



Ultracool and brown dwarf candidates identified via CatWISE-2MASS-Gaia DR3

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Abstract

Ultracool and brown dwarf candidates ($d_{\odot} \lesssim 125$ pc, $|b| > 8^{\circ}$) were identified via multiband and astrometric data from CatWISE ($W_1 W_2$), 2MASS ($J H K_s$), and Gaia DR3 ($G, G_{RP}, \pi, \mu_{\alpha}, \mu_{\delta}$). $N \approx 11.8 \times 10^3$ candidates emerged once simultaneously constrained by color and absolute magnitude criteria (e.g., $G - W_2 \geq 1.75(G - J) - 2.25$), whereby $\simeq 350$ sources are absent from the Gaia Ultracool Dwarf (UCD) catalog. Spectral types were approximated using a hybrid $M_G - M_{W_1}$ sigmoid that offers additional temperature coverage in certain cases. Subsequent efforts may focus on extending sampling to the deeper NIR VVVX footprint that partly encompasses the Galactic plane, and over the long-term spectroscopically (in)validating candidates missing from the Gaia UCD database.

Keywords Brown dwarfs (185) · M dwarf stars (982)

1 Introduction

Ultracool dwarfs occupy the M7V and later spectroscopic regime (e.g., Kirkpatrick et al. 1997). Continued census efforts may facilitate delineating the hydrogen-deuterium fusion boundary and other insightful transitions (e.g., Dieterich et al. 2014), and more broadly, brown dwarfs are lucrative targets for exoplanet search campaigns (e.g., Delrez et al. 2018). Indeed, the multiplanetary TRAPPIST-1 system features an M8V host (Gillon et al. 2017). Toward expand-

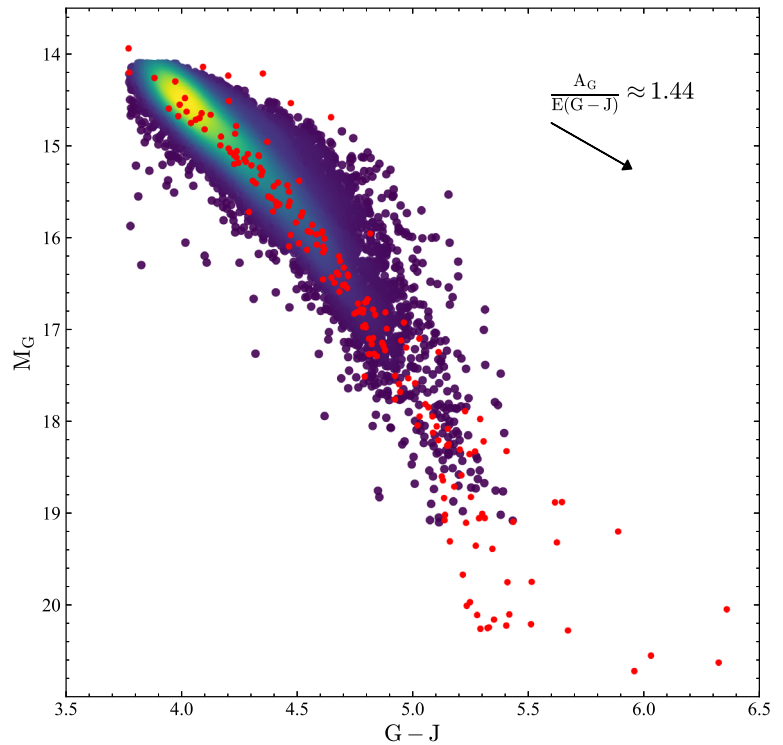
ing the population of known ultracool dwarfs, for example, Reylé (2018) exploited Gaia DR2 to identify 679 new L-dwarf candidates. Smart et al. (2019) likewise employed DR2 and detailed 695 targets (M8–T6), of which 20 were newly discovered multiple systems. Golovin et al. (2023) compiled the Fifth Catalogue of Nearby Stars (CNS5), and characterized 701 brown dwarfs within $d < 25$ pc.

