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Brown dwarfs and isolated planets: fifteen years of a discovery

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Abstract

Since the discovery of the first brown dwarfs, Teide 1 and Gl 229 B in 1995 [74, 70], several hundreds of substellar objects have been discovered. During these fifteen years, the field of brown dwarfs has experimented a great development, only comparable to that carried out in the strongly related field of extrasolar planets. Substellar objects, on the contrary to stars, do not burn hydrogen in their interior, and this determines that their physical properties are very different. At the early stages, they contract, then their interior became degenerated, and later they evolve toward cooler temperatures when age. In this paper, I will review the most relevant results in the field of brown dwarfs and planetary-mass objects, with special interest in those that have taken place during last years. In particular, I will discuss the implications of recent works in the substellar mass function and the discovery of planetary-mass companions. Next, I will review the current knowledge of the physical properties and the evolution of substellar objects, acquired from the recent measurements of dynamical masses of brown dwarf binaries, transits around stellar primaries, and eclipsing brown dwarf binaries. Finally, I will discuss future perspective of the substellar field during the next years, in particular for the discovery of the coolest substellar objects in the solar vicinity and the future search for extrasolar planets around very low-mass stars and brown dwarfs.

1 Introduction

During the celebration of the IX Scientific Meeting of the Spanish Astronomical Society (September 13–17, 2010), we commemorated the 15th anniversary of the discovery of the first brown dwarf, Teide 1, published on 14 September 1995 [74]. Only two months later, the second brown dwarf, Gl229 B, was discovered in the solar vicinity [70]. Since then a lot of efforts have been carried out to identify and characterize the substellar population both in the field and in young open clusters. Hundreds of brown dwarfs and tens of isolated planetary-mass objects have been found in isolation or like companions of stars or other substellar objects [78, 29, 75, 44, 45].

1.1 Definition of brown dwarfs and planets

Brown dwarfs are substellar objects unable to stably burn hydrogen in its interior. For a solar metallicity, this corresponds to masses below $0.072\,\mathrm{M}_\odot$ [21]. Objects below $\sim 0.065\,\mathrm{M}_\odot$ [21] does not also burn lithium, and this property allowed to define a test of substellarity, the "lithium test", by observing the presence of this element in their atmosphere [73]. Brown dwarfs have intermediate masses between stars and planets, but while the separation with stars is well defined, the borderline between planets and brown dwarfs is still under debate. Some authors prefer to establish this separations based on their intrinsic physical properties and define planets like substellar objects that does not fuse deuterium, which for solar metallicity correspond to masses below $0.012\ \mathrm{M}_\odot$ [21]. Some other authors prefer to distinguish brown dwarfs and planets by their formation mechanisms. According to them, planets are substellar objects orbiting a star and formed in proto-planetary disks. Current IAU working definition indicates that objects with masses below the limiting mass for thermonuclear fusion of deuterium that orbit stars are "planets", substellar objects with masses above this limit are "brown dwarfs", and free-floating objects below the deuterium burning mass limit are not "planets". Hereafter, we will call them isolated planetary-mass objects.

1.2 Physical properties and formation of substellar objects

The interior of substellar objects is essentially a nearly totally ionized $\mathrm{H}^+/\mathrm{He}^{++}$ plasma and partially degenerated electron gas, and is entirely convective. As a consequence of the degeneration and the Coulomb pressure, the radius of these objects is almost constant in all the substellar regime, $\sim 1\,\mathrm{R}_\mathrm{Jup}$[20]. The main characteristic of substellar objects is that their central temperature is not high enough to burn hydrogen, and hence, on the contrary to stars, they do not reach a stable phase of "main sequence", and their physical properties change with time. After a initial phase of gravitational contraction, substellar objects continuously evolve getting cooler and fainter. Their effective temperature (T_eff) is below $\sim 3000\,\mathrm{K}$ and their luminosity is below $\log L/L_\odot < -1.5$ (see Fig. 1).

