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

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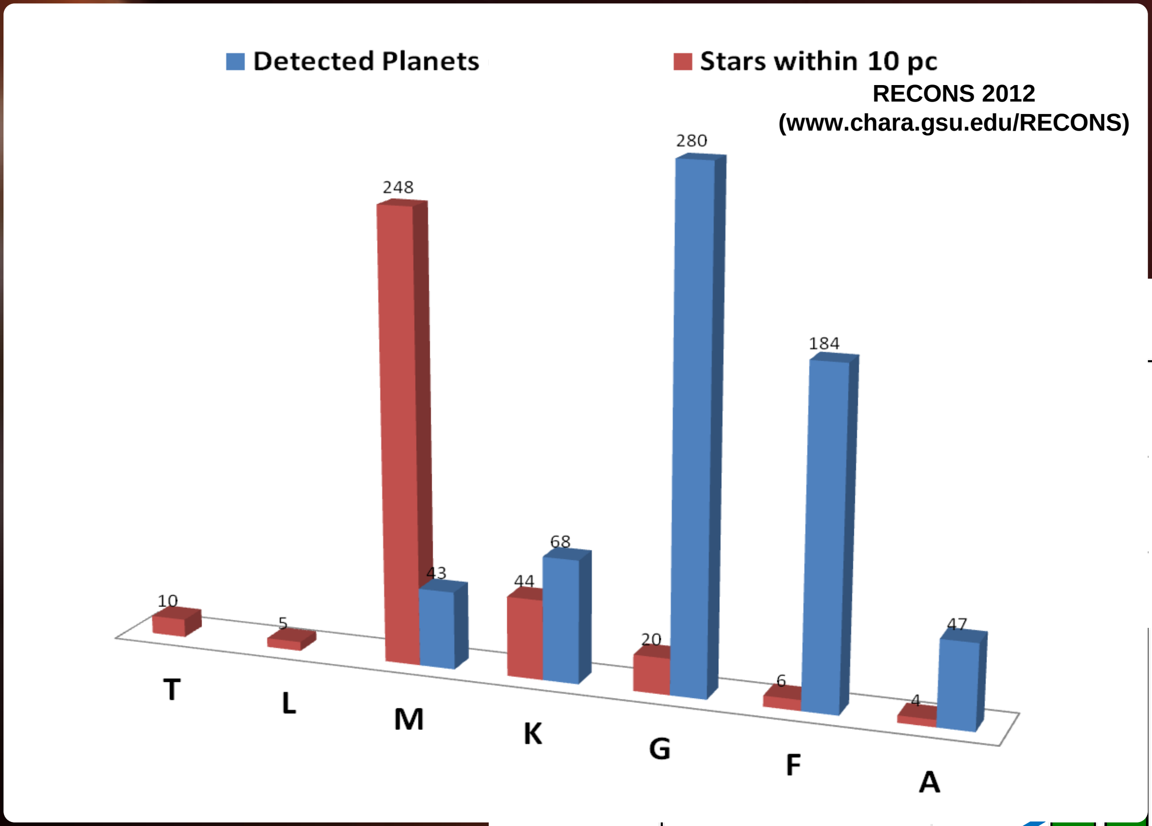
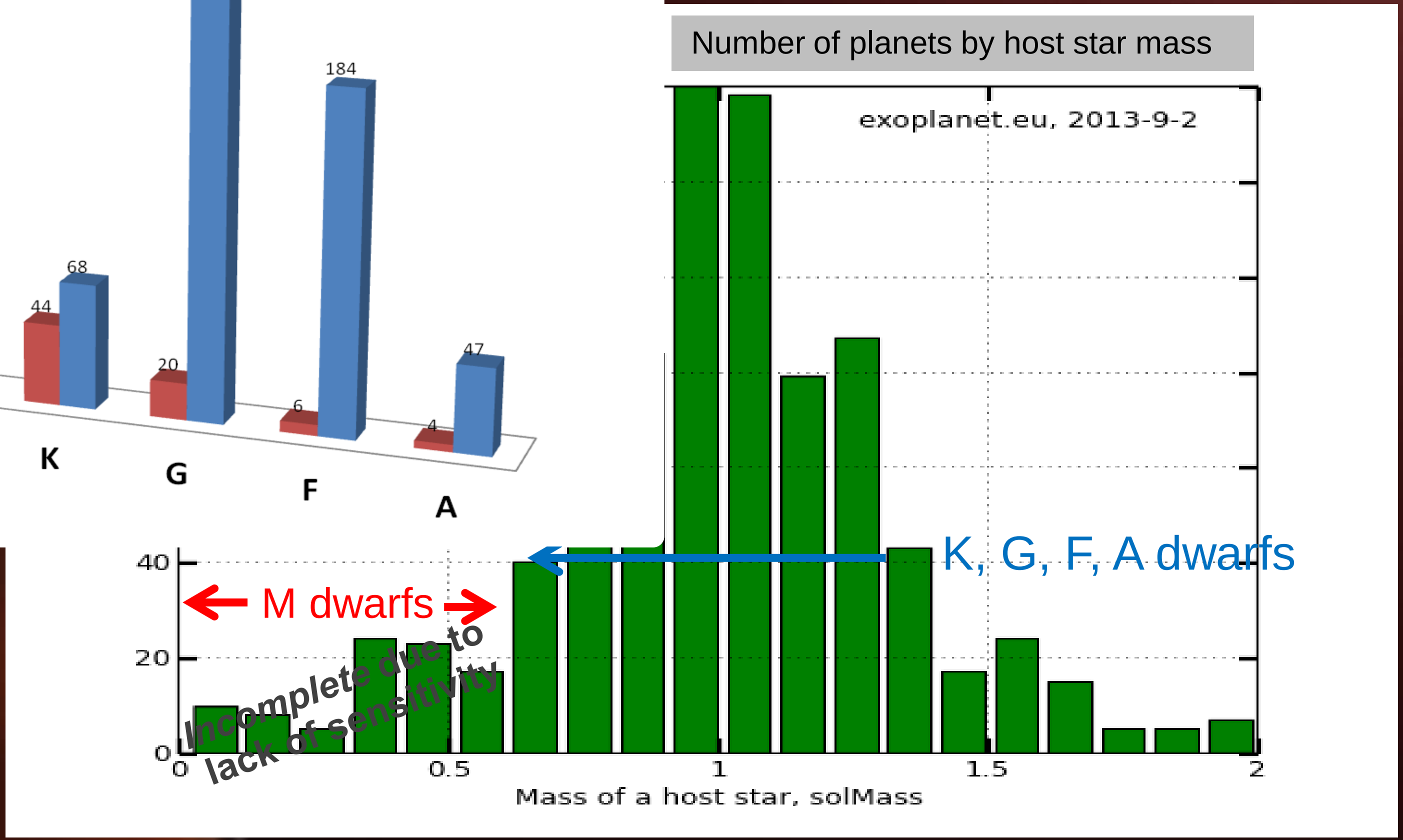
The holy grail of exoplanet hunting – Earth-mass planets

