# Benchmark brown dwarf companions from the VISTA Hemisphere Survey.

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Cerro Calán, July 25th, 2019

# Presentation Outline

- Substellar objects – general introduction
  - From theoretical predictions to first discoveries
  - Main characteristics of brown dwarfs
- The VHS survey and searches for benchmark substellar companions
  - Wide ultracool companions to high proper motion stars
- Methodology
  - Common proper motions, color-mag diagrams
  - Spectroscopic characterization
  - Employing the WISE multi-epoch images to look for Y - type companions
- Selected results, highlights
  - A wide orbit L/T transition brown dwarf companion
  - A young planetary mass companion to a nearby M dwarf
  - Two companions at the $^{2}$H-burning mass limit in Upper Scorpius
  - General results of the searches using early VHS data
- Final remarks

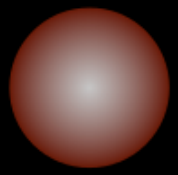
# Substellar objects: fundamental properties

Sun

**Brown dwarfs:**

Objects that can not sustain hydrogen fusion in their interiors.
(Mass < 0.072 $M_{\odot}$ ~ 75 $M_{Jup}$)

Low mass stars



Brown dwarf

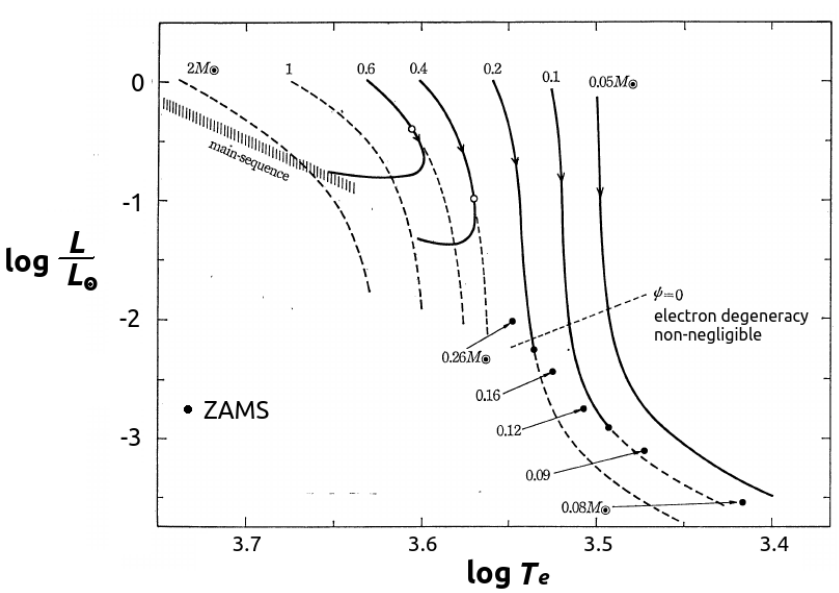
**Planets or planetary mass objects:**

Objects unable to burn deuterium in their interiors.
(Mass < 0.012 $M_{\odot}$ ~ 13 $M_{Jup}$)

Super Jupiters

Jupiter

# Substellar objects: from predictions to first discoveries

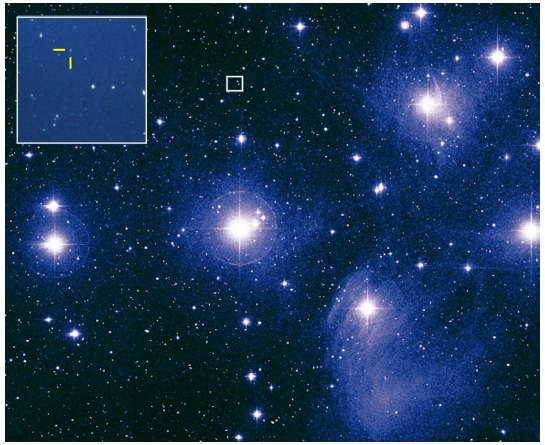


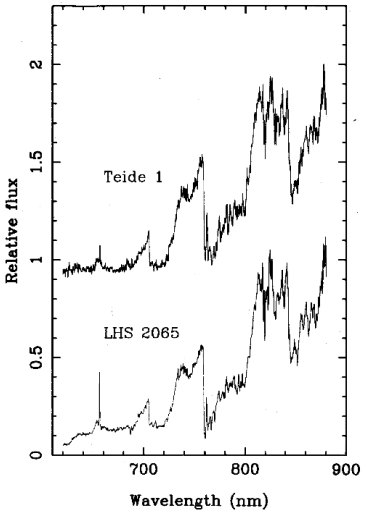

In the early 60s, S. Kumar, T. Nakano and C. Hayashi studied the pre-main sequence evolution of low-mass stars (<1 $M_{sun}$).

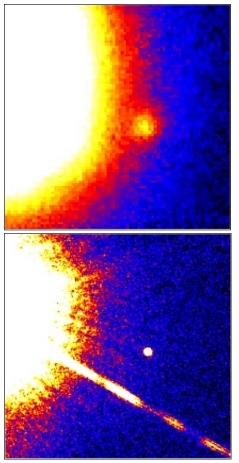
They determined a critical mass, below which an object contracts to a radius limited by electron degeneracy, and never reaches the temperature required to fuse hydrogen.

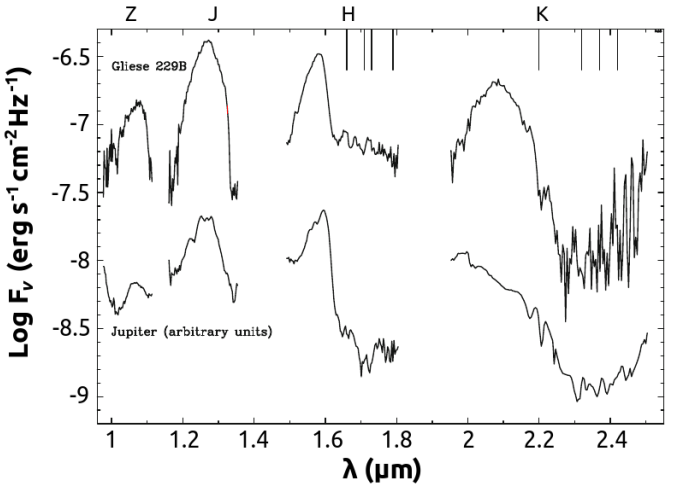
From their numerical results they found the **minimum mass for H-burning to be 0.08 – 0.07 $M_{sun}$** (Kumar 1962, 1963, Hayashi & Nakano 1963).

Roughly **30 years after** later, the first brown dwarf was found in the Pleiades cluster (Rebolo et al. 1995). Shortly after, another discovery was reported. Nakajima et al. (1995) detected a “methane brown dwarf” companion to the nearby star Gliese 229.





