Detecting reflected light from exoplanets with high-resolution spectroscopy

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Outline

Introduction

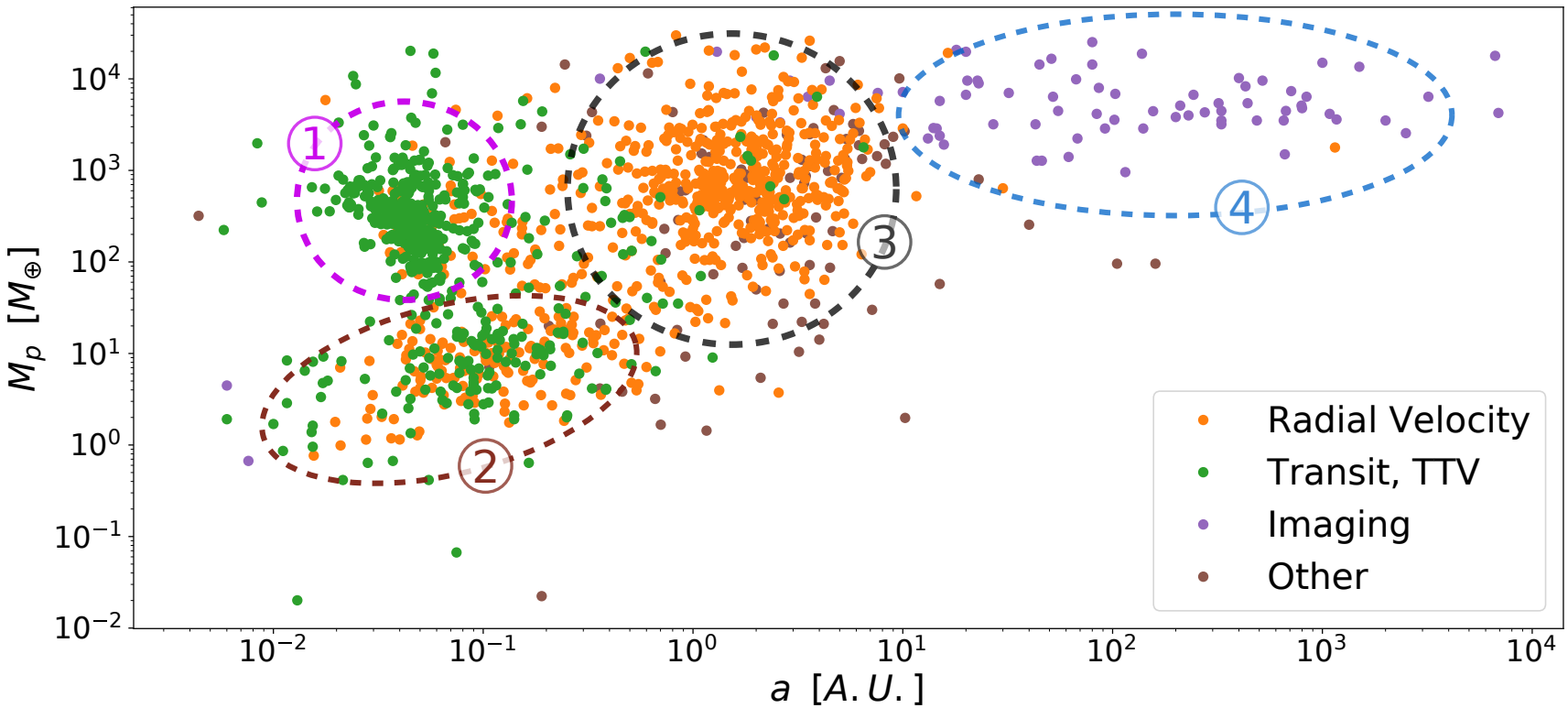
Direct detection of reflected light from exoplanets

Reflected light from 51 Peg b

Prospects for the future: ESPRESSO and ESO's ELT

Planet Detection

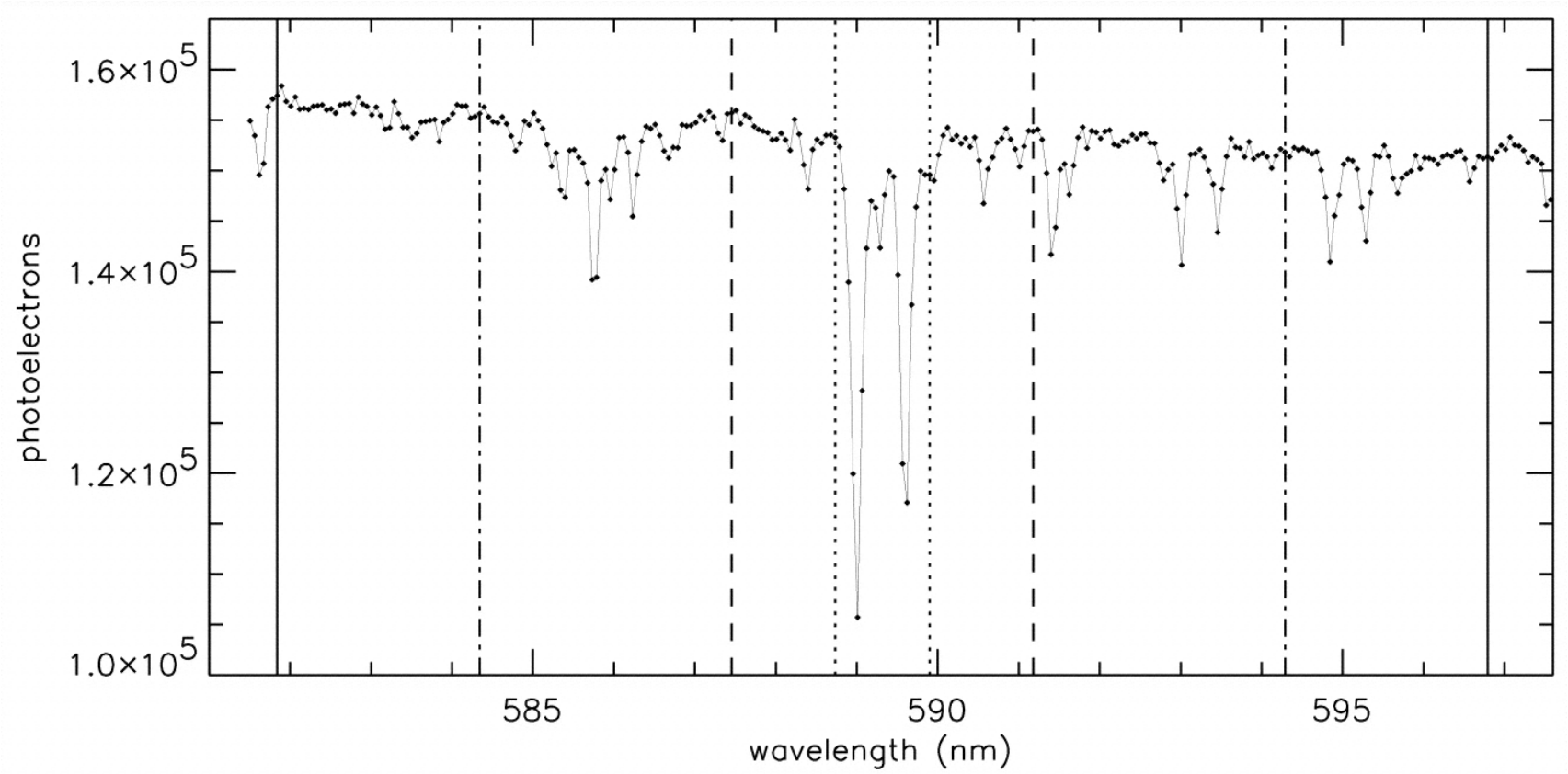
4048 planets / 3022 planetary systems / 659 multiple planet systems
(*http://exoplanet.eu/ - June 2018*)



(1) - hot Jupiters; (2) - hot/warm Neptunes and super-Earths;

(3) - warm gas giants; (4) - cold gas giants.

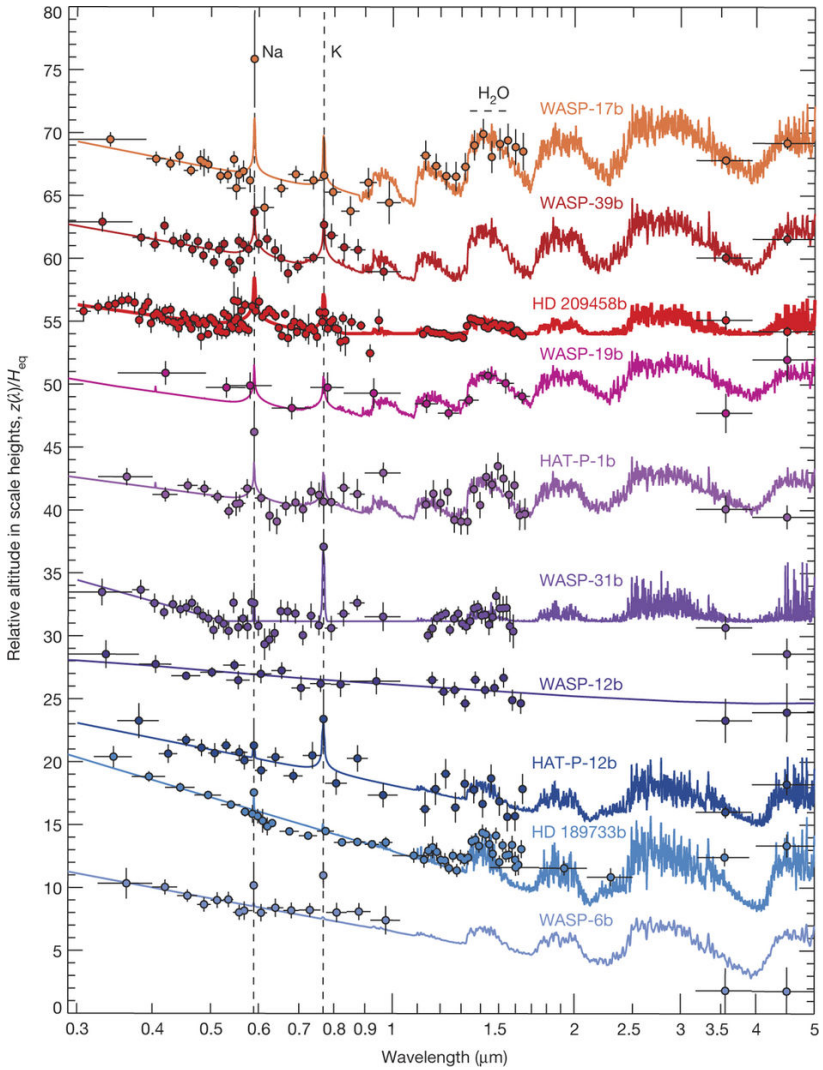
Planet atmospheres



First detection of an exoplanet atmosphere

(from Charbonneau et al. 2002)