Nearest stars vs stars with detected planets



73% M dwarfs



M dwarf planet frequencies

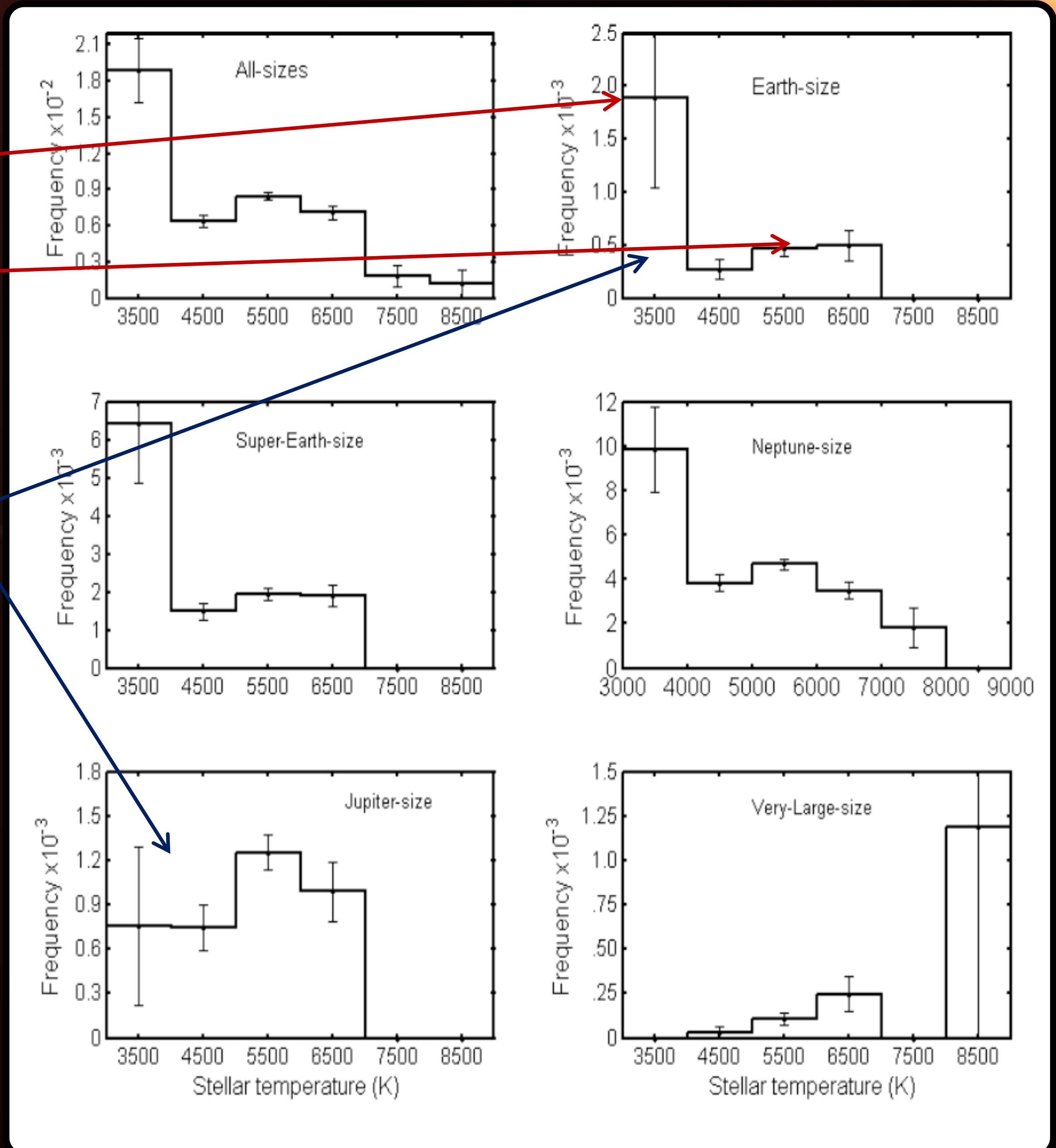
- Kepler planet candidates:

  Earth/super-Earth size planets ~3–4 x 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 close orbits < 0.1 AU.

  - Dressing & Charbonneau (2013, A&A. 767, 95) estimate occurrence rates of $0.9 \pm^{0.04}_{0.03}$ for M dwarf Kepler transit candidates with 0.5 – 4 $R_\oplus$ and P < 50 d



M dwarf planet frequencies

- HARPS early-mid M dwarf sample (Bonfils et al., 2013, 549, 109)

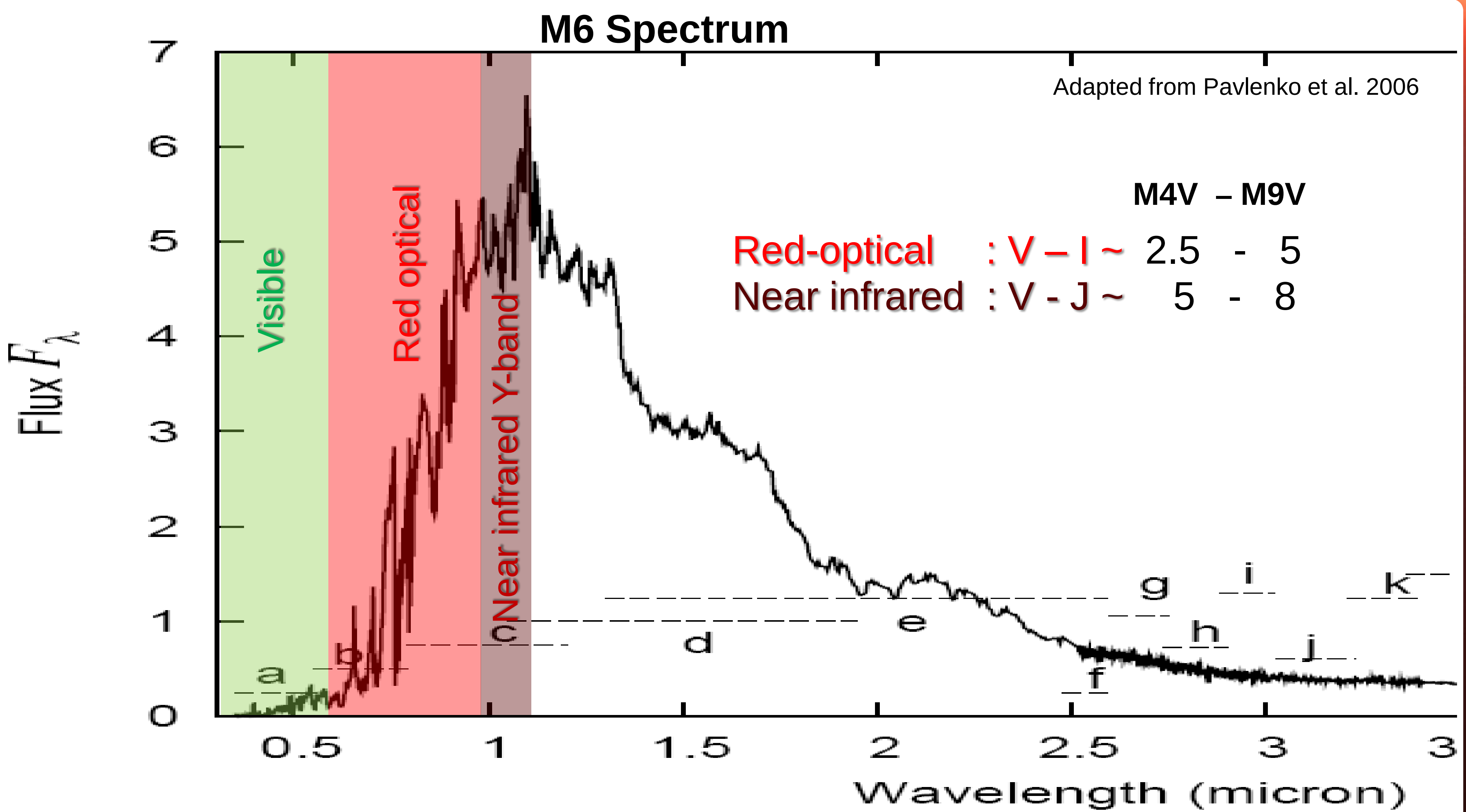
Frequency	100-1000 $M_\oplus$	1-10 $M_\oplus$
P = 1 - 10 d	≤ 0.01	$0.36 \pm ^{0.25}_{0.10}$
P = 10 - 100d	$0.02 \pm ^{0.03}_{0.01}$	$0.52 \pm ^{0.50}_{0.16}$

- **At least 25% of *early* M dwarfs should harbour Earth-mass (1-10 $M_\oplus$) planets in short period orbits!**
- **....but may be as high as 100% !!**

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

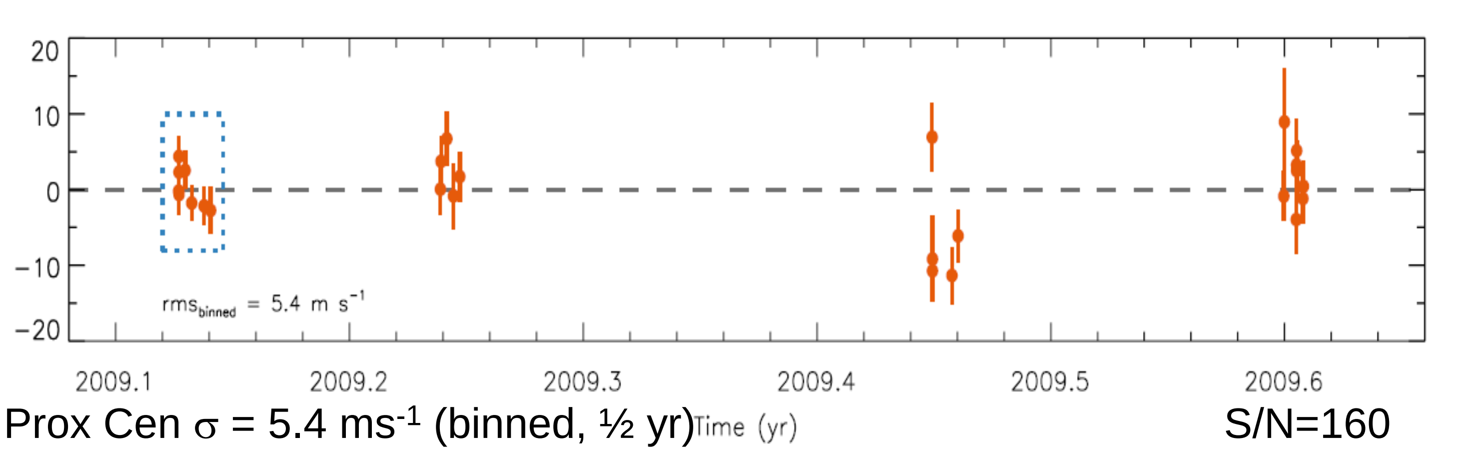
Next talk (Mikko Tuomi)

So many M dwarfs - why so few M dwarf planets….?



