Finding ultracool companions to M dwarfs

(My PhD)

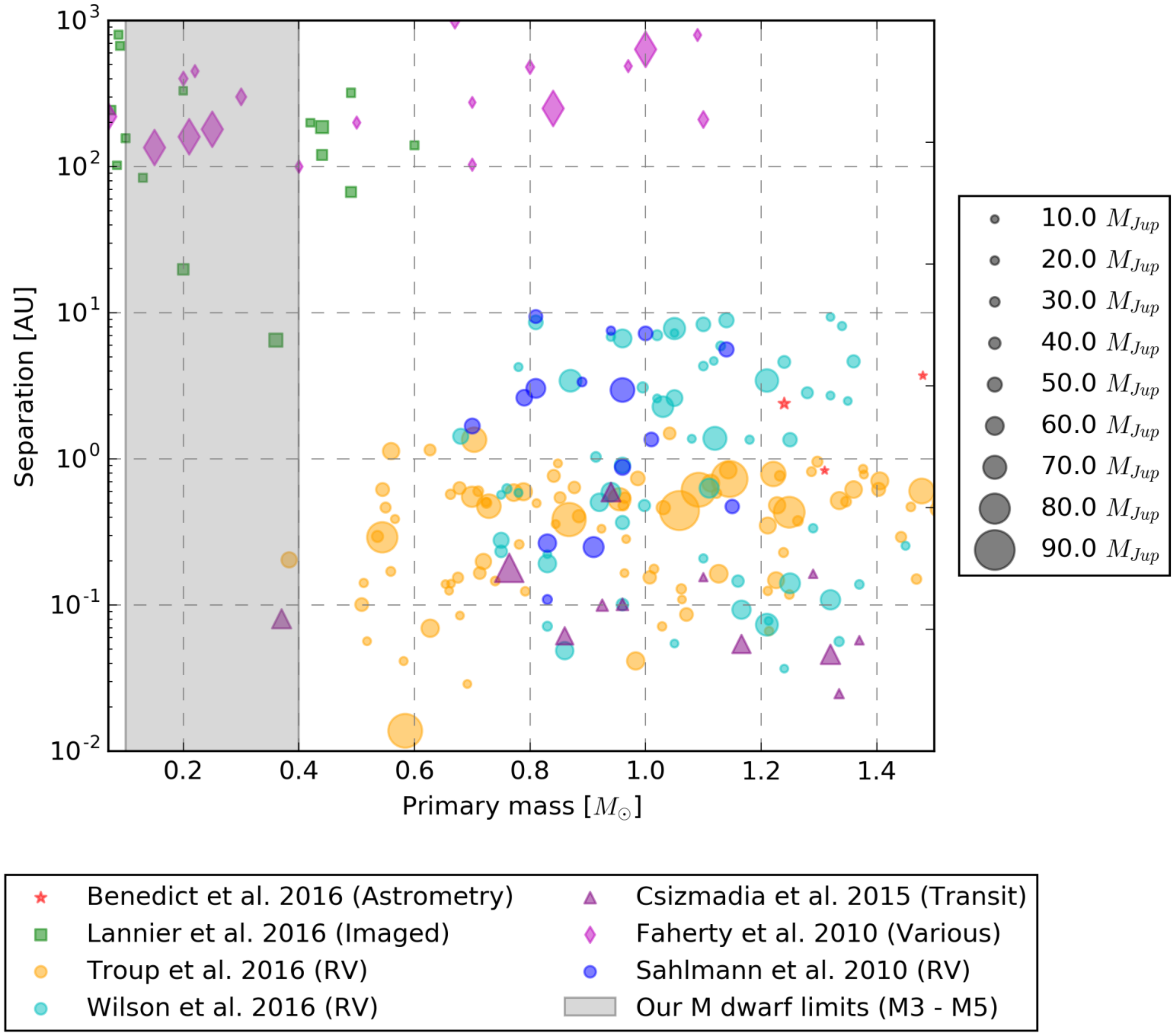
Neil Cook

Problem

- Lack of ultracool dwarf companions to stars at close (< 100 AU)

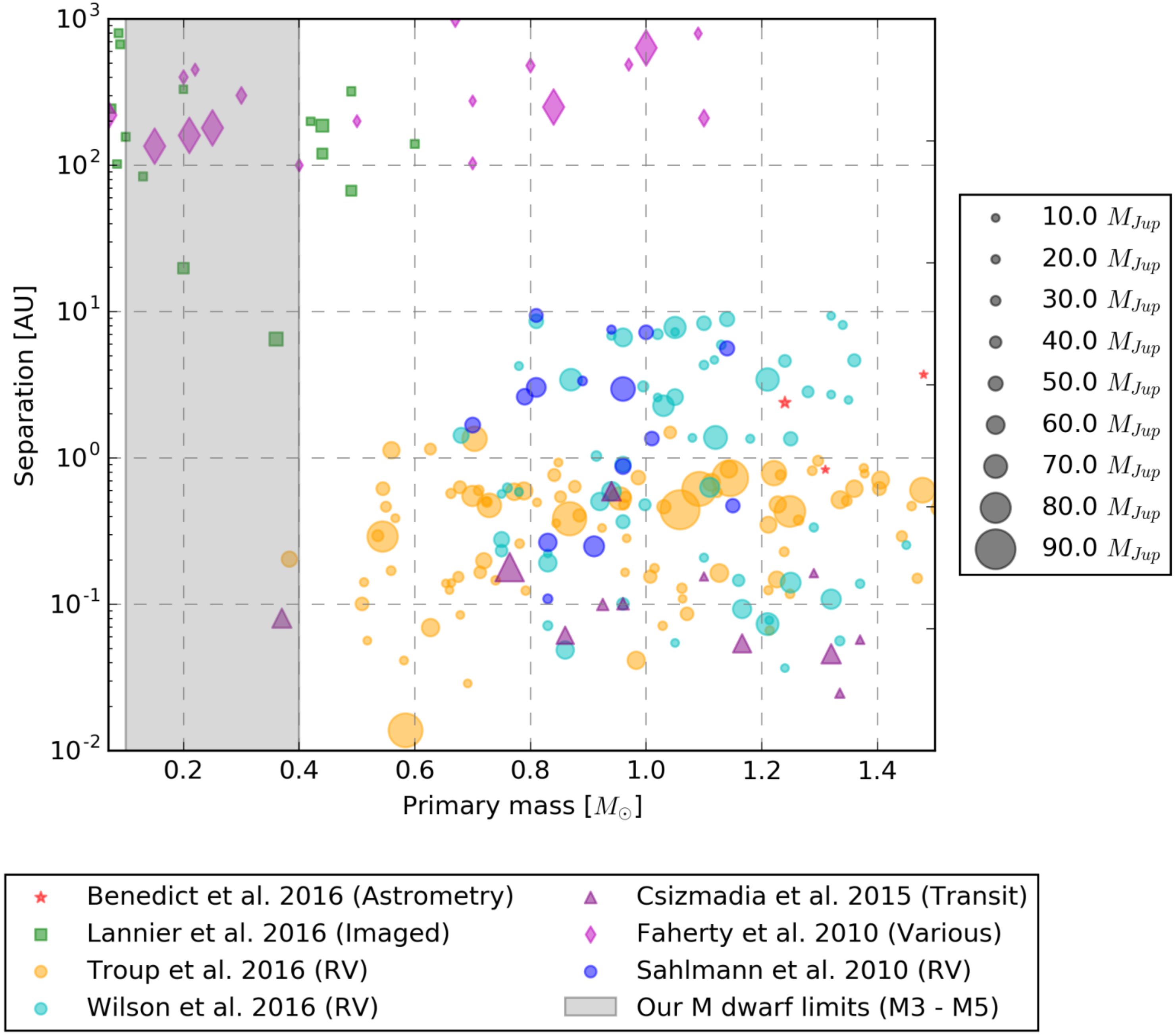
  UCD = Brown dwarf or giant planet

- "brown dwarf desert"
- Lots of small planets – not many Brown dwarfs
- Why? Formation? Bias in searches?
- UCD companions make for great benchmark systems (possibility to measure mass, radius, age, composition etc)



Hard to find

- M dwarfs a lot brighter than UCDs
- Current exoplanet detection methods not sensitive/UCD ignored?
- Not many of them?



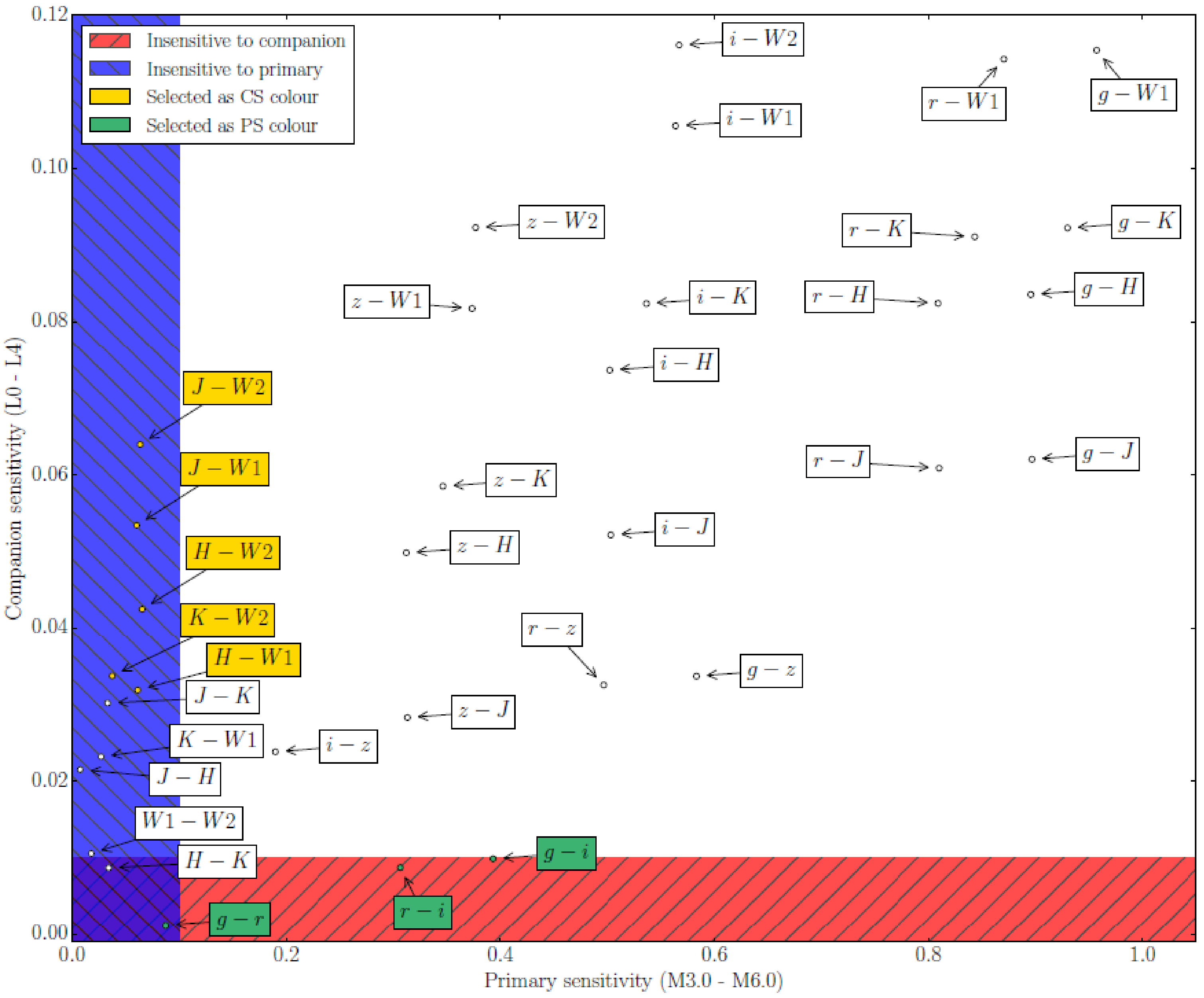
PhD: Paper 1

A method for selecting M dwarfs with an increased likelihood of unresolved ultracool companionship