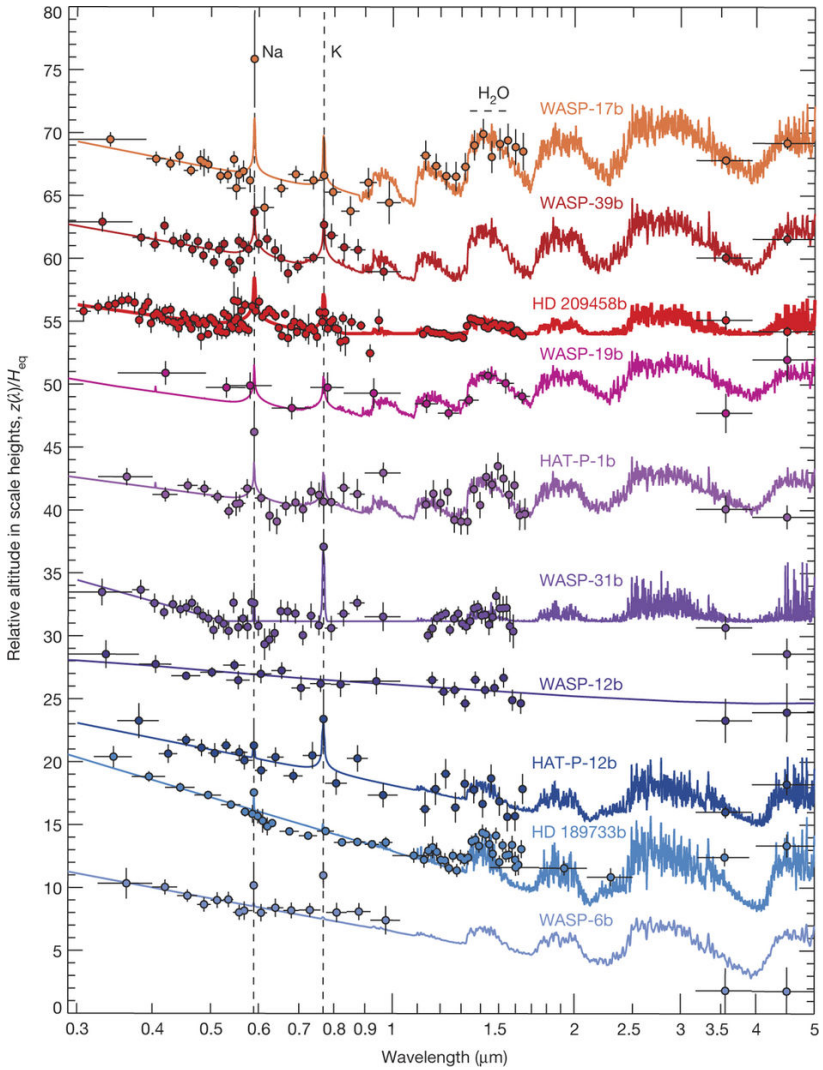
Planet atmospheres



Transmission spectroscopy

(from Sing et al. 2016)

Planet atmospheres



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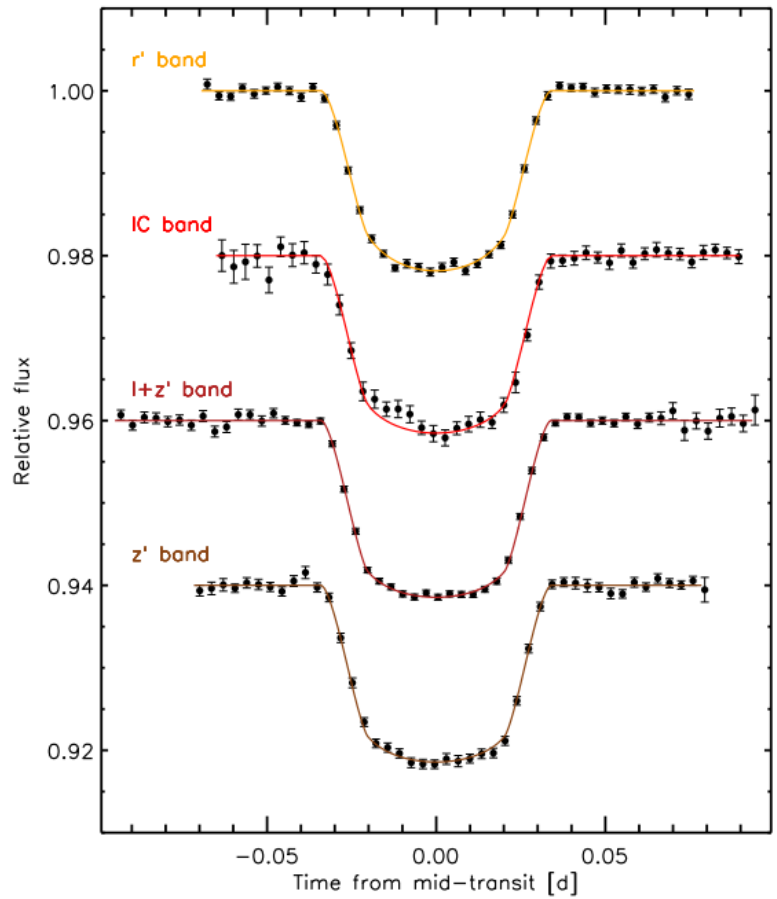
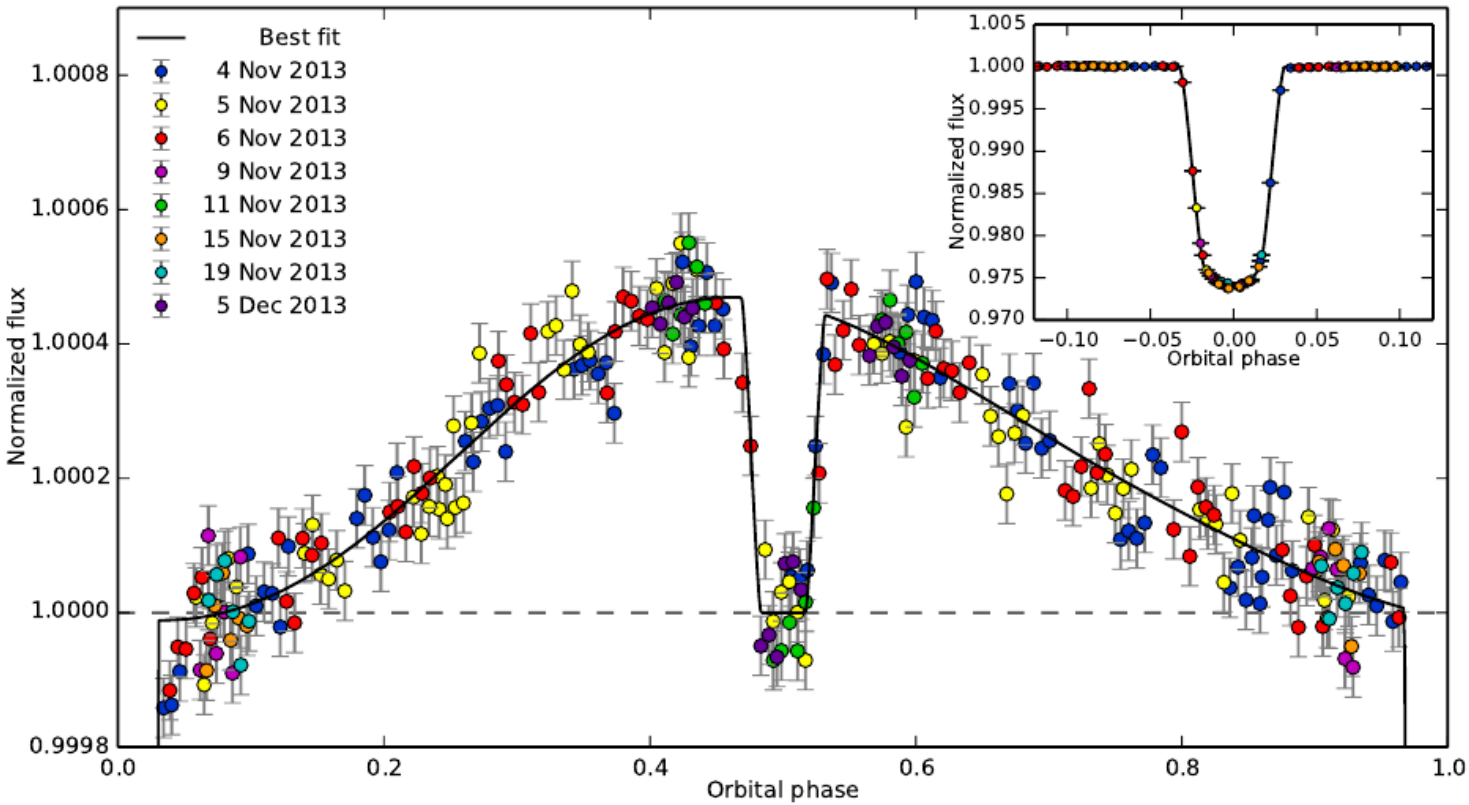


Occultation spectroscopy

(from Lendl et al. 2013)

Planet atmospheres



Phase variations

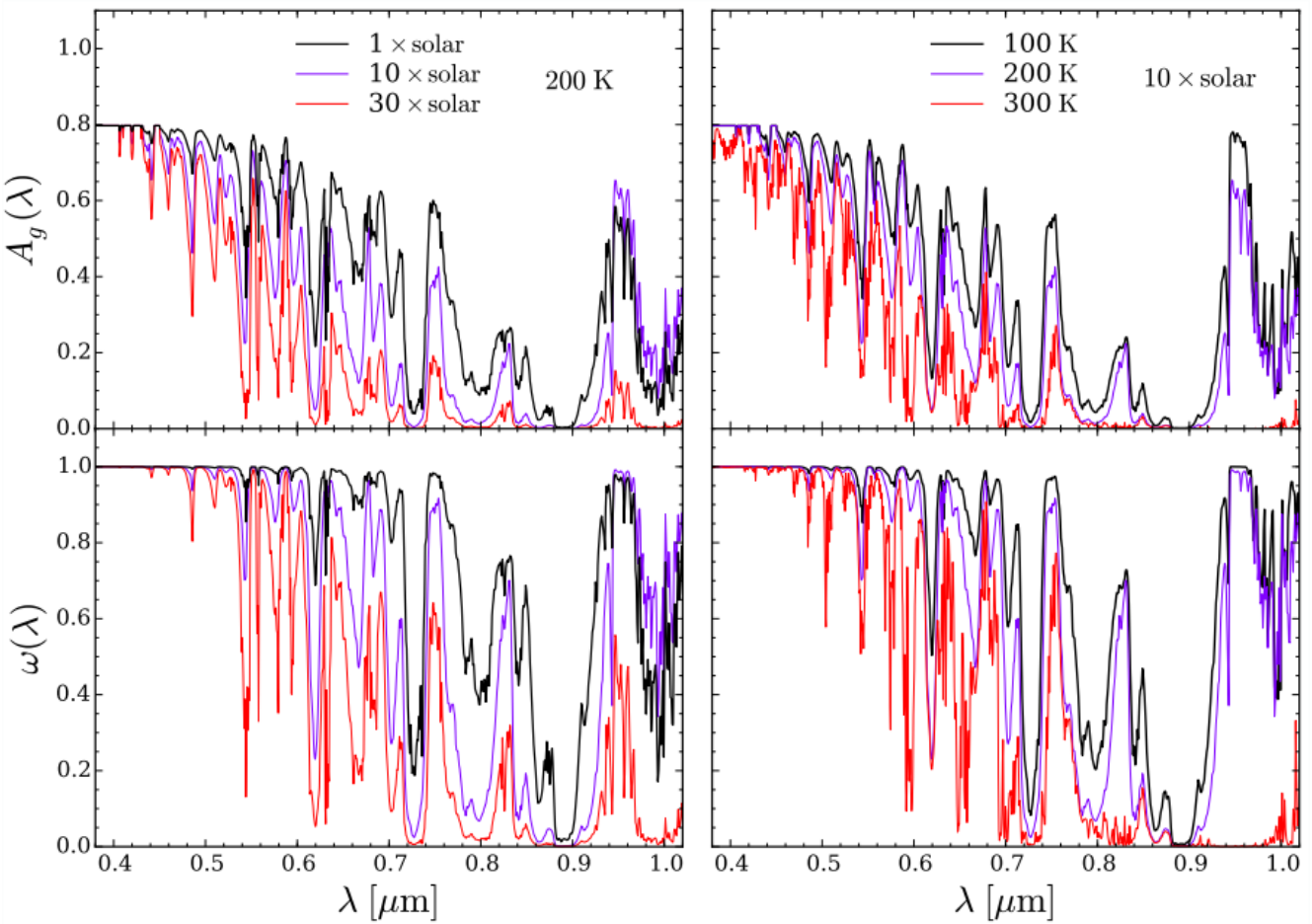
(from Stevenson et al. 2014)

