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# THE ULTRACOOL SPEXTROSCOPIC SURVEY. I. VOLUME-LIMITED SPECTROSCOPIC SAMPLE AND LUMINOSITY FUNCTION OF M7-L5 ULTRACOOL DWARFS. 

Daniella C. Bardalez Gagliuffi, ${ }^{1,2, *}$ Adam J. Burgasser, ${ }^{2}$<br>Sarah J. Schmidt, ${ }^{3}$ Christopher Theissen, ${ }^{2}$ Jonathan Gagné, ${ }^{4}$<br>Michael Gillon, ${ }^{5}$ Johannes Sahlmann, ${ }^{6}$ Jacqueline K. Faherty, ${ }^{1}$<br>Christopher Gelino, ${ }^{7,8}$ Kelle L. Cruz, ${ }^{1,9,10,11}$ Nathalie Skrzypek, ${ }^{12}$ and DAGNY Looper ${ }^{13}$

${ }^{1}$ Department of Astrophysics, American Museum of Natural History, Central Park West at 79th St, New York, NY 10024, USA
${ }^{2}$ Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Dr., Mail Code 0424, La Jolla, CA 92093, USA
${ }^{3}$ Leibniz-Institute for Astrophysics Potsdam (AIP), An der Sternwarte 16, D-14482, Potsdam, Germany
${ }^{4}$ Institute for Research on Exoplanets, Université de Montréal, Département de Physique, C.P. 6128 Succ. Centre-ville, Montréal, QC H3C 3J7, Canada
${ }^{5} 1$ Space sciences, Technologies and Astrophysics Research (STAR) Institute, Université de Liège Allèe du 6 Août 17, Bat. B5C, 4000 Liège, Belgium
${ }^{6}$ Space Telescope Science Institute (STScI), 3700 San Martin Drive, Baltimore, MD 21218, USA
${ }^{7}$ Infrared Processing and Analysis Center (IPAC), California Institute of Technology, 117 Morrisroe Astroscience Lab, Mail Code 100-22, Pasadena CA 91125, USA
${ }^{8}$ NASA Exoplanet Science Institute (NExSci), California Institute of Technology, Mail Code 100-22, 1200 East California Blvd., Pasadena, CA 91125, USA
${ }^{9}$ Hunter College, City University of New York, 695 Park Ave, New York, NY 10065, USA
${ }^{10}$ Department of Physics, Graduate Center, City University of New York, 365 5th Ave, New York, NY 10016, USA
${ }^{11}$ Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010 USA
${ }^{12}$ Blackett Laboratory, Imperial College, Prince Consort Rd, Kensington, London SW7 2AZ, UK
${ }^{13}$ CBS Studios, 4024 Radford Ave, Studio City, CA 91604
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Corresponding author: Daniella C. Bardalez Gagliuffi dbardalezgagliuffi@amnh.org


#### Abstract

We present a volume-limited, spectroscopically-verified sample of M7-L5 ultracool dwarfs within 25 pc. The sample contains 410 sources, of which $93 \%$ have trigonometric distance measurements ( $80 \%$ from Gaia DR2), and $81 \%$ have low-resolution ( $R \sim 120$ ), near-infrared (NIR) spectroscopy. We also present an additional list of 60 sources which may be M7-L5 dwarfs within 25 pc when distance or spectral type uncertainties are taken into account. The spectra provide NIR spectral and gravity classifications, and we use these to identify young sources, red and blue $J-K_{S}$ color outliers, and spectral binaries. We measure very low gravity and intermediate gravity fractions of $2.1_{-0.8}^{+0.9} \%$ and $7.8_{-1.5}^{+1.7} \%$, respectively; fractions of red and blue color outliers of $1.4_{-0.5}^{+0.6} \%$ and $3.6_{-0.9}^{+1.0} \%$, respectively; and a spectral binary fraction of $1.6_{-0.5}^{+0.5} \%$. We present an updated luminosity function for M7-L5 dwarfs continuous across the hydrogen burning limit that agrees with previous studies. We estimate our completeness to range between $69-80 \%$ when compared to an isotropic model. However, we find that the literature late- M sample is severely incomplete compared to L dwarfs, with completeness of $62_{-7}^{+8} \%$ and $83_{-9}^{+10} \%$, respectively. This incompleteness can be addressed with astrometric-based searches of ultracool dwarfs with Gaia to identify objects previously missed by color- and magnitude-limited surveys.


Keywords: astronomical databases: miscellaneous - infrared: stars stars: binaries (including multiple): close - stars: binaries: general - stars: brown dwarfs - stars: fundamental parameters - stars: late-type - stars: low mass - stars: luminosity function - methods: observational - methods: statistical - surveys - techniques: spectroscopic

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## 1. INTRODUCTION

Ultracool dwarfs (UCDs) are the lowest-mass, coldest, and faintest products of star formation, encompassing objects with masses $M \lesssim 0.1 M_{\odot}$, effective temperatures $\leq 2700 \mathrm{~K}$, and spectral types M7 and later (Kirkpatrick et al. 1991). UCDs include both very low-mass (VLM) stars that slowly fuse hydrogen for up to a trillion years (Laughlin et al. 1997); and brown dwarfs, which have insufficient mass to sustain hydrogen fusion in their cores $\left(M_{B D} \lesssim 0.072 M_{\odot}\right.$ for solar metallicity; Kumar 1963; Hayashi \& Nakano 1963). Brown dwarfs never reach thermal equilibrium as they are supported by electron degeneracy pressure, and thus continue to cool and dim over time across spectral types M, L, T, and Y (Kirkpatrick et al. 1999; Burgasser 2002, and Cushing et al. 2011, respectively). The absence of an internal energy generation mechanism results in a degeneracy between mass, age and luminosity (and its proxies, effective temperature, absolute magnitude, and spectral type). As a consequence, the characterization of isolated brown dwarfs is challenging, but the population can be evaluated statistically (e.g. Burgasser 2004; Allen et al. 2005; Metchev et al. 2008; Burningham et al. 2010; Reylé et al. 2010; Day-Jones et al. 2013; Kirkpatrick et al. 2019).

UCDs are yardsticks of Galactic chemical evolution, as their minimal core fusion mostly preserves their natal compositions. Their interiors are fully convective, allowing measurement of both composition and products of fusion (i.e. Li depletion) from their atmospheres. UCDs are ubiquitous, and include some of the closest neighbors to the Sun, such as the L/T transition and flux reversal binary Luhman 16AB (Luhman 2013), and the coldest known brown dwarf, the $\gtrsim$ Y2 WISE J085510.83-071442.5 ( $T_{\text {eff }} \sim 250 \mathrm{~K}$; Luhman 2014), both at a distance of 2 pc . UCDs can host disks (e.g., Ricci et al. 2014; Testi et al. 2016) and exoplanets (e.g., TRAPPIST-1, Gillon et al. 2016, 2017; OGLE-2012-BLG-0358Lb, Han et al. 2013); are found in binary and higher-order multiple systems (e.g., Burgasser et al. 2007c, 2012), and in young clusters and associations (e.g., Gagné et al. 2015a; Zapatero Osorio et al. 2000); they are members of the Galactic halo (e.g., Burgasser et al. 2003; Kirkpatrick et al. 2014; Zhang et al. 2017); and have a broad range of magnetic activity (Schmidt et al. 2015; Gizis et al. 2000) including high levels of radio emission (e.g., Kao et al. 2018; Berger 2006); among other distinct properties. Finally, while UCDs represent the low-mass tail of the stellar initial mass function (IMF; e.g., Chabrier 2005), their formation mechanisms remain poorly understood, since the Jeans mass in typical molecular clouds favors the production of objects with masses $M \sim 0.5 M_{\odot}$ (Jeans 1902). The dense regions that are necessary to produce UCDs are difficult to model (e.g., Bate 2012).
Large area surveys in optical, NIR and mid-infrared (MIR) bands have been crucial to the discovery and population characterization of UCDs. These include the TwoMicron All Sky Survey (2MASS; Skrutskie et al. 2006), the Sloan Digital Sky Survey (SDSS; York et al. 2000), the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence
et al. 2007), the Deep Near Infrared Survey of the Southern Sky (DENIS; Epchtein 1994), the Canada France Brown Dwarf Survey (CFBDS; Delorme et al. 2008), and the Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010). Gaia (Gaia Collaboration et al. 2016), whose second data release (DR2; Gaia Collaboration et al. 2018) has delivered 5-parameter astrometric solutions for 1.3 billion sources, has further uncovered and characterized nearby UCDs (Gaia Collaboration et al. 2018; Reylé 2018).

A homogeneous and unbiased sample is key to understanding the essential mechanisms, physical processes, and environmental conditions favorable to UCD formation and evolution. The IMF is a consequence of formation, and ultracool IMF studies indicate there are fewer brown dwarfs than stars (e.g., Luhman et al. 2000; Chabrier 2005). The incidence of rare subpopulations such as color outliers, young, and metalpoor sources, and binary and higher order systems, all probe formation and evolution mechanisms. The Solar neighborhood is the ideal region to measure these statistics. Bearing in mind the location and motion of the Sun with respect to the Galactic center, and the distinct kinematics and metallicity distributions of the thin disk, thick disk and halo populations (Gilmore \& Reid 1983), the local volume can be treated as broadly representative of the Milky Way. Since brown dwarfs are intrinsically faint ( $M_{K} \gtrsim 10 \mathrm{mag}$; Faherty et al. 2013b), collecting data on the nearest sources is particularly advantageous to building a well-characterized sample. Spectroscopy, broad-band spectral energy distributions, kinematics, multiplicity, magnetic activity, and excesses and variability attributable to weather, magnetic activity, and presence of disks are best investigated with the nearest stars and brown dwarfs.
Previous studies of the nearby UCD population have already revealed some of the statistical properties of these low-mass objects. Reid et al. (2003a) compiled the northern sample of systems within 8 pc of the Sun in $V$-band magnitude, including 142 main sequence stars, 3 brown dwarfs, and 8 white dwarfs, and estimated $\sim 15 \%$ incompleteness. Cruz et al. (2003) compiled a volume-limited sample of 186 M7-L6 dwarfs within 20 pc using a NIR photometric color and magnitude selection in 2MASS. Subsequently, Cruz et al. (2007) built the first UCD NIR luminosity function, finding number densities of $n=4.9 \times 10^{-3} \mathrm{pc}^{-3}$ for M7-M9.5 and a lower limit of $n \geq 3.8 \times 10^{-3} \mathrm{pc}^{-3}$ for L dwarfs ${ }^{1}$. Using the sixth data release of SDSS, Bochanski et al. (2010) compiled luminosity and mass functions of field low-mass stars spanning the M dwarf spectral class. Other studies have focused on the coldest brown dwarfs, to eventually obtain the low-mass end of the substellar mass function. Metchev et al. (2008) measured a T dwarf number density of $n=\left(7.0_{-3.0}^{+3.2}\right) \times 10^{-3} \mathrm{pc}^{-3}$ based on the detection of 15 T dwarfs in $2099 \mathrm{deg}^{2}$ sampled by 2MASS and SDSS. Reylé et al. (2010) measured a late-L dwarf density of $n=\left(2.0_{-0.7}^{+0.8}\right) \times 10^{-3} \mathrm{pc}^{-3}$, and T dwarf densities of $n=\left(1.4_{-0.2}^{+0.3}\right) \times 10^{-3} \mathrm{pc}^{-3}$ for T0.5-T5.5 dwarfs and $n=\left(5.3_{-2.2}^{+3.1}\right) \times 10^{-3} \mathrm{pc}^{-3}$

[^1]for T6-T8 dwarfs in CFBDS. Recently, Kirkpatrick et al. (2019) used a 20 pc volume limited sample of sources T 6 and later and estimated a number density of $0.97 \times 10^{-3} p c^{-3}$ for objects with temperatures $900-1050 \mathrm{~K}$ or roughly T 6 dwarfs, increasing to $3.26 \times 10^{-3} \mathrm{pc}^{-3}$ for objects with temperatures in the $300-450 \mathrm{~K}$ range, roughly corresponding to Y dwarfs.

Despite these concerted efforts, source identification and follow-up has been inhomogeneous for the local 25 pc sample, as evidenced by ongoing nearby discoveries. The M7 dwarf 2MASS J154043.42-510135.7 at 5 pc (Pérez Garrido et al. 2014), the M9.5+T5 binary system WISE J072003.20-084651.2 (Scholz 2014; Burgasser et al. 2015b), the L/T transition binary WISE J104915.57-531906.1 (Luhman 2013), and the 250 K WISE J085510.83-071442.5 (Luhman 2014), all at distances of 6 pc or less, show that the nearby sample remains incomplete. Given the availability of abundant multi-epoch survey data and astrometry from Gaia, it is time to revisit the compilation of UCDs in the local volume.
In this paper we present a new volume-limited sample of M7-L5 ultracool dwarfs within 25 pc, accompanied by NIR spectra homogeneously acquired with the SpeX spectrograph (Rayner et al. 2003) on the NASA Infrared Telescope Facility (IRTF). We follow a similar analysis to those of Cruz et al. (2003) and Reid et al. (2008) by creating an unbiased, homogeneous, NIR spectroscopic sample of M7-L5 dwarfs selected from multiple sources in the literature. Section 2 describes the sample selection and construction of our 25 pc and $+1 \sigma$ samples. Section 3 describes the construction of the spectral sample, which is analyzed in Section 4, for spectral and gravity classifications, color outliers, low gravity sources, spectral binaries, and resolved binaries and higher order multiples previously identified in the literature. In Section 5, we estimate our biases, the completeness of the observed sample, and compute its selection function through a population simulation. We present an updated infrared luminosity function of ultracool dwarfs and compare it to previous work. Conclusions are summarized in Section 6.

## 2. LITERATURE SAMPLE CONSTRUCTION

### 2.1. Compilation of $U C D$ Targets from the Literature

Targets for the sample were drawn from a number of literature sources, including surveys and previous compilations, each designed for its own scientific purposes and with a variety of follow-up. We attempt to average over the various biases from the original surveys by compiling as many sources as possible. Some of the known biases include a red $J-K_{S}$ color bias (e.g., Cruz et al. 2003; Lépine et al. 2013, identified by Schmidt et al. 2015); incomplete compilations (e.g., Gagné et al. 2015b) or partial sky coverage, e.g. Sloan Digital Sky Survey (SDSS; Ahn et al. 2012; Alam et al. 2015), Deep Near-Infrared Southern Sky Survey (DENIS; Epchtein 1994), UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007); and targeted surveys (e.g., young objects, Shkolnik et al. 2009; wide binaries, Deacon et al. 2014; high proper motion

Table 2. Cuts leading to the final sample

|  | Cut |
| :--- | :--- |
| Initial compilation | Targets remaining |
| Deletion of duplicates | 16,322 |
| Optical, NIR or "photometric" spectral type between M7-L5 | 12,711 |
| Estimated distance $\leq 50$ pc | 6,226 |
| Compilation of photometry, recalculation of spectrophotometric distances | 1,664 |
| Deletion of non-stellar sources, giants, compact and young stellar objects | 1,571 |
| Estimated Distance $\leq 30$ pc | 833 |
| Compilation of Gaia astrometry, recalculation of trigonometric distances |  |
| Objects with literature optical, NIR, or SpeX spectral type within M7-L5 (including photo-types only) | 595 |
| Objects with trigonometric or NIR spectrophotometric distance $\leq 25$ pc | $435_{-20}^{+21 \mathrm{a}}$ |
| Objects with trigonometric or NIR spectrophotometric distance $\leq 25$ pc+1 $\sigma$ | $470_{-21}^{+22} \mathrm{a}$ |
| Final samples | $410_{-20}^{+21 \mathrm{a}}$ |
| 25 pc sample of M7-L5 dwarfs | $470_{-21}^{+22} \mathrm{a}$ |
| 25 pc plus $1 \sigma$ sample of M7-L5 dwarfs |  |

${ }^{a}$ Uncertainties based on Poisson statistics.
surveys, i.e. SUPERBLINK, Lépine \& Gaidos 2011). We believe biases due to proper motion selection are negligible due to the completeness of the photometric selection surveys. While proper motion surveys tend to be more incomplete, they also are less likely to scatter distant objects into the sample. Table 1 lists the literature sources used to consolidate a database of $\sim 16,000$ candidate nearby UCDs. Table 2 summarizes the sequence of cuts leading to our final samples.
Duplicate sources were removed with TOPCAT (Taylor 2005) through an internal match that organized sources in near-neighbor groups with a matching radius of $15^{\prime \prime}$, large enough to catch binary components before deletion. This step reduced the number of entries to $\sim 12,700$. We applied a spectral type cut requiring optical or NIR spectral types or photometric spectral type estimates (e.g., Skrzypek et al. 2015; Theissen et al. 2017) to be in the M7-L5 range, shrinking the database to $\sim 6,200$ sources. A rough distance cut eliminating objects farther than 50 pc , trimmed this list to 1,664 sources.
Galaxies, giants, T-Tauri stars and other non-UCD sources as reported in the literature were identified using SIMBAD and removed, reducing the sample to 1,571 sources. After compiling photometric and astrometric data and recalculating spectrophotometric distances (see below), another distance cut at 30 pc was applied for those sources with astrometric parallaxes, yielding 833 sources.

### 2.2. Photometric and Astrometric Data

Photometry from the 2MASS (Skrutskie et al. 2006), SDSS DR9 (Ahn et al. 2012), AllWISE (Wright et al. 2010; Mainzer et al. 2011), UKIDSS-LAS (Lawrence
et al. 2007), and Gaia DR2 (Gaia Collaboration et al. 2018) catalogs were collected for all sources, selecting the closest match up to $15^{\prime \prime}$ through the VizieR interface to account for objects with large proper motions, using a custom routine ${ }^{2}$ built with the Astroquery Python package (Ginsburg et al. 2018). We obtained coordinates, epochs, identifiers, and GrizJHK $K W 1 W 2 W 3$ magnitudes from Gaia, SDSS, 2MASS, UKIDSS, and AllWISE. Spectral types from SDSS spectroscopy were obtained when available. In addition to these surveys, we also obtained rizJHK magnitudes and uncertainties, spectral type, object type, and proper motions from SIMBAD with the same search radius.
Table 4 provides the photometry data for the sample. All sources in our final 25 pc sample (See Table 2) have NIR magnitudes ${ }^{3}$, $88 \%$ have MIR magnitudes from AllWISE, and 39\% have optical magnitudes from SDSS. Resolved NIR photometry on the Mauna Kea Observatory (MKO) filter system (Tokunaga et al. 2002) was obtained from the literature (e.g. Dupuy \& Liu 2012; Best et al. 2018) and selected compilations ${ }^{4}$, particularly for closely-separated components of binary systems. We adopted 2MASS $J H K_{s}$ magnitudes as the standard, and use MKO JHK magnitudes if those were the only NIR ones available.

AllWISE includes a crossmatch with the 2MASS catalog that we used to check for mismatches. We compared the $J H K_{s}$ magnitudes from the 2MASS and AllWISE catalogs and kept the 2MASS magnitudes when the difference was within 0.05 mag (typical magnitude uncertainty for 2MASS $J H K_{s}$ ). Objects whose magnitude differences were $>0.05 \mathrm{mag}$ were flagged for visual examination in multi-wavelength finder charts, and comparison of SIMBAD and VizieR data sets. The mismatches between AllWISE and 2MASS $J H K_{s}$ magnitudes were typically caused by the blending of a bright and faint source ( $\Delta m \sim 3 \mathrm{mag}$ ) in the larger AllWISE pixels. In these cases, we assigned the 2MASS $J H K_{s}$ magnitudes to the source, and replaced the AllWISE $W 1 W 2 W 3$ magnitudes with null entries. The same procedure was followed to consolidate $J H K$ magnitudes from UKIDSS, and literature sources. While UKIDSS uses MKO filters, we keep these measurements separate because the quantum efficiency of the various NIR detectors may differ.
Further inspection on mismatched photometry between SDSS, 2MASS and AllWISE was done with color-color diagrams, as shown in Figure 1, and corrected by visual inspection using finder charts. Figure 1 illustrates the color loci of M7-L5 dwarfs from Schmidt et al. (2015). The most discriminating colors (e.g., $z-J$ ) use filters across surveys. Mismatches were corrected in a similar way as described above, using multi-wavelength finder charts and comparing magnitudes.
Astrometric data (positions, proper motions, and parallaxes) and radial velocities were drawn from SIMBAD when available. The sample was also crossmatched against

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Figure 1. Color locus of the known M7-L5 25 pc sample in SDSS, 2MASS, and WISE colors as a function of $i-J$ (Schmidt et al. 2015). Blue circles are members of the $25 p c$ sample, green triangles are members of the extended $1 \sigma$ sample. The black line represents mean colors from Schmidt et al. (2015) (complete between M7-L2), with the extent of their uncertainties shaded in light gray.
the astrometric samples of Dupuy \& Liu (2012) and Weinberger et al. (2016). Upon the release of Gaia DR2 (Gaia Collaboration et al. 2018), we crossmatched our preliminary sample against this dataset to obtain 5-parameter astrometric solutions. We used the following Astronomical Data Query Language (ADQL) query through the astroquery. Gaia package.