Jan 2016 MNRAS, 457, 2192-2208

Idea

- Find UCD companions to M dwarfs with new method
- Use colour excess (i.e. $J - W2$)
- M dwarfs look "weird" i.e. too red in NIR-MID (due to UCD companion)
- Look 'normal' in optical (no contribution from UCD)
- Don't want to use colours which show sensitivity to both a companion and primary



Colour Excess

- Excess =

"M dwarf observed colour" – "colour of an M dwarf"

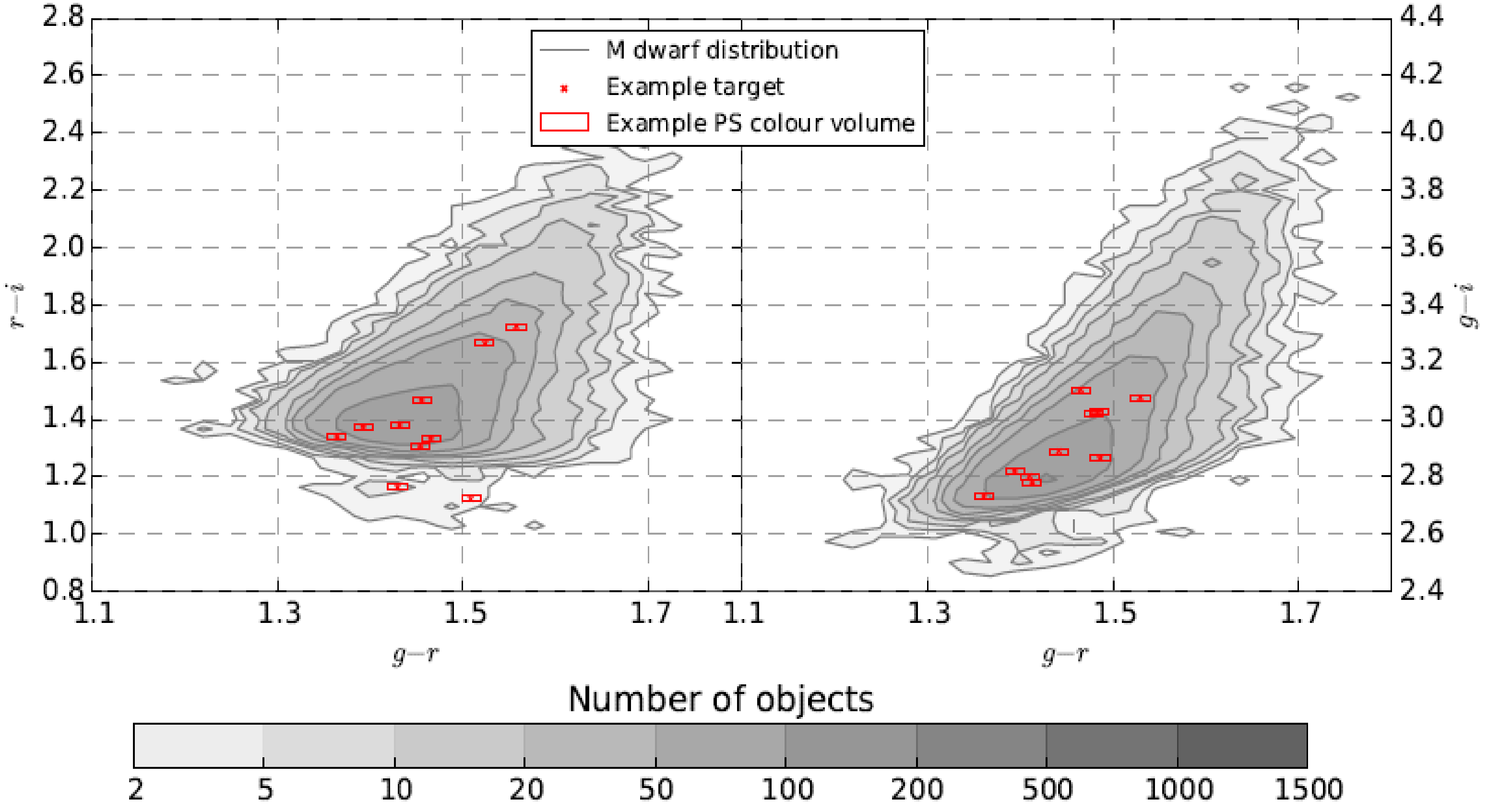
- M dwarfs have large scatter in colour

- How do we define "colour of an M dwarf"?

- Use optical where UCD has little impact

- Define tiny "colour volumes"

$$\Delta(g-r) = 0.01$$
$$\Delta(g-i) = 0.01$$
$$\Delta(r-i) = 0.01$$



Problems

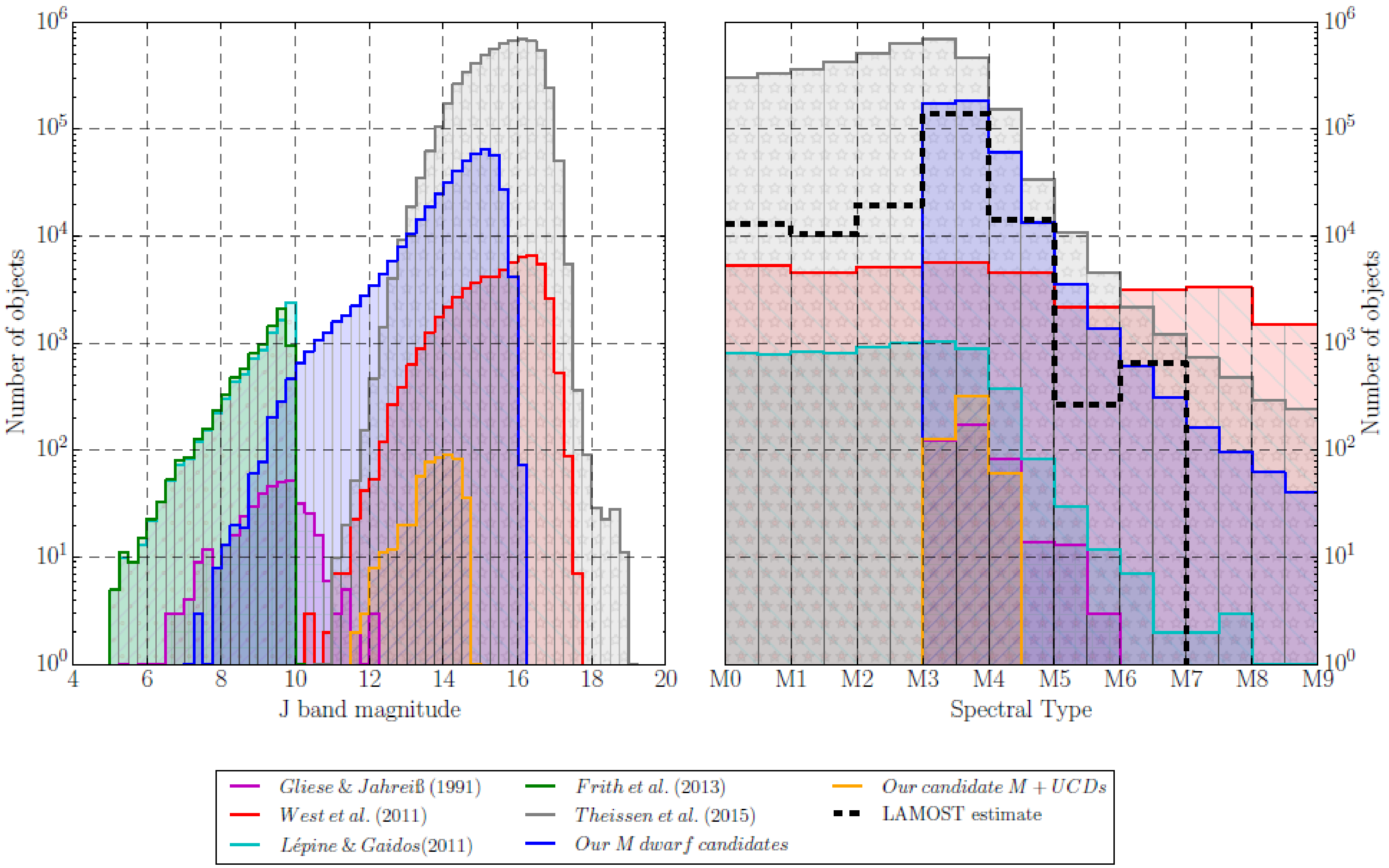
- Excess is small

- Need unreddened, accurate photometry + need to select only M dwarfs
  → lots of harsh cuts needed

- Need a large number of M dwarfs
  → Create large catalogue (~500,000 M dwarfs) using WISE/2MASS/SDSS

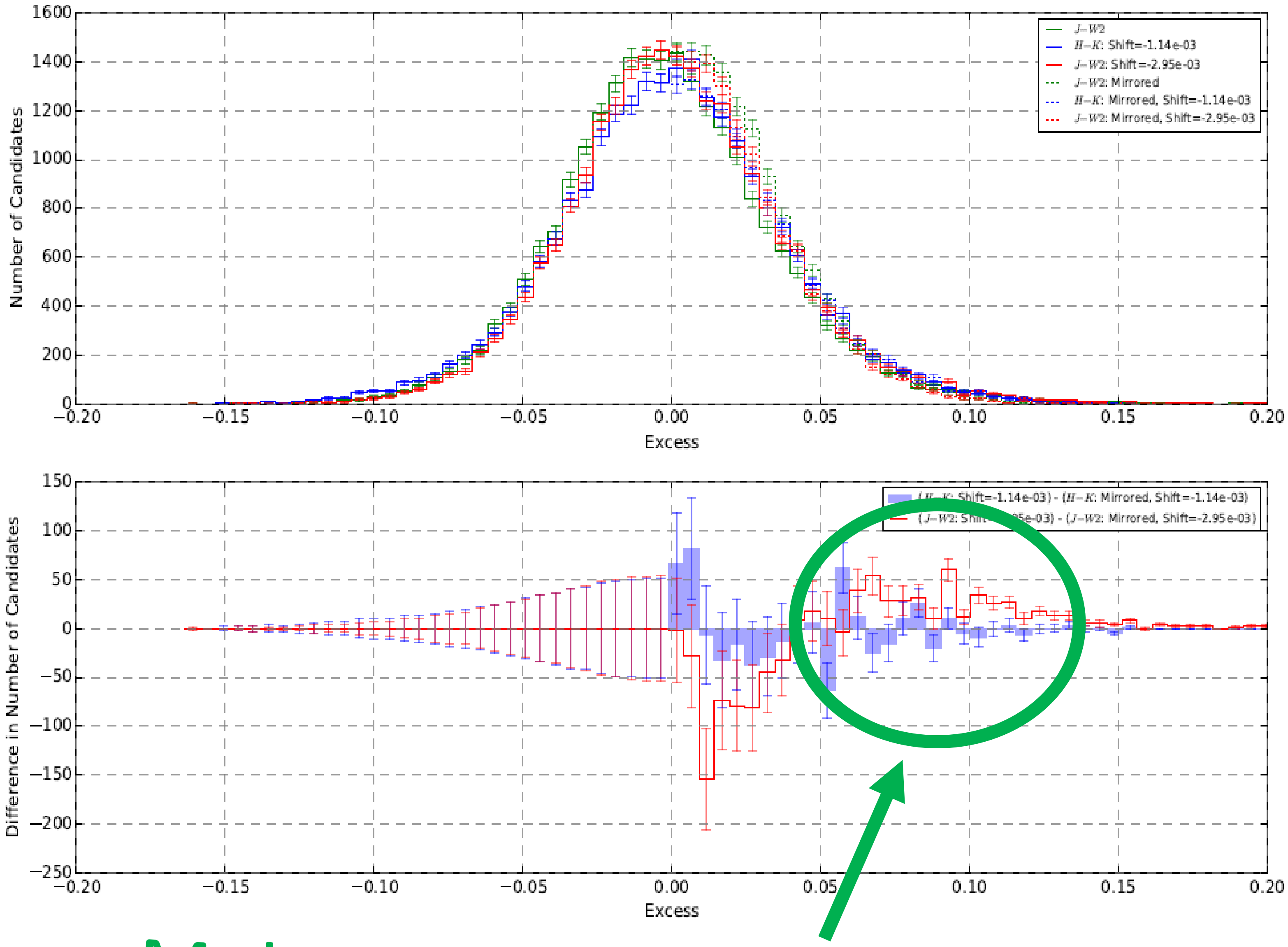
- Large scatter in M dwarf colour
  → Hard to find those M dwarfs with excess