Exoplanet Albedos

	p [$days$]	a [$A.U.$]	R_p [R_{Jup}]	$\left(\frac{R_p}{a}\right)^2$	$\mathbf{A_g}$
HD 209458 b	3.52	0.0475	1.38	185	**0.04**[a)]
Kepler-6 b	3.23	0.0457	1.32	183	**0.07**[b)]
Kepler-12 b	4.44	0.0556	1.70	203	**0.09**[b)]
Kepler-8 b	3.52	0.0483	1.42	188	**0.11**[b)]
Kepler-5 b	3.55	0.0506	1.43	174	**0.16**[b)]
Kepler-7 b	4.89	0.0625	1.61	146	**0.32**[c)]
HD 189733 b	2.22	0.0314	1.14	286	**0.40**[d)]
51 Peg b	4.23	0.052	1.90	292	**0.50**[e)]
Kepler-10 b	0.84	0.0169	0.13	13	**0.55**[f)]

a) Rowe et al. 2008; b) Angerhausen et al. 2015; c) Demory et al. 2011;
d) Evans et al. 2013; e) Martins et al. 2015; f) Hu et al. 2015

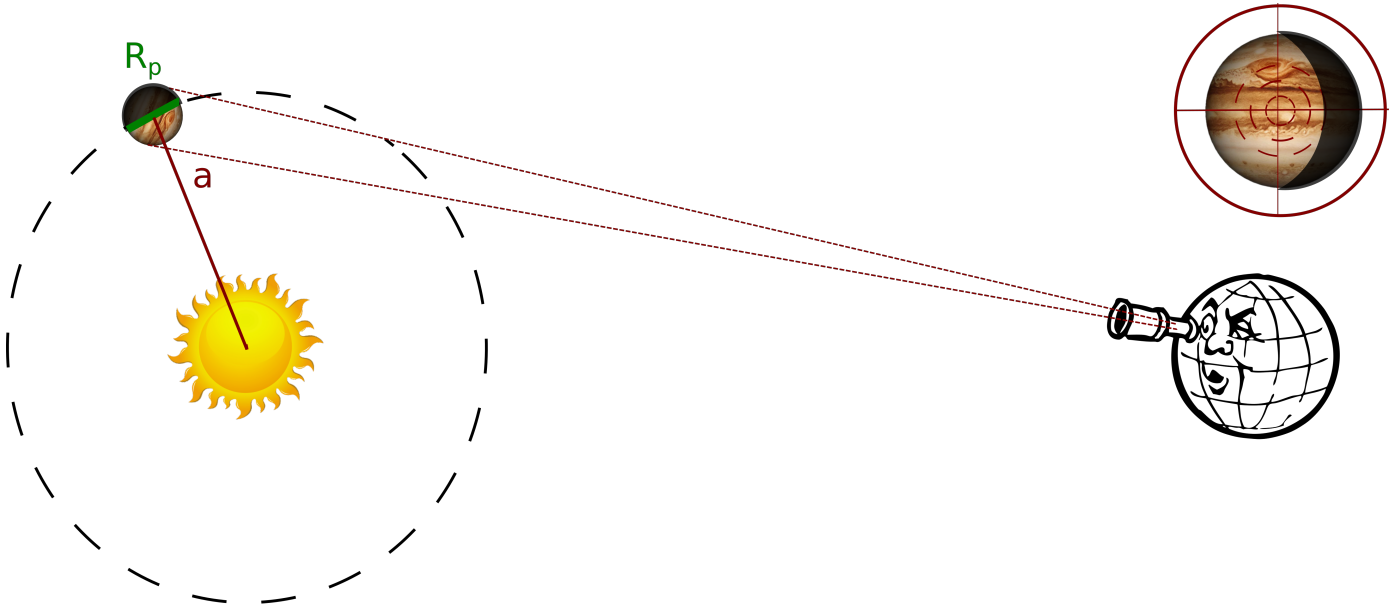
Exoplanet Albedos



Examples of albedo functions

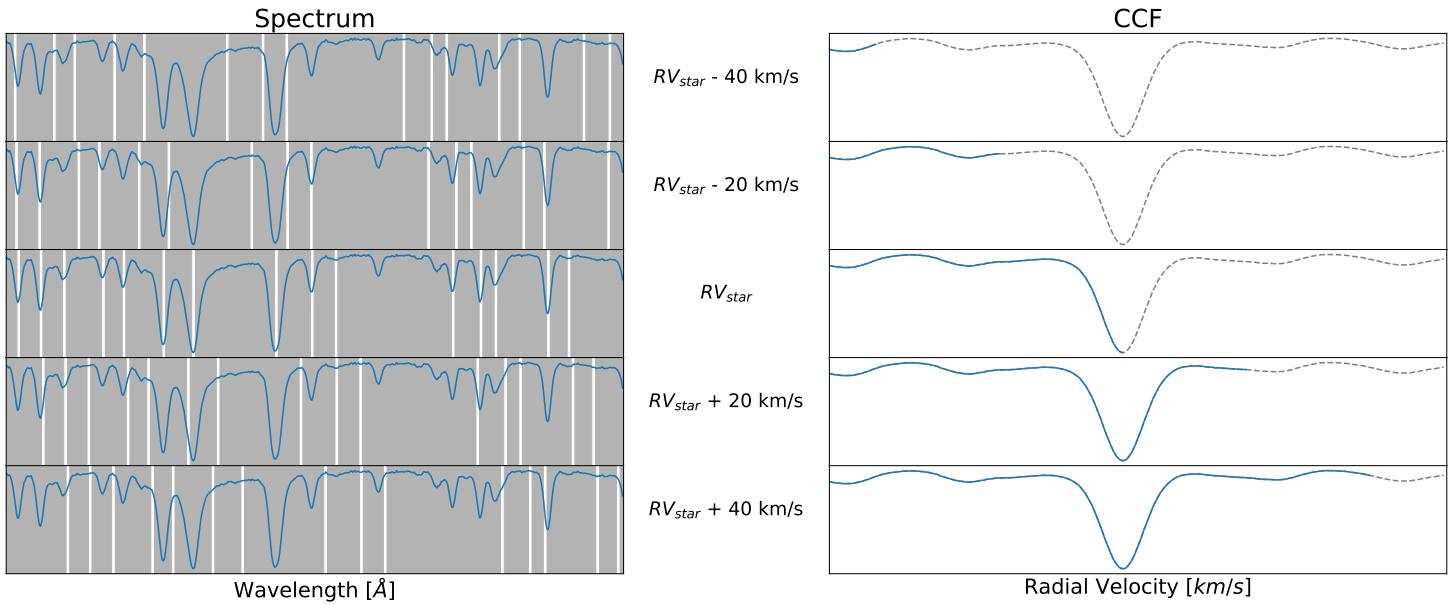
(from Greco et al. 2015)

The problem



$$\frac{F_{Planet}}{F_{Star}}(\lambda) = A_g(\lambda)\ g(\alpha) \left(\frac{R_P}{a}\right)^2$$

The Cross-Correlation Technique



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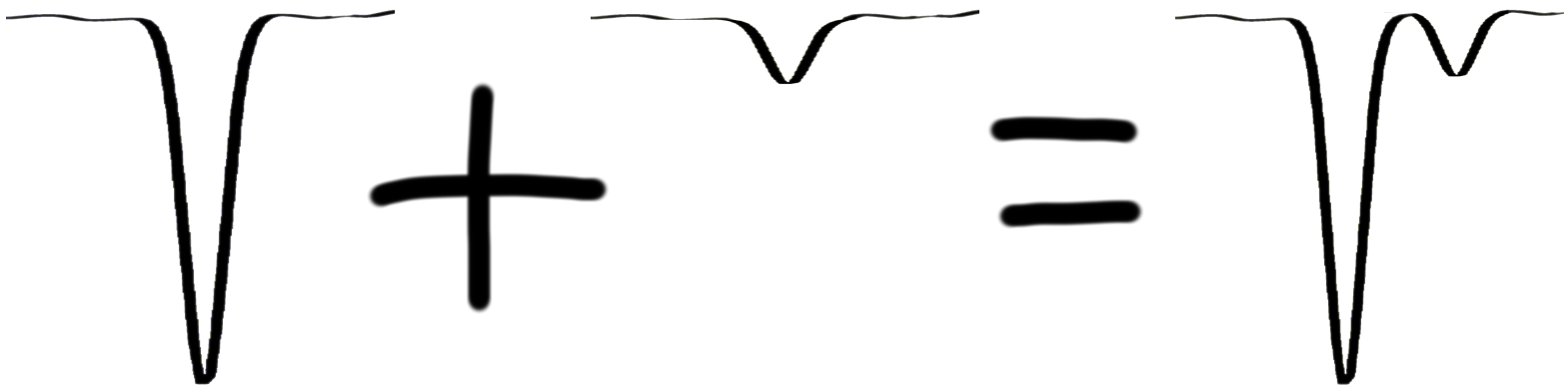

