

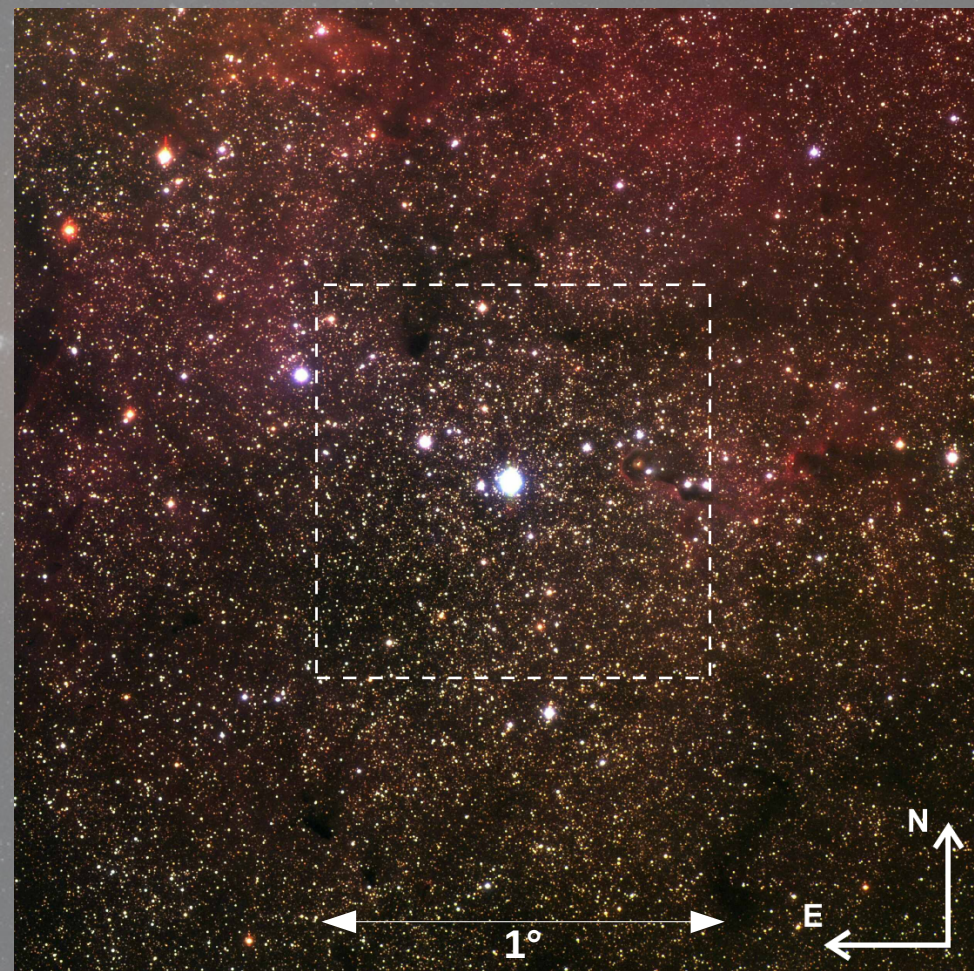
Transiting Planets in the open cluster Trumpler 37

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Maths at the University of Hertfordshire
Hatfield, United Kingdom

Yeti Workshop, 18/10/2018

Trumpler 37

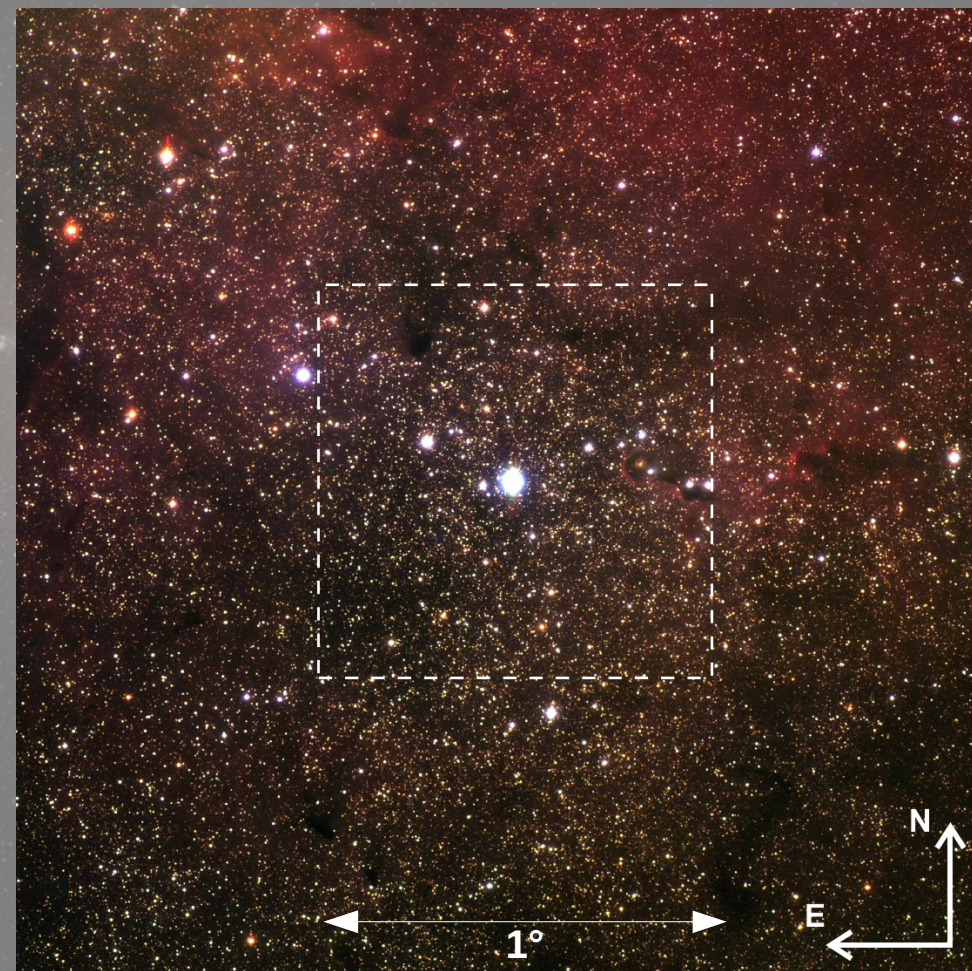
- Open cluster in Cepheus
- Age: 4 Myr (Kun et al. 2008)



Open cluster Trumpler 37 in B-, V-, and R-Filter with FoV of the STK (M. Mugrauer)

Trumpler 37

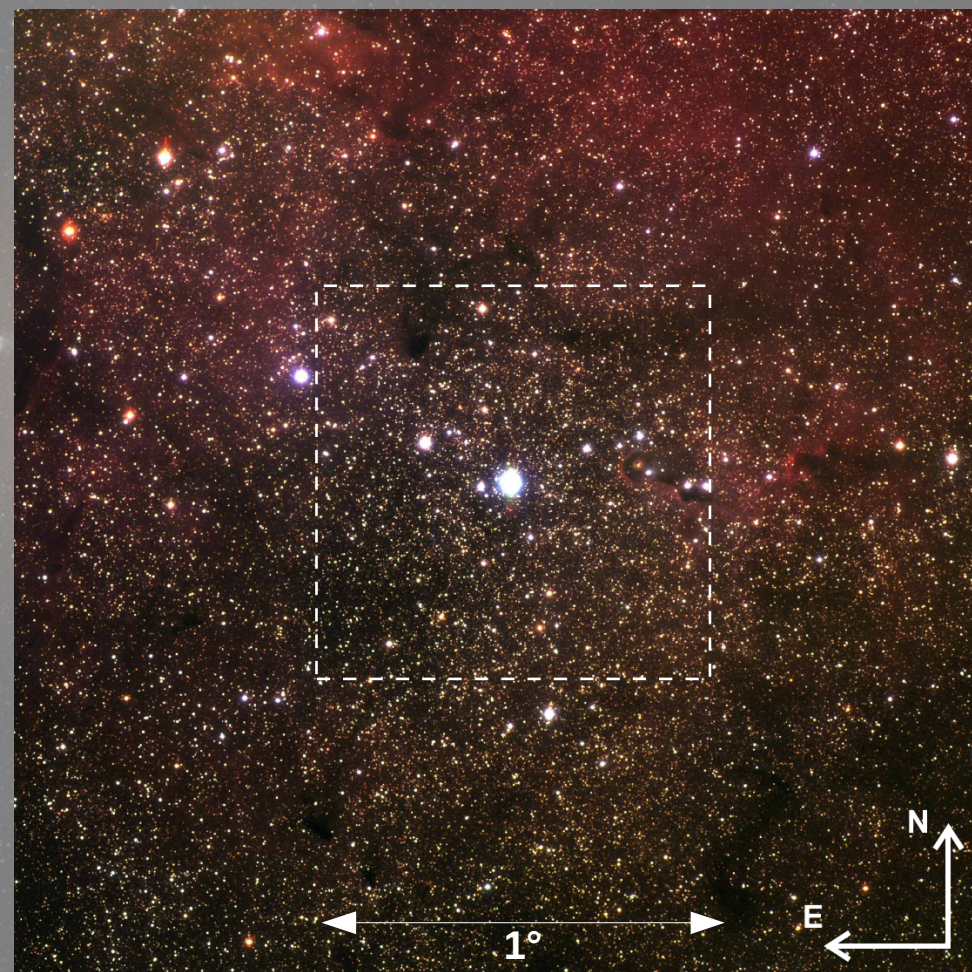
- Open cluster in Cepheus
- Age: 4 Myr (Kun et al. 2008)
- 774-900 probable member stars (using literature data, Errmann et al. 2013)
- Size: $\approx 1.5^\circ$
- 17000 stars in the field of view (FoV) of the Schmidt-Telescope Camera (STK) at the Jena Observatory



Open cluster Trumpler 37 in B-, V-, and R-Filter with FoV of the STK (M. Mugrauer)

Trumpler 37

- Open cluster in Cepheus
- Age: 4 Myr (Kun et al. 2008)
- 774-900 probable member stars (using literature data, Errmann et al. 2013)
- Size: $\approx 1.5^\circ$
- 17000 stars in the field of view (FoV) of the Schmidt-Telescope Camera (STK) at the Jena Observatory
- Distance: 870 pc (Contreras et al. 2002)
- Extinction: 1.67 mag (Sicilia-Aguilar et al. 2004)

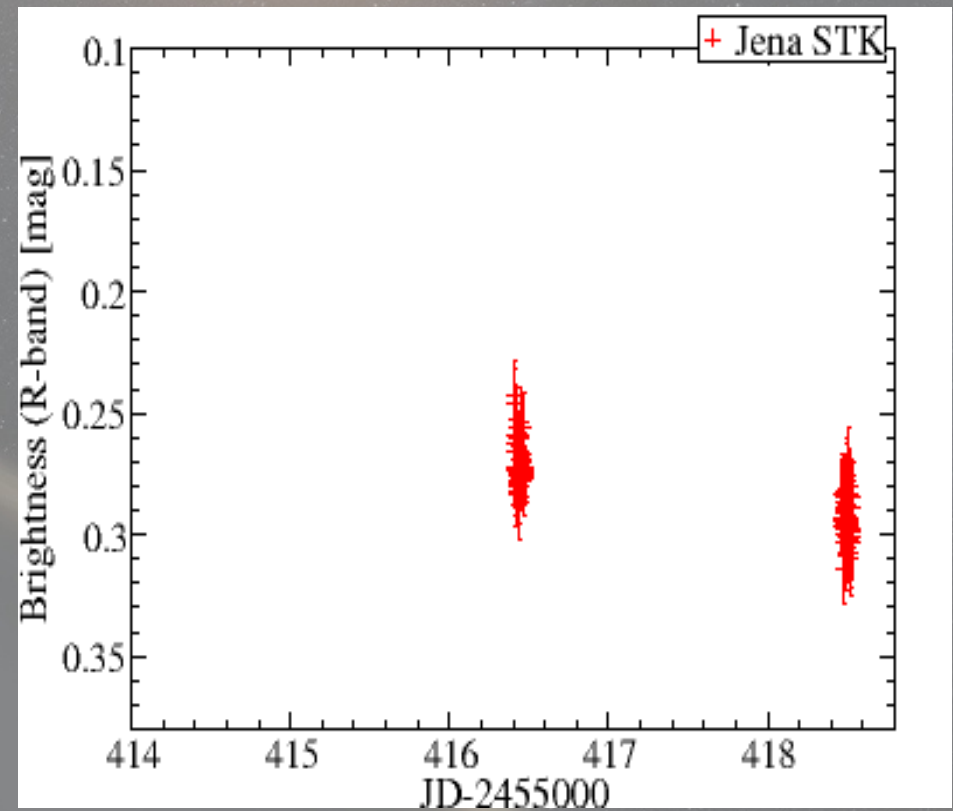


Open cluster Trumpler 37 in B-, V-, and R-Filter with FoV of the STK (M. Mugrauer)

