0       | +03 55 18.0      | 103.29148       | +54.82531    | 0.028           |
| Abell S1063   | 22 48 44.4       | −44 31 48.5      | 349.48345       | −59.93298    | 0.010           |

Note. * Taken from the NASA Extragalactic Database based on Schlafly & Finkbeiner (2011).

Table 2

| Name           | Variable | Value       | Reference            |
|----------------|----------|-------------|----------------------|
| Solar radius   | $r_\odot$ | 8000 pc     | Reid (1993)          |
| Solar height   | $z_\odot$ | 25 pc       | Jurič et al. (2008)  |
| Thin-disk scale length | $r_{\text{sc}}$ | 2500 pc | Jurič et al. (2008)  |
| Thin-disk scale height  | $z_{\text{sc}}$ | 290 pc | Ryan et al. (2011)   |
| Thick-disk scale length  | $R_{\text{sc}}$ | 3600 pc | Jurič et al. (2008)  |
| Thick-disk scale height  | $Z_{\text{sc}}$ | 1000 pc | Jurič et al. (2008)  |
| Fraction of thick disk | $f$ | 0.13 | Jurič et al. (2008)  |

Table 3

| Field          | $\mu_{\text{peak}}$ (mag) | $\mu_{\text{ave}}$ (mag) | $\mu_{\text{peak}}$ (mag) | $\mu_{\text{ave}}$ (mag) |
|----------------|---------------------------|---------------------------|---------------------------|---------------------------|
| Abell 2744     | 8.88                      | 8.30                      | 11.62                     | 11.04                     |
| UKIDSS UDS     | 9.15                      | 8.58                      | 11.62                     | 11.04                     |
| Abell 370      | 9.13                      | 8.53                      | 11.57                     | 10.99                     |
| HUDF/GOODS-S   | 9.13                      | 8.55                      | 11.63                     | 11.05                     |
| MACS J0416−2403 | 9.41                     | 8.83                      | 11.82                     | 11.24                     |
| MACS J0717+3745 | 10.47                   | 9.88                      | 12.55                     | 11.96                     |
| COSMOS         | 9.52                      | 8.94                      | 11.96                     | 11.37                     |
| MACS J1149+2223 | 8.86                     | 8.26                      | 11.47                     | 10.88                     |
| HDFN/GOODS-N   | 9.11                      | 8.56                      | 11.69                     | 11.08                     |
| EGS            | 9.22                      | 8.62                      | 11.79                     | 11.19                     |
| Abell S1063    | 9.28                      | 8.69                      | 12.19                     | 11.60                     |

2.3. Stellar Luminosities

We adopt the local $J$-band luminosity function pieced together from Cruz et al. (2007), Bochanski et al. (2010), and Metchev et al. (2008), but a general calculation could transform to an arbitrary near-infrared passband using the IRTF/Spex library. However, these density estimates have modest uncertainties ($\delta \Phi / \Phi \sim 30\%$), so we take our luminosity function to be a fourth-order polynomial fit for $8.5 \leq J \leq 16.5$: $\mu_{\text{ave}}$ (mag) $\mu_{\text{ave}}$ (mag)

$$\log \Phi(J) = -0.30 + 0.11 (J - 14) + 0.15 (J - 14)^2 + 0.015 (J - 14)^3 - 0.00020 (J - 14)^4$$ (1)

where $\Phi(J)$ has units of $10^{-3}$ pc$^{-3}$ mag$^{-1}$ and $J$ is Vega-based. In Figure 2, we show our polynomial luminosity function (solid line) and the observations as color symbols, where the color and shape represent spectral type and reference, respectively. As our primary goal is to predict the number counts at high Galactic latitude, we do not propagate the uncertainty in these data or the corresponding polynomial model. Finally, we adopt the $M_J$ (Vega)—spectral type relation of Hawley et al. (2002).

2.4. Representative Deep Fields

Table 1: distances for the 11 fields, the 5 fields from the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS; Grogin et al. 2011; Koekemoer et al. 2011) and the 6 Hubble Frontier Fields$^2$ (HFF; Lotz et al. 2014; J. Lotz et al. 2016, in preparation). In Table 1, we list the observational properties of these 11 fields, but regard COSMOS, Abell S1063, Abell 2744, and MACS J0717 as representative fields, since they cover a range of celestial coordinates and give the largest spread in the following predictions.