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

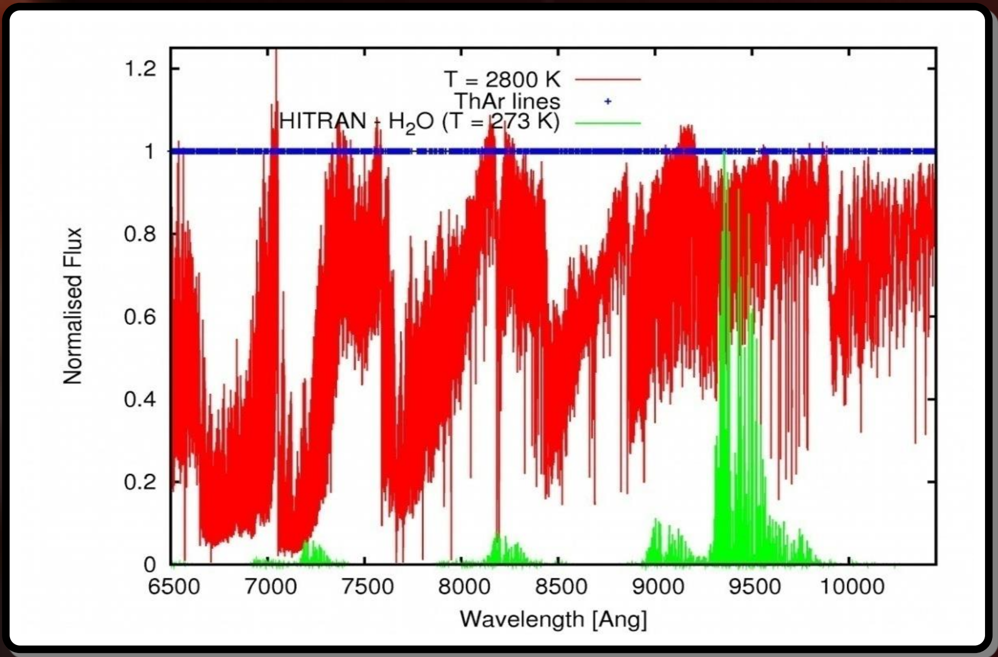
- Keck/NIRSPEC – 1.25 μm R~20,000 (4 orders 150-200 Å)

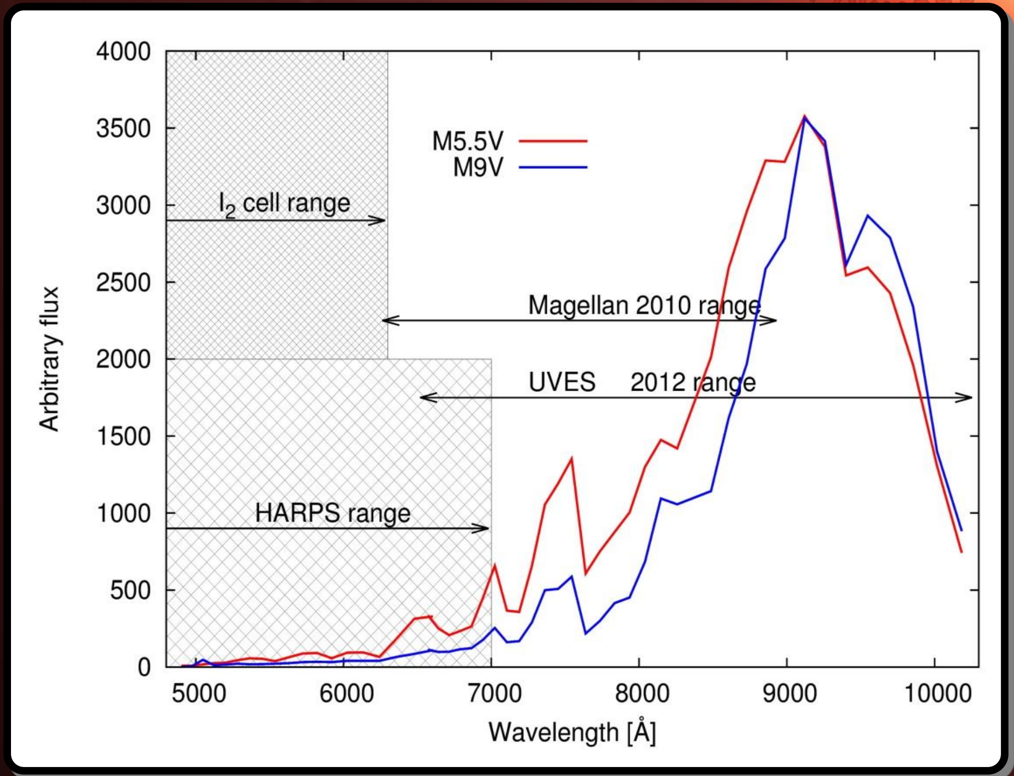
  Tellurics as reference → Precision = 180 – 300 ms^{-1}

  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)

RV sensitivity in the red-optical





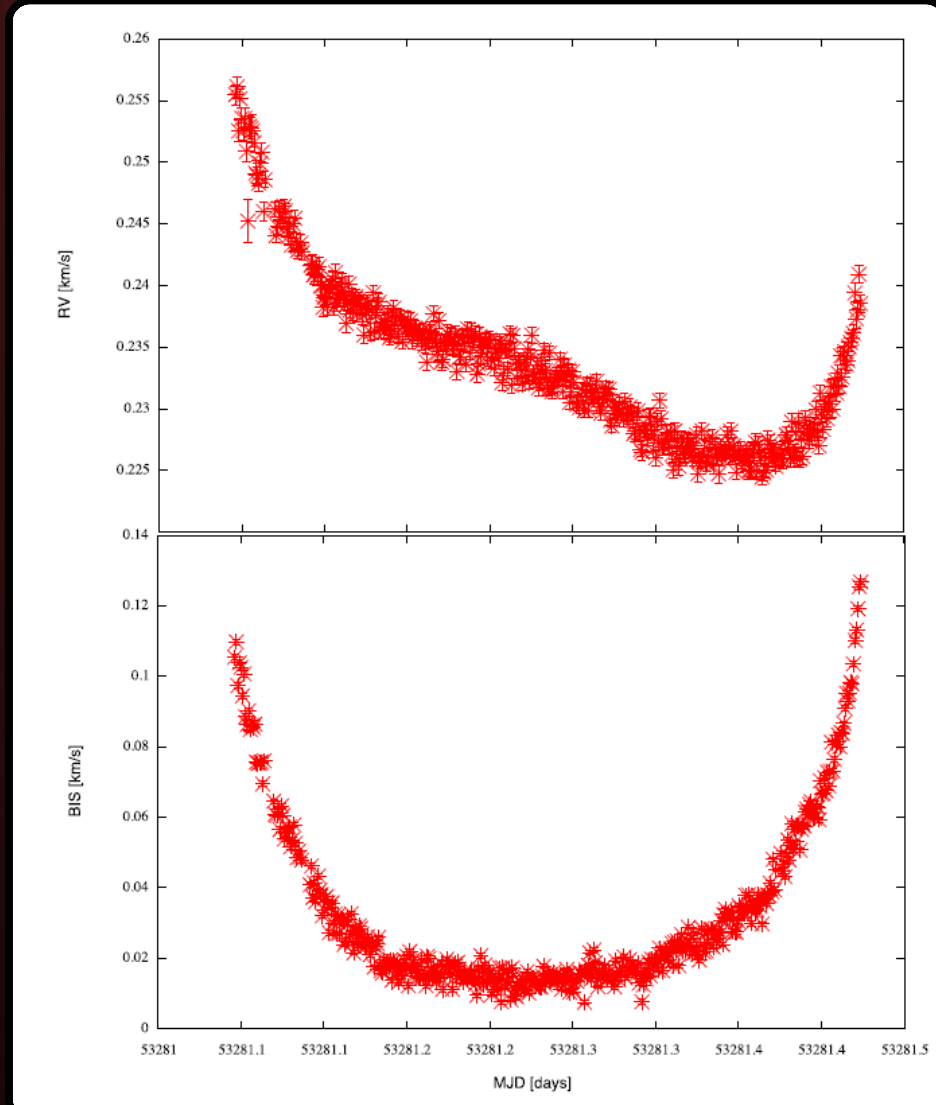
- RO spectral information 0.65 – 1.05 µm region (M6 spectrum – red)
- Atmospheric O_2 and H_2O lines (green)