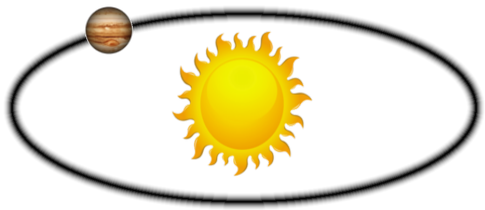

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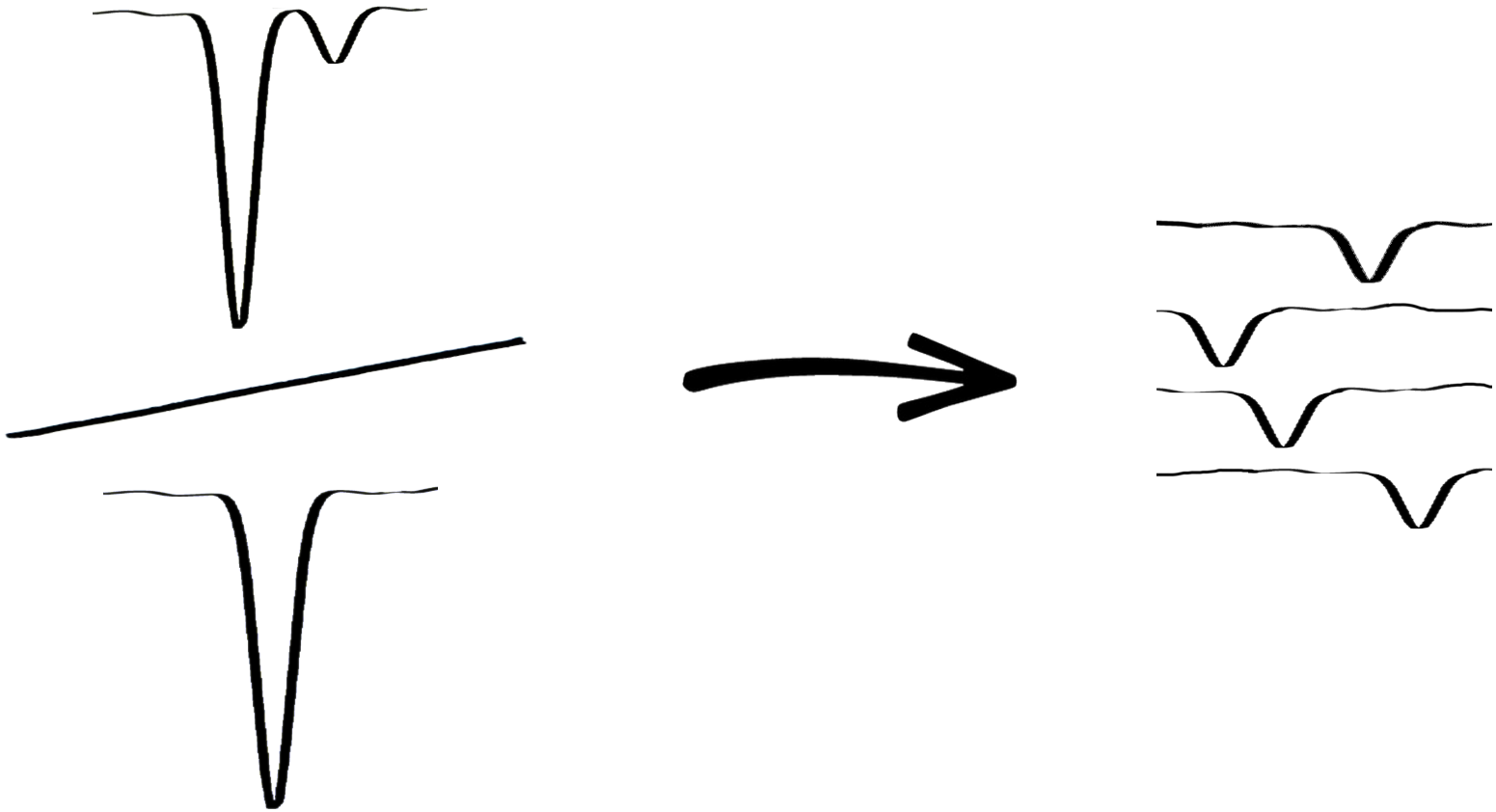
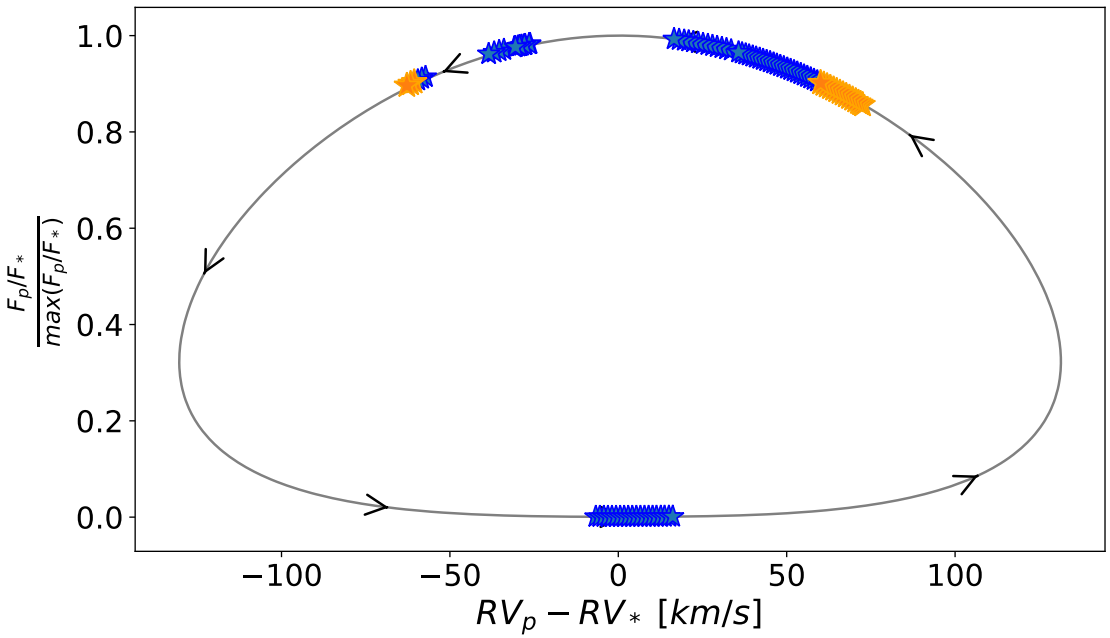
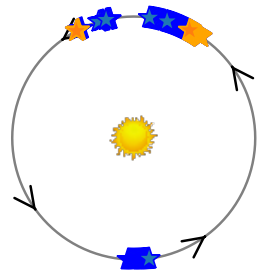


51 Peg b: Data Description





12.5h of HARPS data over 7 nights

93 high-resolution spectra

$145 < S/N < 388$

(ESO PID:091.C-0271, PI:Santos)

51 Peg b: Detected signal as function of k_p

Template T1
(all spectra)

Pros:

- 91 spectra
- Higher S/N

Cons:

- Planet contamination

Template T2
(spectra in "transit")

Pros:

- no planet contamination

Cons:

- only 25 spectra (27%)
- S/N $\sim$ 40% T1

51 Peg b: Detected signal as function of k_p

Template T1
(all spectra)

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- Higher S/N

Cons:

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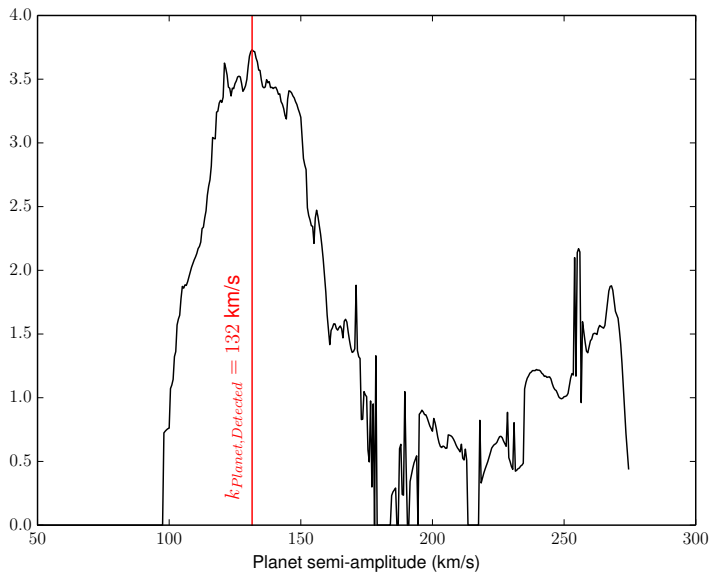

Template T2
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Pros:

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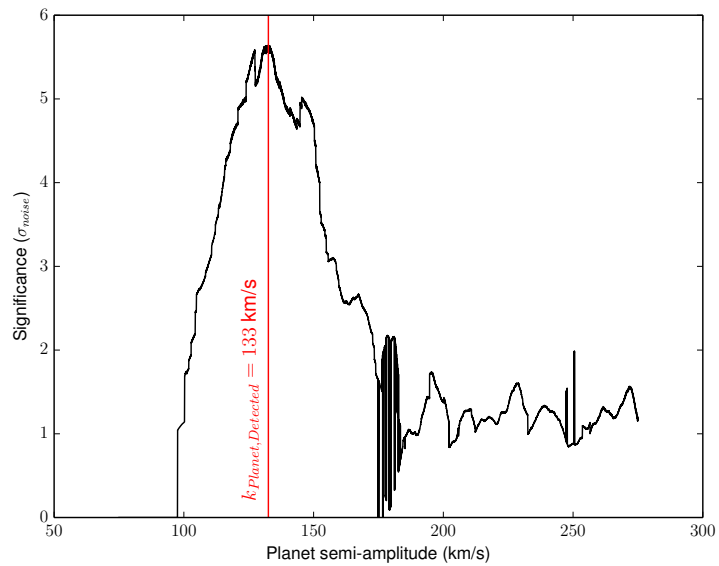
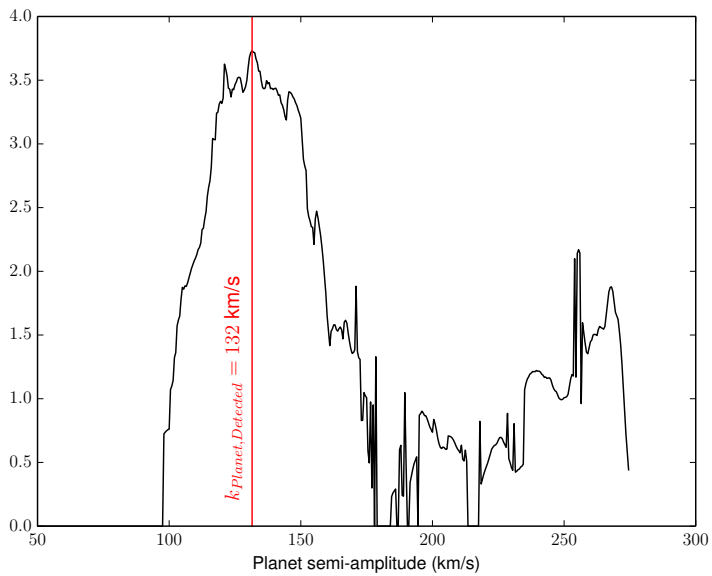


51 Peg b: Detected signal as function of k_p

Template T1
(all spectra)