SELECT g.*, t.*
FROM gaiadr1.tmass_original_valid AS t
LEFT OUTER JOIN gaiadr2.tmass_neighbourhood AS xt ON xt.tmass_oid =
t.tmass_oid

LEFT OUTER JOIN gaiadr2.gaia_source AS g ON xt.source_id = g.source_id where 1=CONTAINS (POINT ('ICRS', t.ra, t.dec), CIRCLE('ICRS', \{\}, \{\}, 5./3600) )

The Gaia crossmatch was done in two steps. First, we crossmatched the sample with the 2MASS-Gaia DR2 crossmatch table (gaiadr2.tmass_neighbourhood) within a radius of 5.10 using 2MASS coordinates from our sample. Second, we joined this crossmatch with the Gaia DR2 source table. We obtained 843 matches in 2MASS (10 objects with 2 matches each), 715 matched Gaia DR2 with a $G$ magnitude, and 705 with parallaxes. To check the validity of our matches, we examined a color magnitude diagram of $G-R P$ versus absolute $G$ magnitude. We considered sources as outliers if $G-R P \leq 1.25$, and if $M_{G} \leq 5$ to avoid giant stars. The 36 sources that failed our color/magnitude constraints were examined for crossmatch accuracy, and we found 22 mismatches of true UCDs with erroneous Gaia data. The remaining 14 sources were dropped from the sample due to their small Gaia parallaxes ( $\vec{\omega} \ll 10 \mathrm{mas}$ ), resulting in 825 sources.

### 2.2.1. Spectral Types

Most catalogs provide information on optical or NIR spectral classification, or classification estimates from photometry (Skrzypek et al. 2015; Theissen et al. 2017). Given variations in classification schemes and intrinsic differences between optical and NIR classification (particularly for L dwarfs), we required at least one optical, NIR or photometric type belonging to the M7-L5 range for sources to be included in the sample. Adopted literature spectral types were chosen by prioritizing optical, NIR and photo-types, in that order. In the final $25 p c$ sample, the adopted spectral type is optical for 334 objects, NIR for 73 , and photometric for 4 . The objects whose adopted literature type is photometric have SpeX observations (see Section 3) confirming their status as M7-L5 dwarfs. Figure 8 shows the distribution of adopted literature spectral types color-coded by the nature of their measurement.
One hundred and eighty-nine objects have both optical and NIR measurements from the literature. With our SpeX observations (see Section 3), we have added 109 NIR classifications (see Section 4.2). Figure 4 shows a comparison between literature optical and NIR spectral types. The size of each circle is proportional to the number of overlapping sources. The scatter between spectral types is 0.95 subtypes; the $3 \sigma$ boundaries are delineated by the dashed light grey lines.

### 2.2.2. Distances

Trigonometric and spectrophotometric distances were calculated from parallaxes and from spectrophotometric empirical relations in the NIR, respectively. Gaia DR2 provided most of the parallaxes in the sample, $80 \%$ of the total or 327 in our 25 pc sample. Distances from Gaia were calculated simply as $d=1000 / \omega$ (mas), rather than using a likelihood function with Bayesian probabilities (e.g., Bailer-Jones et al. 2018), since we are concerned with sources with large parallaxes ( $\omega \geq 35$ mas or $d \leq 28.5 \mathrm{pc}$ to account for uncertainties beyond $d=25 \mathrm{pc}$ ) with small relative errors of the order of $0.04 \%-4 \%$. Trigonometric distances from parallaxes predating Gaia


Figure 2. Gaia Hertzprung-Russell Diagram of the 25 pc sample of M7-L5 dwarfs superimposed on the full 25 pc sample from Gaia. Gaia sources are shown as blue points, and sources from the M7-L5 dwarf 25 pc sample with valid Gaia matches are shown as green stars. Sources in orange correspond to Gaia mismatches.


Figure 3. Adopted literature spectral type for the M7-L5 25 pc sample, broken down by optical (blue), NIR (green), and photometric types (red).


Figure 4. Comparison of optical and NIR spectral types from the literature for the M7-L5 25 pc sample. The size of the circles scales as the cube of the number of repeated points. The solid line marks where the slope equals one, while the dashed lines encompass the $1 \sigma$ and $3 \sigma$ limits in magenta and light grey, respectively.

DR2 were calculated in the same way. We also calculated trigonometric distances from WISE following the prescription of Theissen (2018) for 16 sources.

We calculated spectrophotometric distances using the adopted literature spectral type and the absolute magnitude empirical relations from Dupuy \& Liu (2012). Dis-


Figure 5. Comparison of distance values and uncertainties. The most precise distances are those found through Gaia parallaxes shown as blue dots. Distances found through parallaxes from the literature (i.e. SIMBAD) are plotted as light blue triangles, and show a large scatter since they come from a variety of studies with different systematics. Parallaxes obtained through WISE (Theissen 2018) are shown as orange crosses and have the largest uncertainties. NIR spectrophotometric distance estimates are shown as red stars also with large uncertainties, and growing as a function of distance.
tances were calculated for the NIR filters $J, H$, and $K_{s}$, and averaged, weighted by their uncertainties. We adopt trigonometric distances if available (for $93 \%$ of the sample), and use spectrophotometric distances for 29 sources that do not have a parallax measurement. Distances are reported in Table 6. Figure 5 summarizes the distance uncertainties for these measurements, and Figure 6 compares trigonometric to spectrophotometric distances for the $25 p c$ and $1 \sigma$ samples. Trigonometric and spectrophotometric distances agree within $6.9 \%$ of each other, except for obviously overluminous sources.

Using the best distance measure, a strict cut on 25 pc was applied to select our volume-limited sample with 410 sources whose measured literature optical or NIR spectral types lie within M7-L5, and whose distance was within 25 pc , i.e. excluding objects with only a photometric estimation of their spectral type. We assess Poisson uncertainties as described in Gagné et al. (2017) for our sample size in subsequent analysis. Sources whose $1 \sigma$ uncertainties placed them within 25 pc , amounting to 60 objects, were added to an expanded $25 p c+1 \sigma$ sample of 470 objects.


Figure 6. Spectrophotometric distance estimates compared to trigonometric distance measurements. (Top) Fractional percentage errors between trigonometric $\left(d_{t}\right)$ and spectrophotometric $\left(d_{s}\right)$. (Bottom) The $25 p c$ sample is shown in green and the $1 \sigma$ sample is shown in blue. The black solid line delineates the one-to-one correspondence between trigonometric and photometric distances. Sources significantly above the line and beyond three standard deviations are likely unresolved binaries. In particular, the sources encircled in grey are 2MASS J1733+1655 $\left(d_{t}=16.03 \pm 0.10 \mathrm{pc}\right)$, NLTT $40017\left(d_{t}=22.4 \pm 0.7 \mathrm{pc}\right)$, SDSS $\mathrm{J} 1221+4632\left(d_{t}=30.3 \pm 6.4 \mathrm{pc}\right)$, and SDSS J0911+2248 $\left(d_{t}=35.7 \pm 11.5 \mathrm{pc}\right)$. None of these objects have mentions of binarity in the literature.

## 3. SPECTRAL SAMPLE

Two hundred and forty 25 pc sample members had SpeX spectra in the SpeX Prism Library (SPL; Burgasser 2014) prior to 2015. We observed an additional 286 sources with SpeX between UT 2015 February 24 and 2018 November 22 as part of NASA IRTF programs 2015A074, 2015B087, 2016A079, 2016B114, 2017A102, 2018B120 (PI: Bardalez Gagliuffi), and 2016A038 (PI: Burgasser), over a total of 15 nights. The observations log is summarized in Table 7. The latitude, equatorial mount, and location of IRTF allow for observation of declinations in the $-50^{\circ}<\delta<+67^{\circ}$ range. Ninety percent of the 25 pc sample lies within these declinations, and between existing work and our contributions, we obtained spectra for $89 \%$ of these sources, or $81 \%$ of the $25 p c$ sources overall. Sources were observed in prism mode, which completely
samples wavelengths $0.75-2.5 \mu \mathrm{~m}$ at a dispersion of $20-30 \AA$ pixel $^{-1}$ in a single observation. Most stars were observed with the $0!5$ slit, 10 sources were observed with the 0.18 slit if the seeing rose above $1^{\prime \prime} .2$. The slit was aligned with the parallactic angle. Integration times ranged between $60-150$ s per exposure, depending on the brightness of the source and atmospheric conditions. Observations were carried out in an ABBA dither pattern along the slit, with additional AB cycles if more counts were needed to achieve $\mathrm{S} / \mathrm{N} \sim 100$. Bright A0 stars were observed close in time at a similar airmass and used for flux calibration of the raw science spectra and correction for telluric absorption. Internal flat fields and Ar arc lamps were observed with each flux standard for pixel response and wavelength calibration, respectively. All data were reduced with SpeXtool package v4.1 (Cushing et al. 2004; Vacca et al. 2003) using standard settings.

## 4. SAMPLE CHARACTERIZATION

### 4.1. Spatial Distribution

Figure 7 shows the spatial distribution of all our targets. The $25 p c$ literature sample is evenly distributed across the sky, with the exception of the Galactic plane. Since 25 pc is a relatively small radius compared to the radius of the Milky Way ( $R_{M W} \sim 25 \mathrm{kpc}$ ) and its vertical scale height ( $\sim 300 \mathrm{pc}$; Kent et al. 1991; Bochanski et al. 2010), we assume an isotropic distribution of sources within this volume. There are 217 sources at northern declinations and 193 at southern declinations. In Galactic coordinates, there are 228 sources above the plane of the galaxy and 182 below it. We convert the 381 sources with measured parallaxes in our 25 pc from equatorial to galactic X, Y, Z right-handed coordinates centered at the Sun. In the $\vec{X}$ direction we find 161 objects between the Sun and the Galactic center, and 220 between the Sun and the outer edge of the Galaxy. In the $\vec{Y}$ direction we find 206 objects in the direction of the Sun's motion, and 175 objects trailing behind it. In the $\vec{Z}$ direction, we find 207 objects above the plane of the Sun, and 174 below it. All of these values are within $3 \sigma$ of each other, considering Poisson uncertainties, yet not consistent at the $1 \sigma$ level. Bihain \& Scholz (2016) have suggested an inhomogeneity in the spatial distribution of brown dwarfs compared to stars, most likely an effect of small number statistics and incomplete coverage of observations. The slight preference for northern sources is due to the larger number of panchromatic survey observations in the northern hemisphere (in particular SDSS). The Galactic plane looks sparse due to overcrowding and background source contamination, and this region is excluded from our space density analysis below (c.f. Kendall et al. 2007, 2003).

### 4.2. Spectral Classification

We compared our SpeX spectra to NIR spectral standards defined in Kirkpatrick et al. (2010), following the method described therein, which compares the $0.9-1.4 \mu \mathrm{~m}$ spectrum of an object to standards using a $\chi^{2}$ minimization routine. The resulting distribution of spectral types is shown in Figure 8.


Figure 7. Spatial distribution of $25 p c$ targets in the M7-L5 25 pc sample. The sample is shown as black dots, objects for which we have SpeX spectra are shown as red dots. The sky regions inaccessible by IRTF are shaded in grey. The galactic plane $\left(b=0^{\circ}\right)$ is shown as a dashed light gray line, and the $\pm 15^{\circ}$ parallels from the galactic plane are shown as solid light gray lines.


Figure 8. (Left) Adopted literature spectral type distribution of $25 p c$ and $1 \sigma$ samples. (Right) Spectral type distribution of $25 p c$ and $1 \sigma$ samples according to their SpeX classification. Objects outside of the M7-L5 range have at least one spectral classification within that range.

After classifying the spectra, we compared their literature and measured spectral types. For most objects, we measured a NIR spectral type within one subtype of the published literature type. Objects with only a photometric estimate from the literature and whose SpeX spectral type placed them outside of the M7-L5 range are in the $1 \sigma$ sample.
Figure 9 compares the literature adopted optical or NIR classifications to the SpeX classification. The scatter for the optical-SpeX comparison is $\sigma=0.77$ subtypes, the scatter for the NIR-SpeX comparison is $\sigma=1.06$ subtypes, and the scatter in the
adopted-SpeX comparison is $\sigma=0.82$ subtypes. The larger scatter between NIRSpeX classifications may be due to poorly defined prior NIR types, sensitivity to surface gravity, metallicity, clouds; and variance in the spectral region used for NIR classification.
We also classified our SpeX spectra using spectral indices from Burgasser (2007a), Allers et al. (2007), and Reid et al. (2001). These indices are applicable in the $\mathrm{L} 0-\mathrm{T} 8, \mathrm{M} 5-\mathrm{L} 5$, and M7-L8 spectral type ranges, respectively. Figure 10 shows the comparisons from these index-classification systems against optical and NIR spectral types reported in the literature. The points outside of the allowed classification ranges are plotted in light grey and are not included in the median offset and scatter calculations. The indices from Burgasser (2007a) have a systematic offset of +1.30 and +1.40 subtypes compared to optical and NIR types, respectively, and overestimate the spectral type of our sources. The Allers et al. (2007) indices are the most accurate at predicting optical spectral types with $\sigma=0.90$ subtypes. The scatter is larger for NIR types ( $\sigma=1.05$ subtypes), with a slight tendency to predict spectral types earlier than measured in the literature (offset $=-0.30$ in both cases). For both optical and NIR types, the Reid et al. (2001) indices have the smallest offset ( 0.10 and 0.05 subtypes for optical and NIR spectral types, respectively) but slightly larger scatters than Allers et al. (2007), at $\sigma=1.21$ and $\sigma=1.42$ subtypes, respectively. All spectral types for sample sources are summarized in Table 5.

### 4.3. Gravity Classification and Young Moving Group Membership

Young brown dwarfs ( $\tau \lesssim 200 \mathrm{Myr}$ ) are undergoing cooling and contraction, and are both larger in radius and less massive than their older counterparts at a similar spectral type. These physical properties translate into lower surface gravities, affecting spectral features such as reduced collision-induced absorption, and narrower alkali lines (Allers et al. 2007; Kirkpatrick et al. 2010). Due to their low surface gravity and typically dusty atmospheres, young brown dwarfs share physical properties with directly-imaged exoplanets, making the former ideal analogs to the latter (Faherty et al. 2013a, 2016).
We obtained gravity classifications of our SpeX spectra, following the NIR scheme of Allers \& Liu (2013), defined for the spectral type range M5-L7, except that spectral types were determined from $\mathrm{H}_{2} \mathrm{O}$ indices without a visual comparison of the $J$-band with NIR standards.
Additionally, we obtain 7 very low gravity (VL-G) and 64 intermediate gravity (INT-G) candidate classifications from our spectra in the combined $25 p c$ and $1 \sigma$ samples (Table 8). All low-gravity candidates were examined for visual signatures of low gravity, comparing the spectra band-by-band to low-gravity standards (see Gagné et al. 2015c and Cruz et al. 2018), leading to the rejection of 26 INT-G classifications. We labeled 11 sources with conflicting signatures as peculiar, such as blue $J-K_{S}$ colors, indicating low metallicity effects rather than low gravity (Aganze et al. 2016).


Figure 9. Literature optical and NIR spectral types compared to SpeX spectral types with Kirkpatrick et al. (2010) NIR standards. Circle sizes are proportional to the number of sources in a given optical-NIR spectral type pair. The solid line indicates equal classification, and the pink and grey dashed lines are the $1 \sigma$ and $3 \sigma$ limits, respectively.


Figure 10. Literature optical and NIR spectral types compared against measured spectral types with the index sets of Burgasser (2007a), Allers et al. (2007) and Reid et al. (2001). Points outside the spectral type ranges defined for each index classification are plotted in grey and do not enter the $\sigma$ calculation.

Most VL-G sources are previously known, but we have identified 2MASS J1739+2454 as a new very low-gravity source. Thirteen of the 26 INT-G sources are first reported in this paper. The unresolved spectrum of the M8+M8 binary system 2MASS J0027+2219AB (Forveille et al. 2005) was also classified as an INT-G source. Since both components have the same spectral type, and since the system is coeval, we assume that both components would be independently classified as INT-G, leading to a final number of INT-G objects of 26 plus one more including the $1 \sigma$ sample.


Figure 11. Distribution of spectral types as classified by field spectral standard for different gravity types. Objects with gravity classifications of very-low gravity (VL-G) or intermediate gravity (INT-G) are plotted in red and green, respectively.

While 2MASS J1022+5825 (Reid et al. 2008), 2MASSW J2148+4003 (Looper et al. 2008) and 2MASS J0512-2949 (Cruz et al. 2003) were previously classified as having field gravity (FLD-G; Allers \& Liu 2013; Faherty et al. 2016), our spectra yield INT-G classifications. Similarly, SDSS J0443+0002 was classified as a VL-G in Allers \& Liu (2013), but our spectra yields an INT-G classification. These discrepancies may be due to instrumental or reduction differences.
We used BANYAN $\Sigma$ (Gagné et al. 2018) on our low-gravity candidates to assess possible membership in 27 young moving groups, using new kinematic data from Gaia DR2 (Gaia Collaboration et al. 2018), and report the probabilities for young moving group membership in Table 8. The Allers \& Liu (2013) gravity classification scheme is a spectroscopic test for youth, while BANYAN $\Sigma$ uses kinematic information to determine membership in a young moving group. Many of our low-gravity sources are classified as $0 \%$ probability members of any young group by BANYAN $\Sigma$, which implies that these objects might be young and unassociated, field interlopers, or belonging to moving groups other than the 27 known associations included in BANYAN $\Sigma$, possibly as a result of ejection.
Figure 11 shows the distributions of gravity types from our SpeX spectra by spectral type, as classified by field standards. We find the very-low-gravity and intermediategravity fractions for our $25 p c$ sample to be $2.1_{-0.8}^{+0.9} \%$ and $7.8_{-1.5}^{+1.7 \%}$, respectively, with uncertainties based on Poisson statistics.
The spectral types of our low-gravity objects were further refined using VL-G and INT-G spectral standards from Allers \& Liu (2013). The comparison between classifications is shown on Figure 12. The 7 VL-G sources in our sample have much earlier types (by 1-3 subtypes) when classified with a VL-G standard than with a field standard, although this is too small of a sample to precisely quantify the bias. Figure 12 shows the 7 VL-G sources classified with a field standard and VL-G standard.


Figure 12. (Left) Comparison between spectral classification by very low gravity and field gravity standards for the 4 objects classified as having very low gravity by the prescription of Allers \& Liu (2013). Size of markers is proportional to the number of equally-classified sources. The magenta line represents a one-to-one match between classifications. (Right) Same comparison between intermediate gravity and field gravity standards. Objects with an INT-G classification most likely not young, but metal-poor instead, are shown in grey, with a lower proportionality of number of sources to marker size.

For INT-G sources, there is a better correlation but larger scatter ( $\sigma=1.67$ ), particularly among L dwarfs, which are expected to show stronger gravity features even as INT-G. These differences highlight the strong role of gravity-sensitive features and reinforce the importance of comparing low gravity sources to equivalent standards.

### 4.4. Color Outliers

Red and blue $J-K_{S}$ color outliers are empirically-defined subpopulations. Their unusual color is likely a proxy for physical properties such as age, low or high surface gravity, atmospheric cloud content, opacity, and metallicity (Metchev \& Hillenbrand 2006; Burgasser et al. 2008b; Looper et al. 2008; Faherty et al. 2009).

Clouds play a key role in $J-K_{S}$ color evolution from late-M to L-type, as increased opacity originating from condensates and possibly clouds reddens spectral energy distributions (e.g., Tsuji et al. 1996; Lodders \& Fegley 2006). This is intrinsic reddening, as objects in the 25 pc sample should be minimally reddened by interstellar dust. The thickness of clouds may be an independent parameter (e.g., Ackerman \& Marley 2001; Hiranaka et al. 2016), or may correlate with youth (e.g., Faherty et al. 2013b), and/or metallicity ( e.g., Burgasser et al. 2003). Color outliers may also indicate the presence of an unresolved companion (e.g., Bardalez Gagliuffi et al. 2014). Unusually blue objects and subdwarfs have enhanced collision-induced $\mathrm{H}_{2}$ opacity (Saumon et al. 1994; Burgasser et al. 2003) due to their metal-poor atmospheres.