Transit search in Trumpler 37 – YETI Network

Observation started 2009 - single observatory:

- Big data gaps
- Alias frequencies (et al. earth rotation)

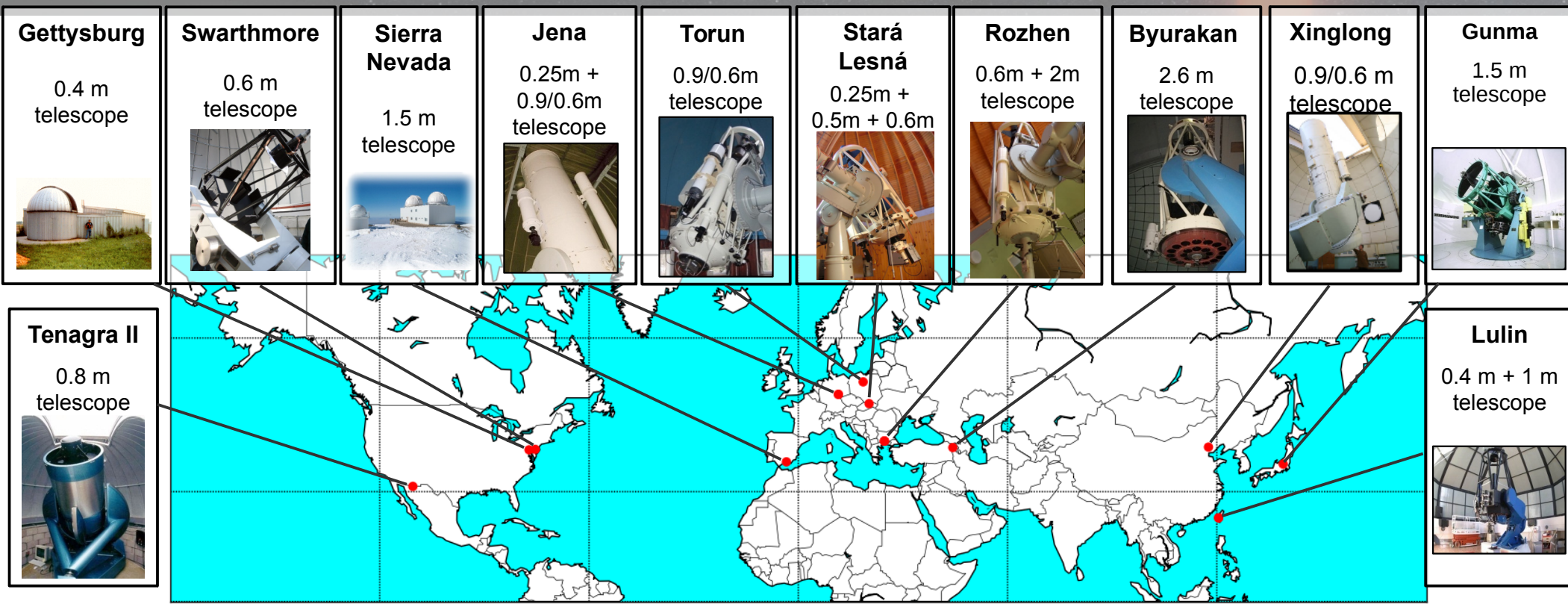


Light curve of star GM Ceph

Transit search in Trumpler 37 – YETI Network

Single telescope:

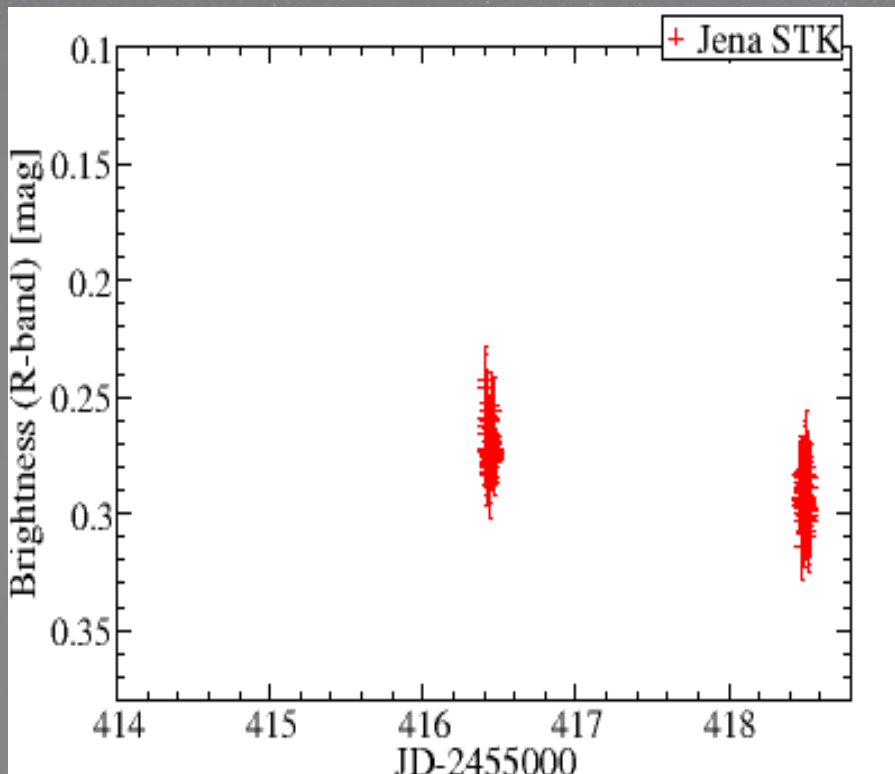
- Big data gaps
 - Alias frequencies (et al. earth rotation)
- Network of telescopes (Young Exoplanet Transit Initiative: **YETI**)
- Different longitudes
 - Size of main mirror: 0.25 m to 2 m



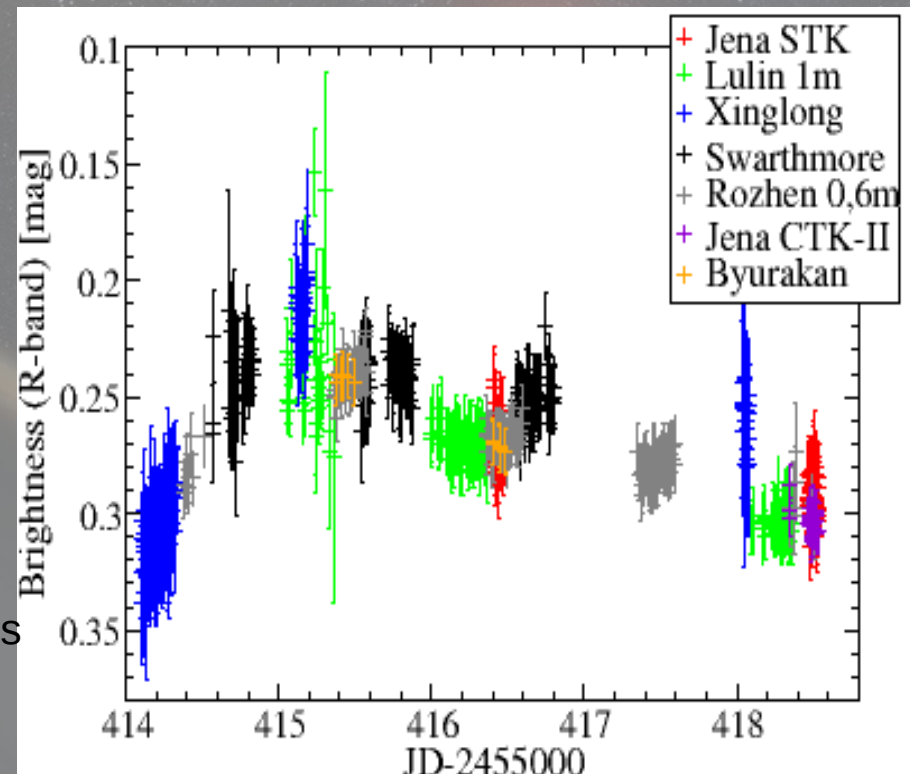
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Light curves
of the star
GM Ceph



Transit search in Trumpler 37 – YETI Network

YETI Campaigns:

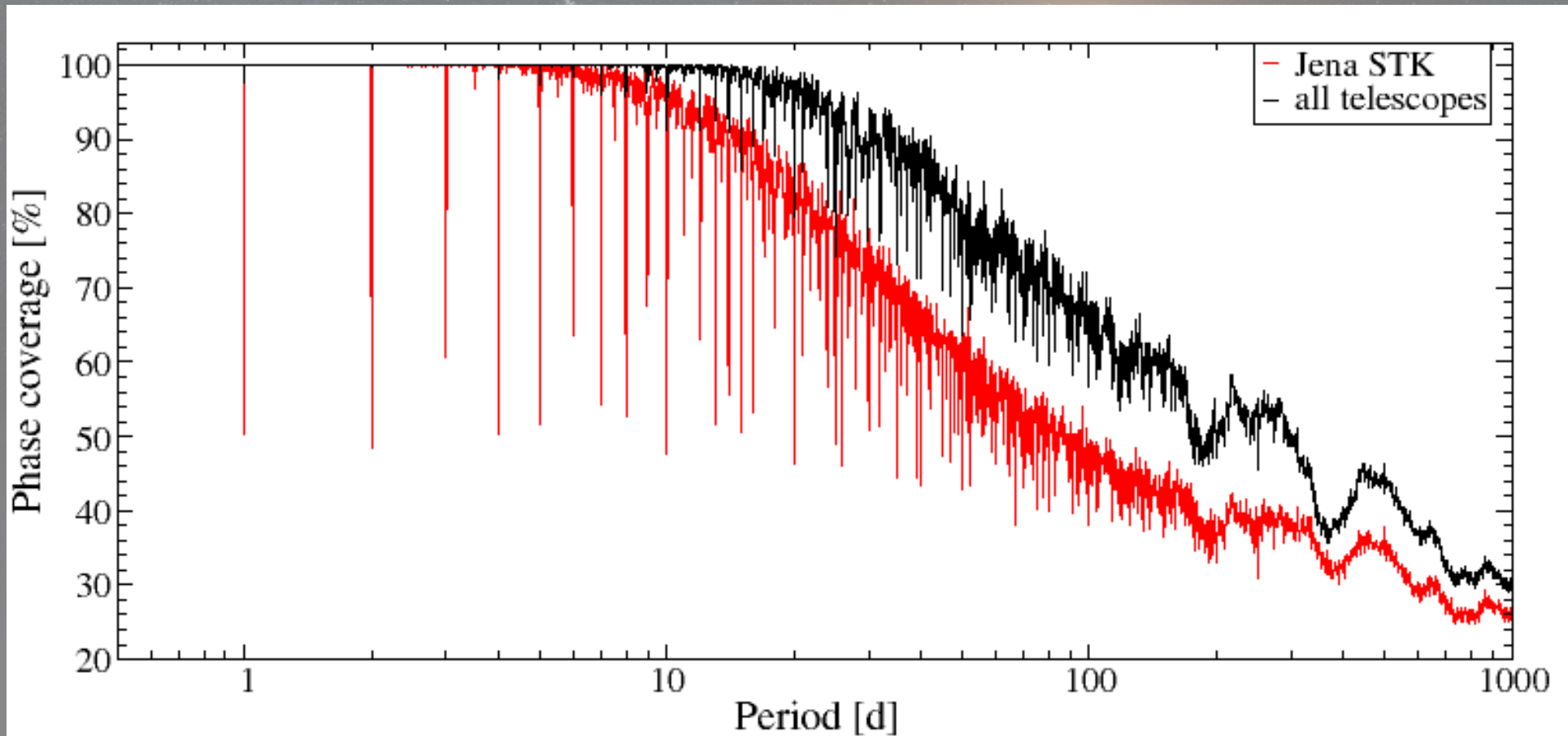
- 2010, 2011: 188 data sets*
- + 156 additional nights with Jena Observatory 2009 - 2011

Most observations in the R-Band:

- 62153 images
- 793 h total exposure time

*One data set equals one Observational night with one telescope

Transit search in Trumpler 37 – YETI Network

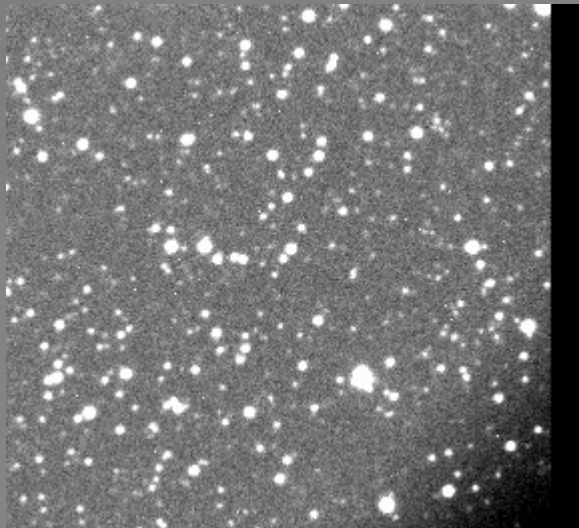


Comparison of the phase coverage between YETI network and observations with a single telescope