The atmospheres of brown dwarfs are very cool and their spectral energy distribution is dominated by the Collision Induced Absorption (CIA) of H_2 and H_2–He, the presence of strong molecular absorption bands (TiO, VO, H_2O, CO, CH_4,...) and the formation of dust grains at $T_\mathrm{eff} < 2800\mathrm{K}$ [2, 82]. Substellar studies have determined the definition of the two new "L" and "T" spectral classes (see Fig. 2). The L-type objects corresponds to $T_\mathrm{eff} = 2200-1500\mathrm{K}$. They are characterized in the optical by the disappearance of TiO, VO,... molecular bands due to the formation of dust grains, the presence of very strong alcaline lines (Li, Na, K, Rb, Cs,...) and hidrures (FeH, CrH), and in the near-infrared by strong water vapor absorption bands [44, 67]. The T-type objects corresponds to $T_\mathrm{eff} = 1500 - 600$ K and in their atmospheres the dust grains deposit below the photosphere. They are characterized by the disappearance of alcalines and hidrures in the optical and by the presence of very strong water vapor and the appearance of methane absorption bands in the infrared [12, 34].

There are two major set of models that try to explain the formation of substellar objects: those representing the extension of the stellar cores to lower masses, through processes of

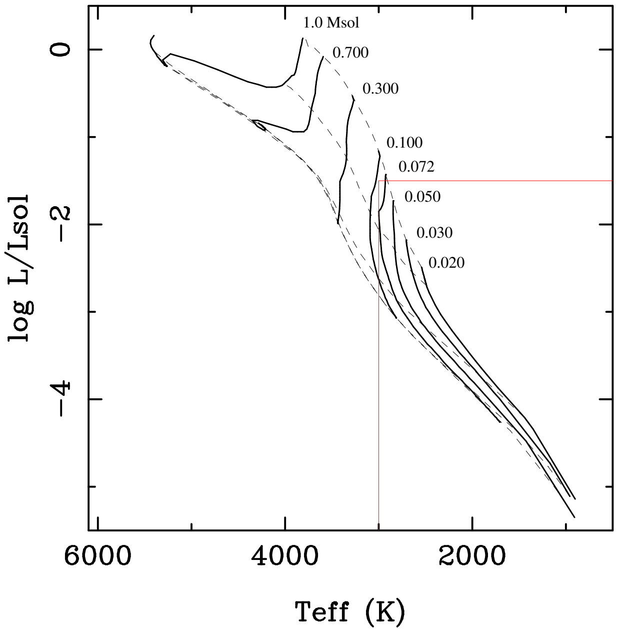

Figure 1: Luminosity–$T_{\rm eff}$ diagram. Theoretical evolutionary models of low-mass stars and brown dwarfs from the Lyon group are shown. Isochrones of 1, 10, 100 and 1000 Myr are also indicated by dashed lines. The region occupied by substellar objects are delimited by the vertical and horizontal line.

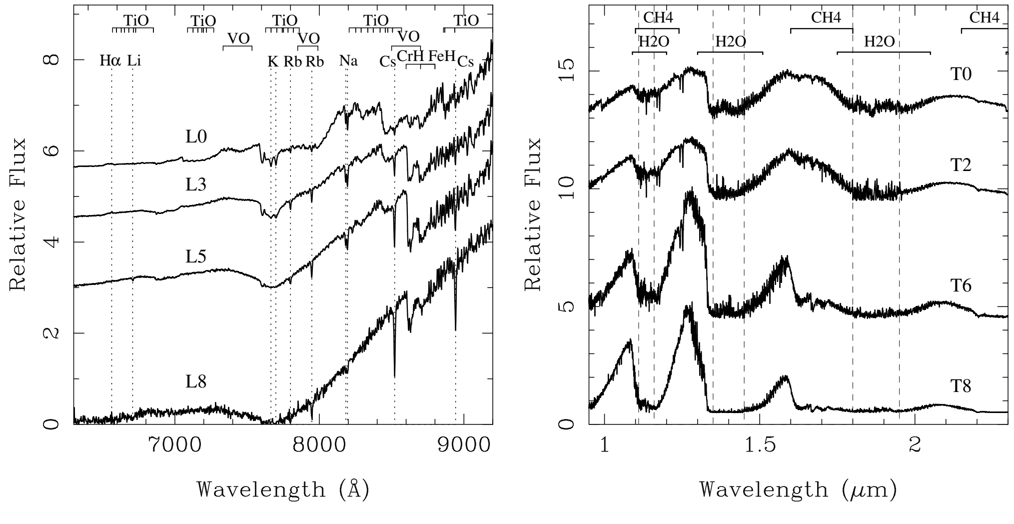

Figure 2: *Left*: Optical spectroscopy of L dwarfs. *Right*: Near-infrared spectroscopy of T dwarfs. Main spectral features are indicated. Spectra have been normalized at 8100Å and 1.0 μm, respectively, and have been shifted for clarity.

turbulent fragmentation, photo-ionization or dynamical ejection of proto-stellar cores, and those resulting from the core-accretion or fragmentation of protoplanetary discs, in a similar way than planets are expected to be formed. These objects can later be ejected and found in isolation (see the review by[85]).

