Spectroscopic analysis of a large sample of L and T dwarfs

Federico Marocco

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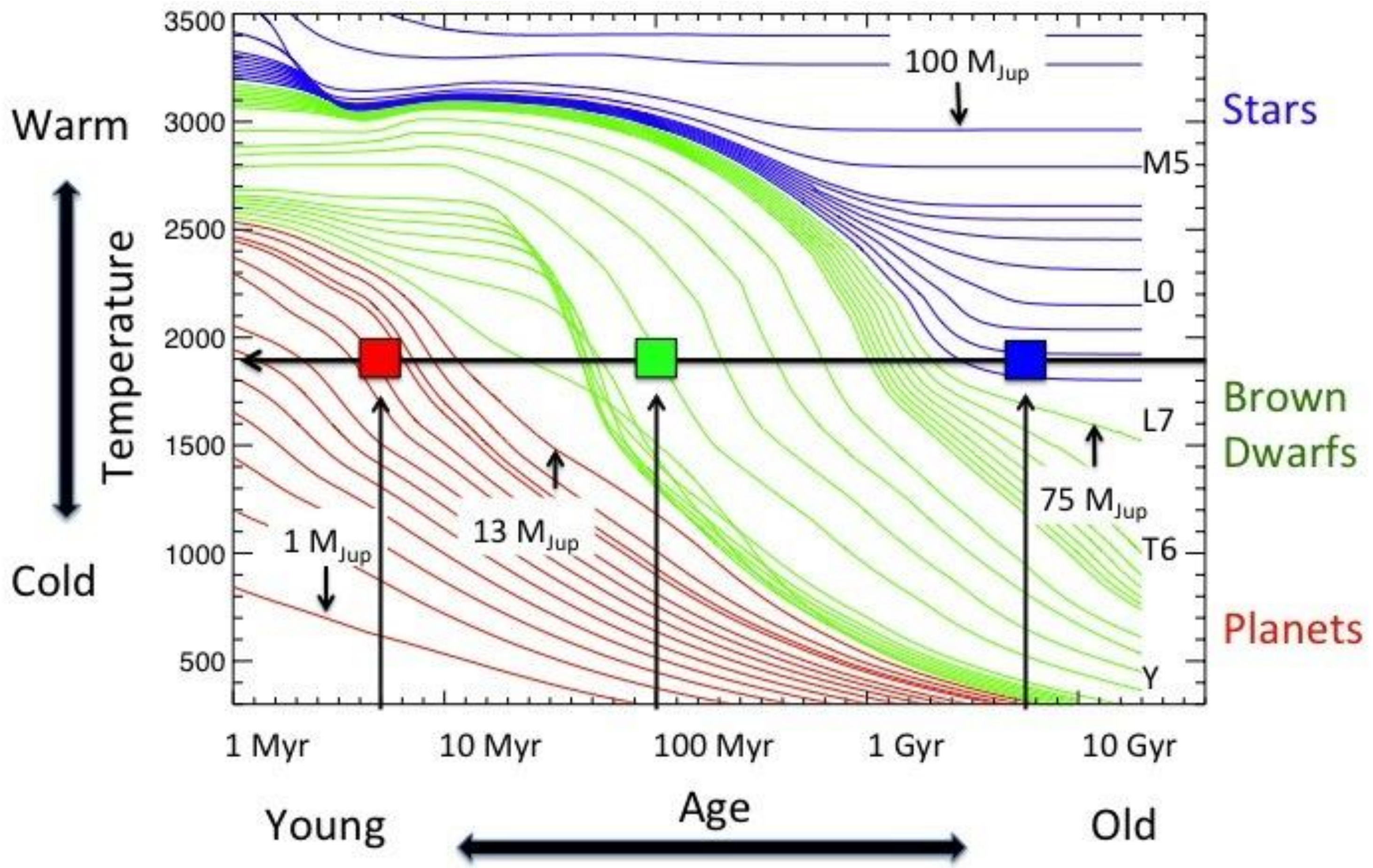
Introduction

Brown dwarfs (BDs) are sub-stellar objects, whose mass is insufficient to trigger and sustain stable hydrogen fusion in their cores. As a result, they cool down over time.

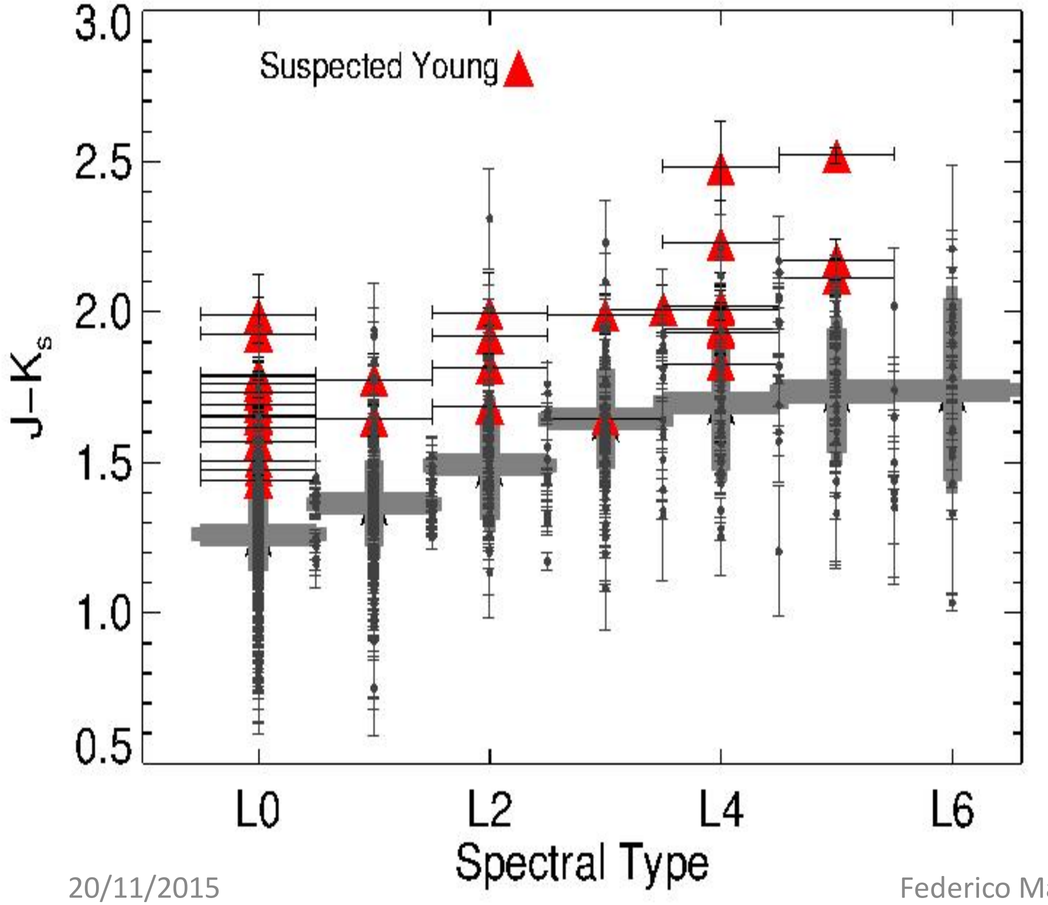


Mass, luminosity and age are therefore "degenerate" parameters.

Introduction

The wide range of parameters covered is reflected by the NIR colours and spectra.

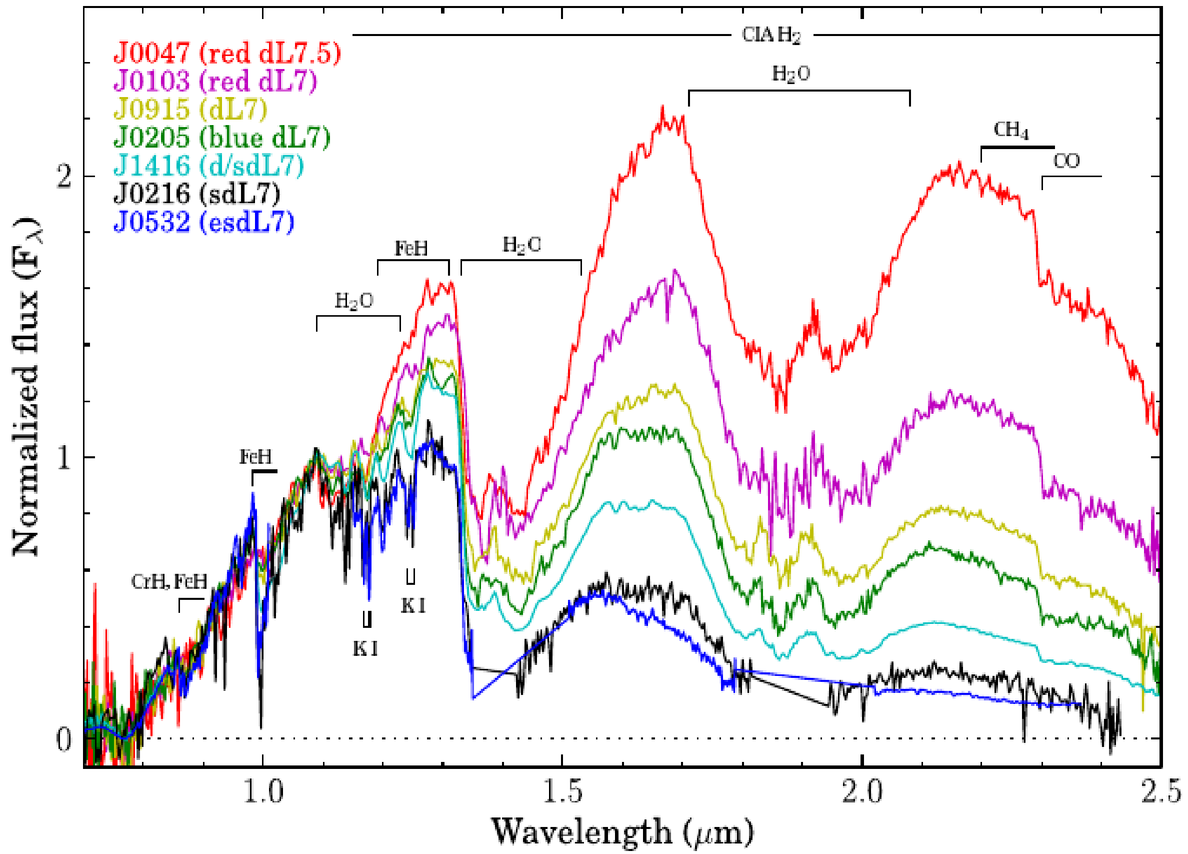
Faherty et al. 2013



Young

Old

Zhang et al. 2013



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Near-infrared spectroscopy is fundamental to characterize BDs. By analyzing the spectra of large samples of BDs, one can understand the atmospheric physics, i.e. the dust formation/settling process, the clouds dynamics, non-equilibrium chemistry.

My work consists of three parallel and complementary projects:

-The spectroscopic follow-up for the PARSEC program;

-The Birthrate program a.k.a. our attempt to constrain the sub-stellar IMF and formation history;

-The quest for outlier benchmark systems with *Gaia* primaries.

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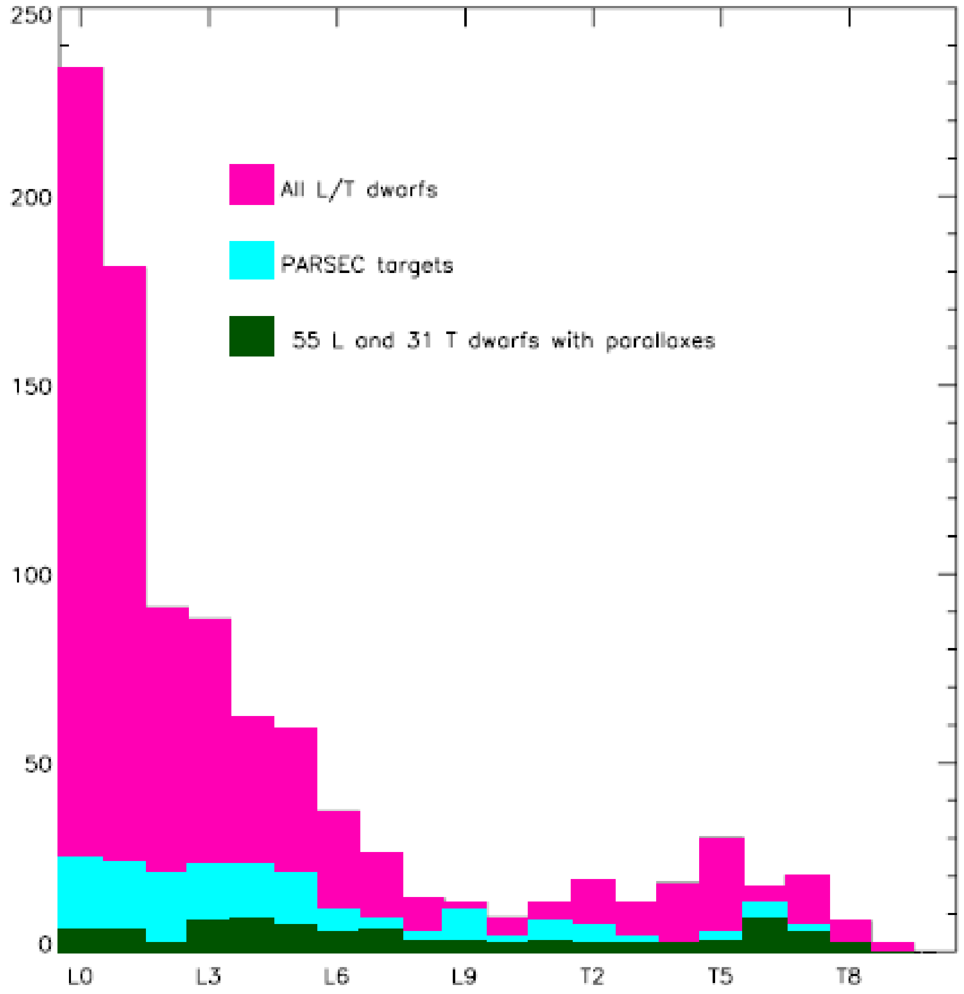
(Andrei et al. 2011, AJ, 141, 54)



Large astrometric program to determine parallaxes and proper motions of ~140 L and early-T dwarfs in the southern hemisphere.

http://parsec.oato.inaf.it

Observations began in April 2007, first results are presented in Andrei et al. (2011, AJ) and Marocco et al. (2013, AJ).

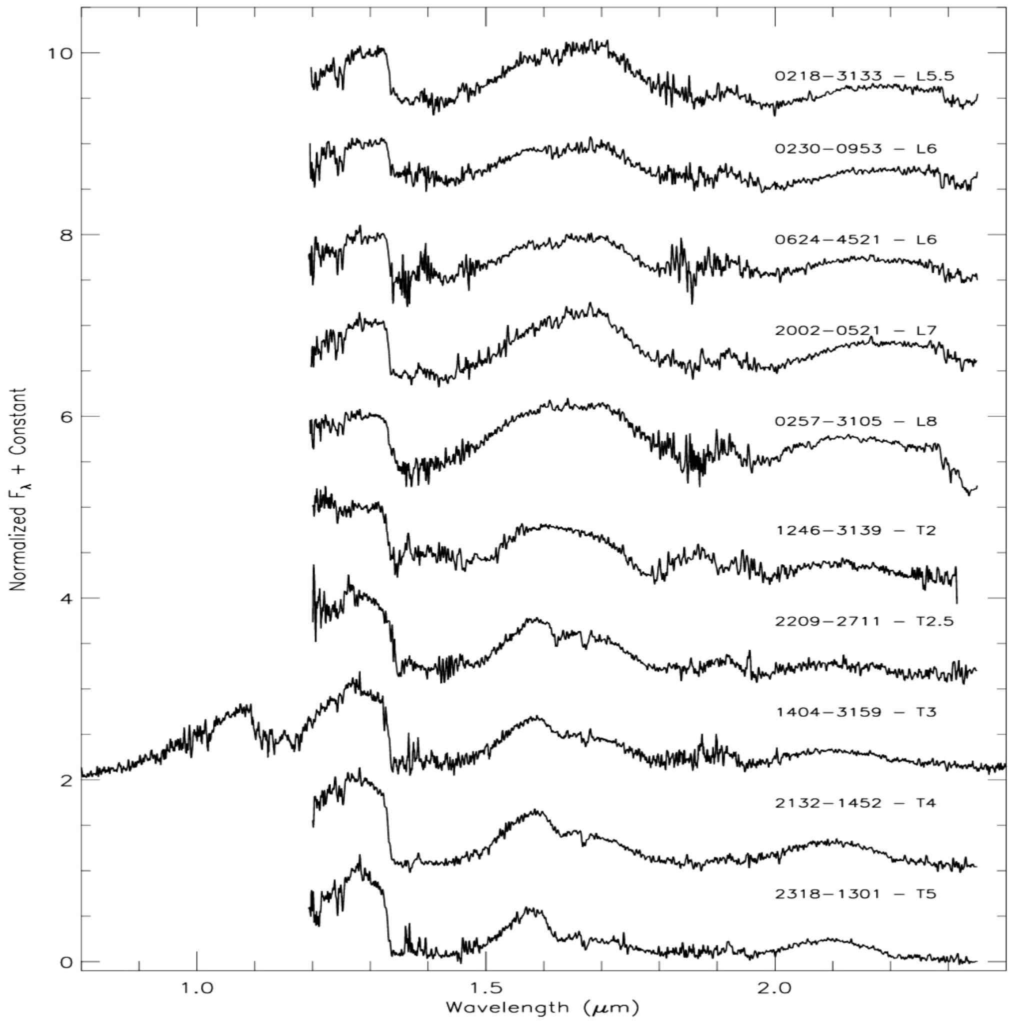
PARSEC doubles the number of L and T dwarfs with parallaxes.

(Marocco et al. 2013, AJ)

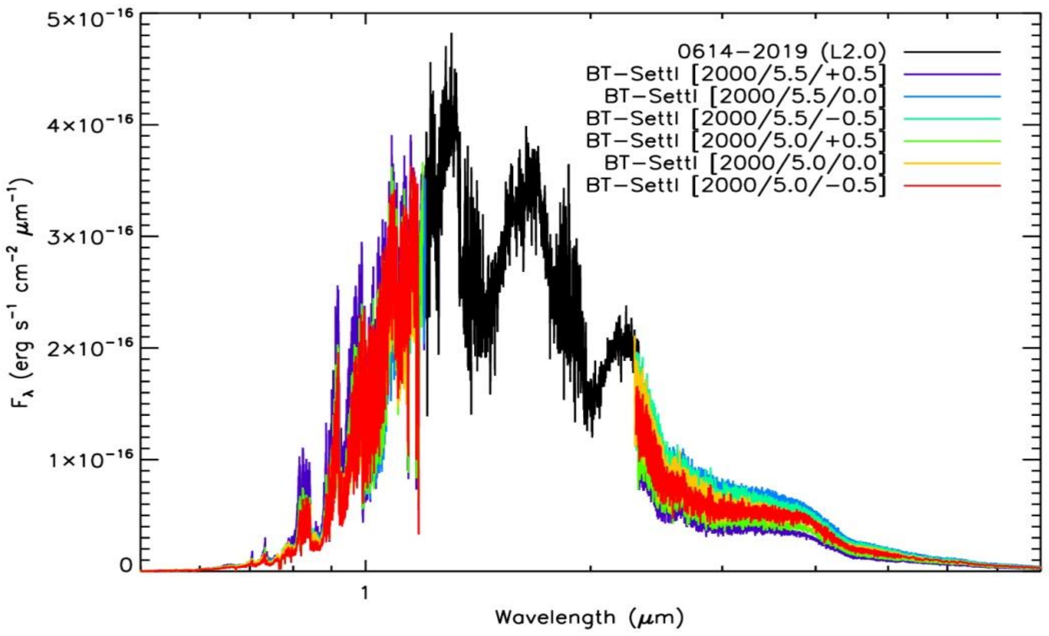
$\sim$50% of the targets did not have NIR spectra, so we started a spectroscopic follow-up campaign using SOAR/OSIRIS, VLT/Xshooter, and NTT/SOFI.