- Improved phase coverage for multiples of a day
- Complete phase coverage for orbital periods up to 15 days (for stars in the FoV of all telescopes)

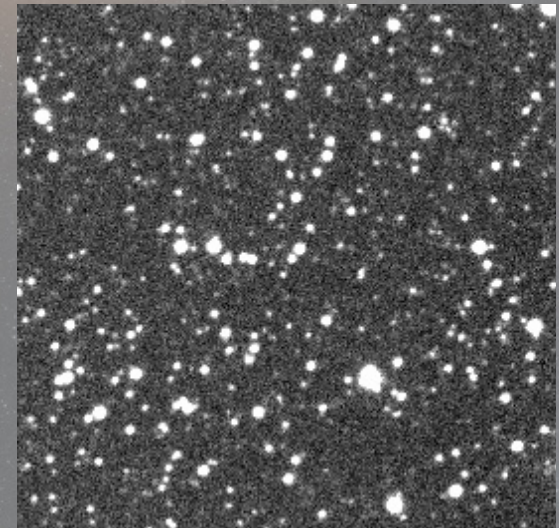
Data analysis

- Standard data reduction and calibration for every data set (each (mosaic pointing) of each night of each telescope)



Part of the Schmidt-Telescope Camera: original image

-
- Bias, Dark, and Flat correction



Part of the Schmidt-Telescope Camera: reduced image

Data analysis

- Standard data reduction and calibration for every data set (each (mosaic pointing) of each night of each telescope)
- Optimised aperture photometry for every data set

Photometric precision

(night 2013-08-30, 115 data points each)

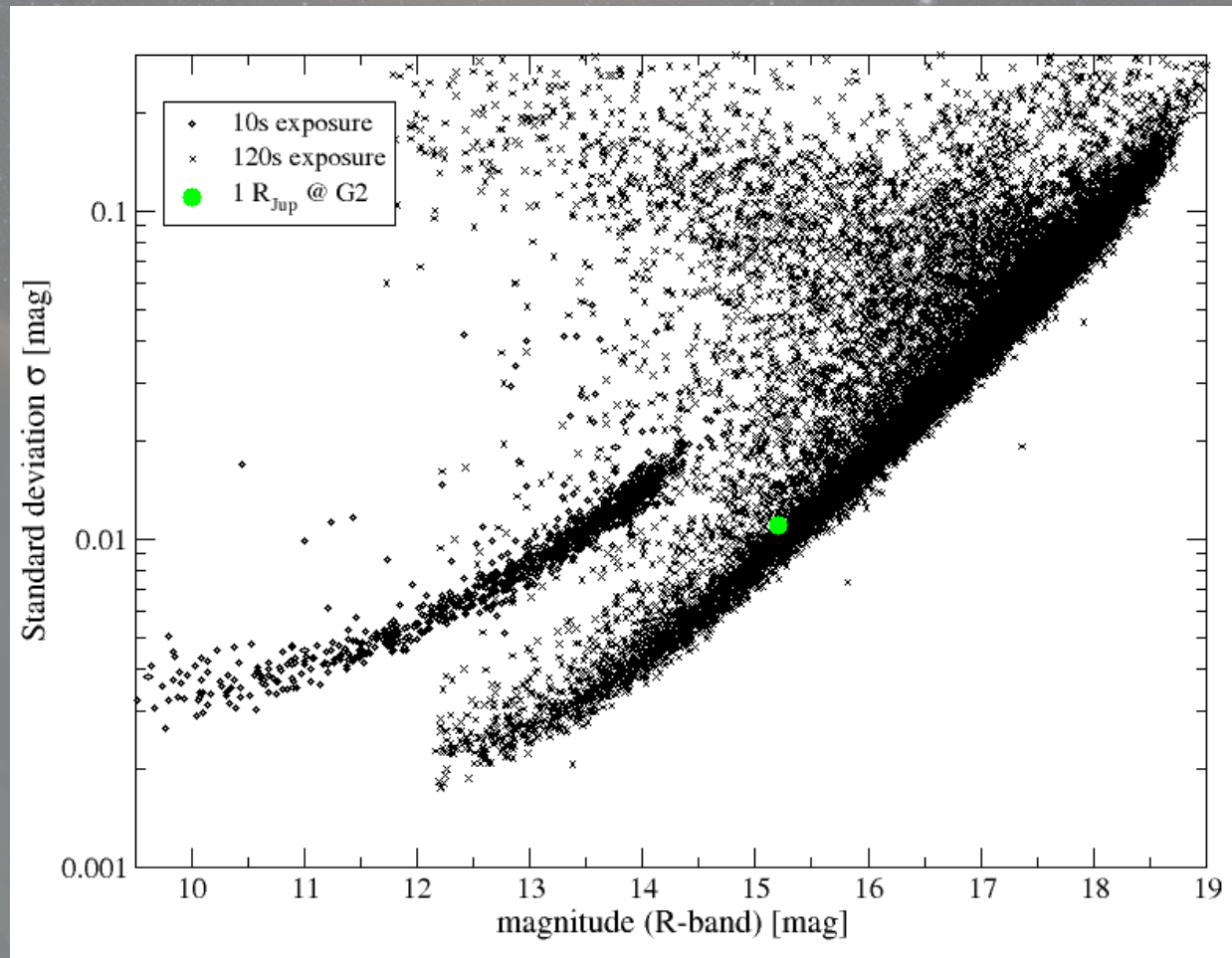
for 10s exposure time:

163 stars: $\sigma < 5$ milli-mag

for 120s exposure time:

690 stars: $\sigma < 5$ mmag

5351 stars: $\sigma < 30$ mmag



Combining data of different nights and telescopes

- Aperture photometry for each night

Combination of the data sets:

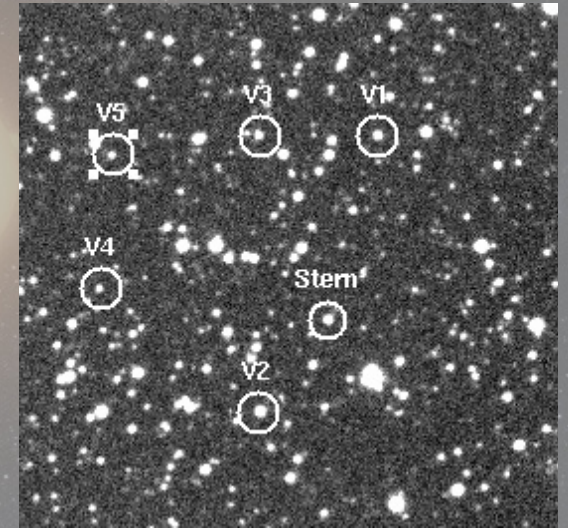


Combining data of different nights and telescopes

- Aperture photometry for each night

Combination of the data sets:

- Differential photometry with individual comparison stars for each star
 - Comparison stars:
 - Small separation,
 - Similar colour and
 - Similar brightness
 - small influence of the optical effects of earth atmosphere (e.g. refraction) and the optical elements in the telescope (e.g. wavelength depended sensitivity)



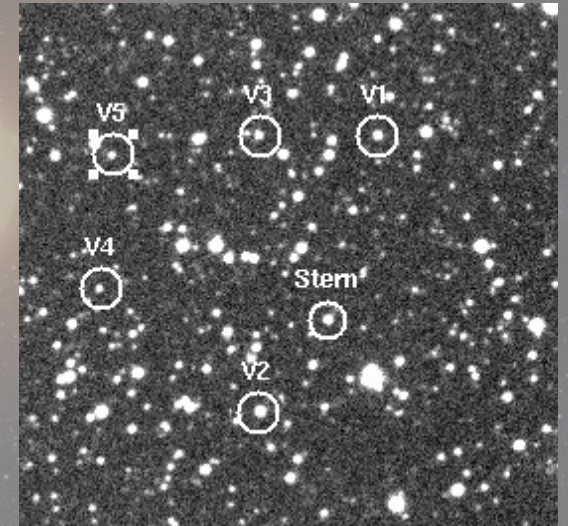
Part of the Schmidt-Telescope Camera: reduced image with star and comparison stars

Combining data of different nights and telescopes

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 - Similar brightness
 - small influence of the optical effects of earth atmosphere (e.g. refraction) and the optical elements in the telescope (e.g. wavelength depended sensitivity)
- Differential Photometry for each telescope
- Combining light curves from different telescopes with overlapping observing times



Part of the Schmidt-Telescope Camera: reduced image with star and comparison stars

Search for transit signals, eclipses and variability

Search for period signals:

- Lomb-Scargle-Periodogramm (Scargle 1982, Lomb 1976):
 - Sinusoidal signals
 - Search for strongest signal
- String length (Dworetzky 1983):
 - Any periodic signal
 - Search for local, significant minimums