- SED (incl. MIKE & CCD response) for typical M5.5V & M9V dwarfs.
- Red optical and HARPS region fluxes: $F_{0.7\text{-}0.9}/F_{0.5\text{-}0.7}$ = 11.5 (M5.5V) and 19 (M9V) (based on MIKE instr & CCD)

Stability with tellurics as a reference fiducial

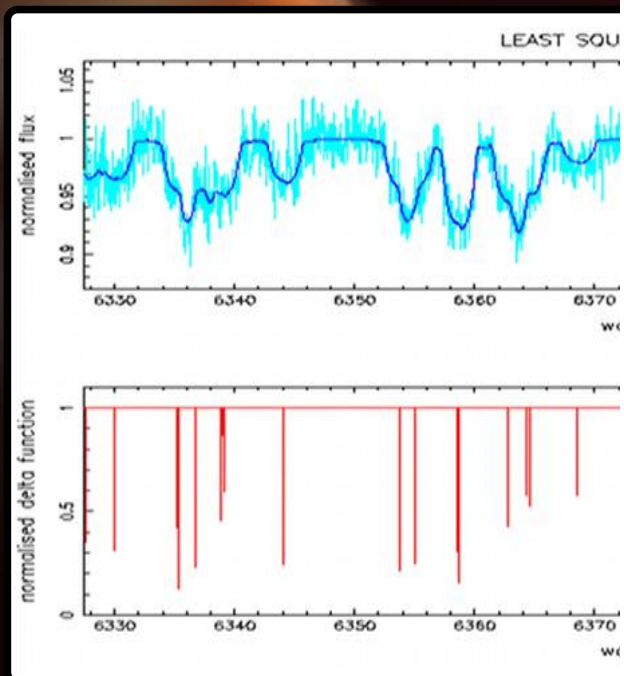
- Tellurics stable to 10 ms^{-1} over 6 years in HARPS data and to ~2-6 ms^{-1} over week timescales Figueira et al. (2010)

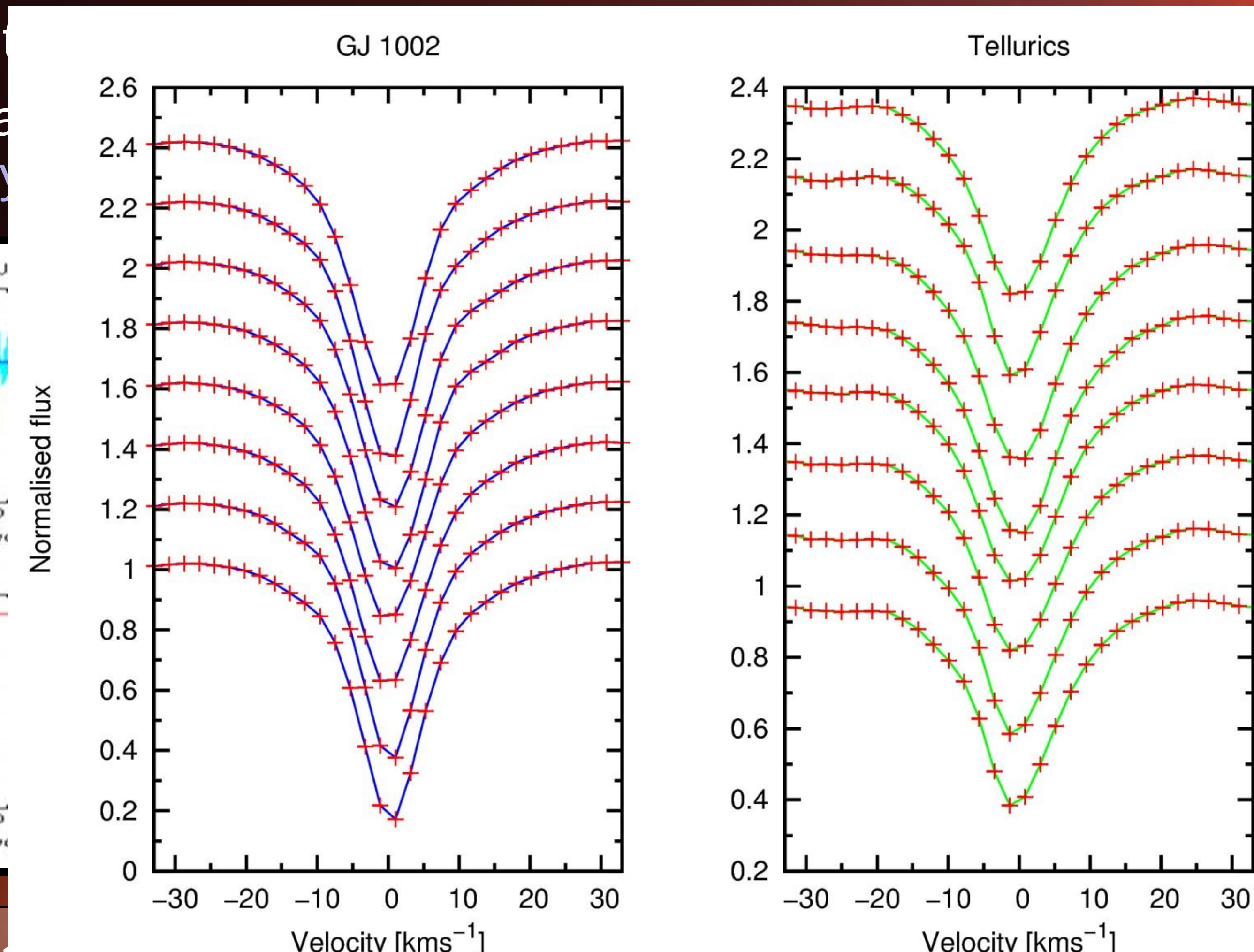
Target	data-set [d]	$\sigma_{(X<1.5)}$	$\sigma_{(X<1.2)}$	$\sigma_{(X<1.1)}$ [m/s]
Tau Ceti	1	4.53	3.38	2.41
	2	5.53	4.07	3.27
	3	5.81	4.55	3.70
	Full	9.77	9.16	8.43
μ Ara	1	5.00	3.36	2.31
	2	6.18	4.14	2.61
	3	6.38	4.27	2.66
	4	5.67	3.86	2.39
	5	5.67	4.01	2.57
	6	6.18	4.71	3.24
	7	6.46	4.93	3.40
	8	6.94	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* t
- A weighted least squa
  the number of lines (ty