3. MODELING PENCIL-BEAM SURVEYS

The majority of recent surveys for high-redshift galaxies are based on deep, narrow-angle imaging observations. The
number of stars $N$ within such fields is given by integrating their density distribution $p(r, M)$ over the sampled volume. Here, we make the usual assumption that the stellar luminosity function $\phi(M)$ is independent of spatial distribution $r$ or position in the Galaxy (Bahcall 1986); hence,

$$p(r, M) \, dr \, dM = n(r) \, \phi(M) \, dr \, dM,$$

(2)

but we recognize that the cooling of the brown dwarfs may lead to a vertical dependence on the luminosity function (Burgasser 2004; Ryan et al. 2011). We take $n(r) \, dr$ and $\phi(M) \, dM$ to be dimensionless and adopt the local luminosity function (as discussed in Section 2.3). Therefore, we must renormalize these distributions as

$$n(r_\odot) \equiv \int \Phi(M') \, dM' = n_\odot,$$

(3)

where $\Phi(M)$ is the local luminosity function in units of pc$^{-3}$ mag$^{-1}$. We renormalize the luminosity function as $\phi(M) \, dM = n_\odot^{-1} \Phi(M) \, dM$ to have units of mag$^{-1}$.

For this work, we consider only disk distributions, as the Galactic halo is at least 11 Gyr old (Kalirai 2012) and any brown dwarfs here would have cooled below our spectral-type range, but we discuss the contribution in Section 4. Assuming the standard double-exponential model, we have

$$\bar{n}(r, z; r_\odot, z_\odot) = n_\odot \exp \left( \frac{r_\odot - r}{r_s} + \frac{z - z_\odot}{z_s} \right),$$

(4)

where $(r_\odot, z_\odot)$ represent the solar position in the Galaxy. So, for a thick and thin disk the total density is given by

$$n(r, z) = \bar{n}(r, z; r_\odot, z_\odot) + f_t \, \bar{n}(r, z; R_h, Z_h)$$

(5)

where $f_t$ is the fraction of thick-disk stars. The conversion from these cylindrical coordinates, assuming azimuthal symmetry based on the Galactic center, to spherical coordinates with respect to the Sun is given by Juric et al. (2008):

$$r = \sqrt{r_\odot^2 + R^2 \cos^2 b - 2 R r_\odot \cos b \cos \ell}$$

$$z = R \sin b + z_\odot,$$

(6)

(7)

where $R$ is the heliocentric distance and $(\ell, b)$ are the Galactic coordinates of the field. In Table 2 we list the published estimates for the parameters of these distributions that we will adopt. With a change of variables from heliocentric distance to distance modulus $\mu = 5 \log R - 5$, the distance modulus distribution is given by

$$n(\mu, \ell, b) \, d\mu = \Delta\Omega \, n(R, \ell, b) \, R^2 \, dR$$

(8)

where $\Delta\Omega$ is the field of view. In Figure 3 we show the distance modulus distributions for the four representative, high-latitude fields. The colors represent the thin disk (blue), thick disk (red), and total (black). For fields at very high latitude (such as Abell 2744), the typical distance for a star is $2 \, z_{\text{scl}}$, which is independent of the luminosity of the star and is generically true for any population confined to the Galactic disk.
We give the peak and average distance modulus for all 11 potential JWST deep fields in Table 3.

The predicted stellar number count is given by integrating Equation (2), which is the so-called fundamental equation of stellar statistics (Equation (1) of Bahcall 1986):

\[ N(m, \ell, b) \, dm = \Delta \Omega \int_0^\infty n(R, \ell, b) \phi(M) R^2 \, dR \, dm, \]

where \( M \) is constrained to satisfy \( M = m - \mu(R) - A(\ell, b, R) \), where \( A(\cdot) \) is the extinction along a given line of sight as a function of distance. Since the typical JWST deep field is likely situated far from the Galactic plane, they will have low color excesses (typically \( E_{B-V} \lesssim 0.03 \) mag; see Table 1; Schlafly & Finkbeiner 2011) and infrared extinctions of \( A_{IR} \lesssim 0.02 \) mag (Schlegel et al. 1998). Moreover, since