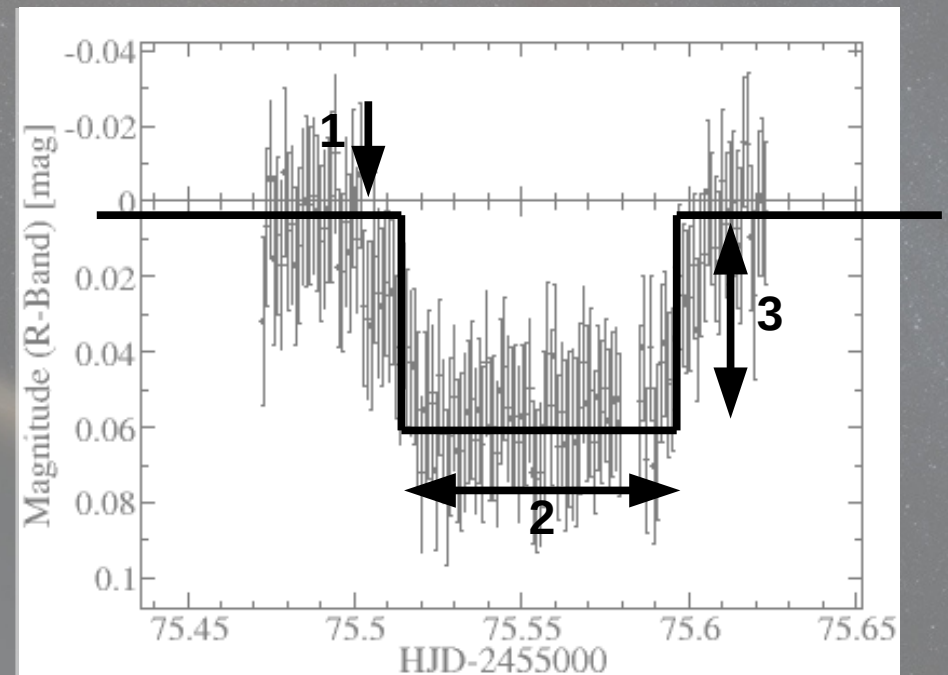
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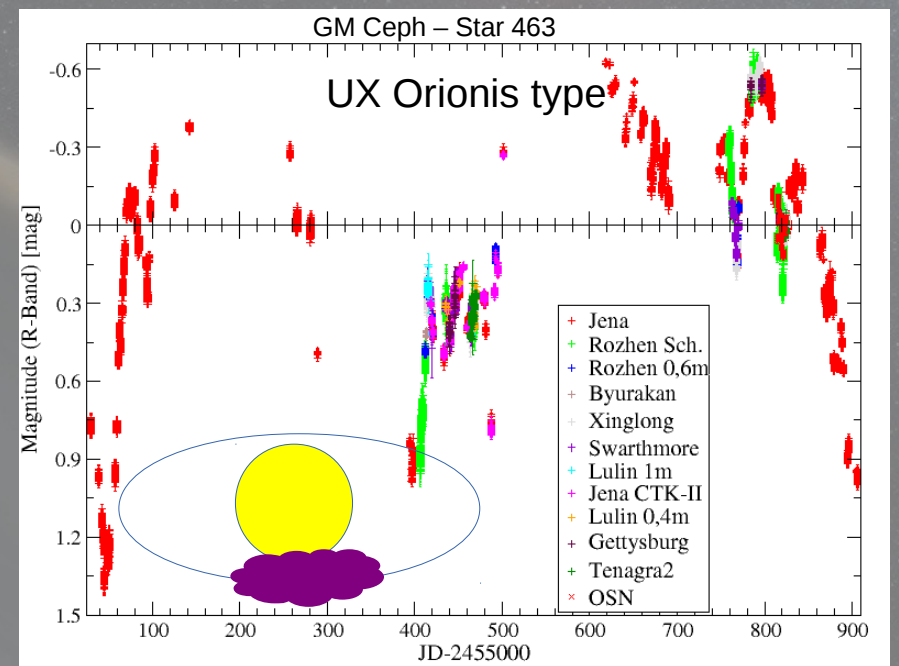
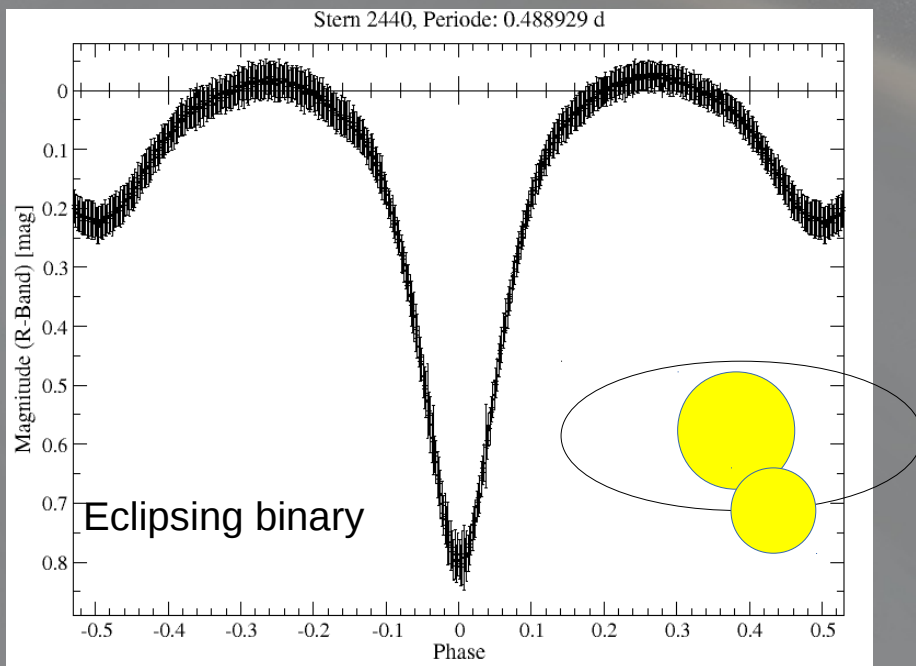
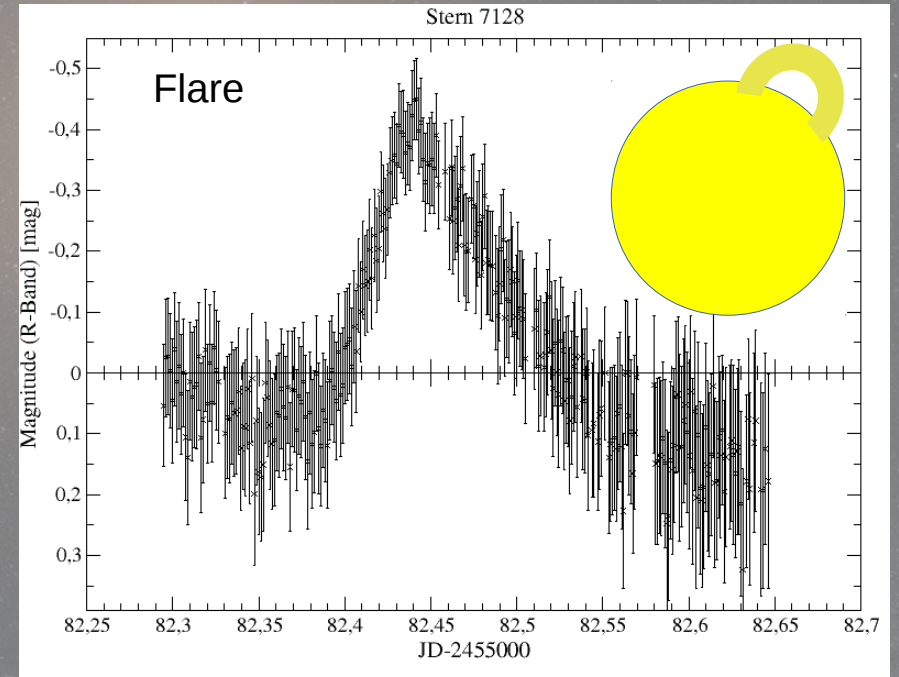
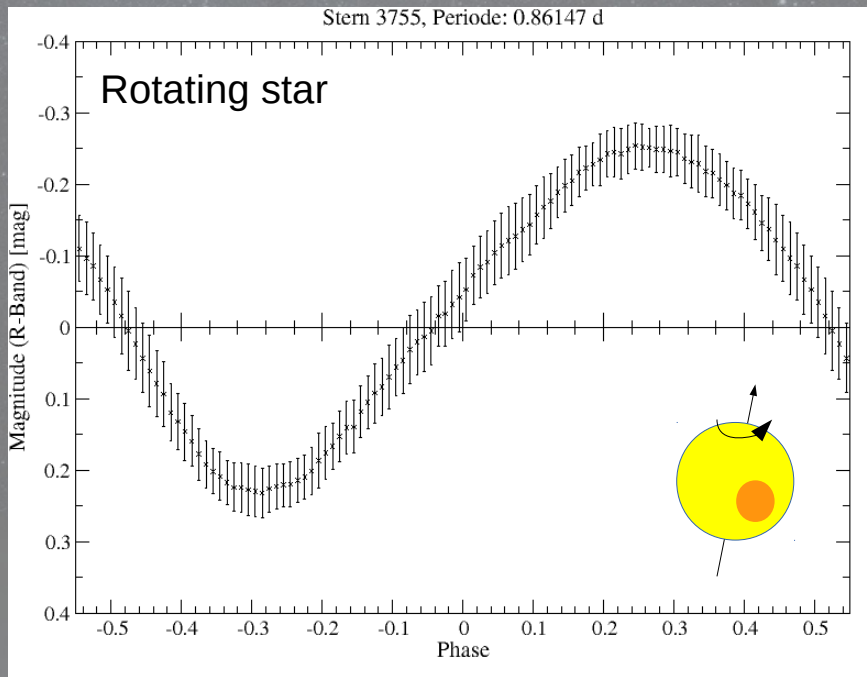
Search for boxes:

- Approach of a transit with a box
 - Variation of the start (1)
 - Variation of the width (2)
 - Fitting the depth to the data (3)
- Significant signals



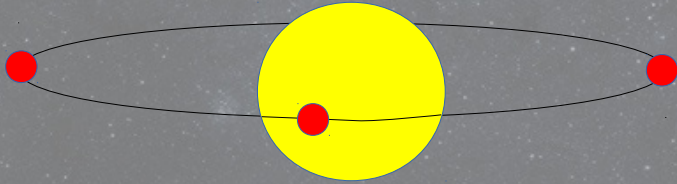
→ Plotting the light curves for periods and boxes, visual inspection

Example light curves



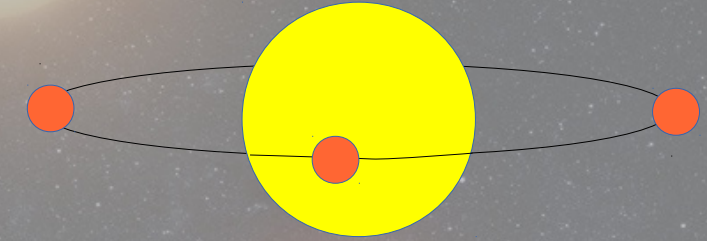
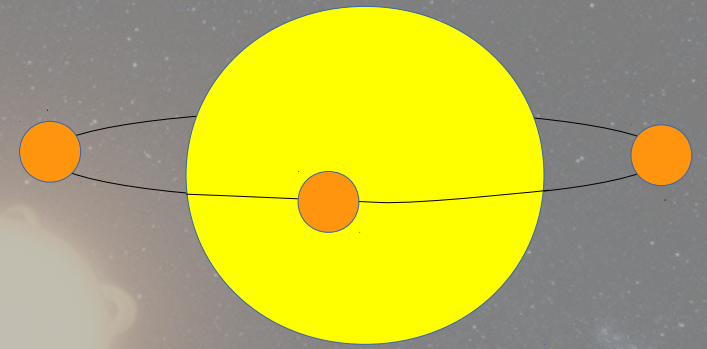
False-positive transit signals

Similar radius ratio of an eclipsing binary, consisting of giant and dwarf

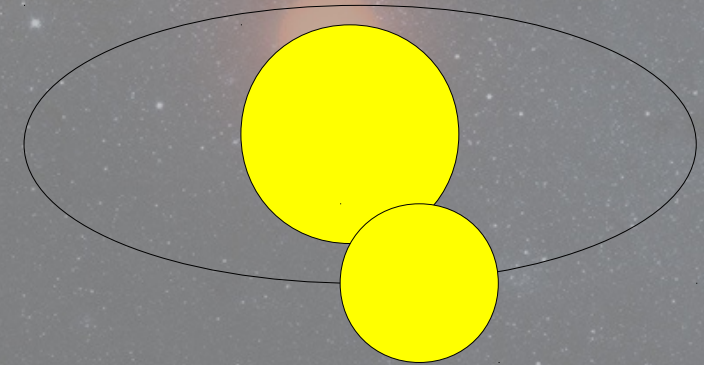


real transit

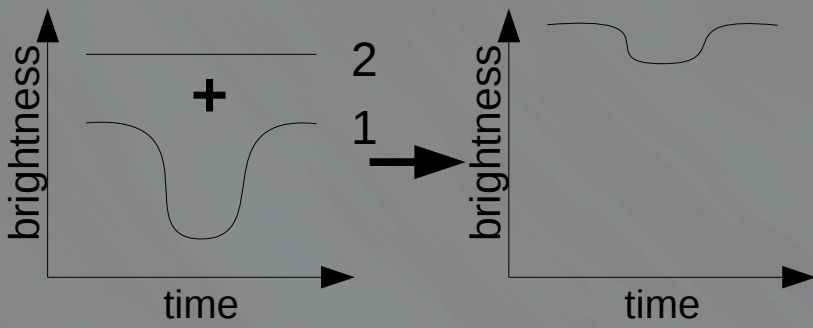
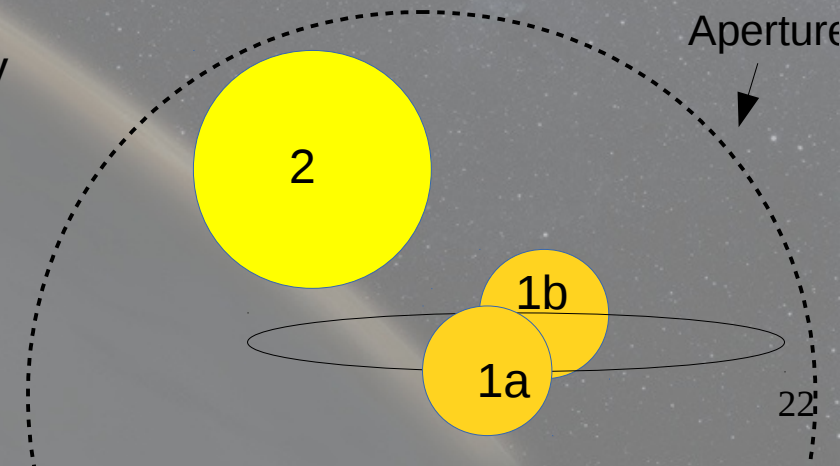
Degeneration of the radius between late type stars, brown dwarfs and giant planets



Grazing eclipse



Blended eclipsing binary



Follow-up

- Imaging with adaptive optics in the infrared to resolve the optical PSF
- Spectroscopy for radial velocity measurements to determine the mass

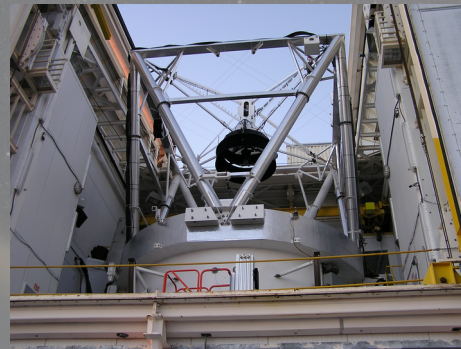
Calar Alto
2.2 m telescope



Isaac Newton telescope
(INT, 2.2 m)



MMT (6 m)



Subaru telescope (8 m)