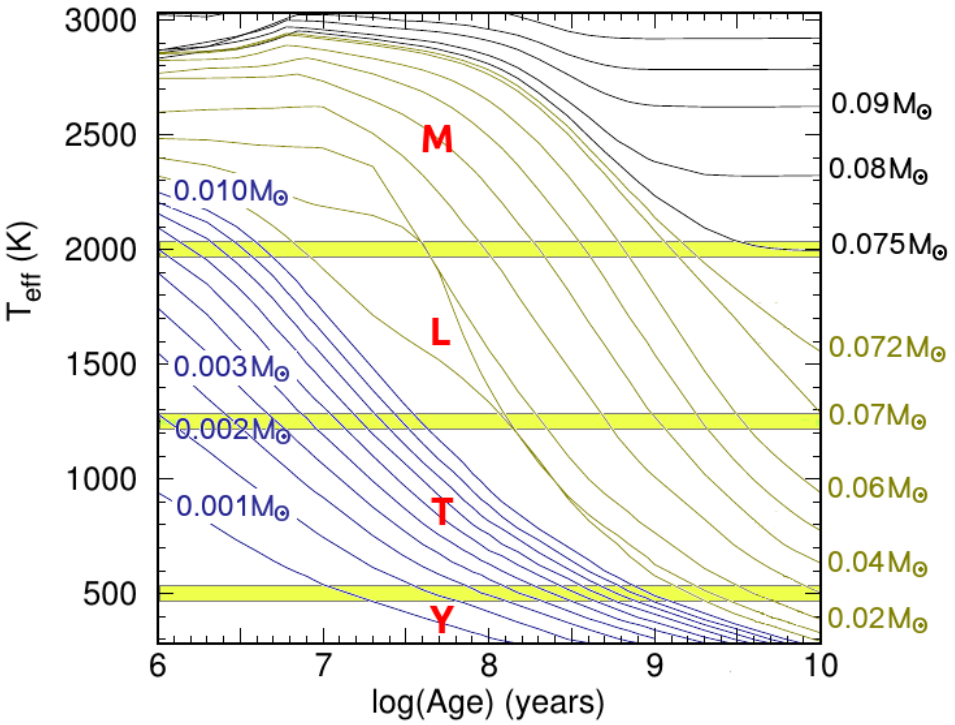


# Substellar objects: fundamental properties

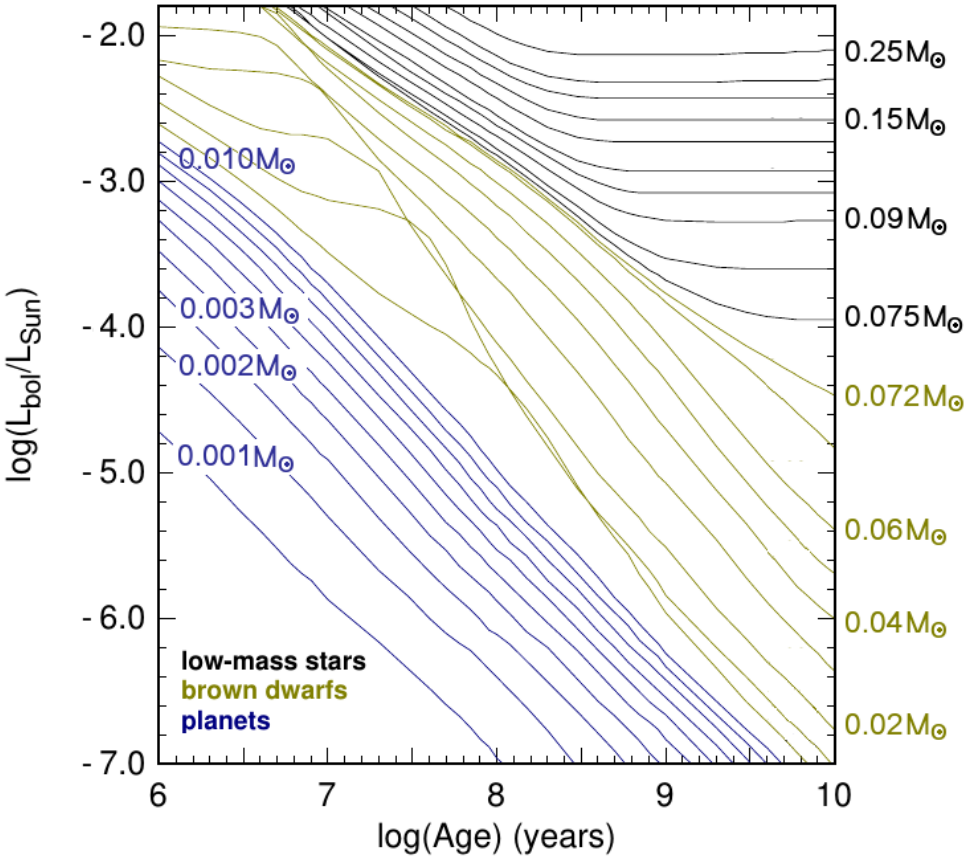
Without the internal source of energy, substellar objects cool down and fade as they evolve.

We cannot disentangle their mass & temperature from luminosity not knowing the age.

Evolutionary tracks of low-mass stars, brown dwarfs and giant planets from the BT-Settl models (Allard & Barman 2004)

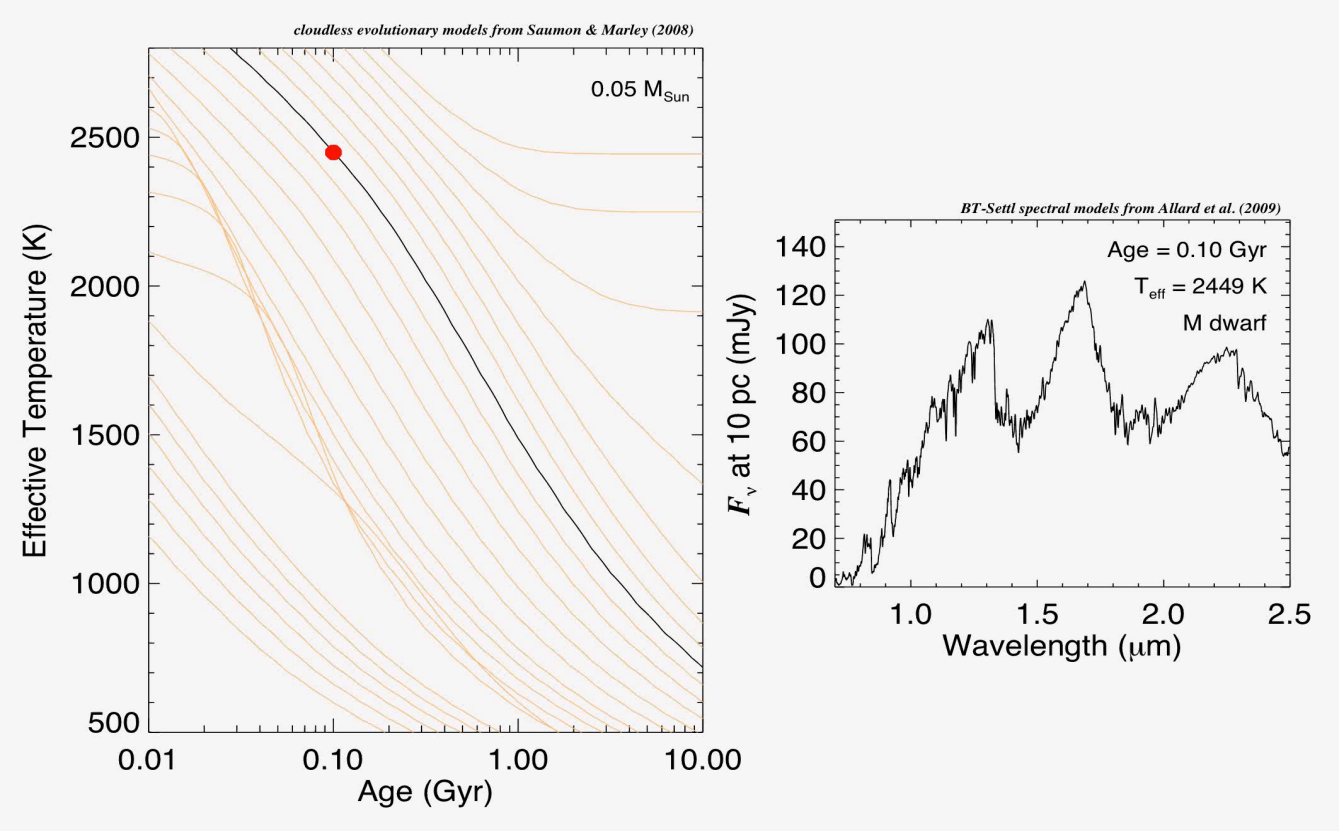



Because of progressive cooling with age, they do not obey a unique mass-luminosity relation.



# Substellar objects: fundamental properties

Near-IR spectral morphology of a 0.05 MSun brown dwarf in the course of its evolution:

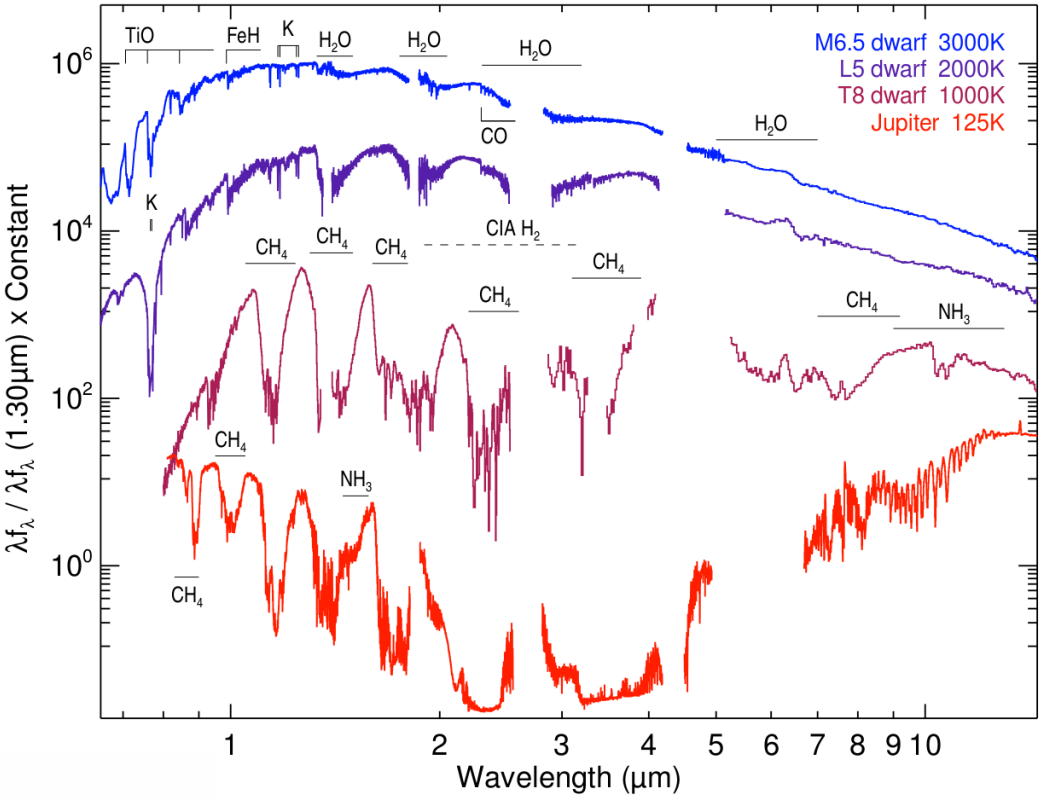


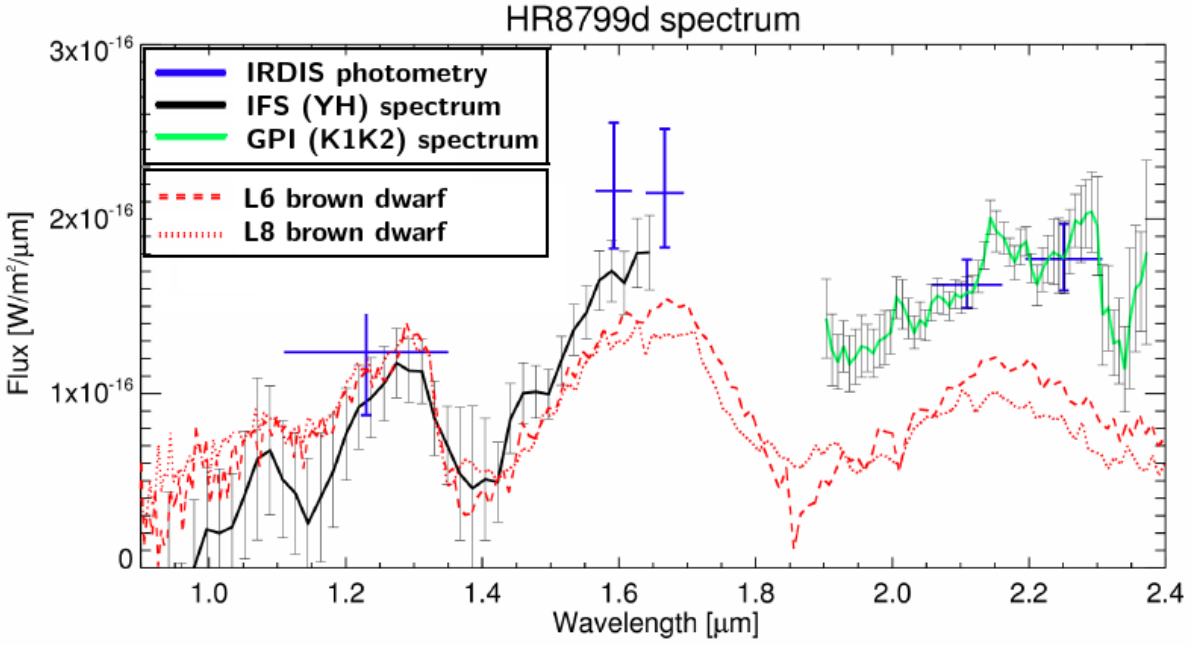

Courtesy of Prof. Adam Burgasser, University of California

# Substellar objects: fundamental properties

Brown dwarfs as analogues of giant planets

Spectral morphology of low-mass M6.5-type star, L5 and T8-type brown dwarfs and the Jupiter; from Marley & Leggett (2008)

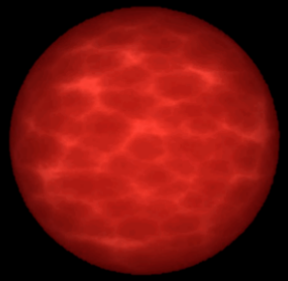


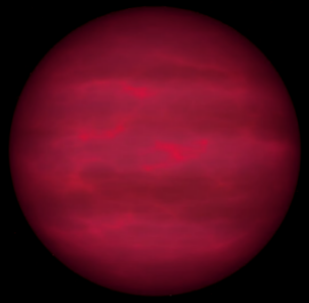

Spectrum of HR 8799 d (7 ± 3 $M_{jup}$) from SPHERE and GPI compared to isolated, L6 and L8-type brown dwarfs. (Zurlo et al., 2016)

# Substellar objects: fundamental properties

**M dwarfs** (3500-2100 K)
The most common, low-mass stars and the youngest (<150Myr) brown dwarfs



**L dwarfs** (2100-1300 K)
~ 1000 known, the least massive stars and brown dwarfs, molecule-rich atmospheres (CO, TiO, CaH, CrH), contain clouds of hot dust



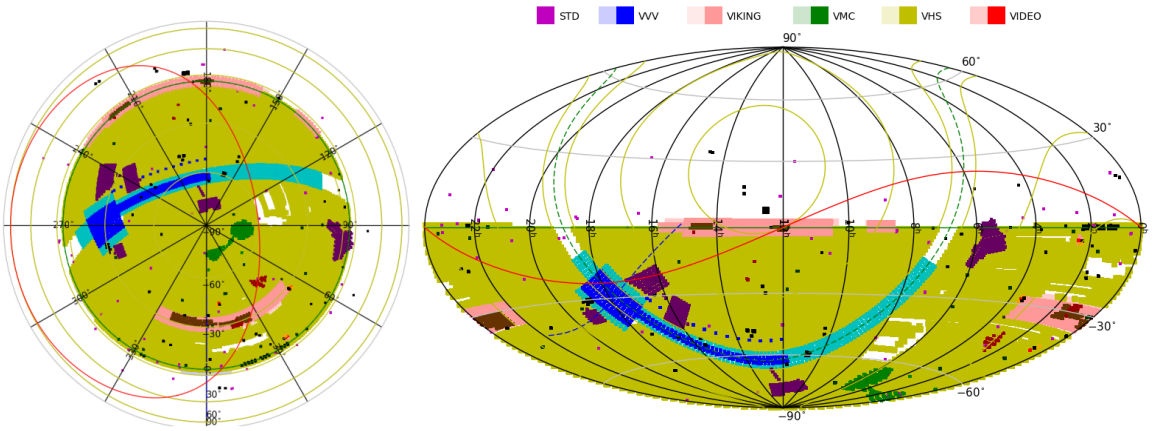
**T dwarfs** (1300-600 K)
~ 300 known, cold brown dwarfs similar to gas giant planets, atmospheres containing methane

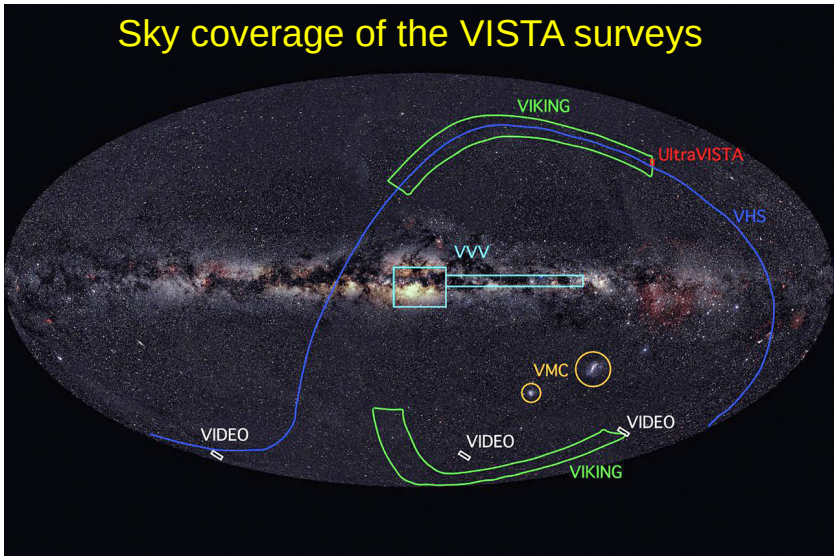
**Y dwarfs** (<600 K)
25 currently known, recently defined class of brown dwarfs and planetary mass objects. Atmospheres containing ammonia and possibly water ice clouds

# Search of substellar companions: the VHS survey

The VISTA Hemisphere Survey (VHS) will map the entire southern hemisphere of the sky (~20,000 deg2). Resulting data are about 4 mag deeper than the 2MASS and DENIS surveys, reaching a median 5σ detection limits of: *J* = 20.2 and *Ks* = 18.1

VISTA coverage maps (last update June 2019)




**Three main groups of targets:**

- ✗ **The nearest stars, up to 10 pc**
  *** RECONS, Gaia, literature**
- ✗ **Young (< 1 Gyr) nearby stars, up to ~150 pc**
  *** known members of AB Dor, Upper Sco etc.,**
- ✗ **High proper motion (μ > 0.15”/yr) stars**
  *** catalogs of HPM stars**
  *** our VHS-2MASS catalog**

Up to date ~150 ultracool (≥ M7 type) dwarfs were identified and confirmed as companions (Faherty et al. 2010, Deacon et al. 2014, Scholz et al. 2016).