Significance: 3.7 σ_{noise}

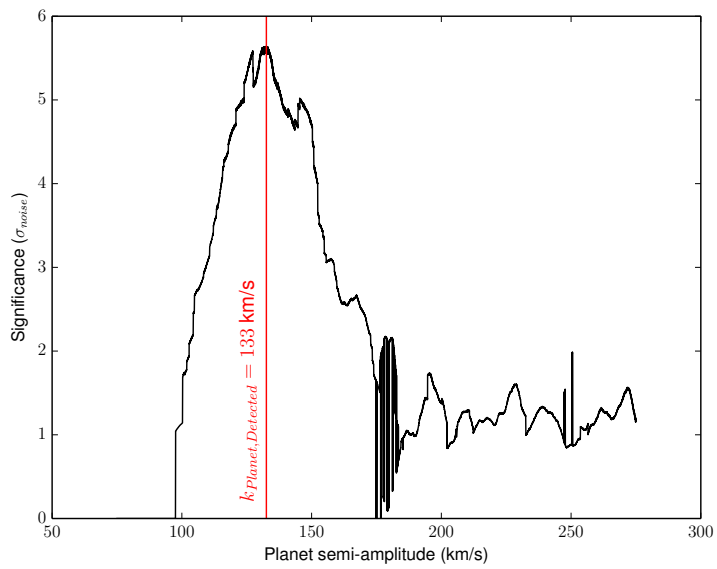
k_p 132^{+19}_{-15} km/s



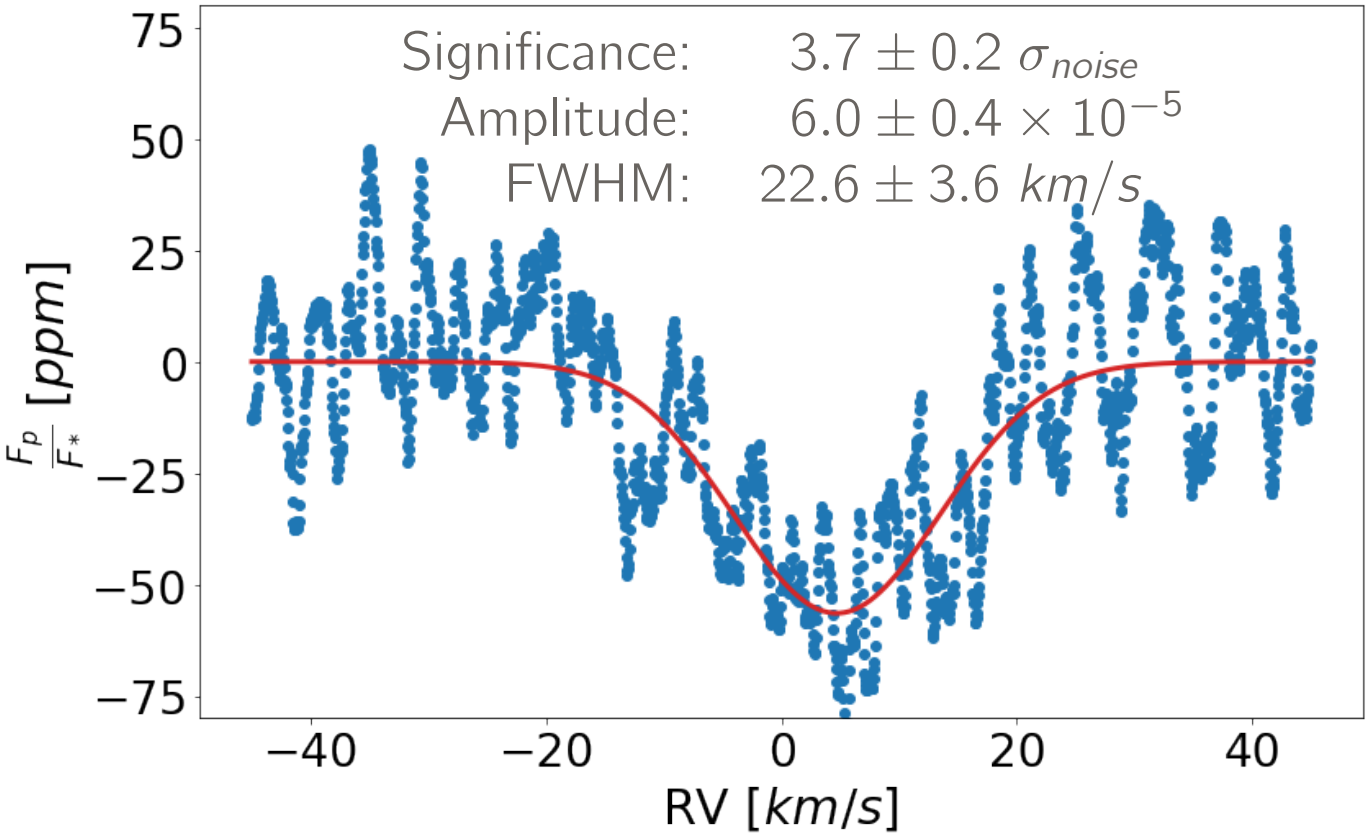
Template T2
(spectra in "transit")

Significance: 5.6 σ_{noise}

k_p 133^{+19}_{-20} km/s

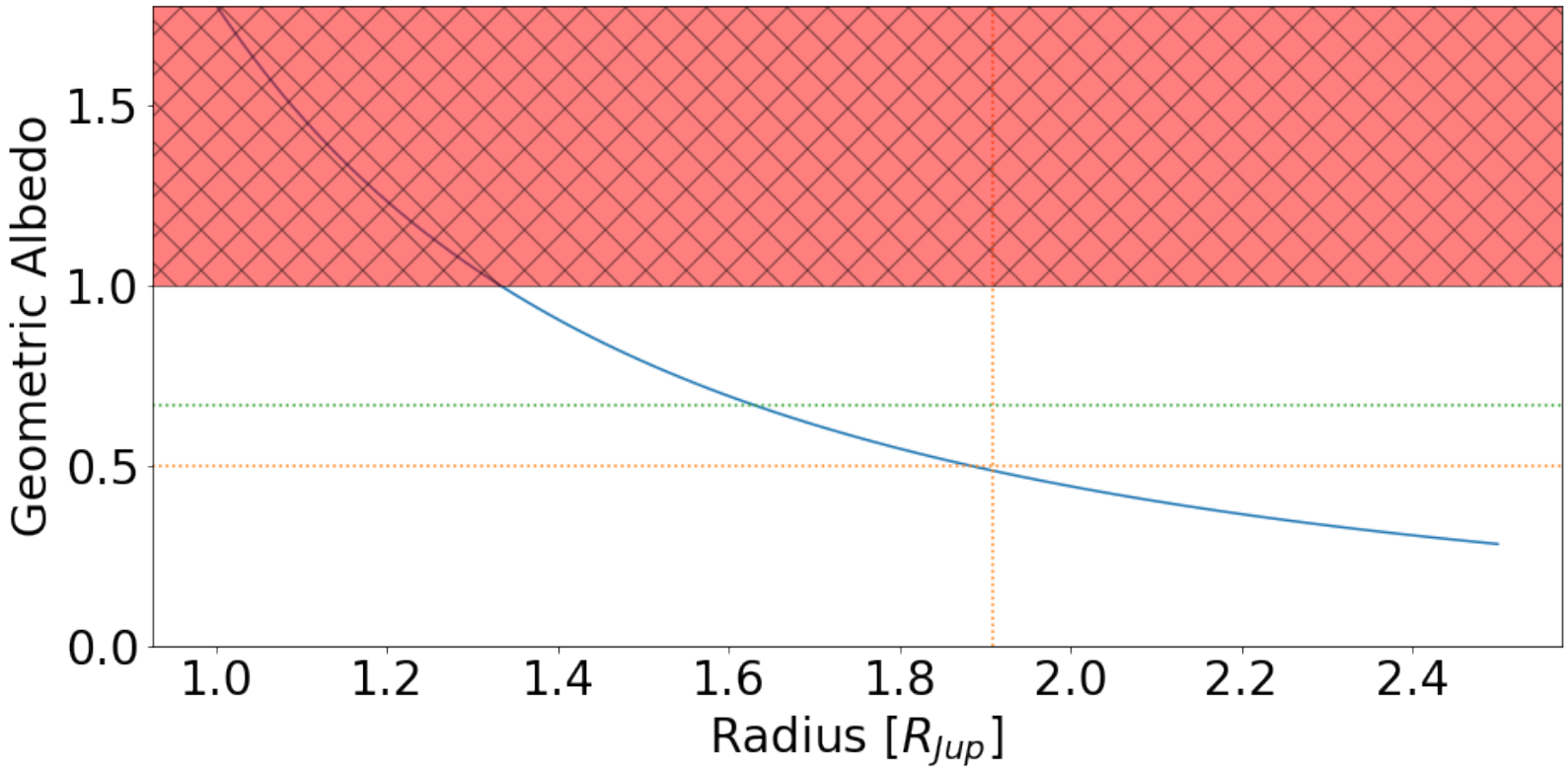


51 Peg b: Detected signal



(from Martins et al., 2015)

51 Peg b: Detected signal



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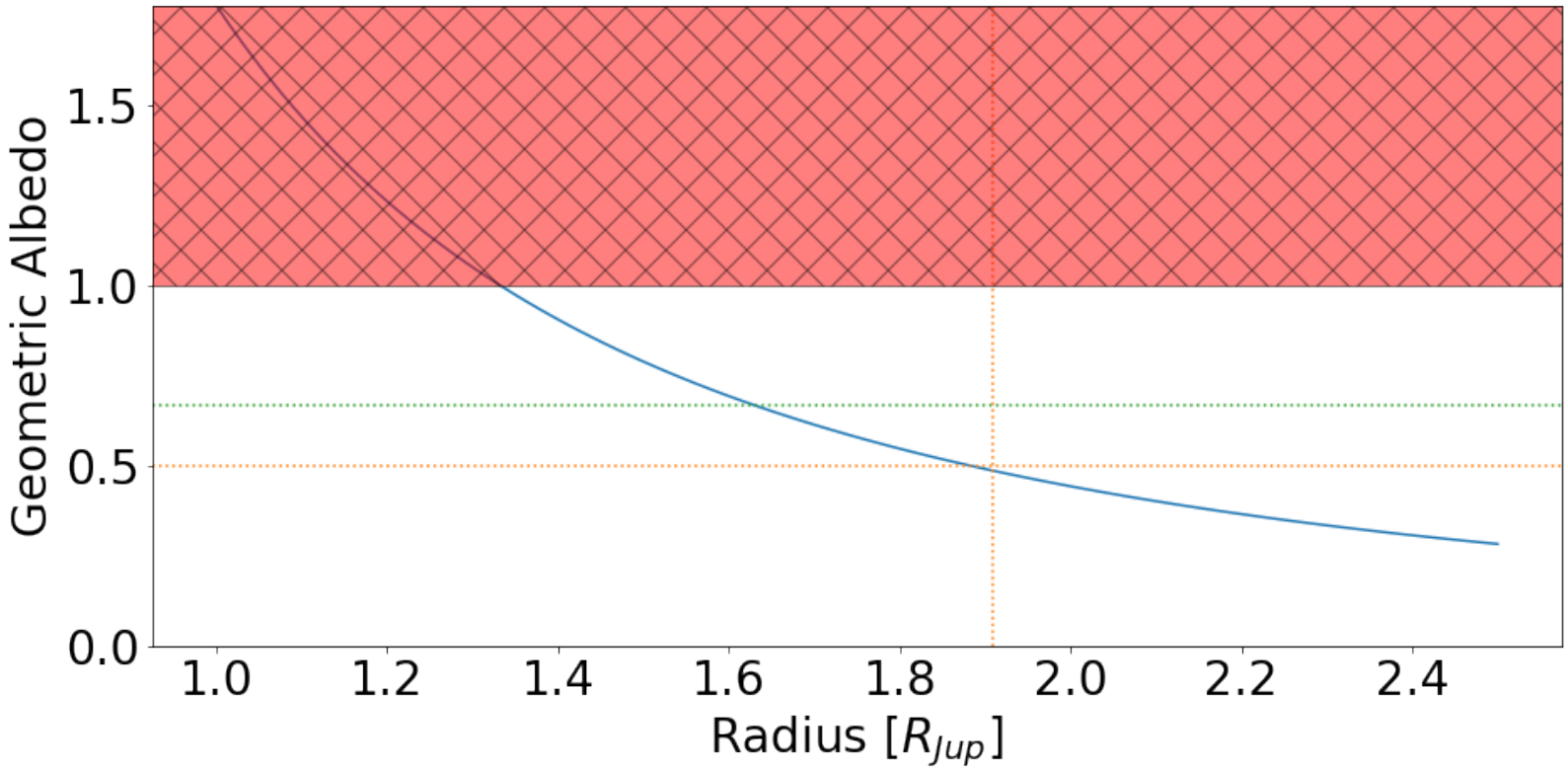
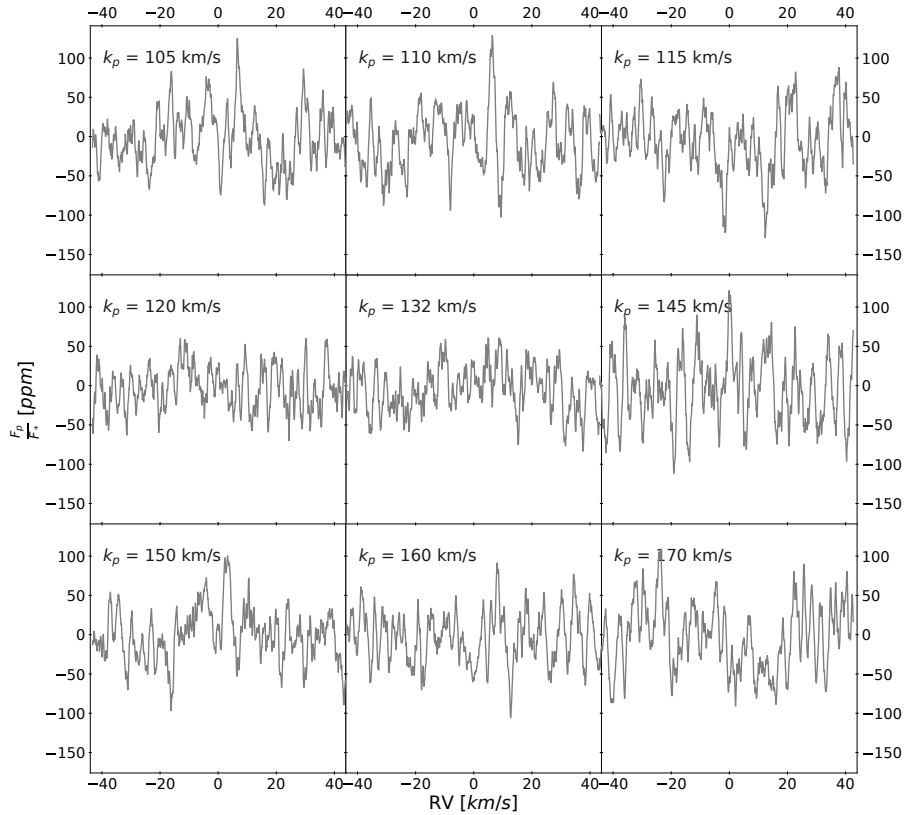


Highly inflated hot Jupiter with a high albedo!