In this study, CatWISE ($W_1 W_2$, Marocco et al. 2021), 2MASS ($J H K_s$, Cutri et al. 2003), and Gaia DR3 ($G, G_{RP}, \pi, \mu_{\alpha}, \mu_{\delta}$, Gaia Collaboration et al. 2023b) are mobilized to expand the population of ultracool dwarfs (e.g., add to the Gaia Ultracool Dwarf (UCD) catalog, Creevey et al. 2023; Sarro et al. 2023, and references therein). An emphasis is placed on leveraging multiband and astrometric criteria to mitigate false-positives. CatWISE provides enhanced $W_1 W_2$ photometry, and for example, Marocco et al. (2021) note the temporal baseline is markedly enhanced relative to ALLWISE. Gaia provides key astrometric constraints which fosters matching to absolute magnitudes endemic to the ultracool domain (e.g., Reylé 2018, DR2). Specifically, Kirkpatrick et al. (2024, 20 pc sample) supplied a calibrating dataset that is exploited to help unveil ultracool dwarfs via photometric cuts (Figs. 1, 2), and is utilized to construct a hybrid spectral type estimator across the temperature domain (Fig. 3).

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Fig. 1 Ultracool candidates identified by pairing MIR CatWISE, NIR 2MASS, and optical Gaia DR3 ($N \approx 11.8 \times 10^3$, $d_\odot \lesssim 125$ pc, $|b| > 8^\circ$), and adopting conservative photometric and astrometric criteria to mitigate false-positives (§2). $N \simeq 350$ sources are absent from the Gaia UCD database (Fig. 2), while 11,402 targets are found therein. The candidate distribution aligns with the trend delineated by the red datapoints (M7 and cooler, Kirkpatrick et al. 2024)



2 Analysis

Photometric culling criteria stemmed from an analysis of the Kirkpatrick et al. (2024) dataset (Fig. 1), and in particular the M7V designated LSR J0515+5911. Breadth was afforded for photometric uncertainties and peculiarities by adopting a $0^m.2$ buffer, relative to that star's absolute magnitudes (G , G_{RP} , J , H , K_s , W_1 , W_2). Similarly, the implied colors $G - G_{RP}$, $G - J$, $G - W_1$, $J - K_s$ were likewise adjusted by that amount (e.g., $J - K_s \gtrsim 4.5$). Subsequent cuts of $W_1 - W_2 > 0.1$ and $G - W_2 \geq 1.75(G - J) - 2.25$ were implemented to mitigate a redward $G - J$ plume (see also §2.1 of Sarro et al. 2023). 2MASS photometry was restricted to QFlg=AAA, and uncertainties in all bands were required. The forthcoming Euclid survey shall provide a marked improvement relative to 2MASS limits (e.g., $\Delta J \simeq 7^m.5$), although with less spatial coverage (i.e., $\simeq \frac{1}{3}$ all-sky). Indeed, the aforementioned faintness constraints on T dwarfs are apparent in Fig. 2 (see also Reylé 2024, their Fig. 5), and a subset of culling criteria are highlighted thereon.

The following constraints were adopted to reduce parallax uncertainties from offsetting absolute magnitudes: $\pi > 8$ mas ($d_\odot \lesssim 125$), $\text{RUWE} < 1.4$, and $\text{RPlx} > 8$ (*parallax over error*, e.g., 10σ was selected by Reylé 2018). The RUWE criterion ensured that the optimal 5-parameter Gaia solution was utilized, and hence all candidates feature proper motions. A positional criterion of $|b| > 8^\circ$ was imposed to lessen confusion from different objects, and minimize the introduction of hotter reddened stars. A separate initiative will build upon existing efforts (Beamin et al. 2014;

Mejías et al. 2022) to investigate ultracool dwarfs within the VVV/VVVX footprint (i.e., covering portions of the Galactic plane, Minniti et al. 2010; Saito et al. 2012, 2024). For example, Mejías et al. (2022) indicated the following could be ultracool dwarfs: Gaia EDR3 5697747496563028352 (M9), 5990656908867751808 (M7), 6062219761378864128 (M7), 5257810972787599360 (M7), 5409811755160786048 (M7), 5323745691499188736 (M7), 5693793442288873984 (M7).