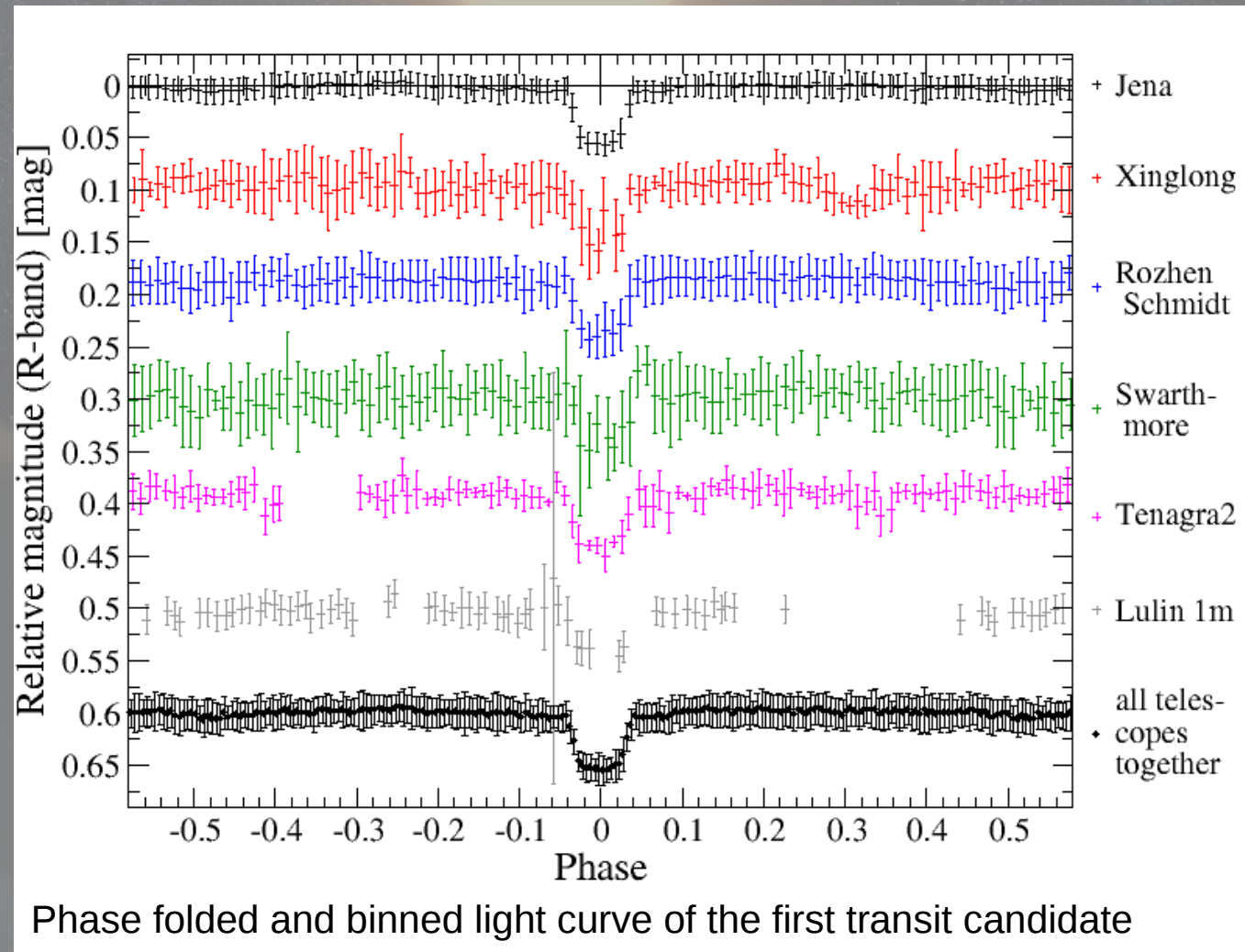
Keck telescope (10 m)



Transit candidate 1 – Star 3218

- Before follow-up from optical and infrared colours:
 - CMD and photometric spectral type consistent with membership in Trumpler 37
 - Low resolution spectroscopy: sun-like star

Period $P = 1.36$ d



Transit candidate 1 – Star 3218

- Before follow-up from optical and infrared colours:
 - CMD and photometric spectral type consistent with membership in Trumpler 37
 - Low resolution spectroscopy: sun-like star

Period $P = 1.36$ d

Modelling the light curve:

Depth:

$$\Delta R = 55 \text{ milli-mag}$$

Duration:

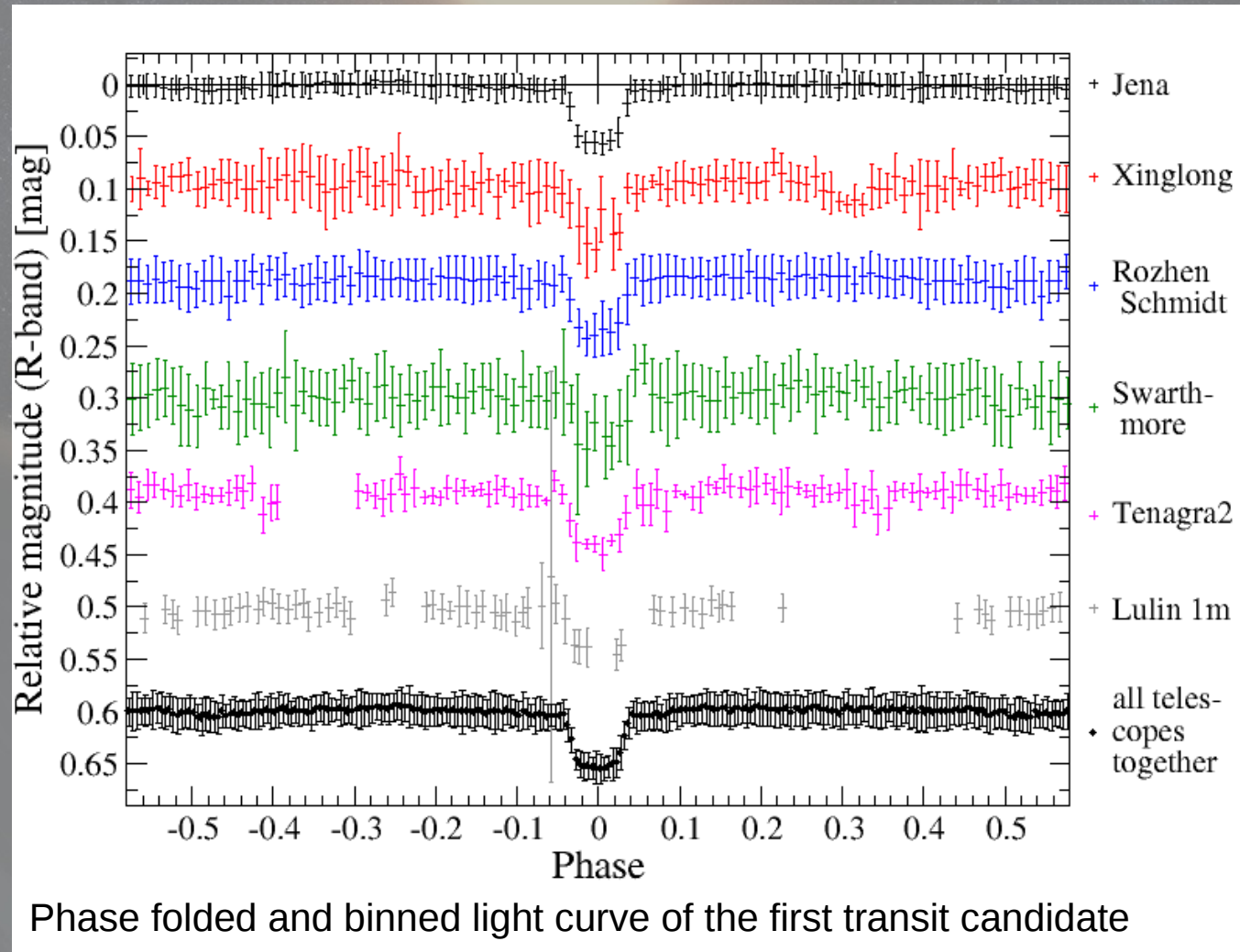
$$t_{\text{trans}} = 160 \text{ min}$$

Radius ratio:

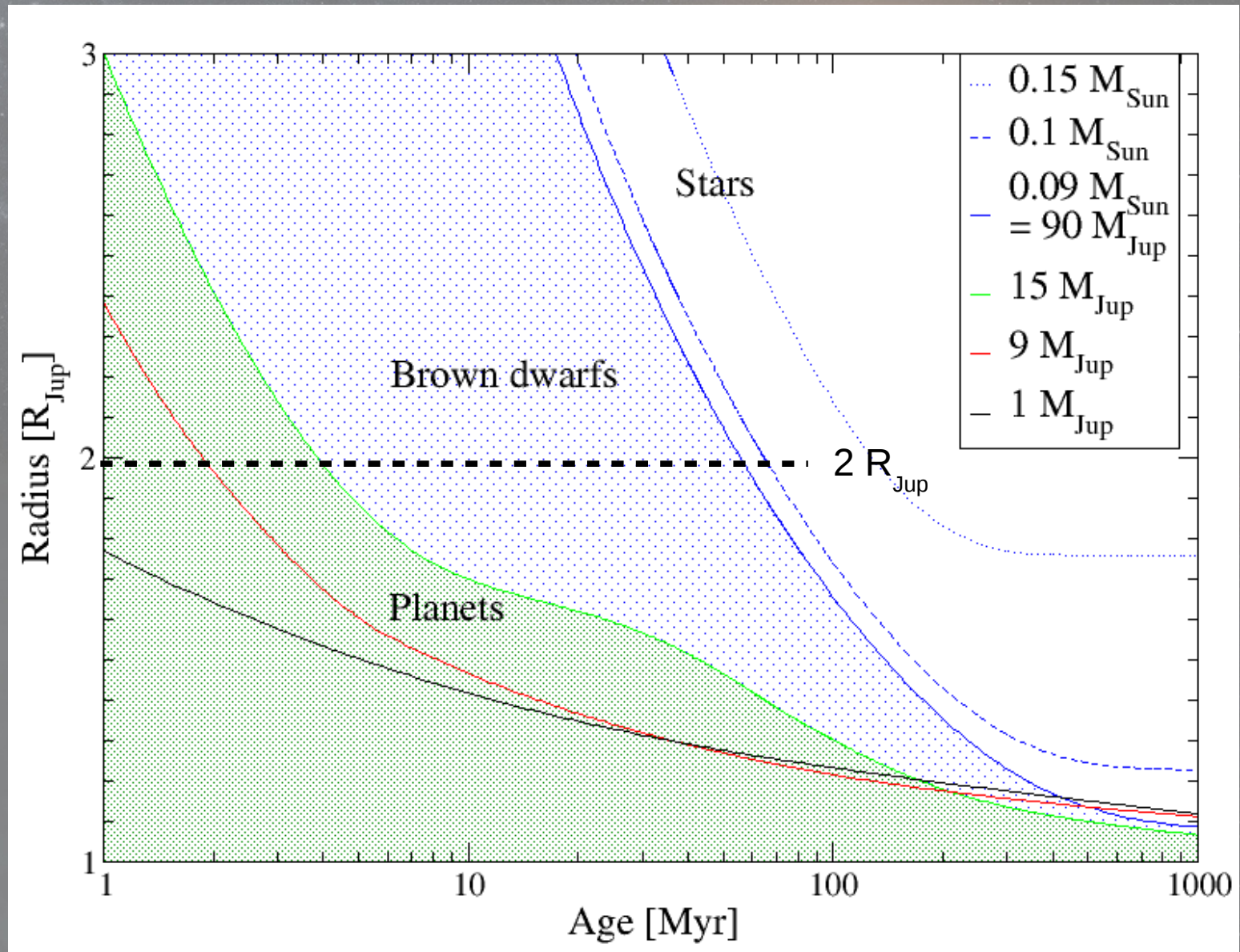
$$R_p/R_* = 0.20$$

Assumption $R_* \approx 1 R_{\odot}$:

$$\rightarrow R_p \approx 2 R_{\text{Jup}}$$



Transit candidate 1 – Star 3218



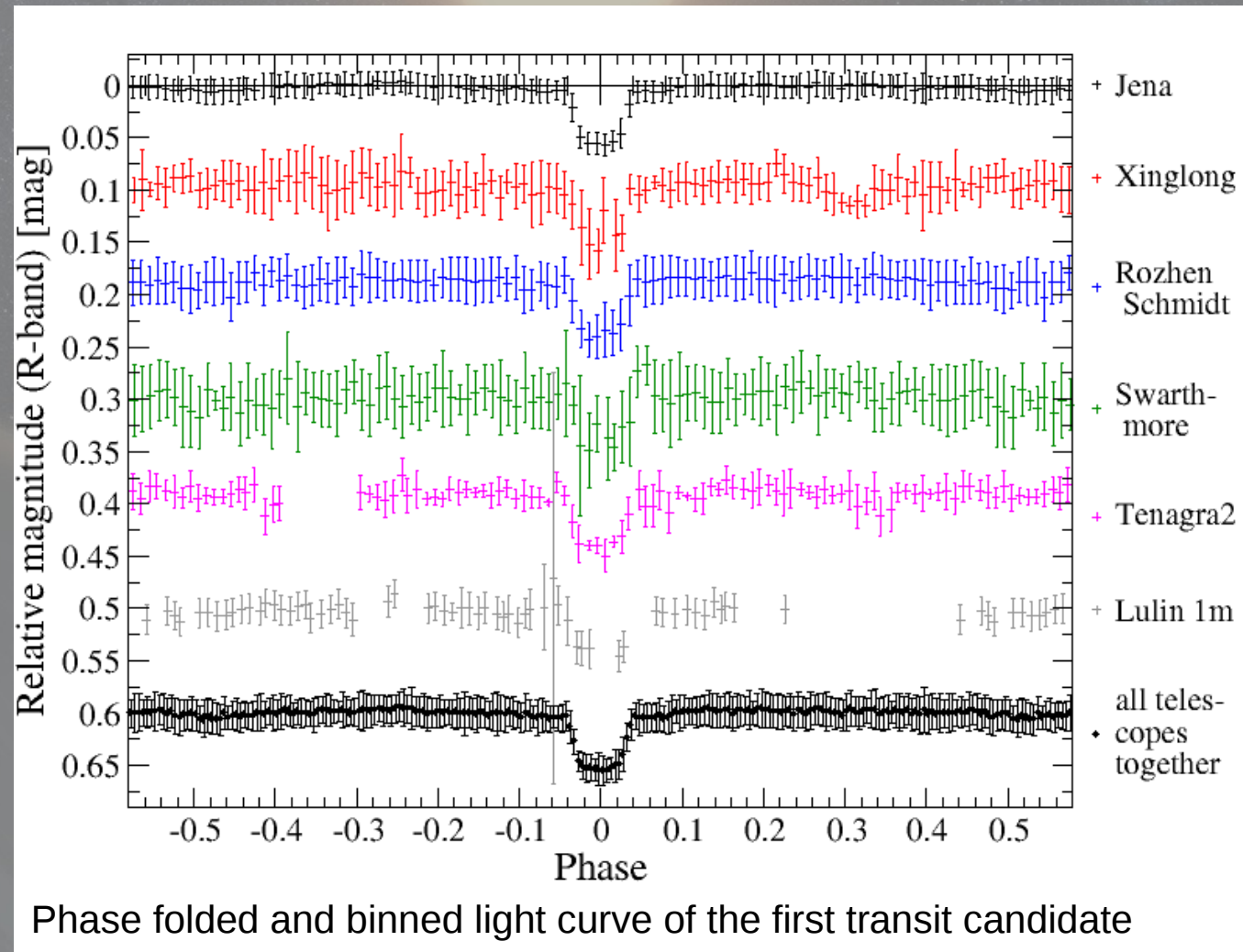
Contraction of the radius (data from Burrows et al. 1997)

Transit candidate 1 – Star 3218

- Before follow-up from optical and infrared colours:
 - CMD and photometric spectral type consistent with membership in Trumpler 37
 - Low resolution spectroscopy: sun-like star

No secondary transit

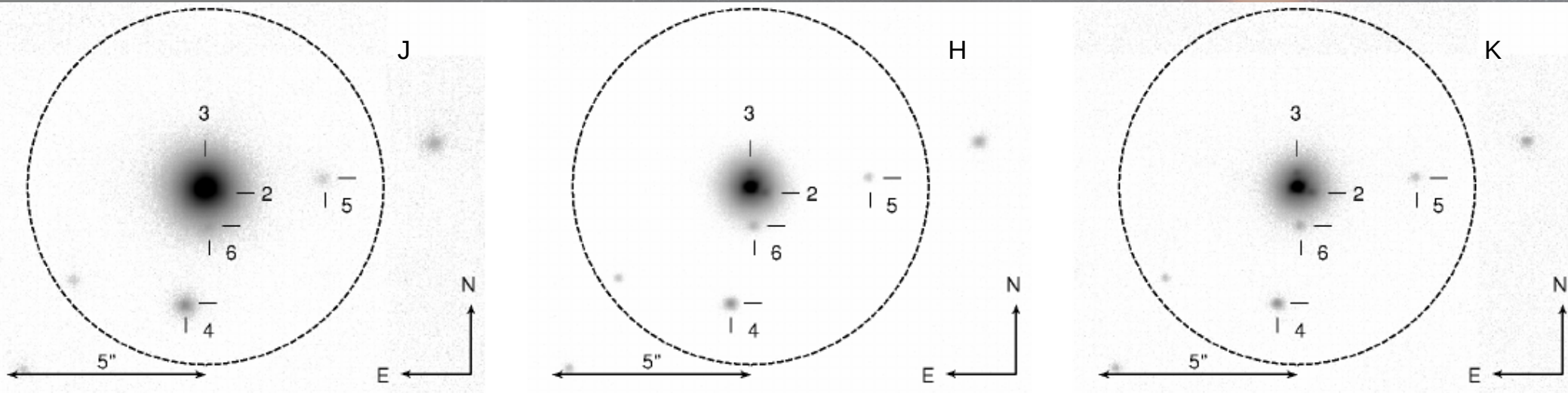
→ planetary transit possible, excluding the false positives



Transit candidate 1

- High resolution imaging IRCS and adaptive optic from the Subaru telescope
- Resolving the stars in the aperture of the YETI-telescopes up to 0.2"
- Several objects
 - Measuring the infrared brightness using PSF-photometry
 - Extrapolating to the optical
 - All too faint for blended eclipsing binary

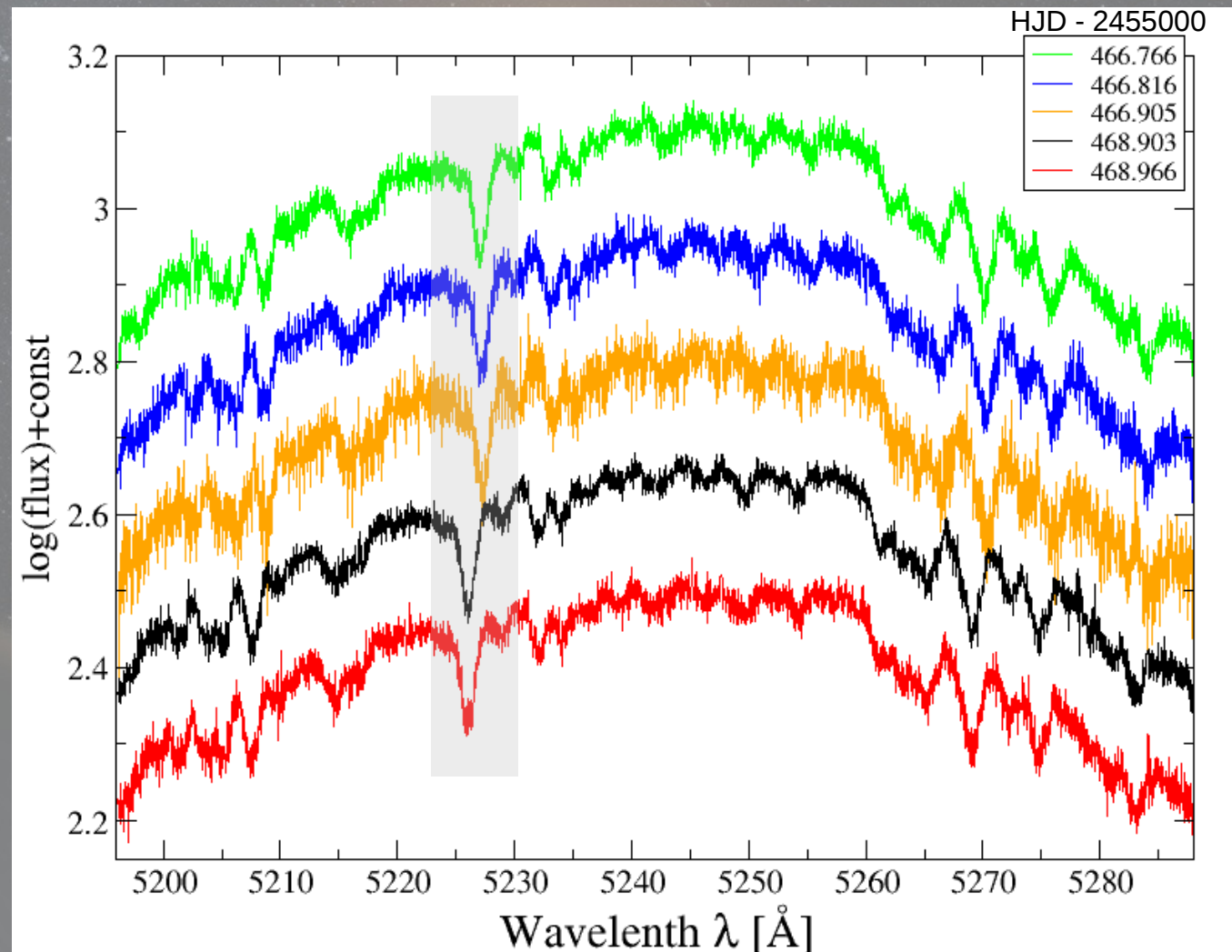
--- Aperture in the YETI-telescopes (4.5")



Reduced IRCS-Pictures of the secondary transit candidate in the H and K filter

Transit candidate 1 – Star 3218

- High resolution spectra from HIRES
- Close to the quadratures



Shift of absorption lines in the HIRES Spectra

Transit candidate 1 – Star 3218

- Cross correlation of the model spectra from the PHOENIX NextGen2 model with the HIRES spectra
 - Range of model spectra
 - stellar parameters
 - Best matching model spectrum
 - radial velocity
 - amplitude of 35 km/s

HJD – 2455000	RV [km/s]
466.765	10.8 ± 2.3
466.816	14.1 ± 3.4
466.906	22.5 ± 2.4
468.903	-47.3 ± 2.1
468.966	-48.4 ± 2.7

HJD: heliocentric julian date
RV: radial velocity

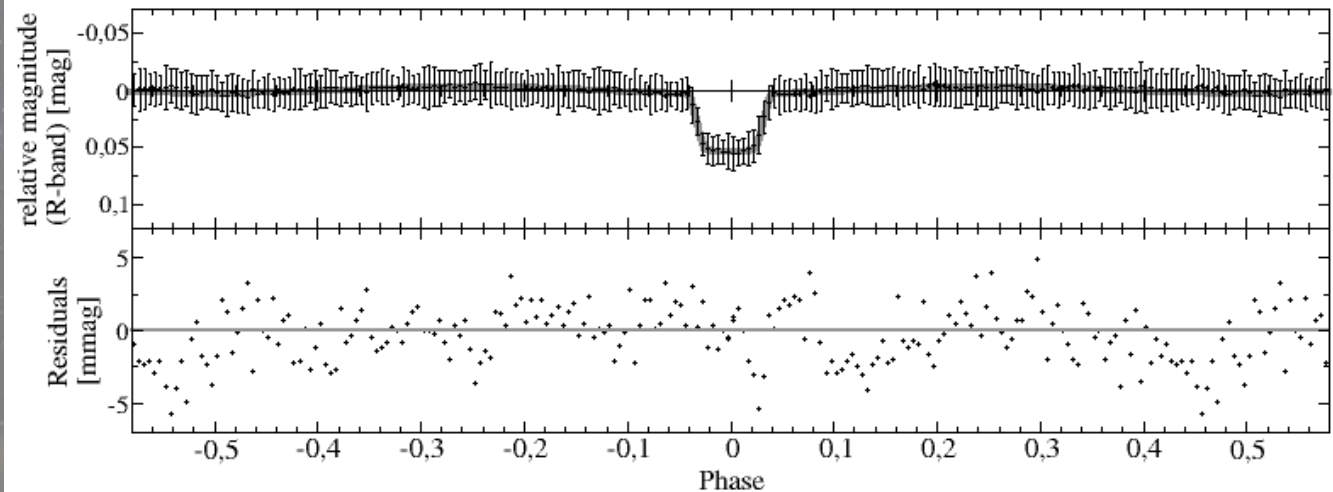
Transit candidate 1 – Star 3218

- Modelling of light curve and radial velocity curve together, using PHOEBE:

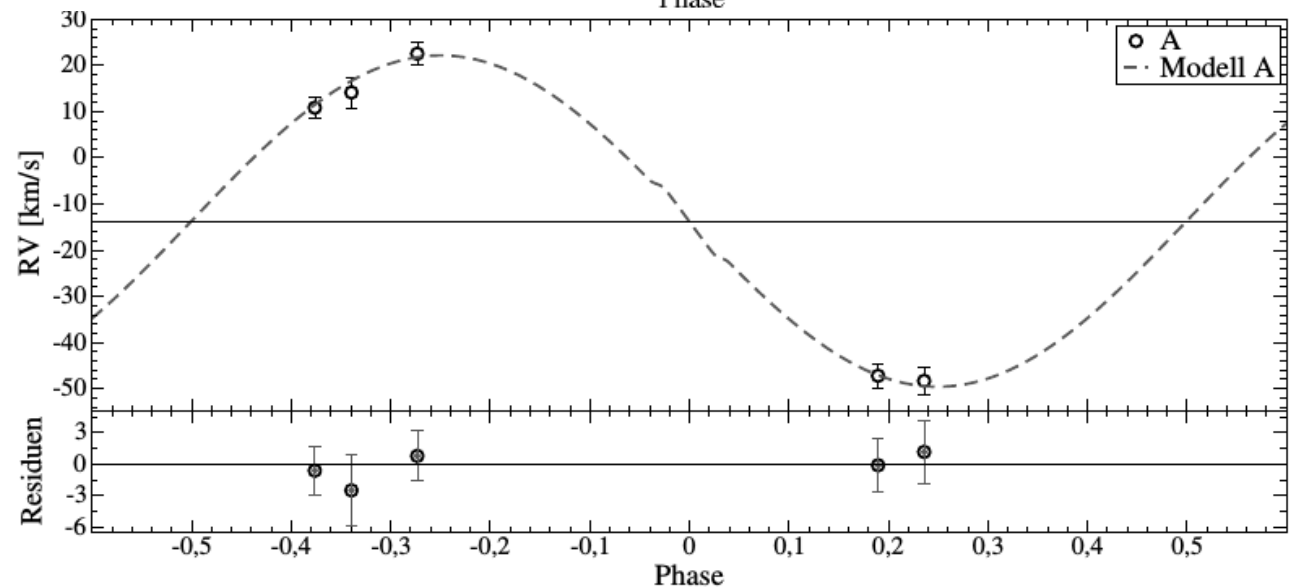
Assumptions:

- Mass and radius of primary component from tables
- Circular orbit

Light curve (R)



Radial velocity



Transit candidate 1 – Star 3218

	<u>Primary star:</u>		<u>Companion:</u>
T_{eff} [K]	6300 ± 300		
γ [km/s]	-13.78 ± 0.13	*	
EW (Li) [mÅ]	< 5	**	
M [M_{\odot}]	1.05 ... 1.38		M [M_{\odot}] 0.22 ... 0.26
R [R_{\odot}]	1.16 ... 1.26		R [R_{\odot}] 0.24 ... 0.26
Spectral type	F4 ... G0		Spectral type M5 ... M6

→ eclipsing binary

* : consistent with membership in Trumpler 37

** : not a young age → no member in Trumpler 37

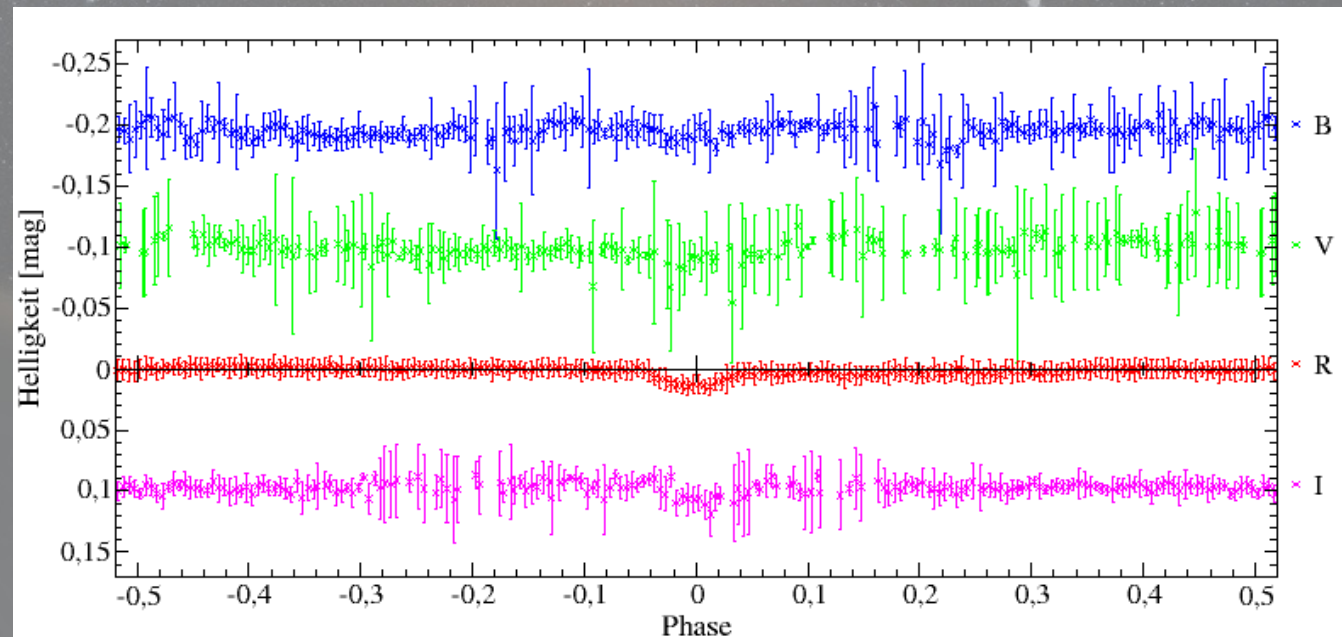
Errmann et al., 2014

$M_{\odot} = M_{\text{sun}} = 1.99 \cdot 10^{30}$ kg (solar mass)

radial velocity of Trumpler 37: (-15.3 ± 3.6) km/s (Sicilia-Aguilar et al. 2006)

Transit candidate 2 – Star 523

- Before follow-ups:
 - Optical and infrared colours: consistent with membership in Trumpler 37
 - Proper motion (Marschall & van Altena 1987) : 4% membership probability in Trumpler 37



Phase folded and binned light curve in B, V, R, and I of the second transit candidate in Trumpler 37

Transit candidate 2 – Star 523

- Before follow-ups:
 - Optical and infrared colours: consistent with membership in Trumpler 37
 - Proper motion (Marschall & van Altena 1987) : 4% membership probability in Trumpler 37

Periode $P = 0.74$ d

Modelling of the light curve:

Depth:

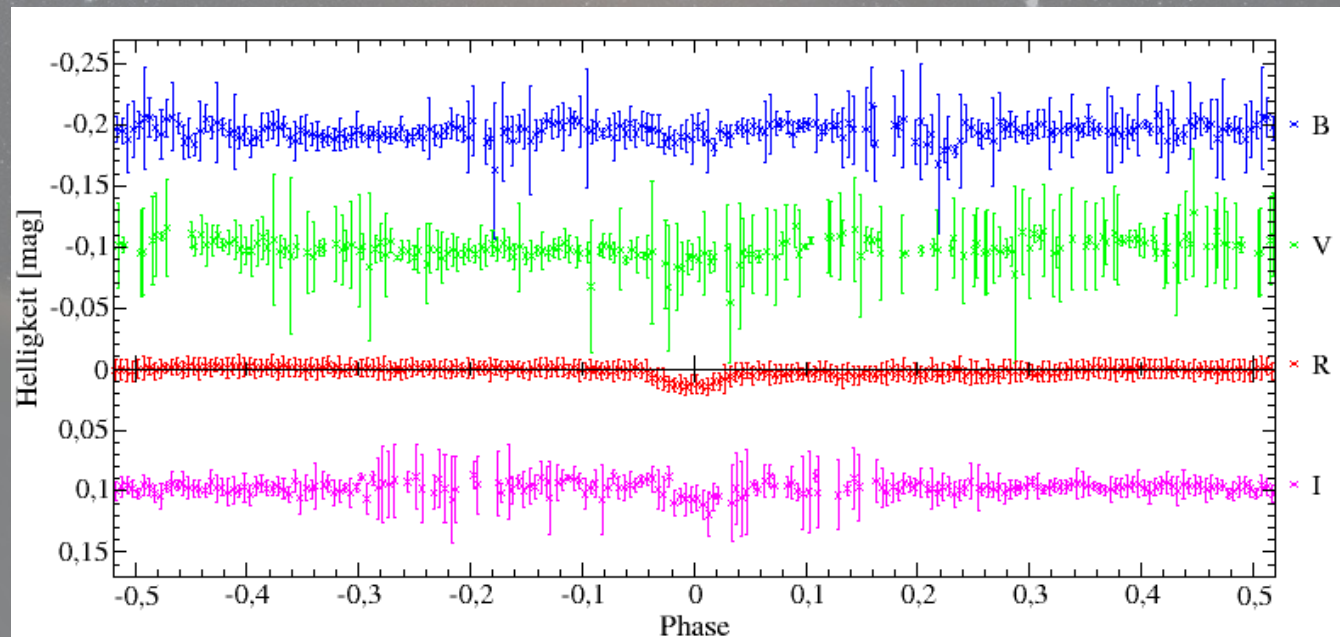
$$\Delta R = 12 \text{ milli-mag}$$

Radius: $R_p/R_* = 0.11$

$$\rightarrow R_p = 1 R_{\text{Jup}}$$

No secondary eclipse

→ planetary transit possible, excluding the false positives



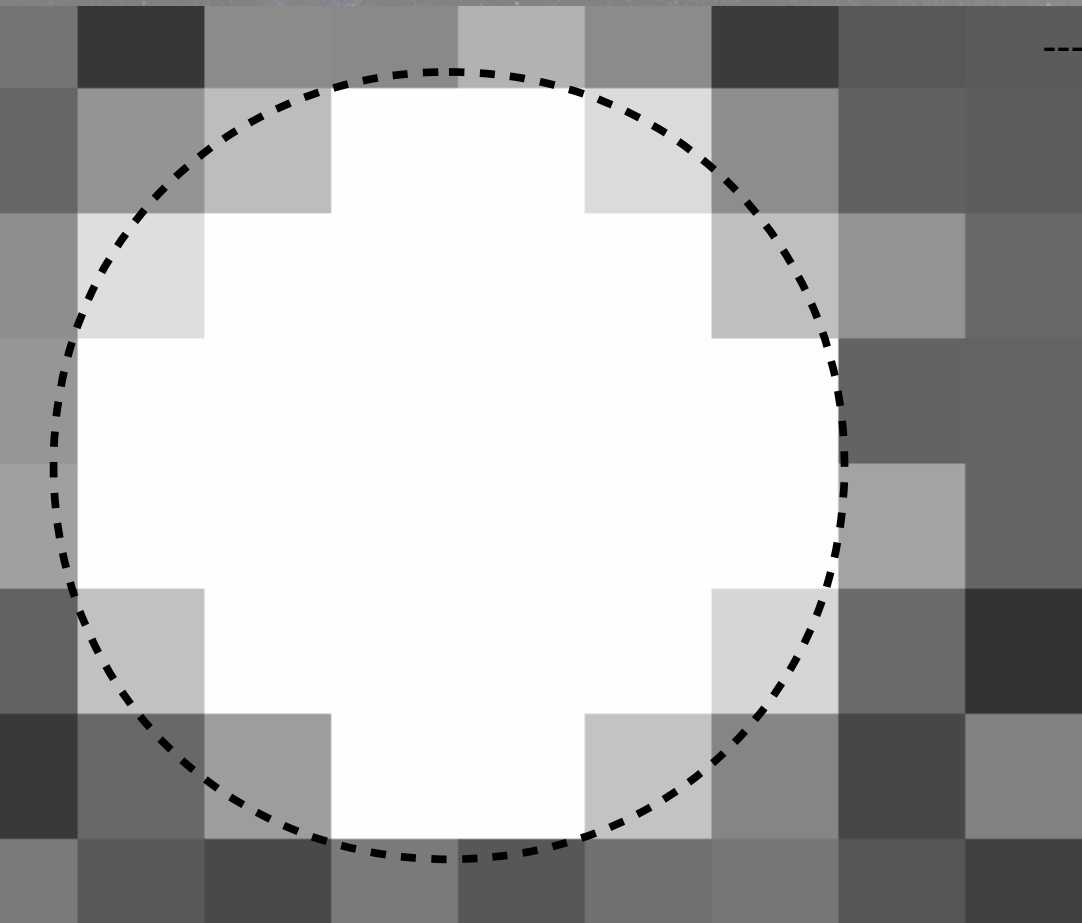
Phase folded and binned light curve in B, V, R, and I of the second transit candidate in Trumpler 37