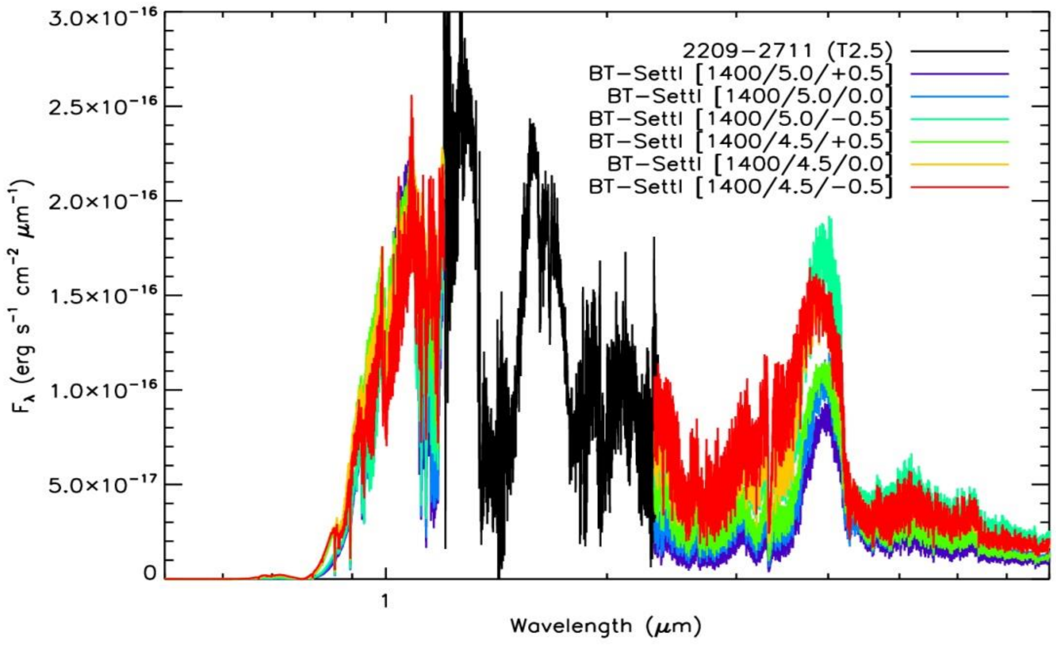
We obtained NIR spectra for 52 targets (45 with OSIRIS, 5 with Xshooter and 2 with SOFI). **21 of them have parallaxes.**

Combining spectroscopy and parallaxes we obtained L_{bol} and T_{eff} for our targets.



To estimate the bolometric correction we used the BT-Settl and BT-Dusty atmospheric models (Allard et al. 2001, 2003, 2011).



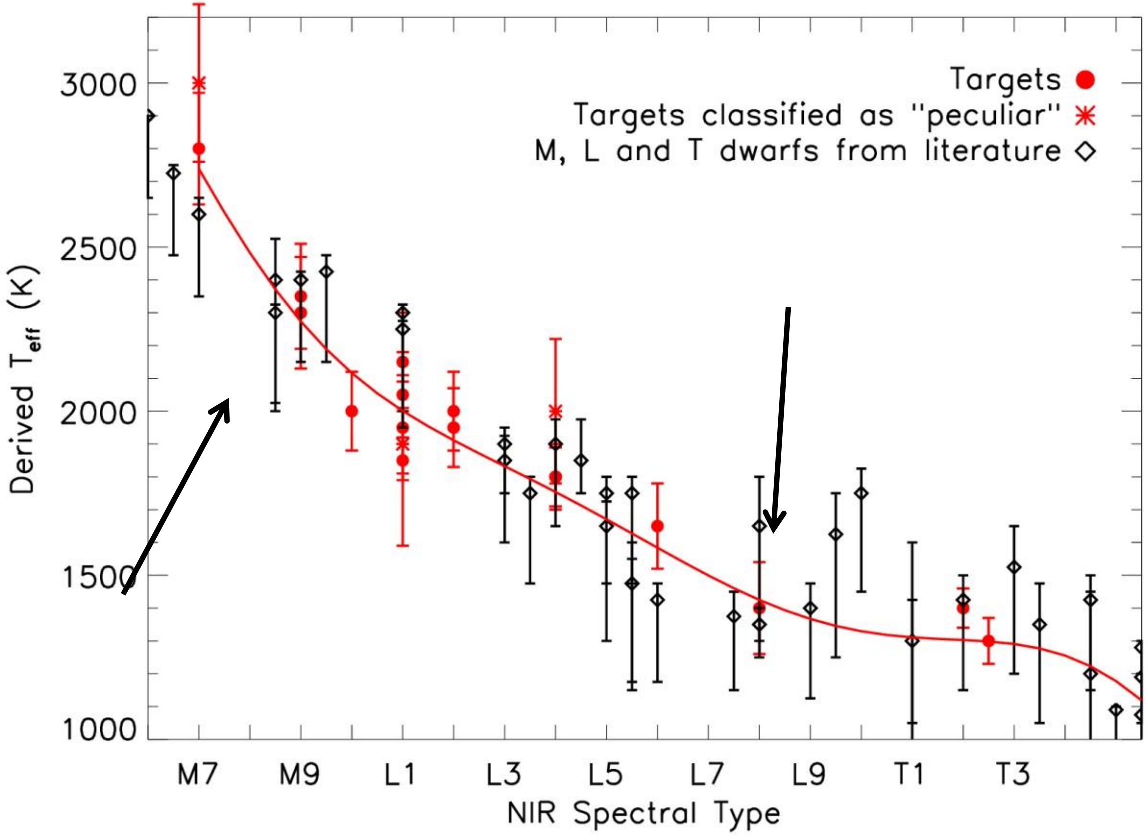


For the coolest objects , at long wavelengths (i.e. λ > 3 μm) the bolometric correction is very sensitive to surface gravity and metallicity, but those parameters are unconstrained!

(Marocco et al. 2013, AJ)

We fit a new T_{eff} vs spectral type polynomial relation.

Change in the slope of the sequence at the M – L transition and at the L – T transition. Effect of dust formation/settling.



Uncertainties are too large and the sample is still to small to be able to say anything definitive. The full sample will allow us to put a stronger constrain on the relation.

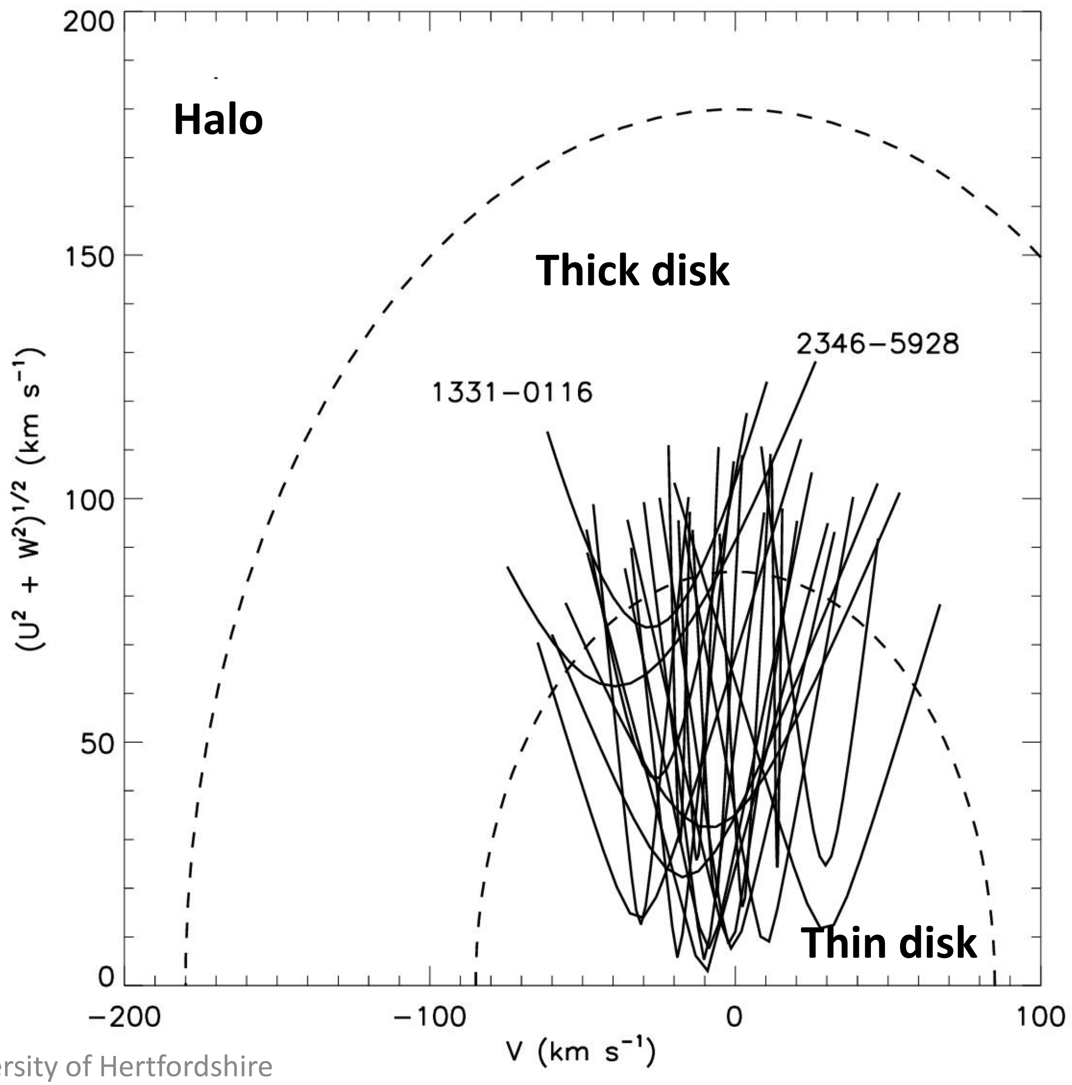
(Marocco et al. 2013, AJ)

The kinematics of the sample provides useful insights on the nature of the targets.

We calculated U,V,W assuming
-100 km/s < V_{rad} < +100 km/s

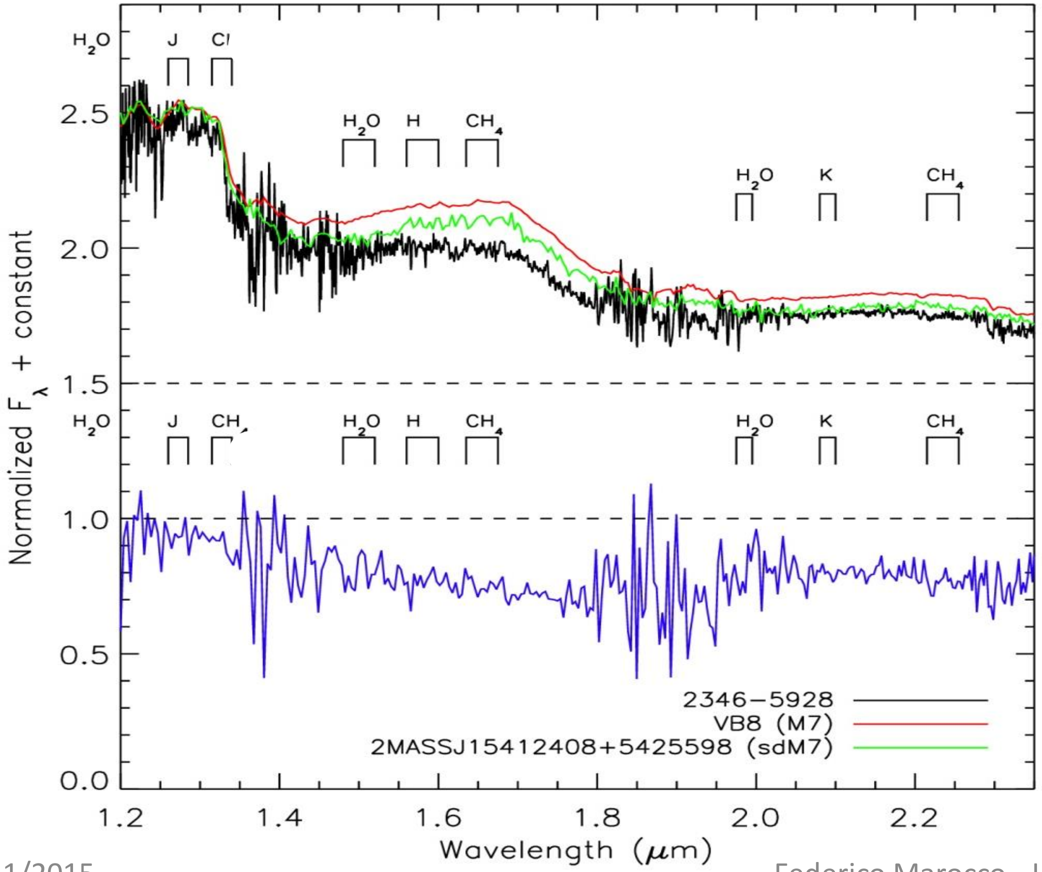
Two objects seem to belong to the thick disk population: 1331-0116 and 2346-5928.

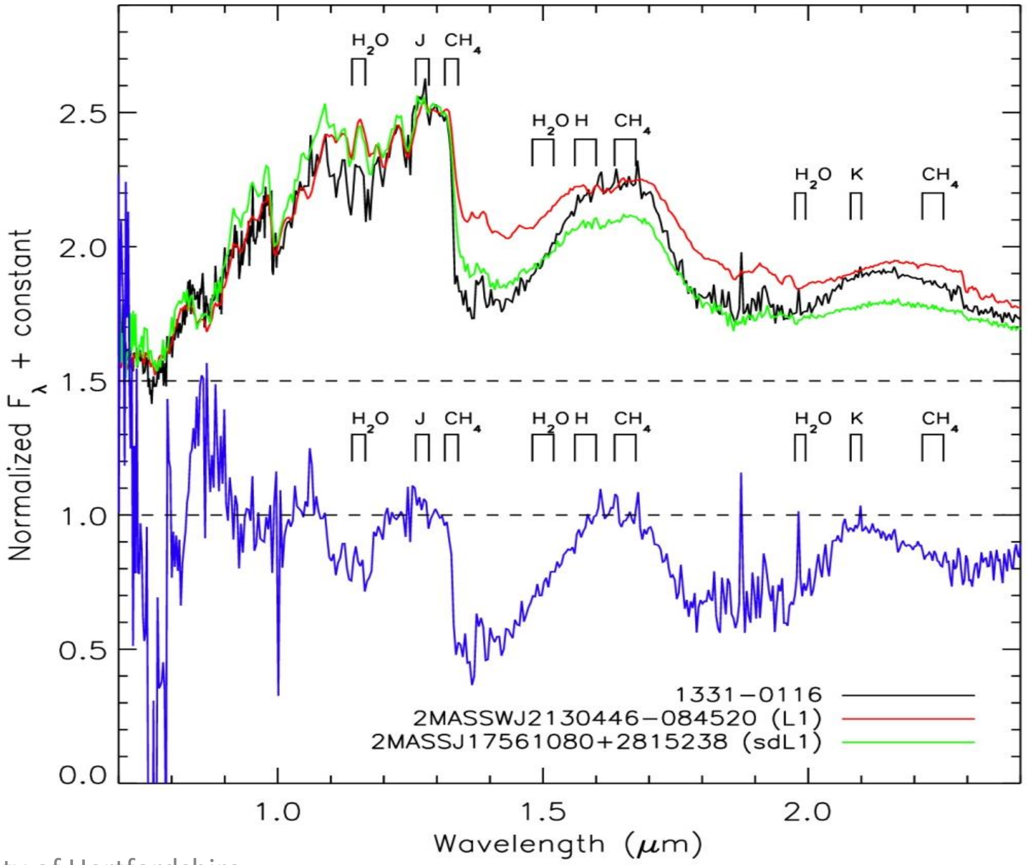
And in fact, if we look at their spectra ...



... both objects are bluer than the spectroscopic standards , and show signs of metal depletion, i.e. stronger H_2O, Na I and K I absorption.

(Marocco et al. 2013, AJ)

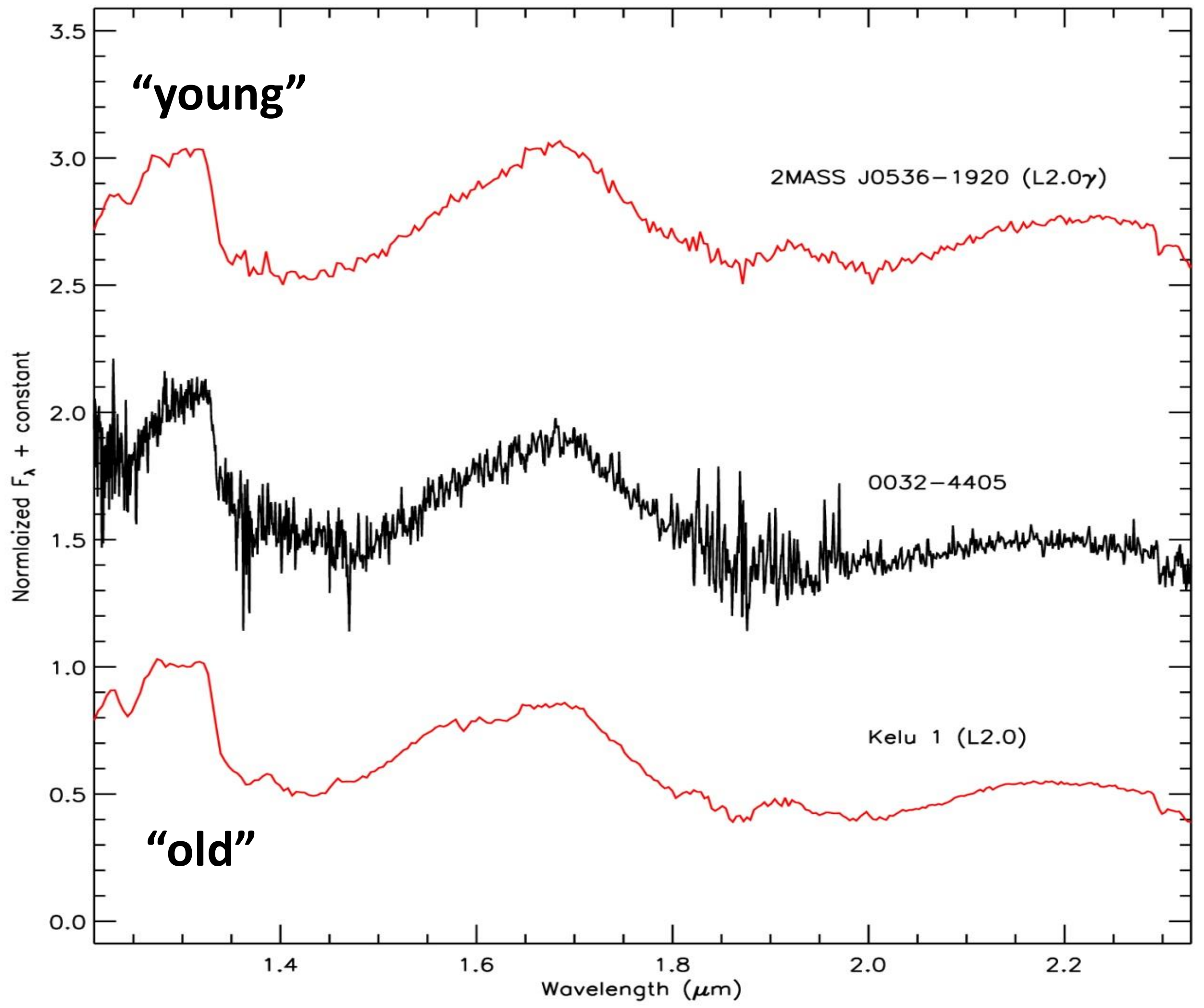




The kinematics can also be used to check the possible membership of the targets to any of the young moving groups.

