Red Optical Planet Survey (ROPS): A radial velocity search for low mass M dwarf planets

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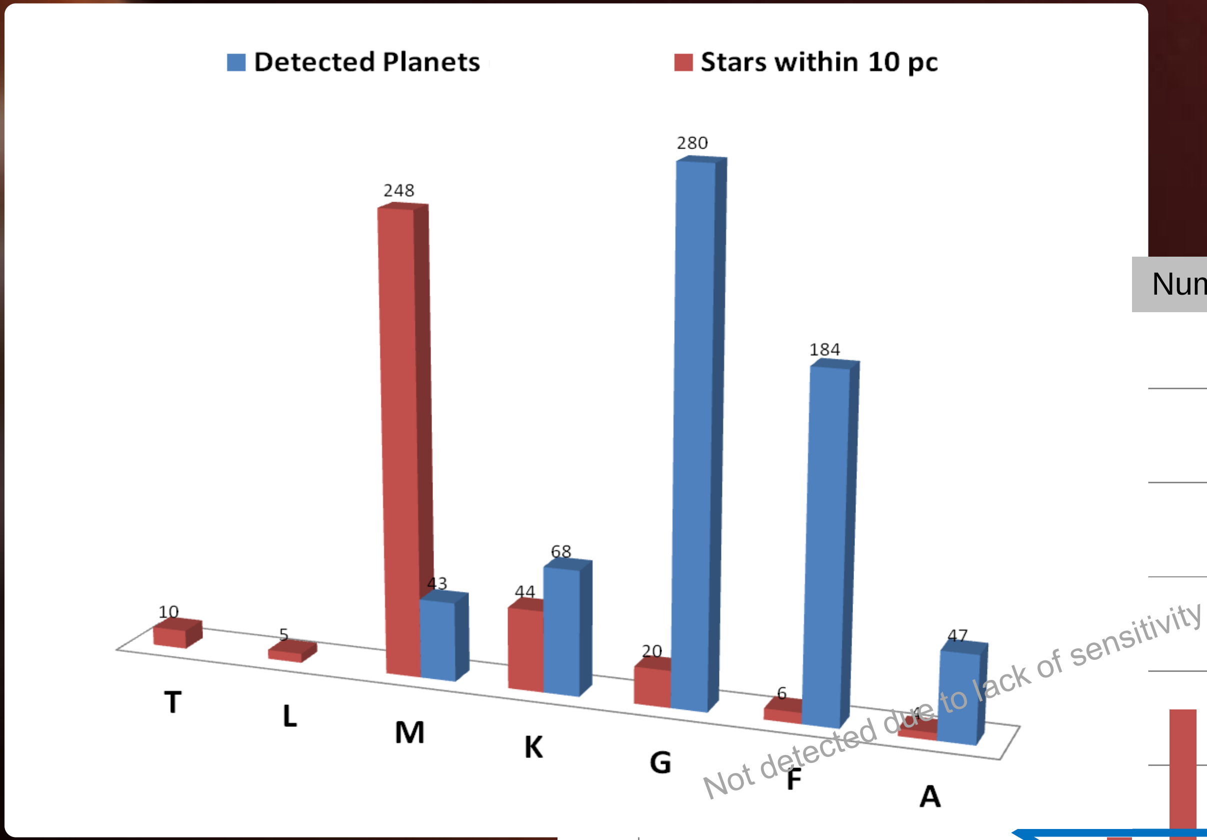
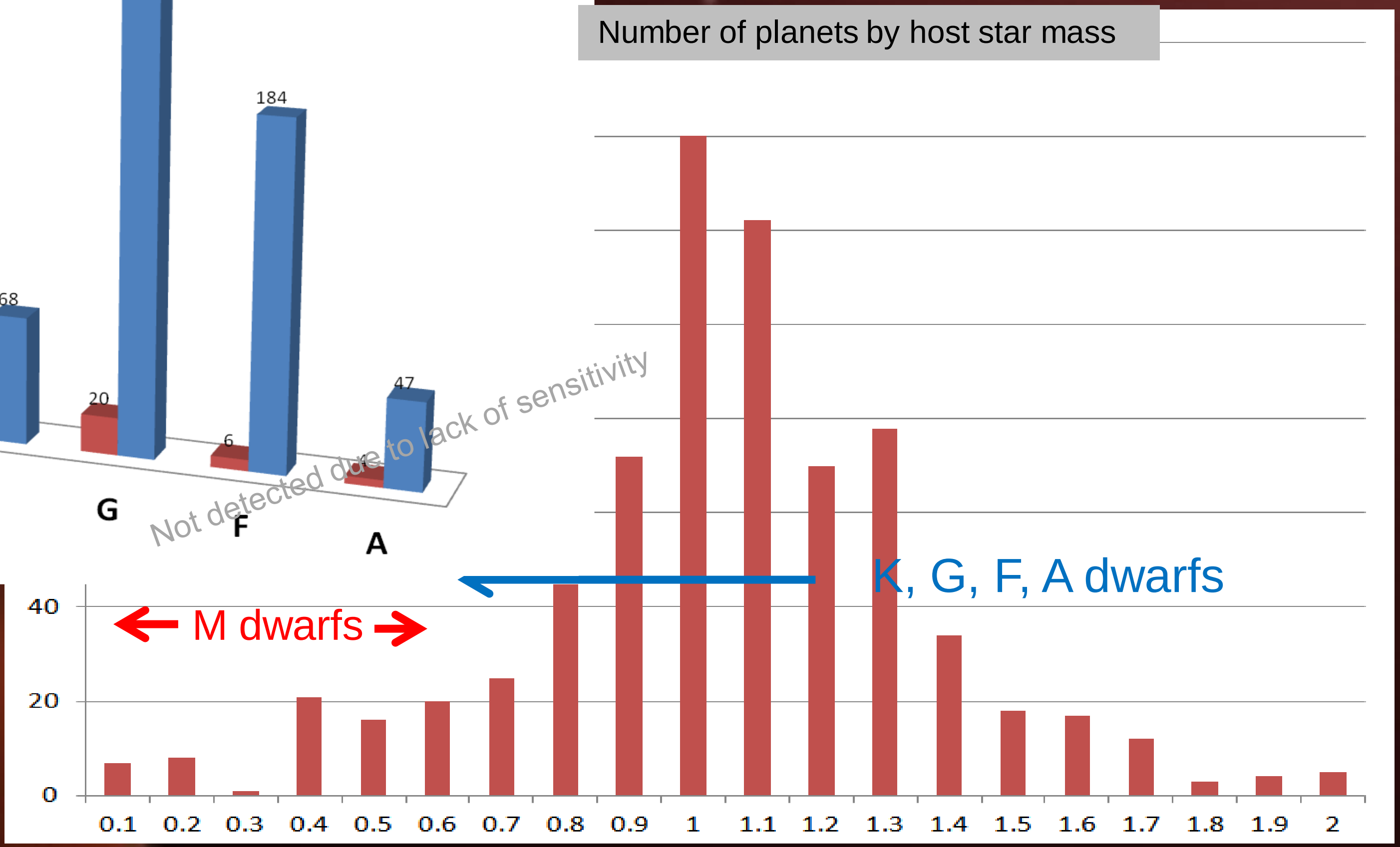
The holy grail of exoplanet hunting – Earth-mass planets

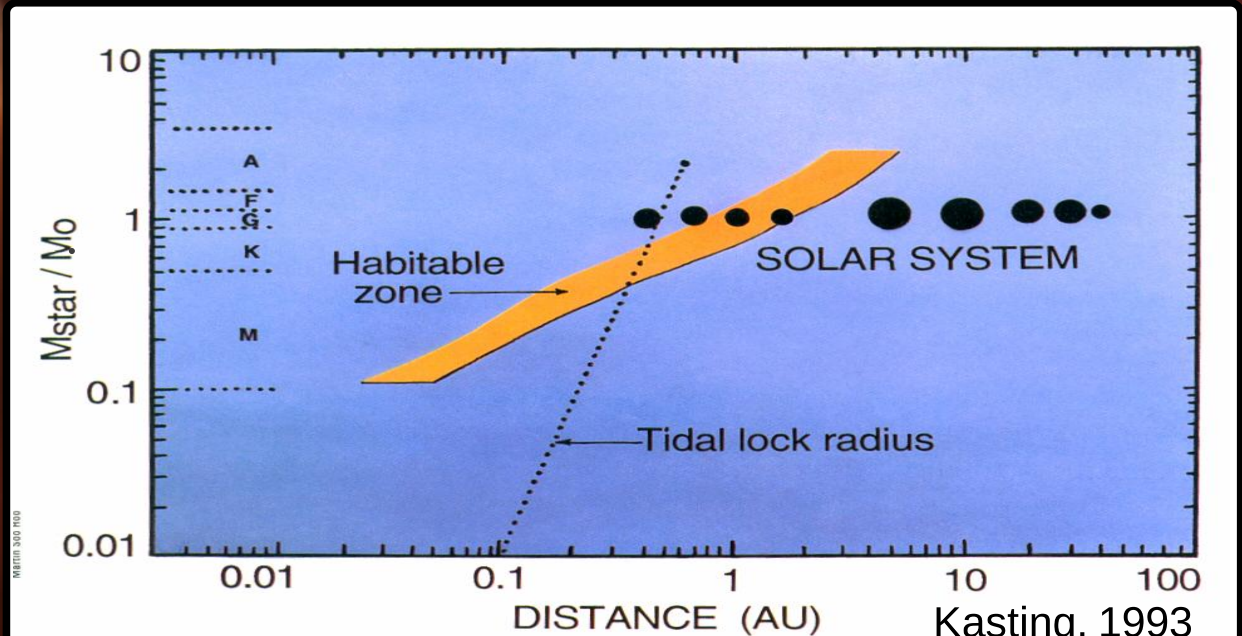
Nearest stars | stars with detected planets





M dwarf radial velocity planet searches

- Lower mass host stars – hence potentially sensitive to lower mass planets
- Effect of starspots is expected to be reduced as the contrast with the stellar photosphere is lower
- Earth mass planets that induce radial velocities large enough for detection will be in short orbits of ~days to 10s of days



Kasting, 1993

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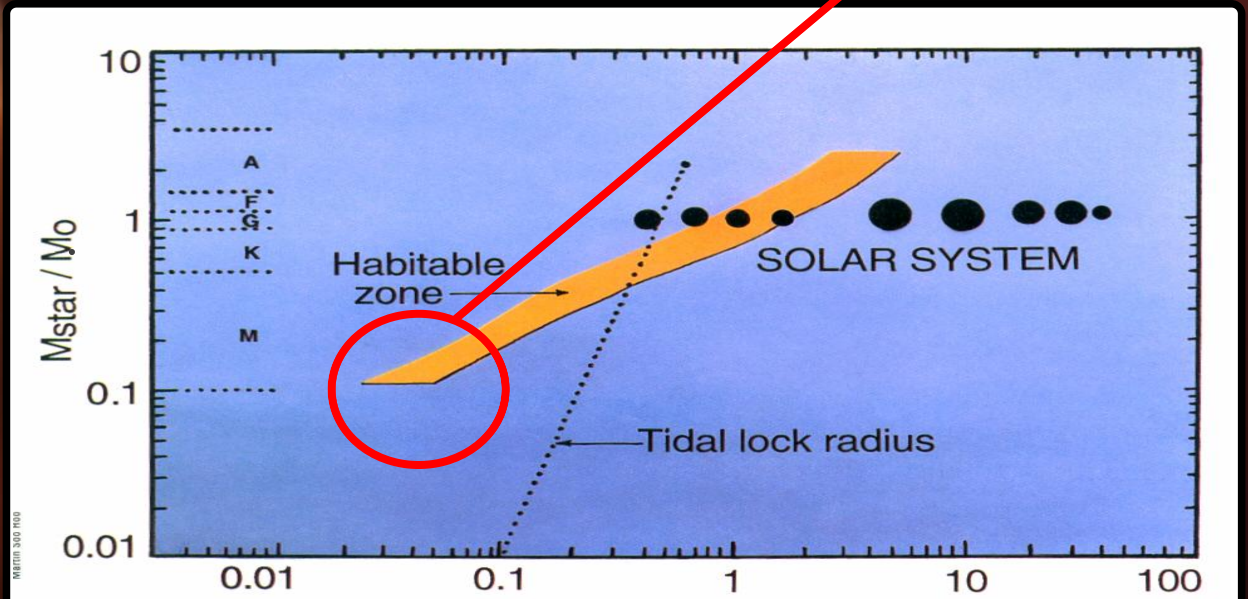
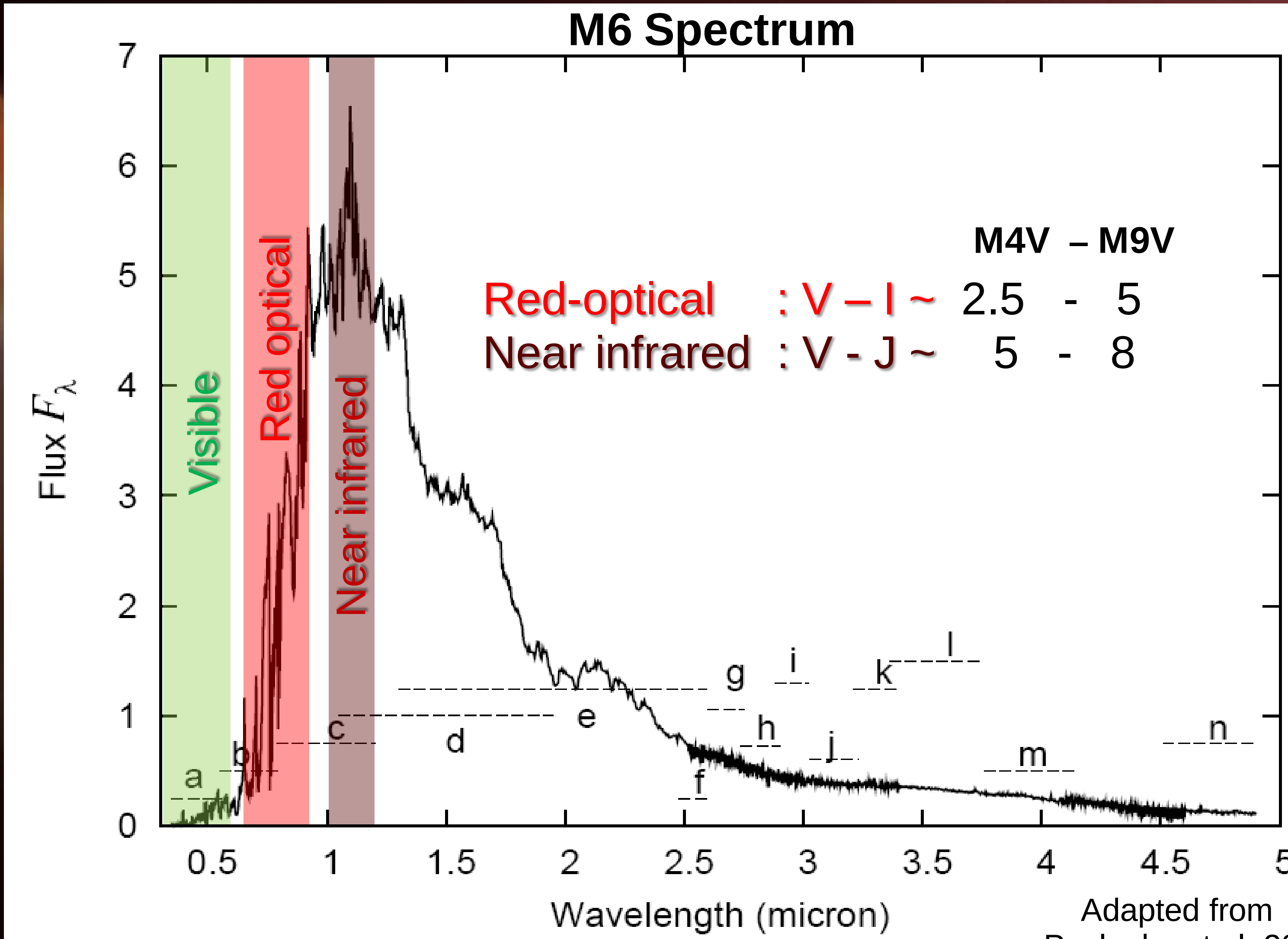