To isolate the color outliers of our sample, we compared their $J-K_{S}$ colors to the average colors and standard deviations as a function of spectral type from Faherty


Figure 13. Sources classified as very-low gravity (VL-G) compared against field (Left) and VL-G (Right) standards. Spectra (black) are consistently redder than their field standards (red). The positive difference between spectra and standards (blue) is clear, emphasizing the need to fit spectra to appropriate gravity standards.


Figure 12. Continued.
et al. (2016), defined over the M7-L8 range. We identified outliers as $2 \sigma$ deviants, shown in Figure 14. From the 387 objects in the $25 p c$ whose adopted spectral type is within M7-L5 $5^{5}$, and with both $J$ and $K_{S}$ photometry ${ }^{6}$, 188 have $J-K$ positive excesses, while 184 have negative color excesses, and 15 do not have a color excess. This even distribution of sources indicates that our sample does not have a NIR color bias, despite widely used 2MASS color selections (Schmidt et al. 2015), for which redder selection criteria were necessary to excise background population.

[^3]The individual outliers are listed in Table 9. In our $25 p c$ sample, 15 objects were found to have unusually blue $J-K_{S}$ colors and 6 have unusually red $J-K_{S}$ colors. In the $1 \sigma$ sample we find 2 more unusually blue objects. Given the numbers of color outliers from the 25 pc sample, we infer fractions of $1.4_{-0.5}^{+0.6} \%$ for red and $3.6_{-0.9}^{+1.0} \%$ for blue M7-L5 dwarfs in the Solar neighborhood (with Poisson uncertainties). Among the 5 red outliers, 2MASS J0355+1133, G 196-3B, and 2MASS J1741-4642 have been reported as young in the literature (Gagné et al. 2015c; Faherty et al. 2016), while LHS2397aA and Kelu-1A are classified as having field gravity, but are also known binaries (Freed et al. 2003; Stumpf et al. 2008). From all the sources with Gaia kinematics, we explored a reduced proper motion diagram and found no potential subdwarfs, i.e. sources with high proper motion, high reduced proper motion, and blue $G-G_{R P}$ colors.
Five blue sources were also classified as INT-G, cementing their status as metalpoor objects (see Section 4.3 and Aganze et al. 2016). Two unusually blue sources, G 203-50B and 2MASS J1721+3344, are also rejected spectral binary candidates, as blue sources tend to be contaminants in the identification of spectral binaries (Bardalez Gagliuffi et al. 2014) ${ }^{7}$.
Additionally, we calibrated our SpeX spectra to 2MASS $J$ and $K_{s}$ magnitudes to find spectrophotometric $J-K_{S}$ colors. These were compared against 2MASS $J-K_{S}$ colors, and found to have a scatter of 0.18 mag . $2 \sigma$ outliers or higher are highlighted in Figure 15, and could be due to intrinsic atmospheric variability (e.g., Radigan et al. 2012). These sources are: LHS 5166B, 2MASS J1152+2438, 2MASS J1200+2048, Kelu-1 A (unusually red), 2MASS J1416+1348A (unusually blue), and 2MASS J1438+6408. Kelu-1 has a variability detection in $410 \AA$ with a peak-to-peak amplitude of $11.9 \pm 0.8 \mathrm{mmag}$ (Clarke et al. 2003), reported before the discovery of its nearby companion (Liu \& Leggett 2005). Khandrika et al. (2013) reported marginal variability in $J$-band for 2MASS J1416+1348A. The remaining outliers have not been targeted in variability surveys.

### 4.5. Spectral Binaries

Spectral binaries of ultracool dwarfs are systems composed of a late-M/L-type primary and a hidden T-dwarf secondary, identifiable only by their peculiar blendedlight spectrum in NIR wavelengths (Cruz et al. 2004; Burgasser et al. 2010; Bardalez Gagliuffi et al. 2014). Identifying these potentially closely-separated binaries allows us to probe the very low mass binary separation distribution at all scales and select potential systems for orbital measurement (see Bardalez Gagliuffi et al. 2015).
We applied the spectral binary technique of Bardalez Gagliuffi et al. (2014) ${ }^{8}$ to the SpeX spectral sample. The spectral binary technique consists of two parts: spectral index selection and binary template fitting, the second of which incurs a hypothe-

[^4]

Figure 14. $J-K$ color outliers per spectral type. $25 p c$ sources with 2MASS photometry are filled grey circles, and $1 \sigma$ sources are open grey circles. Black filled and open circles are sources where the adopted magnitudes are in the MKO system for the $25 p c$ and $1 \sigma$ samples, respectively. Red and blue circles are color outliers for their spectral type, as defined by the color averages of Faherty et al. (2016). The average $J-K_{S}$ color is the dark grey line, and the $2 \sigma$ limits are the red and blue lines. The red outlier at L 2 is the binary Kelu-1A.
sis test to determine whether binary template fits are statistically better fits to a candidate than single templates. Spectral binary candidates are listed in Table 10. Forty-two objects were selected by the index-index parameter spaces as candidates, but rejected by the low confidence from hypothesis testing. Seven objects were rejected despite passing the spectral binary fitting due to their blue colors, as blue objects are known contaminants of the spectral binary technique (Bardalez Gagliuffi et al. 2014).
We found five previously identified and confirmed spectral binaries in our 25 pc sample: 2MASSW J0320284-044636 (Blake et al. 2008; Burgasser et al. 2008a), WISE J072003.20-084651.2 (Burgasser et al. 2015b), 2MASS J08053189 +4812330 (Burgasser 2007b; Burgasser et al. 2016; Dupuy \& Liu 2012), 2MASS J13153094-2649513 (Burgasser et al. 2011b), and 2MASS J22521073-1730134 (Reid et al. 2006). We recover the L4+T3 spectral binary 2MASS J0931+2802 Bardalez Gagliuffi et al. (2014) outside our 25 pc sample. We


Figure 15. Photometric $2 \mathrm{MASS} J-K_{S}$ color from the literature compared to spectrophotometric $J-K_{S}$ color from our SpeX observations. Same color-coding as Figure 14. Objects inside open black circles are $>2 \sigma$ outliers.
identify two previously unreported spectral binary candidates in our spectral sample, both of which lie formally outside our 25 pc distance limit:

2MASS J14111847+2948515. Its spectrum shows a deep $H$-band dip at $1.62 \mu \mathrm{~m}$, and an angled $J$-band peak at $1.25 \mu \mathrm{~m}$, both signs of a hidden T-dwarf companion. The $K_{s}$-band of the object is slightly fainter compared to the binary template, which could be an indication of slightly blue L dwarf, known contaminants to the spectral binary technique. However, the best single fits to its SpeX spectrum fail to reproduce the dip in the $H$-band, and are fainter in $J$ and $K_{s}$-bands in comparison to 2MASS J1411+2948. Its component spectral types are likely to be L4+T4. No parallax has been measured for this source, whose distance would be larger than the estimated spectrophotometric distance of $49 \pm 6 \mathrm{pc}$ if it is a binary.

2MASS J14211873-1618201. The spectrum of this source shows an angled $J$ band peak and a small dip in the $H$-band. Its inferred component spectral types are M8+T5, similar to 2MASS J0320-0446 (Blake et al. 2008; Burgasser et al. 2008a) and 2MASS J0006-0852 (Burgasser et al. 2012), and WISE J0720-0846 (Scholz 2014; Burgasser et al. 2015b). Our strict distance cut left this source outside of the $25 p c$ sample, yet it rests right at the $25 \mathrm{pc} \operatorname{limit}\left(d_{t}=25.15 \pm 0.14 \mathrm{pc}\right.$; Gaia Collaboration et al. 2018).

To calculate the frequency of spectral binary systems, we used the definition of Reipurth \& Zinnecker (1993) (See Section 4.6), where the binary fraction is the number of binaries over the total number of systems. For this calculation, we only consider systems with a measured SpeX spectrum, since otherwise we would not be able to assess spectral binarity ${ }^{9}$. Since 2MASS J1421-1618 lies at our limit distance, we calculate two spectral binary fractions, assuming 24 pc ( 5 spectral binaries $/ 282$ spectra) and $26 \mathrm{pc}\left(6\right.$ spectral binaries $/ 312$ spectra) volumes. The fractions are $1.7_{-0.7}^{+0.9}$ and $1.9_{-0.7}^{+0.8}$ for 24 pc and 26 pc , respectively, or an average of $1.8_{-0.5}^{+0.6} \%$ assuming Poisson errors. This fraction is significantly lower than the total fraction of resolved binaries in the sample $\left(7.5_{-1.4}^{+1.6 \%}\right.$, see Section 4.6$)$, but this is likely because spectral binary systems encompass a specific range of component spectral types to be selected. We analyze the spectral binaries in this sample and their implication for the brown dwarf binary fraction in a companion paper.

### 4.6. Binary systems containing UCDs in the 25 pc volume

Binaries and multiple systems reported in the literature were identified in our sample through crossmatches with the Washington Double Star Catalog ${ }^{10}$ (WDS; Mason et al. 2001), SIMBAD (Wenger et al. 2000), and vlmbinaries.org. Table 11 lists the UCD binaries with primary components between M7-L5 found in our sample previously reported in the literature, as well as UCD companions to main sequence stars. Our $25 p c$ sample contains 410 objects in 393 systems, 341 single systems, 42 binary systems, and 10 triple systems. Only 28 binaries and no triples have a primary with a spectral type M7 or later. Including the $1 \sigma$ sample, we find 4 more binaries and one quintuple system, HD 114762, comprised of $\mathrm{Aa}, \mathrm{Ab}$, and Ac components $\mathrm{F} 9+\mathrm{F} 8+\mathrm{F} 4$ stars, an $11 \pm 0.1 \mathrm{M}_{J}$ (Kane et al. 2011) brown dwarf orbiting the F9 star (Latham et al. 1989), and an M6:: dwarf as the B component 130 AU away from the F triple system (Patience et al. 2002).
We calculate several statistics to represent the multiplicity of the sample: the multiplicity fraction, which provides the probability that a given source is a multiple system; the companion star fraction, which is the probability for an object to be in a multiple system; the pairing factor, which is the mean number of companions per primary; and the companion frequency that indicates the mean number of companions per object. These equations are defined and explained in detail in Reipurth \& Zinnecker (1993) and Goodwin et al. (2004). Since we have no triple systems with primaries M7 or later, our multiplicity fraction is effectively a binary fraction. We determine the binary fraction of the $25 p c$ sample to be $7.5_{-1.4}^{+1.6} \%$, including both spectral binaries and RV variable systems. The companion star fraction for this sample is $14.1_{-1.9}^{+2.1} \%$, the pairing factor is $1 \pm 0.3$, since there are no triple systems with primaries

[^5]

Figure 16. Best fit templates to spectral binaries with M7-L5 primaries with a confidence $>90 \%$. 2MASSW J0320-0446, WISE J0720-0846, 2MASS J0805+4812, 2MASS J1315-2649, 2MASS J2252-1730 are all within 25 pc , whereas 2MASS J0931+2802, 2MASS J1411+2948, and 2MASS J1421-1618 are outside 25 pc . All the spectral binary candidates in the 25 pc sample have already been confirmed as true binaries.
$\geq \mathrm{M} 7$, and the companion frequency is $0.14 \pm 0.02$ companions per object (following the definition of Goodwin et al. 2004).
Figure 18 shows the cumulative binary fraction as a function of distance. Out to a distance of 9 pc , the binary fraction oscillates around $13-25 \%$, and at larger distances it begins to drop and settle around $\sim 7 \%$. The resolved UCD binary fraction has been thoroughly studied (e.g., Bouy et al. 2003; Burgasser 2007a) leading to $\sim 10-20 \%$ for separations $>1 \mathrm{AU}$, while sub-AU systems comprise $1-4 \%$ of the population (Blake et al. 2010; Allen 2007). However, this is the first time the UCD binary fraction has been calculated in a volume-limited sample ${ }^{11}$, and as seen in Figure 17, there may be a significant fraction of overluminous binaries that have not been confirmed by high resolution imaging, astrometry, or RV monitoring yet. Additionally, in the previous Section we found that 5 out of the 25 binaries within 25 pc are spectral binaries. Since spectral binaries require specific combinations of spectral types to be identified as such, we do not expect them to dominate the binary detection yield. Yet in this study, $\sim 20 \%$ of our binaries are spectral binaries, supporting our hypothesis that the population of binaries in the 25 pc sample literature is incomplete. The incompleteness of binaries is shown in Figure 19 as a cumulative histogram over distance which flattens beyond 20 pc compared to the general 25 pc sample. Fitting curves to the $5-10 \mathrm{pc}, 5-15 \mathrm{pc}$, and $5-20 \mathrm{pc}$ regions, and extrapolating to 25 pc , we estimate a large binary incompleteness of $76 \%, 65 \%$, or $56 \%$, respectively.

## 5. SELECTION AND LUMINOSITY FUNCTIONS

The luminosity function measures the number density of sources as a function of luminosity, or equivalently, absolute magnitude, temperature, or spectral type. For main sequence stars there is generally a one-to-one mapping between luminosity and mass functions; for UCDs, because brown dwarfs cool as they age, there is not a one-to-one mapping between a brown dwarf luminosity function and a brown dwarf mass function. However, the luminosity function is the initial crucial measurement towards a fundamental understanding of low mass star and brown dwarf formation through a field present-day mass function. The luminosity function of UCDs covering the M7-L5 spectral type range, has been most notably measured by Cruz et al. (2007), hence here we provide an updated reevaluation.

### 5.1. Area Coverage

The area covered by our spectral survey is limited by the declinations accessible from IRTF, roughly $-50^{\circ}<\delta<+67^{\circ}$. Additionally, our survey suffers from an inherent incompleteness of sources in the Galactic plane. We therefore restrict our analysis to the area of sky outside $-15^{\circ}<b<+15^{\circ}$ and within $-50^{\circ}<\delta<+67^{\circ}$ which corresponds to an area of $26,051.54 \mathrm{deg}^{2}$, or $63.2 \%$ of the sky.

[^6]

Figure 17. Adopted literature spectral type vs. 2MASS $H$ absolute magnitude for our extended $1 \sigma$ sample highlighting the UCD binary systems reported in the literature. Most binaries in this plot have resolved absolute magnitudes, and thus their individual components look normal. The two L4 dwarfs well above the sequence are HD 130948B and C are companions to the young F9 variable star (Goto et al. 2002), known to be overluminous on color-magnitude diagrams (Faherty et al. 2016).

Bright stars reduce the total available sky area by obscuring patches of sky where a UCD could otherwise be found. To account for this effect, we drew one million sources from our sample and reassigned them to random coordinates within our observable area. This list was crossmatched with the 2MASS catalog using TOPCAT with a 5.10 radius, returning 22,126 matches. Of these, 2,345 stars were as bright or brighter than the simulated input targets within the search radius, thus effectively obscuring nearby UCD. Accounting for this effect reduces the effective observable sky by $0.15 \%$ to $25990.45 \mathrm{deg}^{2}$. While we note that $0.5 \%$ of the sky is obscured by bright stars and excluded from the 2MASS survey ${ }^{12}$, we do not take it into account in our calculations, since our sources also come from optical and mid-infrared surveys.

### 5.2. Volume Completeness

A volume within 25 pc around the Sun is well embedded within the thin disk of the Galaxy (scale height $\sim 300$ pc; Kent et al. 1991; Bochanski et al. 2010), and therefore should be relatively uniform in density. Assuming a uniform distribution of sources,

[^7]

Figure 18. Cumulative binary fraction as a function of distance.


Figure 19. Cumulative histogram of sources per unit adopted distance. The full $25 p c$ sample is shown in blue, and the binaries with primaries M7 or later are shown in green. Three curve fits are shown for each histogram, assuming completeness between $5-10 \mathrm{pc}$ (red), $5-15 \mathrm{pc}$ (orange), and $5-20 \mathrm{pc}$ (yellow).

Table 12. Estimated volume completeness.

| Fit Range (pc) | Predicted Numbers |  | Completeness |  |
| :---: | :---: | :---: | :---: | :---: |
|  | Trigonometric | Adopted Distance | Trigonometric | Adopted Distance |
| 25 pc sample $(N=410)$ |  |  |  |  |
| 5-10 | 592 | 592 | $64_{-7}^{+8 \%}$ | $69_{-8}^{+9} \%$ |
| 5-15 | 552 | 583 | $69_{-8}^{+9} \%$ | $70_{-8}^{+9} \%$ |
| 5-20 | 484 | 511 | $79_{-8}^{+9} \%$ | $80_{-8}^{+9} \%$ |
| 25 pc Mdwarfs ( $N=223$ ) |  |  |  |  |
| 5-10 | $\cdots$ | 509 | $\ldots$ | $44_{-6}^{+7} \%$ |
| 5-15 | $\ldots$ | 357 | $\ldots$ | $62_{-7}^{+8 \%}$ |
| 5-20 | $\ldots$ | 283 | $\ldots$ | $78_{-8}^{+9} \%$ |
| $25 p c L \text { dwarfs }(N=187)$ |  |  |  |  |
| $5-10$ | $\cdots$ | 83 | $\ldots$ | $226_{-15}^{+16} \%$ |
| 5-15 | $\cdots$ | 226 | $\ldots$ | $83_{-9}^{+10} \%$ |
| 5-20 | $\ldots$ | 228 | $\ldots$ | $82_{-9}^{+10} \%$ |

the cumulative number of objects should increase with distance following an $r^{3}$ relation. We estimate our volume completeness in trigonometric, spectrophotometric, and adopted distances by fitting power law curves to the cumulative distribution of sources between $5-10 \mathrm{pc}, 5-15 \mathrm{pc}$ and $5-20 \mathrm{pc}$, assuming completeness in those ranges, considering Poisson uncertainties (Figure 21), and extrapolating expected numbers to 25 pc . The ratio of number of objects in our sample to expected number is used to estimate our completeness. These values are summarized in Table 12.
The completeness of late-M dwarfs is lower than that of L dwarfs. Using the 5-15 pc fit, which is a good trade-off between completeness and sample size, our sample contains $62_{-7}^{+8} \%$ of the late-M dwarfs within 25 pc , and $83_{-9}^{+10} \%$ of L dwarfs. Late-M dwarfs may have been missed in previous surveys, due to color-selection biases designed to exclude more numerous and brighter mid-M dwarfs, as indicated by Schmidt et al. (2015). While most L dwarfs in the Solar neighborhood have already been identified in previous searches, many may be hidden in crowded areas like the Galactic plane (e.g. the L8 dwarf recently identified at 11 pc; Faherty et al. 2018). From the trigonometric distances, we estimate our total sample completeness to be between $64-79 \%$. Including spectrophotometric distances when parallaxes are not available, the sample completeness is between $69-80 \%$, but we adopt the value for the $5-15 \mathrm{pc}$ fit, $70_{-8}^{+9} \%$. This completeness value is used in Section 5.5 to scale the corrected number of sources in the 25 pc volume when measuring the luminosity function (see Equation 4). We expect most of the incompleteness to come from missing sources beyond 20 pc , as seen in Figure 20, possibly including sources in the Galactic plane, the


Figure 20. Distributions of trigonometric (top), spectrophotometric (middle) and adopted distances (bottom). Solid line is an $r^{2}$ fit normalized at the 25 pc bin. Note the drop off in the largest distance bins, which reflects incompleteness likely due to brightness limits and selection biases.
southern hemisphere, or UCD candidates recently identified in Reylé (2018) in need of spectroscopic validation.
Additionally, we estimate $\left\langle V / V_{\max }\right\rangle$ averages suggested by Schmidt (1968) to evaluate the homogeneous spatial distribution of our sample. $\left\langle V / V_{\max }\right\rangle$ measures the


Figure 21. Cumulative distance histograms for trigonometric, spectrophotometric, and adopted distances. The red, orange and yellow curves show the cube fit to the histograms in blue up to $10 \mathrm{pc}, 15 \mathrm{pc}$ and 20 pc , including their Poisson uncertainties.


Figure 22. Average $\left\langle V / V_{\max }\right\rangle$ values for our $25 p c$ sample, and also for subsamples of M and L dwarf with uncertainties calculated as described in Kirkpatrick et al. (2019). The numbers indicate the cumulative number of sources counted up to that distance. We used the adopted distances for this calculation.
number of sources in each half of a given volume, approaching 0.5 for a uniformly distributed sample with equal counts on each half-volume. Figure 22 shows the distribution of $\left\langle V / V_{\max }\right\rangle$ values. Uncertainties are calculated as $0.5-\frac{n / 2-a_{\max }}{n}$, where $a_{\max }$ is the distance at which the value of $\left\langle V / V_{\max }\right\rangle$ last equals 0.68 ( 4 pc for the full sample, and M dwarfs only, and 8 pc for L dwarfs), corresponding to one Gaussian standard deviation. For M dwarfs, the largest distance at which $\left\langle V / V_{\max }\right\rangle$ approximates 0.5 is 13 pc , suggesting incompleteness of $\mathrm{M} 7-\mathrm{M} 9.5$ dwarfs at larger distances. Conversely, L dwarfs have $\left\langle V / V_{\max }\right\rangle$ consistent with 0.5 up until 25 pc , indicating a homogeneous distribution of L0-L5 dwarfs in our sample.