($A_g = 0.5$ for $R_p = 1.9\ R_{Jup}$)

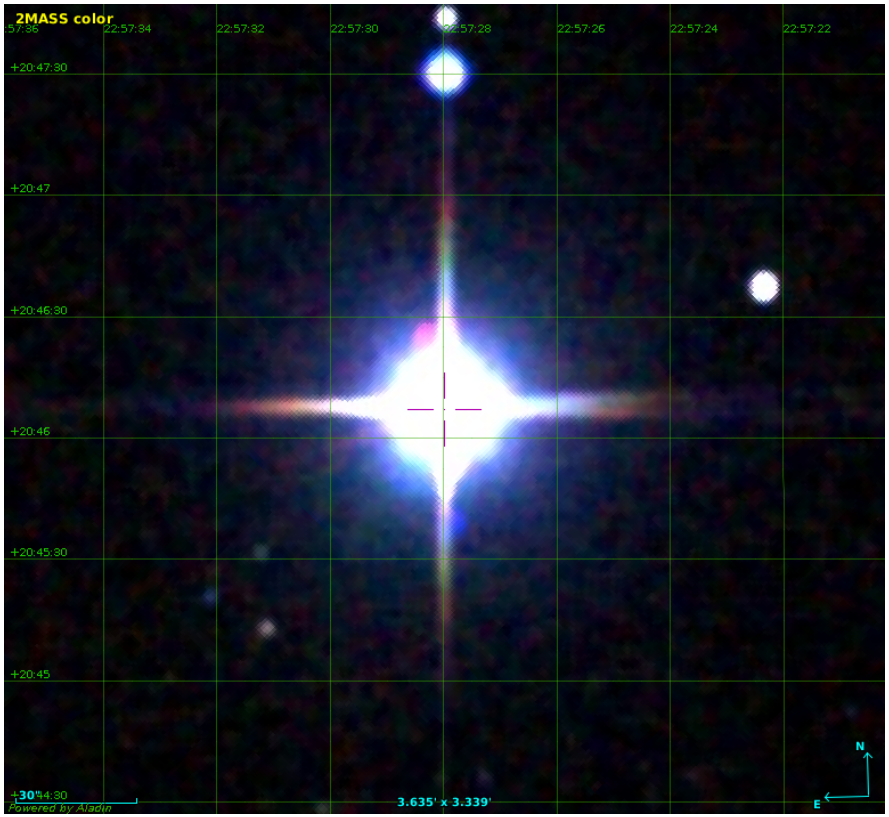
51 Peg b: False positive?

- Spurious combination of random noise?



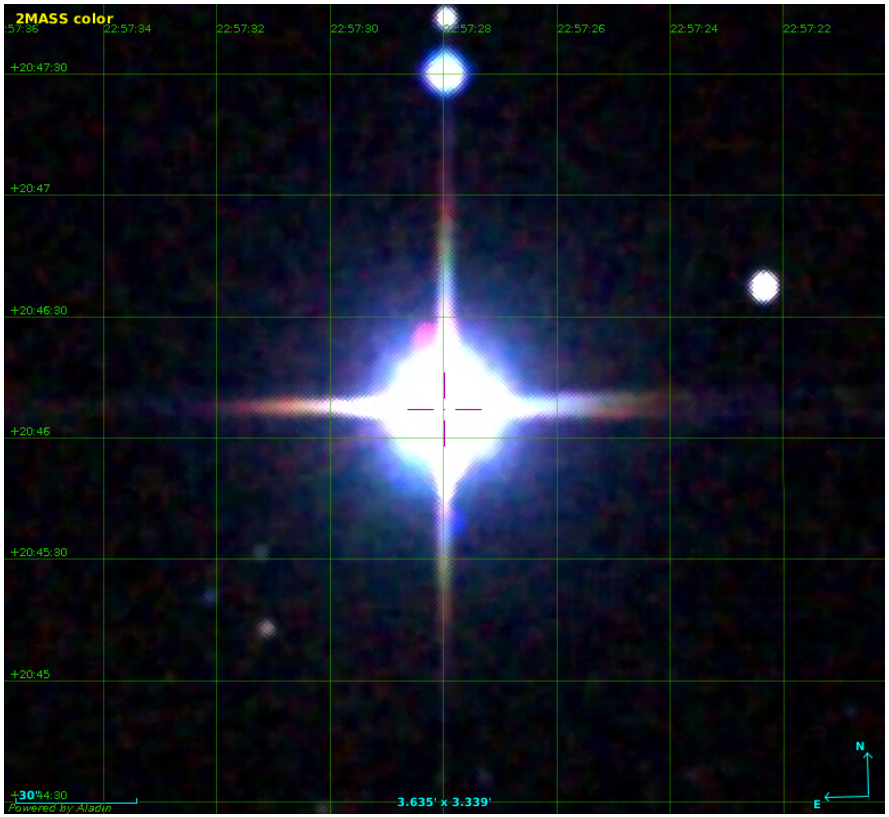
51 Peg b: False positive?

- Spurious combination of random noise?
- Stellar contamination



51 Peg b: False positive?

- Spurious combination of random noise?
- Stellar contamination
  - No stellar companion (Luhman et al. 2002)



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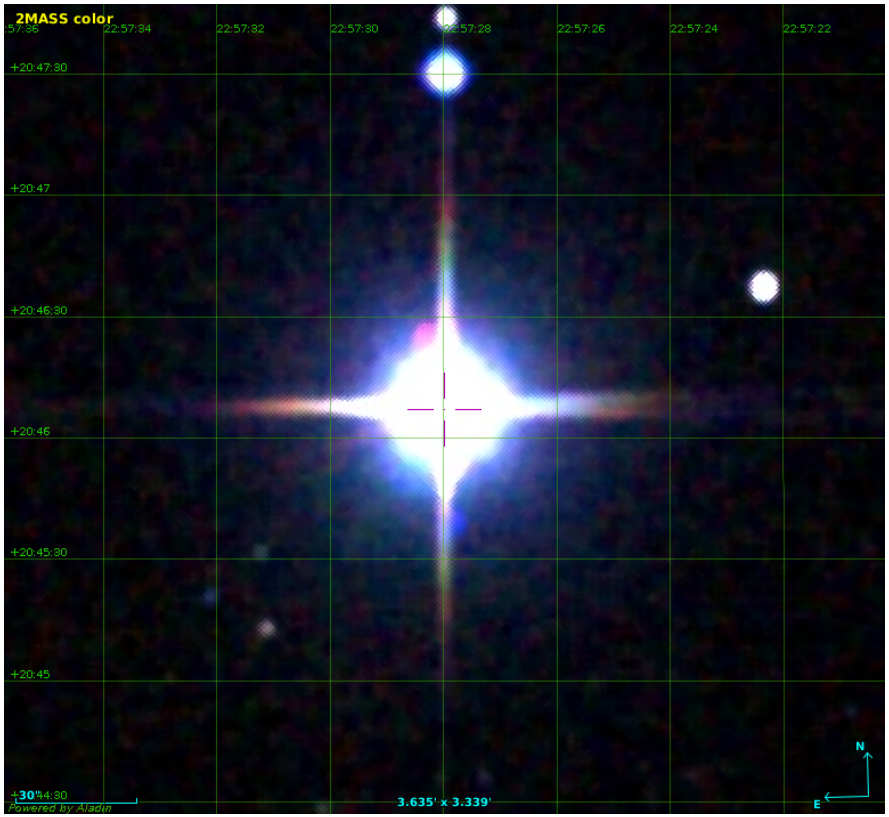
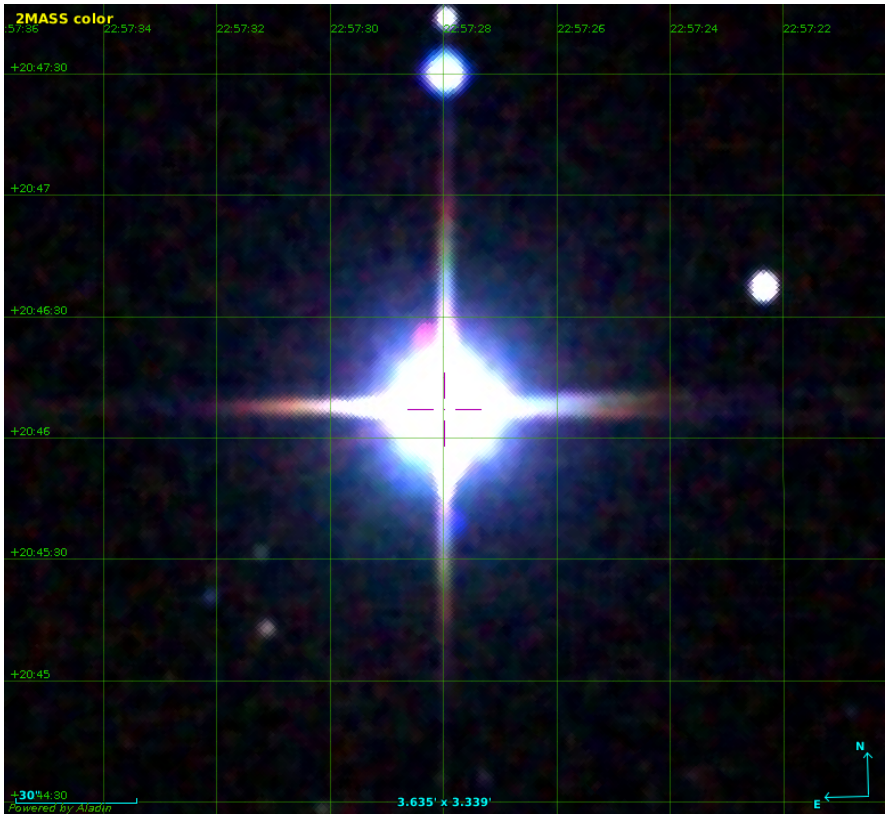
  - Probability of a background star is $< 0.1\%$