Kasting, 1993

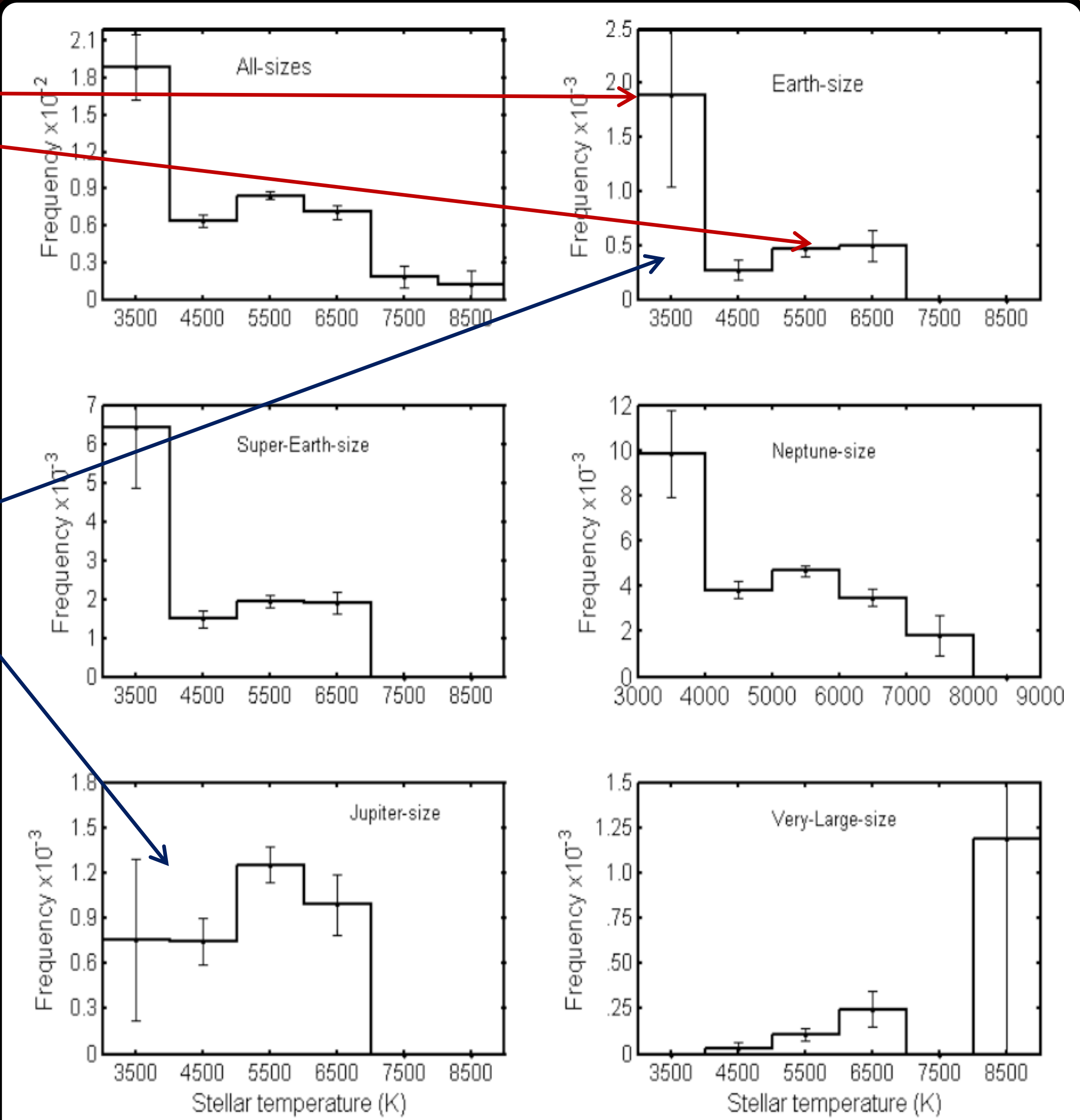
Precision Radial Velocities
Wavelength regime



Adapted from
Pavlenko et al. 2006

M dwarf planet frequencies

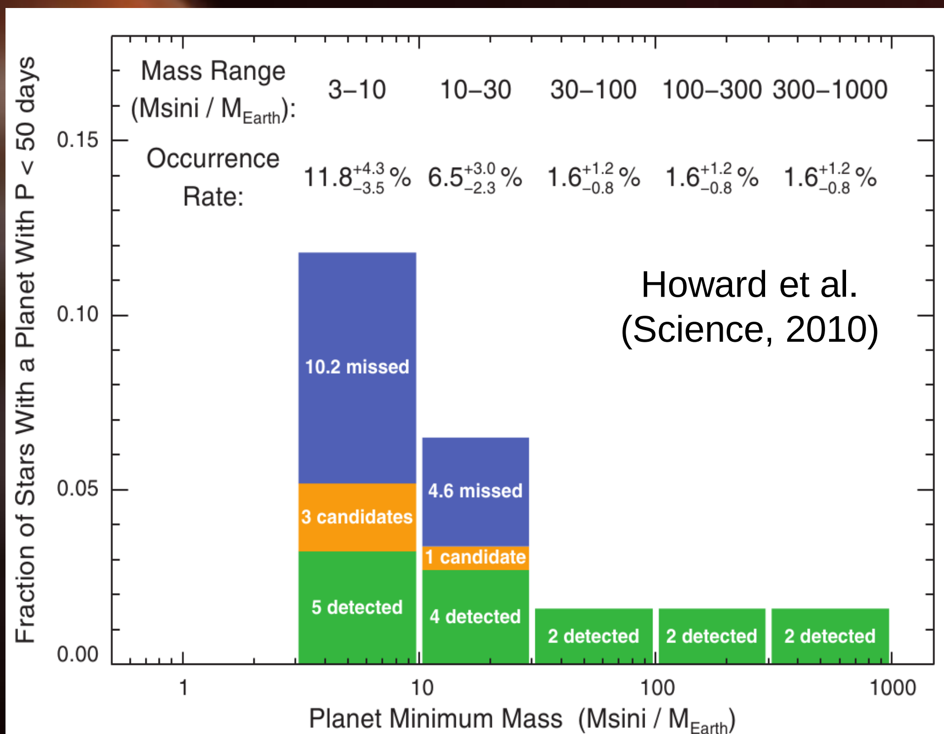
- Kepler planetary candidates suggest Earth-mass to Neptune-mass planets are 2.5 - 4x more numerous around M stars than earlier spectral types (Borucki et al. 2011)
- Found in greater numbers than transiting Jupiter size planets orbiting earlier spectral types
- Many of these candidates are in very close orbits of < 0.1 AU.

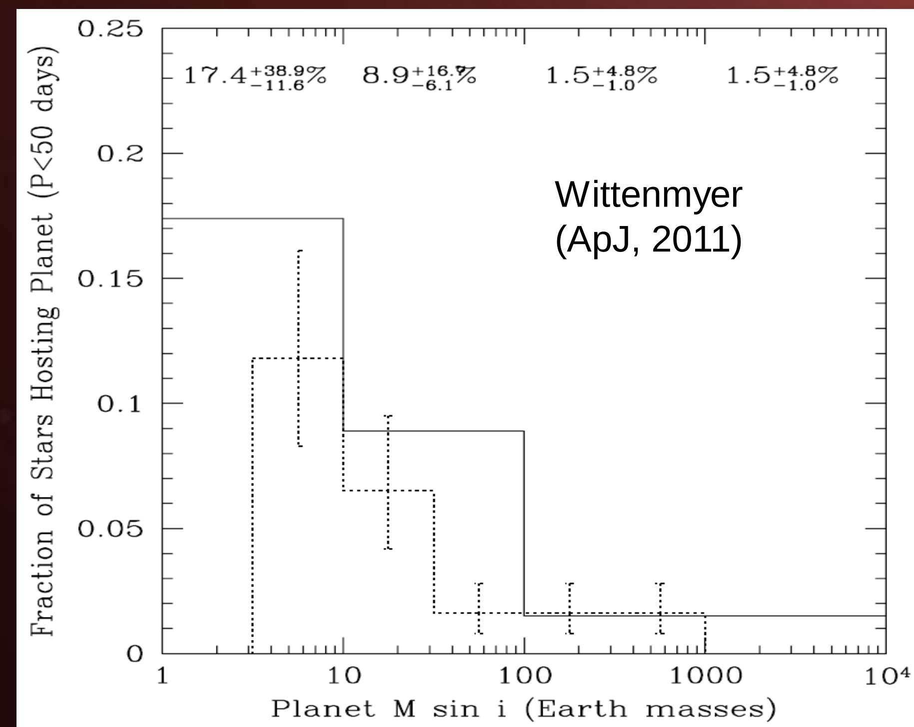


Borucki et al. 2011

M dwarf planet frequencies

- AAPS sample of 67 stars indicates (Wittenmyer et al., 2011) indicates that 17.4% of solar-like stars possess 1 -10 $M_\oplus$ planets
- Howard et al. (2010) estimate (166 stars) 11.8%





- Scaling to the M dwarf regime, using a factor of 2.5 from the Kepler results indicates that at least

At least 30% of M dwarfs should be orbited by 1-10 $M_\oplus$ planets!

M dwarf planet frequencies

- HARPS M dwarf sample (Bofils et al., 2011: arXiv 1111.5019v2) statistics/detection limits

Frequency	100-1000 $M_\oplus$	1-10 $M_\oplus$
P = 1 - 10 d	$\lesssim 0.01$	$0.36 \pm^{0.25}_{0.10}$
P = 10 - 100d	$0.02 \pm^{0.03}_{0.01}$	$0.35 \pm^{0.45}_{0.11}$

- **At least 25% of M dwarfs should harbour Earth-mass (1-10 $M_\oplus$) planets in short period orbits!**
- **....but may be as high as 80% !!**

Freq. of M dwarf HZ planets, $\eta_\oplus = 0.41 \pm^{0.54}_{0.13}$ (i.e. 28% - 95%) !!!