### Table 4
Number Counts for M8–M9\(^a\)

| Field                  | Thin Disk | Thick Disk |
|------------------------|-----------|------------|
|                        | \( J_{\text{peak}} \) | \( J_{1/2} \) | \( \Sigma_{<25} \) | \( \Sigma_{<27} \) | \( \Sigma_{\text{tot}} \) | \( J_{\text{peak}} \) | \( J_{1/2} \) | \( \Sigma_{<25} \) | \( \Sigma_{<27} \) | \( \Sigma_{\text{tot}} \) |
| Abell 2744             | 21.82     | 21.57      | 0.48       | 0.48       | 0.48       | 24.56     | 24.31      | 1.74       | 2.45       | 2.46       |
| UKIDSS UDS             | 22.10     | 21.85      | 0.72       | 0.72       | 0.72       | 24.55     | 24.31      | 1.75       | 2.44       | 2.46       |
| Abell 370              | 22.04     | 21.80      | 0.66       | 0.66       | 0.66       | 24.51     | 24.26      | 1.66       | 2.29       | 2.30       |
| HUDF/GOODS-S           | 22.07     | 21.82      | 0.69       | 0.69       | 0.69       | 24.56     | 24.31      | 1.78       | 2.50       | 2.52       |
| MACS J0416–2403        | 22.35     | 22.09      | 1.00       | 1.01       | 1.01       | 24.75     | 24.50      | 2.15       | 3.26       | 3.30       |
| MACS J0717+3745        | 23.35     | 23.15      | 3.45       | 3.65       | 3.65       | 25.49     | 25.23      | 3.62       | 7.87       | 8.40       |
| COSMOS                 | 22.45     | 22.20      | 0.99       | 0.99       | 0.99       | 24.87     | 24.62      | 2.33       | 3.72       | 3.77       |
| MACS J1149+2223        | 21.78     | 21.53      | 0.39       | 0.39       | 0.39       | 24.40     | 24.15      | 1.42       | 1.88       | 1.89       |
| HDFN/GOODS-N           | 22.08     | 21.83      | 0.59       | 0.59       | 0.59       | 24.59     | 24.34      | 1.76       | 2.50       | 2.52       |
| EGS                    | 22.14     | 21.89      | 0.64       | 0.64       | 0.64       | 24.70     | 24.45      | 1.98       | 2.93       | 2.95       |
| Abell S1063            | 22.22     | 21.97      | 0.84       | 0.84       | 0.84       | 25.12     | 24.87      | 2.89       | 5.22       | 5.36       |

Note.\(^a\) Columns 2–3 and 7–8 are in AB magnitudes while columns 4–6 and 9–11 are in \( 10^{-2} \) arcmin\(^{-2} \).
Table 5

| Field          | $I_{\text{peak}}$ | $J_{12}$ | $J_{25}$ | $S_{\text{peak}}$ | $S_{\text{tot}}$ |
|---------------|-------------------|----------|----------|-------------------|-----------------|
| Abell 2744    | 22.62             | 22.39    | 0.62     | 0.63              | 0.63            |
| UKIDSS UDS    | 22.91             | 22.68    | 0.91     | 0.93              | 0.93            |
| Abell 370     | 22.85             | 22.62    | 0.84     | 0.86              | 0.86            |
| HUDF/GOODS-S  | 22.87             | 22.64    | 0.87     | 0.89              | 0.89            |
| MACS J0416-2403 | 23.15         | 22.92    | 1.25     | 1.30              | 1.30            |
| MACS J0717+3745 | 24.21          | 23.98    | 3.72     | 4.71              | 4.72            |
| COSMOS        | 23.26             | 23.03    | 1.22     | 1.28              | 1.28            |
| MACS J1149+2223 | 22.58          | 22.36    | 0.50     | 0.50              | 0.50            |
| HDFN/GOODS-N  | 22.88             | 22.66    | 0.75     | 0.76              | 0.76            |
| EGS           | 22.94             | 22.71    | 0.80     | 0.83              | 0.83            |
| Abell S1063   | 23.02             | 22.79    | 1.05     | 1.08              | 1.08            |

Note.

a Columns 2–3 and 7–8 are in AB magnitudes while columns 4–6 and 9–11 are in $10^{-2}$ arcmin$^{-2}$.