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

Magellan/MIKE M5.5V-M8V dwarfs

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

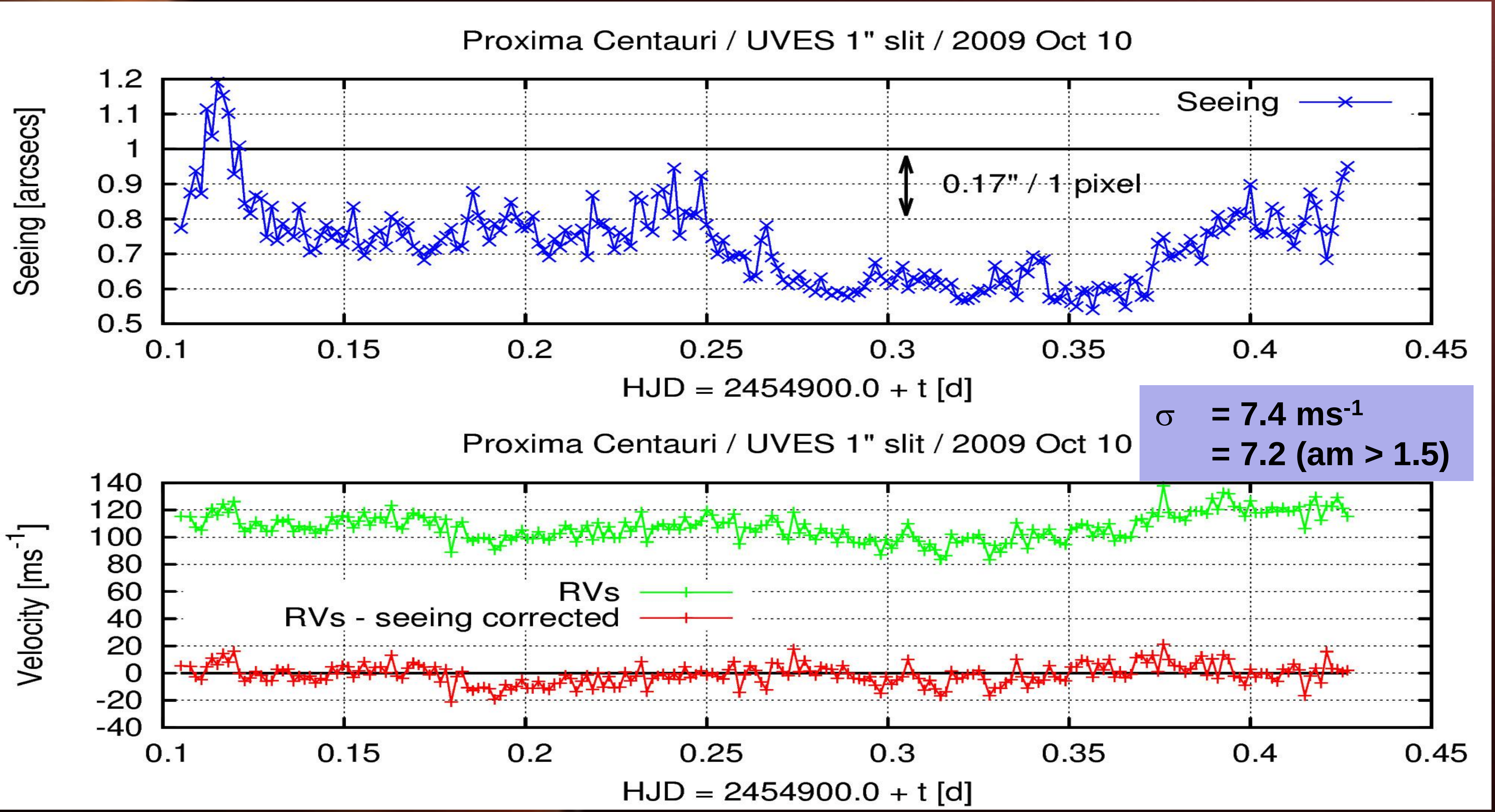
Object	S/N	Error (ms^{-1})	Mean ΔOP (ms^{-1})	rms scatter (ms^{-1})	Discrepancy (ms^{-1})	Photon-limited precision (ms^{-1})
GJ 1002	113	12.8	12.7	32.4	29.7	3.3
GJ 1061	163	9.37	11.8	15.7	12.6	2.5
GJ 1286	84	8.63	8.88	22.1	20.3	4.4
GJ 3128	84	8.80	20.0(12.6)	87.7	87.2	4.4
SO J025300+165258	90	9.91	7.0	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 r.m.s 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 noise sources yet unaccounted for?

Proxima Centauri – a training dataset

- Archival UVES data from 2009 March 10, 12 & 14 taken as a simultaneous wavelength monitoring programme (Fuhermeister, 2010)
- Blue/Red Arm (0.4 – 1.1 μm) Resolution 40,000 – 1´´ slit



σ = 7.4 ms^{-1}
= 7.2 (am > 1.5)

Proxima Centauri

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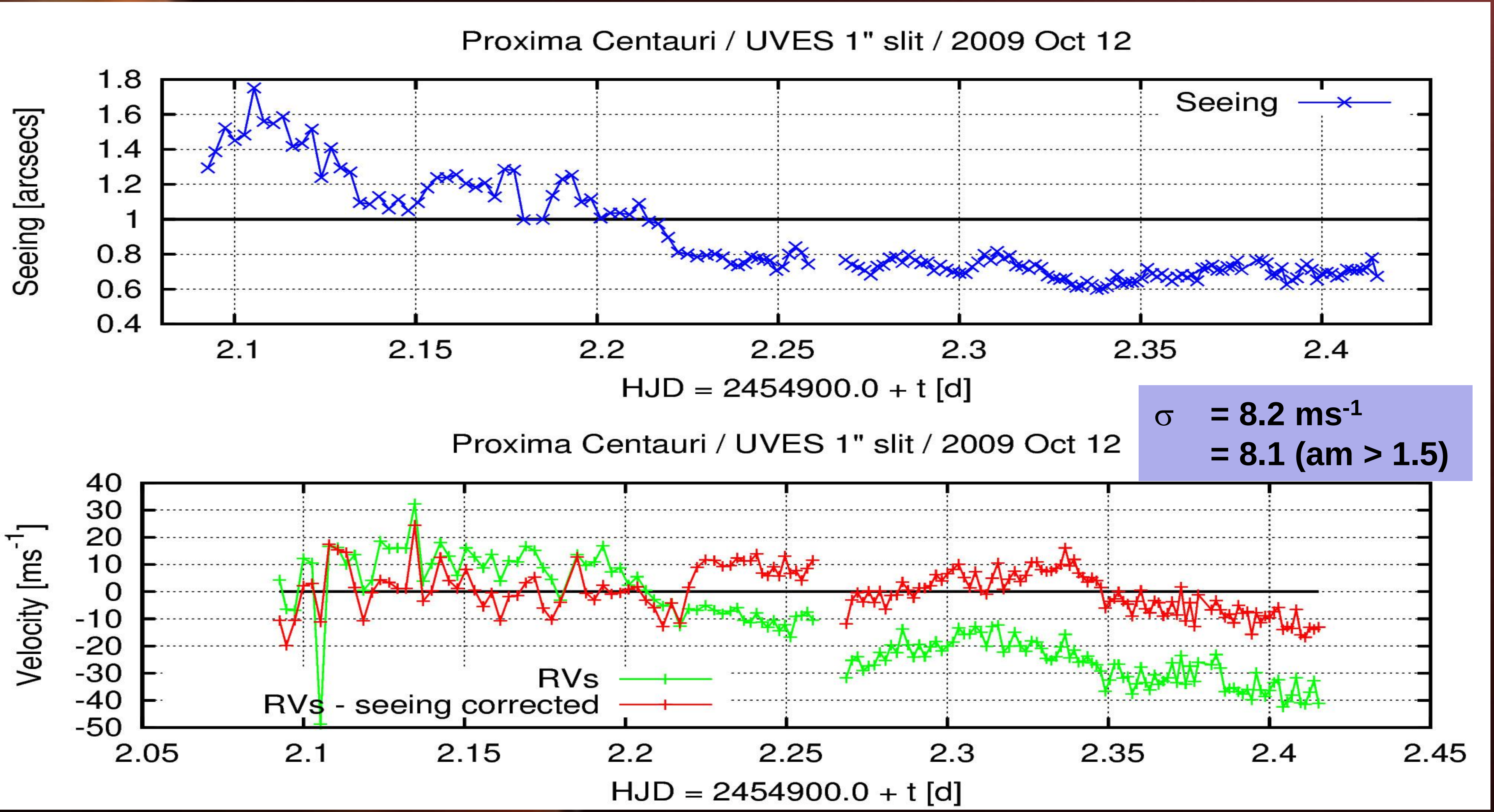
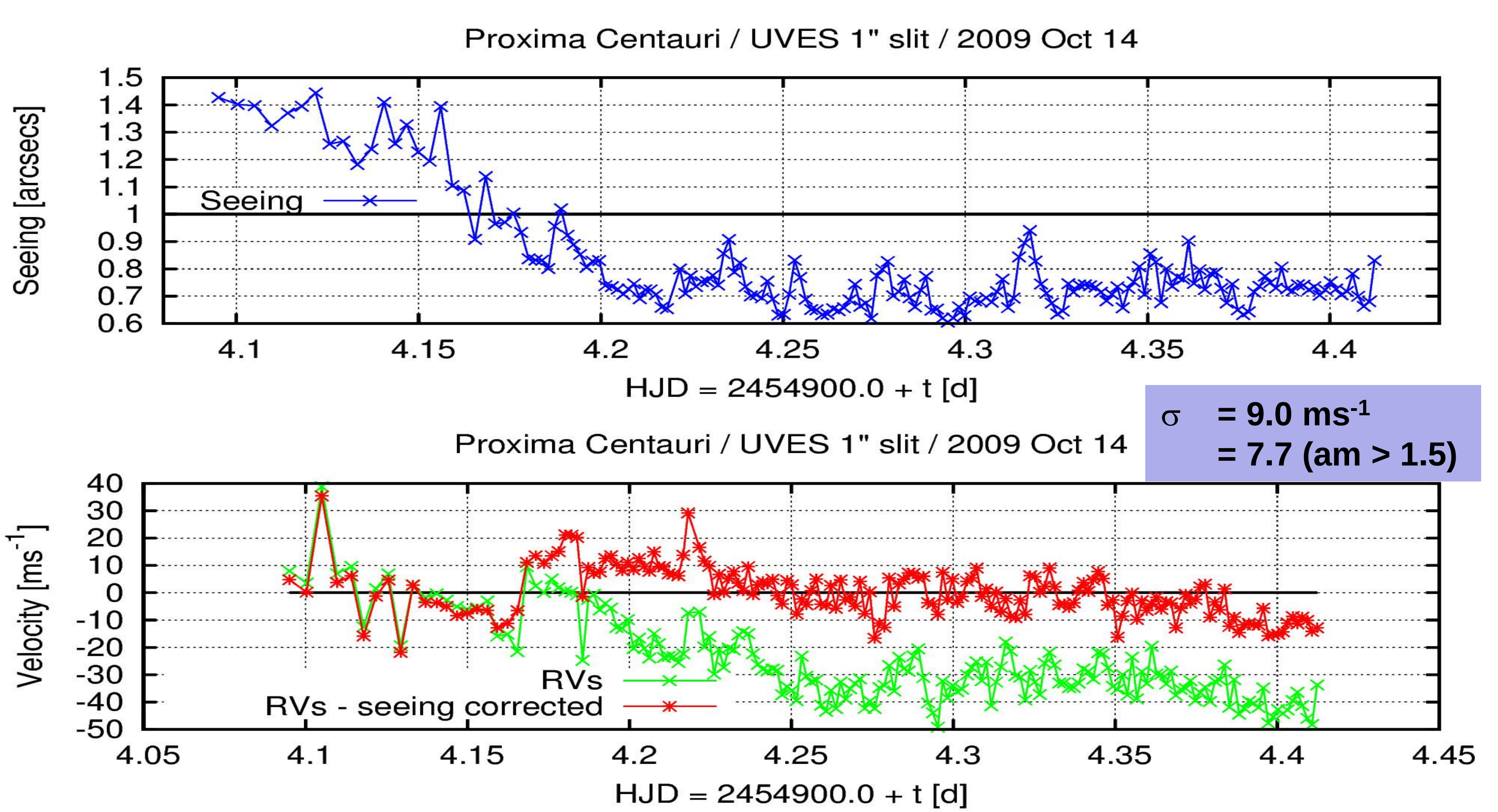