Precision RV in the infrared

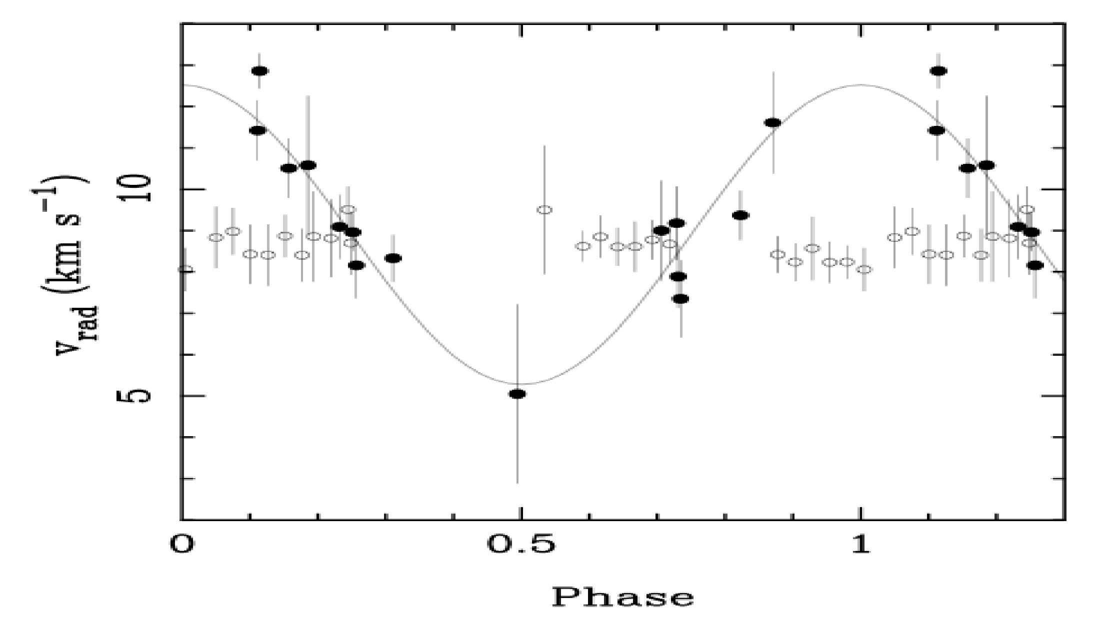
- A number of studies have aimed at characterising the suitability of near infrared wavelengths

→ problems: IR detector quality / atmospheric line contamination

- Generally achieved 100 – 300 ms^{-1} precision:

e.g. Martín et al (2006), 360 ms^{-1} on LP944-20 whereas 3.5 kms^{-1} reported in optical → claimed optical planet absent in IR → starspots

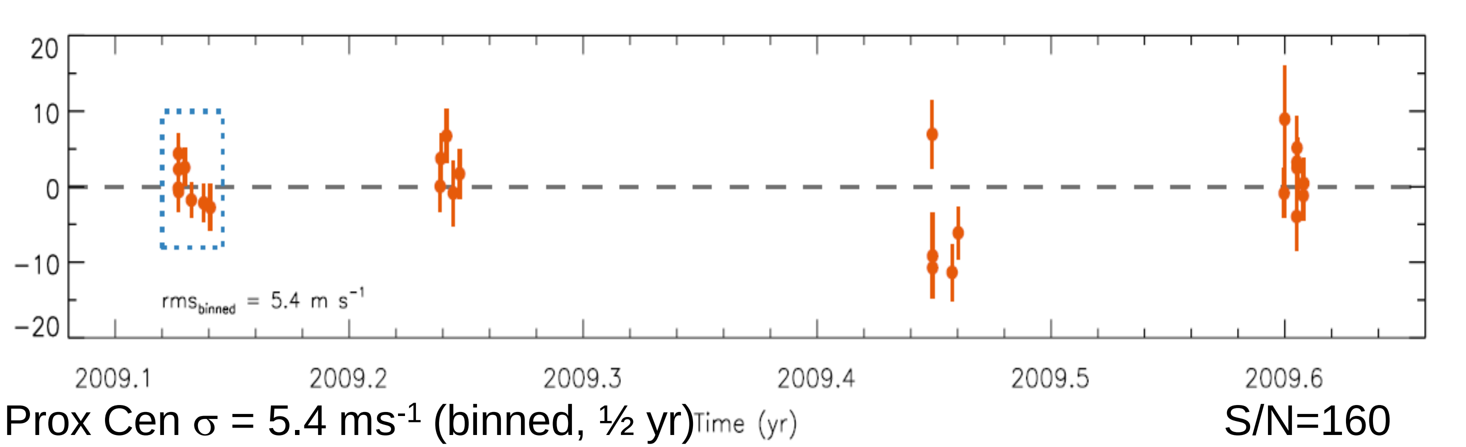
LP944-20 (nearby late-type M9 brown dwarf)



Martín et al (A&A, 2006, 644, L75)

Recent results

- CRIRES/VLT: Infrared K-band using a NH_3 gas cell has achieved ~5ms^{-1} (Bean et al. 2010) using 364 Å of spectrum



Prox Cen σ = 5.4 ms^{-1} (binned, ½ yr) S/N=160

- Keck/NIRSPEC – 1.25 μm R~20,000 (4 orders 150-200 Å)

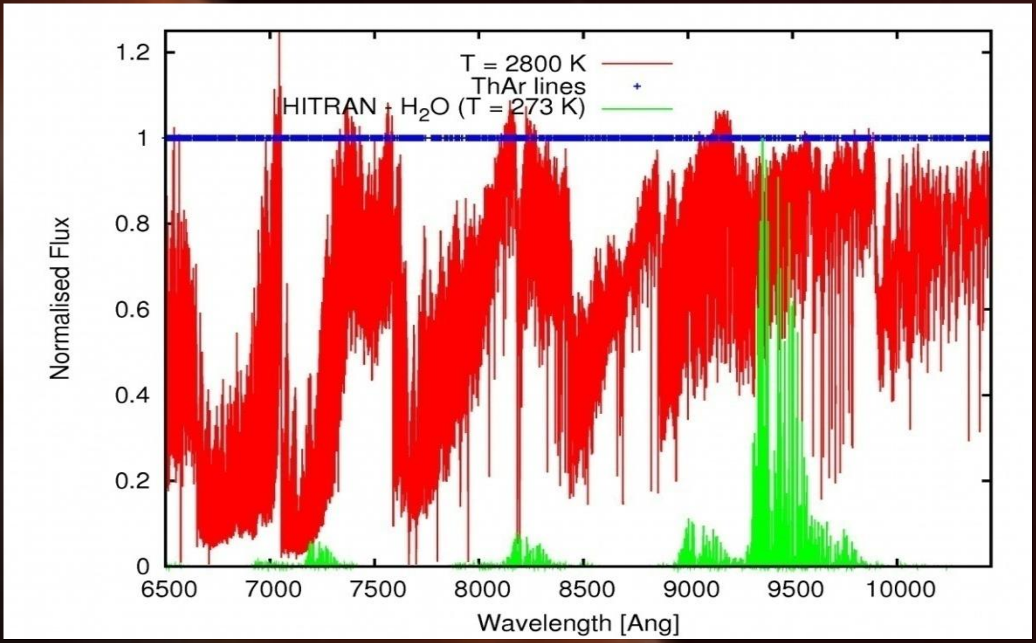
  Tellurics as reference → Precision = 180 – 300 ms^{-1}

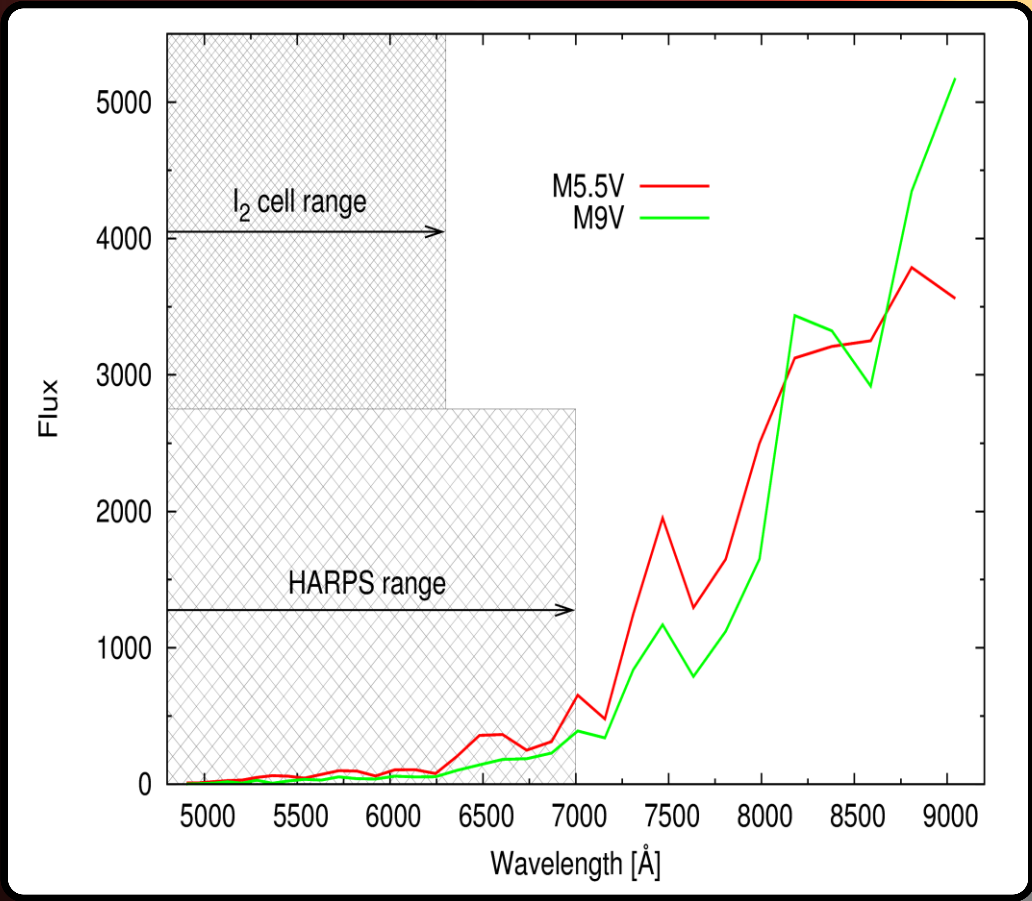
  No evidence for planets around 8 M dwarfs (Rodler et al. 2012, A&A, 538, 141)

- Keck/NIRSPEC : 50 ms^{-1} precision using tellurics (K band) 20 young stars in β-Pic and TW Hya (77 ms^{-1} limited by starspots). Hot/warm Jupiters excluded (Bailey et al. 2012, ApJ, 749, 16)

Magellan / MIKE

Two nights on MIKE / Magellan
Clay 6.5m in Nov 2010





- Spectral information contained in 0.65 – 1.05 micron region (M6 spectrum – red)
- Atmospheric O_2 and H_2O lines

Barnes et al., 2012, MNRAS, 424, 591

- Spectral energy distribution (incl. MIKE & CCD response) for typical M5.5V and M9V dwarfs. A comparison of MIKE and HARPS regions indicates that $F_{0.7\text{-}0.9} / F_{0.5\text{-}0.7}$ = 11.5 and 19 respectively for the two stars.

Magellan / MIKE – RV strategy

- HARPS: Uses simultaneous ThAr reference frames to achieve < 1 ms^{-1} precision

→ Precision relies on instrument stability

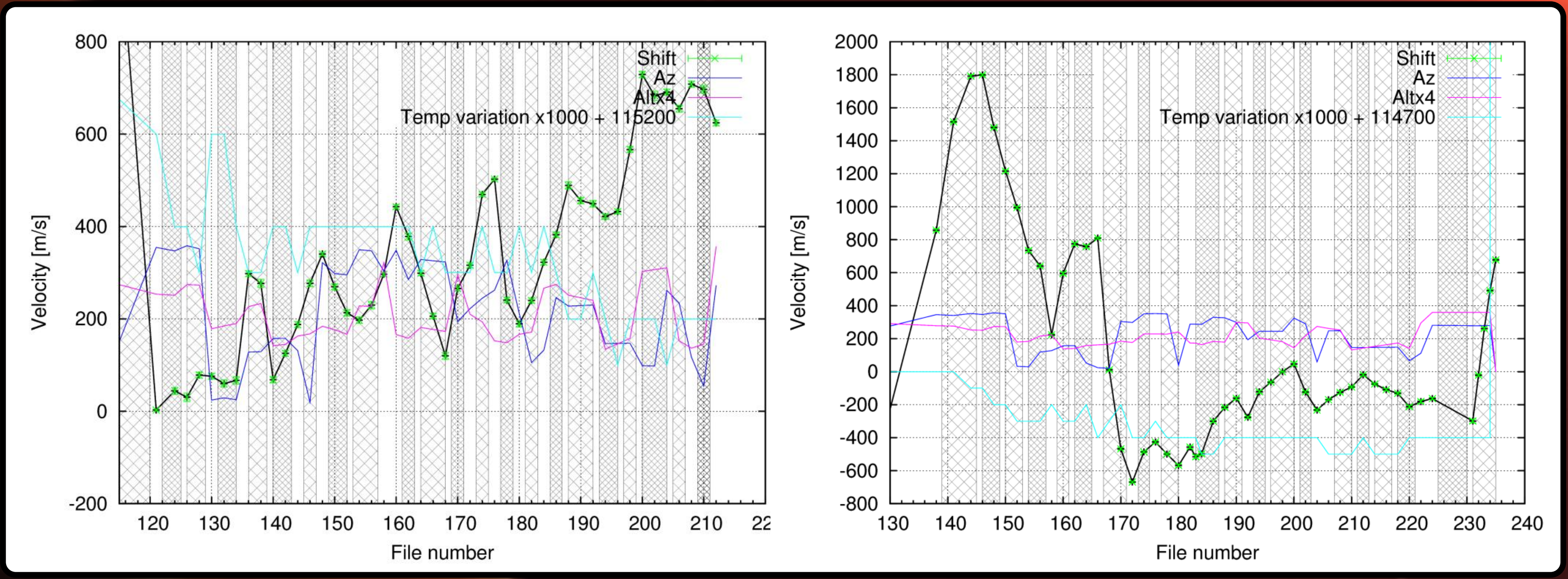
- AAPS/Keck surveys: Use I_2 gas cell to obtain spectra that contain simultaneously recorded stellar lines and iodine lines

→ Good for less stable instruments, but reduces stellar S/N

- MIKE – Use near simultaneous ThAr → precision?

Magellan / MIKE – RV strategy

- Significant shifts seen, even without movement of telescope



PROBLEMS: MIKE does not show slow drifts with time!