2 Early discoveries

Since the discovery of the first confirmed brown dwarfs [74, 70], many searches for brown dwarfs were carried out in the field, in stellar clusters and like companions of stars in the solar vicinity. Most of these objects were late M and L dwarfs. The first L dwarf was identified like companion of the GD165 white dwarf [6], but it is still not clear its substellar nature. The first confirmed L brown dwarf was Kelu1, which was found in isolation in the field[78]. After this result several L dwarfs were also discovered in the field by the all-sky optical and near-infrared surveys 2MASS and DENIS [29, 43, 44, 45]. The first young L dwarf, Roque25, was found in the Pleiades open cluster [66]. Soon later the first young L dwarf companion was discovered around the nearby G196-3 star [75]. At the end of the previous century, the first L dwarfs in a star forming region were located in Orion [86]. According to theoretical evolutionary models, they correspond to masses below deuterium burning mass limit, and hence, they are the first isolated planetary-mass objects [55, 86]. In 2004, [22] obtained the first direct image of a planetary-mass companion: 2M1207b, around a brown dwarf in the TW Hya association. All of these objects are supposed to have a metallicity similar to the Sun, but recently the first low-metallicity L sub-dwarfs have also been reported [51, 13].

After the discovery and characterization of the first T dwarf, Gl229B around the star of the same name [70, 72], large coverage surveys like 2MASS or SLOAN were devoted to search for these objects. Today more than two hundreds of T dwarfs are known in the field, but only a few of them have been found in stellar clusters or associations. The first T-dwarf identified in a young star forming region was SOri 70 in the σ Orionis cluster [87], but its membership is still not confirmed. More recently, other general surveys like UKIDSS or dedicated ones have found some of the coolest T-dwarfs, with estimated temperatures around $500 - 600$ K [15, 16, 30].

All these discoveries allowed a detailed photometric and spectroscopic characterization of brown dwarfs and to determine their relative number with respect to stars. The mass spectrum, defined like the number of objets per interval of mass, have been determined in several stellar clusters and associations, and in the solar vicinity. This is a rising function toward lower masses in the whole brown dwarf domain (see[47] and references therein). This implies that brown dwarfs are very numerous, about 1/3 of the total number of stars, but their contribution in mass is lower than 10%.

3 Recent relevant results

In the last years, the field of substellar objects has experienced a significant development, evolving from the first discoveries to the precise characterization and determination of their physical properties. In this sense, it is notable the first measurement of parallaxes, luminosity and bolometric corrections of L and T field dwarfs [26, 83, 35]. One of the most significant results during that years was also the determination of dynamical masses of the brown dwarf binary GJ 569 B [89]. This was the first time that individual masses for brown dwarfs (~ 70 and 55 $M_{\rm Jup}$) were measured independently of theoretical evolutionary models. Two years later, the first eclipsing binary brown dwarf was discovered in the Orion Nebula [81]. This result allow to measure the $T_{\rm eff}$, radius and masses of very young low-mass brown dwarfs (0.054 ± 0.005 and 0.034 ± 0.003 $\rm M_\odot$) at very early stages of evolution, where they are still contracting ($R = 0.669 \pm 0.034$ and 0.511 ± 0.026 $\rm R_\odot$). More recently, COROT satellite discovered the transiting substellar companion COROT-Exo-3b, with an estimated mass of 21.66 ± 1.0 $\rm M_{Jup}$ and radius of 1.01 ± 0.07 $\rm R_{Jup}$ [28]. This result, although was not emphasized in the paper, confirms the theoretical prediction that old and degenerated brown dwarfs have a similar radius than Jupiter. In the last years, the dynamical masses of several very low-mass binaries have also been measured (see Table 1 and references therein), allowing a direct comparison with theoretical predictions. These works indicates that, although evolutionary models seem to be correct in general, they tend to subestimate the luminosity of substellar objects at a particular age, unless most of these brown dwarf binaries are younger than expected. In this sense, a precise determination of age for these systems is necessary. This is particularly interesting in substellar companions of solar type primaries, for which asterosismologic methods for determining the age can be applied.