Table 6

| Field          | $I_{\text{peak}}$ | $J_{12}$ | $J_{25}$ | $S_{\text{peak}}$ | $S_{\text{tot}}$ |
|---------------|-------------------|----------|----------|-------------------|-----------------|
| Abell 2744    | 24.49             | 24.30    | 0.45     | 0.65              | 0.66            |
| UKIDSS UDS    | 24.77             | 24.58    | 0.60     | 0.95              | 0.98            |
| Abell 370     | 24.72             | 24.53    | 0.57     | 0.88              | 0.91            |
| HUDF/GOODS-S  | 24.74             | 24.55    | 0.58     | 0.91              | 0.94            |
| MACS J0416-2403 | 25.01         | 24.82    | 0.75     | 1.30              | 1.37            |
| MACS J0717+3745 | 26.07          | 25.88    | 1.41     | 3.91              | 4.97            |
| COSMOS        | 25.12             | 24.93    | 0.70     | 1.27              | 1.35            |
| MACS J1149+2223 | 24.45          | 24.26    | 0.37     | 0.52              | 0.53            |
| HDFN/GOODS-N  | 24.75             | 24.56    | 0.50     | 0.78              | 0.80            |
| EGS           | 24.81             | 24.62    | 0.53     | 0.84              | 0.87            |
| Abell S1063   | 24.88             | 24.69    | 0.67     | 1.10              | 1.14            |

Note.

a Columns 2–3 and 7–8 are in AB magnitudes while columns 4–6 and 9–11 are in $10^{-2}$ arcmin$^{-2}$.

Table 7

| Field          | $I_{\text{peak}}$ | $J_{12}$ | $J_{25}$ | $S_{\text{peak}}$ | $S_{\text{tot}}$ |
|---------------|-------------------|----------|----------|-------------------|-----------------|
| Abell 2744    | 25.99             | 25.75    | 0.15     | 0.44              | 0.52            |
| UKIDSS UDS    | 26.26             | 26.03    | 0.18     | 0.60              | 0.77            |
| Abell 370     | 26.22             | 25.98    | 0.17     | 0.57              | 0.71            |
| HUDF/GOODS-S  | 26.25             | 26.00    | 0.18     | 0.58              | 0.74            |
| MACS J0416-2403 | 26.52         | 26.27    | 0.20     | 0.77              | 1.08            |
| MACS J0717+3745 | 27.58          | 27.34    | 0.26     | 1.57              | 3.91            |
| COSMOS        | 26.63             | 26.38    | 0.18     | 0.73              | 1.06            |
| MACS J1149+2223 | 25.96          | 25.71    | 0.13     | 0.36              | 0.41            |
| HDFN/GOODS-N  | 26.26             | 26.01    | 0.15     | 0.50              | 0.63            |
| EGS           | 26.32             | 26.07    | 0.16     | 0.53              | 0.68            |
| Abell S1063   | 26.39             | 26.15    | 0.19     | 0.68              | 0.90            |

Note.

a Columns 2–3 and 7–8 are in AB magnitudes while columns 4–6 and 9–11 are in $10^{-2}$ arcmin$^{-2}$.
JWST will be able to detect L0 to \( \sim 16 \) kpc and T8 to \( \sim 3 \) kpc (assuming \( J \sim 29 \) mag and absolute magnitudes of Hawley et al. 2002), a full three-dimensional description of \( A(\cdot) \) is required for reliable number counts (Sale et al. 2009; Ryan et al. 2011; Green et al. 2014). Therefore, we adopt \( A(\ell, b, R) = 0 \) mag, but stress that fields near the Galactic plane may require a more sophisticated treatment, which will modify our predictions. Using the definition from Equation (8), we find that Equation (9) is simply a convolution between the normalized luminosity function and the distance modulus distribution:

\[
N(m, \ell, b) \, dm = \Delta \Omega \int^{+\infty}_{-\infty} n(\mu, \ell, b) \phi(m - \mu) \, d\mu \, dm.
\]

We show differential (Figure 4) and integral (Figure 5) counts for our representative fields in units of arcmin\(^{-2}\). As in Figure 3, the colors represent thin (blue), thick (red), and total (black) disk components. In the Appendix, we tabulate various statistics of the number counts for the 11 potential JWST deep fields broken down by spectral type (Tables 4–7). Since stars in the Milky Way are predominantly confined to an exponential disk, they are not generally not found at arbitrarily faint brightnesses. Although the ultracool dwarfs have very low-luminosities, they are expected to have \( J \sim 24 \) mag in high-latitude fields (\( |b| \gtrsim 20^\circ \)).

### 4. DISCUSSION

We have demonstrated that for an idealized survey (i.e., one with perfect sample completeness), ultracool dwarfs are expected to be reasonably bright—reaching 50% of their totals near where their counts peak at \( J \sim 24 \) AB mag. However, a realistic survey will not be so complete, and therefore the expression in Equation (9) should be modified to include a completeness function. In most cases, the completeness function does not have an explicit dependence on sky position, but rather is only modulated by the non-uniformity of the survey (Ryan et al. 2011; Holwerda et al. 2014). For most high-redshift galaxy surveys, the completeness is typically a weak function of brightness for \( AB \lesssim 25 \) mag (e.g., Bouwens et al. 2007), which leaves many of our results regarding the surface densities unchanged.