Catalogue of nearly ~500,000 M dwarfs from WISE/2MASS/SDSS



But some M dwarfs do show an Excess

- But they are there!
- Assume negative excess (i.e. deficit) from Gaussian-like process
- Can see a (small) population of M dwarfs with J-W2 excess
- 1082 M+UCD candidates



M dwarfs with J-W2 Excess!

PhD: Paper 2

Low-resolution near-infrared spectroscopic signatures of unresolved ultracool companions to M dwarfs

Submitted Aug 2016 MNRAS

But does this excess come from a UCD companion?

- Excess could come from anything that can make an M dwarf look redder:

- From misclassified objects

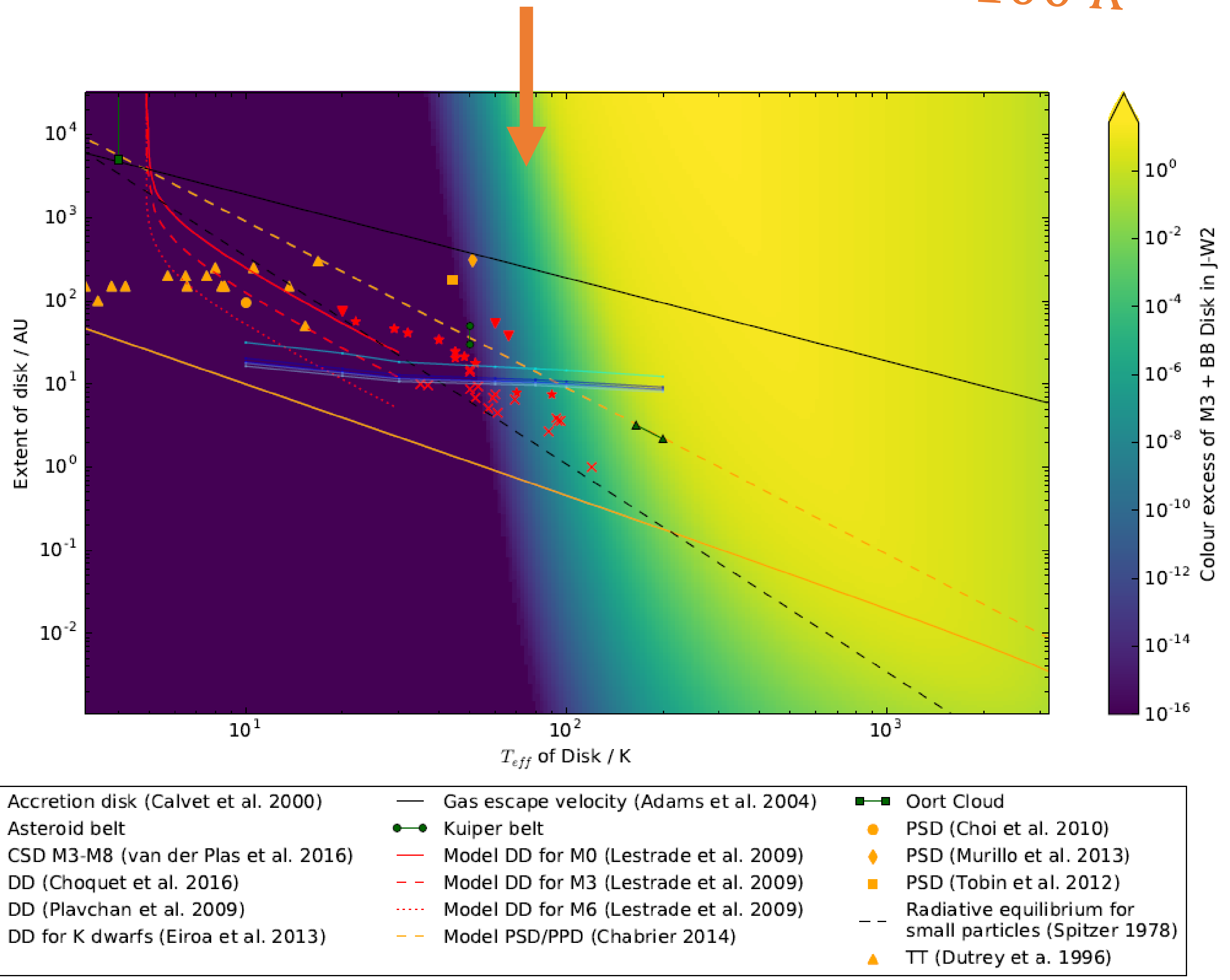
- From circumstellar dust disks (not likely – need a very warm disk)

- Chance aligned red objects
  - ➢other UCDs/M dwarfs (< 0.2 %)
  - ➢M giants ($< 3 \times 10^{-4}$ %)
  - ➢red galaxies (< 9 %)

- Local reddening (unseen by our reddening cuts)

- Preformed tests to check:
  - ➢Random offset test – contamination no worse than ~ 9 %
  - ➢Visual inspection – less than 15% have any nearby objects (DSS/UKIDSS/2MASS/WISE/SDSS)

Would need a disk warmer than $\sim 100\ K$



Therefore need a new method to confirm excess from UCD companion

•Check with LAMOST optical spectra

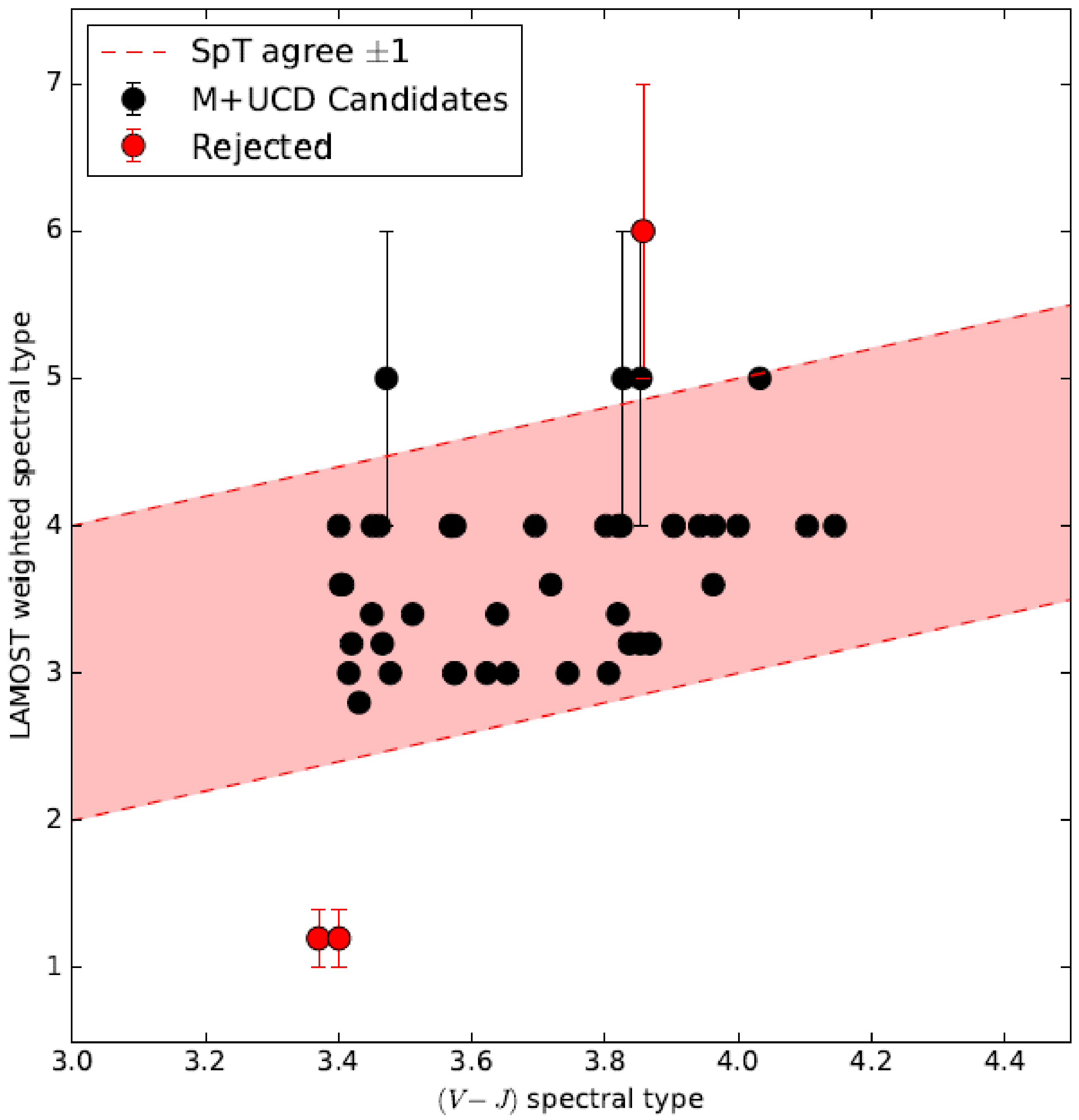
- ➢ are the M+UCD candidates actually M dwarfs? → YES (3/46 rejected)

•Spectral follow-up

- ➢ Cannot observe over 1000 object on large telescope
- ➢ Need to use low resolution

•New method:

- ➢ If optical colours are similar M dwarf spectra should be similar
- ➢ If a UCD is present spectra should be “weird”
- ➢ Subtract M+UCD candidate spectra from non-candidate M dwarf
- ➢ Residual should contain noise + UCD