### 5.3. Sample Simulation

Compiling a sample of objects starting from past literature compilations leads to a complicated selection function. Rather than determining the selection function of each selection process separately, we simulate a sample of UCDs in a volume larger
than 25 pc , including unresolved binaries, and apply selections based on our spectral type and distance cuts, from both parallaxes and spectrophotometric estimates. This procedure aims to measure systematic effects in the sample construction.
We simulate $10^{6}$ UCDs, assigning distances drawn from a uniform spatial distribution out to 50 pc . We calculate "true" parallaxes by inverting the distances. An underlying spectral type distribution was derived by population simulations (c.f. Burgasser 2004) using the Chabrier (2005) IMF, a uniform age distribution, the Burrows et al. (2001) evolutionary models, and the effective temperature to spectral type empirical relations from Pecaut \& Mamajek (2013), which cover the full stellar and substellar spectral type range from O3 to Y2. From this distribution, $10^{6}$ "true" spectral types between M5-L7 were randomly drawn and assigned to our simulated UCD sources.
We calculate absolute magnitudes empirically, from the simulated spectral types, using the following linear relations:

$$
\begin{align*}
M_{J} & =0.37 \times S p T+4.29, r m s=0.35  \tag{1}\\
M_{H} & =0.32 \times S p T+4.61, r m s=0.29  \tag{2}\\
M_{K_{S}} & =0.29 \times S p T+4.67, r m s=0.29 \tag{3}
\end{align*}
$$

determined from a subset of 230 single M7-L5 dwarfs with parallax measurements, 2MASS magnitudes, not classified as VL-G, INT-G, unusually red, or unusually blue from our $25 p c$ sample. The scatter in these relations is slightly smaller than in other empirical relations covering broader spectral type ranges (e.g. Dupuy \& Liu 2012; $\sigma=$ $0.4 \mathrm{mag})$. To simulate the intrinsic brightness distribution of the population, we add offsets to these empirical absolute magnitudes, drawn from a Gaussian distribution centered at zero and scaled by the scatter in the empirical relations.
Parallax-limited and magnitude-limited samples are subject to different biases affecting the total number of included sample members. The Lutz-Kelker bias affects parallax-limited samples by allowing objects from outside a distance limit into the observed volume (Lutz \& Kelker 1973). For an observed parallax $\pi_{0}$, there is a range of true parallaxes $\pi_{0} \pm \delta \pi$ for normally-distributed measurement uncertainties. Assuming a uniform number density of stars, the number of objects per parallax bin will be proportional to $N_{*} \propto 1 / \pi^{4}$, implying that the number of stars increases as the parallax decreases, i.e. there are more objects in the volume outside a given distance than within. Subsequently, this means that more stars will appear to have smaller true parallaxes than their observed parallaxes, and that the average distance for sample members will be farther than the distance limit (Lutz \& Kelker 1973).
In magnitude-limited samples, intrinsically brighter sources (i.e. on the high end of the absolute magnitude distribution) and unresolved binaries will be selected in larger numbers than intrinsically fainter sources, again due to the larger volume sampled by the brighter sources, an effect known as the Malmquist bias (Malmquist 1922). Depending on the relative uncertainty in distance and magnitude measurements, and


Figure 23. True and observed distances from our simulation. The blue histogram shows the distribution of true distances, following an $r^{3}$ shape, defined up to 50 pc . The green histogram shows the distribution of observed trigonometric distances, measured after a Gaussian uncertainty was added to the true parallax, with the scale of the distribution emerging from our sample's parallax uncertainty distribution. The orange histogram shows the distribution of the observed spectrophotometric distances, measured with spectral types, apparent magnitudes, and empirical absolute magnitude relations. This distribution is affected by the Malmquist bias, including sources located farther than the volume limit.
intrinsic scatter in the population, the effect from the Malmquist bias can be significantly larger than that of the Lutz-Kelker bias. Since our sample is defined by both trigonometric and spectrophotometric distances, both effects are significant in our calculations, although the Lutz-Kelker bias plays a more significant role given the large number of parallaxes in our sample ( $93 \%$ of the sample).
We model the Lutz-Kelker bias in our simulation by adding an uncertainty offset to our parallax measurements drawn from the uncertainty distribution of our observed parallaxes (see Figure 23). We excluded 2246 simulated sources with observed negative parallaxes. We account for unresolved binarity by adding a magnitude offset to $20 \%$ of stars in our simulated sample, the fraction based on estimates of the underlying UCD binary fraction (Bouy et al. 2003; Gizis et al. 2003; Burgasser et al. 2007c). We randomly assigned mass ratios from a power law distribution ( $\propto q^{1.8}$; Allen 2007) to compute secondary masses. Effective temperatures, spectral types, and absolute
magnitudes for the secondaries were obtained in the same manner as the primaries, resulting in combined system absolute magnitudes. Magnitude offsets ranged between $\Delta m=0-0.75 \mathrm{mag}^{13}$. For simplicity, we assumed that the addition of flux to the simulated binaries does not affect the spectral type classification, which is likely true for late-M and early-L dwarf primaries but not necessarily for late-L+T dwarf systems (Cruz et al. 2004; Burgasser et al. 2010). The addition of magnitude offsets for simulated binaries, and uncertainties to the true absolute magnitudes for all simulated sources models the effects from the Malmquist bias.
To model observed spectral types, offsets were drawn from a Gaussian distribution with a standard deviation equal to 0.95 subtypes (see Section 2.2.1). Apparent magnitudes were assigned based on the distance modulus and absolute magnitudes, adding an observational uncertainty drawn from a Gaussian distribution with a standard deviation following the same photometric error distribution from our literature sample. Observed parallaxes were modeled by adding a Gaussian uncertainty to the true parallaxes.

### 5.4. Selection Function

We quantify four selection functions, one for trigonometric and one for spectrophotometric distance selections as functions of spectral type and absolute magnitude. First, we define our "intrinsic sample" as those simulated sources whose true distances are $d \leq 25 p c$. We define "observed samples" by requiring observed trigonometric or observed spectrophotometric distances $d \leq 25 p c$. In each sample, we select objects with an observed spectral type between M7-L5, and organize them according to their true spectral type, given that we are concerned with modeling our observations, yet aware that the true subtype may be different from the observed one. For the selection function by absolute magnitudes, we organized this selected sample in bins of 0.5 mag observed absolute magnitudes. Our trigonometric and spectrophotometric selection functions are the ratio of objects selected by observations over the number of objects selected by their true parameters. These selection functions are summarized in Tables 13 and 14 and illustrated in Figure 24.
Our trigonometric selection function is relatively high ( $92-98 \%$ ) for the central part of the M7-L5 spectral type range, except at the edges where the selection rate drops to $71 \%$ for M7 and $69 \%$ for L5. The spectrophotometric selection function runs parallel to the trigonometric one, following a similar shape at a lower rate, $77-82 \%$ for M8-L4 and dropping to $65 \%$ for M7 and $53 \%$ for L5. The trigonometric selection function based on $J$-band absolute magnitudes steadily increases from $66 \%$ at 10.75 mag (roughly equivalent to M7) to $96 \%$ at 12.25 mag , then dropping to $92 \%$ and $76 \%$ in the subsequent fainter bins. The corresponding spectrophotometric

[^8]

Figure 24. Selection functions from trigonometric (blue) and spectrophotometric (green) distance cuts as a function of spectral type (Left) and absolute magnitude in $J$-band (Right).
selection function follows a similar shape at a lower rate as well, starting at $61 \%$ for 10.75 mag , reaching a peak of $80 \%$ at 11.25 mag , and decreasing towards fainter magnitudes down to $62 \%$ at 13.25 mag (roughly equivalent to L4). These results are presented in Tables 13 and 14. As expected, the edges of our sample suffer from higher contamination than the bulk of it. Contamination from bright sources that do not belong in the $25 p c \mathrm{M} 7$-L5 sample is most noticeable in the low spectrophotometric selection rate of the brightest absolute magnitude bins.
We also calculated the proportion of true negatives and false positives per spectral subtype and absolute magnitude bin. True negatives are true M7-L5 dwarfs with true distances within 25 pc which are not selected by observed trigonometric or spectrophotometric cuts at 25 pc , i.e. true sources missed by our selections. The true negative fraction is $2 \%$ for any spectral subtype using a parallax cut, except for L0 where the missed fraction is $3 \%$. However, for a spectrophotometric cut, the true negative fraction rises with spectral type from $8 \%$ to a maximum of $21 \%$ at L 2 , then decreasing again to $17 \%$ at L5. The true negative fraction by absolute magnitude bins is also $2 \%$ for trigonometric cuts and $7-22 \%$ for spectrophotometric cuts, with the maximum at 12.25 mag . False positives are contaminants, either sources outside the M7-L5 spectral range within 25 pc or true M7-L5 dwarfs outside 25 pc selected by observations. The false positive fraction for M7-L5 dwarfs varied between $6-9 \%$ for spectral type bins selected by parallax, and $10-31 \%$ if selected by spectrophotometric distance. The false positive rates by absolute magnitude bins are $2-8 \%$ for trigonometric selections and $14-30 \%$ for spectrophotometric selections. Thus, the true negative and false positive rates for trigonometric and spectrophotometric selections are comparable across spectral type and absolute magnitude bins. Tables 15 and 16 show the fraction of simulated sources outside 25 pc with a given spectral type and their observed spectral type as selected by observed trigonometric and spectrophotometric distances. For example, on Table 15, $4 \%$ of observed M8 dwarfs are actually M9 dwarfs outside of 25 pc . Overall, it appears that parallax selections are more resistant to scattering of earlier type objects. Diagonal elements indicate objects of matching true and observed spectral subtype, outside of 25 pc but falsely selected

Table 15. False positive fractions per spectral subtypes for observed trigonometric selection.

Observed Spectral Type


Table 16. False positive fractions per spectral subtypes for observed spectrophotometric selection.

Observed Spectral Type

|  |  | M7 | M8 | M9 | L0 | L1 | L2 | L3 | L4 | L5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | M5 | 0.25 | 0.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|  | M6 | 0.42 | 0.17 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|  | M7 | 0.08 | 0.20 | 0.06 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
|  | M8 | 0.01 | 0.10 | 0.08 | 0.03 | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 |
|  | M9 | 0.00 | 0.02 | 0.08 | 0.11 | 0.08 | 0.01 | 0.00 | 0.00 | 0.00 |
|  | L0 | 0.00 | 0.00 | 0.01 | 0.06 | 0.16 | 0.10 | 0.01 | 0.00 | 0.0 |
|  | L1 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07 | 0.15 | 0.06 | 0.01 | 0.0 |
|  | L2 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.06 | 0.11 | 0.06 | 0.01 |
|  | L3 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.08 | 0.14 | 0.0 |
|  | L4 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.09 | 0.14 |
|  | L5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.09 |
|  | L6 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |

to be within the volume, possibly very close to the 25 pc limit (Lutz-Kelker bias) or brighter than most other objects of the same subtype (Malmquist bias).

### 5.5. Luminosity Function

### 5.5.1. Luminosity Function with respect to Spectral Types

Luminosity functions are a result of the underlying mass function and stellar birth rates. Calculating a luminosity function of UCDs in the 25 pc volume around the Sun is the first step towards building a field IMF across the stellar/substellar boundary. To measure our luminosity function with respect to spectral types, we prioritize literature optical, SpeX, and literature NIR spectral types in that order, since optical classifications are more precise than NIR ones ${ }^{14}$. Since our study is concerned with the areas accessible by SpeX and outside of $\pm 15^{\circ}$ from the galactic plane, we excluded literature sources outside of these areas, reducing our sample to 331 sources. However, 4 sources do not have unresolved $J$-band magnitude (see Section 2.2), hence our effective sample includes 327 objects. From these, we find 306 sources in our 25 pc sample with prioritized spectral types within M7-L5 within declinations accessible by SpeX $\left(-50^{\circ} \leq \delta \leq+67^{\circ}\right)$, and outside galactic latitudes $\pm 15^{\circ}$ from the galactic plane.
To estimate the expected total number of objects in our $25 p c$ sample per spectral type bin, we scale our counts by our selection functions and completeness. We proportionally apply the trigonometric and spectrophotometric selection functions ( $S F_{p l x}$ and $S F_{p h o t}$, respectively) to each spectral type bin by splitting our counts, $N_{b i n}=N_{p l x}+N_{p h o t}$ according to their type of adopted distance (trigonometric or spectrophotometric), and then scaled by the completeness percentage for the $5-15 \mathrm{pc}$ fit from Section 5.2, i.e.,

$$
\begin{equation*}
N_{\text {corrected }}=\left(\frac{N_{p l x}}{S F_{p l x}}+\frac{N_{\text {phot }}}{S F_{p h o t}}\right) \cdot\left(\frac{1}{\text { completeness }}\right) \tag{4}
\end{equation*}
$$

These corrected counts were divided over the volume estimated in Section 5.1 to obtain our luminosity function with respect to spectral types. Our number densities are listed in Table 17, and shown in Figure 27 with and without selection function and completeness corrections.
Figure 28 compares our number densities to other UCD field studies, including the 20 pc samples of Cruz et al. (2007) and Reid et al. (2008), and the 8 pc sample of Kirkpatrick et al. (2012), extended into the substellar regime. Our number densities areconsistently higher than those of Reid et al. (2008), particularly on the M dwarfs, although their study does not claim completeness on spectral types earlier than L0. Except for the M7 and L5 edges, our number densities are comparable within $2 \sigma$ to those of Cruz et al. (2007) for all spectral types, albeit they claim only a lower limit on L dwarf densities. However, out densities are on average slightly higher than those of Cruz et al. (2007), except for the M8 bin. Cruz et al. (2007) found 99 objects between M7-L8 in 20 pc with a sky coverage of $36 \%$, which scales to 244 sources at

[^9]

Figure 27. Raw and selection-function corrected number densities per subtype for our $25 p c$ sample.

25 pc for our sky coverage of $63.5 \%$ and $69 \%$ completeness, yet we count 327 sources within a shorter spectral type range. This $\geq 34 \%$ difference can be attributed to new discoveries, improvements in source color selection (i.e. Schmidt et al. 2015), and broader availability of parallaxes. The 8 pc sample of Kirkpatrick et al. (2012) is sparse on the L dwarf regime, with only one L5 within that volume, and while they include $11 \mathrm{M} 7-\mathrm{M} 9.5$ dwarfs, they claim no completeness on the M dwarf range. We identify $19 \mathrm{M} 7-\mathrm{M} 9.5$ sources in the literature within the 8 pc volume and therefore have larger number densities than Kirkpatrick et al. (2012), including a few new discoveries since then.
Table 17 also shows number densities for the M7-M9.5, L0-L5, and M7-L5 ranges. We find that the late-M dwarf raw number density agrees within $20 \%$ of Cruz et al. (2007), but our number density corrected by the selection function and incompleteness is $\sim 45 \%$ higher, largely driven by the latter. Our L dwarf densities cover a smaller spectral type range than Cruz et al. (2007), and raw and corrected densities follow the same proportions as for the M-dwarf regime. Taking the full range of M7-L5 spectral subtypes, we find $40 \%$ higher densities than Cruz et al. (2007), with a raw density of $(7.3 \pm 0.4) \times 10^{-3} p c^{-3}$ and a corrected density of $(12.6 \pm 0.6) \times 10^{-3} p c^{-3}$. Our volume density implies that the total number of M7-L5 dwarfs within the 25 pc volume could be as high as $\sim 820$.

### 5.5.2. Luminosity Function with respect to Absolute Magnitudes



Figure 28. Number densities per subtype for the surveys of Cruz et al. (2007), Reid et al. (2008), Kirkpatrick et al. (2012), and this study.

We follow a similar procedure to calculate the luminosity function with respect to absolute magnitude in $J$. We use the subsample of 306 sources described in Section 5.5.1, yet we organize it in absolute magnitude bins. Our luminosity function is described in Table 18. Figure 25 shows the resulting luminosity function, including Poisson error bars. Using the Filippazzo et al. (2015) empirical relations, we determine that the 10.3-14.2 mag range in $J$-band encompasses the M7-L5 dwarf range, including the $1 \sigma(0.4 \mathrm{mag})$ relation uncertainties. Our luminosity function peaks at the $10.25-10.75 \mathrm{mag}$ bin, which roughly corresponds to the peak at the M7-M8 spectral class, matching our spectral type distribution from Figure 8. Our luminosity function then tapers off to a plateau after the 12.25mag bin.

Our luminosity function follows from the faint end of the Reid et al. (2003a) luminosity function, as seen in Figure 26, matching it well within uncertainties. Throughout the $10.75-13.75 \mathrm{mag}$ range, our luminosity function resembles the downward slope of the Cruz et al. (2007) corresponding function.

### 5.6. Towards building a substellar IMF

The IMF is a direct outcome of the formation process. Measurements of the IMF across the hydrogen burning limit have revealed that brown dwarfs are not a significant contributor to dark matter (Reid et al. 2003a), yet brown dwarfs could be as abundant as stars (e.g., Mužić et al. 2017). The efficiency of the star formation process at low masses, and the minimum mass allowed by the gravitational fragmen-


Figure 25. Measured luminosity function for M7-L5 ultracool dwarfs with Poisson error bars, corrected by the selection function and completeness. We do not claim completeness at magnitudes brighter than the dashed line.


Figure 26. Luminosity functions for ultracool dwarfs according to our study (dark blue), Reid et al. (2003a) (orange), Bochanski et al. (2010) (pink), Cruz et al. (2007) (green), and Reylé et al. (2010) (yellow).
tation of a molecular cloud can be determined by quantifying the IMF. Constraining the IMF at low masses is a necessary step towards determining the prevalence of different brown dwarf formation mechanisms (Reipurth \& Clarke 2001; Padoan \& Nordlund 2002; Whitworth \& Zinnecker 2004; Stamatellos et al. 2007), and whether they depend on environmental conditions or not (e.g., Whitworth et al. 2007; Bate 2019).

Mass functions are typically derived from luminosity functions, a straightforward operation for main sequence stars. For ultracool dwarfs, however, the mapping is no longer one-to-one due to the long lifetimes of very low mass stars and the mass-age-luminosity degeneracy of brown dwarfs. Substellar IMFs can be directly measured in clusters and young moving groups where age is known for all members (e.g., Taurus, Luhman 2000; TW Hydrae, Looper 2011; Gagné et al. 2017). Measuring the substellar field IMF requires assumptions about the age distribution (Burgasser 2004). Nevertheless, the field luminosity function presented here is an important step towards measuring an accurate mass function across the hydrogen-burning limit in the field, and the overall formation history and evolution of UCDs in the Milky Way.
This sample also has the potential to reveal ultracool dwarf hosts to habitable zone terrestrial planets like those orbiting TRAPPIST-1 (Gillon et al. 2016, 2017). Currently, this source is the only example of a planetary system around an ultracool dwarf, and the only planetary system known with 3 potentially habitable terrestrial worlds. With this volume-limited ultracool sample, planetary population studies around the lowest mass stars and brown dwarfs can be approached in a systematic way (e.g., SPECULOOS, Delrez et al. 2018).

## 6. SUMMARY

We have compiled a volume-limited sample of M7-L5 ultracool dwarfs out to 25 pc , with targets originating from various surveys in the literature. The variety of selection criteria that goes into defining these surveys makes for a potentially complicated selection function with biases difficult to quantify. Nevertheless, we estimate the compiled sample to be $70_{-8}^{+9} \%$ complete to 25 pc , and highly complete for L dwarfs.
The main results of this study are summarized as follows:

1. We find 410 UCDs in 394 systems in the 25 pc volume surrounding the Sun, with 60 more sources in the $1 \sigma$ periphery of 25 pc . Thanks to Gaia DR2, our sample is largely volume-limited, with $93 \%$ of the sample having parallaxes.
2. We obtained low-resolution, NIR, SpeX prism spectra for $89 \%$ of the observable sample, and uniformly classified them with spectral and gravity standards.
3. We identify 7 very low gravity sources and 26 intermediate gravity sources in our $25 p c$ spectral sample, corresponding to fractions of $2.1_{-0.8}^{+0.9 \%}$ and $7.8_{-1.5}^{+1.7 \%}$, respectively. One new very low gravity source, 2MASS J1739+2454, is identified in this study. Thirteen new intermediate gravity sources are also reported.