# Search of substellar companions: selection methods

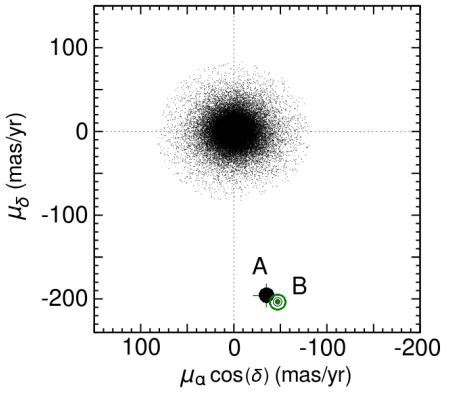
**Selection of candidates:**

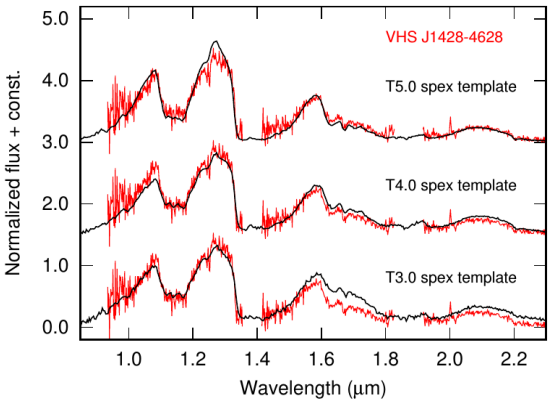
- ✗ Available VHS data (catalog + images)
- ✗ Cross-match with 2MASS sources (J ≤ 17.5 mag) to find high proper motion objects (μ > 0.15”/yr)
- ✗ Cross-match with WISE and USNO catalogs: mid-IR and optical photometry, filtering spurious correlations
- ✗ Over 50,000 objects identified, mostly M dwarfs within ~100pc

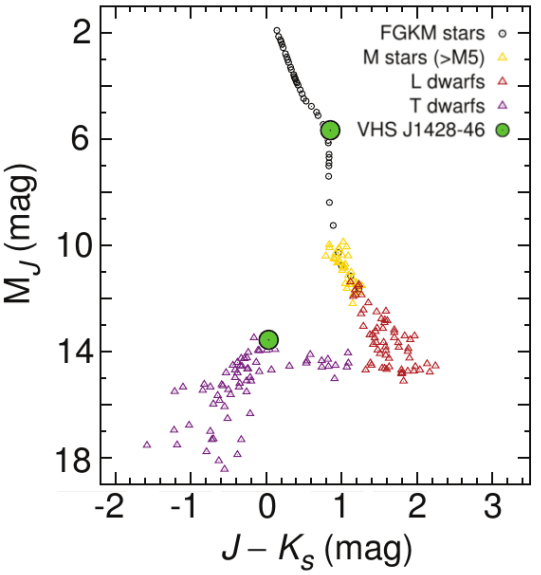
A search for wide (≳50AU), common proper motion systems with ultracool components (i.e., of spectral type ≥ M7)

Verification of candidates:

- ✔ proper motions of the components differ by less than 30 mas/yr in both *μα* and *μδ*
- ✔ estimated spectrophotometric distance is consistent within the uncertainties
- ✔ angular separations are relatively small, less than 1,000 arcsec

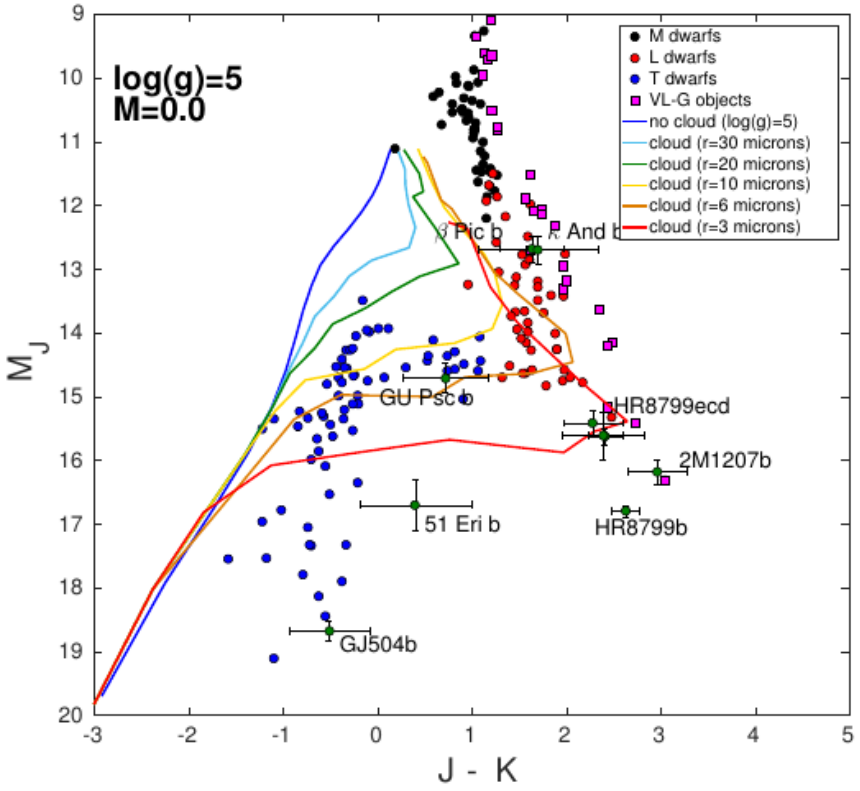


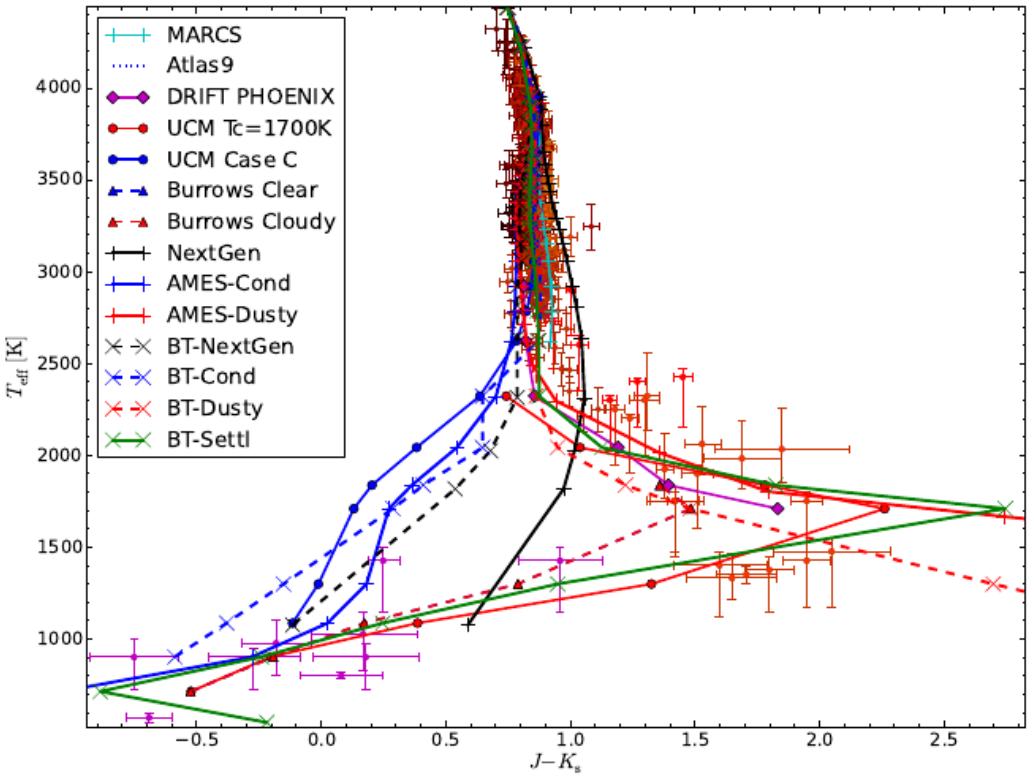



# Search of substellar companions: more benchmarks needed

*MJ, J – Ks* color-magnitude diagram with Exo-REM models for low-mass stars and BDs,
solar metallicity, different cloud particles size; from Charnay et al., (2017)