Quantitative approach

- Subtract M+UCD candidate from 2 or 3 non-candidate M dwarfs

  T = M+UCD candidate

  C1, C2, C3 = non-candidate M dwarfs

- Subtract non-candidate M dwarfs from other non-candidate M dwarfs

- Compare difference in residuals

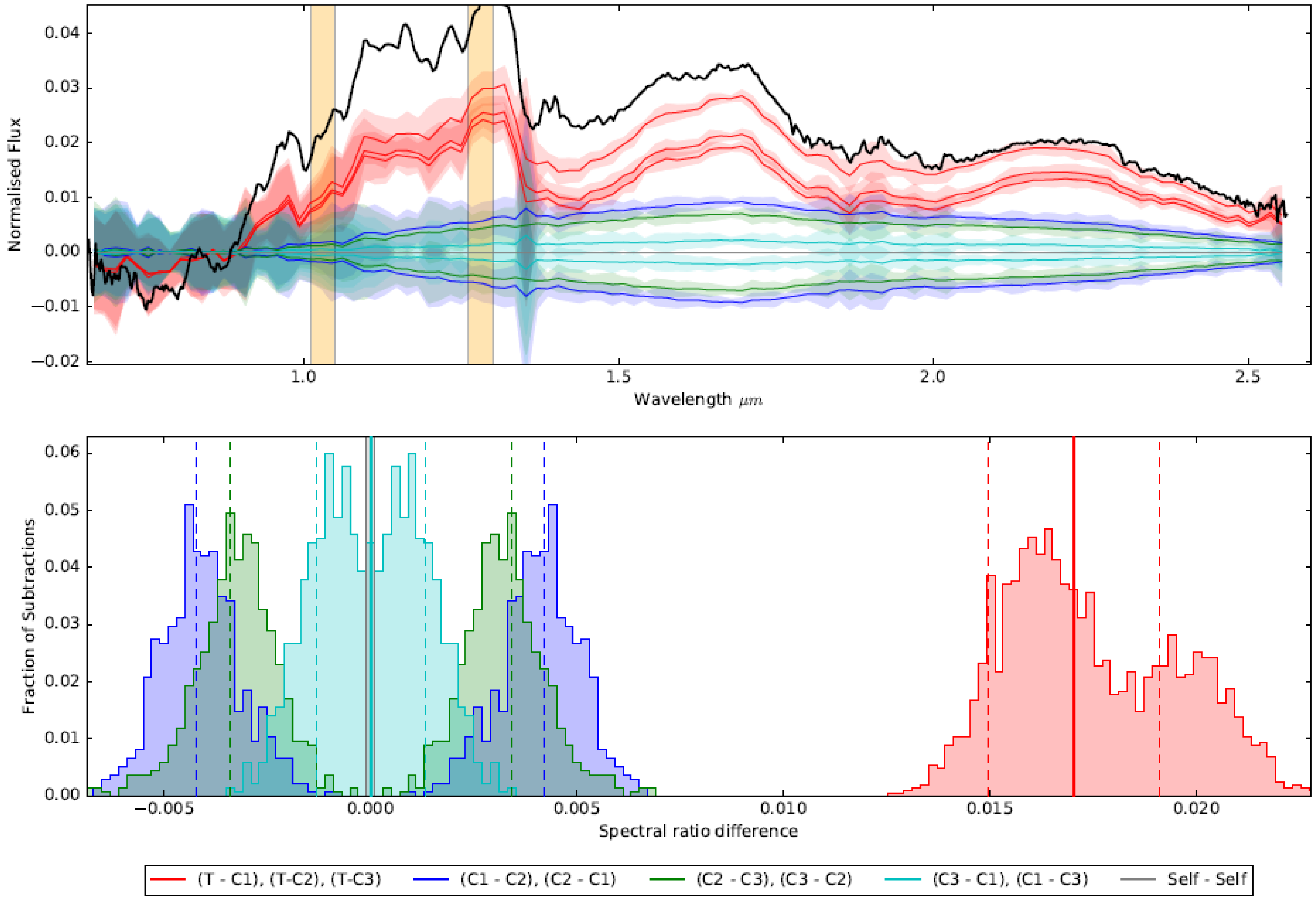
- Define "spectral ratio difference" to pick out UCD signature

- t-test: Is detection significant?
- (t-test > 1.75 YES)

Simulation:

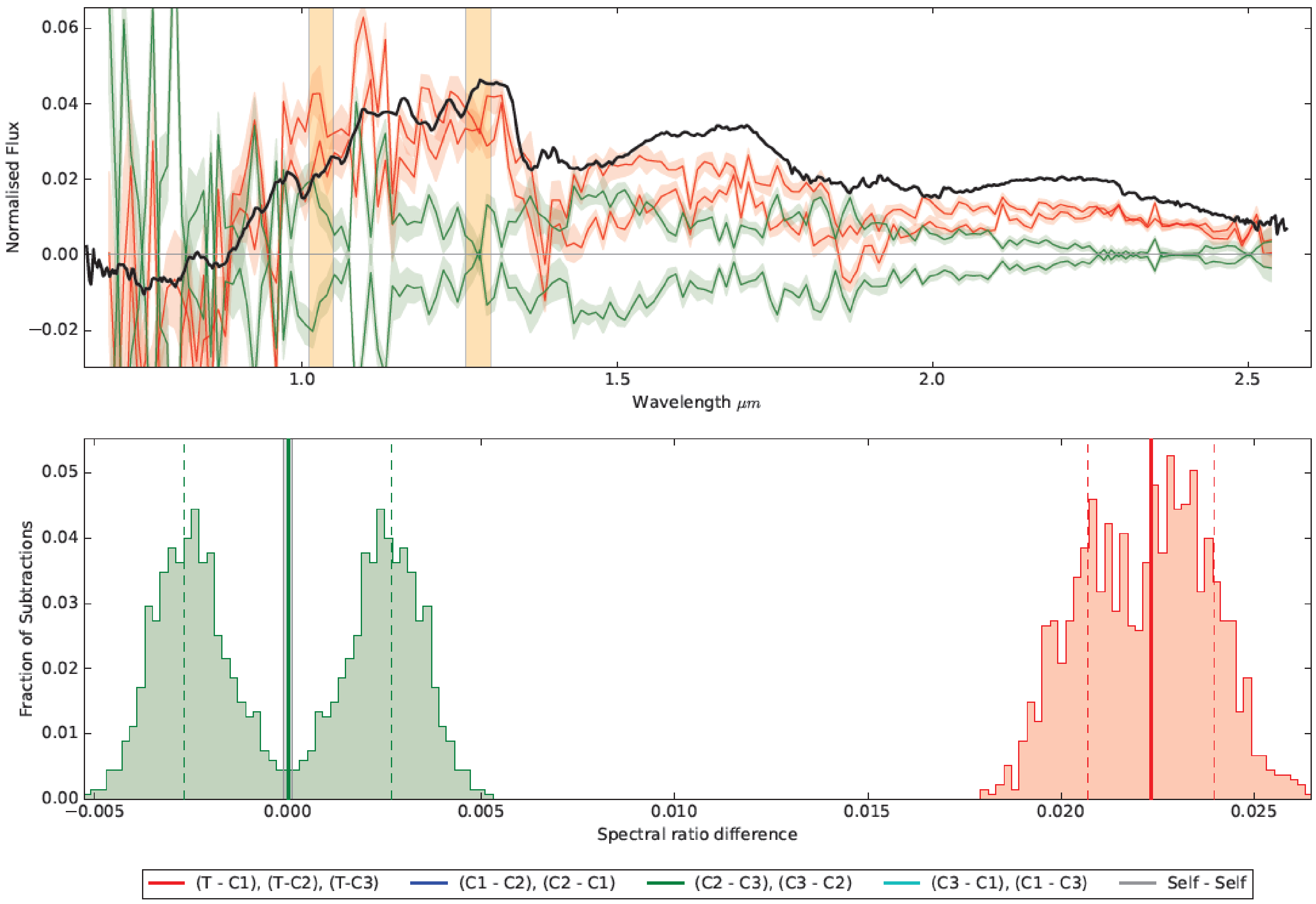
Red = (M+UCD) – M

Blue/Green = M – M



Results – Using SpeX on the IRTF

- •Observed 28 M+UCD candidates in March 2016
- •Found one good detection and three possible detections
- •Right: Our first good detection



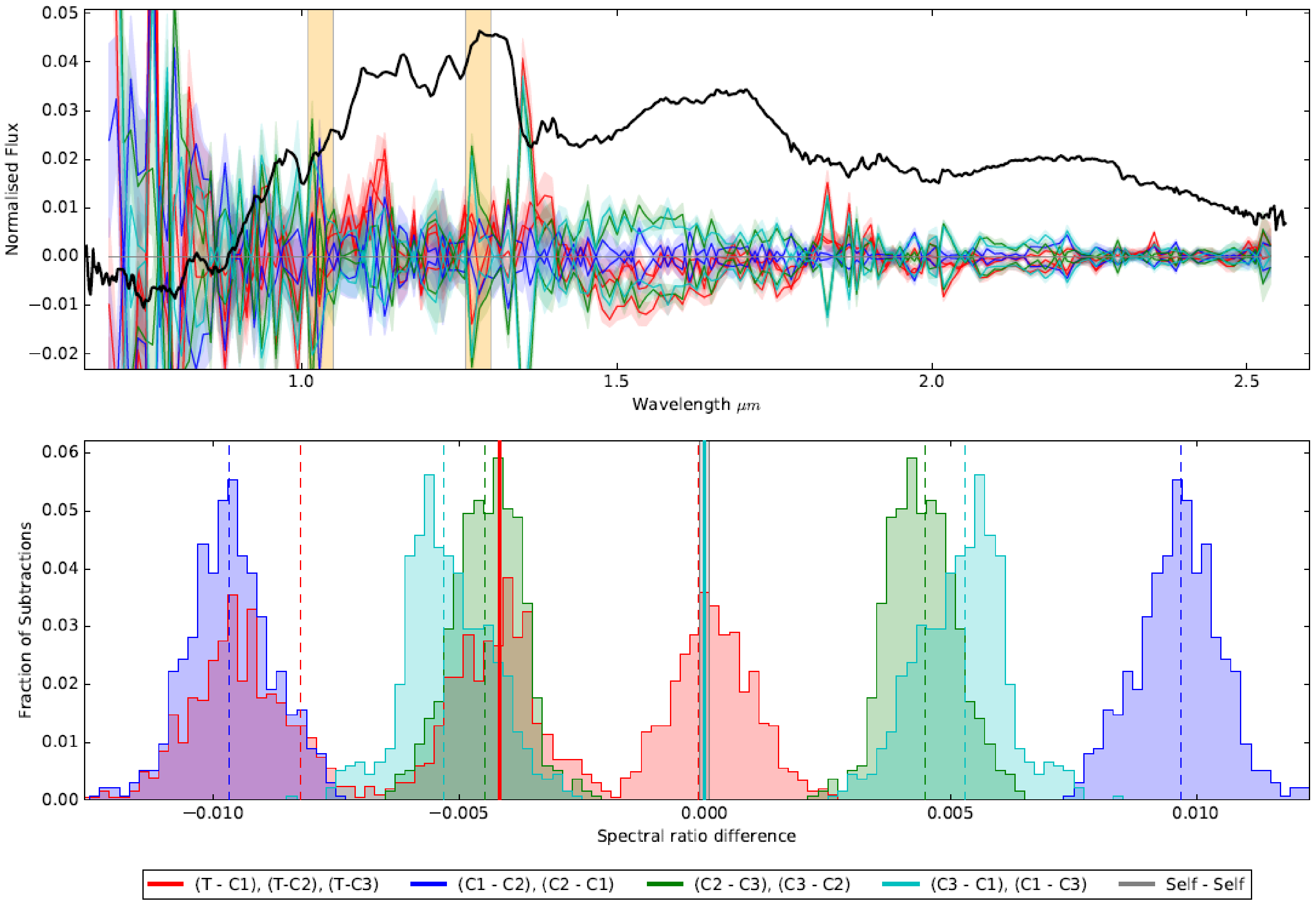
(a) WISE J100202.50+074136.3, part of group 800.