Table 1: Dynamical masses of brown dwarf binaries

Name	Sp. Type	$M_{\rm Tot}$ ($\rm M_\odot$)	References
GJ 569 Bab	M8+M8.5	0.125 ± 0.005	[50, 89]
2M0746+20 AB	L0+L1.5	$0.146^{+0.016}_{-0.006}$	[10]
AB Dor C	M5.5	0.090 ± 0.005	[24]
2M0535-05 AB	M6.5+M6.5	0.088 ± 0.007	[81]
2M1534-29 AB	T5.0+T5.5	0.056 ± 0.003	[52]
GJ802 B	mid-L	0.063 ± 0.005^a	[39]
HD130948 BC	L4+L4	0.109 ± 0.003	[31]
LHS 2397 AB	M8+L7	$0.146^{+0.015}_{-0.013}$	[32]
2M2206-20 AB	M8+M8	$0.15^{+0.05}_{-0.03}$	[33]
ϵ Indi Bab	T1+T6	0.115 ± 0.001	[19]
2MASS 0920+35AB	L6.5+T2	0.11 ± 0.11	[46]
2MASS 1426+15AB	M8.5+L1	$0.11^{+0.08}_{-0.11}$	[46]
2MASS 1728+39AB	L7+L8	$0.15^{+0.25}_{-0.04}$	[46]
2MASS 2140+16AB	M8.5+L2	0.10 ± 0.08	[46]
LP 349-25AB	M8+M9	0.121 ± 0.009	[46]
LP 415-20AB	M7+M9.5	0.09 ± 0.06	[46]

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[a] Only the mass of the brown dwarf secondary is given

Another area of research that has progressed very rapidly during last years, specially after the launch of Spitzer satellite, is the study of discs around substellar objects. First evidence of the existence of accretion discs around brown dwarfs were found by [25, 71, 41, 69] based on the presence of near and mid-infrared excesses and broad, asymmetric Hα emission lines. Since then, many studies have determined the frequency of discs around substellar objects in several young clusters or associations (see Table 2 and references therein). These works indicate that the frequency of discs is similar in substellar objects than in low-mass stars. These results suggest that both stars and brown dwarfs may share a similar formation mechanisms and that planets can be formed around substellar objects. In this sense, evidence of the formation of planetesimals around brown dwarfs have been found by [3].

Table 2: Fraction of objects with mid-IR excesses in stellar clusters and associations

Region	brown dwarfs (%)	stars (%)	References
Taurus	40–80	61	[37, 61, 36]
IC348	42	33	[59]
Chamaeleon I	50–58	45–65	[59, 63, 27]
Chamaeleon II	80	80	[1]
σ Orionis	34–50	33	[18, 90, 38, 79, 62, 8]
λ Orionis	40	25	[5]
Upper Scorpius	11–50	>35	[11, 80, 77]
TW Hya	60	24	[76]

Since the discovery of the isolated planetary-mass objects, many studies have investigated the low-mass end of the mass function. Currently, more than 50 candidates with estimated masses below the deuterium burning mass limit are known in several young clusters and star forming regions. Most of them are located in the σ Orionis [86, 87, 88, 4, 68, 18, 9] and Trapezium clusters [55, 56, 57, 84], where half of these objects have spectroscopic information and several of them shows low gravity features and/or mid infrared excesses that confirm their membership. Other star forming regions where planetary-mass candidates have been found are Upper Scorpius [53, 54], Chamaeleon [58, 63], Taurus [64] and IC348 [14]. Recent determinations of the substellar mass spectrum indicate that this function is still rising down to ~ 6 $\mathrm{M_{Jup}}$, but may decrease below these masses [55, 9], which could be an indication that there is a minimum mass in the formation of these objects.