σ = 8.2 ms^{-1}
= 8.1 (am > 1.5)

Proxima Centauri

- Archival UVES data from 2009 March 10, 12 & 14 taken as a simultaneous wavelength monitoring programme (Fuhermeister, 2010)
- Blue/Red Arm (0.4 – 1.1 μm) Resolution 40,000 – 1´´ slit



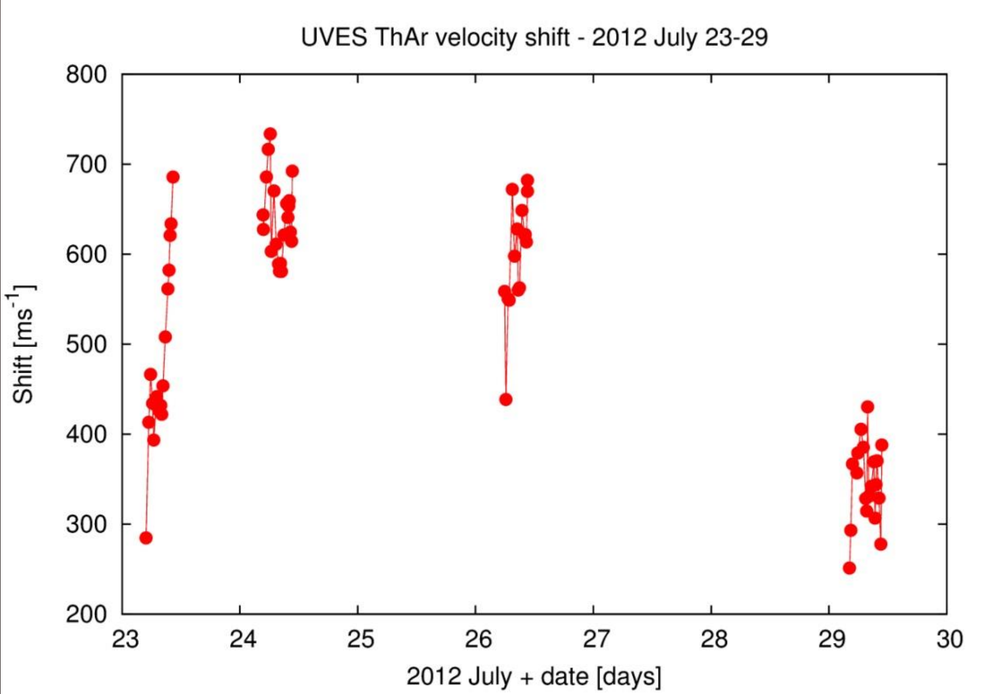
σ = 9.0 ms^{-1}
= 7.7 (am > 1.5)

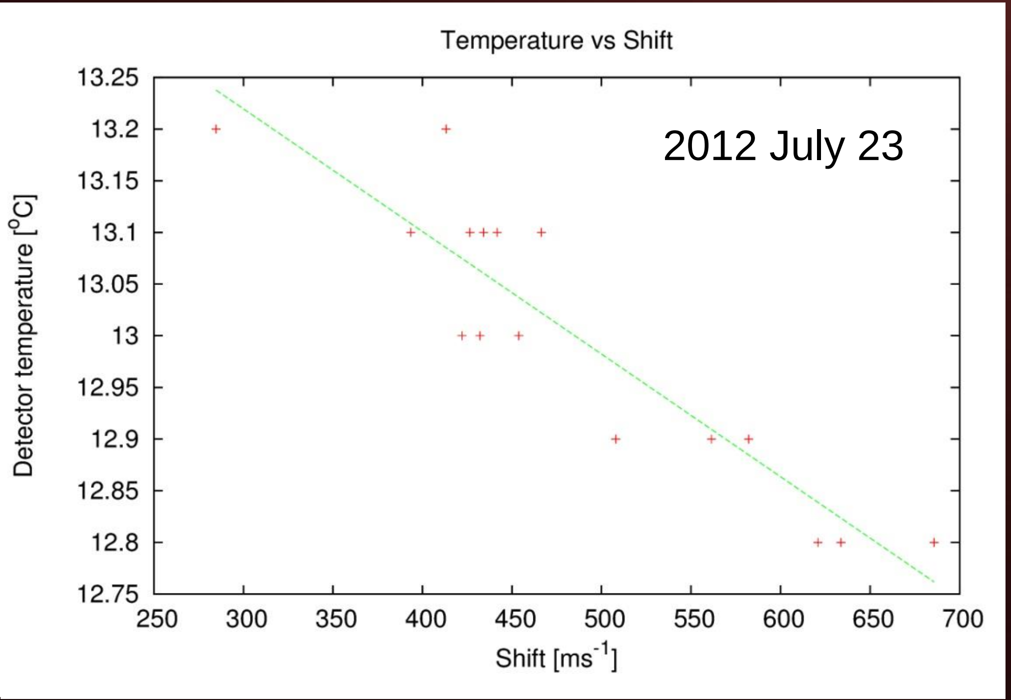
Continuing ROPS with UVES

Four half nights on UVES/VLT – 2013 July 22-28

Advantages of UVES:

- Better order separation
- Wavelength coverage 0.64 - 1.03 μm (MIKE: 0.62 – 0.89 μm)
- Improved resolution R~50,000 (MIKE: 35,000)
- ~1200 m/s/pixel (MIKE: 2150 m/s/pixel)
- Parallactic angle maintained during observations