Results – Using SpeX on the IRTF

- Observed 28 M+UCD candidates in March 2016

- Found one good detection and three possible detections

- Right: Comparison non-detection



(b) WISE J140145.91+310640.6, part of group 228.

Other Work

During PhD

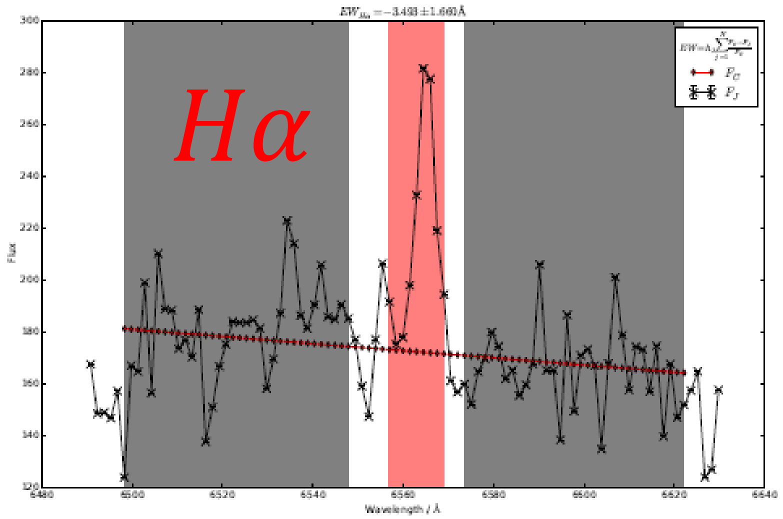
- Used the large ($\sim 500{,}000$ M dwarfs) to:
  - Find Young M dwarfs (Using LAMOST spectroscopy to measure pseudo-equivalent widths of $H\alpha$ and NaI
  - Find Young M dwarfs (Using Kepler 2 light curves to measure rotation periods)
  - Find Late M dwarfs (Using the SDSS/2MASS photometry)
  - Find Late M dwarfs (LAMOST spectroscopy)
  - Find M dwarf companions Tycho-2 stars (via common proper motion)
  - Find M+M binaries (via common proper motion)
  - Model fitting of the M dwarfs with LAMOST spectra (~ 10000)

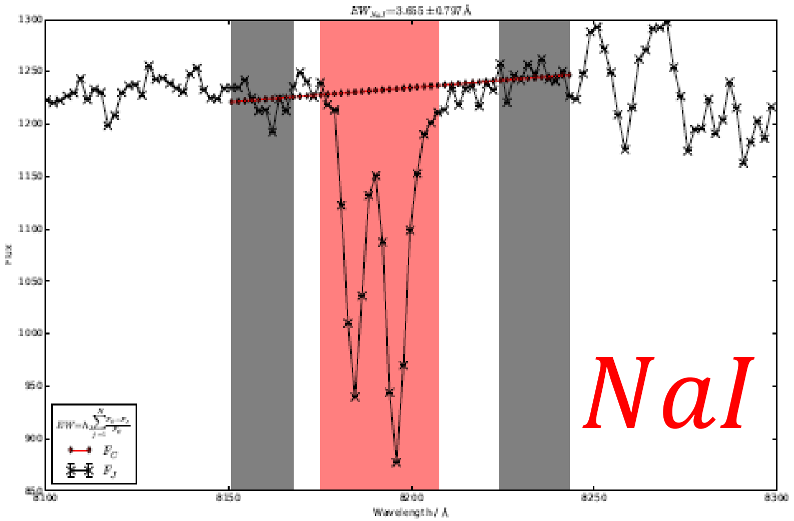
Post PhD

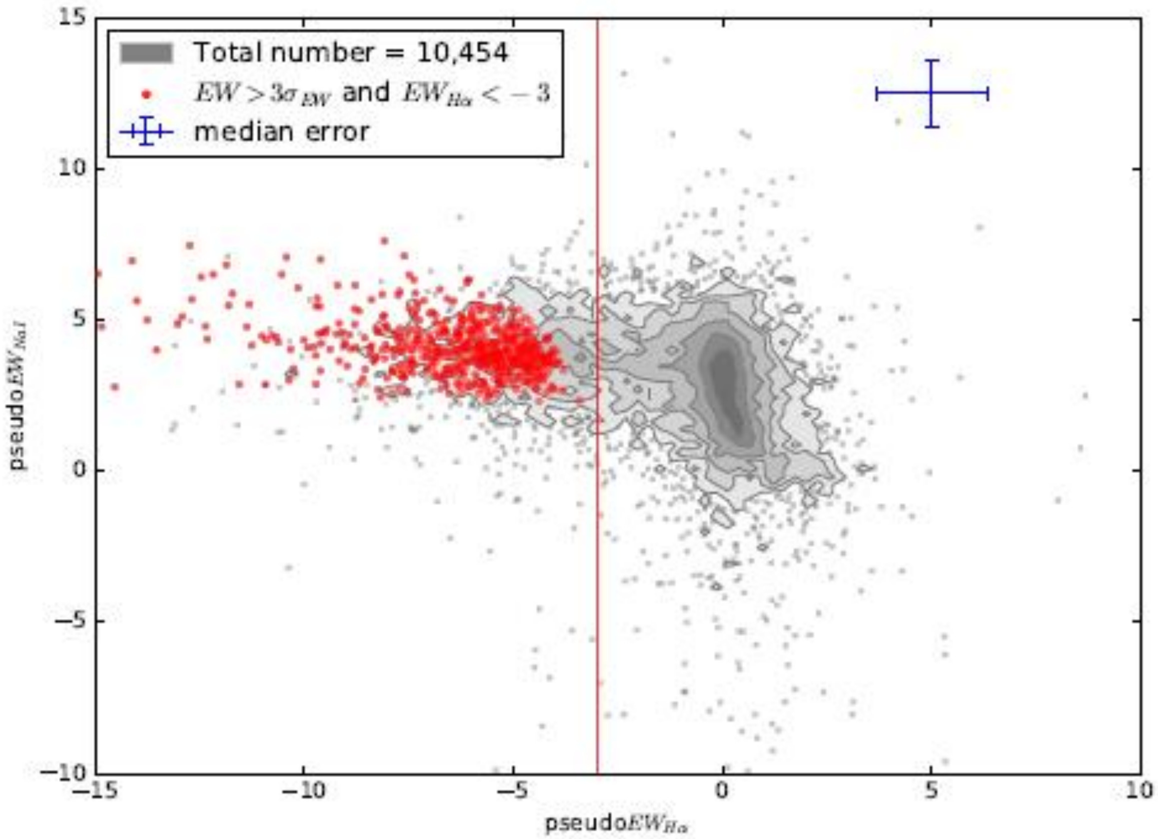
- With David Pinfield: Continued follow-up of the M+UCD candidates (and referee comments to Paper 2)
- With Hugh Jones: Built a spectra pipeline to reduce echelle spectra from CCDs where the optics setup is changing all the time (i.e. cannot use pre-existing masks
- With Nick Cowan: Playing with some principal component analysis and MCMC to use on time series observations of brown dwarfs to try to infer cloud surfaces
- Will be working at York University, Toronto (With Ray Jaayawardhana) on two projects:
  - Analyzing some SuperWASP light curves of stars in moving groups
  - Looking at the prospects of using Gaia to help made the 3D structure of the Upper Scorpious moving group
  - Very preliminary

Find Young M dwarfs (Using spectroscopy)

- Measure pseudo-equivalent widths of $H\alpha$ and NaI
- Require detection in both (EW > 3 sigma)
- $EW(H\alpha) < -3$ may be young
- 577/10454 possibly young