Thus far we have explicitly omitted a halo component, since the Galactic halo has an age of \( \gtrsim 11 \) Gyr (Kalirai 2012), but here we illustrate its potential effect on our results. To have colors consistent with a high-redshift galaxy, an ultracool dwarf would have a spectral type of roughly L5–T5 (see Figure 1) and hence a temperature of 2000–1200 K (Figure 7 of Kirkpatrick 2005). Based on the expected cooling curves (Burrows et al. 1997; Chabrier et al. 2000; Allard et al. 2001; Baraffe et al. 2003), a star with an age of 11.4 Gyr and temperature 1200–2000 K would have a mass of 0.075–0.08 \( M_\odot \) and likely sustain hydrogen fusion. Therefore, we include a Galactic halo following the parameterization and values of Sesar et al. (2011), but...
calculated over this narrow temperature range. The halo distribution peaks around \( J \approx 30 \) AB mag and increases the total surface density of \( \sim 0.1 \) arcmin\(^{-2}\). This estimate depends strongly on the cooling models and star formation history of brown dwarfs, and so should be regarded as preliminary. Nevertheless, JWST will have the ability to easily detect early-T dwarfs in the Galactic halo; indeed, the existence of a sizable population veritably associated with the halo will be a useful boundary condition on the cooling models.

Throughout this work we have tacitly assumed that none of the ultracool dwarfs are in unresolved binary systems. If we assume that equal-mass unresolved binaries would have the same colors, luminosities, and Galactic distributions as single stars, then the stars would be \( 2.5 \log 2 = 0.75 \) mag too bright. If all stars were in binary pairs, then the number counts would shift \( \sim 0.75 \) mag to brighter limits, but the overall number of sources identified would remain constant (since the binaries are unresolved). Certainly this would exacerbate the issue of contamination, however this maximum binarity assumption is very conservative since the observed binary fractions are more like \( \lesssim 25\% \) (e.g., Burgasser et al. 2007; Aberasturi et al. 2014). Moreover, Ryan et al. (2011) showed that the model number counts do not significantly change for binary fractions \( \lesssim 40\% \).

**5. SUMMARY**

Since brown dwarfs have long been recognized as a potential contaminating source in high-redshift galaxy surveys (Yan et al. 2003; Ryan et al. 2005; Caballero et al. 2008; Wilkins et al. 2015), we have provided tangible predictions for the surface density of these ultracool dwarfs using the best estimates for their luminosity function and Galactic distribution. We find that the highest surface densities are (not surprisingly) near the Galactic plane and with \( \sim 1 \) arcmin\(^{-2}\). Therefore, in existing data sets with \( HST \) the numbers are typically \( \lesssim 1 \) for a single WFC3 field of view (such as the HFF or HUDF) or \( \sim 40 \) for wide-field mosaics (such as CANDELS: UDS, EGS, or COSMOS). With JWST it will be possible to obtain many shallow fields (AB \( \sim 27 \)) and search for dwarfs out to \( \sim 6 \) kpc, veritably sampling the Galactic halo. However, conclusively identifying a given dwarf as a member of the halo will require kinematic data, which will yield new constraints on the cooling models of ultracool dwarfs by providing robust samples of very old, but massive, objects.
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Facility: JWST (NIRCam).

APPENDIX
RESULTS BY SPECTRAL TYPE

In the main text we presented differential and integral counts for all dwarfs near or below the hydrogen-burning limit, whose colors may be consistent with any high-redshift galaxy (i.e., z ≥ 6 Yan et al. 2003; Ryan et al. 2005; Caballero et al. 2008; Wilkins et al. 2015). However, there are numerous methods for selecting high-redshift samples (e.g., photometric redshifts, color/dropout selection, spectroscopic), which will undoubtedly have unique selection biases and purities. Therefore, we have broken down the above results into four broad spectral classes M8–M9 (upper left), L0–L5 (upper right), L5–L9 (lower left), and T0–T5 (lower right) in Figures 6 and 7. We freely distribute J-band number counts for each field and spectral type, available as a tar.gz file.

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Figure 7. Cumulative counts for various spectral type ranges. Here the colors have the same meaning as Figure 5, but we show the differential counts of separate spectral types M8–M9 (upper left), L0–L5 (upper right), L5–L9 (lower left), and T0–T5 (lower right).
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