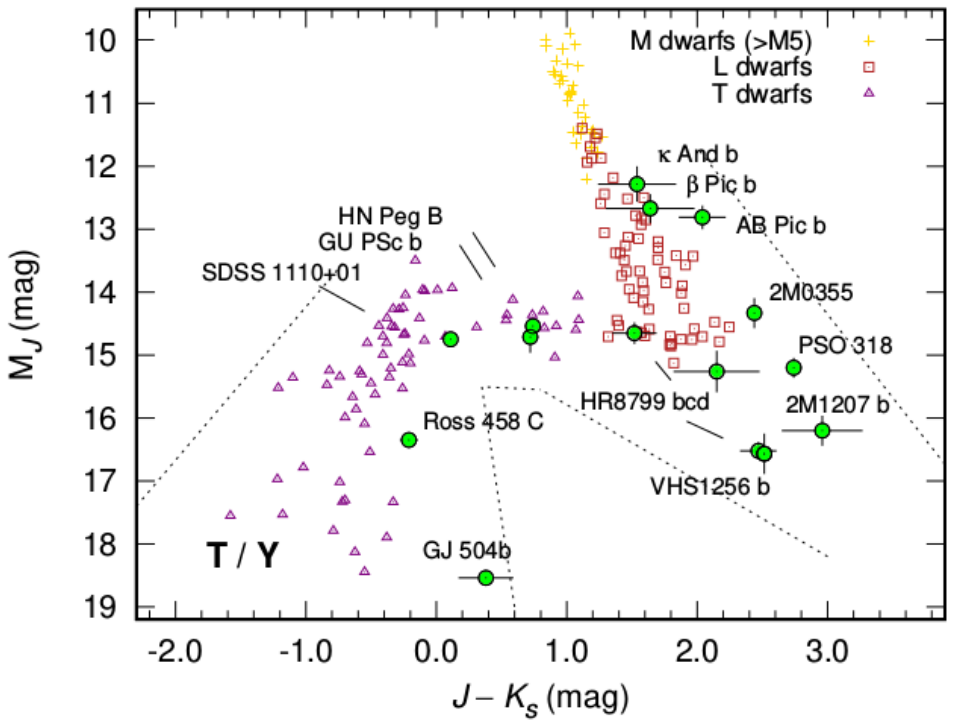


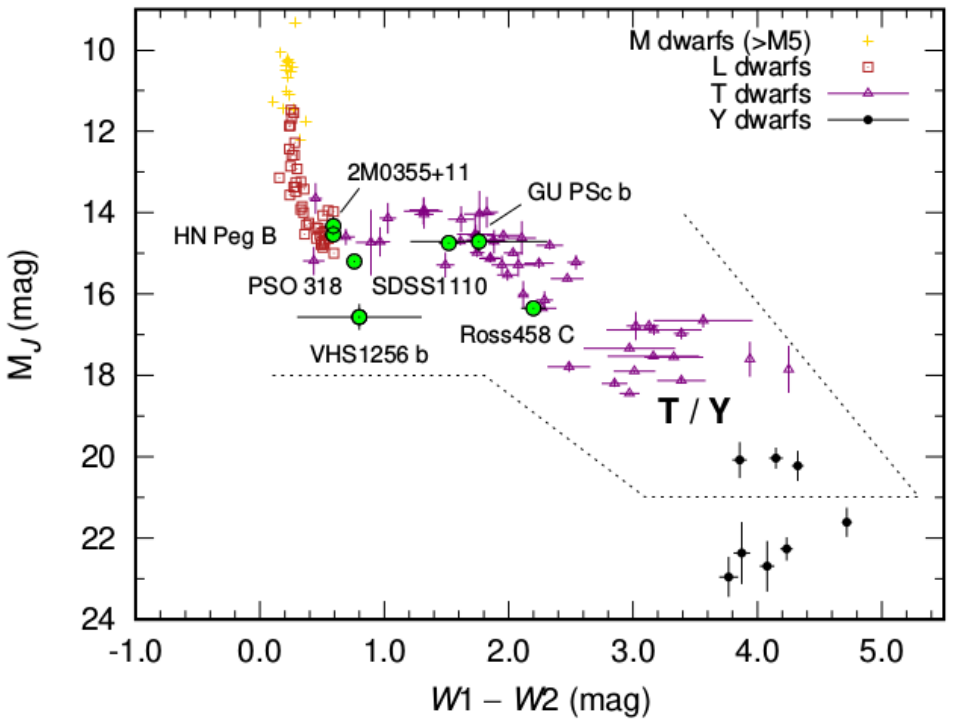

Comparison of isochrones of low-mass stars and brown dwarfs (for an age of 3 Gyrs) from state-of-the-art theoretical models.
Figure from Allard et al., (2013)



# Search of substellar companions

## The T/Y boundary and the young L and T dwarfs



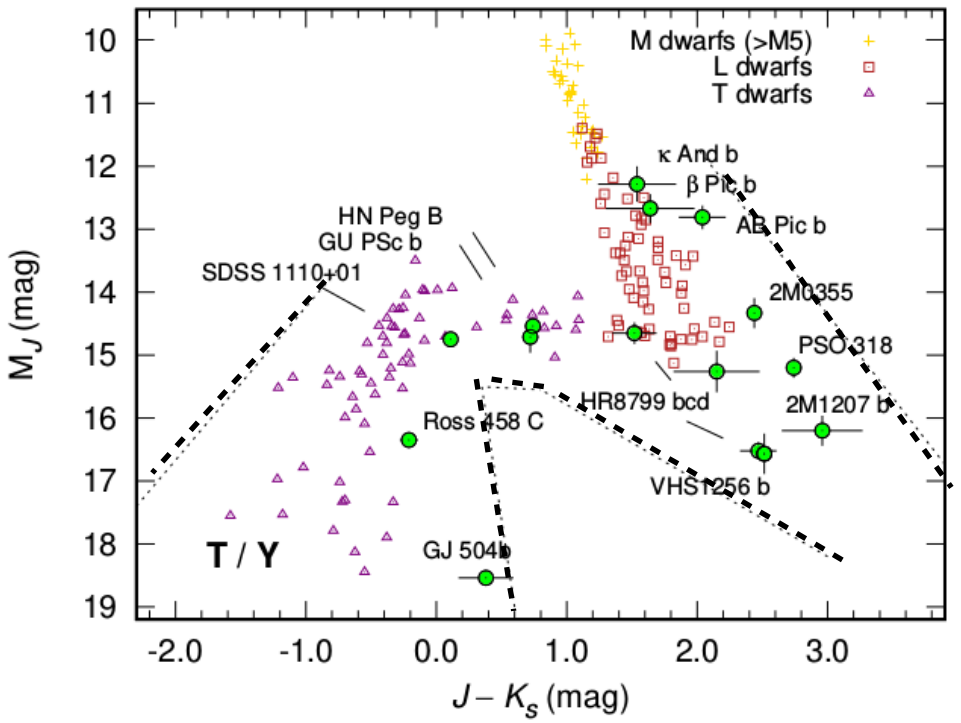

We use the VHS to explore the T/Y boundary, looking for such companions around the nearest **stars (within 10 pc).** This will be possible given the VHS sensitivity: ***J* = 20.2 mag**.

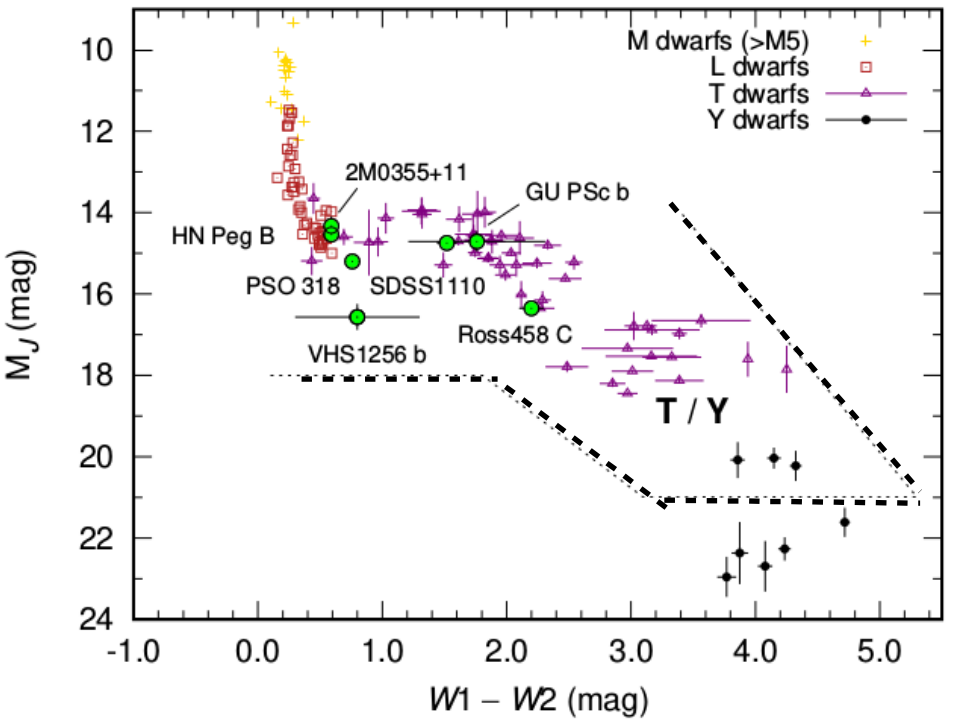
With a **sample of ~200 stars** we plan to estimate the Y-type companion frequency at wide (>20 AU) orbits.

We also carry a search for **young L and T-type companions** of known members of young moving groups and associations, expecting several hundred stars to be covered by VHS.

# Search of substellar companions

## The T/Y boundary and the young L and T dwarfs

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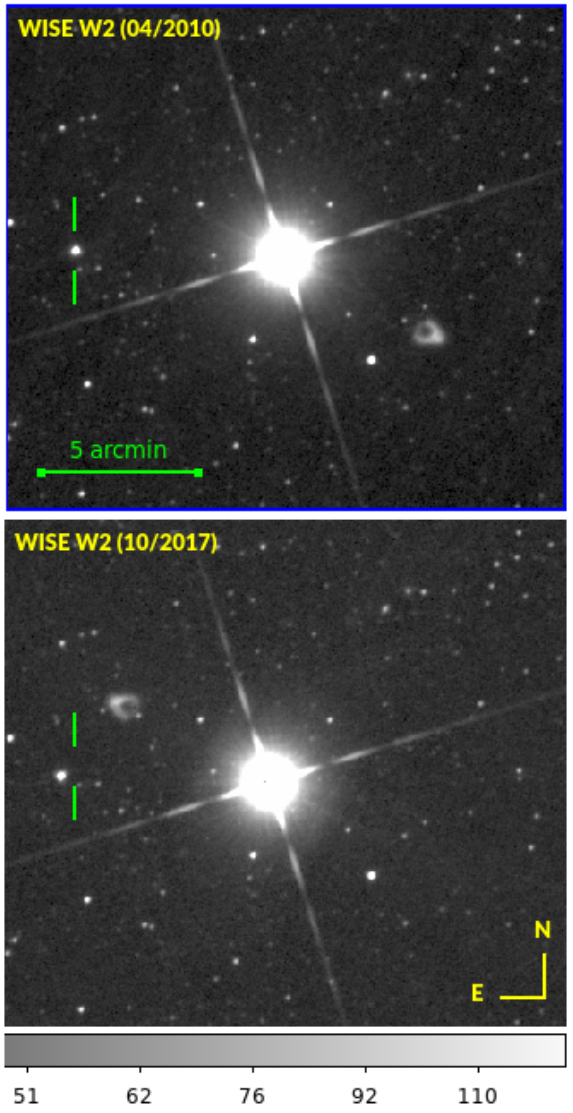
# The coldest companion(s) from the WISE multi-epoch images