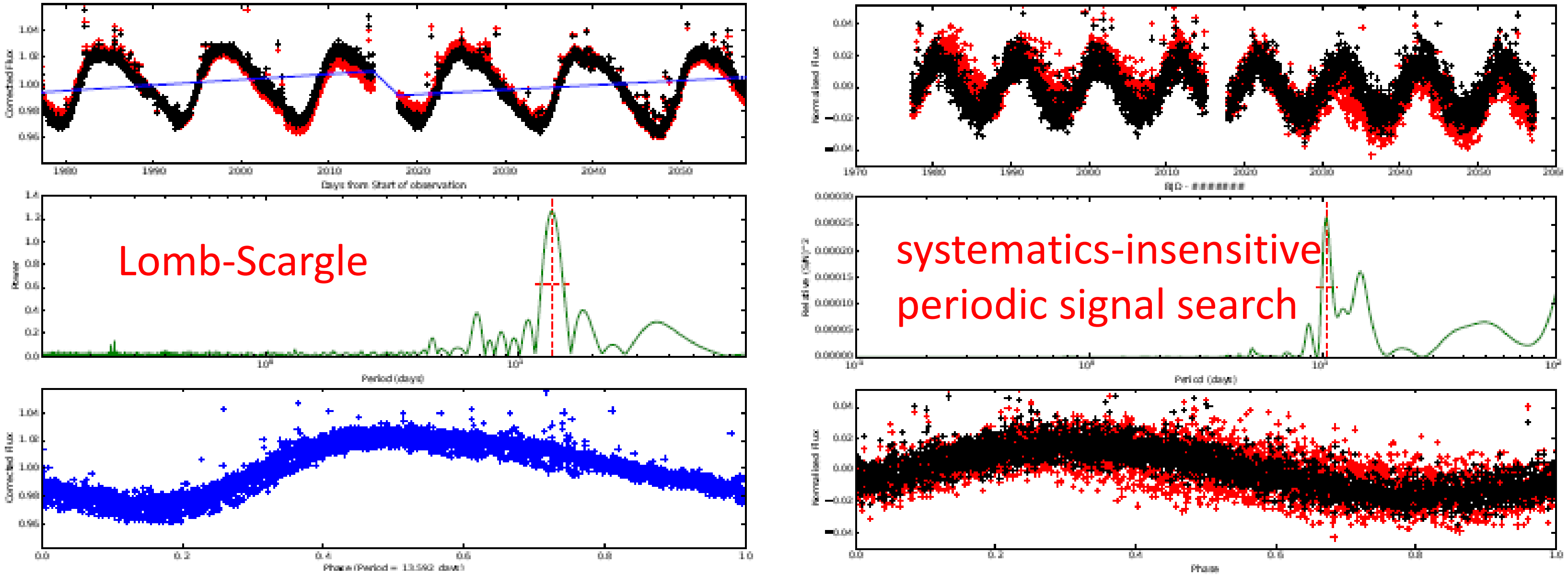


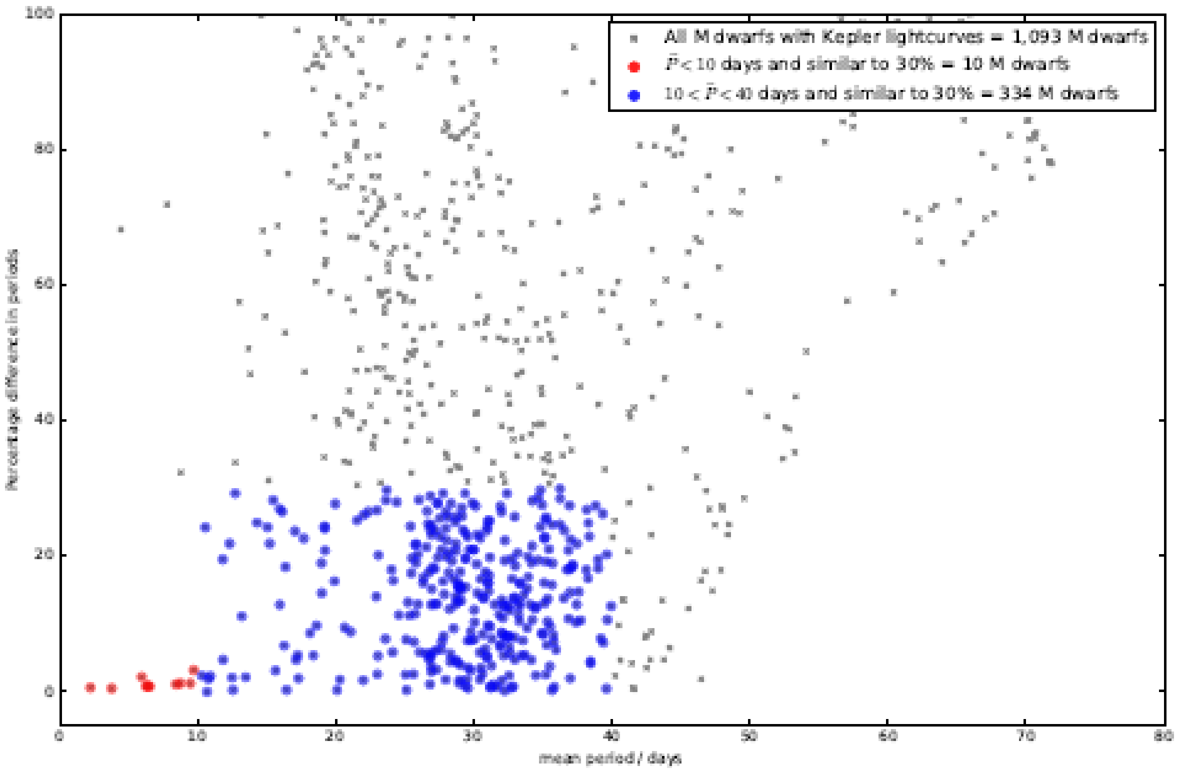
x-axis: $EW(H\alpha)$

y axis: $EW(NaI)$

Find Young M dwarfs (Using light curves)

- Light curves from Kepler 2 (C0, C1, C2)
- Compare two methods for determining periods
  - ➢ Lomb-Scargle approach:
    Vanderburg & Johnson 2014
  - ➢ Systematics-insensitive periodic signal search:
    Angus + 2016
- If two methods agree then period is probably correct
- Select those with short periods < 10 days and 10 – 40 days (i.e. possibly young)



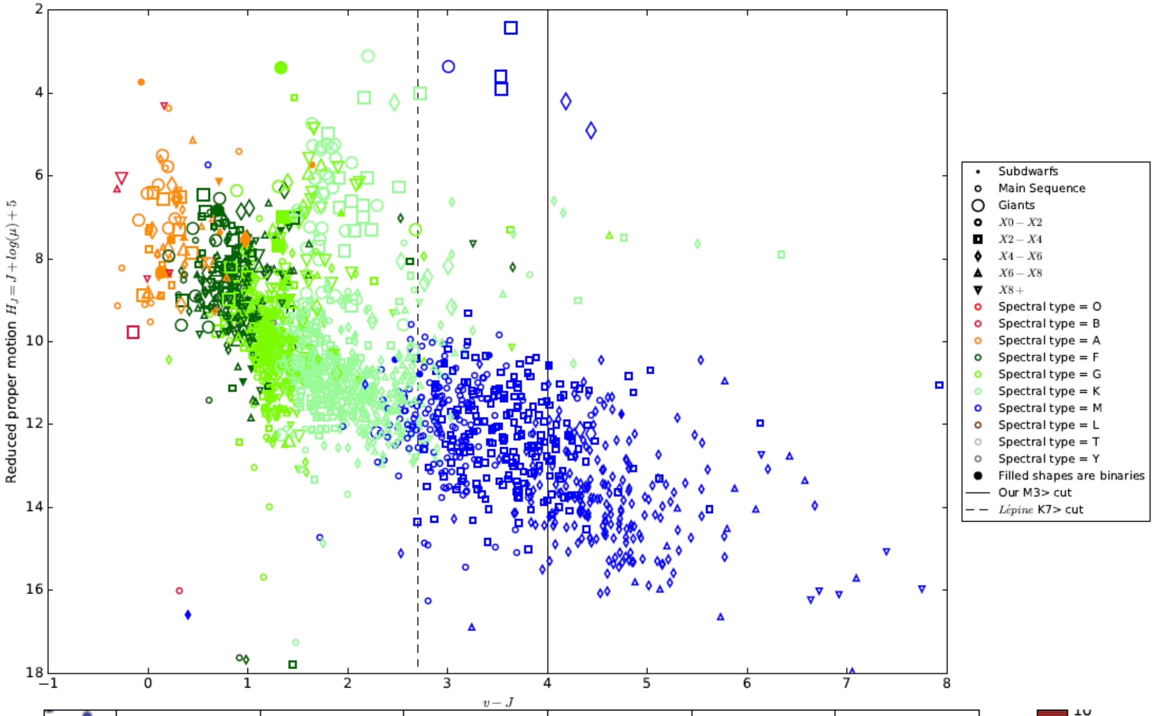


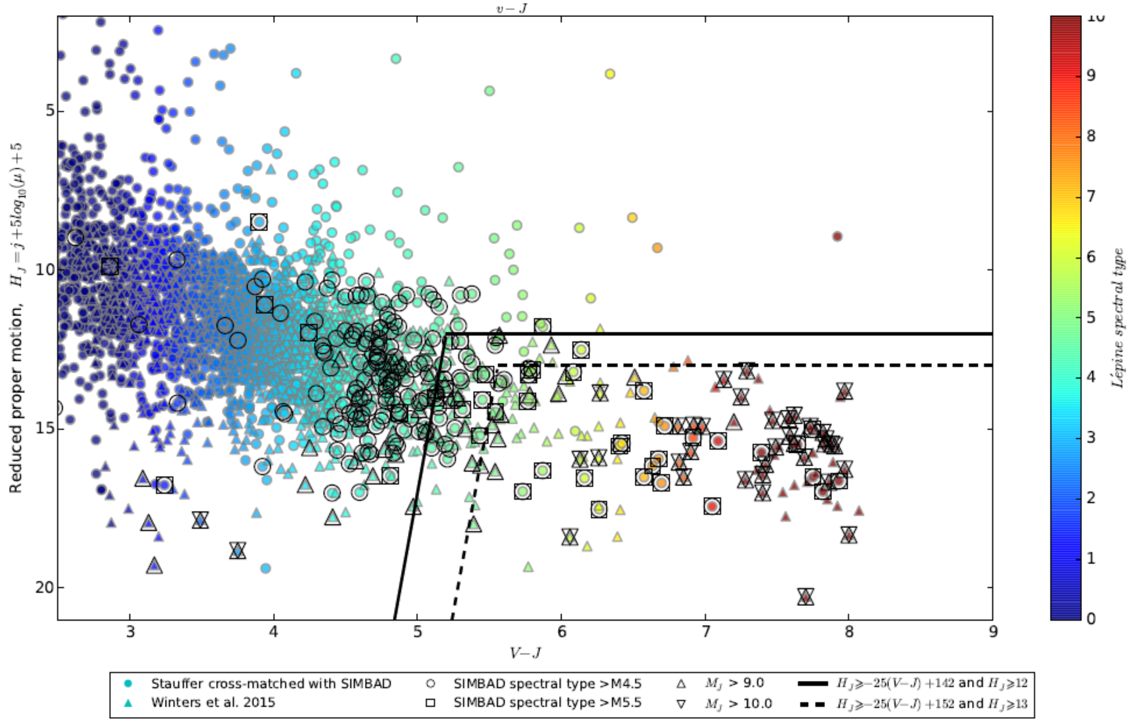
x-axis:
Mean period

y axis:
% difference in periods

Find Late M dwarfs (Using the SDSS/2MASS photometry)

- Cuts based on Gliese-SIMBAD crossmatch:
  - Reduced proper motion H_V cut
  - V-J cut
- Cuts from Covey + 2007
  - $(g - r) > 1.59$
  - $(r - i) > 0.94$
  - $(i - z) > 1.73$
- 9,015 M dwarfs later than M4.5
- 3,013 M dwarfs later than M5.5



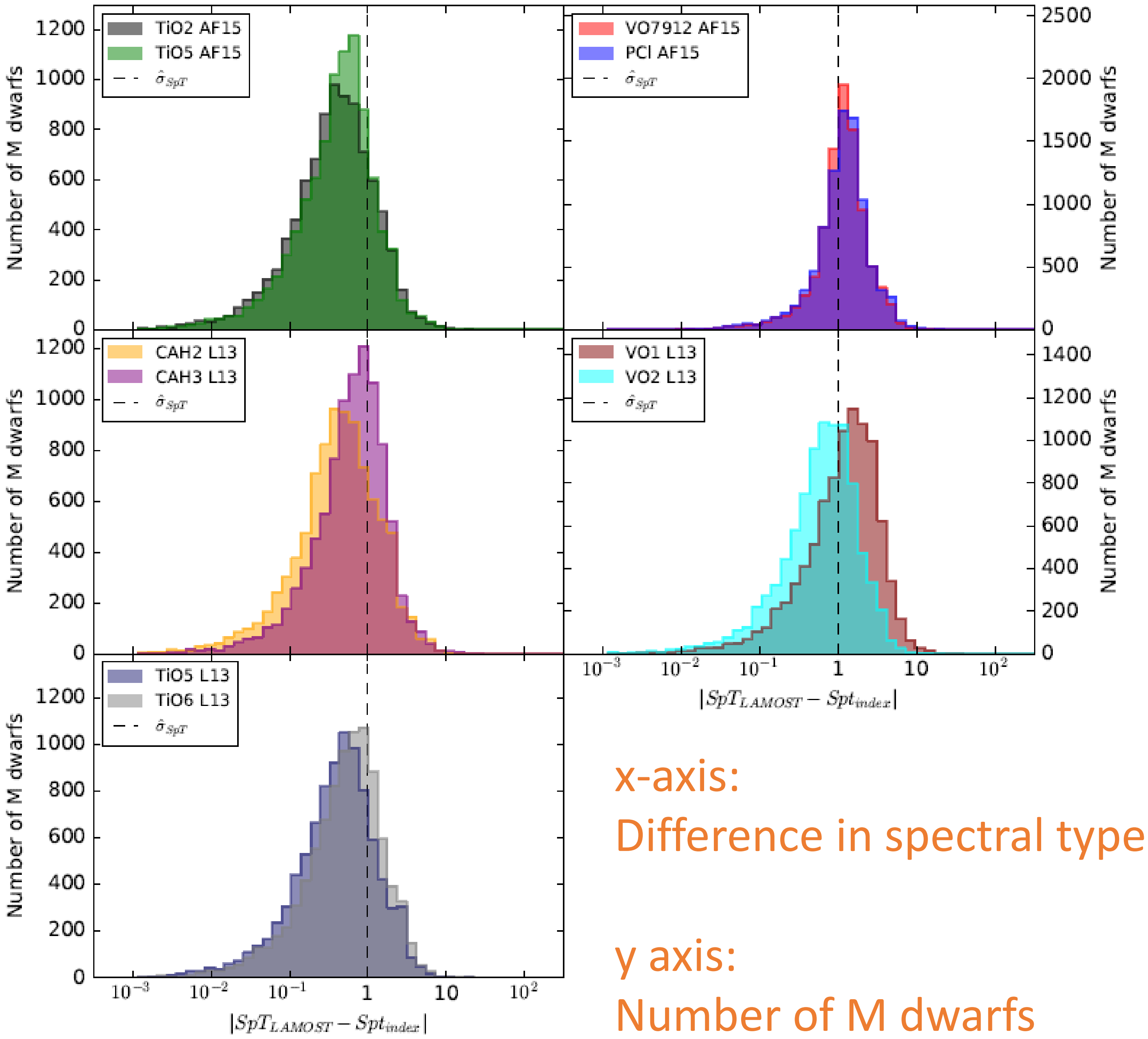


x-axis: $V - J$

y axis: H_V

Find Late M dwarfs (LAMOST spectroscopy)