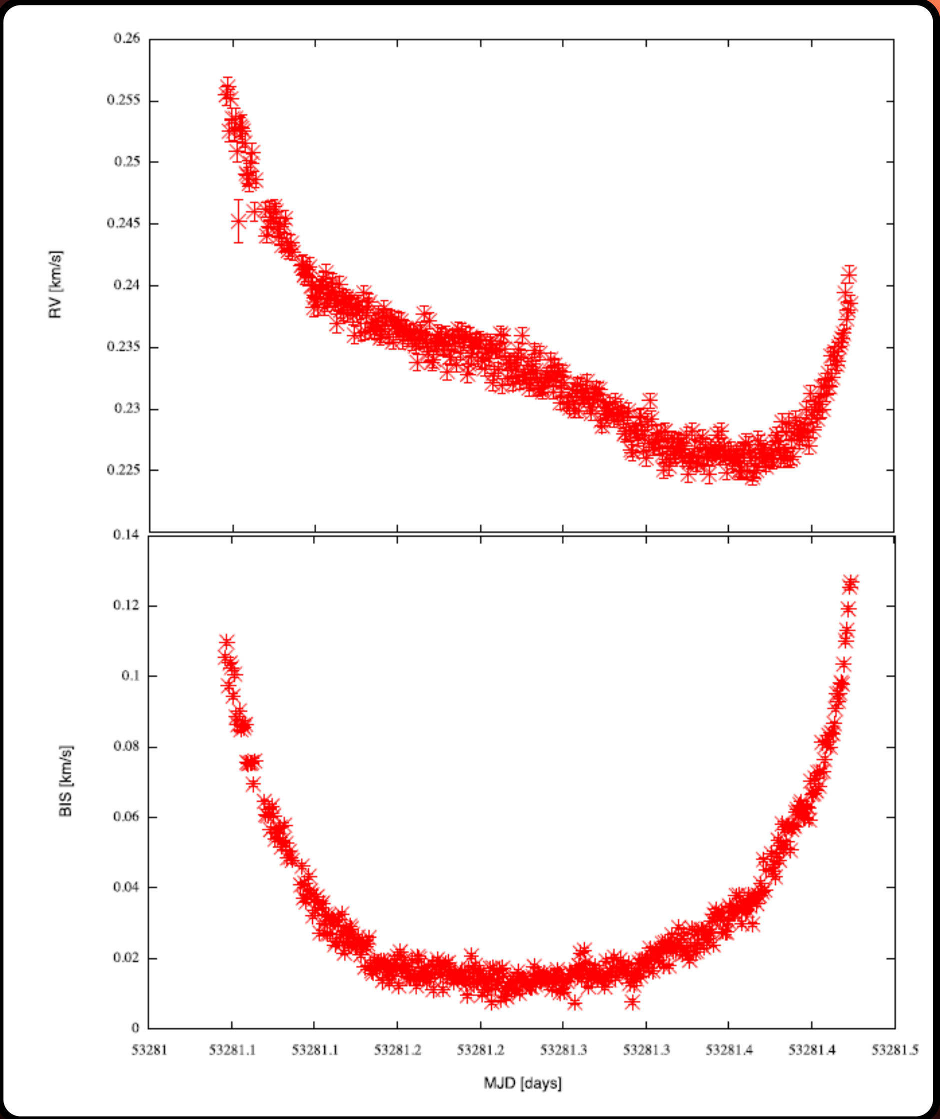
~1 pixel drift in WAVELENGTH seen on short timescales

→ SOLUTION: Use tellurics as reference fiducial

How stable are tellurics?

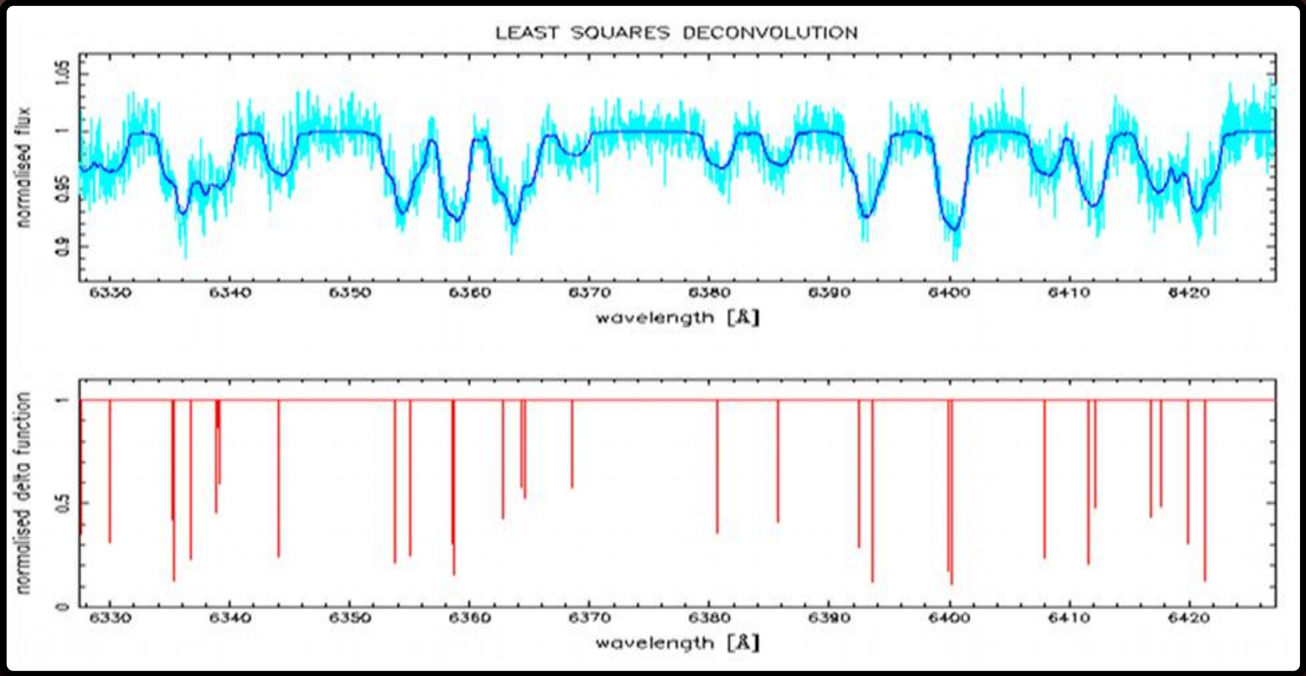
- Depends on 1) airmass and 2) wind velocity along line of sight
- Figueira et al. (2010) have found that with simple corrections, O_2 lines are stable to $10 ms^{-1}$ over 6 years in HARPS data and to ~2-6 ms^{-1} over week timescales

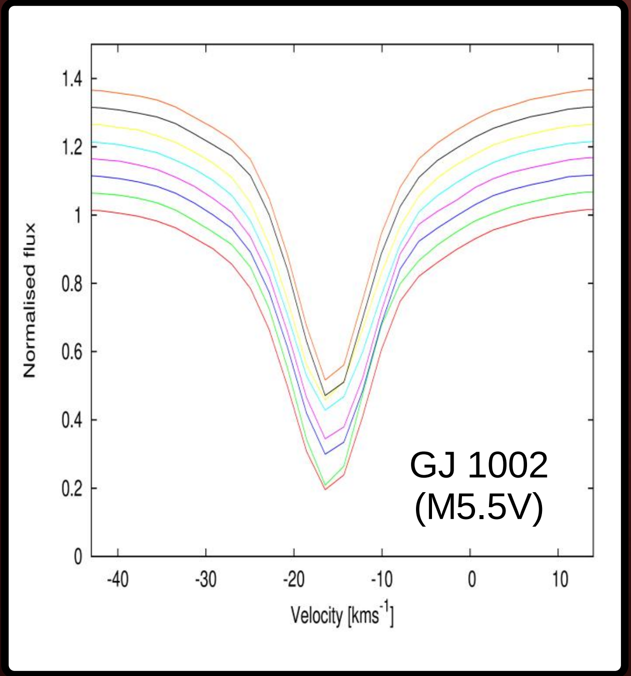
Target	data-set [d]	$\sigma_{(X<1.5)}$	$\sigma_{(X<1.2)}$	$\sigma_{(X<1.1)}$ [m/s]
Tau Ceti	1	4.53	3.38	2.41
	2	5.53	4.07	3.27
	3	5.81	4.55	3.70
	Full	9.77	9.16	8.43
μ Ara	1	5.00	3.36	2.31
	2	6.18	4.14	2.61
	3	6.38	4.27	2.66
	4	5.67	3.86	2.39
	5	5.67	4.01	2.57
	6	6.18	4.71	3.24
	7	6.46	4.93	3.40
	8	6.94	5.42	3.91
	Full	9.88	10.10	10.23
ϵ Eri	Full	10.82	10.55	9.61



Deconvolution

- S/N in a single spectrum is typically of order a few to to a few hundred
- Several hundred to several thousand lines in a typical spectrum
  - Use *model spectrum* to deconvolve *mean profile* from observed spectra
- A weighted least squares profile is derived, boosting the S/N ratio by a factor depending on the number of lines Typically factor of a few x10 gain





S/N ratios of order ~1000+ can be achieved for a single spectrum, enabling radial velocities with high precision to be determined

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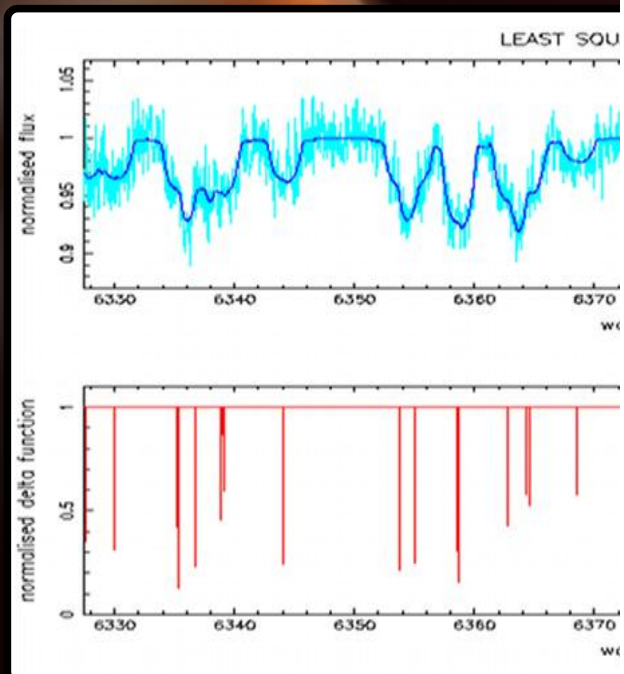