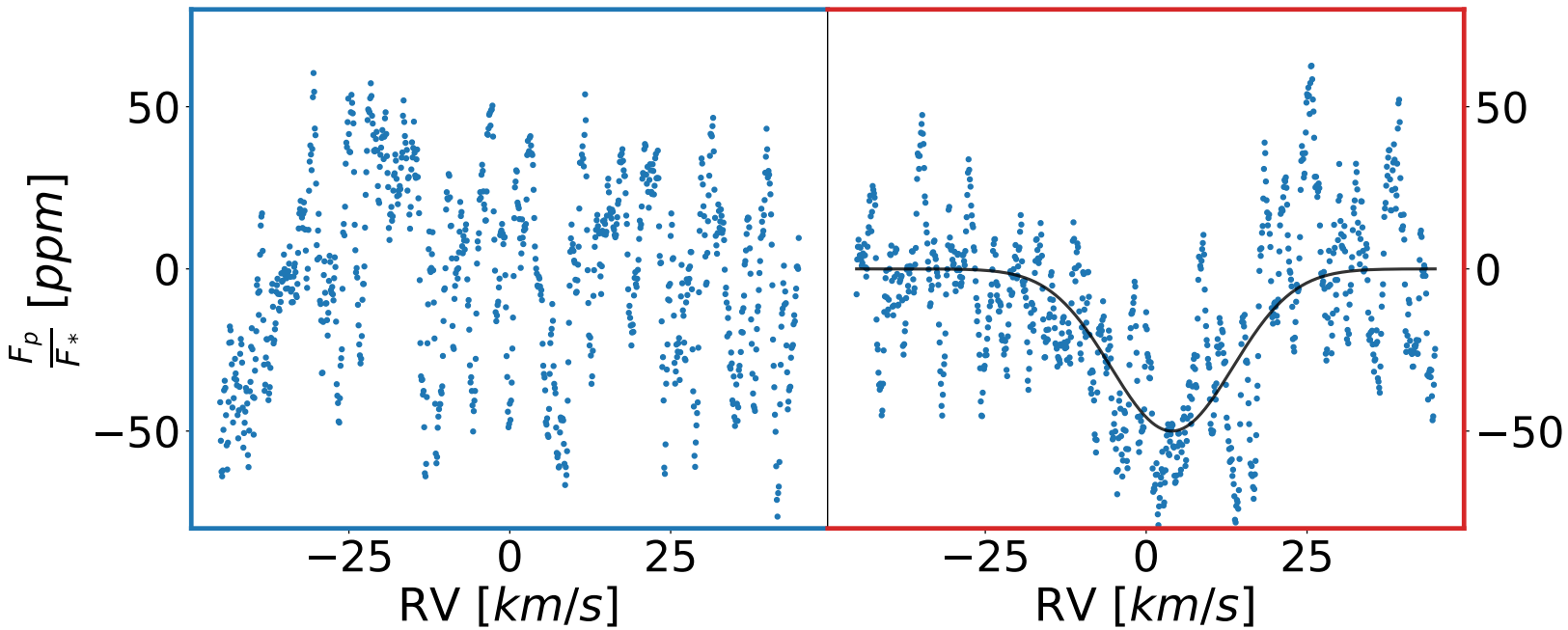


51 Peg b: False positive?

- Spurious combination of random noise?
- Stellar contamination
  - No stellar companion (Luhman et al. 2002)
  - Probability of a background star is $< 0.1\%$
- Recovery algorithm error



51 Peg b: Wavelength dependent albedo?



Inconclusive, waiting on observations from ESO PID 0101.C-0106

Prospects: the instruments

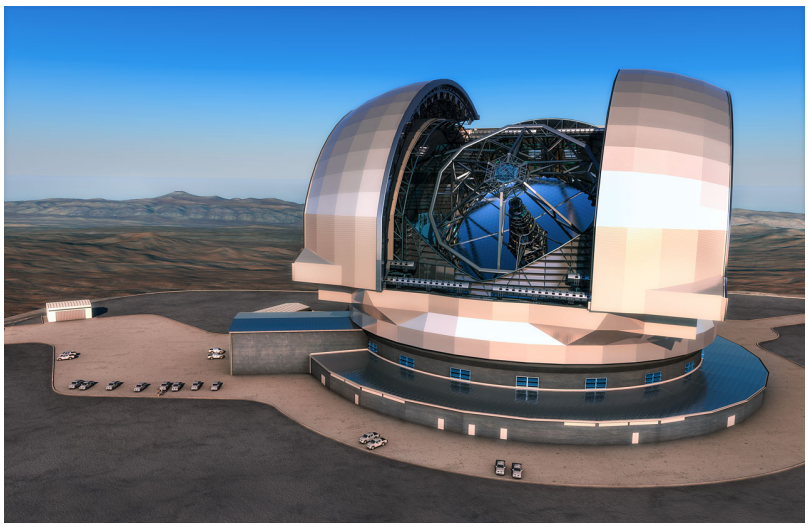
ESPRESSO@VLT

Modes	HR	MHR	UHR
Resolution	130 000	60 000	220 000
UTs	1	1 & 4	1
Fiber	1”	1”	0.5”

HIRES@ELT

HARPS like

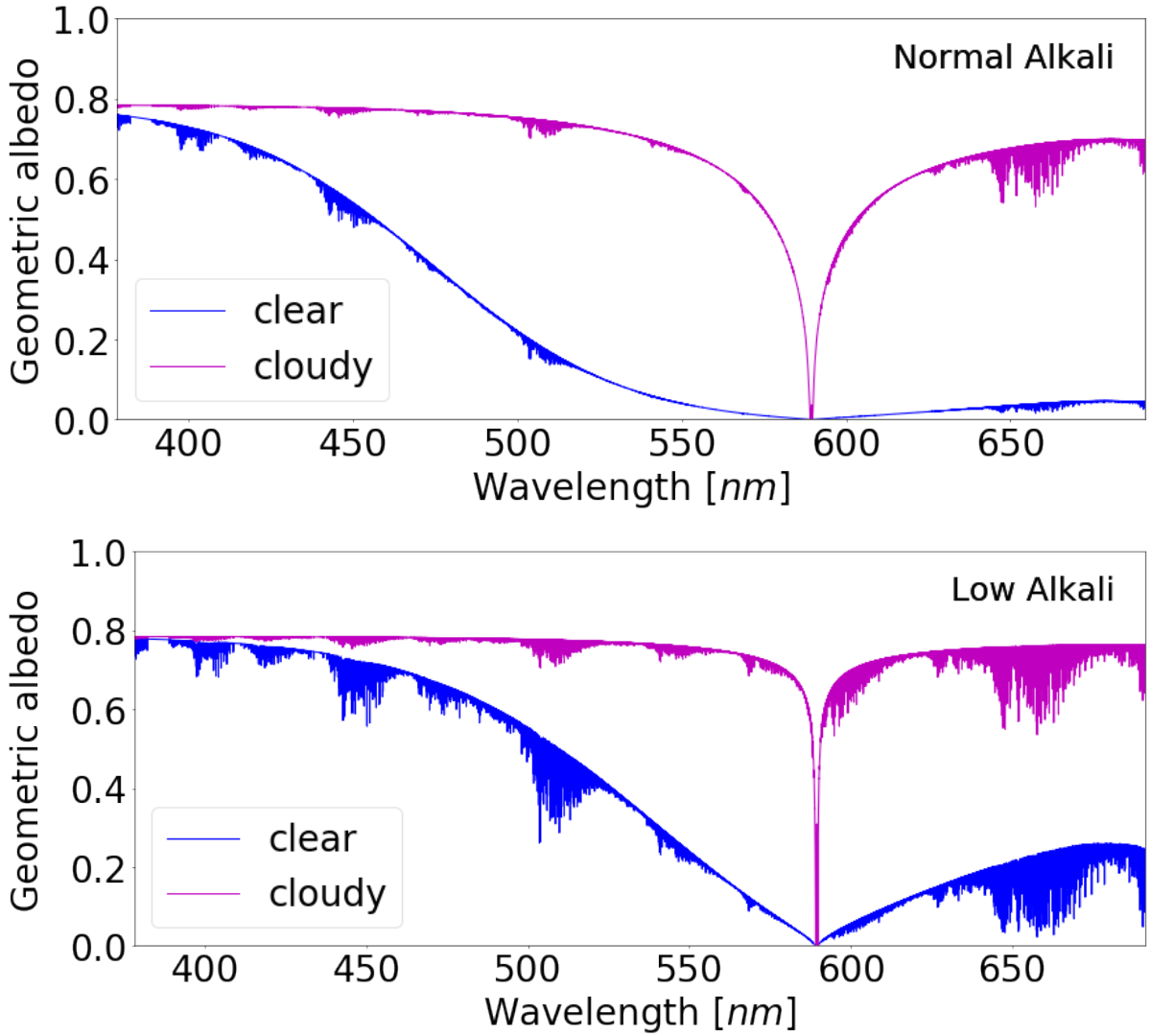
Resolution	115 000
Mirror	39 m



Prospects: Simulated Systems

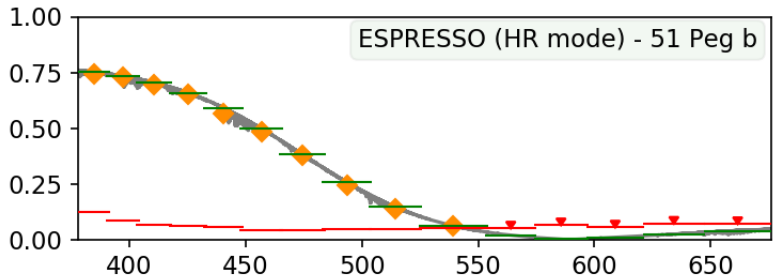
Planet	Host mag_V	$\left(\frac{\mathrm{R_{planet}}}{\mathrm{a}}\right)^2$ [*ppm*]	N_{bins}	Required SN	**Total Exposure** [*hours*]
ESPRESSO/HIRES					
51 Peg b	5.49	120	15/70	1300000	**11/7**
HD 209458 b	6.45	203	15/70	760000	**5/15**
HIRES					
55 Cnc e	5.95	27	5	2800000	**13**
HD 109749 b	8.1	62	6	1360000	**21**
HD 76700 b	8.13	89	6	940000	**10**

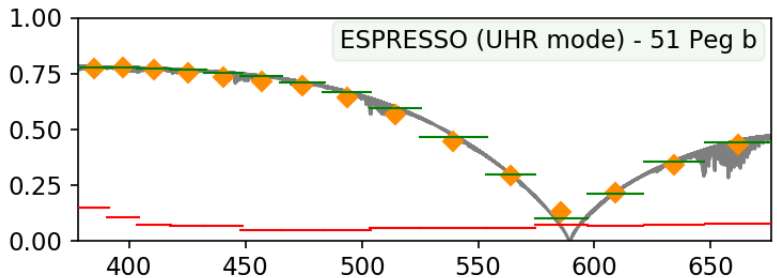
Prospects: Albedo Models

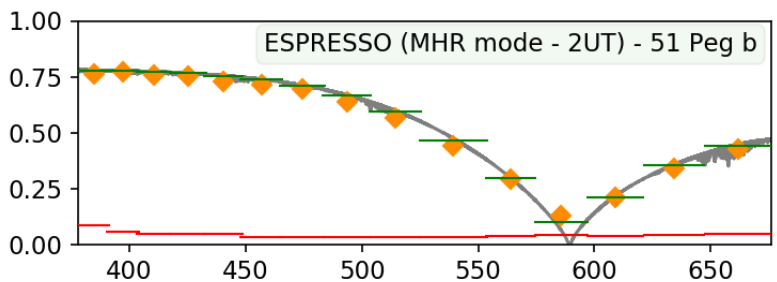


Garcia-Muñoz (2016) - private communication

Prospects: Results - ESPRESSO







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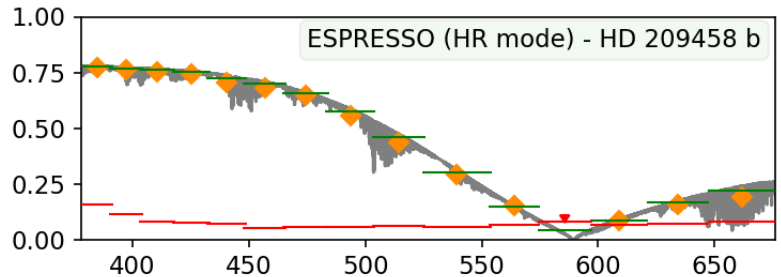
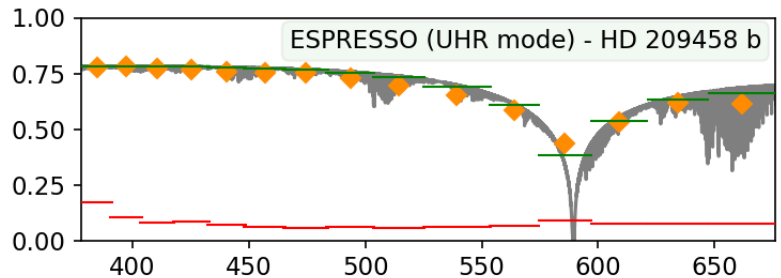
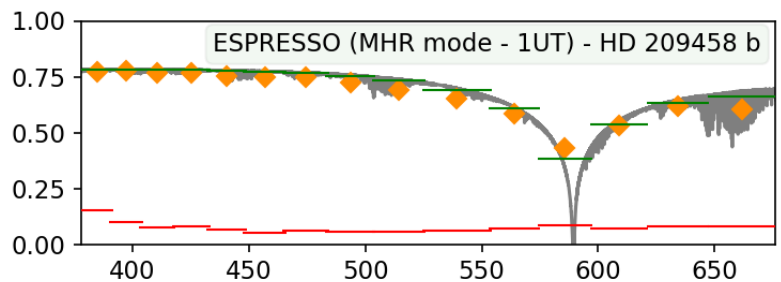
Wavelenght [*nm*]