0032-4405 likely member of β Pic (93%, cf. Manjavacas et al. 2014, A&A).

The spectrum shows triangular H band!



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Constraining the IMF and formation history

Because of the mass-age-luminosity degeneracy, the luminosity function of BDs depends on the formation history. IMF and formation history of sub-stellar objects are poorly constrained.

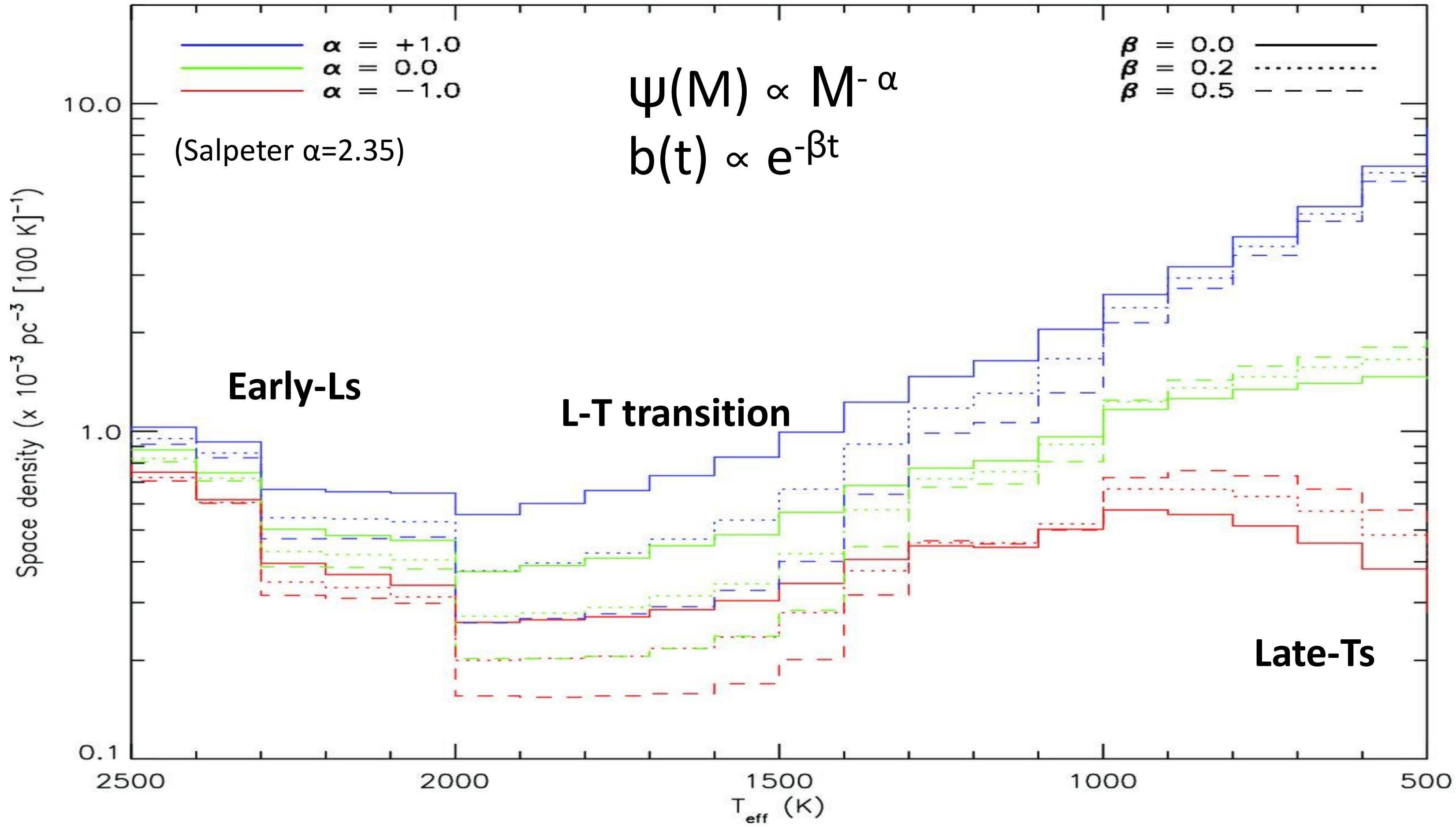
Moreover, the formation process of BDs is still a matter of debate. Two different mechanisms (star-like and planet-like) could contribute to the current population of BDs.

↓

Determining the luminosity function of BDs can help us understand the formation process of sub-stellar objects.

Constraining the IMF and formation history

Monte Carlo simulations show that the L-T transition regime is the most sensitive to the formation history.



(Day-Jones et al, 2013, MNRAS)

BD candidates selection

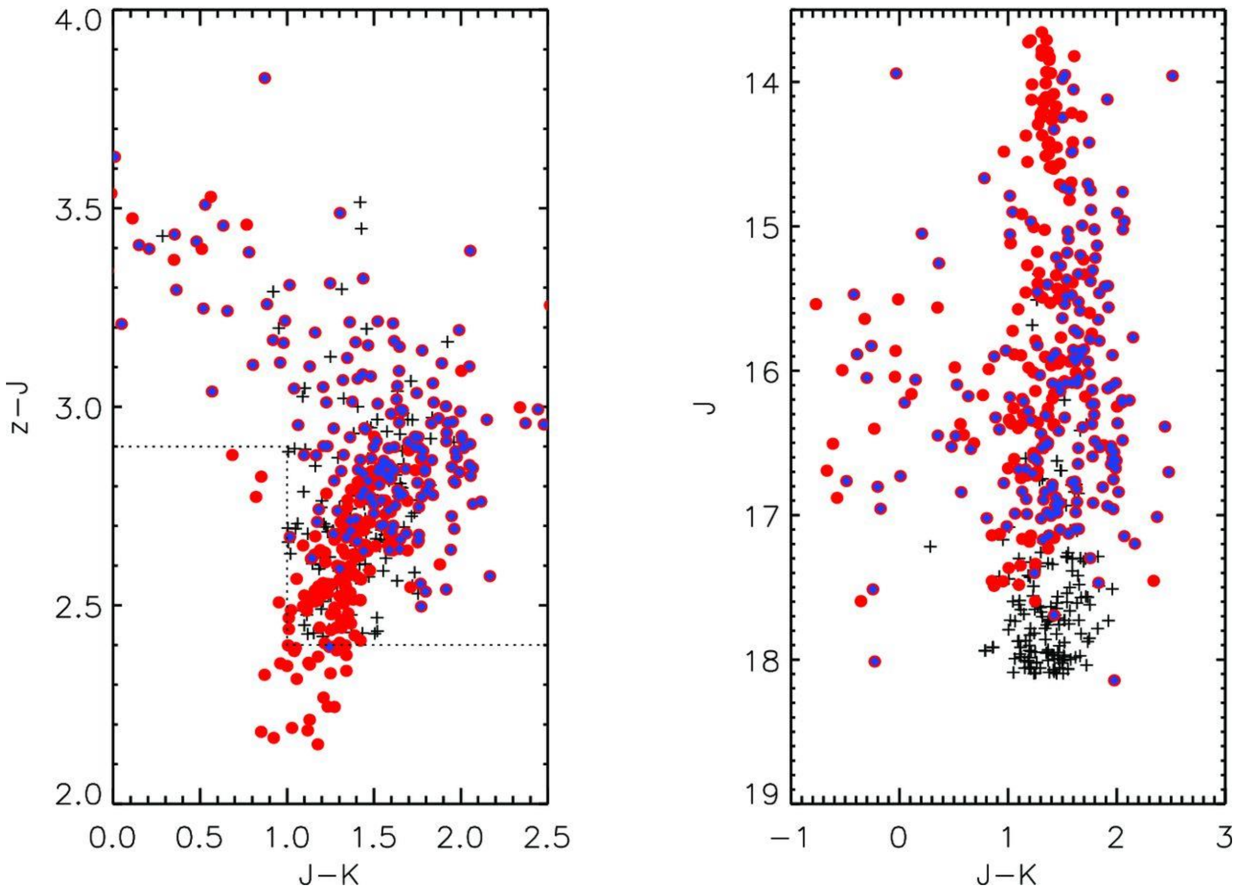
Spectroscopic campaign to follow-up a sample of 250 L-T transition BD candidates, photometrically selected from UKIDSS LAS + SDSS.

(Day-Jones et al. 2013, MNRAS)

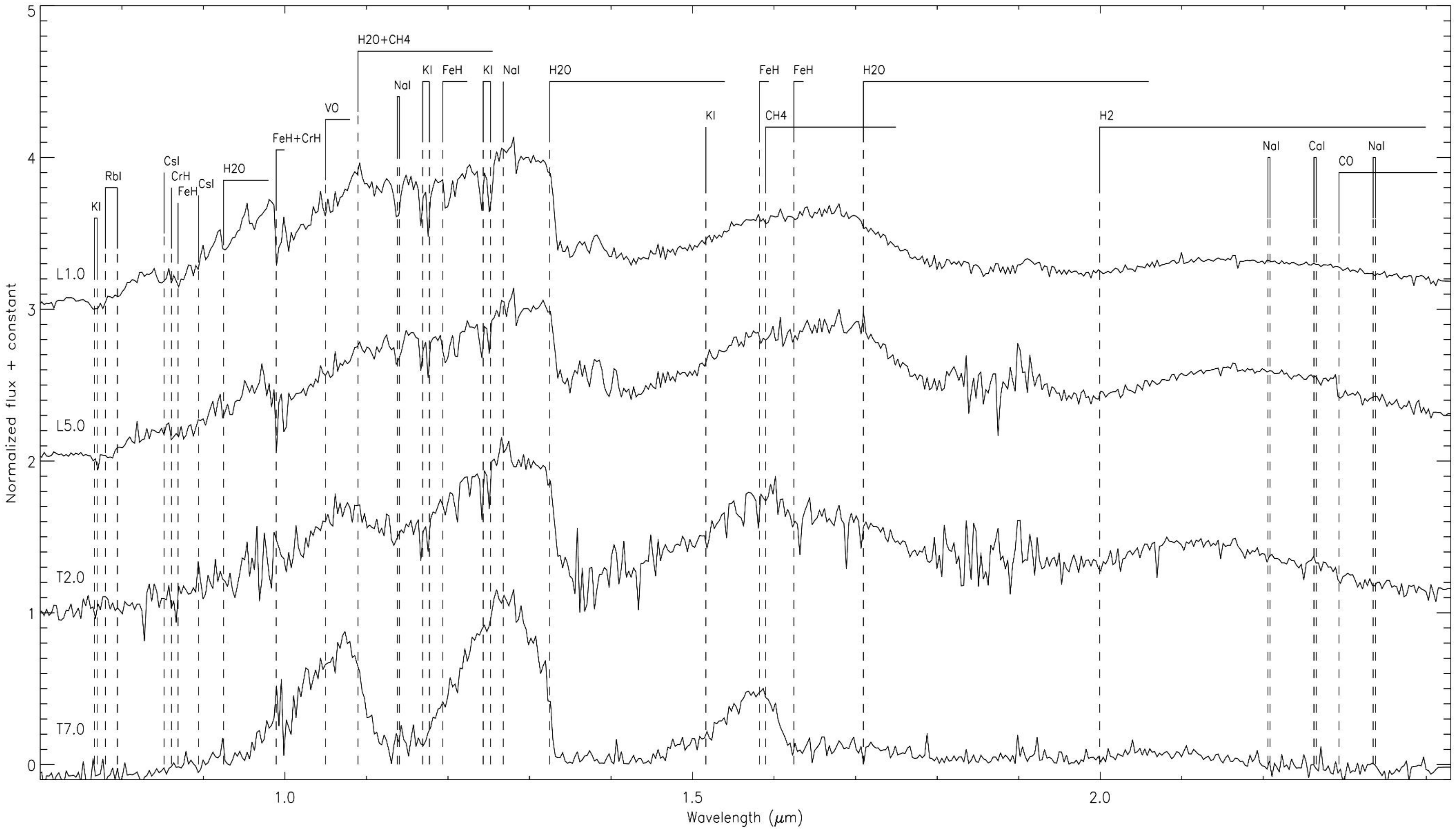
J <= 18.1
Y-J >= 0.8

z-J >= 2.4 and J-K >= 1.0
OR
z-J >= 2.9 and J-K < 1.0

i-z > 2.0
i-J > 4.7
z-K > 3.5 and J-K < 1.0



Follow-up of 196 candidates with VLT/Xshooter (Day-Jones et al. 2013, Marocco et al. 2015).


H2O+CH4
KI
FeH
KI
NaI
H2O
FeH
FeH
H2O
NaI
VO
FeH+CrH
KI
CH4
H2
CsI
RbI
CrH
FeH
CsI
H2O
KI
NaI
CaI
NaI
CO
L1.0
L5.0
T2.0
T7.0
Normalized flux + constant
Wavelength (μm)
0
1
2
3
4
5
1.0
1.5
2.0

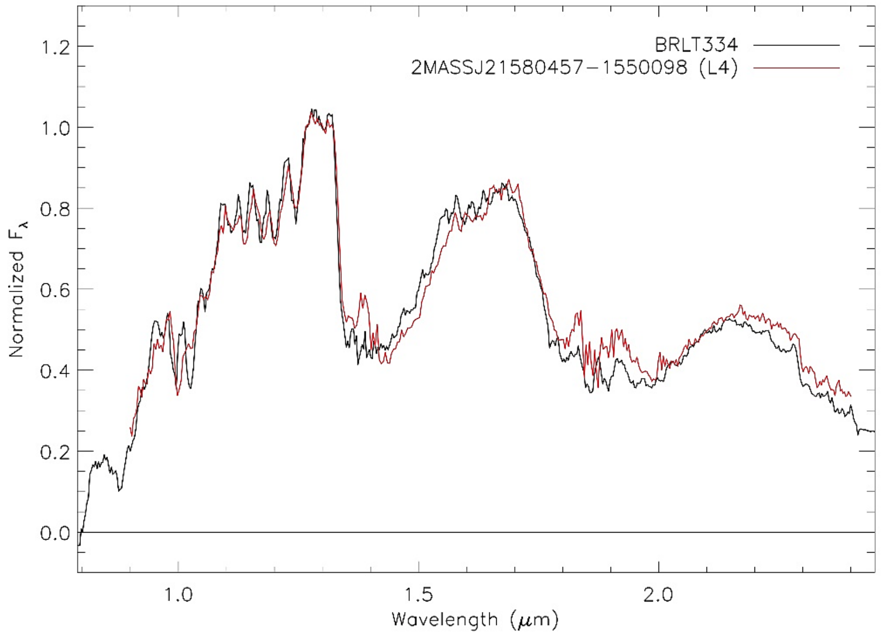
Constraining the IMF and formation history

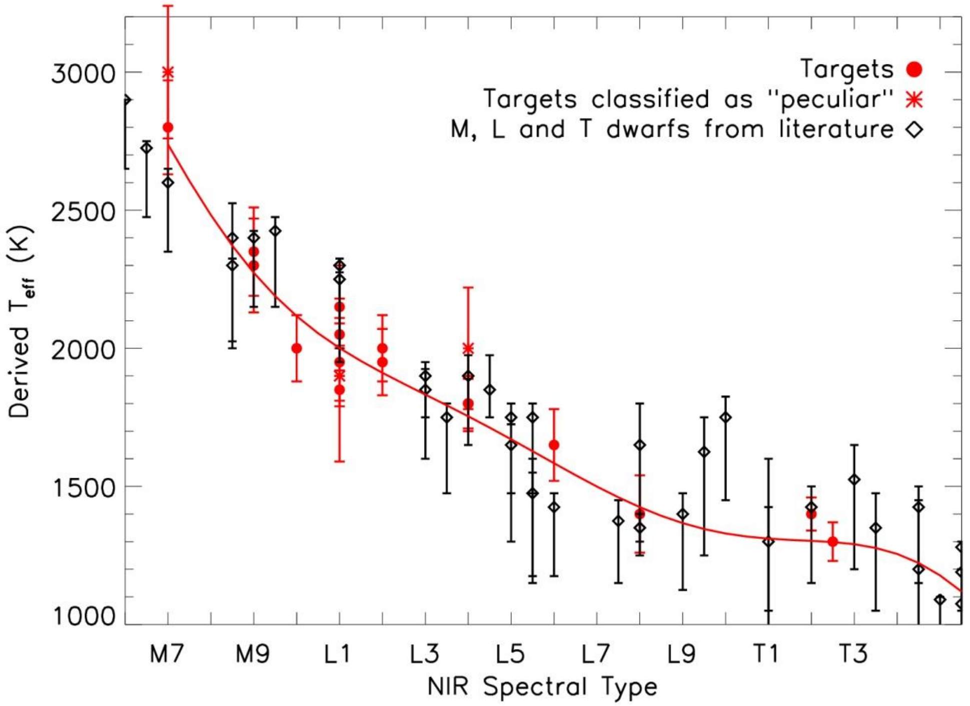
To compare our sample to the simulations we need to:

1) Determine the T_{eff} of the targets (i.e. their spectral types);
2) Determine the volume sampled (i.e. calculate the distance to our targets);
3) Check the completeness of the sample;
4) Correct for binarity, Malmquist bias, etc...

Step 1: determine T_{eff}

The spectral types of the objects were determined via comparison with spectroscopic standards.