ε Indi A + Bab
K5V + T1 + T6, d = 3.6 pc,
μα = 3960.93 ± 0.24 mas/yr
μδ = −2539.23 ± 0.17 mas/yr

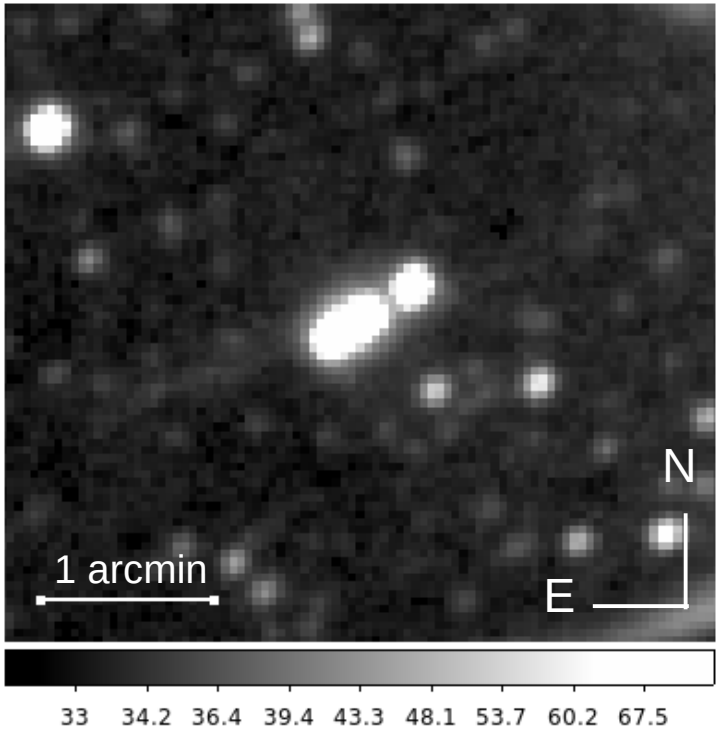



Combining WISE/NEOWISE *W*1,*W*2-bands images of all available epochs (2010 – 2017)

A 5-σ detection limit about **2.0 – 2.5 mag** deeper than the original AllWISE Source Catalog

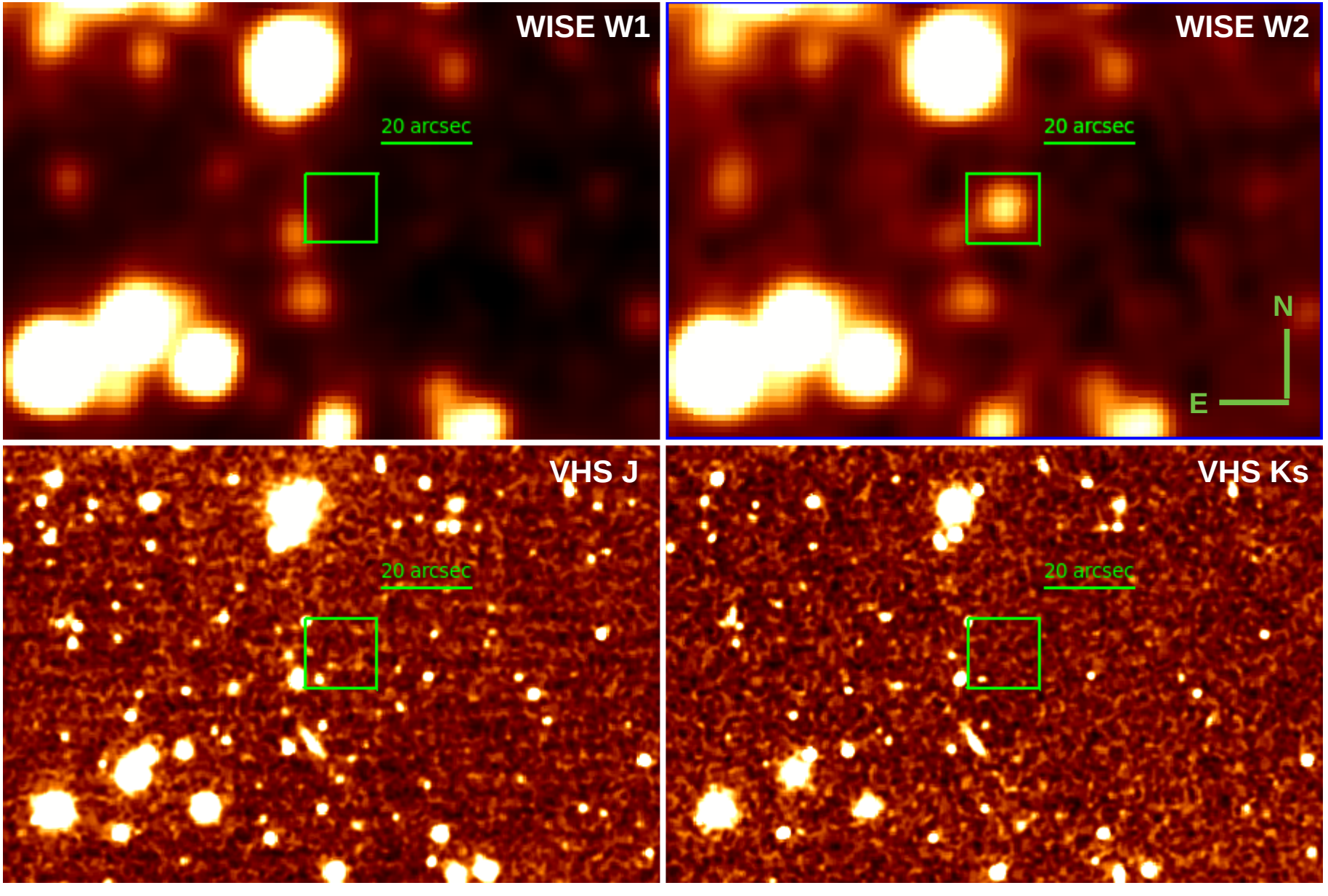
Shift and add method to account for the known proper motion of a given star

**133** individual **stars at d < 10 pc** currently covered by the VHS (165 in total)



# The coldest companion(s): Y0 example

WISE J0713-2917 Y0 at *d* = 9.2 pc, *J* = 19.4, *Ks* = 21.3 mag
VHS 3-sigma detection limit in *J* = 19.9 mag



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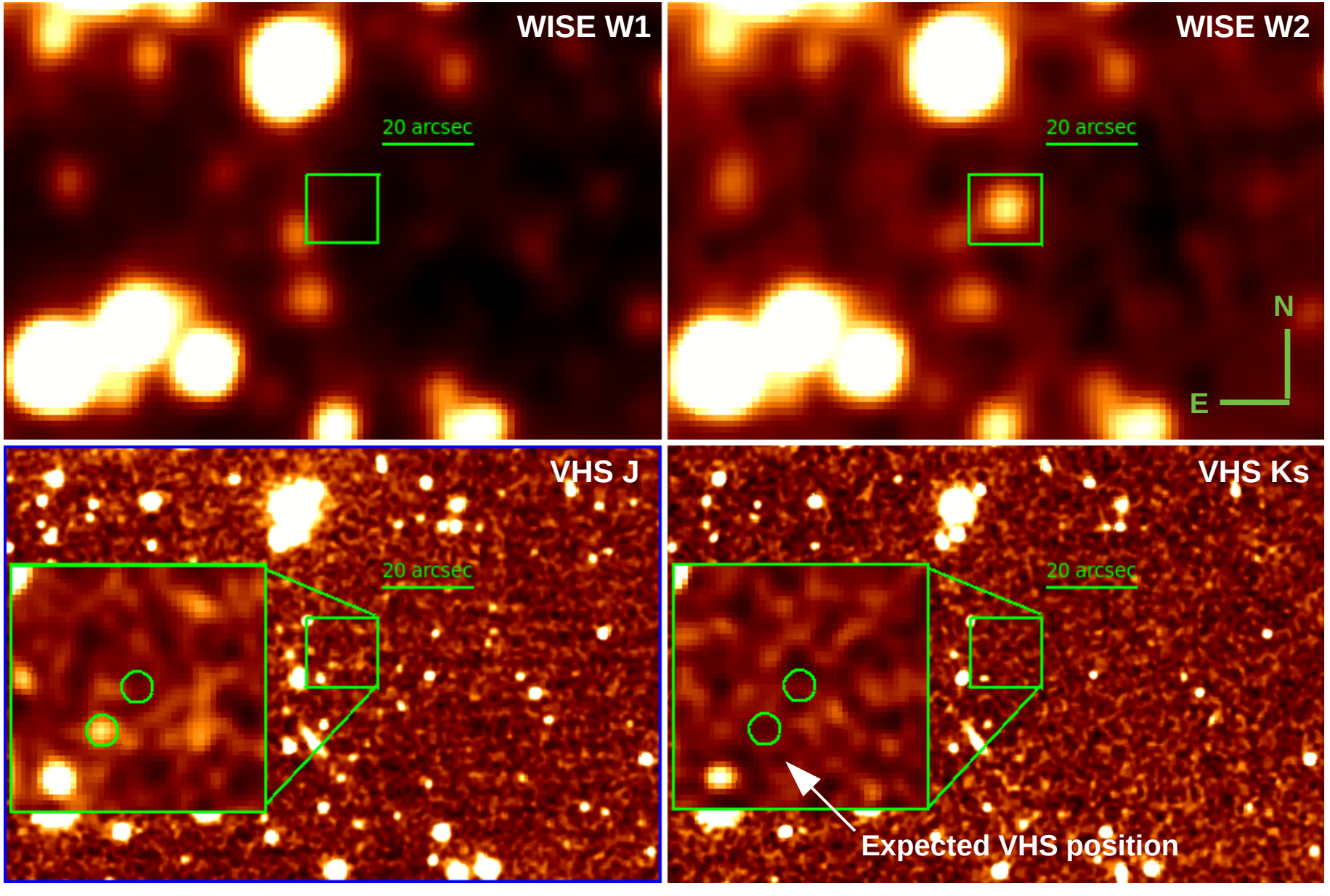
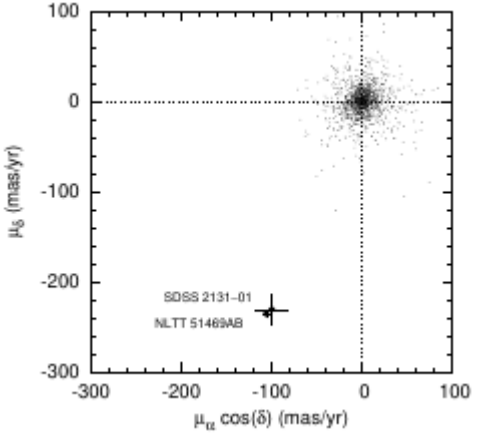
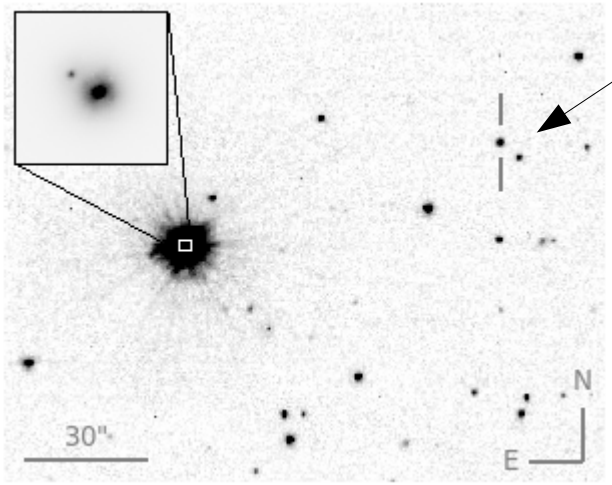