Eleven other sources identified as having intermediate gravity also have blue $J-K_{S}$ colors, suggesting instead low metallicity effects.
4. We calculate $J-K_{S}$ infrared colors and use them to determine the color distribution of our sample, and identify the red and blue color outlier fractions of $1.4_{-0.5}^{+0.6} \%$ for red and and $3.6_{-0.9}^{+1.0 \%}$ for blue, from 5 and 15 red and blue color outliers, respectively. We do not identify a color bias in our sample given approximately equal numbers of sources with positive and negative $J-K_{S}$ color excesses.
5. We identify 5 previously confirmed spectral binaries in the 25 pc volume, and 2 new additional candidates outside the 25 pc volume. The resulting spectral binary fraction is $1.8_{-0.5}^{+0.6 \%}$. In a future paper, we will explore the significance of this fraction with respect to the true ultracool binary fraction of M7-L5 dwarfs.
6. We also identified 25 resolved binaries and 13 ultracool companions to main sequence stars in the literature. The literature binary fraction from this sample is $7.5_{-1.4}^{+1.6 \%}$. We expect that the identification of overluminous binaries and potentially hidden low gravity and small separation systems will increase this fraction closer to an ultracool resolved binary fraction of $10-20 \%$.
7. Our sample is $70_{-8}^{+9} \%$ complete for all sources, mostly incomplete for late-M dwarfs. The completeness for M7-M9.5 is $62_{-7}^{+8} \%$, while for L0-L5 dwarfs it is $83_{-10}^{+11} \%$.
8. We have produced a $J$-band luminosity function for the 25 pc sample that closely agrees with previous work but with smaller statistical uncertainties.
9. We have calculated space densities per subtype and find a $40 \%$ increase in our densities compared to Cruz et al. (2007). Our predicted number density of $\mathrm{M} 7-\mathrm{L} 5$ dwarfs is $(12.6 \pm 0.6) \times 10^{-3} p c^{-3}$, or $\sim 820$ objects within 25 pc .

This homogeneous, volume-limited sample of ultracool dwarfs, with uniformly determined spectral types, measured distances, and masses that span the hydrogen burning limit, has important potential for future statistical studies of UCDs, such as the incidence of magnetic activity, binarity, color outliers, young sources, low metallicity sources, and searches for planetary systems around UCDs.

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Software: Astropy (Astropy Collaboration et al. 2013), Astroquery (Ginsburg et al. 2018), BANYAN $\Sigma$ (Gagné et al. 2018), Matplotlib (Hunter 2007), Pandas (McKinney 2013), SpeXtool (Cushing et al. 2004), SpeX Prism Library Analysis Toolkit (SPLAT; Burgasser \& Splat Development Team 2017), Tool for OPerations on Catalogues and Tables (TOPCAT; Taylor 2005).

## Facilities: IRTF (SpeX)

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Table 1. Literature sources providing UCD targets to the final sample

| Reference | Survey/Compilation | UCD Targets |
| :---: | :---: | :---: |
| Burgasser (2014) | SpeX Prism Library (SPL) | 510 |
| Best et al. (2015) | L/T Transition Dwarfs from Pan-STARRS1 | 5 |
| Best et al. (2018) | MLT Dwarfs from Pan-STARRS1 | 1041 |
| Boyd et al. (2011) | The Solar Neighborhood XXVIII | 119 |
| Caballero et al. (2016) | Carmencita, CARMENES Input Catalogue | 63 |
| Castro et al. (2013) | High Proper Motion L Dwarfs | 29 |
| Chiu et al. (2006) | SDSS L and T Dwarfs | 71 |
| Clarke et al. (2010) | Southern ultracool dwarfs in young moving groups | 98 |
| Crifo et al. (2005) | Spectroscopy of DENIS nearby candidates | 19 |
| Cruz et al. (2003) | Meeting the Cool Neighbors V | 304 |
| Deacon et al. (2009) | UKIDSS-2MASS Proper Motion Survey | 233 |
| Deacon et al. (2014) | Wide UCD Companions in Pan-STARRS I | 98 |
| Dhital et al. (2015) | SLoWPoKES-II | 44 |
| Dieterich et al. (2014) | The Solar Neighborhood XXXII | 63 |
| Dittmann et al. (2016) | MEarth Photometry Calibration | 90 |
| Folkes et al. (2012) | Ultra-cool dwarfs at low Galactic latitudes | 90 |
| Gagné et al. (2015c) | List of M6-M9.5 Dwarfs | 1570 |
| Gagné et al. (2015c) | List of All Ultracool Dwarfs | 335 |
| Gaidos et al. (2014) | CONCH-SHELL | 23 |
| Gálvez-Ortiz et al. (2017) | Wide VLM binary systems using Virtual Observatory tools | 46 |
| Hawley et al. (1996) | Palomar/MSU Nearby-Star Spectroscopic Survey II (PMSU) | 12 |
| Hawley et al. (2002) | M, L, and T Dwarfs in SDSS | 25 |
| Kirkpatrick et al. (2010) | 2MASS Proper Motion Survey | 193 |
| Kirkpatrick et al. (2011) | First Hundred Brown Dwarfs Discovered by WISE | 93 |
| Kirkpatrick et al. (2016) | AllWISE Motion Survey | 63 |
| Knapp et al. (2004) | NIR Photometry and Spectroscopy of L and T Dwarfs | 27 |
| Lépine et al. (2013) | Brightest ( $J<9)$ M Dwarfs in the Northern Sky | 56 |
| Lépine \& Shara (2005) | LSPM North | 4042 |
| Lépine \& Gaidos (2011) | Bright M Dwarfs | 137 |
| Luhman \& Sheppard (2014) | WISE High Proper Motion Objects | 41 |
| Lodieu et al. (2005) | Red high proper motion objects in the Southern Sky | 55 |
| Lodieu et al. (2017) | Ultracool subdwarfs with Virtual Observatory tools | 3 |
| Luhman \& Sheppard (2014) | High Proper Motion Objects from WISE | 239 |
| Mace et al. (2013) | WISE T Dwarfs | 91 |
| Marocco et al. (2015) | UKIDSS LAS LT Dwarfs | 262 |
| Newton et al. (2014) | Metallicities, Radial Velocities, and Spectral Types for MEarth M Dwarfs | 72 |
| Newton et al. (2015) | Cool Dwarf Fundamental Parameters for MEarth M Dwarfs | 38 |
| Phan-Bao et al. (2003) | DENIS late-M dwarfs | 50 |
| Reid et al. (1995) | Palomar/MSU Nearby-Star Spectroscopic Survey I (PMSU) | 7 |
| Reid et al. (2004) | NLTT Catalog | 13 |
| Reid \& Gizis (2005) | LHS Catalog II | 50 |

Table 1 (continued)

| Reference | Survey/Compilation | UCD Targets |
| :---: | :---: | :---: |
| Reid et al. (2008) | Meeting the Cool Neighbors X | 227 |
| Reylé et al. (2006) | Optical spectroscopy of high proper motion stars | 8 |
| Riaz et al. (2006) | New M Dwarfs in Solar Neighborhood | 1080 |
| Riedel et al. (2014) | The Solar Neighborhood XXXIII | 4 |
| Schmidt et al. (2010) | SDSS L Dwarfs | 484 |
| Schmidt et al. (2015) | BOSS Ultracool Dwarfs | 225 |
| Schneider et al. (2016) | NEOWISER Proper Motion Survey | 17 |
| Shkolnik et al. (2009) | Young LMS within 25 pc | 11 |
| Skrzypek et al. (2015) | Photometric brown-dwarf classification | 50 |
| Smart et al. (2017) | The Gaia ultracool dwarf sample | 153 |
| Theissen et al. (2017) | LaTE-MoVeRS | 1796 |
| Thompson et al. (2013) | WISE MLT Dwarfs | 41 |
| Weinberger et al. (2016) | Carnegie Astrometric Planet Search Program | 78 |
| West et al. (2008) | SDSS DR5 Low-Mass Star Spectroscopic Sample | 922 |
| West et al. (2011) | SDSS DR7 Spectroscopic M Dwarf Catalog | 34 |
| West et al. (2015) | Kinematic Analysis of Nearby Mid-to-Late-Type M Dwarfs | 58 |
| Winters et al. (2015) | The Solar Neighborhood XXXV | 175 |
| Winters et al. (2017) | The Solar Neighborhood XXXVIII | 33 |
| Zhang et al. (2009) | SDSS and 2MASS UCD | 806 |
| Unrefereed Publications |  |  |
| Cruz \& Gagné (2014) | Ultracool RIZzo Spectral Library | 632 |
| dwarfarchives.org | Dwarf Archives (C. Gelino) | 404 |
| M. Gillon (priv. comm.) | SPECULOOS Input Target List | 732 |
|  | SIMBAD M dwarfs $J>14 \mathrm{mag}$ | 760 |
|  | SIMBAD LT dwarfs $J>14 \mathrm{mag}$ | 115 |
| S. Pineda (priv. comm.) |  | 534 |

Table 3. Bona fide and $1 \sigma$ samples of M7-L5 ultracool dwarfs in the 25 pc volume

| Designation | SIMBAD Name | Adopted SpT | SpT Flag | $J$ (mag) | $J-K_{S}$ | Distance (pc) | Distance Type | Ref. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Bona fide sample |  |  |  |  |  |  |  |  |
| LP 584-4 | J00020649+0115366 | M9.0 | NIR | $12.17 \pm 0.02$ | $1.04 \pm 0.03$ | $20.81 \pm 0.06$ | Trig | 2 |
| GJ 1001 C | J00043484-4044058B | L5.0 | OPT | $13.76 \pm 0.04$ | $1.7 \pm 0.06$ | $12.18 \pm 0.06$ | Trig | 2 |
| GJ 1001 B | J00043484-4044058C | L5.0 | OPT | $13.9 \pm$ nan | $1.6 \pm$ nan | $12.18 \pm 0.06$ | Trig | 3 |
| 2MASS J00044144-2058298 | J000441442-20582984 | M7.0 | NIR | $12.4 \pm 0.02$ | $1.01 \pm 0.03$ | $15.08 \pm 0.04$ | Trig | 4 |
| 2MASS J00145575-4844171 | J00145575-4844171 | L2.5 | OPT | $14.05 \pm 0.04$ | $1.33 \pm 0.05$ | $19.96 \pm 0.16$ | Trig | 5 |

References- (1) This paper; (2) Cutri et al. (2003); (3) Leggett et al. (2002); (4) Gaia Collaboration (2018); (5) Kirkpatrick et al. (2008); (6) Kirkpatrick et al. (2000); (7) Cruz et al. (2003); (8) Irwin et al. (1991); (9) McCarthy et al. (1964); (10) Leinert et al. (1994); (11) Reid et al. (2008); (12) Deacon et al. (2005); (13) Gizis et al. (2003); (14) Reid et al. (2000); (15) Wilson et al. (2003); (16) Trimble (1986); (17) Crifo et al. (2005); (18) Theissen et al. (2017); (19) Cruz et al. (2007); (20) Liebert et al. (2003); (21) Ahn et al. (2012); (22) Gizis et al. (2001);(23) Tinney (1993); (24) Basri et al. (2000); (25) Lodieu et al. (2005); (26) Phan-Bao et al. (2006); (27) Kirkpatrick et al. (1997); (28) Kendall et al. (2007); (29) Castro et al. (2013); (30) Adelman-McCarthy \& et al. (2009); (31) Hawley et al. (2002); (32) Kirkpatrick et al. (2016); (33) Reid et al. (2004); (34) Lépine et al. (2002b); (35) Pokorny et al. (2004); (36) Kirkpatrick et al. (2014); (37) Salim et al. (2003); (38) Zacharias et al. (2012); (39) Phan-Bao et al. (2008); (40) Gizis et al. (2000); (41) Reylé et al. (2006); (42) Reid et al. (2003b); (43) Scholz (2014); (44) Scholz \& Meusinger (2002); (45) Liebert (1976); (46) Haro \& Chavira (1966); (47) Lépine \& Shara (2005); (48) Shkolnik et al. (2009); (49) West et al. (2008); (50) Schneider et al. (2014); (51) Rebolo et al. (1998); (52) Gizis (2002); (53) Kirkpatrick et al. (1995); (54) Close et al. (2003); (55) Davison et al. (2015); (56) Schneider et al. (2016); (57) Delfosse et al. (1997); (58) Bessell (1991); (59) Gagné et al. (2015c); (60) Koerner et al. (1999); (61) Looper et al. (2008); (62) Phan-Bao et al. (2003); (63) Schmidt et al. (2010); (64) West et al. (2011); (65) Fan et al. (2000); (66) Tinney et al. (1993); (67) Kirkpatrick et al. (1999); (68) Hartwick et al. (1984); (69) Jenkins et al. (2009); (70) Kirkpatrick et al. (1993); (71) Gauza et al. (2015); (72) Burgasser et al. (2015b); (73) Liu \& Leggett (2005); (74) Patience et al. (2002); (75) Alonso-Floriano et al. (2015); (76) Schmidt et al. (2007); (77) Kendall et al. (2004); (78) Reid \& Gizis (2005); (79) Sheppard \& Cushing (2009b); (80) Faherty et al. (2012); (81) Scholz et al. (2004b); (82) Goto et al. (2002); (83) Martín et al. (2000); (84) Kirkpatrick et al. (2011); (85) Reid et al. (2007); (86) Kellogg et al. (2017); (87) Chiu et al. (2006); (88) Pérez Garrido et al. (2014); (89) Zhang et al. (2009); (90) Rajpurohit et al. (2013); (91) M. Gillon (priv. comm.); (92) Gizis et al. (2002); (93) Günther et al. (2014); (94) Martín et al. (2010); (95) Luhman \& Sheppard (2014); (96) McElwain \& Burgasser (2006); (97) Radigan et al. (2008); (98) Schneider et al. (2011); (99) Zacharias et al. (2003); (100) Costa et al. (2005); (101) Beamín et al. (2013); (102) Newton et al. (2014); (103) Kirkpatrick et al. (2010); (104) Luhman et al. (2012); (105) Folkes et al. (2012); (106) Lépine et al. (2002a); (107) Lépine et al. (2003); (108) Marocco et al. (2015); (109) Gizis et al. (2011); (110) Herbig (1956); (111) Gray et al. (2006); (112) Dupuy et al. (2009); (113) Kirkpatrick et al. (2001a); (114) Dahn et al. (2002); (115) Deshpande et al. (2012); (116) Allen et al. (2007); (117) Pokorny et al. (2003); (118) Phan-Bao \& Bessell (2006).

[^10]Table 4. Multi-wavelength photometry for bona fide and $1 \sigma$ samples of M7-L5 ultracool dwarfs in the 25 pc volume

| Column Number | Label | Description |
| :--- | :---: | :---: |
| 1 | SIMBAD Name | Source name as listed in SIMBAD |
| 2 | Adopted Spectral Type | Adopted spectral type following the preference order described in Section 2.2.1. |
| 3 | Spectral Type Flag | Source of spectral type |
| 4,5 | SDSS $r$ (mag) | SDSS $r$ magnitude and uncertainty |
| 6,7 | SDSS $i(\mathrm{mag})$ | SDSS $i$ magnitude and uncertainty |
| 8,9 | SDSS $z(\mathrm{mag})$ | SDSS $z$ magnitude and uncertainty |
| 10,11 | 2MASS $J(\mathrm{mag})$ | 2MASS $J$ magnitude and uncertainty |
| 12,13 | 2MASS $H$ (mag) | 2MASS $H$ magnitude and uncertainty |
| 14,15 | 2 MASS $K_{s}(\mathrm{mag})$ | 2MASS $K_{s}$ magnitude and uncertainty |
| 16,17 | MKO $J(\mathrm{mag})$ | MKO $J$ magnitude and uncertainty |
| 18,19 | MKO $H(\mathrm{mag})$ | MKO $H$ magnitude and uncertainty |
| 20,21 | MKO $K(\mathrm{mag})$ | MKO $K$ magnitude and uncertainty |
| 22,23 | UKIDSS $J(\mathrm{mag})$ | UKIDSS $J$ magnitude and uncertainty |
| 24,25 | UKIDSS $H(\mathrm{mag})$ | UKIDSS $H$ magnitude and uncertainty |
| 26,27 | UKIDSS $K(\mathrm{mag})$ | UKIDSS $K$ magnitude and uncertainty |
| 28,29 | WISE $W 1(\mathrm{mag})$ | WISE $W 1$ magnitude and uncertainty |
| 30,31 | WISE $W 2(\mathrm{mag})$ | WISE $W 2$ magnitude and uncertainty |
| 32,33 | WISE $W 3(\mathrm{mag})$ | WISE $W 3$ magnitude and uncertainty |
| 34 | Reference | Discovery reference |

References- (2) Cutri et al. (2003); (3) Leggett et al. (2002); (4) Gaia Collaboration (2018); (5) Kirkpatrick et al. (2008); (6) Kirkpatrick et al. (2000); (7) Cruz et al. (2003); (8) Irwin et al. (1991); (9) McCarthy et al. (1964); (10) Leinert et al. (1994); (11) Reid et al. (2008); (12) Deacon et al. (2005); (13) Gizis et al. (2003); (14) Reid et al. (2000); (15) Wilson et al. (2003); (16) Trimble (1986); (17) Crifo et al. (2005); (18) Theissen et al. (2017); (19) Cruz et al. (2007); (20) Liebert et al. (2003); (21) Ahn et al. (2012); (22) Gizis et al. (2001); (23) Tinney (1993); (24) Basri et al. (2000); (25) Lodieu et al. (2005); (26) Phan-Bao et al. (2006); (27) Kirkpatrick et al. (1997); (28) Kendall et al. (2007); (29) Castro et al. (2013); (30) Adelman-McCarthy \& et al. (2009); (31) Hawley et al. (2002); (32) Kirkpatrick et al. (2016); (33) Reid et al. (2004); (34) Lépine et al. (2002b); (35) Pokorny et al. (2004); (36) Kirkpatrick et al. (2014); (37) Salim et al. (2003); (38) Zacharias et al. (2012); (39) Phan-Bao et al. (2008); (40) Gizis et al. (2000); (41) Reylé et al. (2006); (42) Reid et al. (2003b); (43) Scholz (2014); (44) Scholz \& Meusinger (2002); (45) Liebert (1976); (46) Haro \& Chavira (1966); (47) Lépine \& Shara (2005); (48) Shkolnik et al. (2009); (49) West et al. (2008); (50) Schneider et al. (2014); (51) Rebolo et al. (1998); (52) Gizis (2002); (53) Kirkpatrick et al. (1995); (54) Close et al. (2003); (55) Davison et al. (2015); (56) Schneider et al. (2016); (57) Delfosse et al. (1997); (58) Bessell (1991); (59) Gagné et al. (2015c); (60) Koerner et al. (1999); (61) Looper et al. (2008); (62) Phan-Bao et al. (2003); (63) Schmidt et al. (2010); (64) West et al. (2011); (65) Fan et al. (2000); (66) Tinney et al. (1993); (67) Kirkpatrick et al. (1999); (68) Hartwick et al. (1984); (69) Jenkins et al. (2009); (70) Kirkpatrick et al. (1993); (71) Gauza et al. (2015); (72) Burgasser et al. (2015b); (73) Liu \& Leggett (2005); (74) Patience et al. (2002); (75) Alonso-Floriano et al. (2015); (76) Schmidt et al. (2007); (77) Kendall et al. (2004); (78) Reid \& Gizis (2005); (79) Sheppard \& Cushing (2009b); (80) Faherty et al. (2012); (81) Scholz et al. (2004b); (82) Goto et al. (2002); (83) Martín et al. (2000); (84) Kirkpatrick et al. (2011); (85) Reid et al. (2007); (86) Kellogg et al. (2017); (87) Chiu et al. (2006); (88) Pérez Garrido et al. (2014); (89) Zhang et al. (2009); (90) Rajpurohit et al. (2013); (91) M. Gillon (priv. comm.); (92) Gizis et al. (2002); (93) Günther et al. (2014); (94) Martín et al. (2010); (95) Luhman \& Sheppard (2014); (96) McElwain \& Burgasser (2006); (97) Radigan et al. (2008); (98) Schneider et al. (2011); (99) Zacharias et al. (2003); (100) Costa et al. (2005); (101) Beamín et al. (2013); (102) Newton et al. (2014); (103) Kirkpatrick et al. (2010); (104) Luhman et al. (2012); (105) Folkes et al. (2012); (106) Lépine et al. (2002a); (107) Lépine et al. (2003); (108) Marocco et al. (2015); (109) Gizis et al. (2011); (110) Herbig (1956); (111) Gray et al. (2006); (112) Dupuy et al. (2009); (113) Kirkpatrick et al. (2001a); (114) Dahn et al. (2002); (115) Deshpande et al. (2012); (116) Allen et al. (2007); (117) Pokorny et al. (2003); (118) Phan-Bao \& Bessell (2006).