A $25''$ matching radius was selected between Gaia and 2MASS, and thereafter relative to CatWISE. The criterion bolstered the detection of higher proper motion dwarfs. Sources that passed the aforementioned suite of criteria were classified as ultracool candidates (Fig. 1). Reassuringly, the curvature of the ultracool sequence emerges, and since it is unveiled primarily by limits inferred from an upper-end M7V calibrator: that implies the sample is primarily *bona fide* ultracool dwarfs. Indeed, 71% overlap with the Gaia UCD catalog's golden subsample (Gaia Collaboration et al. 2023a), 11,402 from a total of 11,753 sources presented here are in the broader UCD database (i.e., 97%, whereby the full UCD catalog extends to $\pi > 1.7$ mas and features 94×10^3 entries). That points to $\simeq 350$ missing datapoints. Relative to Reylé (2018), Smart et al. (2019), and Golovin et al. (2023, CNS5), from the missing sources 42, 27, and 12 overlap, accordingly. $N \simeq 276$ remain after removing duplicates with one preliminary candidate featuring $d < 25$ pc (3591011474602344320), and the mode is approximately a magnitude fainter than the overlapping UCD sample (i.e., $G \simeq 20^m.6$). That subset partly emerges from DR3 improve-

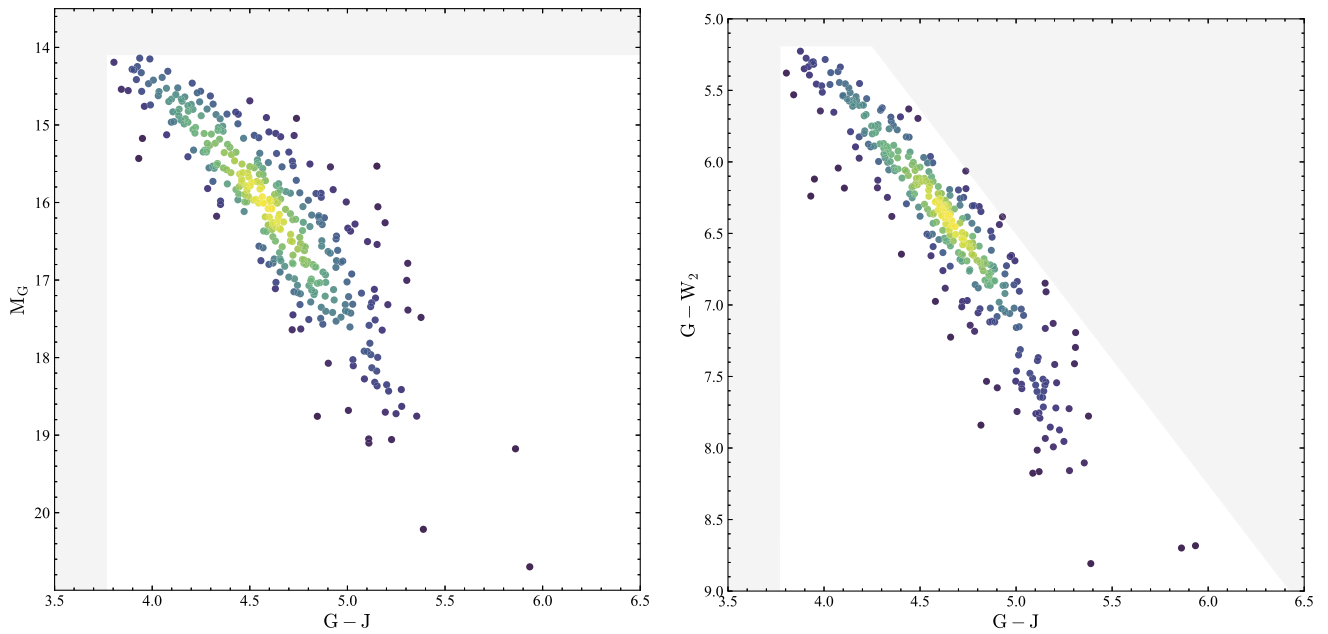
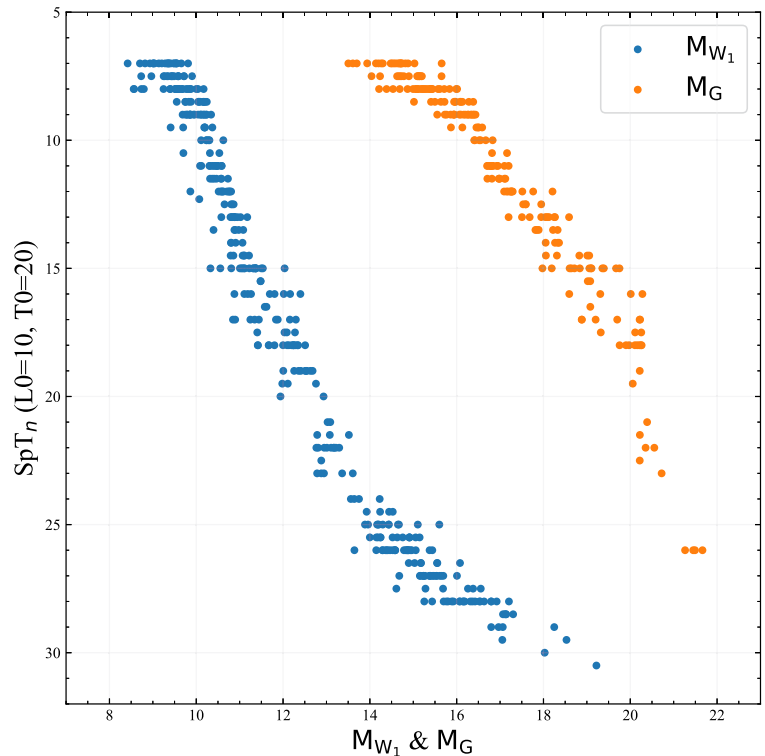