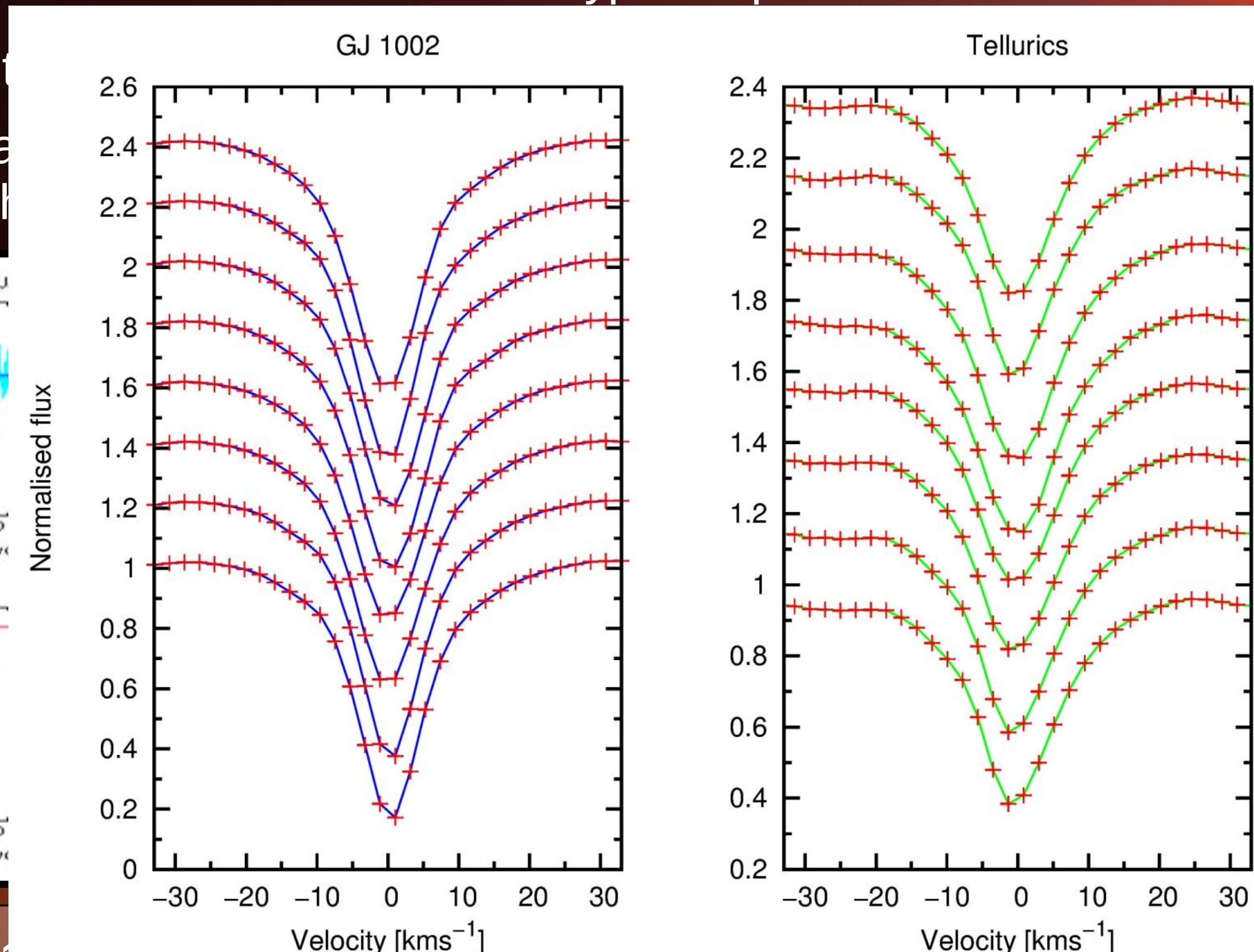

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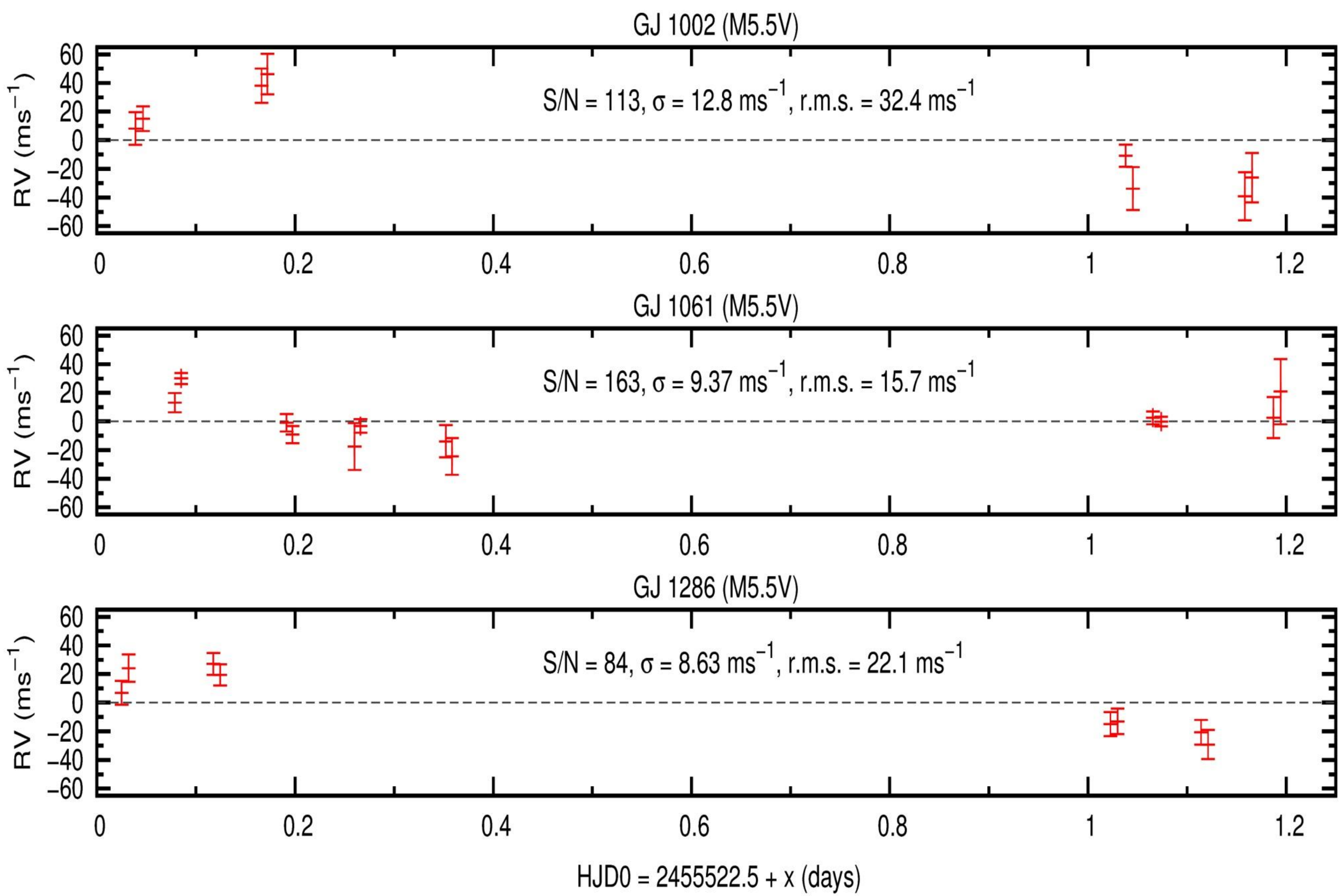
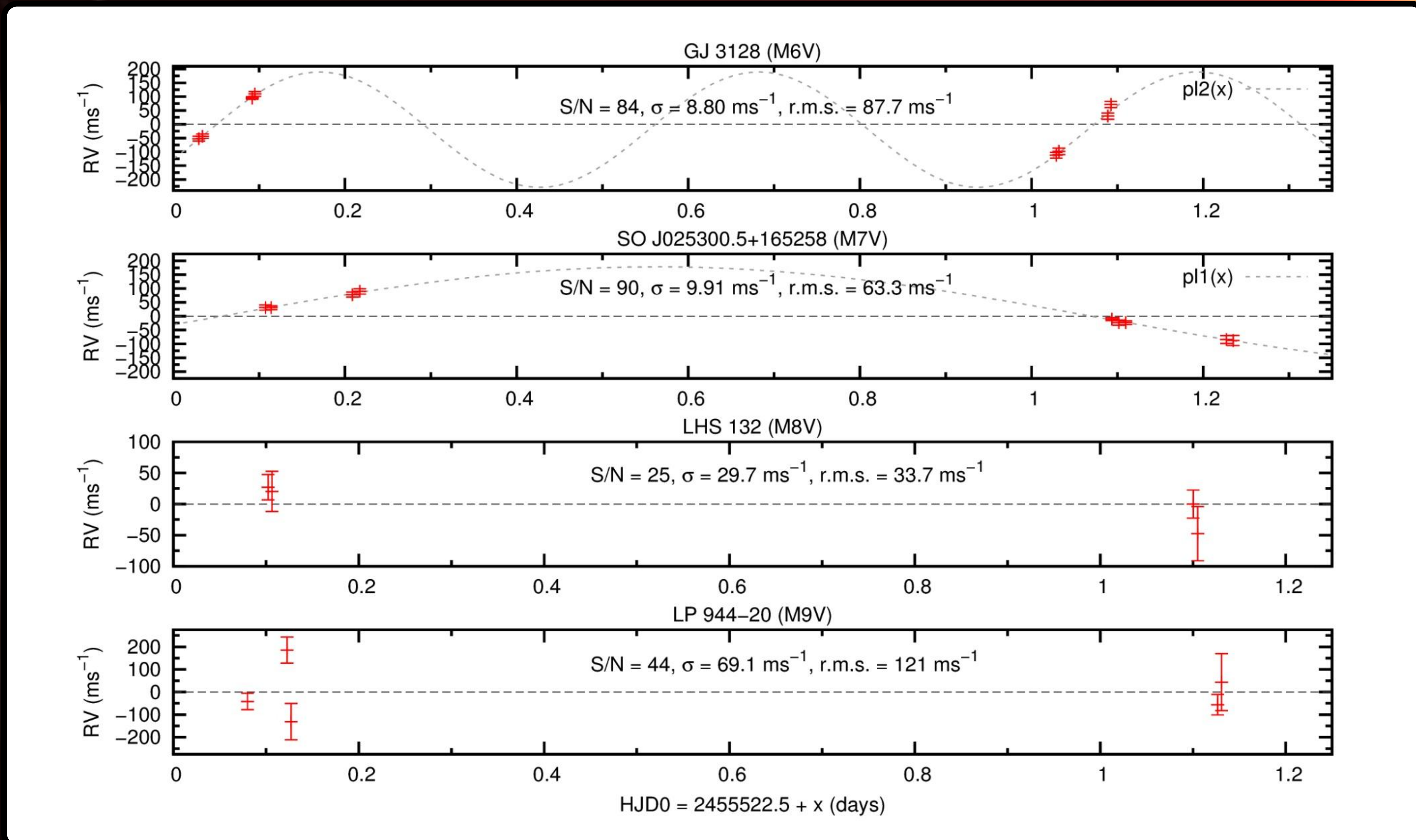
Radial velocities for three M5.5 dwarfs



Radial velocities for M6 & M7 dwarfs



- SO J0253+1652 shows opposite trends on consecutive nights at a level of 6 σ
- K = 183 m/s, P ~ 2.1 days → Equivalent to a 4.9 M_{Nept} planet

Radial velocities for three M5.5 dwarfs

Object	S/N	Error (ms^{-1})	Mean ΔOP (ms^{-1})	rms scatter (ms^{-1})	Discrepancy (ms^{-1})	Photon-limited precision (ms^{-1})
GJ 1002	113	12.8	12.7	32.4	29.7	3.3
GJ 1061	163	9.37	11.8	15.7	12.6	2.5
GJ 1286	84	8.63	8.88	22.1	20.3	4.4
GJ 3128	84	8.80	20.0(12.6)	87.7	87.2	4.4
SO J025300+165258	90	9.91	7.0	63.3	62.5	4.2
LHS 132	25	29.7	27.2	33.7	16.0	14.5
LP 944−20	44	69.1	208	121	99.3	7.6

- Observation pair rms in good agreement with cross-corr. errors
- 10σ and 6σ signals for GJ 3128 and SOJ0253+1653
- GJ 3128: P = 0.51 d, K_* = 209.4 m/s – $m_p \sin i$ = 3.3 M_{Nep}
- SO J0253+1653: P = 2.1 d, K_* = 182.7 m/s -- $m_p \sin i$ = 4.9 M_{Nep}

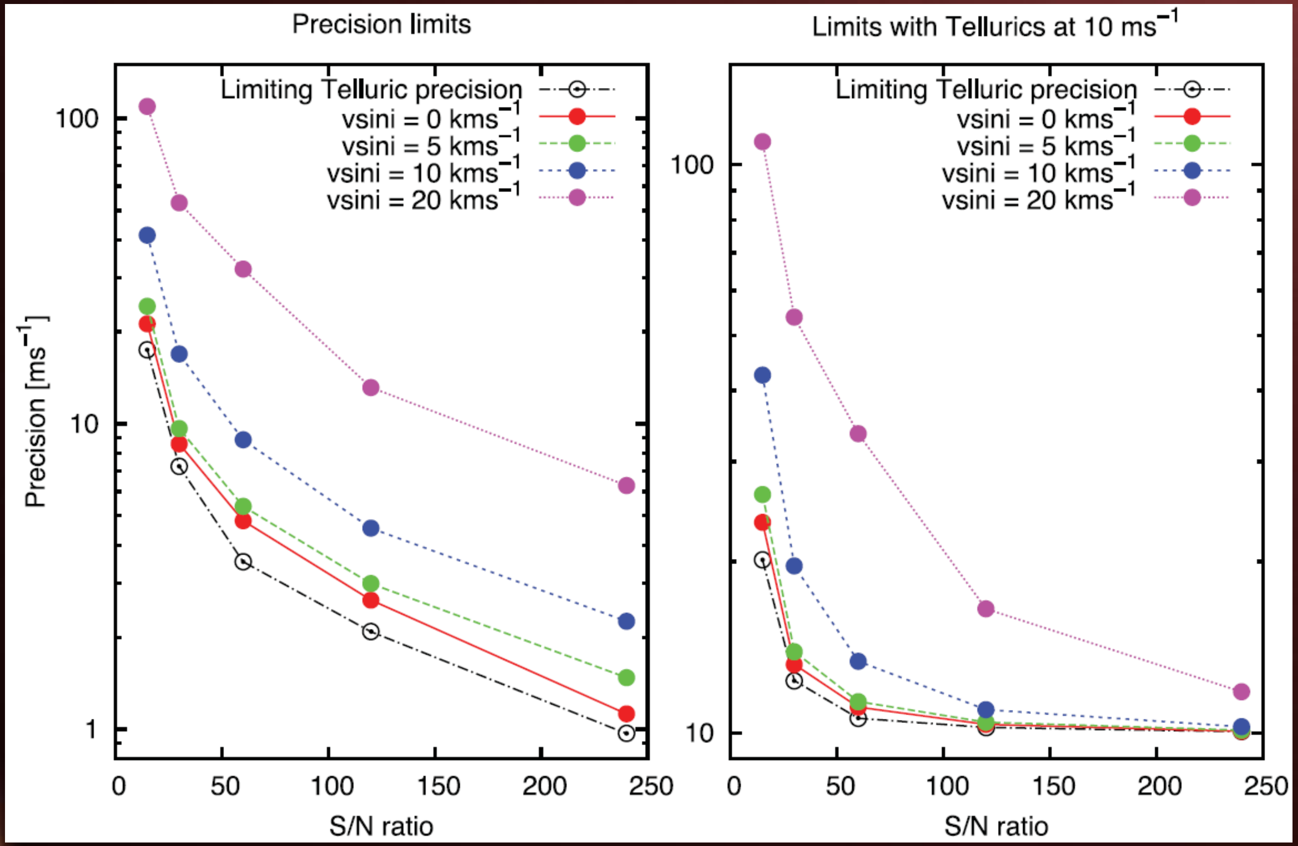
Are there significant nose sources yet unaccounted for?

Poisson limited precision using deconvolution method?

- Synthetic spectra telluric & spectral lines → deconvolve for spectra with S/N scaled to 15,30,60,120,240. →MC simulation to obtain mean scatter.
- e.g. GJ 1002, S/N = 120 → ~2 m/s (2 - 3.5 m/s for observed sample

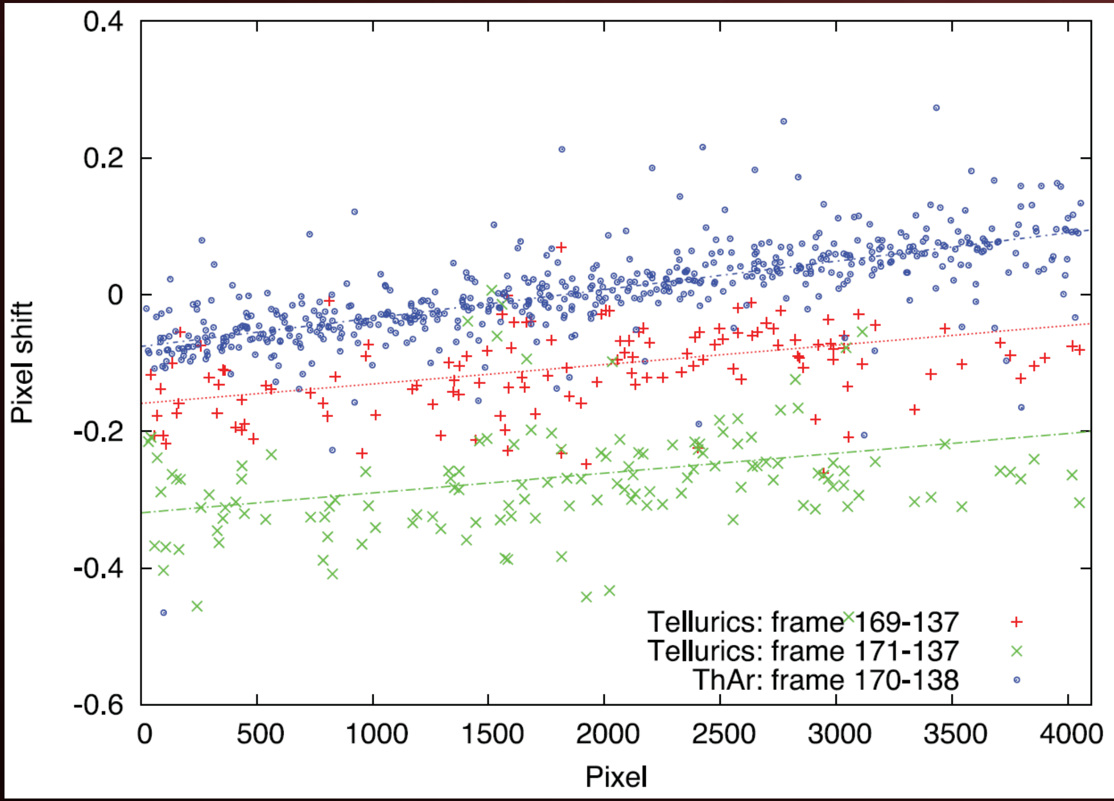
- OBSERVE: 1.5 – 12 ms^{-1} on observation pairs
- Cross-correlation errors of 12.3 – 21.2 ms^{-1}
- Scatter of 9.6 – 66 ms^{-1}

What's going on for medium term - long timescales?