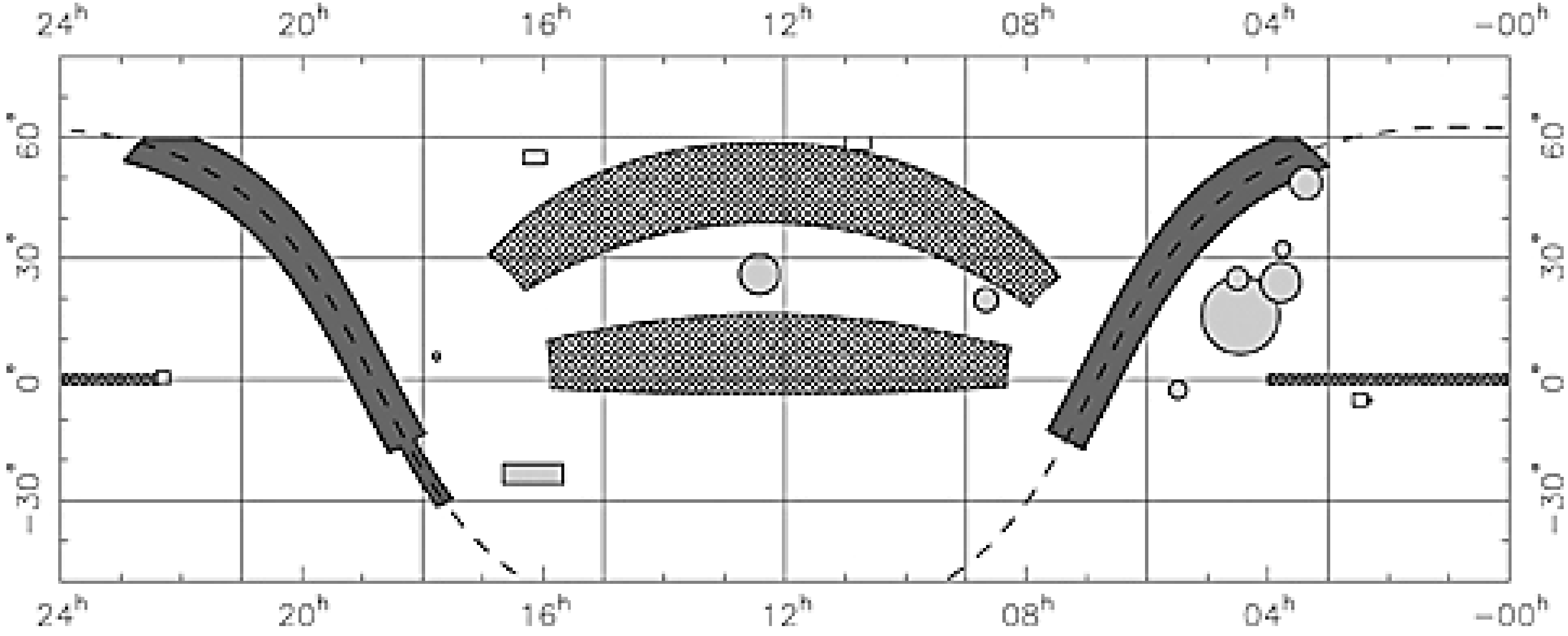


The spectral types were converted into T_{eff} using the Marocco et al. (2013) relation.

Step 2: determine the volume sampled

The spectroscopic follow-up is completed for -3 < Dec < +19, corresponding to an area of ~1700 deg^2, containing 167 objects.

The distance to the targets was estimated using the photometric distance calibration from Dupuy et al. (2012, ApJ).



Step 3: check completeness

We checked the completeness of our photometric selection using a control sample.

We took all the known L and T dwarfs from dwarfarchives.org, and cross-matched with UKIDSS and SDSS to obtain *ugriz* and MKO YJHK photometry.

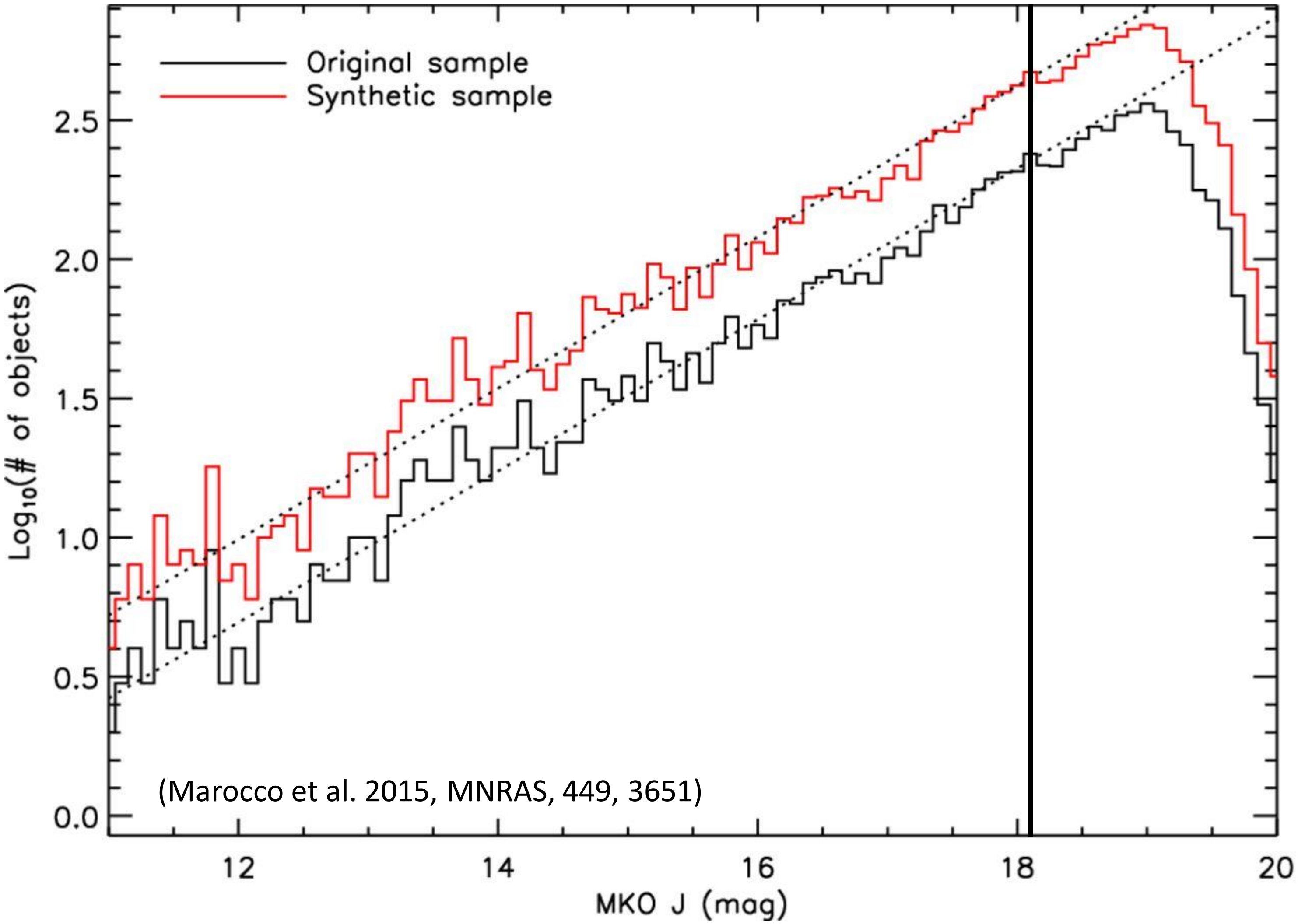
Then we applied our selection criteria to the control sample.

Applying our selection criteria we retrieve 88% in the L4-L6 range, 94% in the L7-T0, and 99% in the T1-T4 range.

Step 3: check completeness

$J < 18.1$ is $\sim 12\,\sigma$ in ULAS, so **no missed detections** (completeness > 99%).

Blending is not an issue (completeness > 99%).

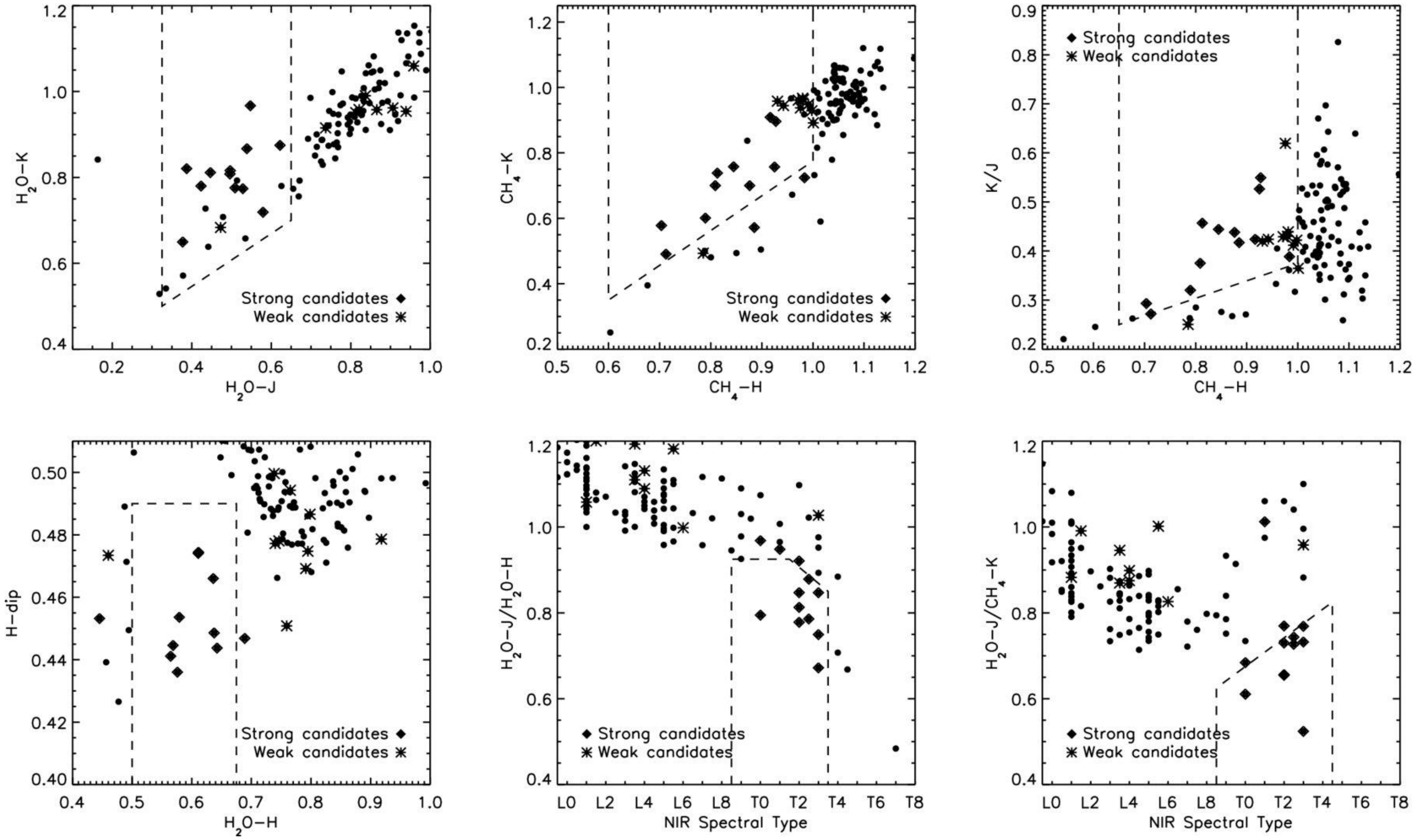


(Marocco et al. 2015, MNRAS, 449, 3651)

Step 4: correct for binarity & biases

Unresolved binaries can be identified using their spectral indices. The criteria are defined in Burgasser et al. (2010, ApJ).

(Day-Jones et al. 2013, MNRAS)

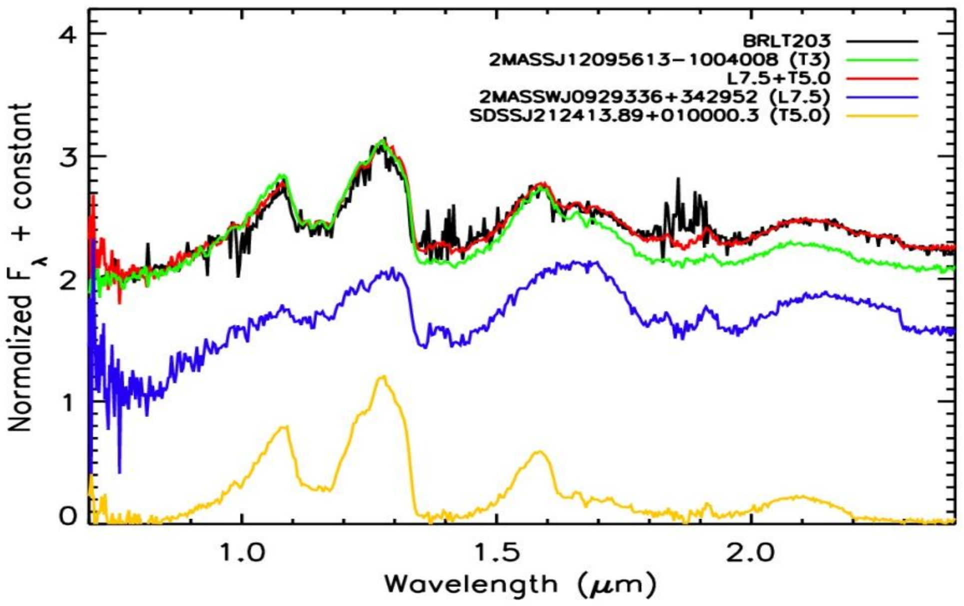


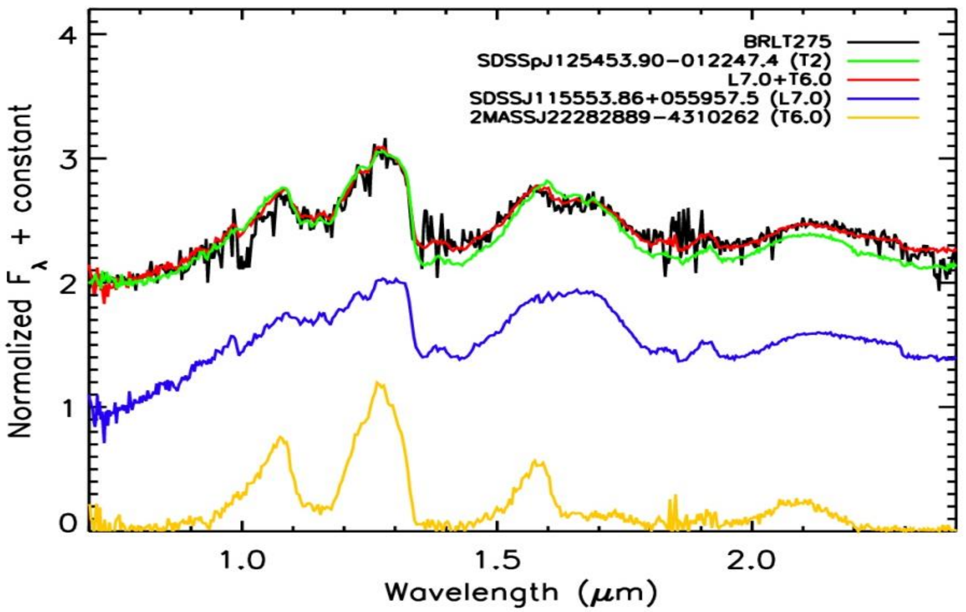
We identified 24 binary candidates

Step 4: correct for binarity & biases

The spectral types of the components can be determined via spectral deconvolution.

The results of the deconvolution are tested against the results of the templates fitting using an F-test.





16 of the 24 candidates passed this second selection. Need AO follow-up!

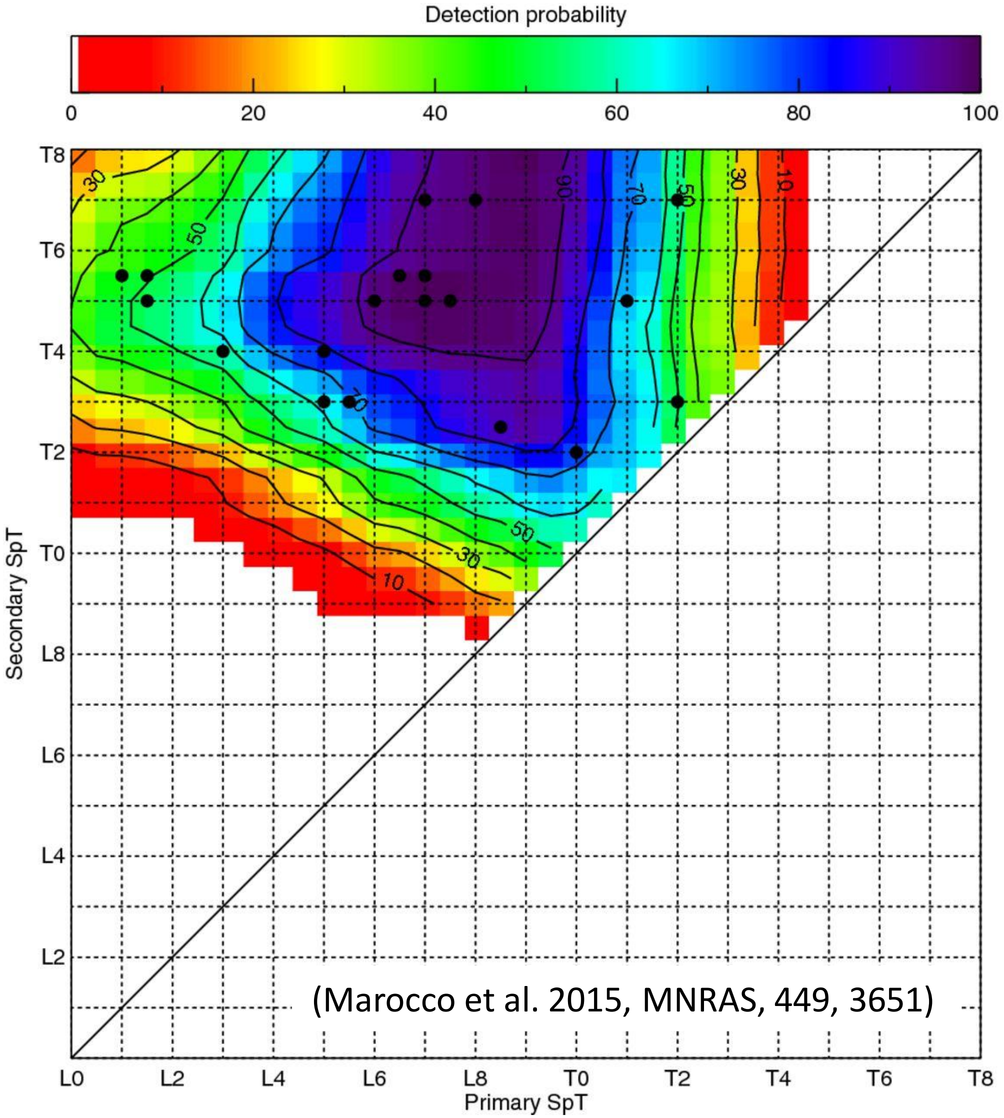
If confirmed, BF $\sim$ 8%, but we need to account for incompleteness!

Step 4: correct for binarity & biases

We combined the spectral templates taken from the SpeX-Prism library to create a sample of synthetic unresolved binaries, that were then run through our binary identification pipeline, to assess the completeness of the selection method.

The technique is most efficient at the L/T transition, and the fraction of detected binaries steeply declines when moving towards very low mass ratios and early L-type binaries.

The completeness corrected BF is 14%.



(Marocco et al. 2015, MNRAS, 449, 3651)

Step 4: correct for binarity & biases

Our technique is only sensitive to non-equal spectral type binaries. We still need to correct for equal spectral type binaries.