Note-This table is available in its entirety in a machine-readable form in the online journal.

Table 5. Bona fide and $1 \sigma$ samples of M7-L5 ultracool dwarfs in the 25 pc volume

| Column Number | Label |  |
| :--- | :--- | :--- |
| 1 | Source Name | Description |
|  | Literature spectral types | Name of source as shown in SIMBAD |
| 2 | Adopted Spectral Type | Spectral type as reported in the literature adopted in this study |
| 3 | Flag of Adopted Spectral Type | Type of spectral classification adopted |
| 4 | Optical Spectral Type | Optical spectral classification as reported in the literature |
| 5 | NIR Spectral Type | NIR spectral classification as reported in the literature |
| 6 | SIMBAD Spectral Type | Spectral classification reported in SIMBAD, either optical or NIR |
| 7 | SDSS Spectral Type | Spectral classification as reported in SDSS |
|  | Spectral types by indices |  |
| 8,9 | Burgasser (2007a) indices | Spectral type according to Burgasser (2007a) indices and uncertainty |
| 10,11 | Allers et al. (2007) indices | Spectral type according to Allers et al. (2007) indices and uncertainty |
| 12,13 | Reid et al. (2001) indices | Spectral type according to Reid et al. (2001) indices and uncertainty |
|  | Spectral types by standard |  |
| 14 | Classification by Standard | Spectral type measured by comparison to Kirkpatrick et al. (2010) spectral standards |
| 15 | References | References for optical, NIR, SIMBAD, and spectral classification by standard |

References- (1) This paper; (5) Kirkpatrick et al. (2008); (6) Kirkpatrick et al. (2000); (7) Cruz et al. (2003); (11) Reid et al. (2008); (13) Gizis et al. (2003); (14) Reid et al. (2000); (15) Wilson et al. (2003); (19) Cruz et al. (2007); (20) Liebert et al. (2003); (22) Gizis et al. (2001); (25) Lodieu et al. (2005); (26) Phan-Bao et al. (2006); (28) Kendall et al. (2007); (29) Castro et al. (2013); (31) Hawley et al. (2002); (32) Kirkpatrick et al. (2016); (33) Reid et al. (2004); (35) Pokorny et al. (2004); (36) Kirkpatrick et al. (2014); (37) Salim et al. (2003); (39) Phan-Bao et al. (2008); (40) Gizis et al. (2000); (42) Reid et al. (2003b); (43) Scholz (2014); (44) Scholz \& Meusinger (2002); (47) Lépine \& Shara (2005); (48) Shkolnik et al. (2009); (49) West et al. (2008); (50) Schneider et al. (2014); (52) Gizis (2002); (53) Kirkpatrick et al. (1995); (54) Close et al. (2003); (55) Davison et al. (2015); (58) Bessell (1991); (59) Gagné et al. (2015c); (61) Looper et al. (2008); (62) Phan-Bao et al. (2003); (63) Schmidt et al. (2010); (64) West et al. (2011); (65) Fan et al. (2000); (67) Kirkpatrick et al. (1999); (69) Jenkins et al. (2009); (71) Gauza et al. (2015); (72) Burgasser et al. (2015b); (75) AlonsoFloriano et al. (2015); (76) Schmidt et al. (2007); (77) Kendall et al. (2004); (78) Reid \& Gizis (2005); (80) Faherty et al. (2012); (82) Goto et al. (2002); (83) Martín et al. (2000); (84) Kirkpatrick et al. (2011); (85) Reid et al. (2007); (86) Kellogg et al. (2017); (87) Chiu et al. (2006); (88) Pérez Garrido et al. (2014); (90) Rajpurohit et al. (2013); (94) Martín et al. (2010); (95) Luhman \& Sheppard (2014); (96) McElwain \& Burgasser (2006); (97) Radigan et al. (2008); (101) Beamín et al. (2013); (102) Newton et al. (2014); (103) Kirkpatrick et al. (2010); (104) Luhman et al. (2012); (105) Folkes et al. (2012); (106) Lépine et al. (2002a); (107) Lépine et al. (2003); (108) Marocco et al. (2015) ; (109) Gizis et al. (2011); (111) Gray et al. (2006); (112) Dupuy et al. (2009); (113) Kirkpatrick et al. (2001a); (115) Deshpande et al. (2012); (116) Allen et al. (2007); (118) Phan-Bao \& Bessell (2006); (119) Rajpurohit et al. (2012); (120) Forveille et al. (2005); (121) Cruz et al. (2009); (122) Liebert \& Ferguson (1982); (123) Bardalez Gagliuffi et al. (2014); (124) Teegarden et al. (2003); (125) McCaughrean et al. (2002); (126) Siegler et al. (2005); (127) Kendall et al. (2003); (128) Gálvez-Ortiz et al. (2010); (129) Lépine et al. (2009); (130) Faherty et al. (2009); (131) Salim \& Gould (2003); (132) Thorstensen \& Kirkpatrick (2003); (133) West et al. (2015); (134) Bochanski et al. (2011); (135) Dieterich et al. (2014); (136) Hambaryan et al. (2004); (137) Law et al. (2006); (138) Martín et al. (1999); (139) Jahreiß et al. (2001); (140) Koen (2013); (141) Barrado Y Navascués (2006); (142) Metodieva et al. (2015); (143) Winters et al. (2015); (144) Schmidt et al. (2014); (145) Scholz et al. (2005); (146) Henry \& Kirkpatrick (1990); (147) Kirkpatrick et al. (1994); (148) Malkov et al. (2012); (149) SpeX Prism Library; (150) Knapp et al. (2004); (151) Marocco et al. (2013); (152) Allers et al. (2010); (153) Terrien et al. (2015); (154) Phan-Bao (2011); (155) Burgasser et al. (in prep.); (156) Allers \& Liu (2013); (157) Faherty et al. (2016); (158) Burgasser et al. (2010); (159) Dupuy et al. (2010); (160) Burgasser et al. (2007a); (161) Burgasser et al. (2008b); (162) Aberasturi et al. (2014); (163) Geballe et al. (2002); (164) Stumpf et al. (2008); (165) Gomes et al. (2013); (166) Bowler et al. (2009); (167) Burgasser et al. (2011b); (168) Bowler et al. (2010); (169) Sheppard \& Cushing (2009a); (170) Forveille et al. (2004); (171) Witte et al. (2011); (172) Burgasser et al. (2007b); (173) Aganze et al. (2016); (174) Geißler et al. (2011); (175) Kasper et al. (2007); (176) Liu et al. (2002); (177) Ireland et al. (2008); (178) Dupuy \& Liu (2012); (179) Liu et al. (2016); (180) Leggett et al. (2001); (181) Leinert et al. (2000); (182) Konopacky et al. (2010); (183) Henry et al. (2004); (184) Burgasser et al. (2005); (185) Stephenson (1986); (186) Kirkpatrick et al. (1991); (187) Koen et al. (2010); (188) Burgasser et al. (2011a); (189) Tinney et al. (1998); (190) Scholz et al. (2004a).

Note-This table is available in its entirety in a machine-readable form in the online journal.

Table 6. Trigonometric and spectrophotometric distances of bona fide and $1 \sigma$ samples of M7-L5 ultracool dwarfs in the 25 pc volume

| Source Name |  | Spectral Type |  | Parallax | Distance |  | Ref. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | Adopted | Flag |  | Trigonometric | Spectrophotometric (NIR) |  |
| Bona fide sample |  |  |  |  |  |  |  |
|  | LP 584-4 | M9.0 | NIR | $48.05 \pm 0.14$ | $20.81 \pm 0.06$ | $15 \pm 2$ | 191 |
|  | GJ 1001 C | L5.0 | OPT | $82.09 \pm 0.38$ | $12.18 \pm 0.06$ | $11 \pm 1$ | 191 |
|  | GJ 1001 B | L5.0 | OPT | $82.09 \pm 0.38$ | $12.18 \pm 0.06$ | $\cdots$ | 191 |
| 2MASS | J00044144-2058298 | M7.0 | NIR | $66.33 \pm 0.16$ | $15.08 \pm 0.04$ | $23 \pm 3$ | 191 |
| 2MASS | J00145575-4844171 | L2.5 | OPT | $50.11 \pm 0.39$ | $19.96 \pm 0.16$ | $20 \pm 2$ | 191 |

References- (1) This paper; (4) Gaia Collaboration (2018); (72) Burgasser et al. (2015b); (80) Faherty et al. (2012); (129) Lépine et al. (2009); (135) Dieterich et al. (2014); (151) Marocco et al. (2013); (178) Dupuy \& Liu (2012); (191) Gaia Collaboration et al. (2018); (192) Dittmann et al. (2014); (193) Weinberger et al. (2016); (194) Bartlett et al. (2017); (195) Lindegren et al. (2016); (196) Sahlmann et al. (2015); (197) van Leeuwen (2007); (198) Pravdo et al. (2005).

Note-This table is available in its entirety in a machine-readable form in the online journal.

Table 7. SpeX observing log

| Designation | 2MASS $J$ | 2MASS $K_{s}$ | Slit | Total $\mathrm{t}_{\text {exp }}(\mathrm{s})$ | Airmass | Obs. Date Median S/N | A0 Standard |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Within 25 pc |  |  |  |  |  |  |  |  |
| J00130931-0025521 | 12.167 | 11.319 | $0.5 \times 15^{\prime \prime}$ | 539 | 1.098 | 20151006 | 379.34 | HD 1154 |
| J00192626+4614078 | 12.603 | 11.502 | $0.5 \times 15^{\prime \prime}$ | 539 | 1.127 | 20151117 | 296.67 | HD 222749 |
| J00525468-2705597 | 13.611 | 12.54 | $0.5 \times 15^{\prime \prime}$ | 719 | 1.461 | 20150804 | 186.29 | HD 222332 |
| $\ldots$ | $\ldots$ | $\ldots$ | $0.5 \times 15^{\prime \prime}$ | 717 | 1.474 | 20151116 | 163.85 | HD 225200 |
| J01004911-1933398 | 13.487 | 12.755 | $0.5 \times 15^{\prime \prime}$ | 478 | 1.348 | 20161007 | 85.90 | HD 13433 |

[^11]Table 8. Intermediate gravity and very low gravity sources in the M7-L5 25 pc Sample

| Source Name | Literature SpT |  | SpeX SpT |  |  |  |  | Trigonometric <br> Distance (pc) | BANYAN $\Sigma$ <br> YMG Prob. | Ref. ${ }^{\text {a }}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Optical | NIR | Field Low Gravity $\mu$ |  | \% $\mu_{\alpha}$ (mas/yr) | $\mu_{\delta}(\mathrm{mas} / \mathrm{yr})$ | $\mathrm{RV}(\mathrm{km} / \mathrm{s})$ |  |  |  |  |  |
| Very Low Gravity Sources |  |  |  |  |  |  |  |  |  |  |  |  |
| 2MASSW J0045214+163445 | L2 $\beta$ | L3.5 | L3.0 | L1.0 $\gamma$ | $358.92 \pm 0.4$ | $-48.07 \pm 0.24$ | $3.16 \pm 0.83$ | $15.38 \pm 0.05$ | Argus (99.9\%) | $191 ; 15$ | 7;191 | 1;156,216 |
| 2MASS J03552337+1133437 ${ }^{\text {b }}$ | L5 $\gamma$ | L3 $\gamma$ | L7.0 | L4.0 $\gamma$ | $219.76 \pm 1.57$ | $-631.28 \pm 0.82$ | $11.92 \pm 0.22$ | $9.12 \pm 0.06$ | AB Dor (99.9\%) | 191; | 218; | ;191;59 |
| 2MASS J05012406-0010452 | L4 $\gamma$ | L3 $\gamma$ | L7.0 | $\mathrm{L} 4.0 \gamma$ | $189.25 \pm 1.52$ | $-145.31 \pm 1.16$ | $21.77 \pm 0.66$ | $21.24 \pm 0.40$ | Field (0\%) | 191;15 | 7;19 | 91;59,156 |
| 2MASS J06244595-4521548 | L5: | L5 | L7.0 | $\mathrm{L} 4.0 \gamma$ | $-35.75 \pm 0.89$ | $376.67 \pm 1.24$ | ... | $12.25 \pm 0.07$ | Argus (95.1\%) | 191; | . . | ;191;59 |
| G 196-3B ${ }^{\text {b }}$ | L3 $\beta$ | L4 $\gamma$ | L7.0 | L2.0 $\gamma$ | $-137.82 \pm 0.93$ | $-208.52 \pm 1.67$ | $\ldots$ | $22.55 \pm 0.41$ | Field (45.3\%) | 191; | $\cdots$ | ;191;156 |

References- (1) This paper; (49) West et al. (2008); (50) Schneider et al. (2014); (56) Schneider et al. (2016); (59) Gagné et al. (2015c); (80) Faherty et al. (2012); (102) Newton et al. (2014); (115) Deshpande et al. (2012); (156) Allers \& Liu (2013); (157) Faherty et al. (2016); (191) Gaia Collaboration et al. (2018); (192) Dittmann et al. (2014); (216) Gagné et al. (2014); (217) Seifahrt et al. (2010); (218) Monet et al. (2003); (219) Burgasser et al. (2015a); (220) Blake et al. (2010); (221) Casewell et al. (2008); (222) Reiners \& Basri (2009); (223) Jameson et al. (2008); (224) Morin et al. (2010); (225) Hawley et al. (1996); (226) Burgasser \& Mamajek (2017).

Note-This table is available in its entirety in a machine-readable form in the online journal.

Table 9. Red and blue $J-K_{s}$ color outliers

| Source Name | Adopted SpT | SpT Flag | $J-K_{s}$ | $J-K_{s}$ Excess | YMG | Ref. |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Red Outliers |  |  |  |  |  |  |
| 2MASS J03552337+1133437 ${ }^{\text {b }}$ | L5.0 | OPT | $2.52 \pm 0.03$ | 0.77 | 11;59 |  |
| $\mathrm{G} 196-3 \mathrm{~B}^{\mathrm{b}}$ | L3.0 | OPT | $2.05 \pm 0.06$ | 0.44 | 51 |  |
| LHS2397aA | M8.0 | OPT | $1.28 \pm 0.03$ | 0.22 | 60 |  |
| Kelu-1 A | L2.0 | OPT | $2.41 \pm 0.17$ | 0.90 | 2 |  |
| 2MASSW J1728114+394859A | L5.0 | NIR | $2.21 \pm 0.09$ | 0.46 | 6 |  |
| 2MASS J17410280-4642218A ${ }^{\text {b }}$ | L5.0 | NIR | $2.35 \pm 0.08$ | 0.60 | 50;157 |  |
| Blue Outliers |  |  |  |  |  |  |
| 2MASS J09230296-2300415 ${ }^{\text {c }}$ | M8.0 | NIR | $0.55 \pm 0.03$ | -0.51 | 2 |  |
| LHS 286 | M8.0 | OPT | $0.82 \pm 0.03$ | -0.24 | 2 |  |
| 2MASS J11263991-5003550 | L5.0 | OPT | $1.17 \pm 0.04$ | -0.58 | 50 |  |
| LHS 2839 | M7.0 | OPT | $0.74 \pm 0.03$ | -0.23 | 2 |  |
| 2MASS J14162408+1348263 | L5.0 | OPT | $1.03 \pm 0.03$ | -0.72 | 50 |  |
| $\text { 2MASS J14343616+2202463 }{ }^{\text {d }}$ | L2.5 | NIR | $0.97 \pm 0.06$ | -0.54 | 79 |  |
| 2MASS J14442067-2019222 | M9.0 | OPT | $0.61 \pm 0.04$ | -0.54 | 81 |  |
| 2MASS J15552651+0954099 ${ }^{\text {c }}$ | M8.0 | PHOT | $0.73 \pm 0.04$ | -0.33 | 91 |  |
| G 203-50B | L5.0 | NIR | $1.20 \pm 0.07$ | -0.54 | 97 |  |
| $\text { GJ } 660.1 \mathrm{~B}^{\mathrm{c}}$ | M7.5 | NIR | $0.82 \pm 0.05$ | -0.24 | 98 |  |
| $\text { UCAC2 } 11845260^{\mathrm{d}}$ | M7.0 | OPT | $0.50 \pm 0.03$ | -0.47 | 99 |  |
| 2MASS J17210390+3344160 ${ }^{\text {c }}$ | L3.0 | OPT | $1.14 \pm 0.03$ | -0.47 | 100 |  |
| 2MASS J17264070-2737593 | L5.0 | OPT | $1.18 \pm 0.04$ | -0.57 | 101 |  |
| 2MASS J17430860+8526594 | L5.0 | NIR | $1.09 \pm 0.06$ | -0.66 | 104 |  |
| LEHPM 2-90 ${ }^{\text {c }}$ | M9.0 | NIR | $0.84 \pm 0.03$ | -0.31 | 35 |  |
| GJ 802 b | L5.0 | NIR | $1.14 \pm 0.28$ | -0.61 | 2 |  |
| LEHPM 6344 | M9.5 | NIR | $0.75 \pm 0.03$ | $-0.47$ | 117 |  |

References- (2) Cutri et al. (2003); (6) Kirkpatrick et al. (2000); (11) Reid et al. (2008); (35) Pokorny et al. (2004); (50) Schneider et al. (2014); (51) Rebolo et al. (1998); (59) Gagné et al. (2015c); (60) Koerner et al. (1999); (79) Sheppard \& Cushing (2009b); (81) Scholz et al. (2004b); (91) M. Gillon (priv. comm.); (97) Radigan et al. (2008); (98) Schneider et al. (2011); (99) Zacharias et al. (2003); (100) Costa et al. (2005); (101) Beamín et al. (2013); (104) Luhman et al. (2012); (117) Pokorny et al. (2003); (157) Faherty et al. (2016).
${ }^{a}$ Discovery Reference; Young Moving Group Reference.
$b_{\text {2MASS J0355 }}+1133$ and 2MASS J1741-4642 are members of the AB Doradus young moving group, while G 196-3B is a young, unassociated source.
${ }^{c}$ Also classified as INT-G, indicating low metallicity rather than low gravity.
${ }^{\mathrm{d}}$ Member of extended $25 p c+1 \sigma$ sample.