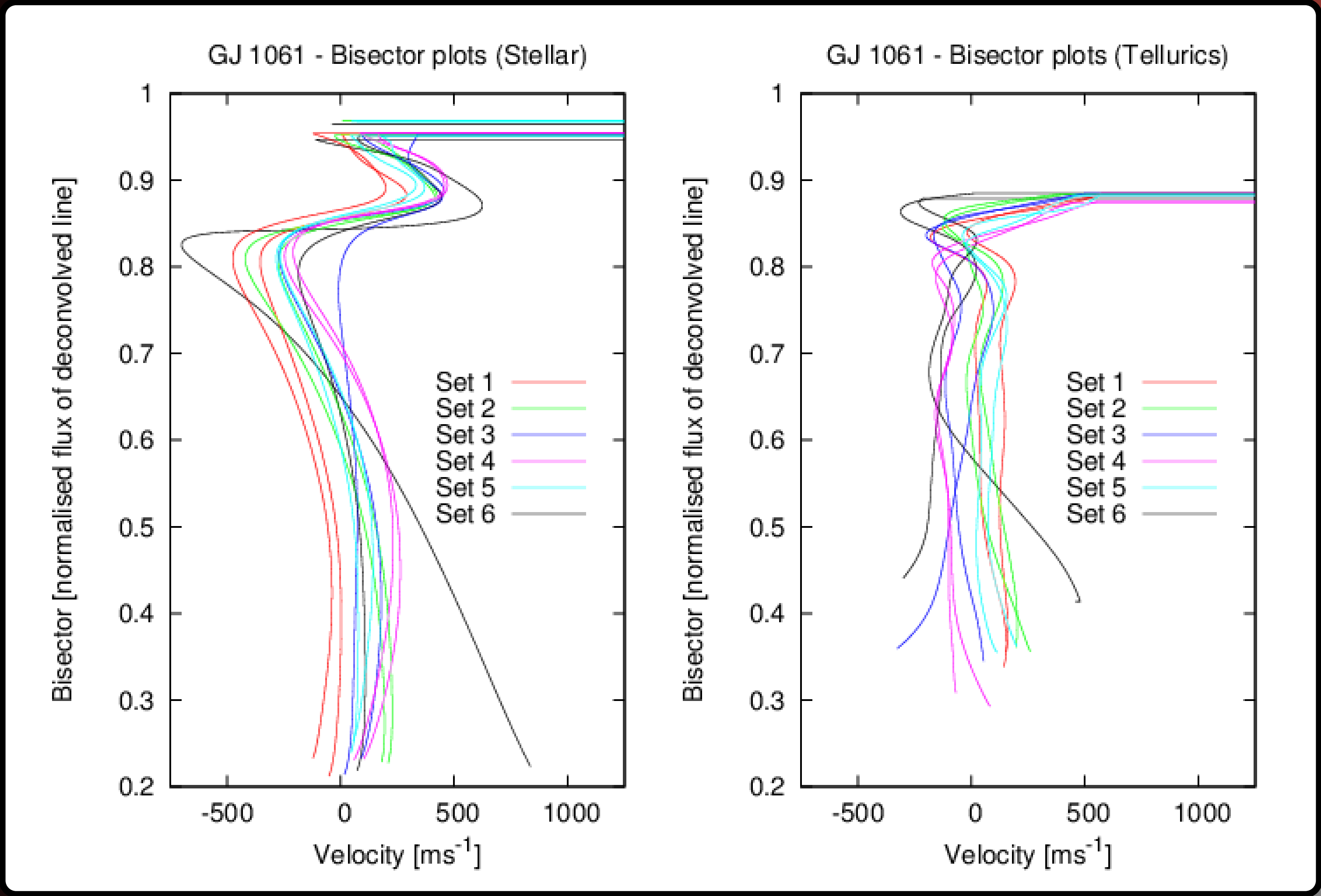


Wavelength solution?

- Important to obtain a good, and crucially, stable wavelength solution for deconvolution
- Order 3 (λ dirn.) x 5 (x-dispersion) 2D poly yields solution with ~3-5 ms^{-1} zero point rms
  - 2D reference solution with iterative rejection of outliers leaves ~450 arc lines
  - Apparent lack of stability of MIKE – internal/ mechanical?
- Mean tilt common to all orders used to obtain local wavelength solution



Line bisectors

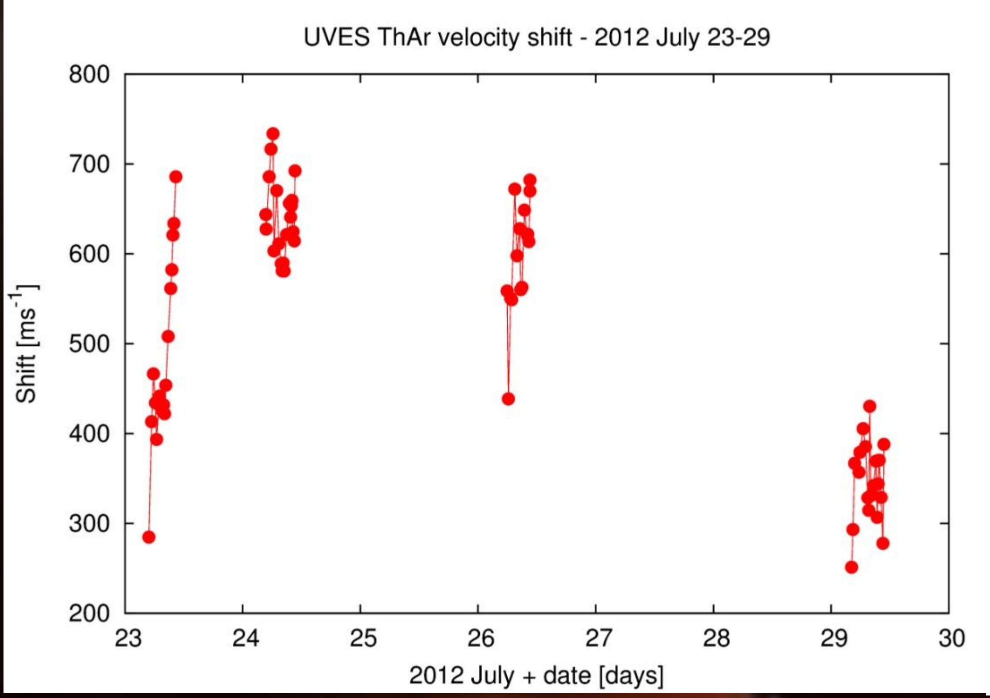


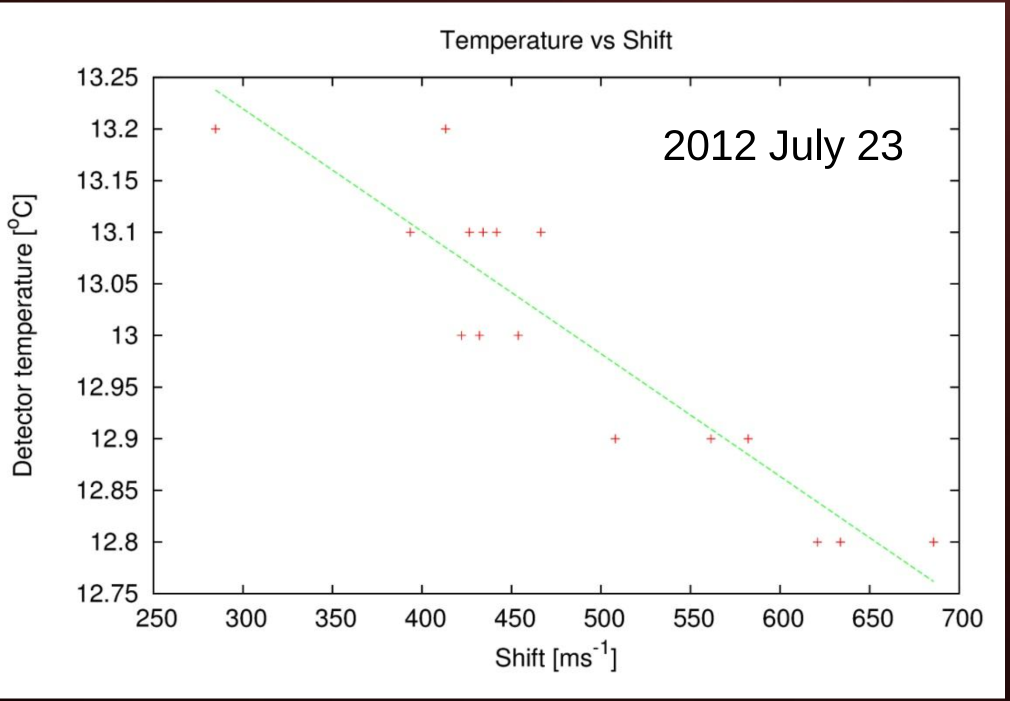
- Last spectrum shows large bisector deviation when compared with other profiles.
- Visual inspection of spectra shows no obvious cause.

Continuing ROPS with UVES

Advantages:

- Better order separation
- Wavelength coverage 0.64 - 1.03 μm (MIKE: 0.62 – 0.89 μm)
- Improved resolution R~50,000 (MIKE: 35,000)
- 1180 m/s/pixel (MIKE: 2150 m/s/pixel)
- Parallactic angle maintained during observations