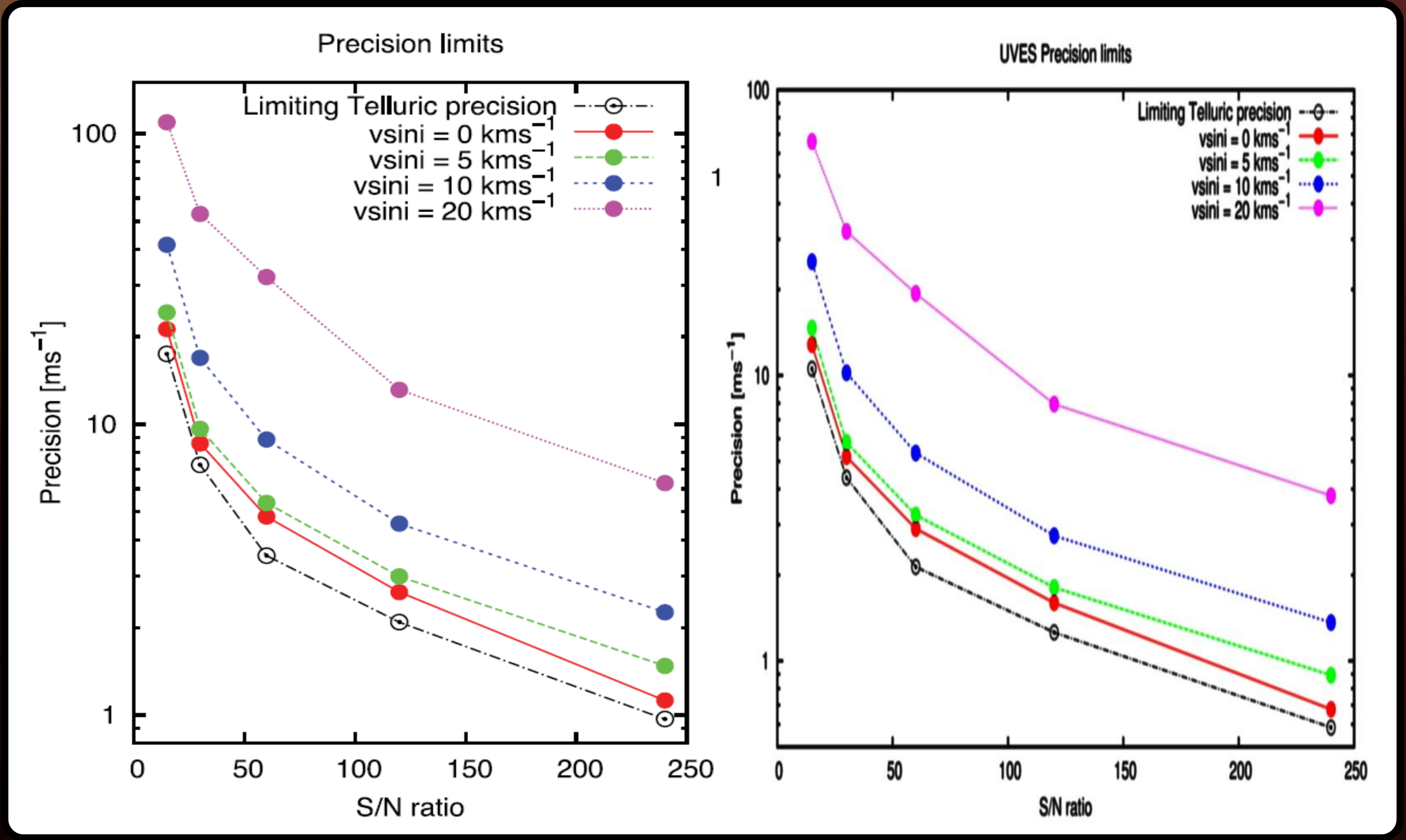




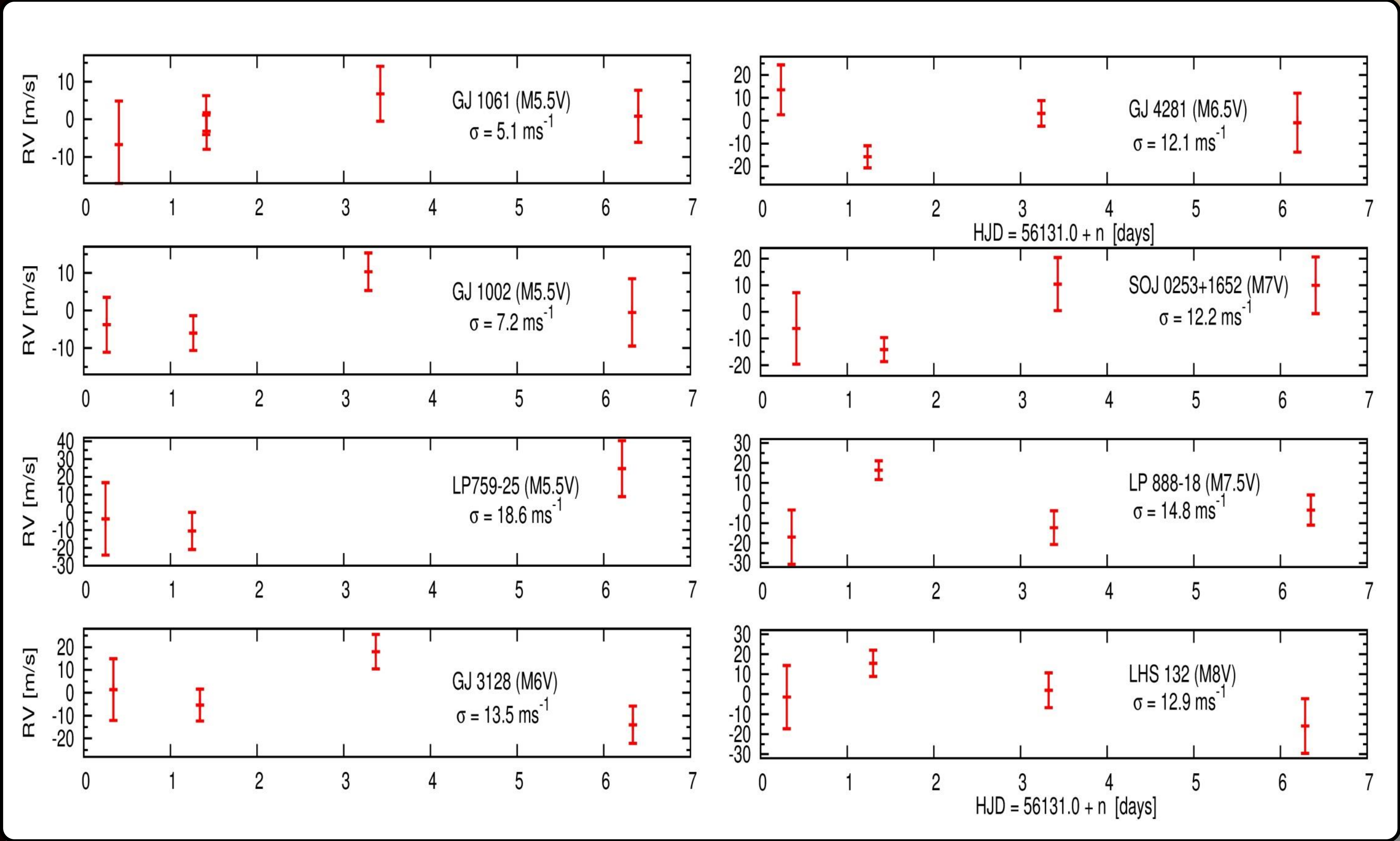
Poisson limited precision using deconvolution method?