One of the most relevant discoveries of the last years in the substellar field has been the discovery of planetary-mass companions by direct image. The first one, 2M1207b, was found around the brown dwarf of the same name in the TW Hya [22]. Currently, only a few of these objects have been found at wide separations (8–700 AU) from young (1–100 Myr) stars and brown dwarfs [23, 40, 60, 7, 48, 65, 42, 49]. Notable cases are the discovery of the first planetary system around HR 8799 [65] and the determination of the orbital motion of several of these planetary-mass objects [65, 42]. All these works have allowed a detailed study of their spectra, which are very similar to those of isolated planetary-mass objects.

The effective temperature and the physical properties of their atmospheres resemble to those of the close-in giant planets found by radial velocity and transits techniques.

4 Future perspectives of the substellar field

It is expected that some of the most interesting results of substellar field in the next future will be related with some of the recent development mentioned in previous section. One of them is the determination of dynamical masses of substellar objects. The discovery of eclipsing and short period brown dwarf binaries in young clusters and associations will offer an unique opportunity to directly test evolutionary substellar models, providing dynamical masses, luminosities and other physical parameters of systems with well-known age and distances. Another area of research with a growing interest is the study of the low-mass end of the substellar mass function and in particular, the search for T-type objects in young star forming regions. All these works will allow us to determine whether there is a minimum mass in the formation of of isolated substellar objects and whether this mechanism is universal or not.

Another area of great interest in the substellar field is the study of objects cooler than T-dwarfs, i.e. the so called “Y” dwarfs, which correspond to $T_{\rm eff}$ below $\sim$500 K, a range of temperatures intermediate between brown dwarfs and the planets of our Solar System. According to theoretical models, they have estimated masses close or below the deuterium burning mass limit, and hence they are very low-mass brown dwarfs and giant planets. At these low temperatures their flux is shifted from the near-IR to the mid-IR. As can be seen from Fig. 3, while the absolute magnitude in the J-band for these objects is more than 10 mag fainter than for younger and more massive brown dwarfs, the absolute magnitude in the N-band varies by less than 5 mag. In this sense, searches using new mid-IR cameras like CanariCam at GTC and MIRI at JWST will be more sensitive for less massive and older substellar objects. While CanariCam could detect some of the coolest substellar companions with $T_{\rm eff}$ below $\sim$500 K in the solar vicinity, MIRI will detect these objects up to distances of 100 pc. Both instruments are equipped with high contrast capabilities, which allow to explore the presence of giant planets at the typical distances (< 30 AU) where they are found in our Solar System.

Another field where the study of brown dwarfs will be important is the search for rocky planets using the radial velocity technique. The discovery of a Earth-like planet in the Habitable Zone (HZ), defined as the region where liquid water can exists, is currently one of the major goals in Astrophysics. The amplitude of the radial velocity variations induced by a planet around very low-mass star or a brown dwarf is larger than around a more massive star and hence, it is easier to detect. For example an Earth-like planet in the HZ of a solar type stars produces a radial velocity variation of $10\,{\rm cm\,s^{-1}}$, while this is larger than $1\,{\rm m\,s^{-1}}$ in intermediate and late M stars and larger than $3\,{\rm m\,s^{-1}}$ below the star/brown dwarf borderline. In Fig. 4, it is represented the radial velocity variation amplitudes produced by planets with masses of 1, 3 an 10 $M_\oplus$ orbiting around very low-mass stars and brown dwarfs in the HZ. Assuming a radial velocity precision of $1{\rm m\,s^{-1}}$, we can see from this figure that planets with masses below 3 and 1 $M_\oplus$ can be detected at a 3-σ level around objects with spectral types later than M5.5 and L2.5, respectively. The only inconvenient is that