- LAMOST spectral types (using HAMMER code – Covey+2014)
- LAMOST spectral types from other sources (Zhong+2015a, Gou+2014, Lou+2014)
- Compare these spectral types to known spectral type indices (calculated from LAMOST spectra)
- Use weighted mean of "good" spectral types to calculate spectral type
- 703 M dwarfs later than M4.5
- 257 M dwarfs later than M5.5



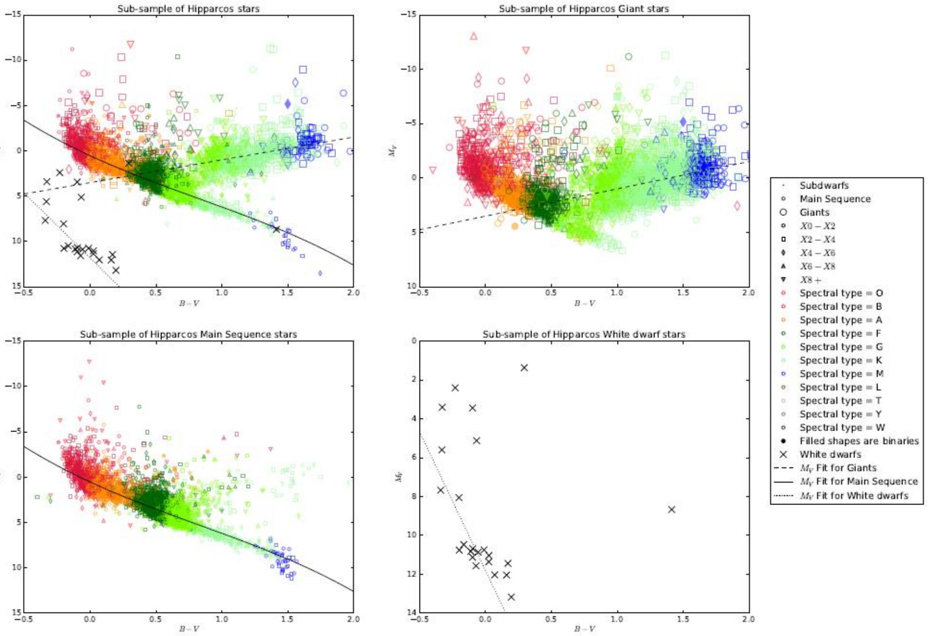
x-axis:
Difference in spectral type

y axis:
Number of M dwarfs

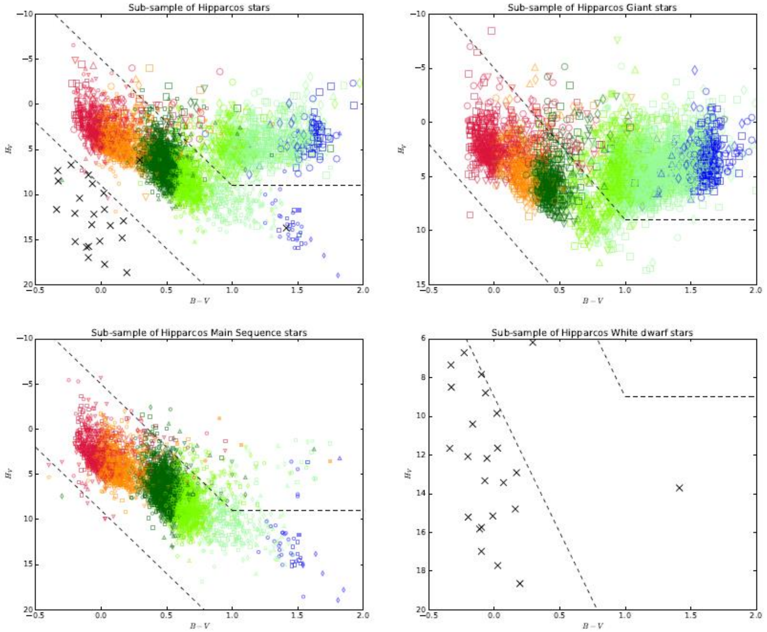
Find M dwarf companions Tycho-2 stars (via common proper motion)

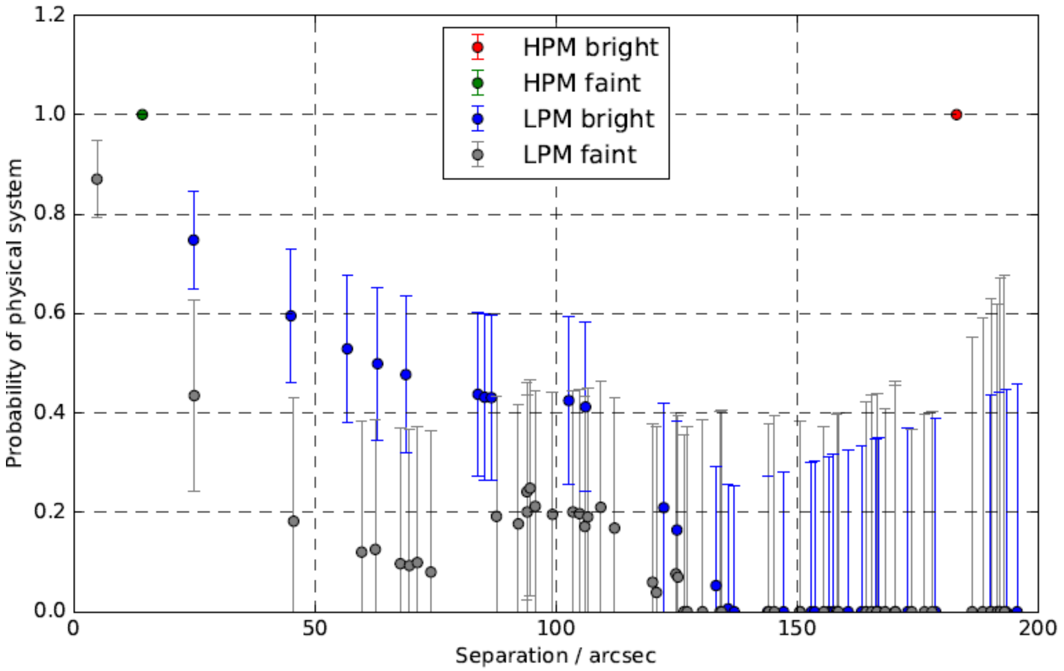
- Worked out distance constraints for Tycho-2 main sequence, giant and white dwarf stars
  - using $M_V(\mathrm{B-V})$ and $H_V(B-V)$ relations
- Used this to look for common proper motion pairs with M dwarfs from my catalogue
- Separated them in to:
  - high proper motion, bright (1)
  - High proper motion, faint (1)
  - Low proper motion, bright (10)
  - Low proper motion, faint (2)
- Calculated probabilities of systems being physical
- 14 with probability > 0.25

x-axis: $(B-V)$ y–axis: M_V



x-axis: $(B-V)$ y–axis: H_V





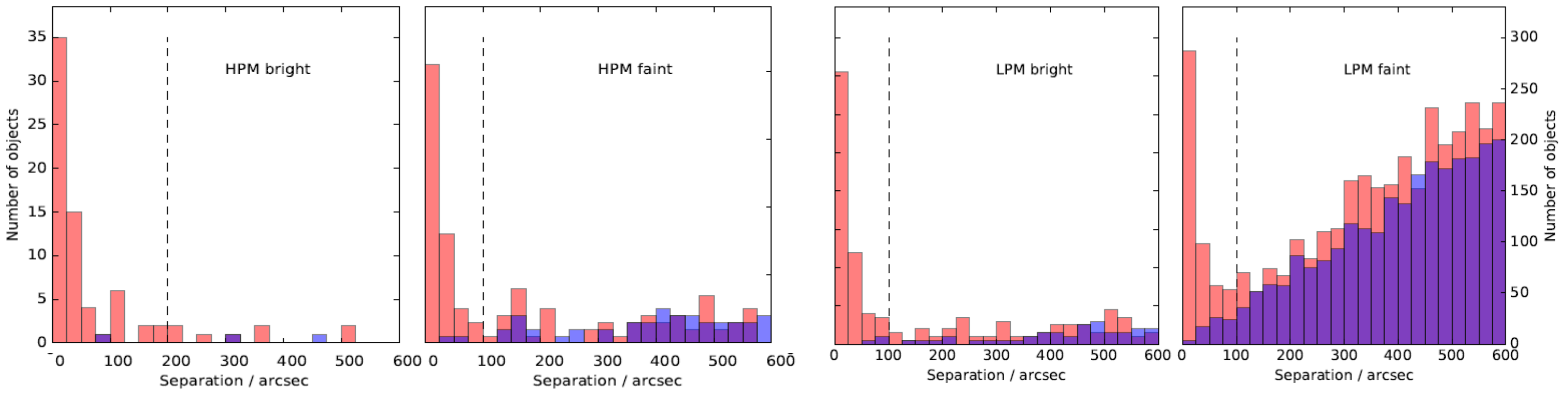
x-axis: separation in arcsec

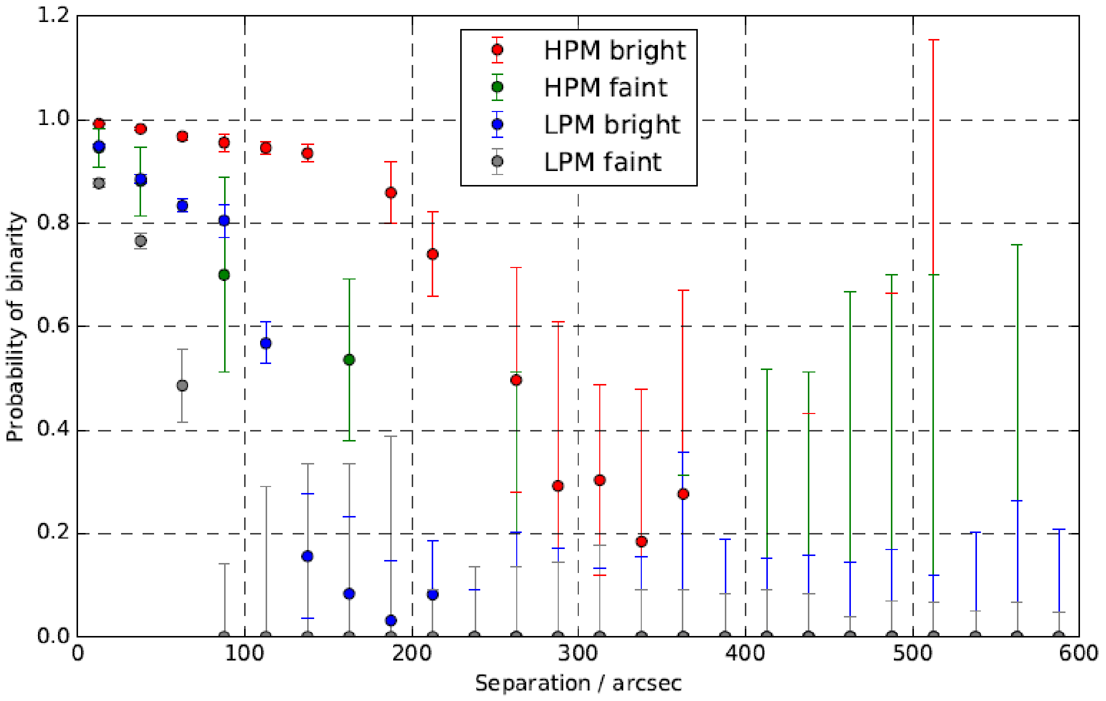
y-axis: probability of being a physical system