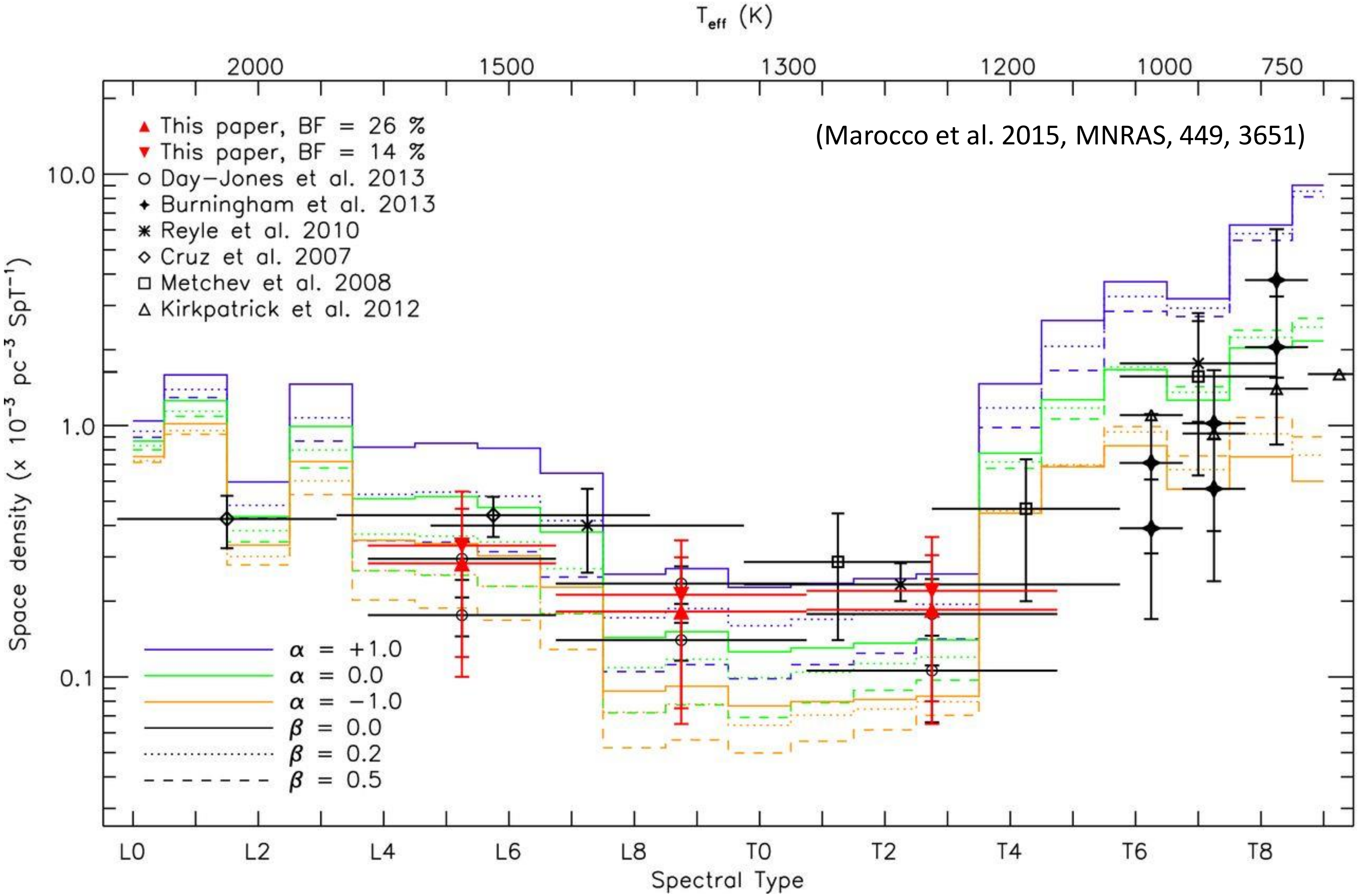
To do that we follow Burgasser et al. 2003 (ApJ, 586, 512):

$$f_{excl} = \frac{\gamma - 1}{\gamma + \frac{1}{BF} - 1}$$

Where $\gamma = 2\sqrt{2}$ for equal spectral type binaries, and BF is the “true” binary fraction.

PROBLEM: BF is unconstrained. In the literature 5% < BF < 45%

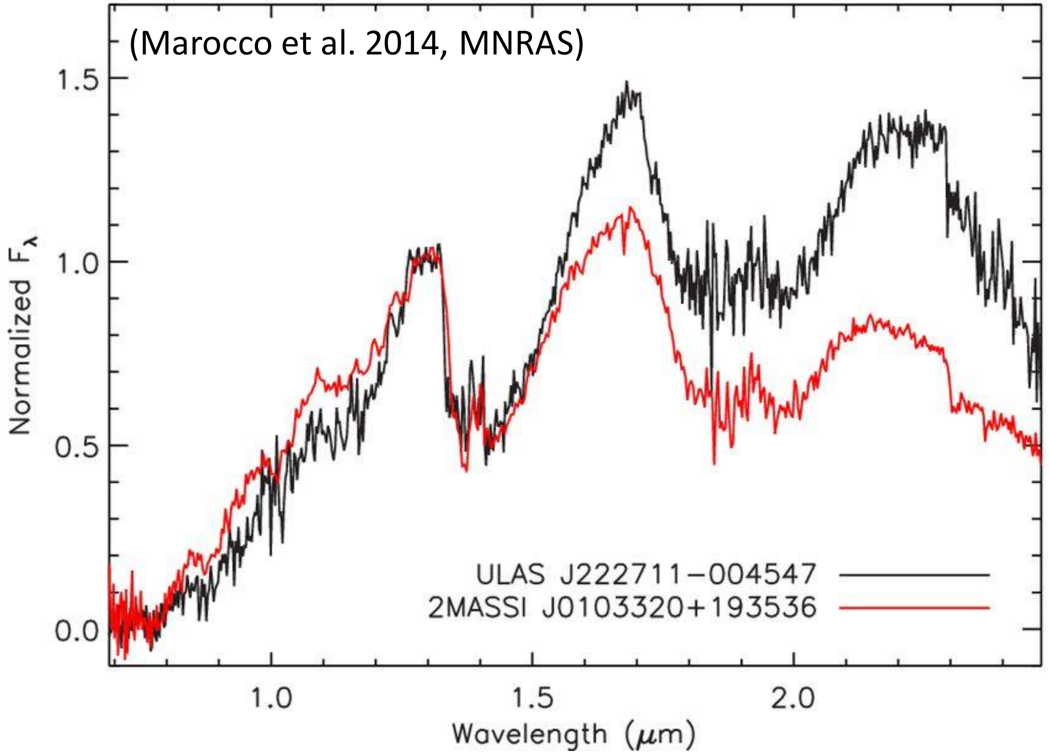
Results



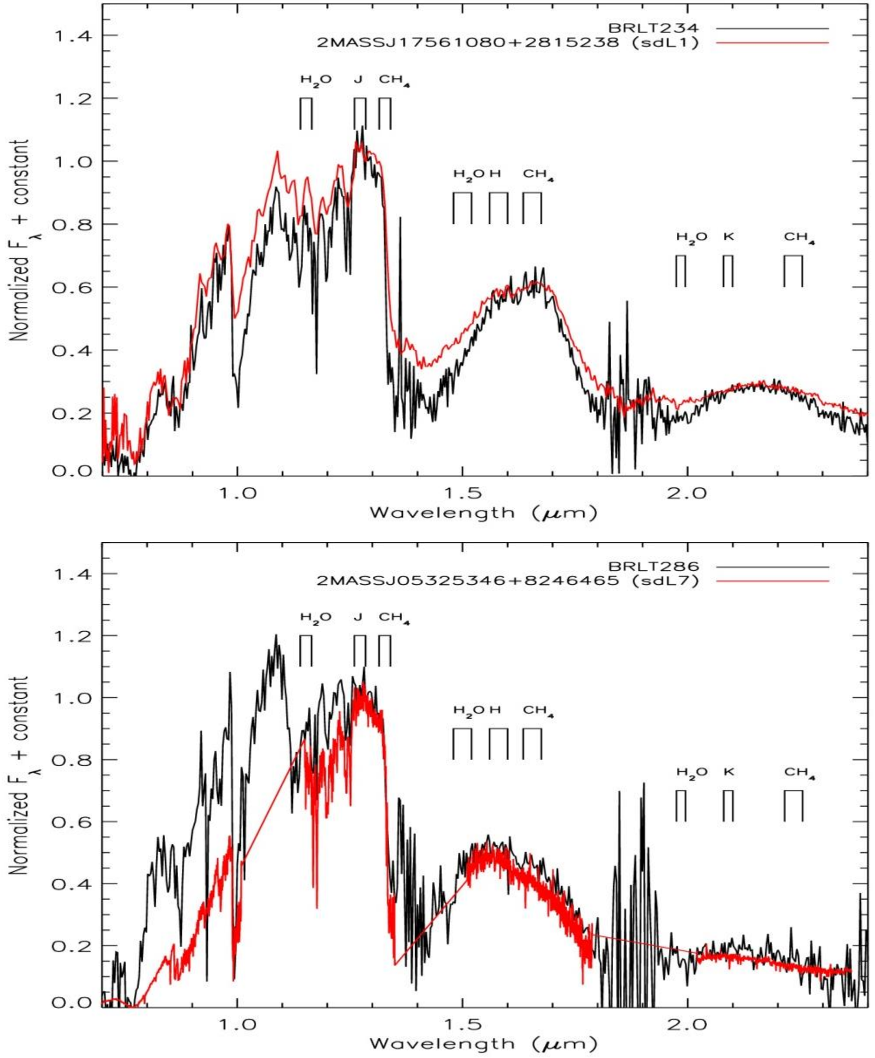
T_eff (K)
2000
1500
1300
1200
1000
750
This paper, BF = 26 %
This paper, BF = 14 %
Day−Jones et al. 2013
Burningham et al. 2013
Reyle et al. 2010
Cruz et al. 2007
Metchev et al. 2008
Kirkpatrick et al. 2012
(Marocco et al. 2015, MNRAS, 449, 3651)
10.0
1.0
0.1
Space density (x 10^-3 pc^-3 SpT^-1)
α = +1.0
α = 0.0
α = −1.0
β = 0.0
β = 0.2
β = 0.5
L0
L2
L4
L6
L8
T0
T2
T4
T6
T8
Spectral Type

Peculiar objects

The wide wavelength coverage of Xshooter is ideal to identify peculiar objects, i.e. BDs that are bluer/redder than the spectroscopic standards.



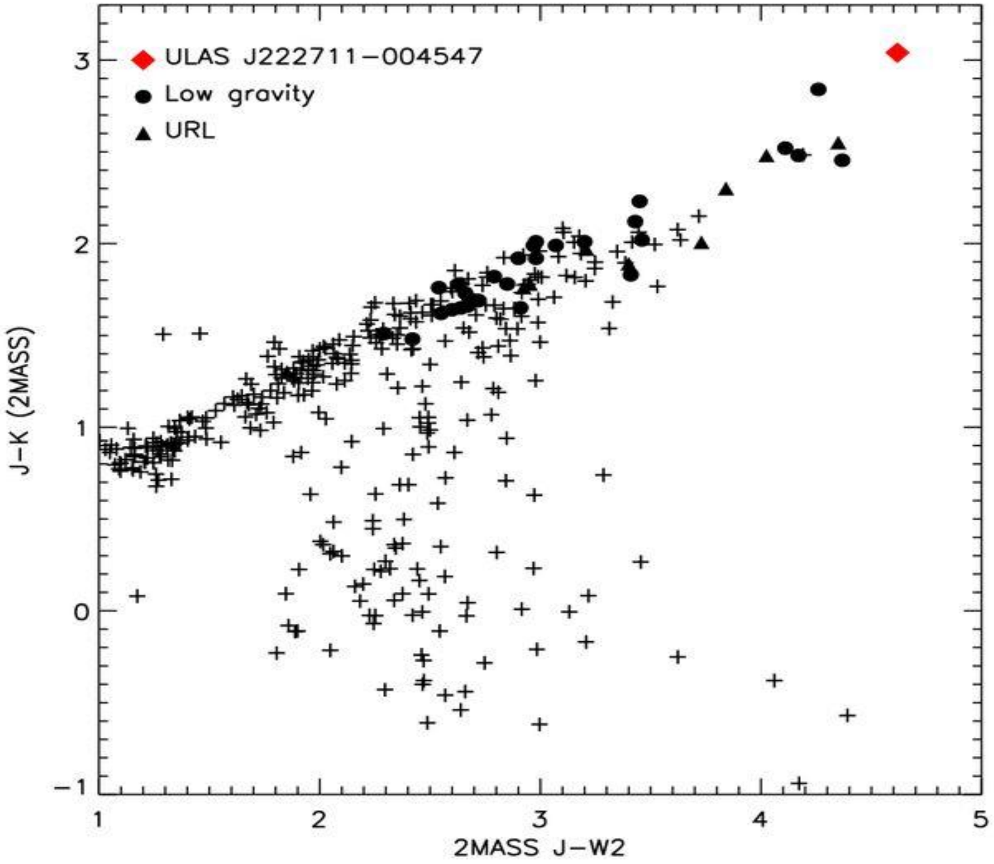
(Zhang et al. in prep)

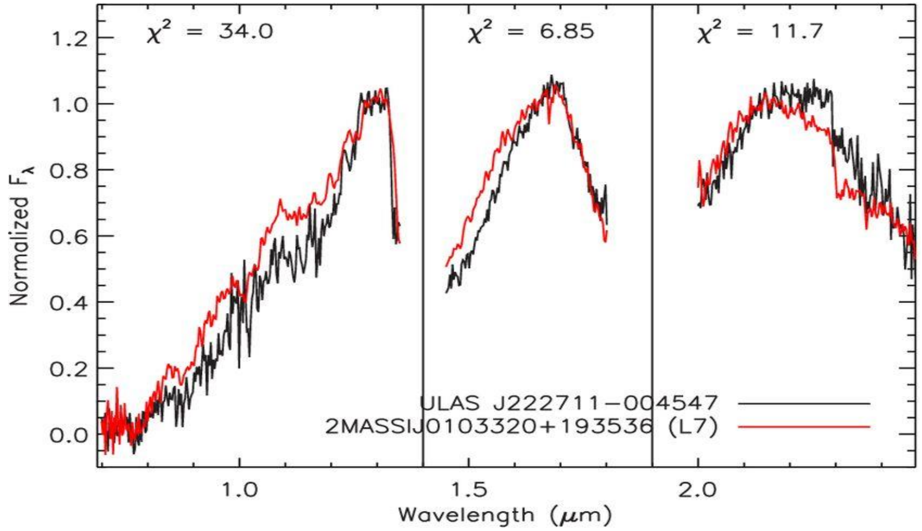


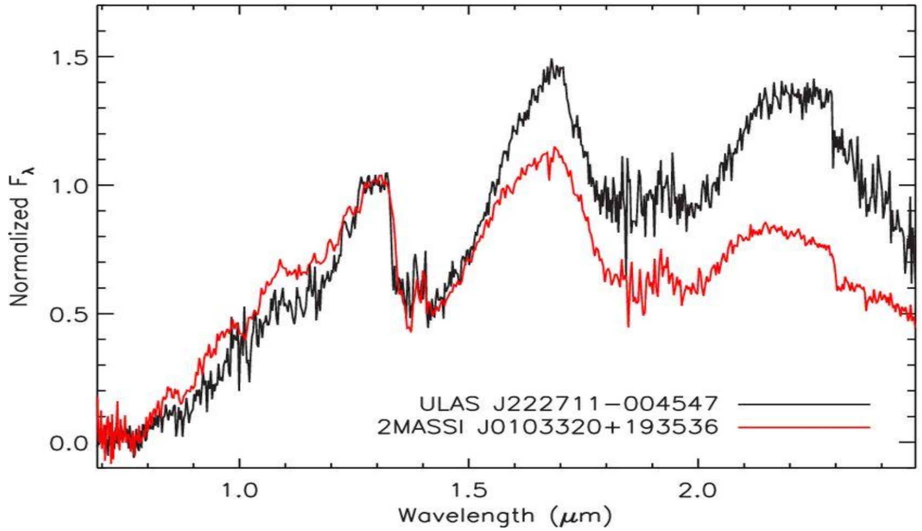
ULAS J222711-004547

(Marocco et al. 2014, MNRAS)

One of the reddest BD known. Its colours (and spectrum) look very similar to those of gas giant exoplanets.







ULAS J222711-004547

Extinction curves for corundum or enstatite with typical grain sizes r = 0.40-0.55 μm give extremely good results.

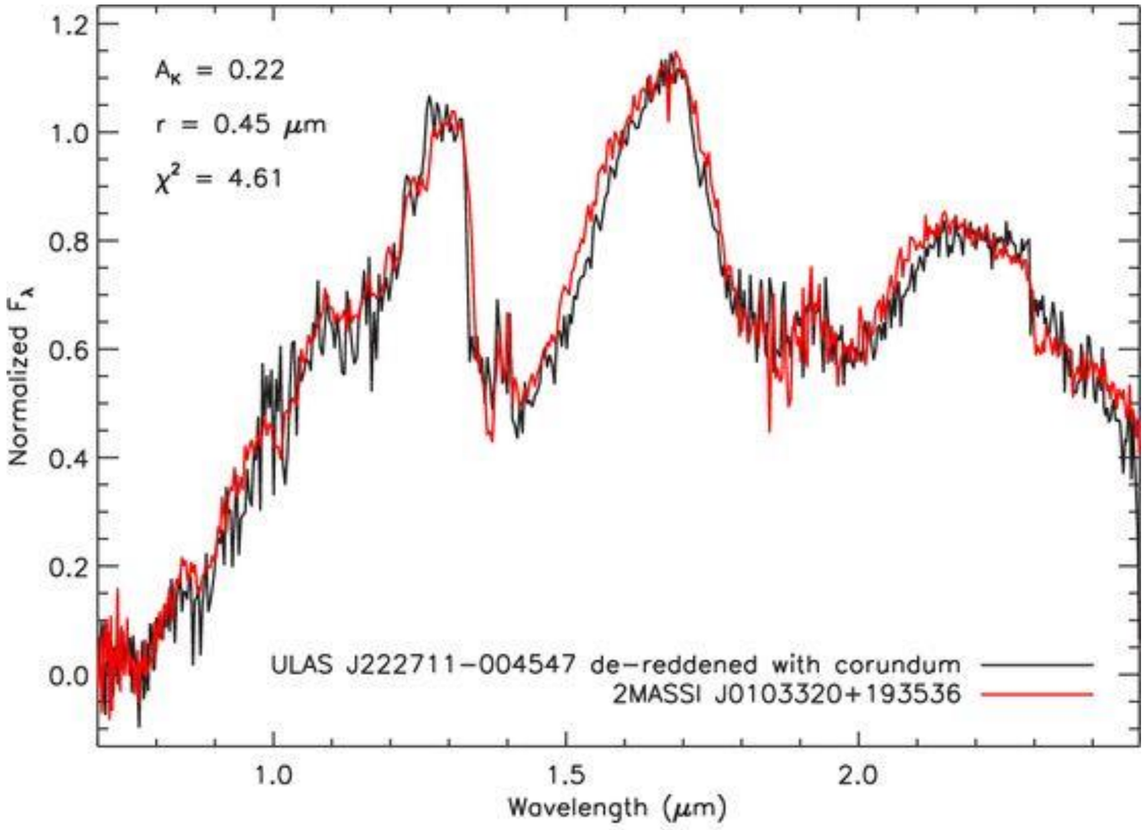
↓

Excess of dust in the higher layers of the photosphere

Typical in young objects (e.g. Manjavacas et al .2014, A&A), but this object is **not young!**

Unusual metallicity?