Table 10. Spectral binary candidates with M7-L7 primary components.

| Designation | Spectral Type |  |  | $2 \mathrm{MASS} \Delta J$ | Confidence | Spectral Indices ${ }^{\text {b }}$ | References* |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | Primary ${ }^{\text {a }}$ | Secondary ${ }^{\text {a }}$ |  |  |  |  |
| Within 25 pc |  |  |  |  |  |  |  |
| 2MASSW J0320284-044636 | M8.0 | M9.6 $\pm 0.2$ | T5.6 $\pm 1.0$ | $3.5 \pm 0.5$ | 96\% | 12 | 202,213;191 |
| WISE J072003.20-084651.2 | M9.0 | M8.9 $\pm 0.0$ | T5.1 $\pm 0.7$ | $3.5 \pm 0.2$ | 100\% | 6 | 71;63 |
| 2MASS J08053189+4812330 | L4.0 | $\mathrm{L} 4.3 \pm 0.4$ | T5.0 $\pm 1.1$ | $1.5 \pm 0.3$ | > 99\% | 6 | 214;188 |
| 2MASS J13153094-2649513 | L5.5 | $\mathrm{L} 4.7 \pm 0.4$ | T5.4 $\pm 3.0$ | $2.1 \pm 0.8$ | 95\% | 12 | 168;158 |
| 2MASS J22521073-1730134 | T0.0 | $\mathrm{L} 4.8 \pm 0.5$ | T4.4 $\pm 0.7$ | $1.24 \pm 0.25$ | > $99 \%$ | 11 | $\cdots ; 205$ |
| Outside 25 pc |  |  |  |  |  |  |  |
| 2MASS J09311309+2802289 | L3.0 | L1.4 $\pm 0.1$ | $\mathrm{T} 2.3 \pm 0.8$ | $2.3 \pm 0.1$ | > 99\% | 11 | $\ldots$ |
| 2MASS J14111847+2948515 | L3.5 | $\mathrm{L} 4.1 \pm 1.0$ | T3.9 $\pm 0.9$ | $1.2 \pm 0.5$ | > $99 \%$ | 6 | $\ldots$ |
| 2MASS J14211873-1618201 | M7.5 | M8.3 $\pm 0.2$ | $\mathrm{T} 5.1 \pm 1.4$ | $3.7 \pm 0.5$ | 95\% | 5 | $\ldots$ |
| Rejected candidates |  |  |  |  |  |  |  |
| WISE J000622.67-131955.2 | L5.0 | L5.3 $\pm 0.7$ | T5.3 $\pm 2.6$ | $1.7 \pm 0.9$ | $54 \%$ | 11 | $\ldots$ |
| 1RXS J002247.5+055709 | M7.0 | M6.6 $\pm 0.0$ | T6.0 $\pm 1.2$ | $4.9 \pm 0.6$ | $66 \%$ | 5 | $\ldots$ |
| 2MASS J00525468-2705597 | M7.5 | M8.6 $\pm 0.3$ | T6.0 $\pm 1.1$ | $4.0 \pm 0.6$ | 78\% | 4 | $\ldots$ |
| 2MASS J02150802-3040011 | M8.0 | M7.8 $\pm 0.3$ | T6.1 $\pm 1.3$ | $4.4 \pm 0.6$ | 58\% | 4 | $\ldots$ |
| 2MASS J02354955-0711214 | M7.0 | M7.2 $\pm 0.1$ | T6.2 $\pm 1.3$ | $4.7 \pm 0.6$ | $53 \%$ | 4 | $\ldots$ |
| LSPM J0240+2832 | M7.5 | M7.2 $\pm 0.4$ | T5.6 $\pm 1.6$ | $4.5 \pm 0.6$ | 61\% | 6 | $\ldots$ |
| SDSS J031225.12+002158.3 | M7.0 | M7.1 $\pm 0.1$ | T6.6 $\pm 0.8$ | $4.9 \pm 0.5$ | 69\% | 5 | $\ldots$ |
| LP 356-770 | M7.0 | M7.1 $\pm 0.1$ | $\mathrm{T} 6.2 \pm 1.4$ | $4.8 \pm 0.6$ | 55\% | 4 |  |
| 2MASS J04430581-3202090 | L5.0 | $\mathrm{L} 4.4 \pm 0.1$ | $\mathrm{T} 1.3 \pm 0.3$ | $1.1 \pm 0.1$ | 83\% | 5 | $\ldots$ |
| WISE J044633.45-242956.9 | L5.0 | $\mathrm{L} 4.8 \pm 0.4$ | T1.9 $\pm 0.5$ | $0.8 \pm 0.2$ | > $99 \%$ | 9 | $\ldots$ |
| 2MASS J06431685-1843375 | M8.0 | M8.5 $\pm 0.0$ | $\mathrm{T} 6.1 \pm 1.3$ | $4.2 \pm 0.6$ | $86 \%$ | 6 | $\ldots$ |
| 2MASS J07410681+1738459 | M7.0 | M7.3 $\pm 0.0$ | T3.6 $\pm 2.9$ | $4.3 \pm 0.9$ | 88\% | 4 | $\ldots$ |
| 2MASS J09041916+4554559 | M7.0 | M6.6 $\pm 0.0$ | $\mathrm{T} 6.0 \pm 1.9$ | $5.1 \pm 0.7$ | $34 \%$ | 5 | $\ldots$ |
| SDSS J091130.53+224810.7 | M7.0 | M6.6 $\pm 0.0$ | $\mathrm{T} 6.0 \pm 1.7$ | $5.0 \pm 0.7$ | $39 \%$ | 5 | $\ldots$ |
| 2MASS J09473829+3710178 | M7.0 | M6.6 $\pm 0.1$ | T4.7 $\pm 1.9$ | $4.5 \pm 0.6$ | 88\% | 6 | $\ldots$ |
| 2MASS J11073750-2759385B | M7.0 | M7.2 $\pm 0.1$ | T5.6 $\pm 2.0$ | $4.6 \pm 0.7$ | $52 \%$ | 4 | $\ldots$ |
| SDSS J112329.35+015404.0 | M7.0 | M7.8 $\pm 0.4$ | T5.0 $\pm 2.1$ | $4.1 \pm 0.6$ | $41 \%$ | 5 | $\ldots$ |
| 2MASS J12560215-1257217 | M7.5 | M7.2 $\pm 0.2$ | T6.4 $\pm 1.1$ | $4.8 \pm 0.6$ | 45\% | 4 | $\ldots$ |
| 2MASS J13261625+5640448 | M7.0 | M7.4 $\pm 0.2$ | T5.4 $\pm 1.7$ | $4.3 \pm 0.6$ | 67\% | 4 | $\ldots$ |
| 2MASS J13365044+4751321 | M8.0 | M7.5 $\pm 0.2$ | $\mathrm{T} 6.2 \pm 1.4$ | $4.6 \pm 0.6$ | 67\% | 4 | $\cdots$ |
| 2MASS J14162408+1348263A | L5.0 | L4.0 $\pm 0.2$ | T2.3 $\pm 0.5$ | $1.2 \pm 0.1$ | > $99 \%$ | 10 | 159; . ${ }^{\text {a }}$ |
| 2MASS J14442067-2019222 | M9.0 | M7.8 $\pm 0.2$ | T3.7 $\pm 1.5$. | $3.5 \pm 0.3$ | 99\% | 6 | $\cdots$ |
| 2MASS J15072779-2000431 | M7.5 | M8.0 $\pm 0.2$ | $\mathrm{T} 6.4 \pm 1.2$ | $4.5 \pm 0.6$ | $45 \%$ | 5 | $\ldots$ |

Table 10 continued on next page

Table 10 (continued)

| Designation | Spectral Type |  |  | $2 \text { MASS } \Delta J$ | Confidence | Spectral Indices b | References* |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | Primary ${ }^{\text {a }}$ | Secondary ${ }^{\text {a }}$ |  |  |  |  |
| SDSS J151500.62+484744.8 | L6.0 | L4.6 $\pm 0.4$ | T1.8 $\pm 0.6$ | $1.0 \pm 0.2$ | 94\% | 6 | $\cdots$ |
| 2MASS J15394189-0520428 | L4.0 | $\mathrm{L} 2.9 \pm 0.9$ | T4.1 $\pm 2.6$ | $2.4 \pm 0.6$ | $65 \%$ | 4 | $\cdots$ |
| 2MASS J15583862+2211112 | M8.0 | $\mathrm{M} 7.0 \pm 0.3$ | T4.8 $\pm 1.9$ | $4.3 \pm 0.6$ | 88\% | 6 | $\ldots$ |
| G 203-50B | L5.0 | $\mathrm{L} 4.0 \pm 0.2$ | T2.4 $\pm 0.6$ | $1.2 \pm 0.1$ | 99\% | 6 | 79; |
| LHS 3227 | M6.0 | $\mathrm{M} 6.8 \pm 0.1$ | T5.4 $\pm 2.0$ | $4.7 \pm 0.7$ | 77\% | 6 | $\cdots$ |
| 2MASS J17312974+2721233 | L0.0 | $\mathrm{M} 8.7 \pm 0.0$ | T6.9 $\pm 0.7$ | $4.5 \pm 0.5$ | 47\% | 4 | $\cdots$ |
| 2MASS J17335314+1655129 | M7.0 | $\mathrm{M} 6.1 \pm 0.1$ | T5.2 $\pm 1.8$ | $5.0 \pm 0.7$ | 70\% | 5 | $\ldots$ |
| 2MASS J17334227-1654500 | L0.5 | $\mathrm{L} 0.2 \pm 0.3$ | T4.2 $\pm 1.7$ | $3.0 \pm 0.5$ | 80\% | 7 | $\ldots$ |
| 2MASS J17351296+2634475 | M7.5 | $\mathrm{M} 8.1 \pm 0.1$ | T5.6 $\pm 1.3$ | $4.0 \pm 0.5$ | 80\% | 4 | $\cdots$ |
| SDSS J174919.27+475605.3 | M7.0 | $\mathrm{M} 6.5 \pm 0.1$ | T5.3 $\pm 1.3$ | $4.6 \pm 0.6$ | 90\% | 5 | $\cdots$ |
| 2MASS J18353790+3259545 | M8.5 | $\mathrm{M} 8.8 \pm 0.1$ | T5.7 $\pm 2.0$ | $4.1 \pm 0.7$ | 41\% | 4 | $\ldots$ |
| 2MASS J18393308+2952164 | M6.5 | $\mathrm{M} 7.4 \pm 0.3$ | T6.0 $\pm 1.5$ | $4.5 \pm 0.6$ | $57 \%$ | 4 | $\ldots$ |
| 2MASS J18432213+4040209 | M8.0 | $\mathrm{M} 7.6 \pm 0.2$ | T6.4 $\pm 1.3$ | $4.6 \pm 0.6$ | 32\% | 4 | $\ldots$ |
| 2MASS J18451889+3853248 | M8.0 | $\mathrm{M} 7.7 \pm 0.2$ | T5.6 $\pm 2.0$ | $4.4 \pm 0.6$ | 77\% | 5 | $\ldots$ |
| WISE J204027.24+695923.7 | L0.0 | $\mathrm{M} 7.7 \pm 0.3$ | T5.4 $\pm 1.4$ | $4.1 \pm 0.6$ | 91\% | 4 | $\ldots$ |
| 2MASS J21363029+0515329 | M8.5 | $\mathrm{M} 8.0 \pm 0.2$ | T5.6 $\pm 1.9$ | $4.2 \pm 0.7$ | 51\% | 5 | . $\cdot$ |
| 2MASS J22010456+2413016 | M8.0 | M7.6 $\pm 0.5$ | T4.9 $\pm 1.7$ | $4.0 \pm 0.6$ | 82\% | 4 | $\ldots$ |
| 2MASS J22021125-1109461 | M6.5 | M7.5 $\pm 0.1$ | T5.4 $\pm 1.7$ | $4.3 \pm 0.6$ | $83 \%$ | 5 | . $\cdot$ |
| 2MASS J22060209+0311059 | M7.0 | $\mathrm{M} 6.6 \pm 0.0$ | T5.6 $\pm 1.5$ | $4.7 \pm 0.6$ | 55\% | 5 | . $\cdot$ |
| 2MASS J22120703+3430351 | L5.0 | $\mathrm{L} 3.7 \pm 1.0$ | T5.4 $\pm 1.9$ | $2.2 \pm 0.8$ | 54\% | 7 | $\cdots$ |
| 2MASS J22285440-1325178 | M6.5 | $\mathrm{M} 6.9 \pm 0.5$ | T5.5 $\pm 1.5$ | $4.5 \pm 0.6$ | 41\% | 6 | . $\cdot$ |
| LP 702-50 | M6.0 | $\mathrm{M} 6.9 \pm 0.2$ | T6.1 $\pm 1.3$ | $4.8 \pm 0.6$ | 60\% | 5 | . $\cdot$ |
| LP 460-44 | M7.0 | $\mathrm{M} 7.1 \pm 0.1$ | T5.6 $\pm 1.7$ | $4.5 \pm 0.6$ | 80\% | 4 | $\cdots$ |
| LHS 3954 | M7.0 | $\mathrm{M} 7.3 \pm 0.4$ | T6.5 $\pm 1.1$ | $4.8 \pm 0.6$ | 40\% | 6 | . $\cdot$ |
| 2MASS J23312174-2749500 | M7.5 | $\mathrm{M} 8.3 \pm 0.1$ | T6.1 $\pm 1.3$ | $4.2 \pm 0.6$ | $74 \%$ | 6 | . $\cdot$ |
| 2MASS J23515044-2537367 | M8.0 | $\mathrm{M} 8.3 \pm 0.4$ | T5.5 $\pm 1.5$ | $3.9 \pm 0.6$ | 74\% | 5 | $\cdots$ |

* Candidate; Confirmed.
${ }^{a}$ Primary and secondary spectral types are a weighted average of the best binary template fits, inversely proportional to their ranked $\chi^{2}$.
${ }^{b}$ Strong candidates have been selected by 8 or more index-index plots up to 12 , weak candidates by 4- 8 .
References- (63) Burgasser et al. (2015b); (79) Radigan et al. (2008); (158) Burgasser et al. (2011b); (159) Bowler et al. (2010); (188) Dupuy \& Liu (2012); (191) Burgasser et al. (2008a); (213) Blake et al. (2008); (214) Burgasser (2007b).
Table 11. Ultracool Binaries with M7-L5 Primaries in the 25 pc Sample

| Name | Spectral type |  |  |  | Binary Reference |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | UCD Primary | UCD Secondary | Adopted Distance (pc) |  |
| Ultracool Binaries |  |  |  |  |  |
| 2MASS J00275592+2219328AB | M7. 5 | M7 | M8 | $15.27 \pm 0.89$ | 120 |
| 2MASSW J0320284-044636AB | M8 | M8 | T5 | $20.04 \pm 0.2$ | 199 |
| 2MASS J04291842-3123568AB | $\ldots$ | M7.5: | L1 | $12 \pm 1$ | 126 |
| V* V780 Tau | M7 | M7.0 | unknown | $10.25 \pm 0.29$ | 200 |
| 2MASS J06523073+4710348AB | L4.5 | L3.5 | L6.5 | $9.12 \pm 0.04$ | 182 |
| 2MASS J07003664+3157266AB | . | L3.5 | L6 | $12.2 \pm 0.3$ | 182 |
| LHS 1901AB | $\cdots$ | M7 | M7 | $12.85 \pm 0.5$ | 200 |
| 2MASS J07200325-0846499AB | M8 | M9 | T5 | $6.02 \pm 1.02$ | 72 |
| 2MASSI J0746425+200032AB | L0.5 | L1 | L1.5 | $11.6 \pm 0.62$ | 150 |
| 2MASS J08053189+4812330AB | L5 | L4 | T5 | $21.38 \pm 0.44$ | 178 |
| DENIS J0823031-491201AB | L3 | L1.5 | L5. 5 | $20.67 \pm 0.2$ | 105 |
| GJ 1116AB | $\cdots$ | M7 | M8 | $5.14 \pm 0.0$ | 102 |
| 2MASS J09153413+0422045AB | L5 | L6 | L6 | $18.23 \pm 0.36$ | 201 |
| LHS2397aAB | ... | M8 | L7. 5 | $15.19 \pm 0.47$ | 204 |
| Kelu-1AB | L2 | L2 | L3.5 | $18.57 \pm 0.25$ | 164 |
| LP 497-33AB | M7 | M7 | M7.0 | $16.39 \pm 0.75$ | 137 |
| 2MASS J12281523-1547342AB | L5 | L5 | L5.5 | $20.24 \pm 0.78$ | 205 |
| 2MASS J12392727+5515371AB | L5 | L5 | L6 | $23.58 \pm 1.17$ | 13 |
| 2MASS J12560215-1257217A B | $\cdots$ | M7. 5 | L7 | $15.62 \pm 4.39$ | 71 |
| 2MASS J13153094-2649513AB | L5 | L3.5 | T7 | $18.56 \pm 0.39$ | 167 |

Table 11 continued on next page
Table 11 (continued)

| Name | Spectral type |  |  |  | Binary Reference |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | UCD Primary | UCD Secondary | Adopted Distance (pc) |  |
| 2MASS J14162408+1348263AB |  | L5 | T7.5 | $9.3 \pm 0.03$ | 168 |
| 2MASS J15200224-4422419AB | $\ldots$ | L1 | L4.5 | $21 \pm 2,19 \pm 2$ | 172 |
| 2MASS J16334908-6808480AB | $\ldots$ | M8 | M8.5 | $15.3 \pm 0.02$ | 95 |
| 2MASS J17072343-0558249AB |  | M9 | L3 | $16 \pm 2$ | 96 |
| 2MASSW J1728114+394859AB | $\cdots$ | L5 | L7 | $24.1 \pm 1.89$ | 211 |
| 2MASS J17351296+2634475AB |  | M7. 5 | L0 | $14.99 \pm 0.31$ | 137 |
| 2MASS J18450541-6357475AB |  | M8.5 | T6 | $4.0 \pm 0.0$ | 210 |
| 2MASS J21321145 $+1341584 \mathrm{AB}^{\text {a }}$ | L6 | L4.5 | L8.5 | $33.33 \pm 9.11$ | 211 |
| 2MASSW J2206228-204705AB ${ }^{\text {a }}$ | M8 | M8 | M8 | $26.67 \pm 2.39$ | 112 |
| 2MASS J22521073-1730134AB | L7.5 | L4.5 | T3.5 | $16.91 \pm 0.24$ | 201 |
| 2MASS J22551861-5713056AB ${ }^{\text {a }}$ | L5.5 | L5 | L8 | $12 \pm 1$ | 213 |
| Higher Order Multiples Containing Ultracool Dwarf Binaries |  |  |  |  |  |
| GJ 1001BC | M4+L5+L5 | L5 | L5 | $12.18 \pm 0.06$ | 150 |
| LP 881-64BC | M6+M9.5+L0 | M9.5 | L0 | $7.72 \pm 0.15$ | 10 |
| Gl 417 BC | A3+L4.5+L6 | L4.5 | L6: | $23.33 \pm 0.6$ | 203 |
| WDS J10472+4027Bab | M6+M8+L0 | M8 | L0 | $24.92 \pm 0.08$ | 54 |
| HD 114762B ${ }^{\text {a }}$ | F9+F8+F4+M9+planet? | M9.0 | d/sdM9 91 | $28 \pm 3$ | 74 |
| HD 130948BC | G2+L4+L4 | L4 | L4 | $18.17 \pm 0.11$ | 208 |
| BD+16 2708Bab | M3+M8.5+M9 | M8.5 | M9 | $9.65 \pm 0.16$ | 83 |
| Ultracool Companions to Main Sequence Primaries |  |  |  |  |  |
| GJ 1048B | K3.5+L1.5 | $\ldots$ | L1.5 | $21.47 \pm 0.13$ | 22 |
| CD-35 2722 B | M1+L3 | $\ldots$ | L3 | $22.14 \pm 0.17$ | 156 |

Table 11 continued on next page
Table 11 (continued)

| Name | Spectral type |  |  |  | Binary Reference |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | UCD Primary | UCD Secondary | Adopted Distance (pc) |  |
| G 196-3B | M3+L2 | $\ldots$ | L3 | $22.55 \pm 0.41$ | 51 |
| LHS 5166B | M4+L4 | $\cdots$ | L4 | $18.77 \pm 0.2$ | 202 |
| 2MASS J11240487+3808054B | M4.5+M8.5 | $\ldots$ | M8. 5 | $18.47 \pm 0.07$ | 54 |
| NLTT 31198 ${ }^{\text {a }}$ | M5-7+M6-7 | $\cdots$ | M7 | $23.26 \pm 3.24$ | 137 |
| LHS 2839 | K4 4 M7 | $\ldots$ | M7 | $22 \pm 3$ | 207 |
| G 239-25 B | M3+L0 | $\ldots$ | L0 | $10.97 \pm 0.04$ | 170 |
| 2MASS J14562776+1755090 | M5+M7 | $\ldots$ | M7.0 | $19 \pm 2$ | 209 |
| 2MASS J15552651+0954099 | M3+M8 | $\ldots$ | M8.0 | $22 \pm 3$ | 149 |
| VB 8 | M $3.5+\mathrm{M} 3.5+\mathrm{M} 7$ | $\cdots$ | M7.0 | $6.5 \pm 0.0$ | 207 |
| G 203-50B | M4.5+L5 | $\ldots$ | L5 | $21.08 \pm 0.29$ | 97 |
| GJ 660.1B | M1+M7.5 | $\ldots$ | M7. 5 | $23.01 \pm 0.1$ | 98 |
| 2MASS J19165762+0509021BB | M3+M8 | $\ldots$ | M8.0 | $5.92 \pm 0.0$ | 207 |
| G1 779B | G0+L4.5 | $\ldots$ | L4.5 | $17.24 \pm 0.27$ | 176 |
| LSPM J2010+0632B | M $3.5+\mathrm{M} 4+\mathrm{M} 8.5$ | M4 | M8. 5 | $16.13 \pm 0.05$ | 104 |
| GJ 802b | M $+\mathrm{M}+\mathrm{L} 5$ | $\ldots$ | L5 | $15.87 \pm 1.39$ | 177 |
| G 216-7B | M0+M9.5 | $\ldots$ | M9.5 | $21.0 \pm 0.09$ | 212 |
| LEHPM 1-6443C | WD+M4+M9 | ... | M9 | $23.22 \pm 0.1$ | 189 |