Fig. 2 Ultracool dwarf candidates absent from the Gaia UCD. Possibly $\simeq 77\%$ are not featured in complementary catalogs examined, however, there may be research the authors are inevitably unfamiliar with, and duplicates may exist. Long-term spectroscopic follow-up shall proceed for brighter targets (e.g., a potential offshoot of the envisioned KMOS VVVX-GalCen initiative), which will eliminate false-positives

emerging solely from photometry and astrometry, and owing to confusion arising from the sampling radius. Gray regions represent color and absolute magnitude cuts, and the dearth in candidates arises from faintness limits (e.g., 2MASS $J \lesssim 16^m.3$, and for Gaia G see Fig. 5 in Reylé 2024). Hence an advantage of VVVX and Euclid

Fig. 3 M_{W_1} (blue datapoints) can provide spectral coverage toward cooler brown dwarfs. A hybrid $M_G - M_{W_1}$ function (see text) was constructed to provide *approximate* spectral types for the ultracool dwarf catalog assembled. A sigmoid regulates the changeover from M_G for hotter candidates to M_{W_1} for cooler targets (Eqn. (1)). The subsample presented stems from Kirkpatrick et al. (2024)



ments and additional sampling of fainter targets, relative to DR2.

Figure 1 hosts $\approx 11.8 \times 10^3$ candidates, and the data will be made available as a CDS VizieR catalog. Table 1