ULAS 2227-0045 de-reddened with **corundum**: r= 0.45 μm



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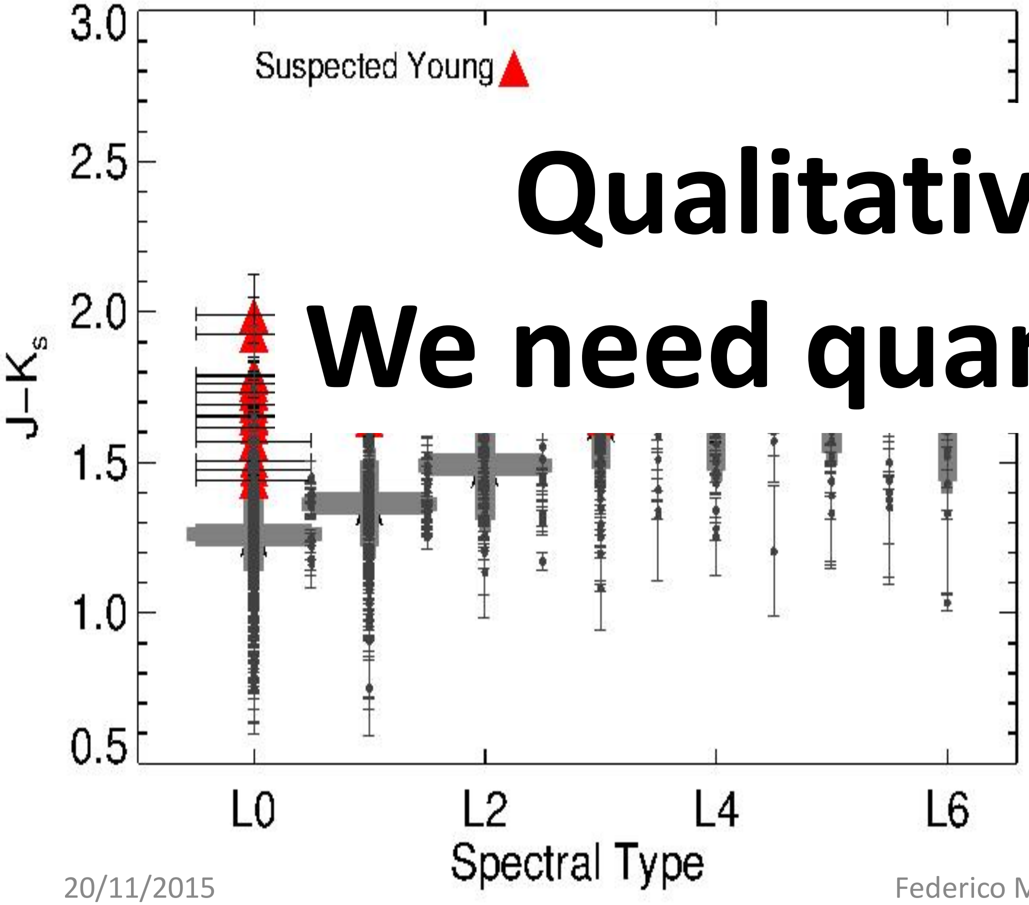
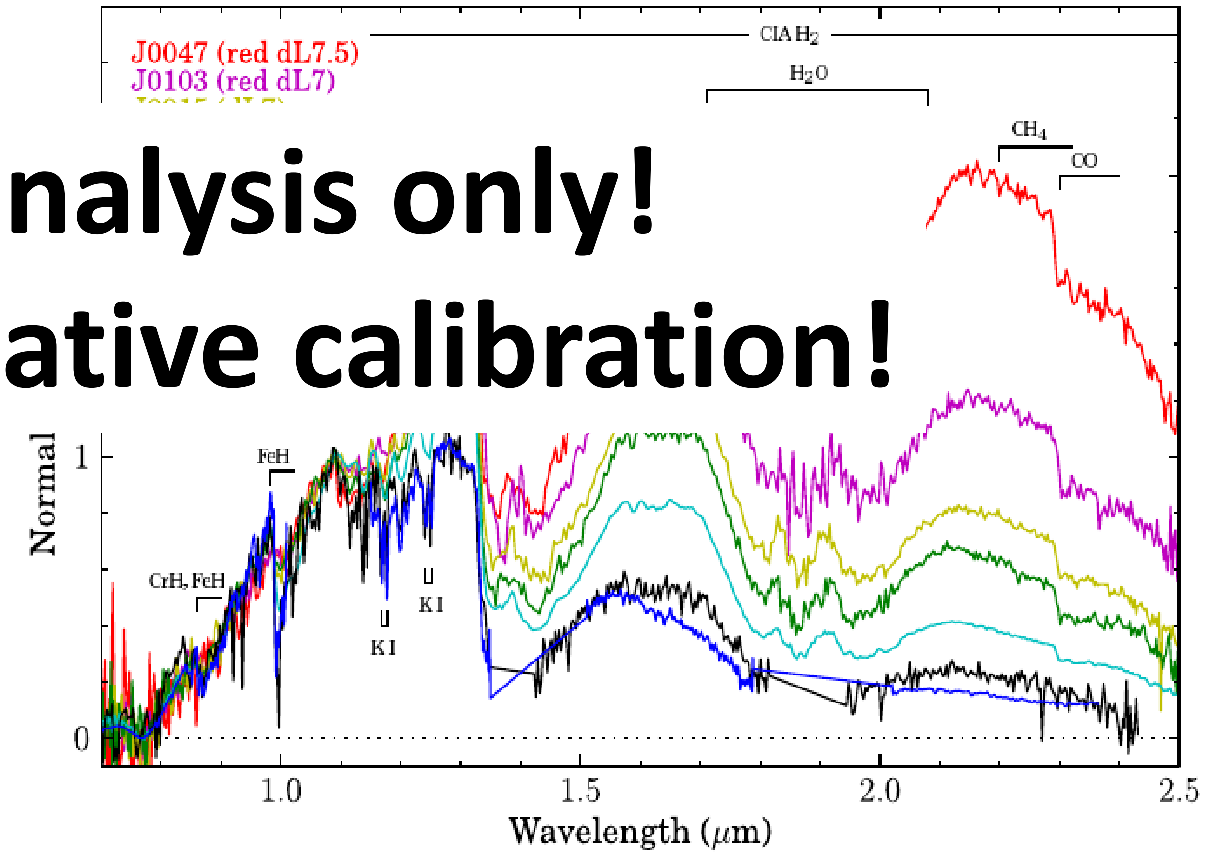
Faherty et al. 2013



Young

Old

Zhang et al. 2013



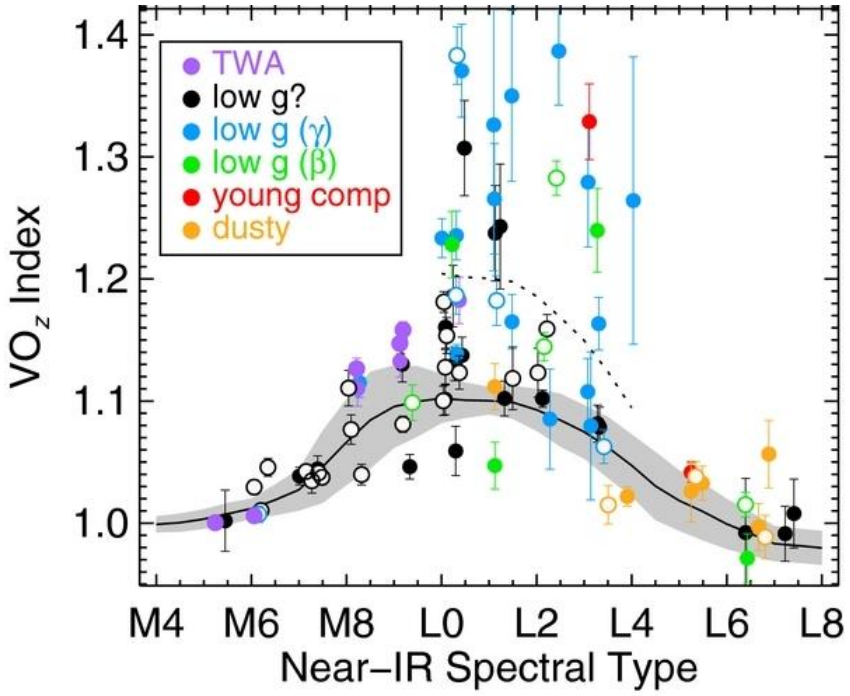
Qualitative analysis only!

We need quantitative calibration!

Benchmark systems

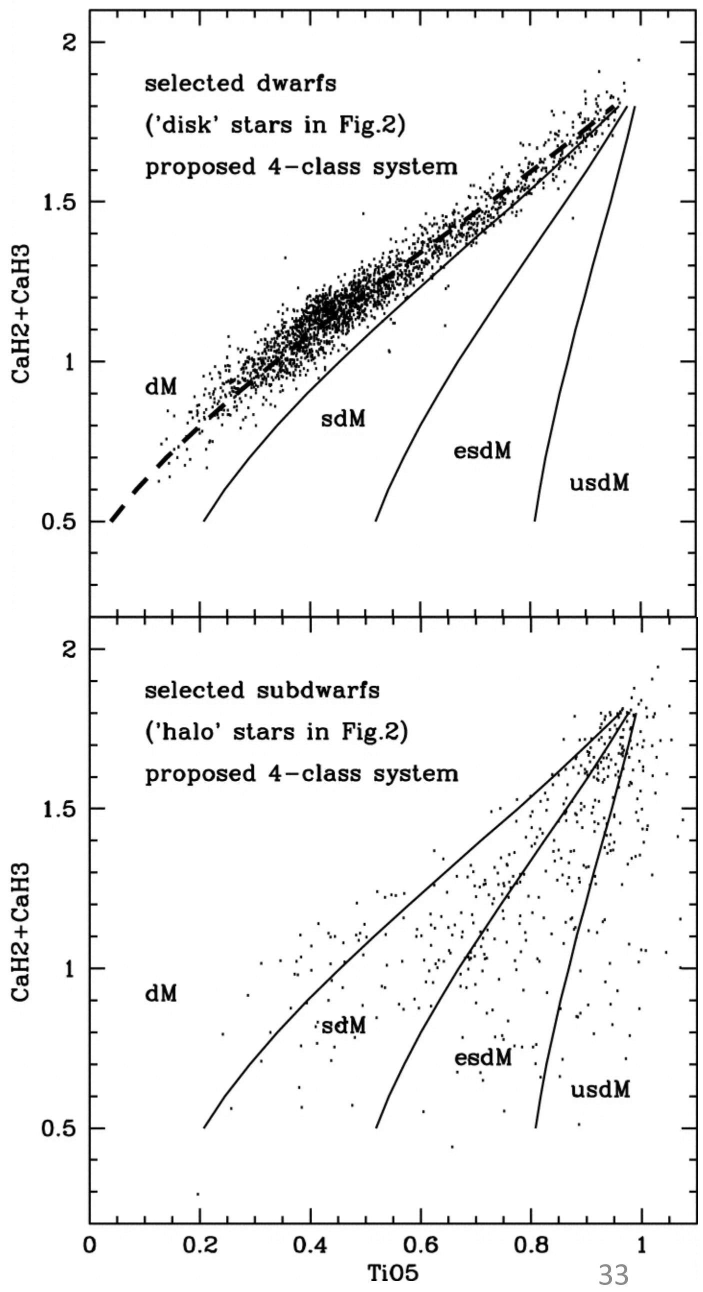
A direct way to overcome this challenge is to identify ultra-cool dwarfs (UCDs) whose physical properties can be inferred indirectly – so-called “benchmark systems” (e.g. Pinfield et al. 2006).

Allers & Liu (ApJ, 2013)



A number of atomic (KI and NaI) and molecular (FeH, VO, TiO, CaH) features have been shown to be sensitive to surface gravity and metallicity, but **the current calibrations suffer from limited sample size**.

Lepine, Rich & Shara (ApJ, 2007)



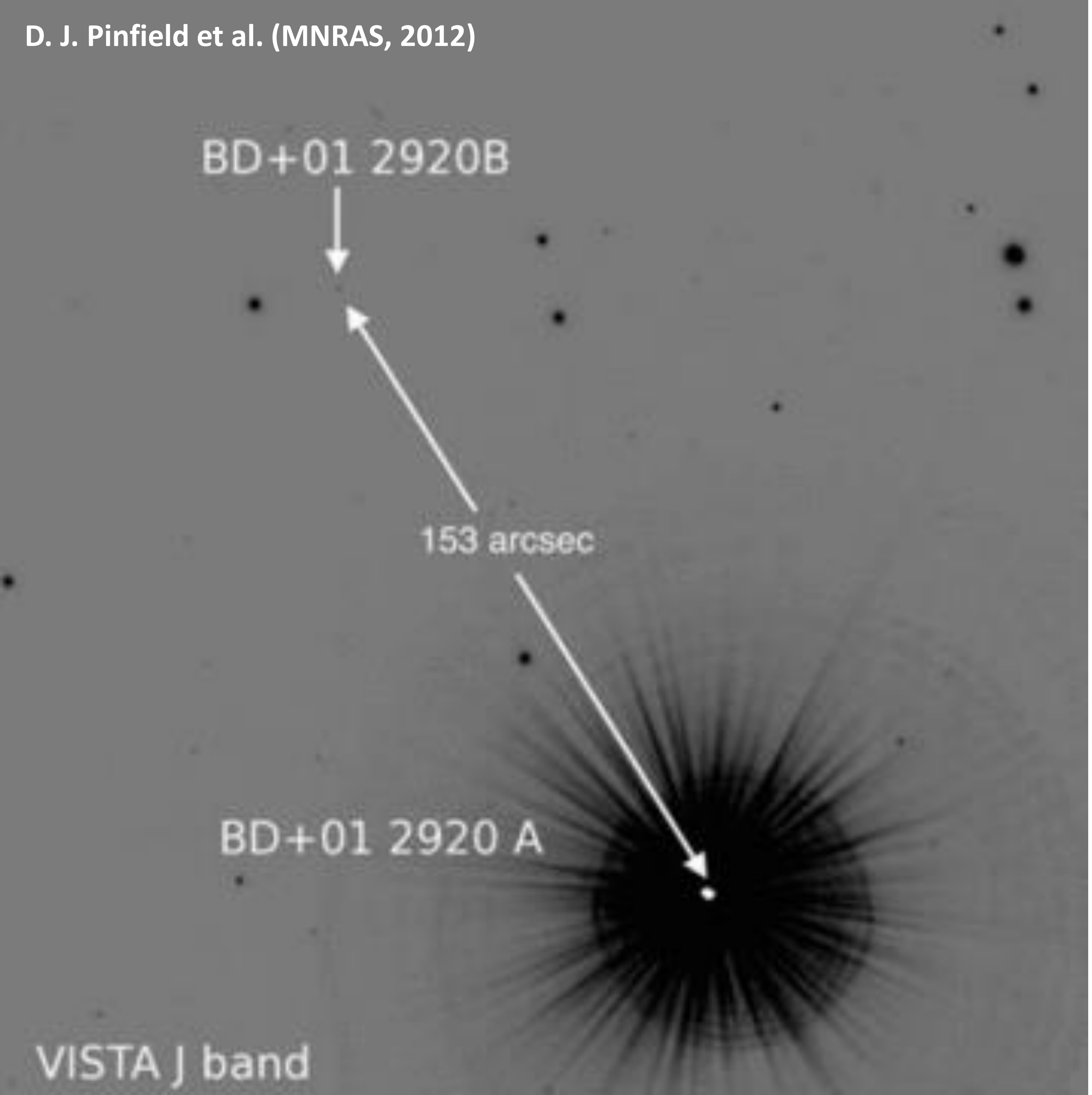
Benchmark systems

UCDs as wide companions to stars or stellar remnants of various type are a particularly crucial source of benchmarks, for which common age and compositional constraints can be determined from studies of the primaries.

Wide companions can be identified via common proper motion (e.g. Gomes et al., MNRAS, 2013; Burningham et al., MNRAS, 2013; Deacon et al., ApJ, 2014) or common radial velocity (cf. Dithal et al., AJ, 2012).

To date 98 >M7 dwarfs in 92 multiple systems

0.33 % of main sequence stars should host L dwarf companions



BD+01 2920 AB

BD+01 2920 A
G1V
D = 17.2 ± 0.2 pc
V_r= 19.6 ± 0.3 km s^{-1}
Space motion UVW= 22, 15, 39 → thin disk

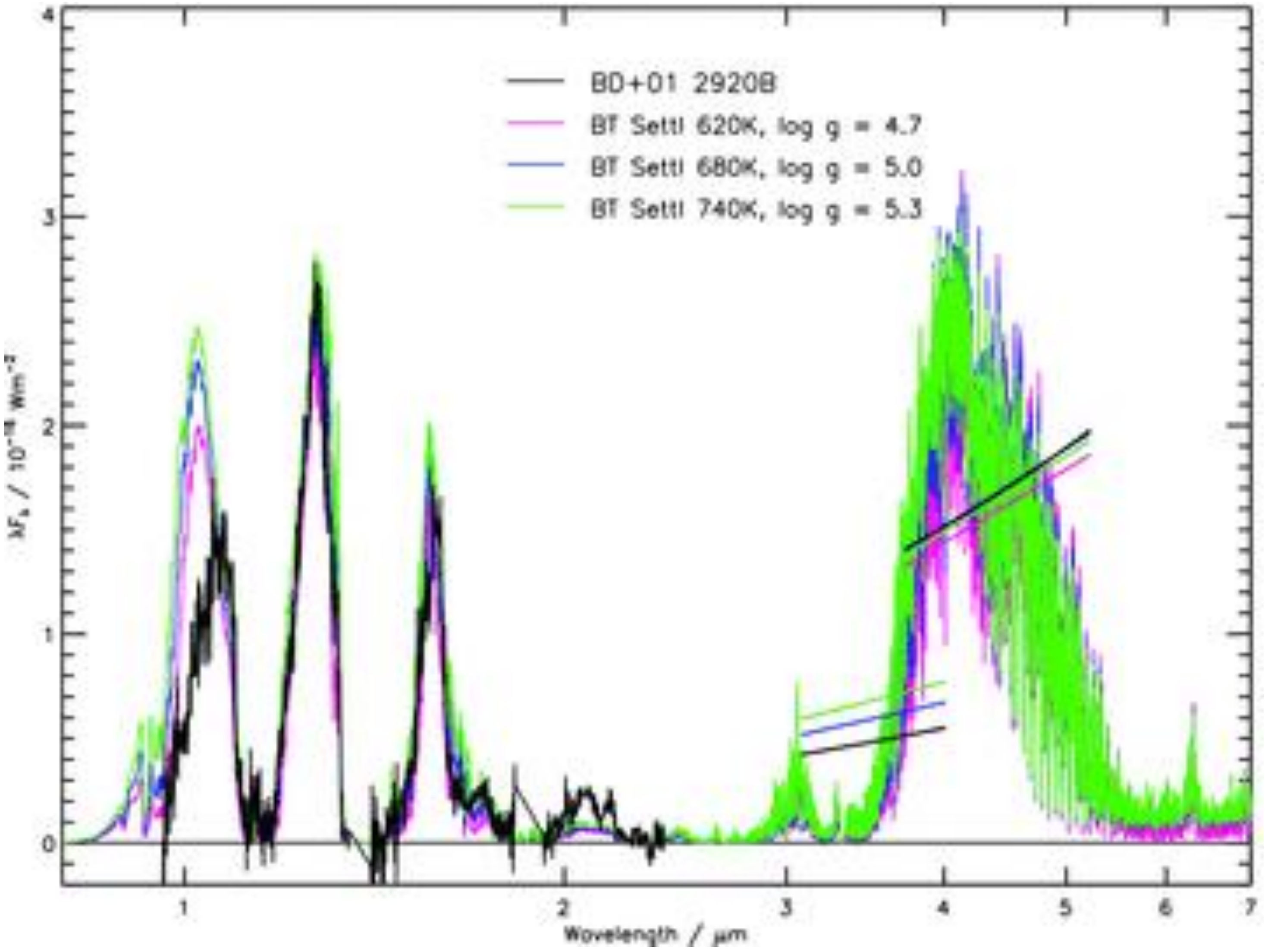
T_{eff} = 5750 ± 100 K
log *g* = 4.45 ± 0.05 dex
Mass = 0.87 ± 0.07 $M_\odot$
[Fe/H] = −0.38 ± 0.06 dex
Age = 2.3–14.4 Gyr
v sin(i)= 1–2 km s^{-1}
Low-activity star