Table 11 continued on next page
Table 11 (continued)

| Name | Spectral type |  |  |  | Binary Reference |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Combined | UCD Primary | UCD Secondary | Adopted Distance (pc) |  |  |
| References- (10) Leinert et al. (1994); (13) Gizis et al. (2003); (22) Gizis et al. (2001); (51) Rebolo et al. (1998); (54) Close et al. (2003); (71) Gauza et al. (2015); (72) Burgasser et al. (2015b); (74) Patience et al. (2002); (83) Martín et al. (2000); (95) Luhman \& Sheppard (2014); (96) McElwain \& Burgasser (2006); (97) Radigan et al. (2008); (98) Schneider et al. (2011); (102) Newton et al. (2014); (104) Luhman et al. (2012); (105) Folkes et al. (2012); (112) Dupuy et al. (2009); (120) Forveille et al. (2005); (126) Siegler et al. (2005); (137) Law et al. (2006); (149) SpeX Prism Library; (150) Knapp et al. (2004); (156) Allers \& Liu (2013); (164) Stumpf et al. (2008); (167) Burgasser et al. (2011b); (168) Bowler et al. (2010); (170) Forveille et al. (2004); (172) Burgasser et al. (2007b); (176) Liu et al. (2002); (177) Ireland et al. (2008); (178) Dupuy \& Liu (2012); (182) Konopacky et al. (2010); (190) Scholz et al. (2004a); (199) Burgasser et al. (2008a); (200) ?; (201) Montagnier et al. (2006); (202) Reid et al. (2006); (203) Seifahrt et al. (2005); (204) Smith et al. (2015); (205) Freed et al. (2003); (206) Martin et al. (1999); (207) Dupuy et al. (2016); (208) van Biesbroeck (1961); (209) ?; (210) Dahn et al. (2017); (211) Bouy et al. (2003); (212) Biller et al. (2006); (213) Siegler et al. (2007); (214) Kirkpatrick et al. (2001b); (215) Burgasser et al. (2006). |  |  |  |  |  |  |
| ${ }^{a}$ Member of extended $25 p c+1 \sigma$ sample. |  |  |  |  |  |  |

Table 13. Selection functions for trigonometric and spectrophotometric distance cuts per spectral type bin.

| SpT <br> (1) | Total <br> (2) | Intrinsic <br> (3) | Observed <br> Selected |  | Selection <br> Function |  | Observed Not Selected |  | Fraction <br> Missed |  | Not Intrinsic <br> (12) | Observed <br> Selected |  | False Positive <br> Fraction |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Trig <br> (4) | Phot <br> (5) | Trig <br> (6) | Phot <br> (7) | Trig <br> (8) | Phot <br> (9) | Trig <br> (10) | Phot <br> (11) |  | Trig <br> (13) | Phot <br> (14) | Trig <br> (15) | Phot <br> (16) |
| M5 | 189460 | 23612 | 2129 | 2123 | 0.09 | 0.09 | 38 | 44 | 0.00 | 0.00 | 165848 | 174 | 2400 | 0.01 | 0.12 |
| M6 | 173166 | 21535 | 4475 | 4469 | 0.21 | 0.21 | 106 | 112 | 0.00 | 0.01 | 151631 | 353 | 4517 | 0.02 | 0.24 |
| M7 | 75002 | 9459 | 6704 | 6113 | 0.71 | 0.65 | 181 | 772 | 0.02 | 0.08 | 65543 | 490 | 2417 | 0.06 | 0.30 |
| M8 | 51619 | 6490 | 5946 | 5210 | 0.92 | 0.80 | 160 | 896 | 0.02 | 0.14 | 45129 | 461 | 1726 | 0.08 | 0.31 |
| M9 | 80893 | 10141 | 9861 | 8282 | 0.97 | 0.82 | 251 | 1830 | 0.02 | 0.18 | 70752 | 763 | 2347 | 0.09 | 0.27 |
| L0 | 83302 | 10572 | 10305 | 8427 | 0.97 | 0.80 | 267 | 2145 | 0.03 | 0.20 | 72730 | 754 | 2192 | 0.08 | 0.24 |
| L1 | 54934 | 6926 | 6770 | 5562 | 0.98 | 0.80 | 156 | 1364 | 0.02 | 0.20 | 48008 | 528 | 1581 | 0.09 | 0.26 |
| L2 | 44754 | 5574 | 5438 | 4416 | 0.98 | 0.79 | 134 | 1156 | 0.02 | 0.21 | 39180 | 392 | 1296 | 0.08 | 0.26 |
| L3 | 51654 | 6413 | 6248 | 5146 | 0.97 | 0.80 | 143 | 1245 | 0.02 | 0.19 | 45241 | 462 | 1688 | 0.08 | 0.30 |
| L4 | 52264 | 6542 | 6039 | 5035 | 0.92 | 0.77 | 149 | 1153 | 0.02 | 0.18 | 45722 | 442 | 1444 | 0.08 | 0.25 |
| L5 | 55985 | 7098 | 4869 | 3767 | 0.69 | 0.53 | 121 | 1223 | 0.02 | 0.17 | 48887 | 400 | 639 | 0.07 | 0.10 |
| L6 | 51527 | 6484 | 1856 | 1250 | 0.29 | 0.19 | 47 | 653 | 0.01 | 0.10 | 45043 | 160 | 63 | 0.03 | 0.01 |

Note-Columns: (1) Spectral type bins; (2) Number of objects per bin; (3) Number of true objects per spectral
type bin within 25 pc , i.e. intrinsic objects; (4) Number of intrinsic objects selected by an observed parallax cut at 25 pc ; (5) Number of intrinsic objects selected by an observed spectrophotometric distance cut at 25 pc ; (6) Selection function by parallax, i.e. fraction of intrinsic objects selected by their parallax cut at 25 pc ; (7) Selection function by spectrophotometric distance; (8) Number of intrinsic objects not selected by a trigonometric cut at 25 pc ; (9) Number of intrinsic objects not selected by a spectrophotometric cut at 25 pc ; (10) Fraction of intrinsic objects missed by a trigonometric cut at 25 pc ; (11) Fraction of intrinsic objects missed by a spectrophotometric cut at 25 pc ; (12) Number of objects per spectral type bin outside of 25 pc ; i.e. non-members (13) Number of non-members selected by an observed parallax cut at 25 pc ; (10) Number of non-members selected by an observed
spectrophotometric distance cut at 25 pc ; (11) False positive rate for trigonometric selection; (12) False positive rate for spectrophotometric selection.
Table 14. Selection functions for trigonometric and spectrophotometric distance cuts per absolute magnitude bin.

| $\mathrm{M}_{J}$ | Total | Intrinsic | Observed <br> Selected |  | Selection <br> Function |  | Observed <br> Not Selected |  | Fraction <br> Missed |  | Not Intrinsic(12) | Observed <br> Selected |  | False Positive Fraction |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| (1) | (2) | (3) | Trig <br> (4) | Phot <br> (5) | Trig <br> (6) | Phot <br> (7) | Trig <br> (8) | Phot <br> (9) | Trig <br> (10) | Phot <br> (11) |  | Trig <br> (13) | Phot <br> (14) | Trig <br> (15) | Phot <br> (16) |
| 9.75 | 161816 | 20008 | 2962 | 3155 | 0.15 | 0.16 | 39 | 98 | 0.00 | 0.00 | 141808 | 272 | 4129 | 0.02 | 0.23 |
| 10.25 | 186252 | 23385 | 6363 | 6346 | 0.27 | 0.27 | 128 | 336 | 0.01 | 0.01 | 162867 | 451 | 4531 | 0.02 | 0.22 |
| 10.75 | 117183 | 14691 | 9628 | 8925 | 0.66 | 0.61 | 221 | 1099 | 0.02 | 0.07 | 102492 | 715 | 3561 | 0.06 | 0.28 |
| 11.25 | 101656 | 12726 | 11672 | 10136 | 0.92 | 0.80 | 268 | 1998 | 0.02 | 0.16 | 88930 | 899 | 3285 | 0.08 | 0.30 |
| 11.75 | 94099 | 11843 | 11358 | 9325 | 0.96 | 0.79 | 272 | 2472 | 0.02 | 0.21 | 82256 | 811 | 2585 | 0.08 | 0.25 |
| 12.25 | 75482 | 9411 | 9022 | 7296 | 0.96 | 0.78 | 218 | 2080 | 0.02 | 0.22 | 66071 | 568 | 2228 | 0.07 | 0.27 |
| 12.75 | 70205 | 8823 | 8099 | 6675 | 0.92 | 0.76 | 174 | 1728 | 0.02 | 0.20 | 61382 | 435 | 2059 | 0.06 | 0.27 |
| 13.25 | 71507 | 8952 | 6788 | 5510 | 0.76 | 0.62 | 179 | 1608 | 0.02 | 0.18 | 62555 | 199 | 1122 | 0.03 | 0.14 |
| 13.75 | 55588 | 6908 | 3669 | 2657 | 0.53 | 0.38 | 86 | 1278 | 0.01 | 0.19 | 48680 | 70 | 270 | 0.01 | 0.04 |

Note-Columns: (1) Bins of absolute magnitude in J-band; (2) Number of objects per bin; (3) Number of true objects per absolute magnitude bin within 25 pc, i.e. intrinsic objects; (4) Number of intrinsic objects selected by an observed parallax cut at 25 pc ; (5) Number of intrinsic objects selected by an observed spectrophotometric distance cut at $25 \mathrm{pc} ;(6)$ Selection function by parallax, i.e. fraction of intrinsic objects selected by their parallax
cut at $25 \mathrm{pc} ; ~(7)$ Selection function by spectrophotometric distance; (8) Number of intrinsic objects not selected by a trigonometric cut at 25 pc ; (9) Number of intrinsic objects not selected by a spectrophotometric cut at 25 pc ; (10) Number of true objects per absolute magnitude bin outside of 25 pc; i.e. extrinsic objects; (11) Number of extrinsic objects with observed trigonometric distances within 25 pc ; (12) Number of extrinsic objects with observed spectrophotometric distances within 25 pc ; (13) Number of extrinsic objects selected by an observed parallax cut at 25 pc; (14) Number of extrinsic objects selected by an observed spectrophotometric distance cut at 25 pc; (15) False positive rate for parallax selection; (16) False positive rate for spectrophotometric selection.

Table 17. Number Densities by Spectral Subtype in units of object $p c^{-3}$.

| Spectral Type | Cruz et al. (2007) | Reid et al. (2008) | Kirkpatrick et al. (2012) | N* | Raw | SF-corrected |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| M5 | $\cdots$ | ... | $6.99_{-1.59}^{+2.05} \times 10^{-3}$ | $\ldots$ | $\ldots$ |  |
| M6 | $\ldots$ | $9.50_{-4.70}^{+9.50} \times 10^{-5}$ | $1.07_{-0.20}^{+0.25} \times 10^{-2}$ | $\ldots$ | $\ldots$ | $\ldots$ |
| M7 | $1.08{ }_{-0.26}^{+0.34} \times 10^{-3}$ | $9.50_{-4.70}^{+9.50} \times 10^{-5}$ | $1.40_{-0.61}^{+1.07} \times 10^{-3}$ | 64 | $1.54_{-0.18}^{+0.21} \times 10^{-3}$ | $3.20_{-0.27}^{+0.29} \times 10^{-3}$ |
| M8 | $3.73_{-0.52}^{+0.60} \times 10^{-3}$ | $9.47_{-1.89}^{+2.37} \times 10^{-4}$ | $2.33_{-0.84}^{+1.30} \times 10^{-3}$ | 61 | $1.47_{-0.18}^{+0.20} \times 10^{-3}$ | $2.34_{-0.23}^{+0.25} \times 10^{-3}$ |
| M9 | $9.95{ }_{-2.49}^{+3.32} \times 10^{-4}$ | $8.53_{-1.79}^{+2.26} \times 10^{-4}$ | $9.33_{-4.66}^{+9.33} \times 10^{-4}$ | 44 | $1.06{ }_{-0.15}^{+0.17} \times 10^{-3}$ | $1.588_{-0.18}^{+0.21} \times 10^{-3}$ |
| L0 | $6.63-1.97 \times 10^{-4}$ | $5.688_{-1.42}^{+1.89} \times 10^{-4}$ | $4.66_{-2.88}^{+7.54} \times 10^{-4}$ | 21 | $5.04{ }_{-0.99}^{+1.23} \times 10^{-4}$ | $7.50_{-1.23}^{+1.47} \times 10^{-4}$ |
| L1 | $4.97_{-1.66}^{+2.49} \times 10^{-4}$ | $2.37{ }_{-0.85}^{+1.32} \times 10^{-4}$ | ... | 28 | $6.72_{-1.16}^{+1.40} \times 10^{-4}$ | $1.02_{-0.15}^{+0.17} \times 10^{-3}$ |
| L2 | $8.29{ }_{-2.24}^{+3.07} \times 10^{-4}$ | $3.79_{-1.12}^{+1.60} \times 10^{-4}$ | $\cdots$ | 21 | $5.04{ }_{-0.99}^{+1.23} \times 10^{-4}$ | $7.75{ }_{-1.26}^{+1.50} \times 10^{-4}$ |
| L3 | $4.14_{-1.48}^{+2.31} \times 10^{-4}$ | $2.37{ }_{-0.85}^{+1.32} \times 10^{-4}$ | $\cdots$ | 16 | $3.84{ }_{-0.86}^{+1.10} \times 10^{-4}$ | $5.80_{-1.07}^{+1.31} \times 10^{-4}$ |
| L4 | $5.80{ }_{-1.82}^{+2.65} \times 10^{-4}$ | $3.79_{-1.12}^{+1.60} \times 10^{-4}$ | $\ldots$ | 23 | $5.52_{-1.05}^{+1.29} \times 10^{-4}$ | $8.75{ }_{-1.34}^{+1.58} \times 10^{-4}$ |
| L5 | $4.97{ }_{-1.66}^{+2.49} \times 10^{-4}$ | $3.32_{-1.04}^{+1.51} \times 10^{-4}$ | $4.66_{-2.88}^{+7.54} \times 10^{-4}$ | 28 | $6.72_{-1.16}^{+1.40} \times 10^{-4}$ | $1.44_{-0.18}^{+0.20} \times 10^{-3}$ |
| L6 | $4.14_{-1.48}^{+2.31} \times 10^{-4}$ | $2.84_{-0.95}^{+1.42} \times 10^{-4}$ | ... | $\cdots$ | ... | ... |
| L7 | $7.46_{-2.11}^{+2.94} \times 10^{-4}$ | $4.70_{-2.90}^{+7.70} \times 10^{-5}$ | $\cdots$ | $\cdots$ | $\ldots$ |  |
| L8 | $4.97_{-1.66}^{+2.49} \times 10^{-4}$ | $1.42_{-0.62}^{+1.09} \times 10^{-4}$ | $\cdots$ | $\cdots$ | $\cdots$ | $\ldots$ |
| M7-M9.5 | ... | ... | $\ldots$ | 169 | $(4.1 \pm 0.3) \times 10^{-3}$ | $(7.1 \pm 0.5) \times 10^{-3}$ |
| L0-L5 | $\cdots$ | $\cdots$ | . | 137 | $(3.3 \pm 0.3) \times 10^{-3}$ | $(5.4 \pm 0.4) \times 10^{-3}$ |
| M7-L5 | $\cdots$ | $\cdots$ | $\cdots$ | 306 | $(7.3 \pm 0.4) \times 10^{-3}$ | $(12.6 \pm 0.6) \times 10^{-3}$ |

* Number of sources within 25 pc , declinations accessible by SpeX ( $-50^{\circ} \leq \delta \leq+67^{\circ}$ ), and galactic latitudes outside of $\pm 15^{\circ}$ from the plane.

Note-The units for all values are $\mathrm{pc}^{-3}$. These number densities take into account the sky coverage in each survey, but not the survey incompleteness. For the 20 pc sample of Cruz et al. (2007) the volume coverage is $36 \%$, for the Reid et al. (2008) survey of the same volume, the coverage is $63 \%$. For the Kirkpatrick et al. (2012) 8 pc sample, the volume coverage is $100 \%$. For this study, the volume coverage is $63.6 \pm 0.59 \%$. Uncertainties are calculated from Poisson statistics.

Table 18. Luminosity Function.

| $M_{J}$ | N | $\mathrm{~N}_{\text {trig }}$ | $\mathrm{N}_{\text {phot }}$ | SFplx | SFphot | $\mathrm{N}_{\text {corrected }}$ | Density $\left(\mathrm{mag} \mathrm{pc}^{-3}\right)$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 9.75 | 4 | 4 | 0 | 0.15 | 0.16 | 38.65 | $9.28_{-1.39}^{+1.62} \times 10^{-4}$ |
| 10.25 | 51 | 41 | 10 | 0.27 | 0.27 | 273.75 | $6.57_{-0.39}^{+4.14} \times 10^{-3}$ |
| 10.75 | 68 | 60 | 8 | 0.66 | 0.61 | 150.76 | $3.62_{-0.29}^{+0.31} \times 10^{-3}$ |
| 11.25 | 50 | 49 | 1 | 0.92 | 0.80 | 79.00 | $1.90_{-0.20}^{+0.23} \times 10^{-3}$ |
| 11.75 | 41 | 39 | 2 | 0.96 | 0.79 | 62.55 | $1.50_{-0.18}^{+0.20} \times 10^{-3}$ |
| 12.25 | 30 | 28 | 2 | 0.96 | 0.78 | 45.99 | $1.10_{-0.15}^{+0.18} \times 10^{-3}$ |
| 12.75 | 25 | 24 | 1 | 0.92 | 0.76 | 39.71 | $9.54_{-1.41}^{+1.65} \times 10^{-4}$ |
| 13.25 | 26 | 24 | 2 | 0.76 | 0.62 | 50.44 | $1.21_{-0.16}^{+0.18} \times 10^{-3}$ |
| 13.75 | 16 | 14 | 2 | 0.53 | 0.38 | 45.91 | $1.10_{-0.15}^{+0.18} \times 10^{-3}$ |


[^0]:    * AMNH Kalbfleisch Fellow.

[^1]:    ${ }^{1}$ This study also converted an earlier luminosity function of the 8 pc sample in $V$-band from Reid et al. (2003a) into $J$-band magnitudes.

[^2]:    ${ }^{2}$ Available at https://github.com/daniellabardalezgagliuffi/M7L5_download_phot
    ${ }^{3}$ Except for GJ 1116B, where only unresolved photometry for the system was available (Newton et al. 2014). Several companions and close binaries do not have magnitudes in all three 2MASS bands (e.g., Gl 779 B, LSPM J1314+1320AB, LHS 1901AB).
    ${ }^{4}$ https://jgagneastro.wordpress.com/list-of-ultracool-dwarfs/

[^3]:    ${ }^{5}$ Objects with an adopted spectral type outside of the M7-L5 range have an optical spectral type also outside the range, but either a NIR or photometric type estimation within the range.
    ${ }^{6}$ GJ 1116 AB only has unresolved photometry, so we do not count the B component in this calculation. Gl 779B only has $K_{S}$ photometry, so it is excluded as well.

[^4]:    ${ }^{7}$ When identifying spectral binaries via spectral indices alone, objects with a bluer spectral slope are often false positives that are rejected by visual inspection of their binary template fits.
    ${ }^{8}$ The boundaries of the parameter spaces were modified in Bardalez Gagliuffi et al. (2015) to include the M9+T5 spectral binary WISE J072003.20-084651.2 (Scholz 2014; Burgasser et al. 2015b).

[^5]:    ${ }^{9}$ I.e. spectra of secondaries are not counted in the calculation since we are only concerned with the number of systems, neither do spectra of UCD components of higher order systems.
    ${ }^{10}$ Eight matches to the WDS were ruled out in the notes from the Sixth Catalog of Orbits of Visual Binary Stars, found at https://ad.usno.navy.mil/wds/orb6/orb6notes.html. 2MASS J0355 + 1603 was refuted as a binary in Faherty et al. (2013b), and 6 other sources are only binary candidates, so are not considered in our binary statistics.

[^6]:    ${ }^{11}$ In their 6.5 pc volume literature study, Bihain \& Scholz (2016) identify $48.5 \%$ of stars and $15.4 \%$ of brown dwarfs as part of multiple systems, but no combined UCD fraction.

[^7]:    12 See 2MASS Explanatory Supplement, https://old.ipac.caltech.edu/2mass/releases/ second/doc/

[^8]:    13 Systems with a magnitude offset larger than 0.75 (corresponding to an equal mass binary) occurred when the secondary was slightly brighter than the primary in any band as allowed by the added scatter, despite a larger primary mass. This is the case for 33,194 sources, $3.3 \%$ of the simulated sample or $16.6 \%$ of the simulated binaries. All of these systems were dropped from the simulation, resulting in 964,560 objects total.

[^9]:    14 We made an exception to prioritize literature NIR over SpeX classification for 2MASS J22521073-1730134A, which has a literature NIR spectral type of L4, no literature optical spectral type, and an unresolved SpeX spectral type of T0.

[^10]:    Note-This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.

[^11]:    ${ }^{a}$ Magnitudes are for combined system.
    ${ }^{b}$ Background source.
    Note-This table is available in its entirety in a machine-readable form in the online journal.