Table 1 Subsample of ultracool dwarfs

Gaia DR3	π (mas)	μ (mas yr ⁻¹)	G	G_{RP}	J	H	K_s	W_1	W_2	Ref.	SpT
4703216410071320832	17.6	104	20.67	19.14	16.02	15.15	14.57	14.37	14.10	R18	L2
2308116769195247360	12.4	186	20.49	18.98	15.96	15.29	14.76	14.61	14.36	—	M9
2423078853137423488	23.0	179	20.55	18.95	15.68	14.82	14.50	13.88	13.52	—	L3
5178144483388552832	13.0	344	20.61	19.07	16.03	15.42	14.85	14.59	14.33	—	L0
4722209515662513920	18.9	458	20.66	19.05	15.81	15.12	14.68	14.17	13.95	—	L2
5107303911284277504	32.3	135	20.63	19.04	15.48	14.44	13.86	13.34	13.07	R18	L4
495947643267031040	15.2	32	20.44	18.90	15.78	15.03	14.51	14.08	13.71	—	L0
284894801473847296	11.3	31	20.61	19.10	15.97	15.29	14.88	14.52	14.30	—	M9
944440390446800768	18.0	114	20.56	19.03	15.72	14.91	14.26	13.90	13.73	—	L0
954562326987474304	10.8	110	20.38	18.92	15.86	15.19	14.88	14.48	14.27	—	M8
3361948739720043776	19.4	137	20.54	18.99	15.81	14.92	14.56	14.17	13.97	R18	L2
5193549977029793792	14.3	53	20.42	18.85	15.82	15.17	14.45	14.37	14.13	—	M9
901999138535923840	16.7	48	20.67	19.15	15.95	15.09	14.54	14.19	13.98	—	L1
907818338184084096	17.6	154	20.57	19.02	15.75	14.98	14.28	14.02	13.84	—	L1
587601798685457792	20.3	167	20.53	18.92	15.79	14.89	14.34	14.11	13.84	—	L3
5443893385806317440	18.8	123	20.13	18.58	15.41	14.56	14.30	13.66	13.48	R18	L0
723985800815301248	17.3	93	20.57	19.04	15.77	15.11	14.63	14.17	13.88	—	L1
3564538223902705280	27.1	134	20.76	19.19	15.66	14.60	14.02	13.50	13.20	—	L3
3808497893938381824	14.7	229	20.42	18.89	15.78	15.17	14.60	14.36	14.12	—	L0
3760469851647361664	15.6	64	20.53	19.00	15.90	15.13	14.65	14.52	14.26	—	L2
3814316135810315904	17.1	162	20.40	18.87	15.53	14.85	14.49	14.10	13.92	S19	L0
3812678894277121920	29.6	291	20.78	19.15	15.65	14.71	13.95	13.41	13.13	—	L3
3917930950515862272	17.9	267	20.47	18.93	15.70	14.93	14.42	14.05	13.82	—	L1
5379915930922278400	11.4	34	20.68	19.19	16.08	15.30	14.78	14.56	14.37	—	M9
3893817767165654400	29.0	242	20.68	19.11	15.53	14.55	14.02	13.45	13.14	S19	L3
1371557673804322176	13.8	64	20.83	19.29	16.07	15.38	14.87	14.56	14.22	—	L0
1631078603058453632	19.6	185	20.86	19.31	16.10	15.24	14.68	14.35	14.09	—	L3
1434750111746029056	12.4	100	20.05	18.50	15.50	14.90	14.45	14.12	13.98	—	M8
1421716951881370752	16.4	114	20.71	19.18	15.99	15.20	14.66	14.30	14.06	—	L1
2257578507499901312	28.3	178	20.55	18.93	15.44	14.60	14.13	13.34	13.19	—	L2
6733294760528587008	16.3	182	19.50	17.91	14.93	14.28	14.02	13.69	13.49	—	M8
4088155897620238336	14.7	169	20.13	18.58	15.61	14.97	14.52	14.33	14.16	—	M9
6773385703237821312	15.0	113	20.41	18.83	15.82	14.99	14.61	14.39	14.19	—	L0

Table 1 (Continued)

Gaia DR3	π (mas)	μ (mas yr ⁻¹)	G	G_{RP}	J	H	K_s	W_1	W_2	Ref.	SpT
1816087549148430848	37.5	393	20.45	18.90	15.31	14.36	13.75	13.11	12.93	—	L4
422893588971277824	11.5	112	20.71	19.25	16.07	15.32	14.79	14.35	14.16	—	M9
2663586537698797184	12.3	104	20.33	18.72	15.70	14.93	14.47	14.15	13.97	S19	M9
223322229000888064	39.7	209	20.63	19.10	15.35	14.39	13.65	12.92	12.47	CNS5	L4
2420682536264210944	15.8	257	20.61	18.99	15.87	15.11	14.67	14.41	14.23	—	L1
...											

The complete findings shall be available on CDS VizieR, and a portion of the database is relayed in terms of quantity and columns (e.g., the VizieR catalog will exhibit astrometric and photometric uncertainties). References include Reylé (2018, R18), Smart et al. (2019, S19), and Golovin et al. (2023, CNS5). Photometry stems from 2MASS (Cutri et al. 2003), CatWISE (Marocco et al. 2021), and Gaia DR3 (Gaia Collaboration et al. 2023b)

relays a subset of the information to be presented, such as a column indicating whether a target is featured in the Gaia UCD golden sample (UCD_golden), the broader Gaia UCD (UCD), Reylé (2018, R18), Smart et al. (2019, S19), Golovin et al. (2023, CNS5), or potentially missing (—). Admittedly, there is research the authors are invariably unaware of, and overlap may exist. $T_{\text{eff}} \pm \Delta T_{\text{eff}}$ from the Gaia UCD will be added to the VizieR catalog for overlapping entries, and rounded to the nearest integer.