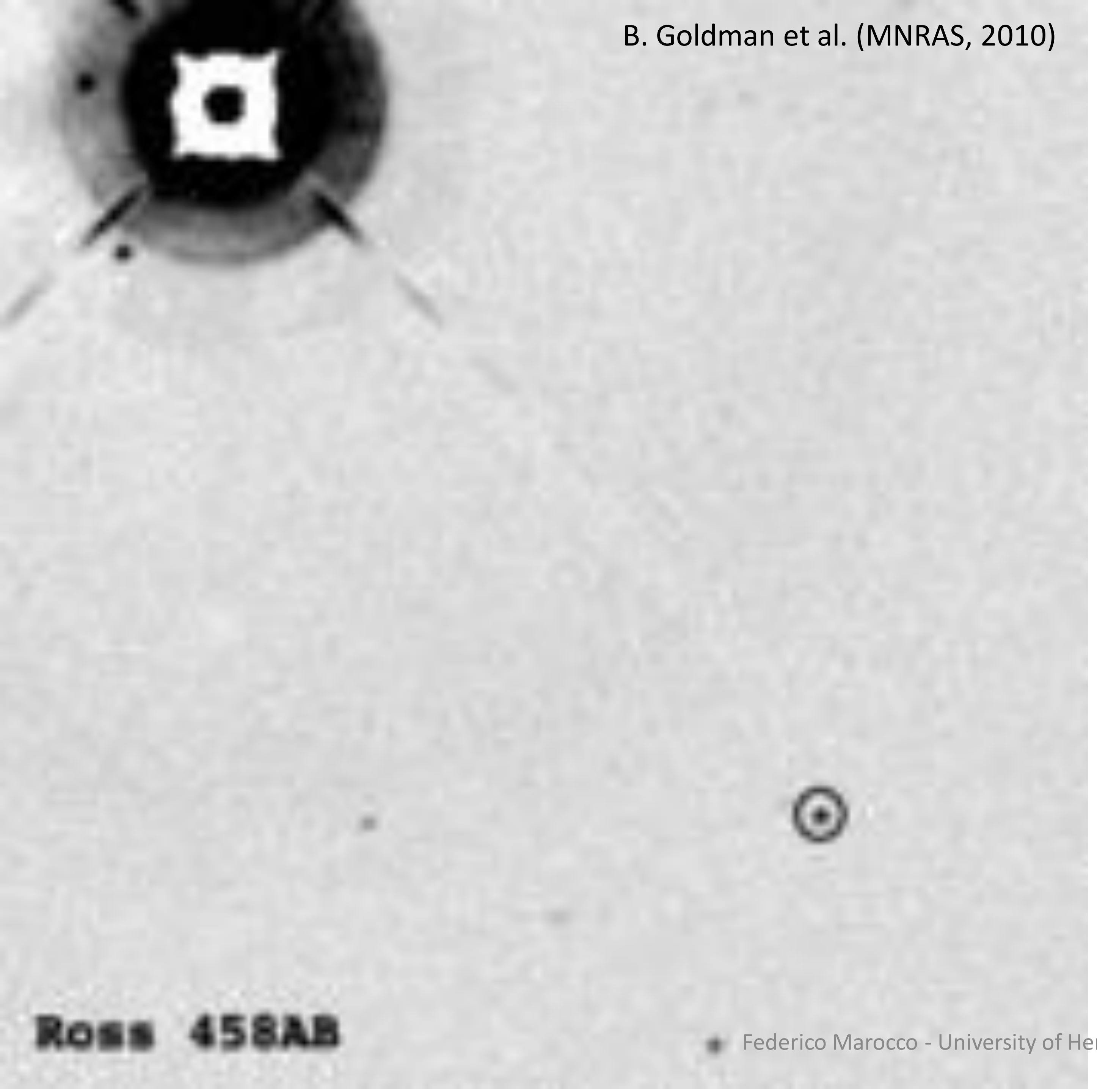
BD+01 2920 AB

D. J. Pinfield et al. (MNRAS, 2012)

BD+01 2920 B
T8p
log $L/L_{\odot}$ = −5.83 ± 0.05
Mass = 20–50M_{Jup}
Radius = 0.80–0.99 R_{Jup}
log *g* = 4.68–5.30 dex
T_{eff} = 680 ± 55 K

Discrepancy with model atmospheres in both NIR and MIR!





B. Goldman et al. (MNRAS, 2010)

Ross 458 ABC

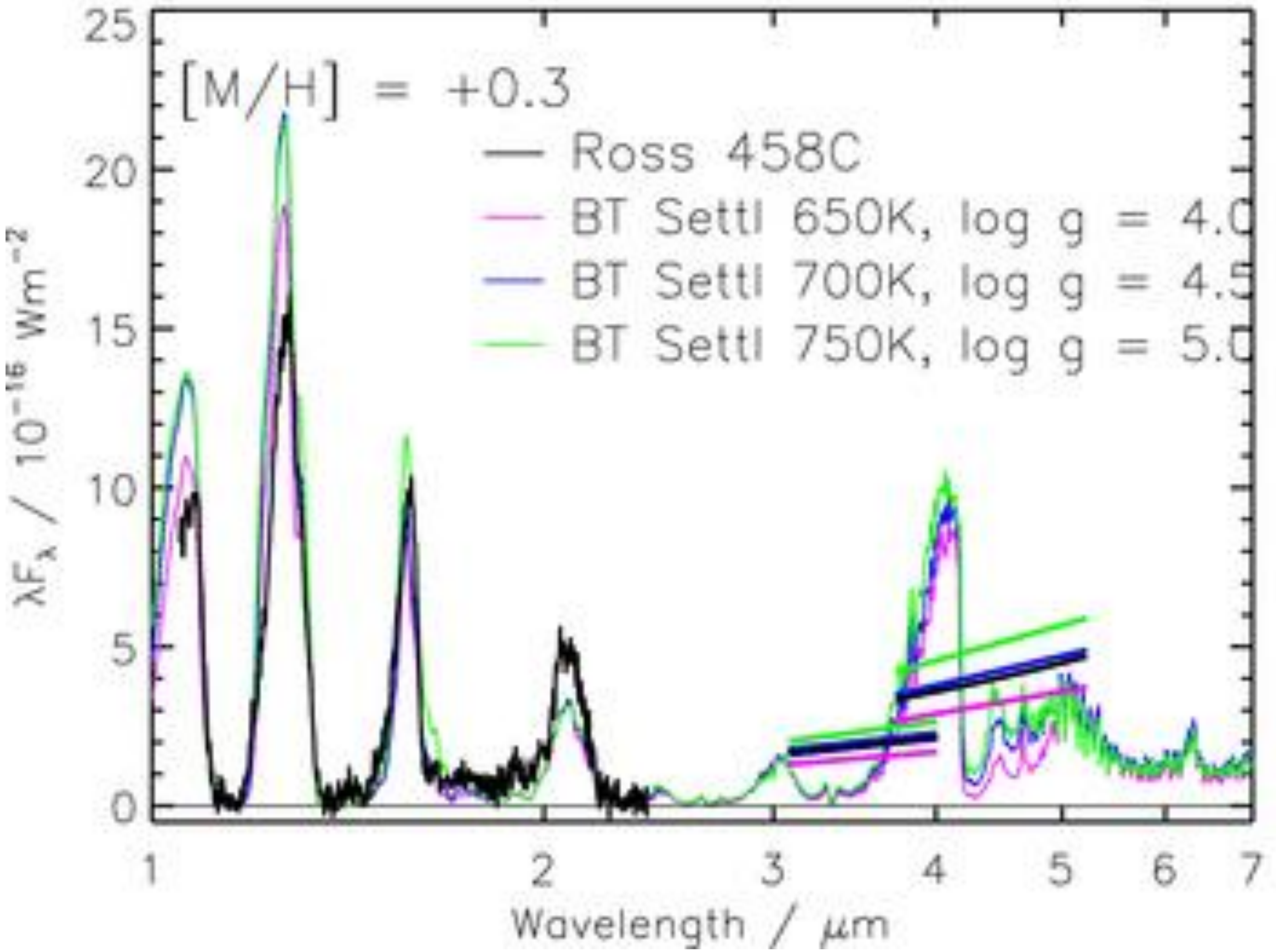
Ross 458AB
M0.5 + M7
Age ≤1 Gyr
D = 11.4 ± 0.2 pc
[Fe/H] = 0.20–0.31 dex
Member of the Hyades?

Ross 458 ABC

Ross 458C
T8.5
T_{eff} = 695 ± 60 K
log *g* = 4.0–4.7 dex

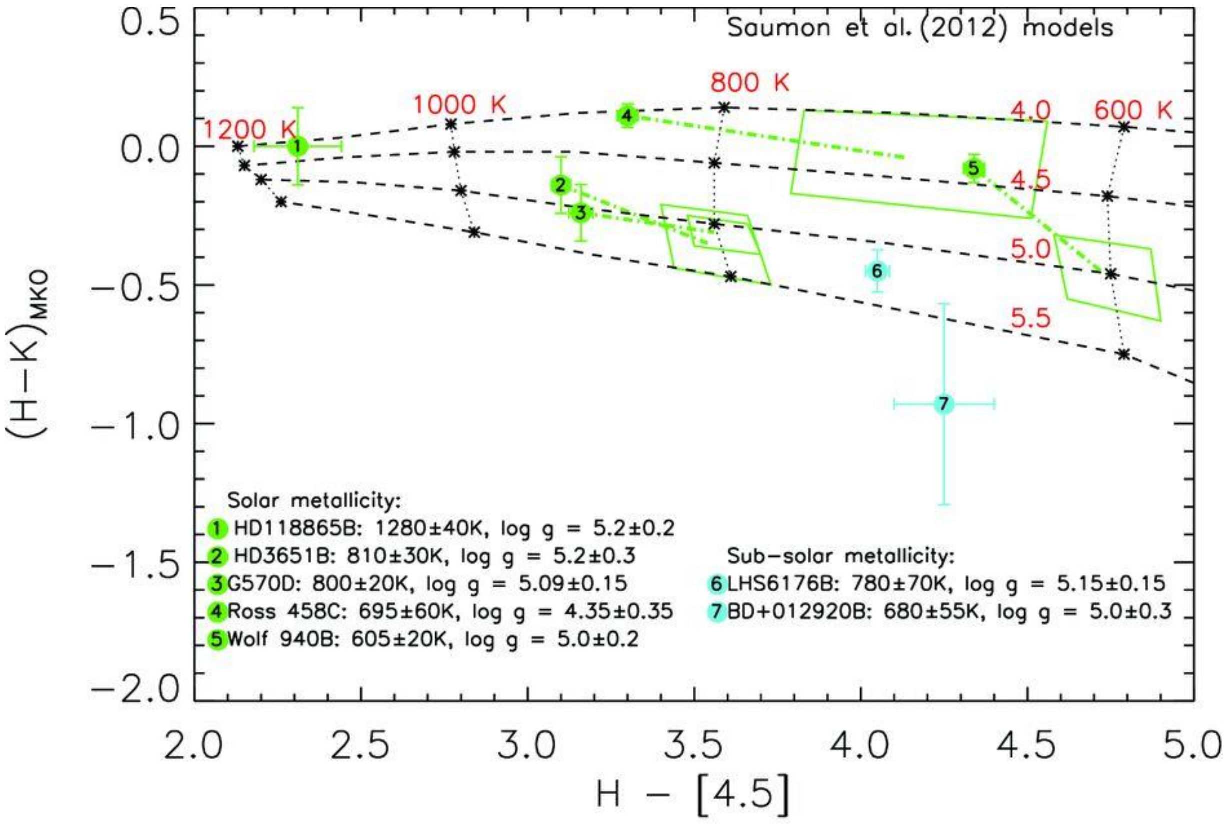
Discrepancy with model atmospheres in both NIR and MIR!

Burningham et al. (MNRAS, 2011)

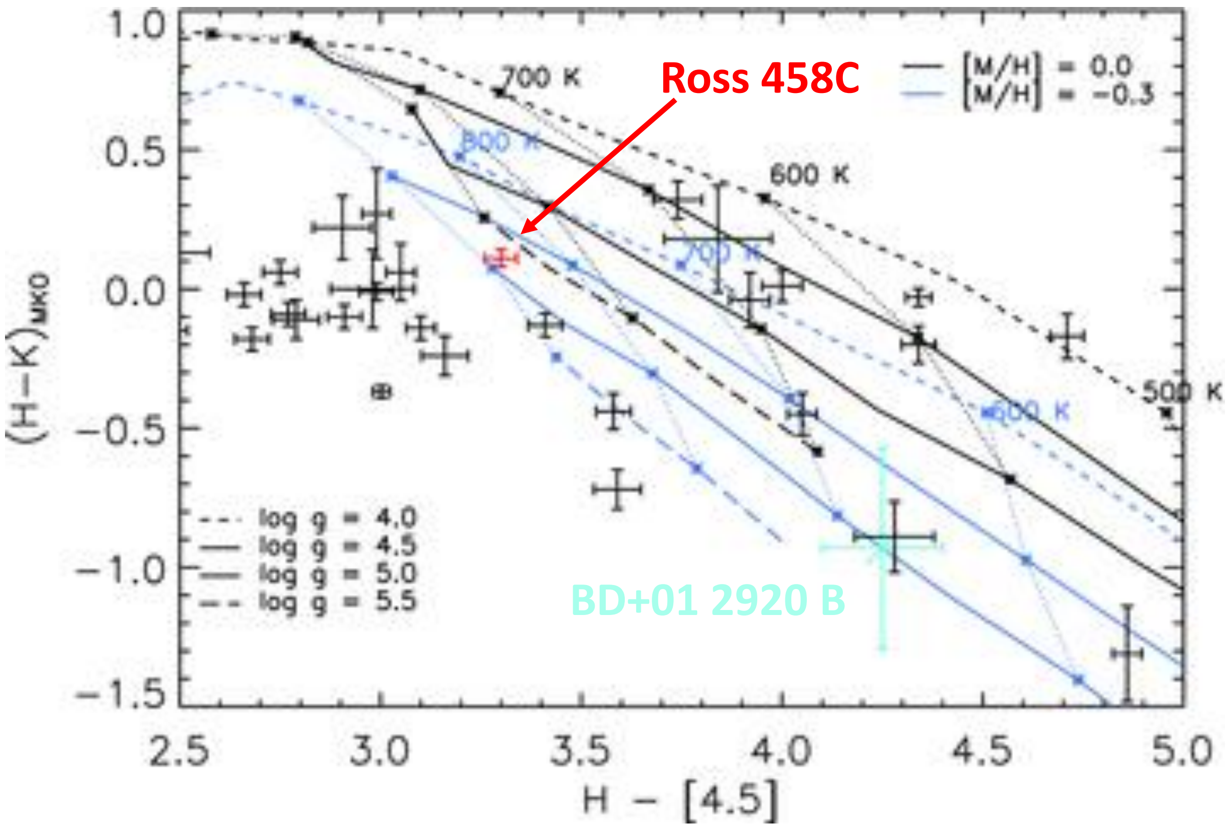


Benchmark systems

Burningham et al. (MNRAS, 2013)



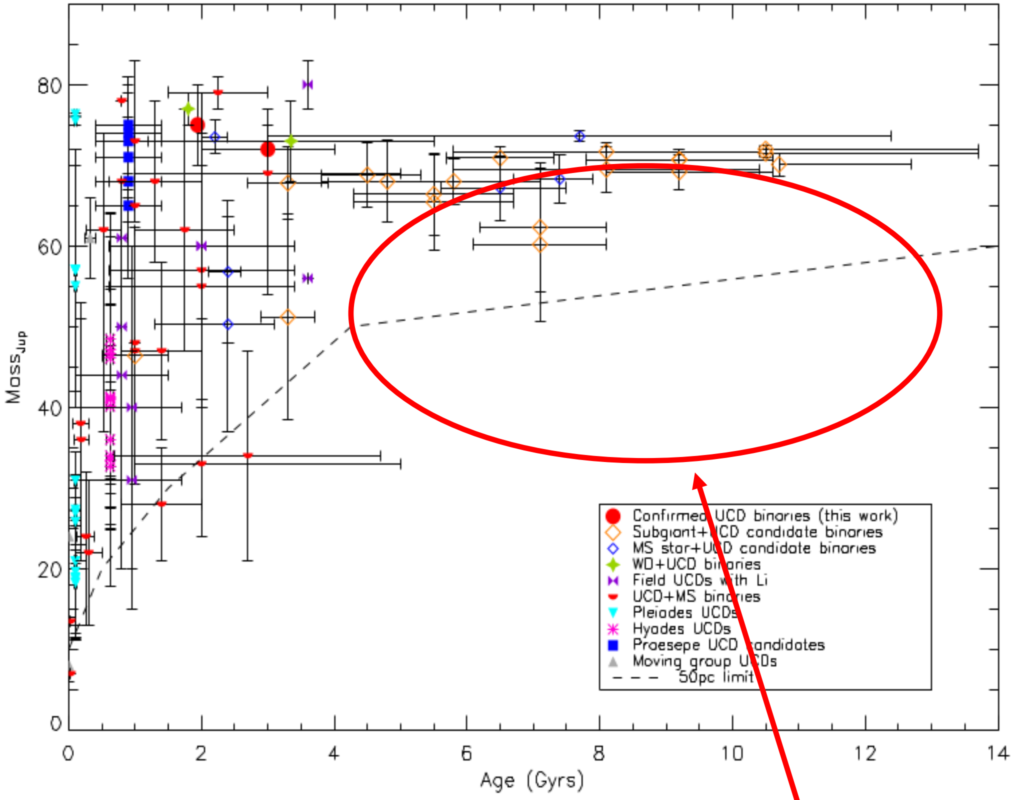
Pinfield et al. (MNRAS, 2012)

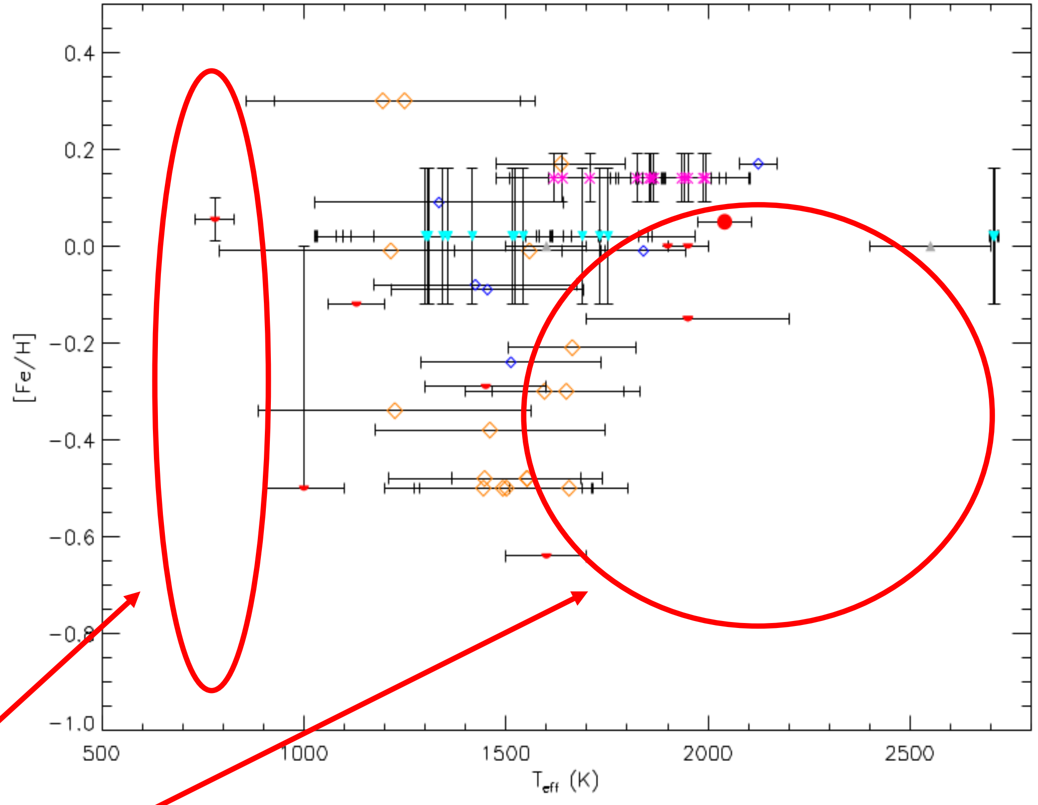


Models fail to reproduce properly the NIR and MIR colours of benchmark systems!