# Highlights: a low-mass triple system with L / T transition BD

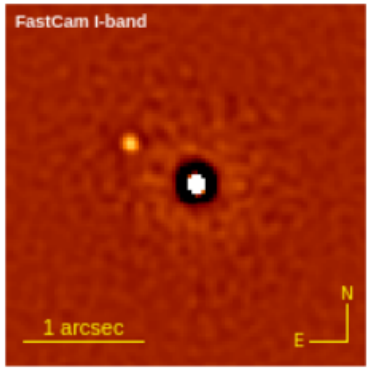


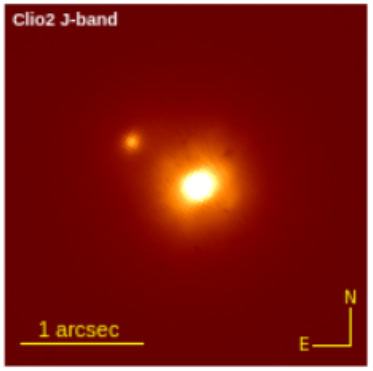

Previously known high-proper motion star NLTT 51469 and an L9 +/- 1 type brown dwarf SDSS 2131-0119,
<u>Found to be co-moving.</u>

One of the widest systems
$\rho \approx 3800$ AU
And with very low binding energy
$Eb \approx -2.48 \times 10^{42}$ erg

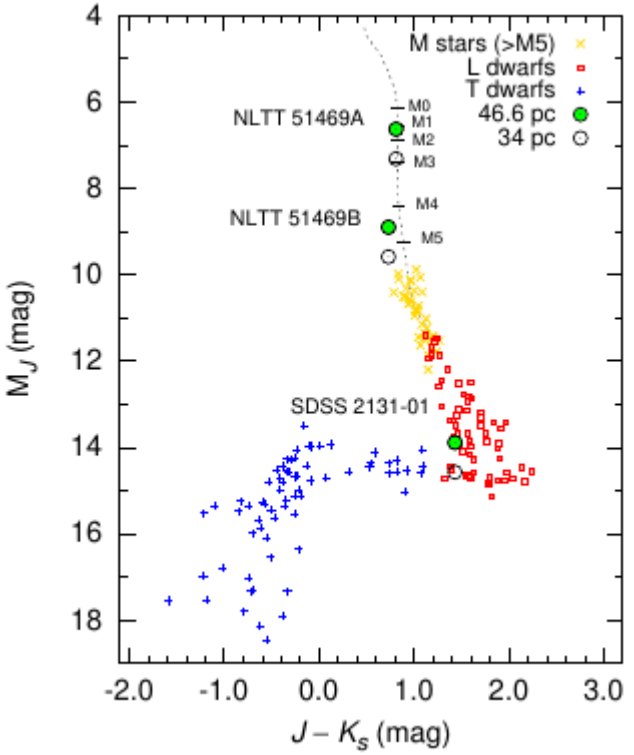



Primary star resolved to be a binary at 0.64” ± 0.01” (~30 AU) separation.
Classified as M3V + M6V



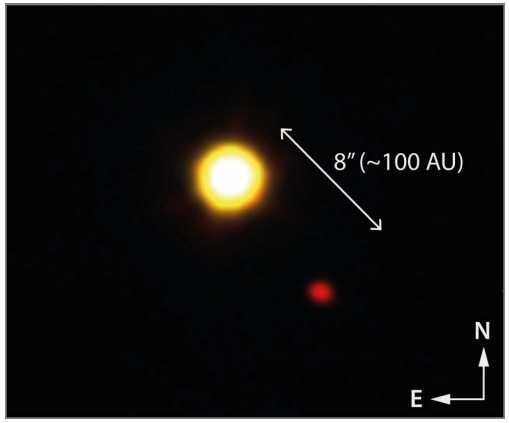



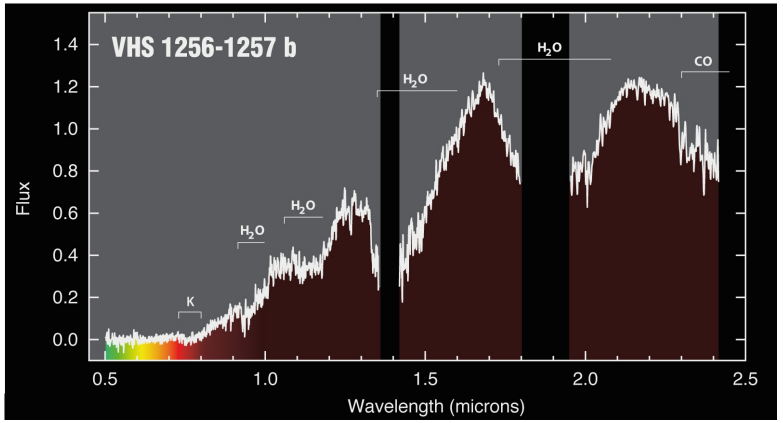

**A younger age at around 1-2 Gyr would imply the mass of L9 brown dwarf at or below 0.055 $M_\odot$, and thus preservation of lithium**




MJ, J – Ks color mag diagram, all three components follow the UCD photometric sequence