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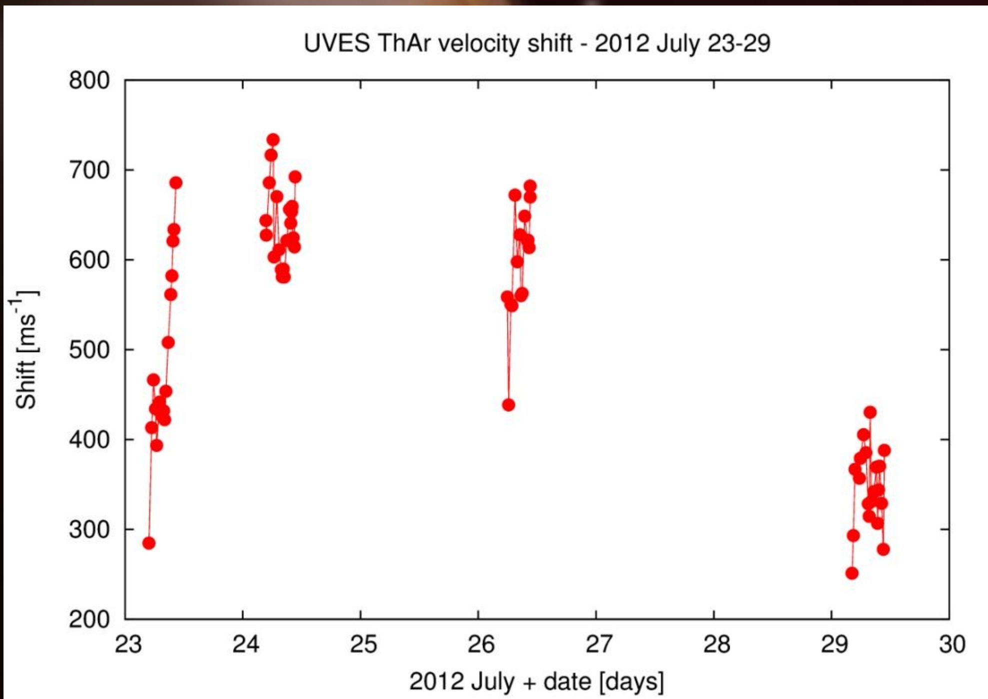
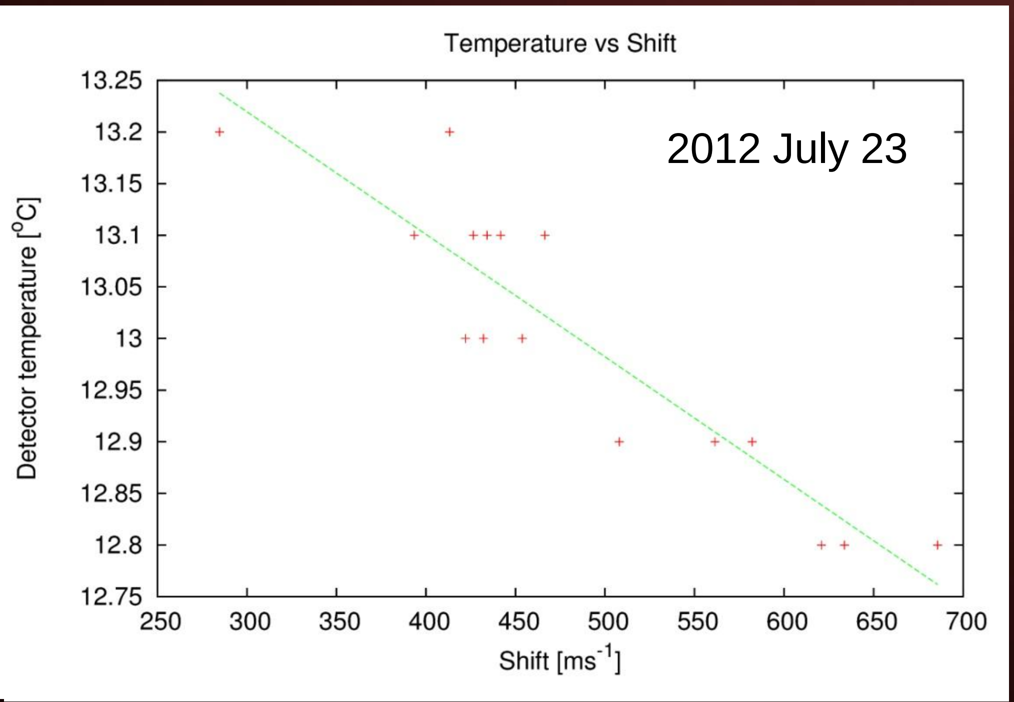
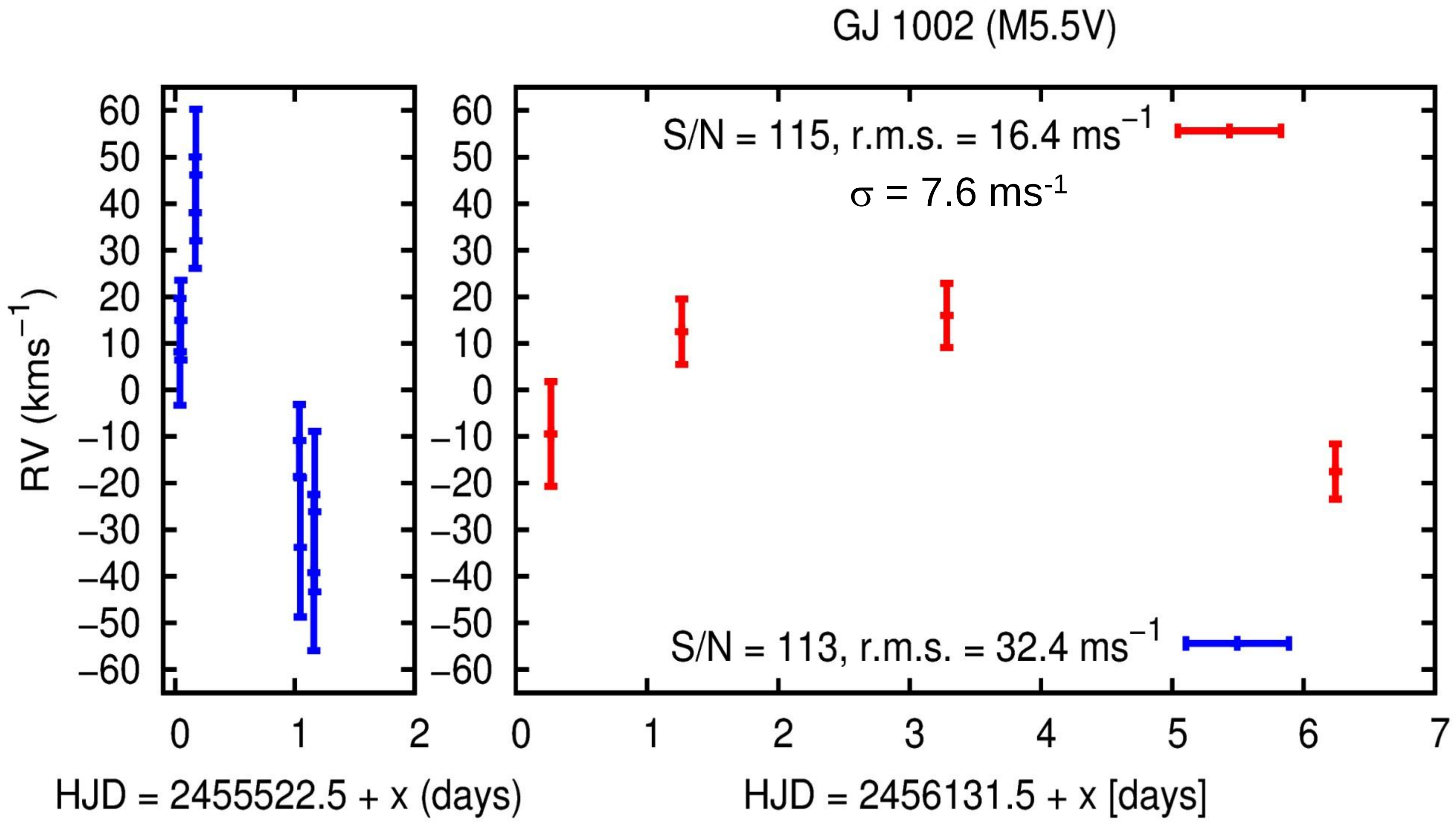
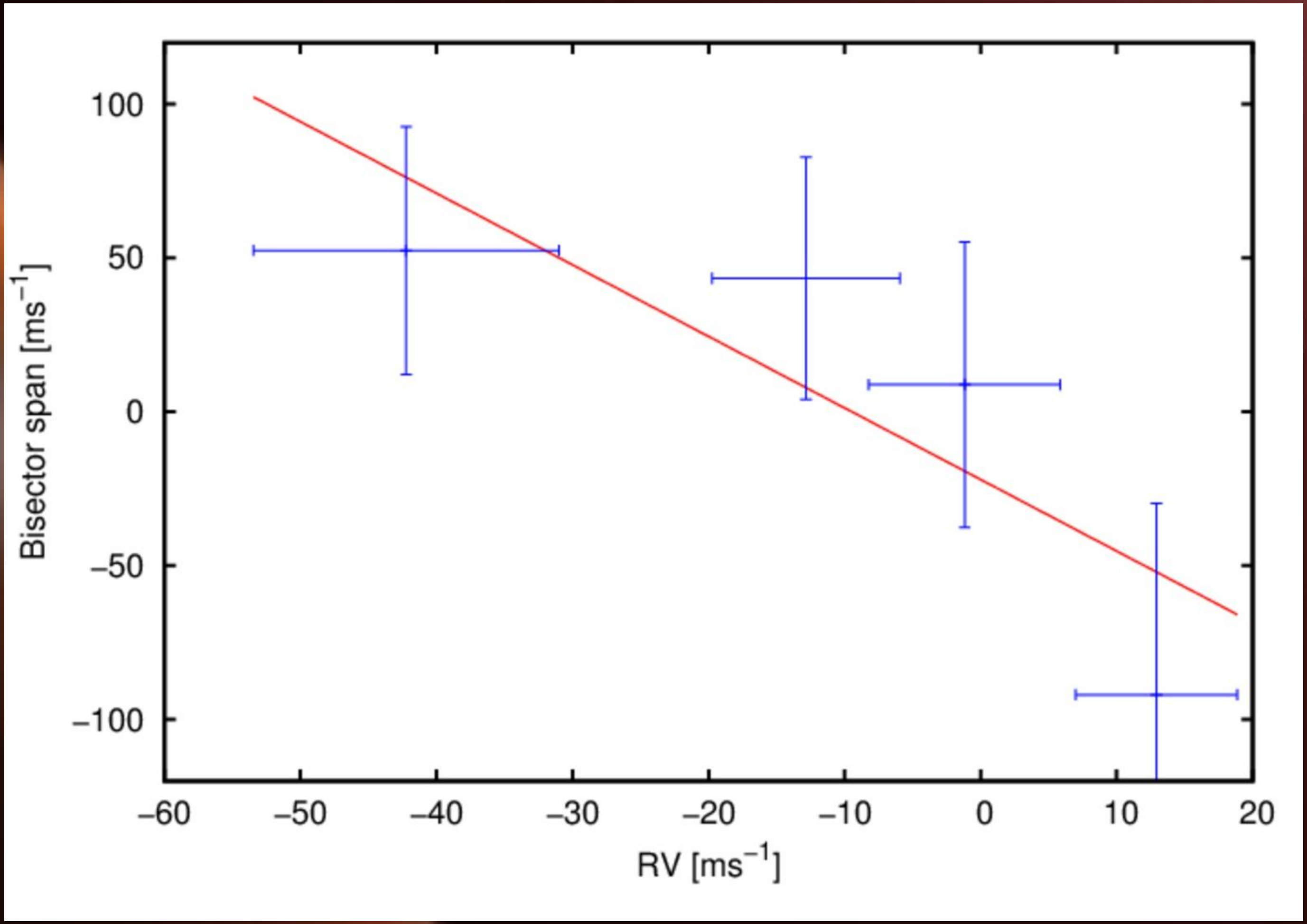




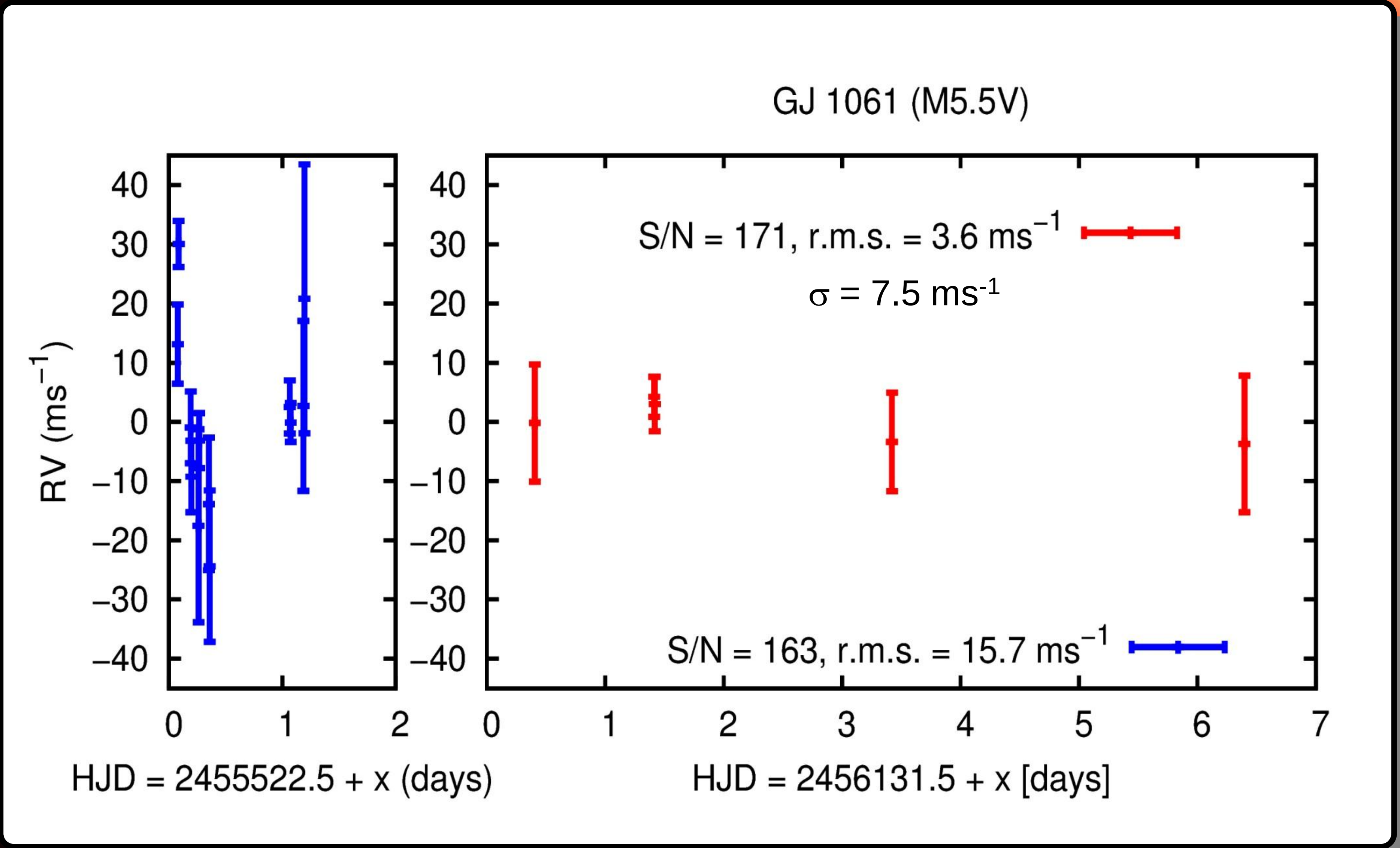
GJ 1002 (MIKE and UVES)