- 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. S/N = 120 → ~3 m/s (MIKE/Magellan), ~2 m/s (UVES/VLT)

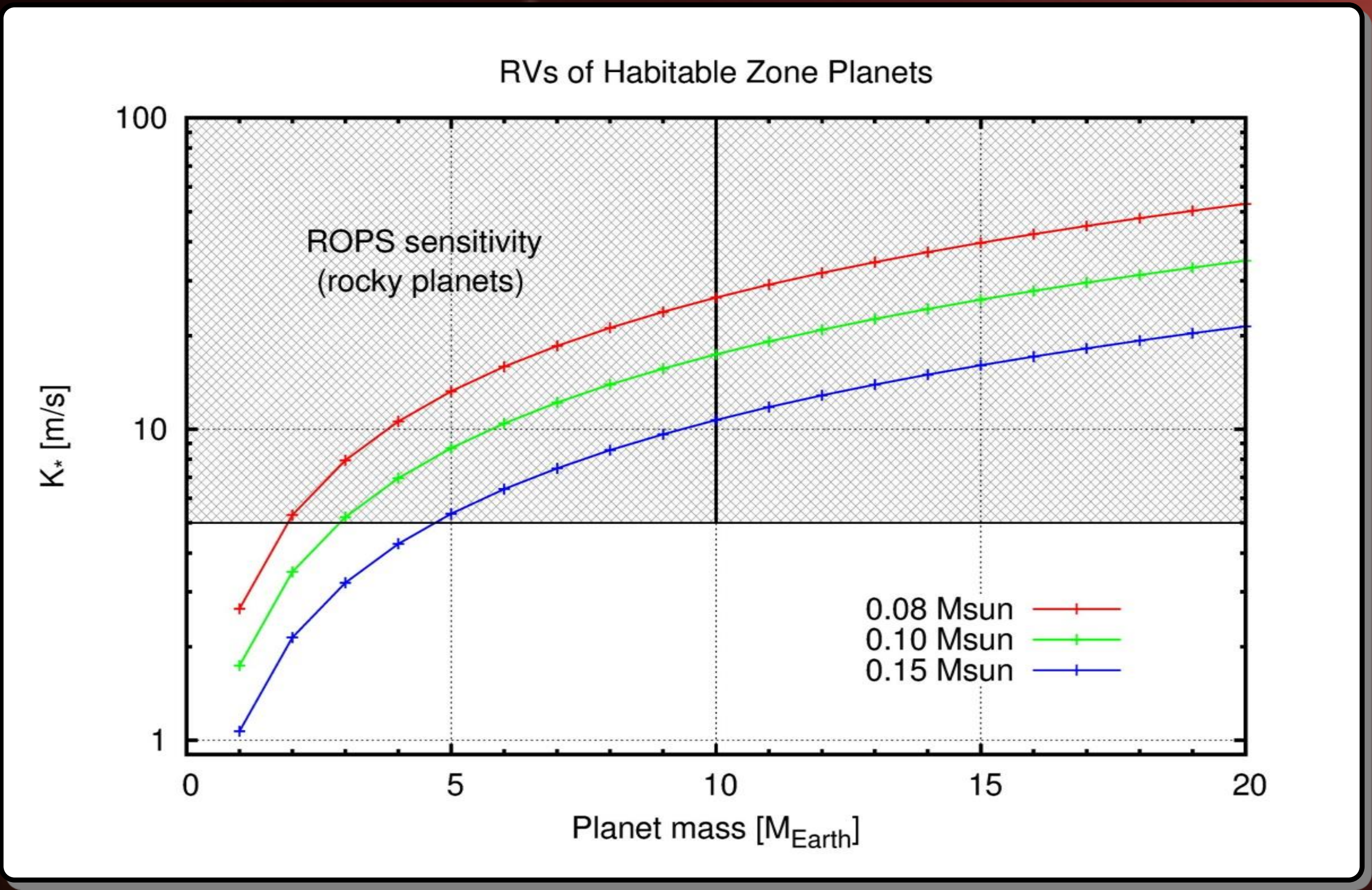


ROPS RVs for eight M5.5-M8 dwarfs



- 4 epochs spread over 6 nights: 5.1 – 18.6 ms

Sensitivities

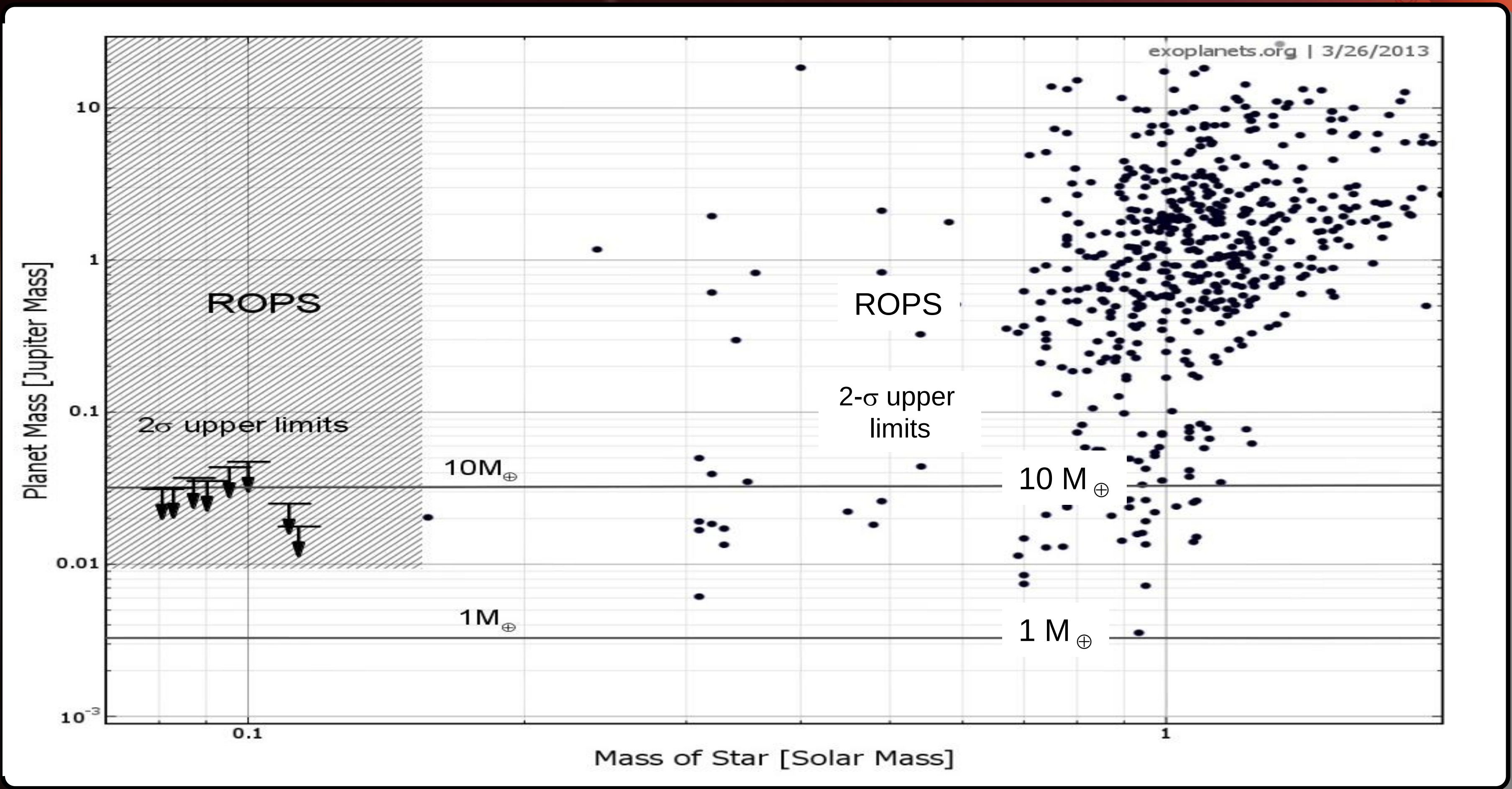


- For UVES - 5 ms^{-1} - 1, 2, 3-σ K_* sensitivities

3,6,9 $M_\oplus$ at M6V

2,4,6 $M_\oplus$ at M9V

ROPS parameter space



- Lowest mass M dwarf RVS
- HZ 2-σ upper limits of 5.7 – 14.5 $M_{\oplus}$
- Rocky planet sensitivities *should* be achieved for M6V – M9V targets

Summary

- Initial 2 night study of 7 mid-late M dwarfs with MIKE: 10 ms^{-1} precision on brightest / most stable targets

- UVES survey of 14 mid-late M dwarfs - 4 nights with 6 night baseline: RV precisions of ~5 - 19 ms^{-1} achieved on 8 targets (6 further targets yet to be fully analysed)

SP Type	r.m.s sensitivity (HZ)
M5.5V - M6.5V	2.9 $M_\oplus$ – 7.8 $M_\oplus$ (11 $M_\oplus$)
M7V – M9V	4.6 $M_\oplus$ – 5.6 $M_\oplus$

- Exclude BD companions ($M \geq 13\ M_J$) in 6/12 day orbits (0.03/0.05 AU, $K_* \geq$ 6.7/5.2 <u>kms^{-1}</u>)

  (BD desert: $0.0 \pm^{0.25}_{0.10}$ % of M stars with L companions @ 5-70 AU Dieterich et al, 2012)

- Four half nights pending (MIKE) in Oct / Nov 2013 – extend observations to 8 – 10 epochs