Benchmark systems

A. Day-Jones (UHRA, 2009)



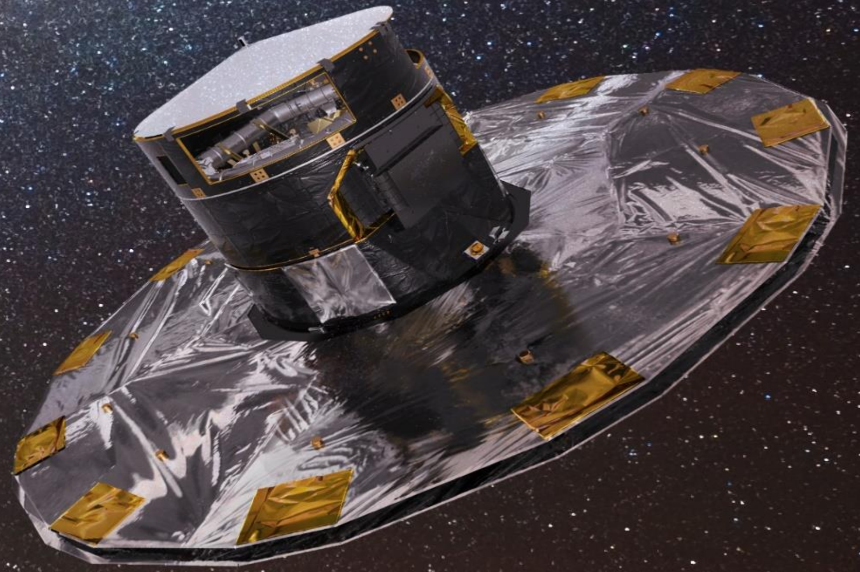


Vast regions of the parameter space are unexplored/under-sampled!

Gaia

600,000 stars out to ∼100 pc from *Gaia*
+
0.33% L dwarf companions fraction
=
more than 2000 benchmarks!

Combining *Gaia* capabilities (form primaries) with UKIDSS/VISTA/SDSS survey depth (for the companions), we can pre-select sizeable sub-samples with extreme (outlier) physical properties, that will provide a complete test of the spectral sensitivities across a broad parameter-space.



UCD candidates selection

We have begun a programme to identify outlier benchmark systems with *Gaia* primaries, with a focus on metal-rich and metal-poor systems.

UCD candidates were selected cross-matching **UKIDSS LAS + SDSS** and **UKIDSS GCS**.

The initial selection is VERY conservative. We select all the objects with typical colours of known L/T dwarfs from the literature:

Y – J > 0.85
and
J – H > 0.50
and
SDSS *z* – J > 2.1 (1.667 for GCS *z*)

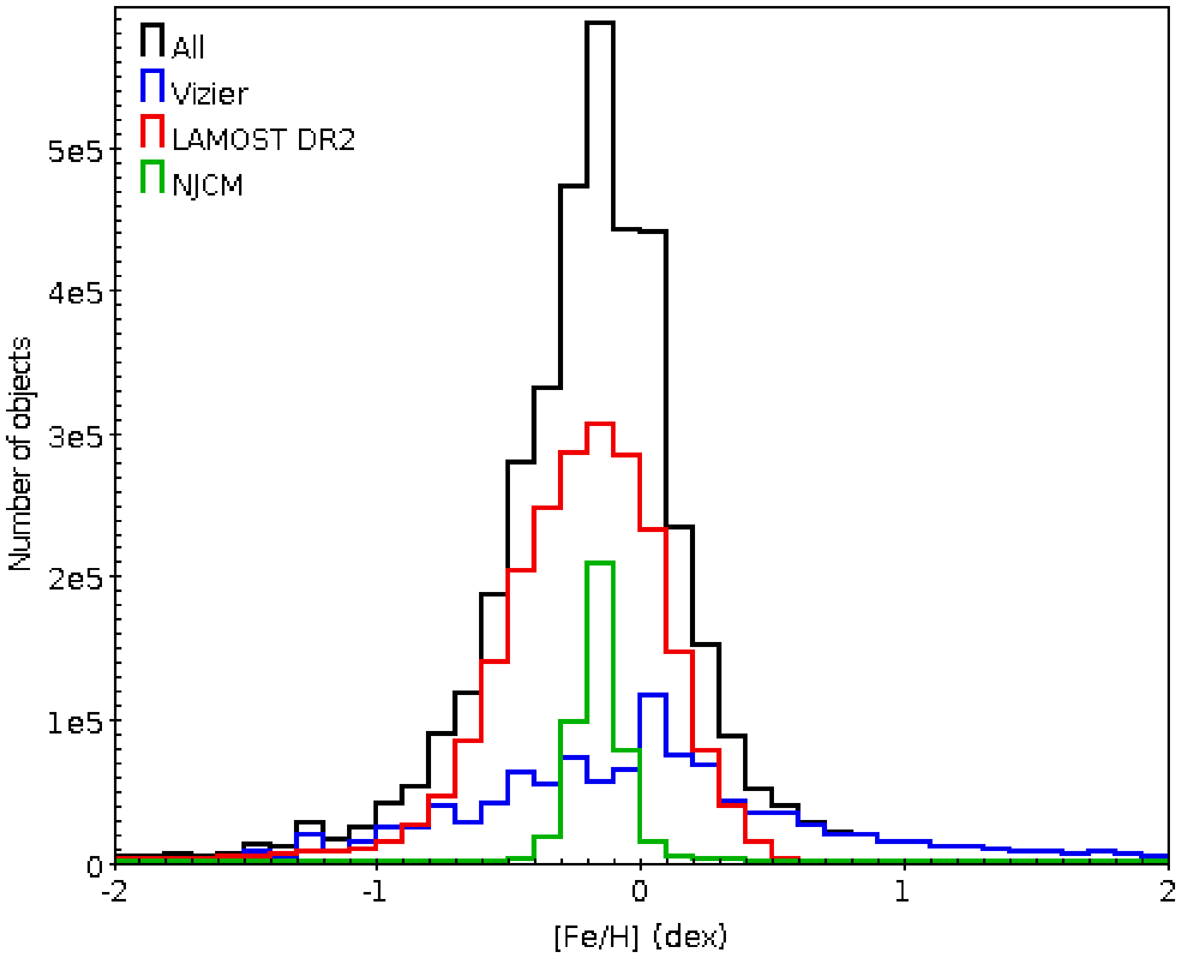
These criteria return a total of **82842 UCD candidates**.

Primaries selection

We have constructed a sample of outlier *Gaia* primaries with [Fe/H] < -0.3 or [Fe/H] > 0.3 dex using:

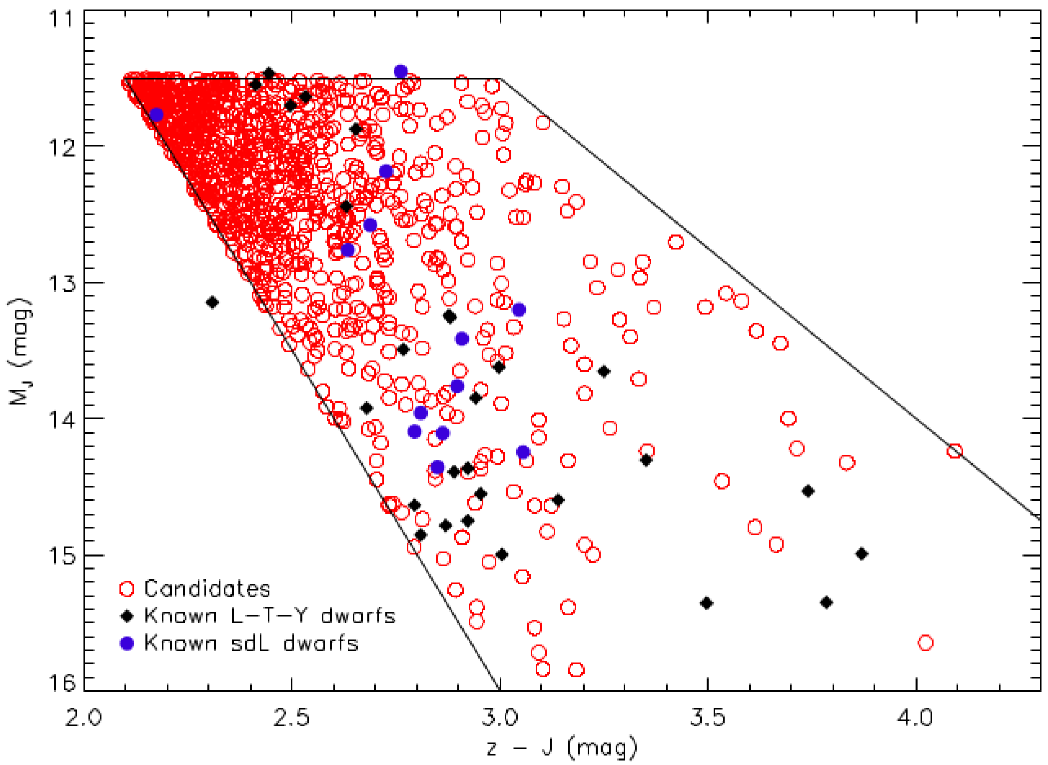
- published catalogues from *Vizier* (e.g. RAVE, Kordopatis et al. 2013; N2K, Ammons et al. 2006);
- the LAMOST DR2 (Yuan et al. 2015);
- the NJCM catalogue (Cook et al., in prep), with [Fe/H] estimated using the Neves et al. (2012) calibration.

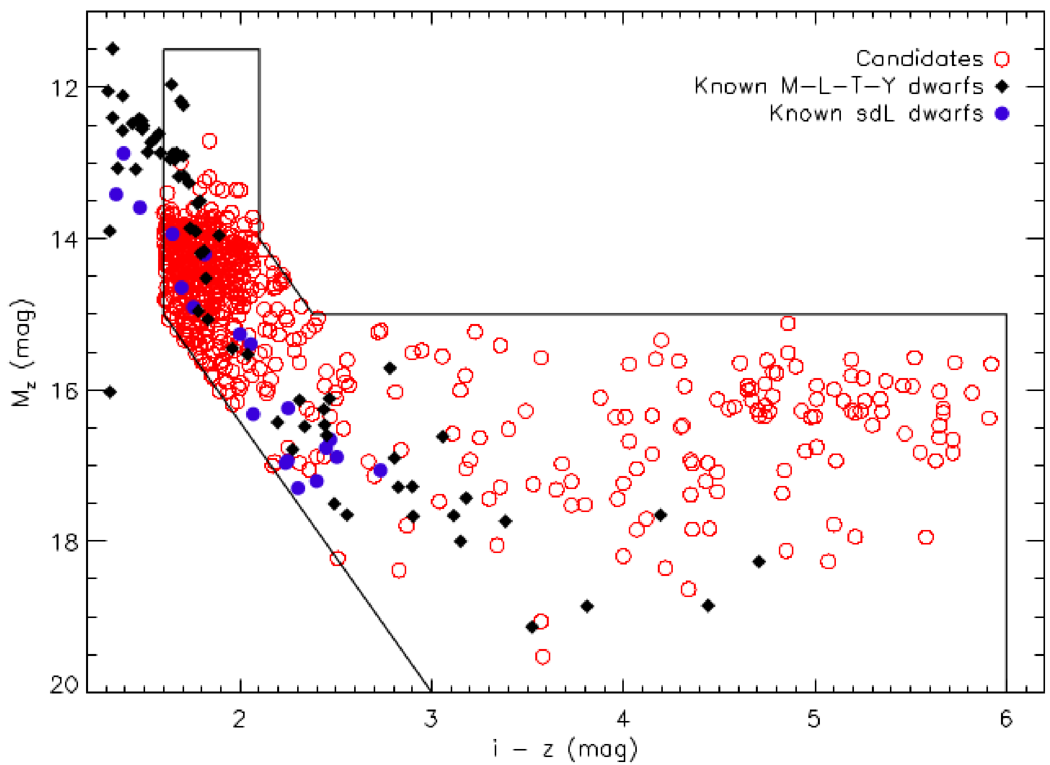
The final list includes ~**1.6 million FGKM stars**.



Benchmark system candidates selection

Our candidate benchmark systems were selected using primary-secondary separation limits of < 3 arcminutes. We employ distance constraints for the primaries, to apply a colour-magnitude test for the UCD companions.



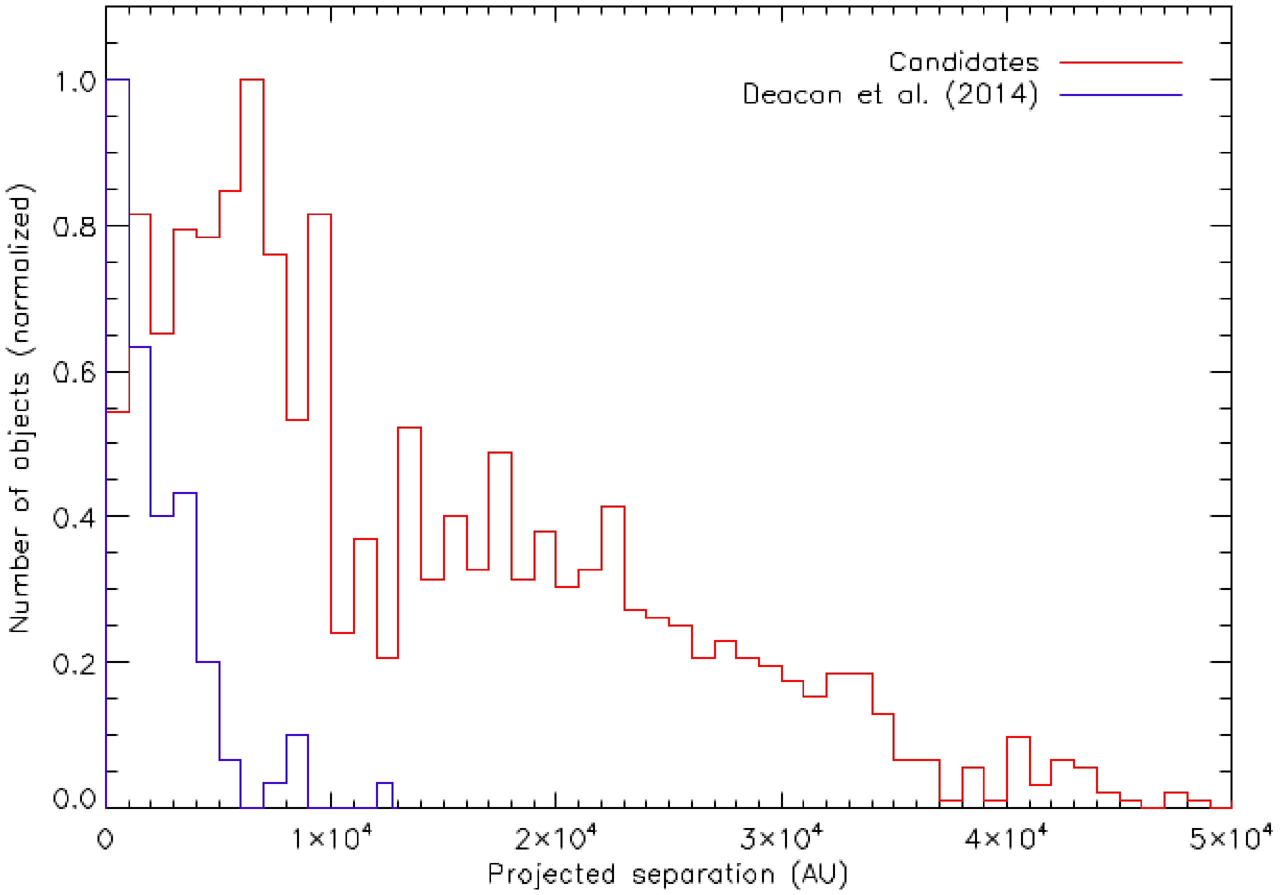


Benchmark system candidates selection

Our selection yields **1397 system candidates.**

- **330 high proper motion systems** (i.e. total PM ≥ 50 mas yr^{-1}), TBC via common PM
- **1067 low proper motion systems,** TBC via common RV

We do not expect to be dominated by contamination.



Future work

Statistical assessment of companionship & characterization of the genuine systems.

Awarded 40h on GTC/OSIRIS + 8 nights on Mercator/HERMES + 4 nights on WHT/LIRIS over the next 2 semesters via CCI-ITP!

Summary

- The T_{eff} sequence gets shallower at the M-L transition and flattens at the L-T transition: effect of dust.

- There seems to be an excess of L-T transition objects wrt late-T objects: different IMFs? Varying BF? Wrong cooling tracks?

- Dust clouds are important and can explain the peculiar spectra of extremely red L/T dwarfs.

- Outlier benchmark systems are needed to test/improve atmospheric models and retrieval methods.

Thank you!