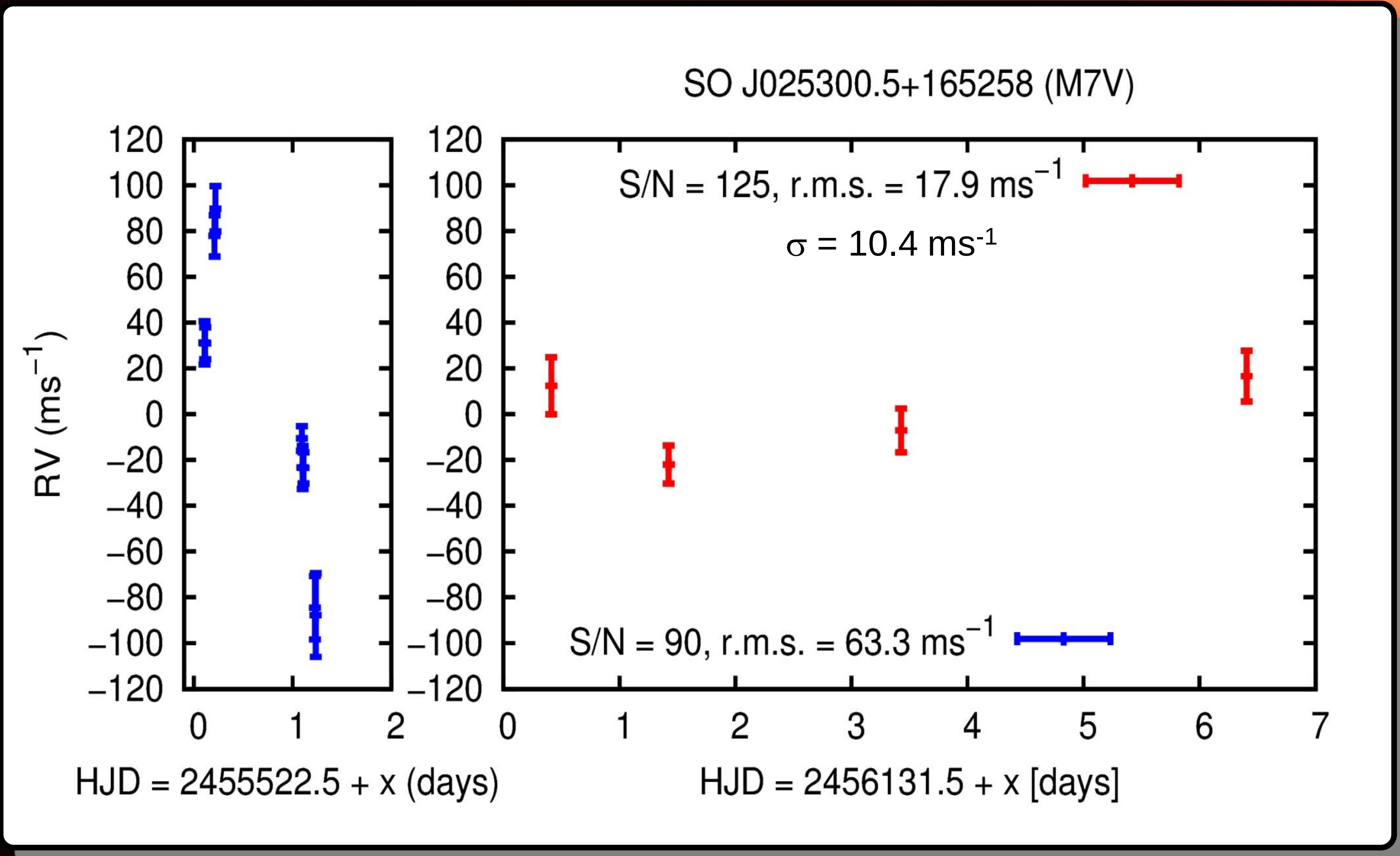
Bisector-RV relationship



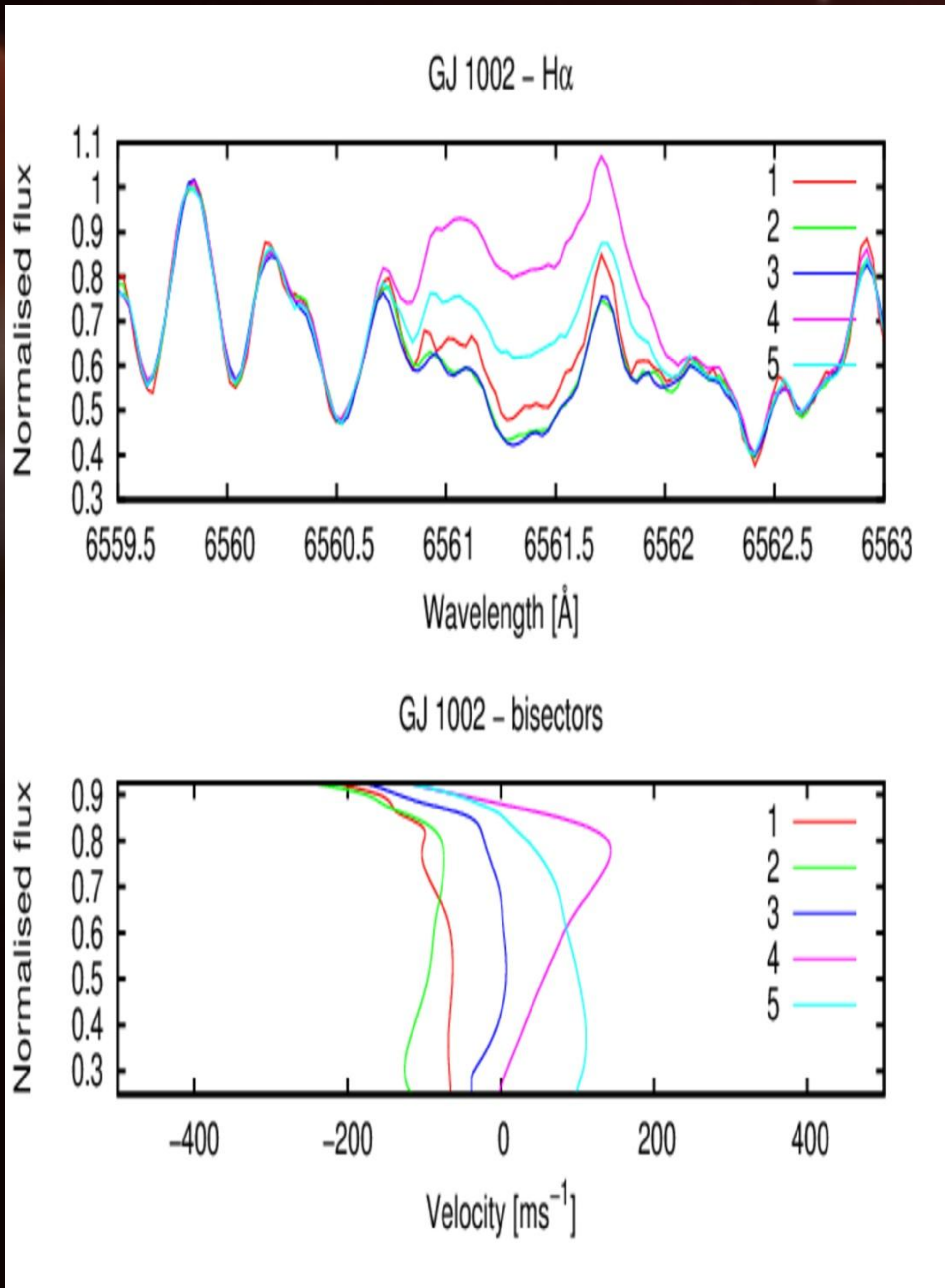
GJ 1061 (MIKE and UVES)

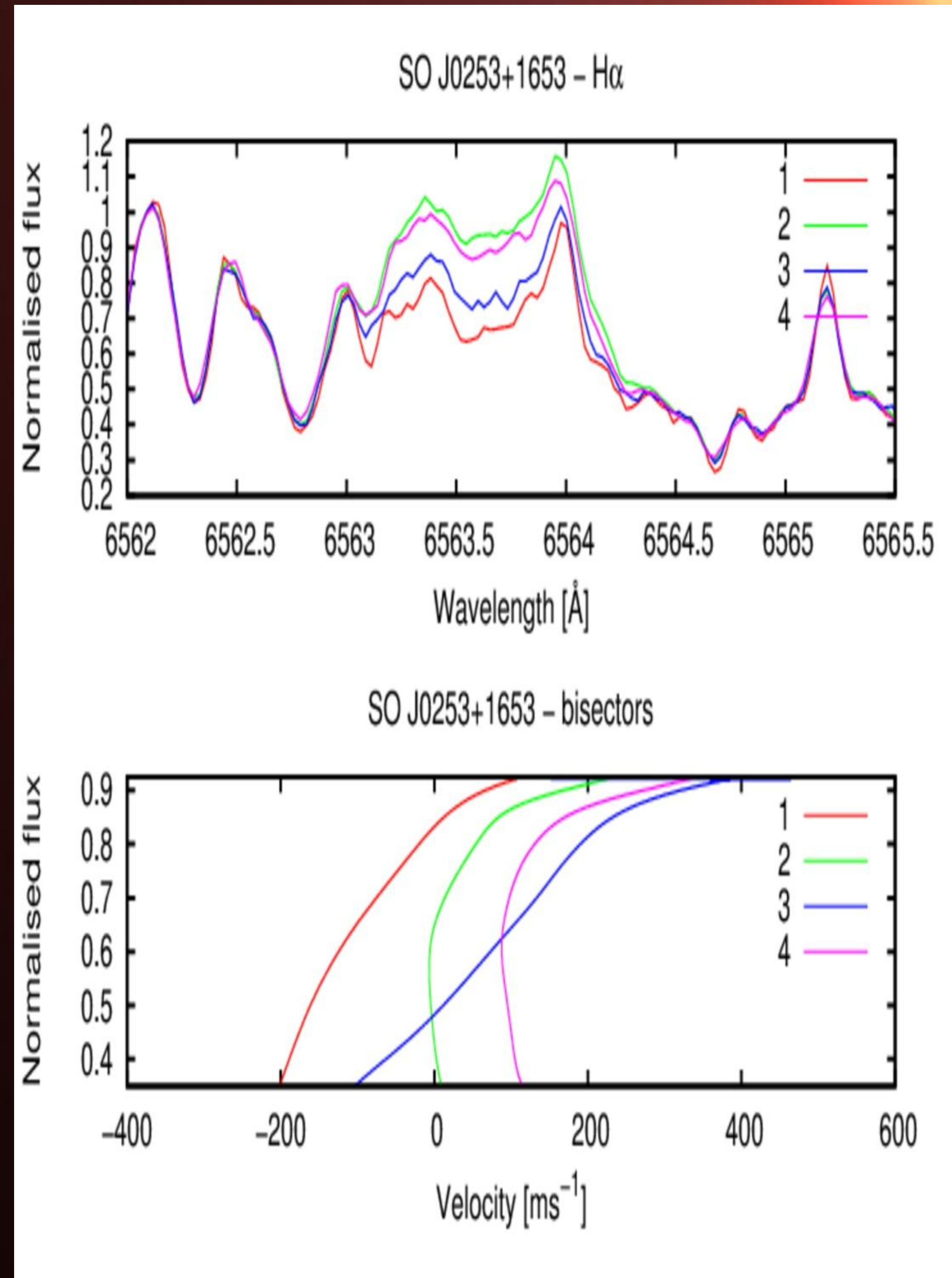


SO J0253+1653 (MIKE and UVES)

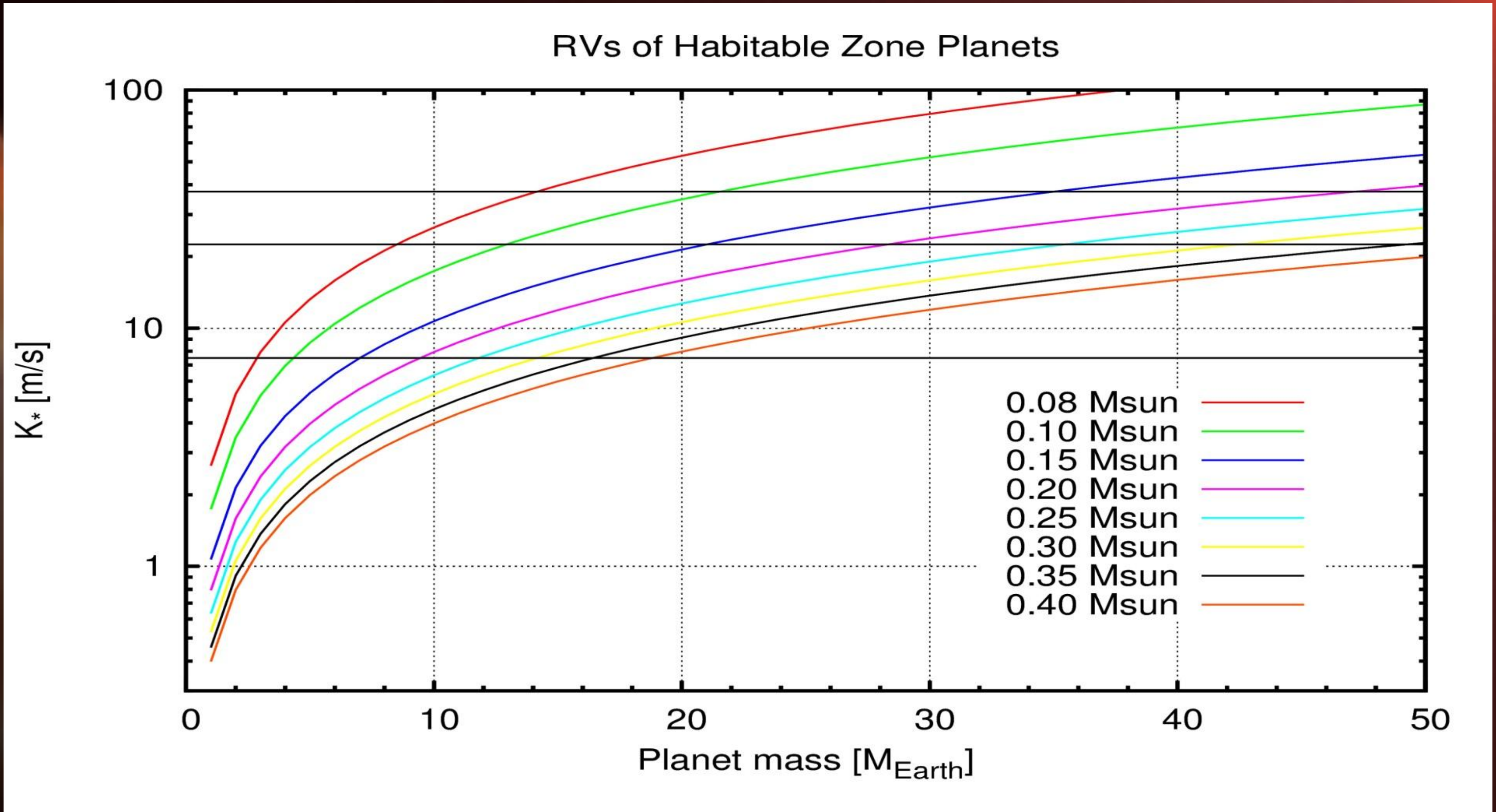


Hα / Line Bisectors





Sensitivities



For UVES, 7.5 ms^{-1} achieved - 1, 3, 5-σ RV amplitudes indicate

4,13,22 M_{Earth} at M6V

3, 8, 12 M_{Earth} at M9V

Summary

- 7 objects with MIKE/Magellan Clay enable precisions of <=10 ms^{-1} over 2 consecutive nights

  - CCF/r.m.s.-pair indicate sensitivity equivalent to the amplitude induced by 6 $M_\oplus$ HZ planets

- Two planets with significant RV trends are consistent with Neptune mass planets with a frequency that agrees with estimates for $\eta_\oplus$ ~ 30%

- Instrument stability issues and lack of correlation between line bisectors *may* largely account for r.m.s in some stars

- UVES sample of 15 M5V - M9V objects with improved r.m.s. precision by a factor of ~2 - 4.5 times for M 5.5-7V stars

  - Results for remaining 12 objects imminent