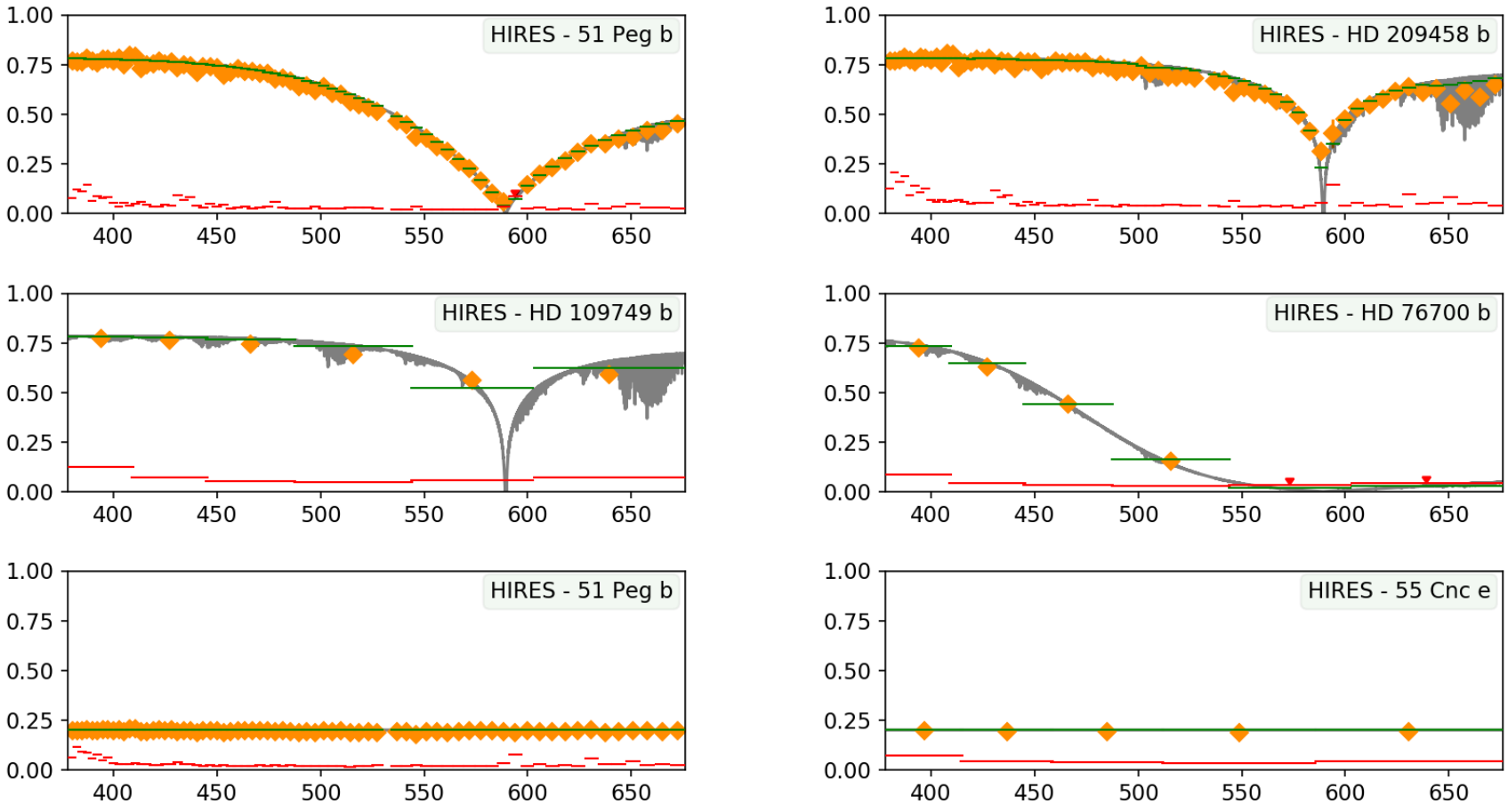




Wavelenght [*nm*]

(from Martins et al., 2018)

Prospects: Results - HIRES@E-ELT



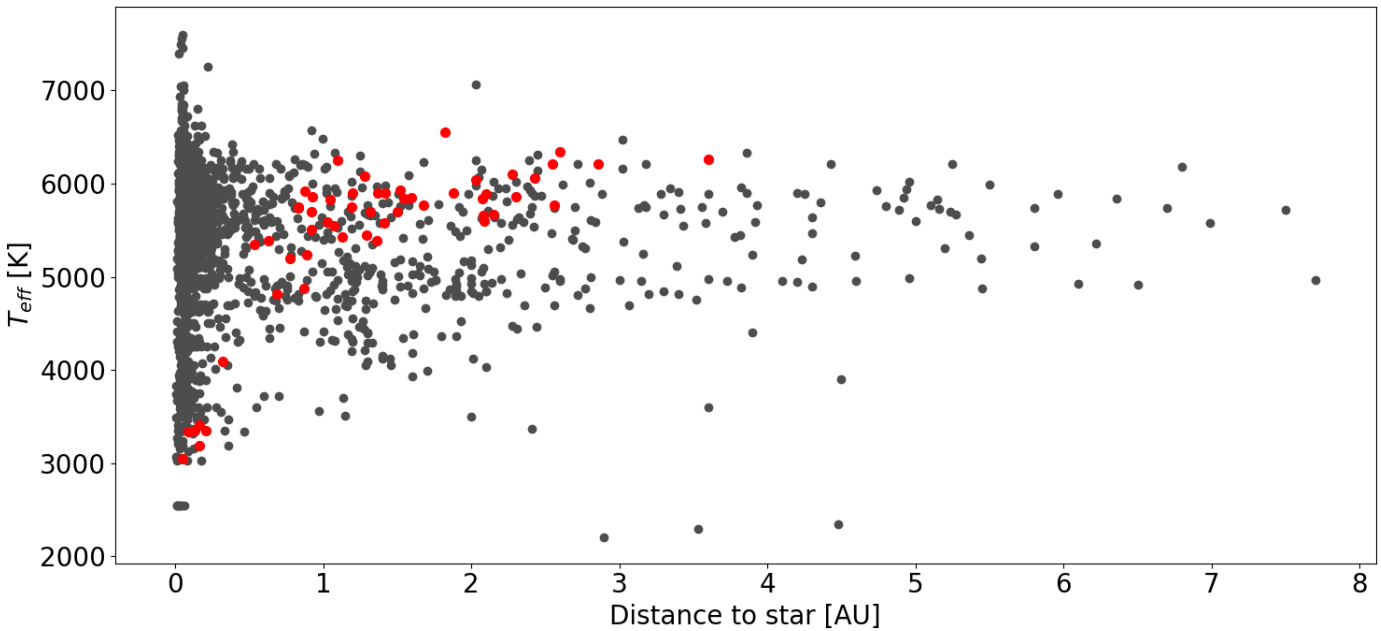
(from Martins et al., 2018)

Prospects: Planets in their hosts HZ

$$r_i = \left[r_{is} - a_i \left(T_{eff} - T_S \right) - b_i \left(T_{eff} - T_S \right)^2 \right] \sqrt{\frac{L_*}{L_\odot}}$$

$$r_o = \left[r_{os} - a_o \left(T_{eff} - T_S \right) - b_o \left(T_{eff} - T_S \right)^2 \right] \sqrt{\frac{L_*}{L_\odot}}$$

Kastings et al. (1993); Selsis et al (2007); Underwood et al. (2003)



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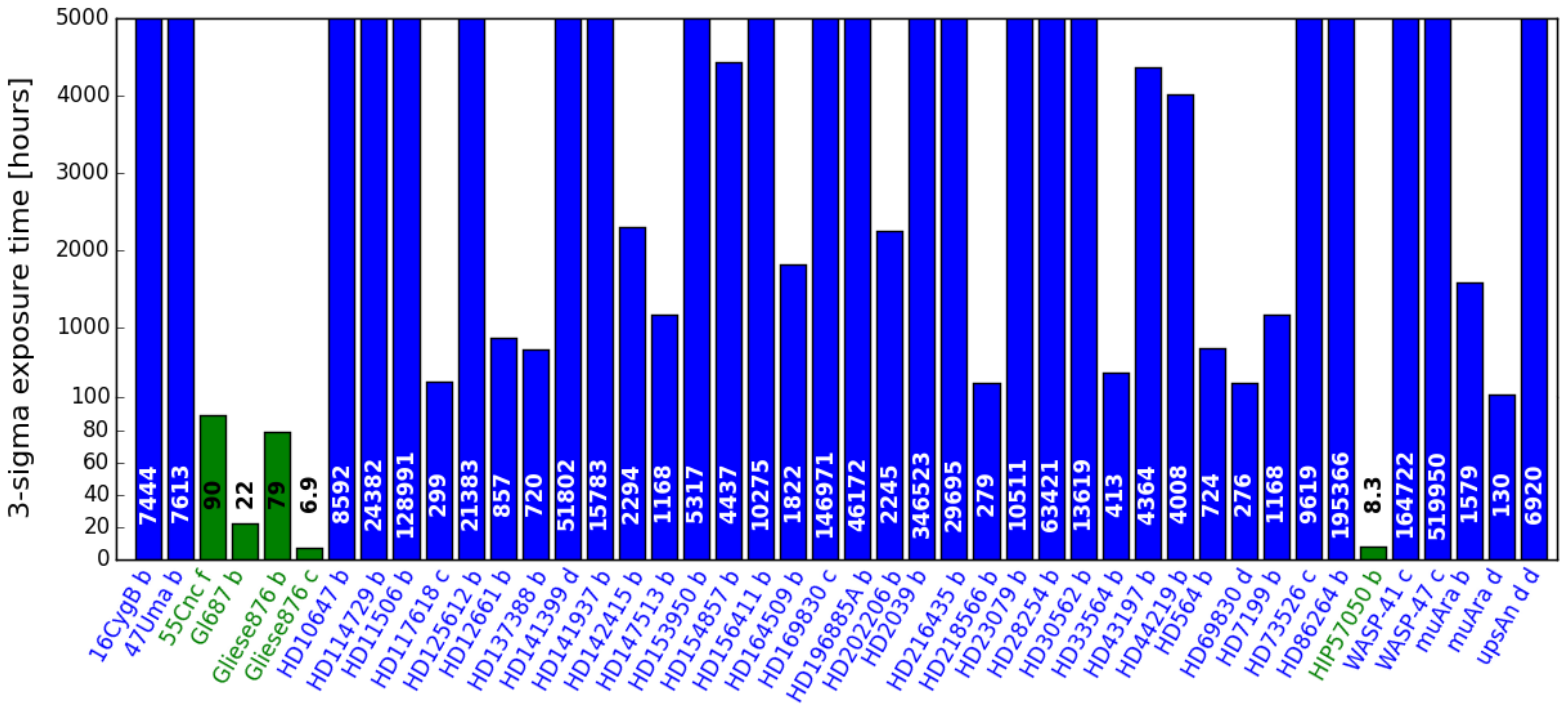

(from Martins et al., 2016)

Take Home Messages

- The reflected spectrum from exoplanets plays a crucial role in the characterization of exoplanets;
- Current generation facilities already allow us to detect the reflected optical spectrum from exoplanets;
- Next generation observing facilities will enable us to use reflected light to probe in greater detail at exoplanet atmospheres and smaller planets

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Thank you!