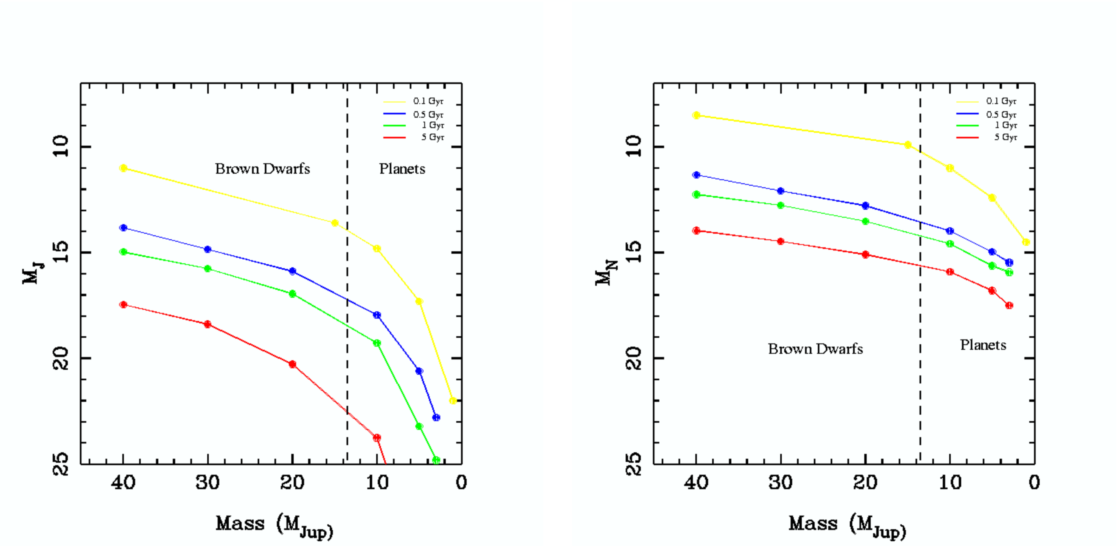

Figure 3: Change of J-band (*left*) and N-band (*right*) absolute magnitudes with mass for brown dwarfs and planets [17]. From top to bottom, isochrones of 0.1, 0.5, 1 and 5 Gyr are also indicated.

very low-mass stars and brown dwarfs emit most of their flux in the near-infrared and high resolution spectrograph at this wavelength are required to carry out this kind of searches. In Spain there are currently two major projects that are developing near-infrared high-resolution spectrographs: NAHUAL at GTC and CARMENES at the 3.5 m CAHA.

5 Summary

To summarize the investigations carried out during the last fifteen years and the future perspectives of the substellar field, we may emphasize:

- Since the discovery of first brown dwarfs: Teide 1 and Gl 229 B, in 1995, hundreds of brown dwarfs and tens of planetary-mass objects have been found.
- All these investigations have led to the conclusion that brown dwarfs are as numerous as low-mass stars and isolated planetary-mass objects up to 6 $M_{\rm Jup}$ are about 30% of brown dwarfs.
- Recently, we have been able to directly measure the luminosity, radius and dynamical masses of brown dwarfs, which is crucial to test theoretical evolutionary models.
- In the next future, we expect to detect the coolest substellar objects in the solar neighborhood and it is possible that the first Earth-like planet will be detected around a brown dwarf.

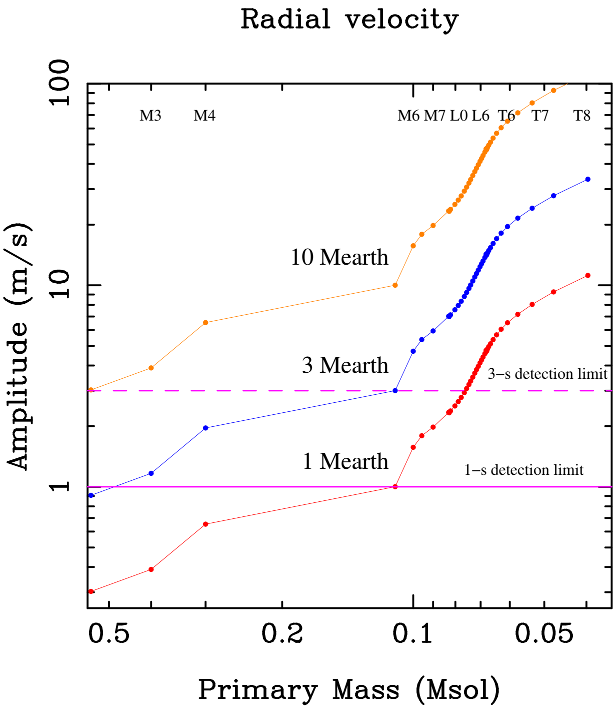

Figure 4: Radial velocity variation amplitudes induced by 1, 3 and 10 $M_\oplus$ planets around very low-mass stars in the HZ. The corresponding spectral types and the 1 and 3-σ detection limits for a $1\,\mathrm{m\,s^{-1}}$ precission (solid and dashed lines, respectively) are also indicated.

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