Find M+M binaries (via common proper motion)

- Looked for common proper motion pairs of M dwarfs from my catalogue
- Separated them in to:
  - high proper motion, bright (81)
  - High proper motion, faint (10)
  - Low proper motion, bright (96)
  - Low proper motion, faint (54)
- Calculated probabilities of systems being physical
- 241 with probability > 0.5

x-axis: separation y-axis: number of objects



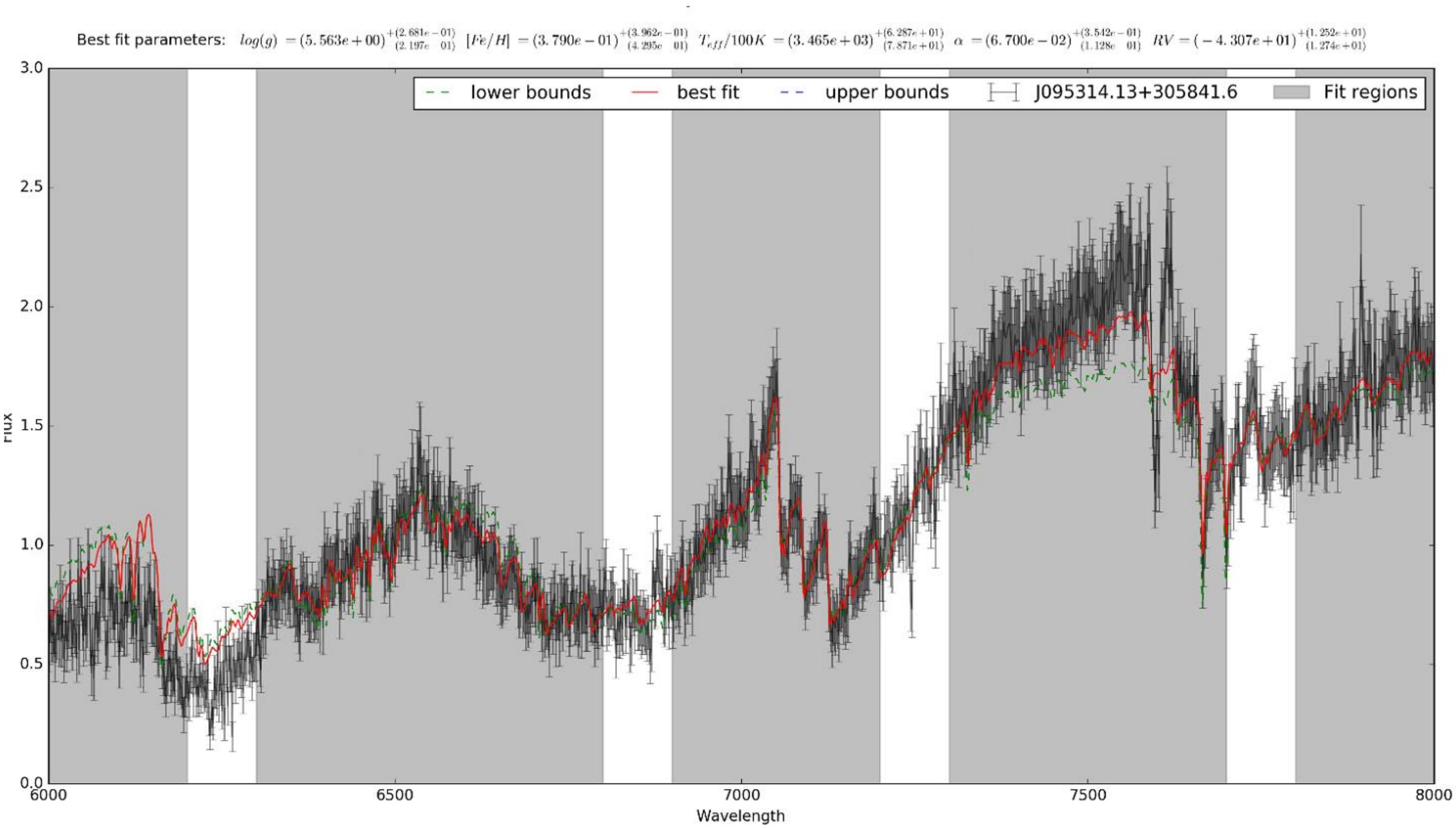


x-axis: separation in arcsec

y-axis: probability of being a physical system

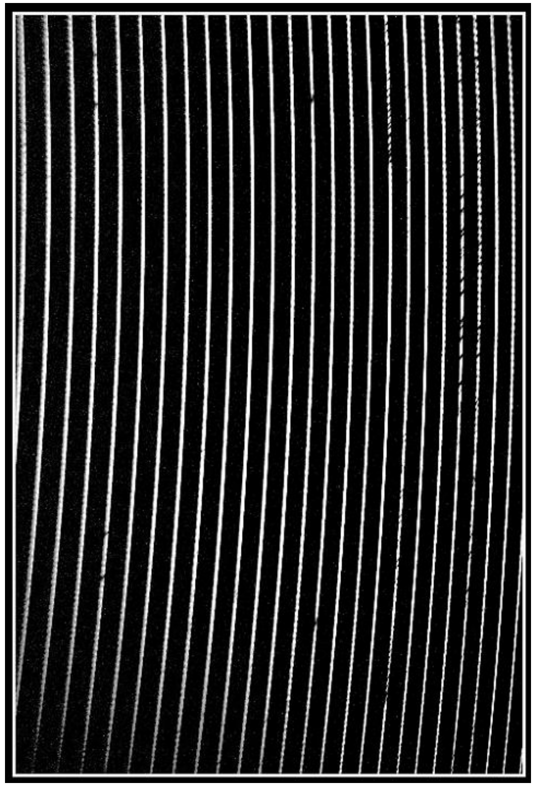
Model fitting of the M dwarfs with LAMOST spectra (~ 10000)

- Used models:
  - BT-Settl CIFIST models (Baraffe+2015)
  - PHOENIX ACES AGSS COND models (Passegger+2016)
- Used an MCMC routine to fit LAMOST spectra (between 6000 and 8000 Å) to extract $\log(g)$, T_{eff}, $\left[\frac{Fe}{H}\right]$ etc
- Have 10,591 spectra to fit
- Fitting spectrum to multiple normalized bands
- Work in progress
- Need better resolution in models

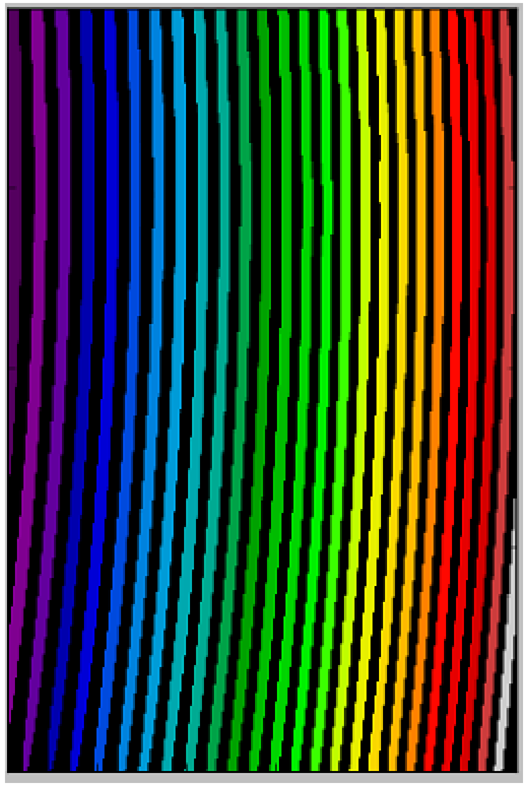


Echelle Spectra pipeline

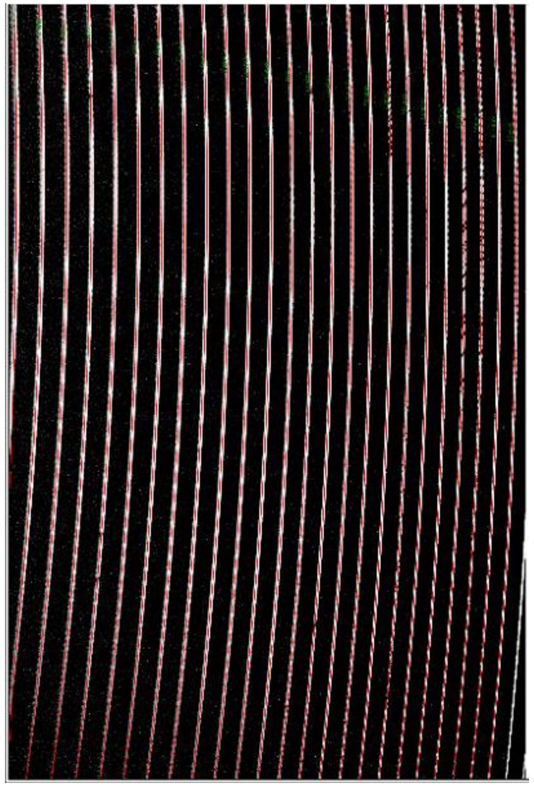
- Small telescope with "optical bench" echelle spectrograph
- In development thus setup changes regularly – no masks for orders
- Task: design a pipeline that can be used on "any" setup
- Used python "blob" finding algorithm (skimage.measure.label) to locate orders
- Orders seem to fit well



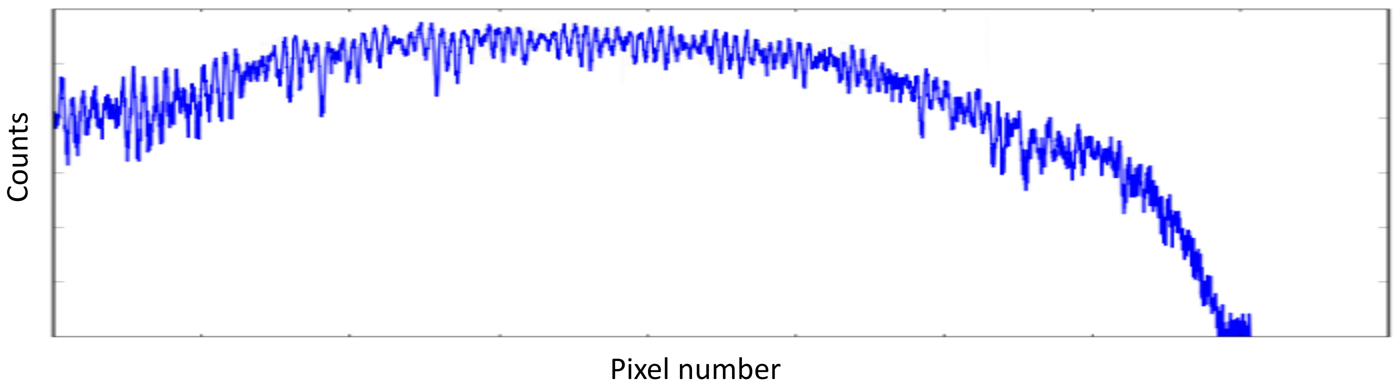
Original CCD image



Found "blobs"



Fitted orders



Example extracted order