# Highlights: VHS 1256b, a young planetary mass companion

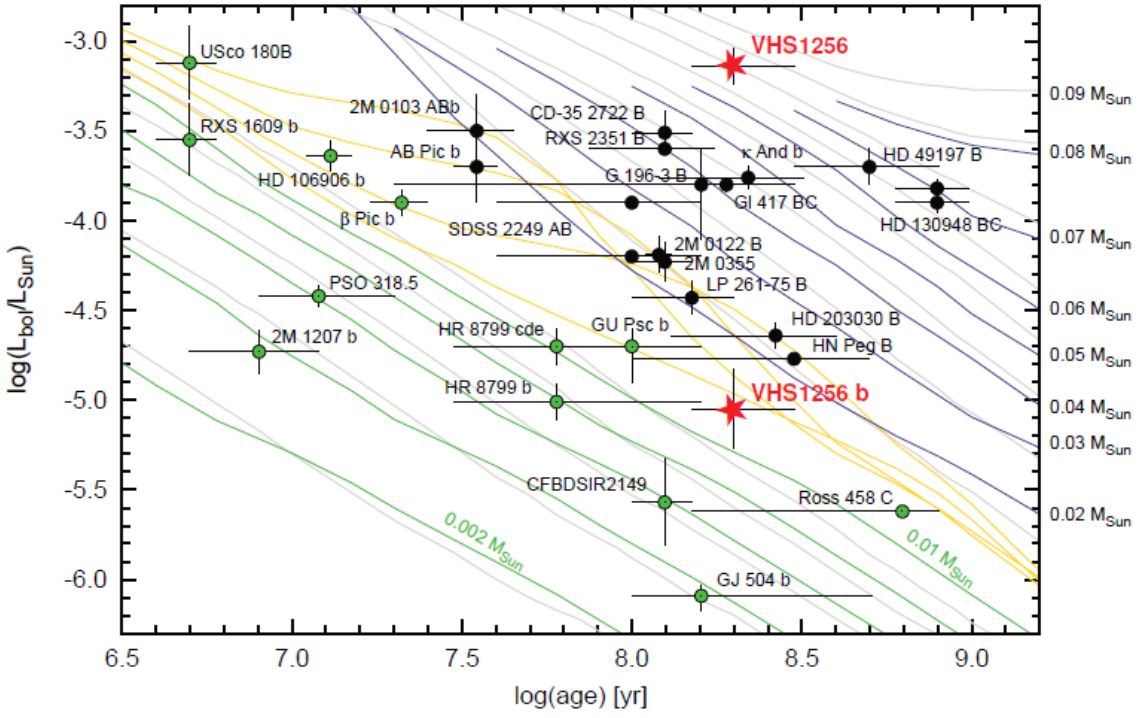


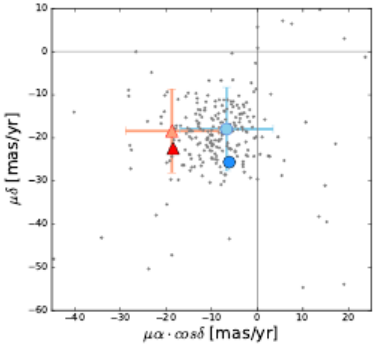

A new planetary mass companion to a nearby M7.5 dwarf, at **~8 arcsec** separation (**~102 AU** at d = **12.7* pc**)

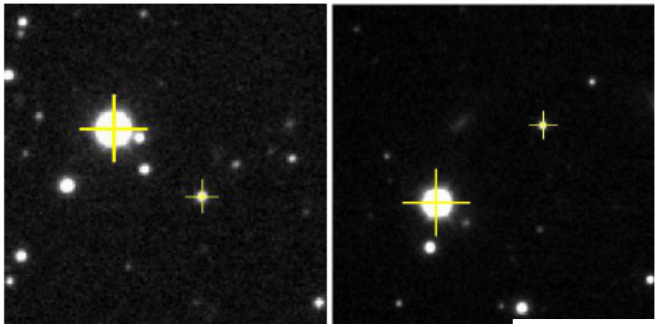
- No Li I and a likely membership to the Local Association constrains the age of the system to **150 – 300 Myr** range.
- The primary has a mass of **73 (+20, -15) *M*Jup** at around the substellar limit and the companion a mass of **11.2 (+9.7, -1.8) *M*Jup,** near the deuterium burning mass limit
- The first optical + near-IR spectrum of a planetary mass object
- It is among the nearest known planetary mass companions detected by direct imaging.

**BT-Settl** (Baraffe et al. 2003; with the Caffau et al. (2011) solar abundances **and** cloudy atmosphere models of **Saumon & Marley (2008)**



# Highlights: two members of the USco at the $^2$H-burning limit

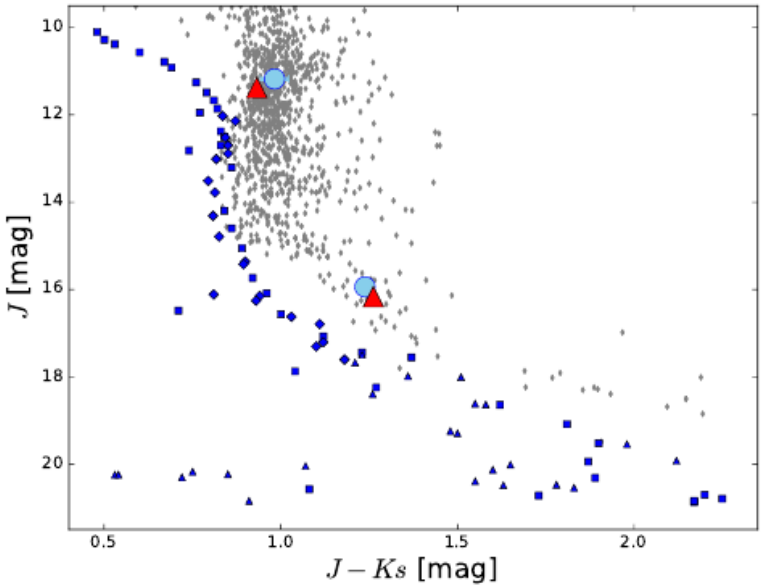


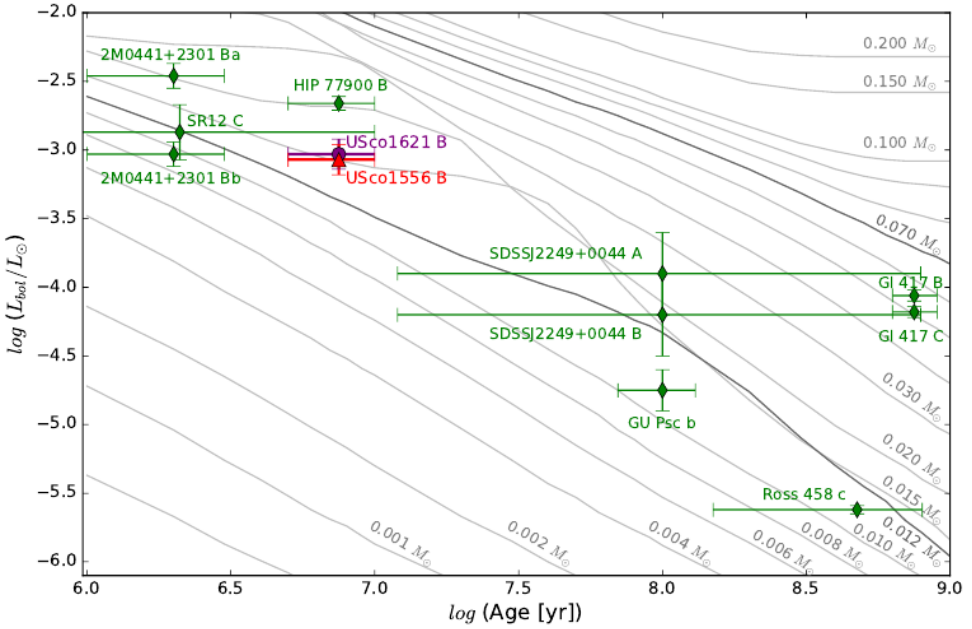



The Upper Scorpius region is part of the Scorpius Centaurus (Sco-Cen) Association, the **nearest OB association to the Sun**. USco has an estimated average age of ~ **5–10 Myr** and is located at a distance of **146 ± 6 pc.**

| | USco1621 B | USco1556 B |
|---|---|---|
| SpType | L0 ± 0.5 | L0.5 ± 0.5 |
| Separation | 2910 ± 160 | 3530 ± 180 |
| Mass (Msun) | 0.015 (2) | 0.014 (2) |
| Teff (K) | 2270 ± 100 | 2240 ± 100 |

A typical overluminosity with respect to the field-age sequence, compatible with a very young age.



# General results, employing early VHS data

## Confirmed companions, estimation of occurrence frequency

In total, we confirmed 30 previously unknown common proper motion systems, and one additional component in a known triple system

3 candidates at very wide angular separations (from ~1,200 to 3,400 arcsec) remain as probable companions, but their status is not yet confirmed

The confirmed ones consist of 27 binaries, 3 triples and 1 quadruple systems, including:

- **36** newly found **M dwarf** components
- **10** of which are **M7-M9** type
- **7 L** dwarfs
- **2 T** dwarfs

| Contaminants |
| --- |
| ✗ Expected: ~10 - 15% |
| ✗ 12 of 15 individual candidates (80%) at > 1,000” |
| ✗ 5 of 38 individual candidates (~13%) at < 1,000” |
| ✗ The majority of contaminants could be avoided by restricting the search radius to 15-20 arcmin |

We have attempted to derive a preliminary estimation of the occurance frequency of ultracool companions at wide orbital separations beyond ~50 AU and extending up to about 30,000 AU, (angular separations from ~2 arcsec to 20 arcmin, for a mean distance of 25 pc). Considering the sub-sample of confirmed candidates to NLTT stars, we derived **a frequency of the order of 0.5 +/- 0.1%**.

# Final remarks

- We search for substellar, common proper motion companions employing the VISTA Hemisphere Survey data. ~20,000 deg$^2$ area in total, up to *J* ~ 20 mag
- We aim at exploring the T/Y boundary and young L, T-type populations using VHS and WISE data
- 30 new systems were confirmed, including 18 new ultracool components: **10 M7-M9, 7 L and 2 T dwarfs**, at angular separation from ~5 to 800 arcsec
- Using early VHS data (8,500 deg$^2$) we find the (preliminary) **lower limit on the frequency** of ultracool companions at separations larger than 50 AU to be **0.5 ± 0.1%**
- Among the newly found companions **we identified and characterized in detail several particularily interesting systems**, which become valuable benchmarks for studies of substellar objects, e.g., a low-mass triple system with a L/T transition brown dwarf component, and a young planetary mass companion to a nearby M dwarf VHS J1256-1257.

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**Thank you!**