Spectral type approximations were deduced via a sigmoid weighted $M_G - M_{W_1}$ function, in tandem with estimates from Reylé (2018) for overlapping entries. M_{W_1} provides complimentary constraints owing to increasing coverage across later spectral types (blue datapoints in Fig. 3). The sigmoid issues hotter dwarfs spectral types inferred from M_G , and thereafter a smooth transition occurs across early-L ($M_{W_1} = 10.3$) where estimates are from both M_G and M_{W_1} , and subsequently cooler candidates rely on M_{W_1} :

$$\begin{aligned} \text{SpT}_n &= w(42.52 - 5.70M_G + 0.225M_G^2) + (1 - w) \\ &\quad \times (-56.94 + 9.02M_{W_1} - 0.233M_{W_1}^2) \\ w &= (1 + e^{10(M_{W_1} - 10.3)})^{-1} \end{aligned} \quad (1)$$

M7V was adopted as the spectral type index number $\text{SpT}_n = 7$, L0 is 10, and T0 is 20 (see also Reylé 2018). The cited spectral type is merely indicative (Table 1), and the approach may be unsuitable for other objectives.

A reddening vector $A_G/E(G - J) \approx 1.44$ is displayed in Fig. 1 (Wang and Chen 2019, their Table 3). Importantly, an effort was made to minimize the impact of dust obscuration by instituting the $|b| > 8^\circ$ cutoff, together with an upper distance limit ($d < 125$ pc, and the median is ≈ 70 pc). Confusion arising from a background source in concert with reddening may foster false-positives for a comparatively marginal subsample, an assertion underpinned by the dataset naturally adhering to the intrinsic curvature of the calibrating sample (Figs. 1, 2).

3 Conclusions

A catalog of $N \approx 11.8 \times 10^3$ ultracool and brown dwarf candidates was produced (Figs. 1, 2), and is tied to observations from CatWISE, 2MASS, and Gaia DR3. Kirkpatrick et al. (2024) ultracool dwarf observations were utilized to infer the applied absolute magnitude and photometric color cuts. This initiative semi-independently contributes to overarching efforts aiming to characterize the relatively local ultracool demographic (e.g., Reylé 2018; Smart et al. 2019; Reylé et al. 2021; Sarro et al. 2023; Kirkpatrick et al. 2024; Ravinet et al. 2024). The catalog shall be posted to CDS VizieR (Table 1), and contains approximate spectral

types inferred from a hybrid $M_G - M_{W_1}$ function (Fig. 3, Eqn. (1)). In this instance a sigmoid was implemented to modulate the transition between M_G and M_{W_1} estimators across early-L.

A key next step is beginning a longer-term spectroscopic initiative to (in)validate candidates as done previously (e.g., VVV BD001 and WISE 2121-6239, Beamín et al. 2013, 2015). That undertaking may emerge as an offshoot from the forthcoming KMOS VVVX-GalCen project, and the observations may focus on brighter candidates absent from the Gaia UCD. For example, Beamín et al. (2013) acquired spectra for the L-dwarf VVV BD001 using the Folded-port InfraRed Echellette at the Magellan Baade telescope. Furthermore, bypassing or complementing the optical Gaia G-band faint limit by relying on NIR VVVX (π & μ) could result in expanded ultracool dwarf statistics (e.g., Beamín et al. 2013 exploited VVV photometry to establish π for VVV BD001), and determinations of such parallaxes continue improving. That may partly foster the identification of simultaneous color-color and absolute magnitude-color slope discontinuities across numerous passbands, which could aid demarcate pertinent transitions such as increasing atmospheric condensates, or the hydrogen-deuterium fusion boundary. More broadly atmospheric parameters, metallicity dependencies, and binaries may be characterized (e.g., Ravinet et al. 2024).

However, the deeper NIR VVVX footprint partly encompasses the Galactic plane where false-positives increase from confusion and reddening, and thus enhanced judiciousness is warranted. For example, earlier M-dwarfs near the M7V ultracool boundary may seep into the domain via reddening. For coverage beyond the Galactic plane the Euclid survey shall considerably surpass 2MASS JH limiting magnitudes, and can be paired with Gaia. Furthermore, the next release of low-resolution Gaia XP spectra shall provide a pertinent dataset for validating candidates (see also Sarro et al. 2023, and discussion therein).

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Data availability All data are available on CDS VizieR or within the published works cited.

Declarations

Competing interests The authors declare no competing interests.

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