$$R_{\odot} = 695 \cdot 10^6 \text{ m (Solar radius),}$$

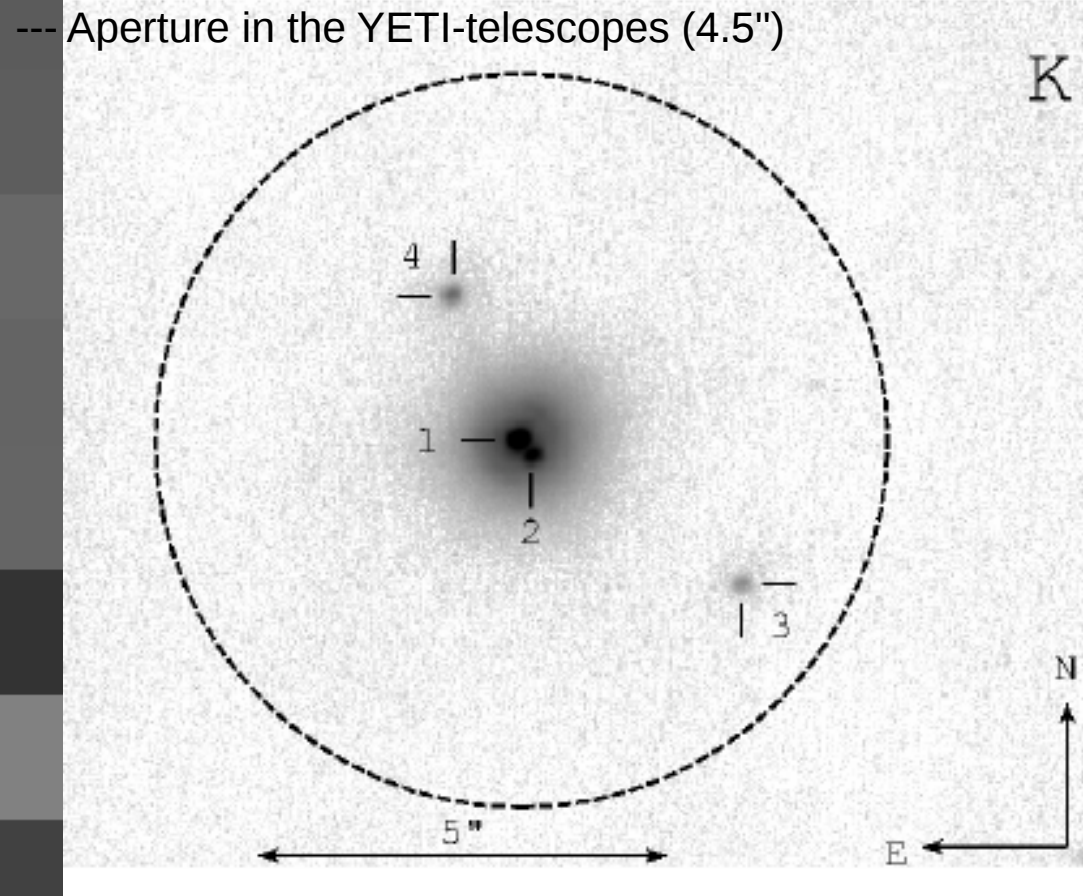
$$R_{\text{Jup}} = 71.5 \cdot 10^6 \text{ m (Jupiter radius)}$$

Transit candidate 2 – Star 523

- High resolution imaging IRCS and adaptive optic from the Subaru telescope
- Resolving the stars in the aperture of the YETI-telescopes up to 0.2"



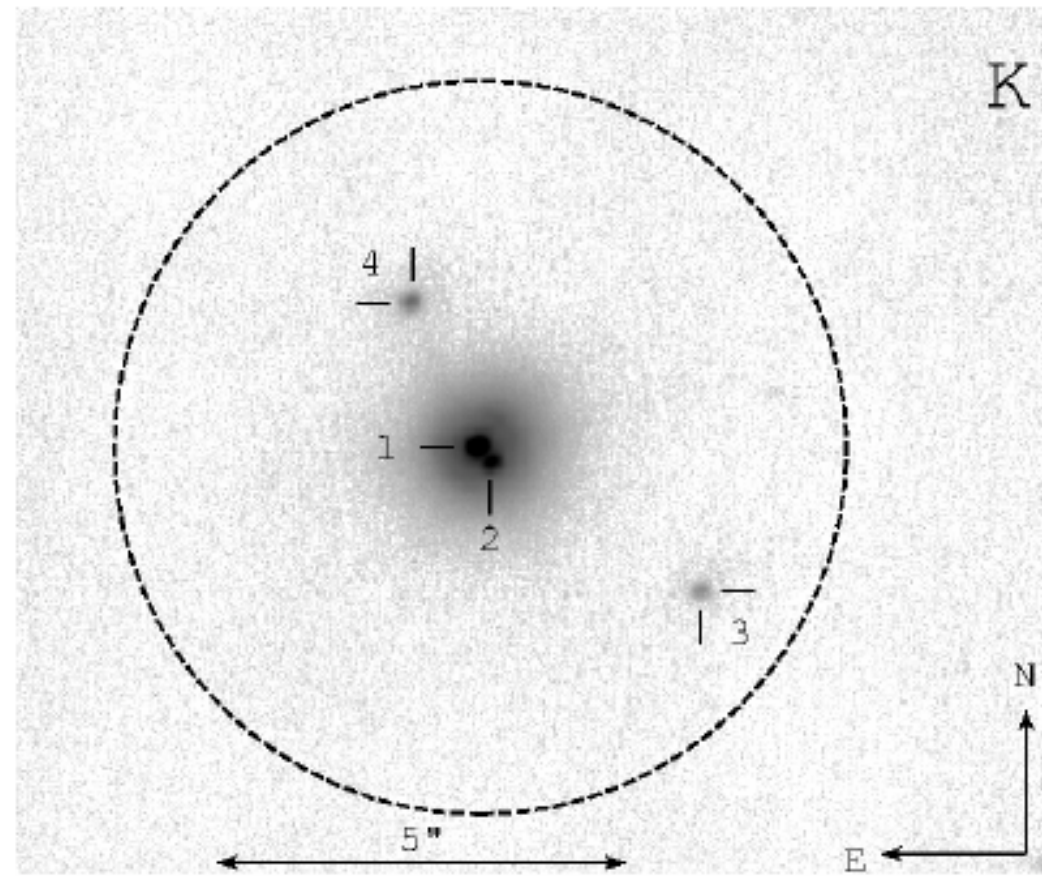
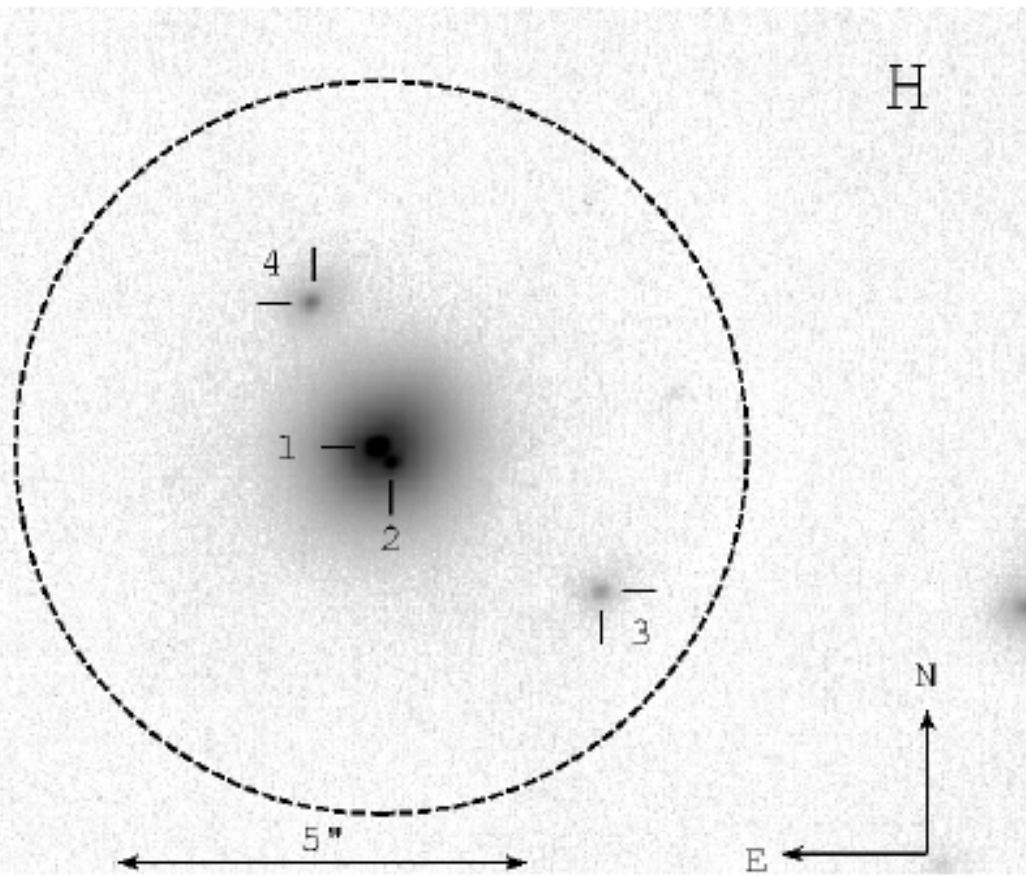
STK image of the star 523 in R filter



Reduced IRCS-Picture of the secondary transit candidate in the K filter

Transit candidate 2 – Star 523

- High resolution imaging IRCS and adaptive optic from the Subaru telescope
- Resolving the stars in the aperture of the YETI-telescopes up to 0.2"

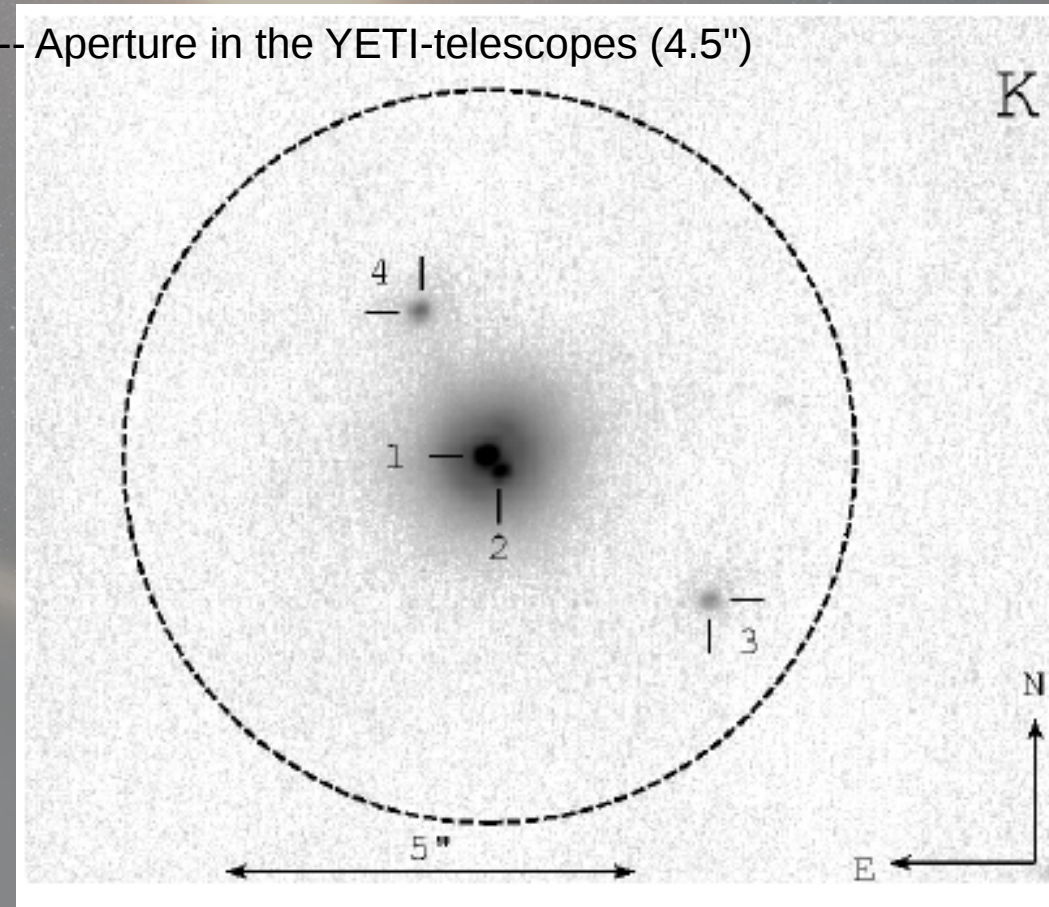


Reduced IRCS-Pictures of the secondary transit candidate in the H and K filter

Transit candidate 2 – Star 523

- High resolution imaging IRCS and adaptive optic from the Subaru telescope
- Resolving the stars in the aperture of the YETI-telescopes up to 0.2"
- Brightness of star 4 and 2 in H and K → reason for signal, if eclipsing binary
- Other ground based searches:
 - only few transit signals are real planets (O'Donovan et al. 2006, Street et al. 2007, Latham et al. 2009)
 - low probability that real transit

--- Aperture in the YETI-telescopes (4.5")



Reduced IRCS-Picture of the secondary transit candidate in the K filter

Results in Trumpler 37

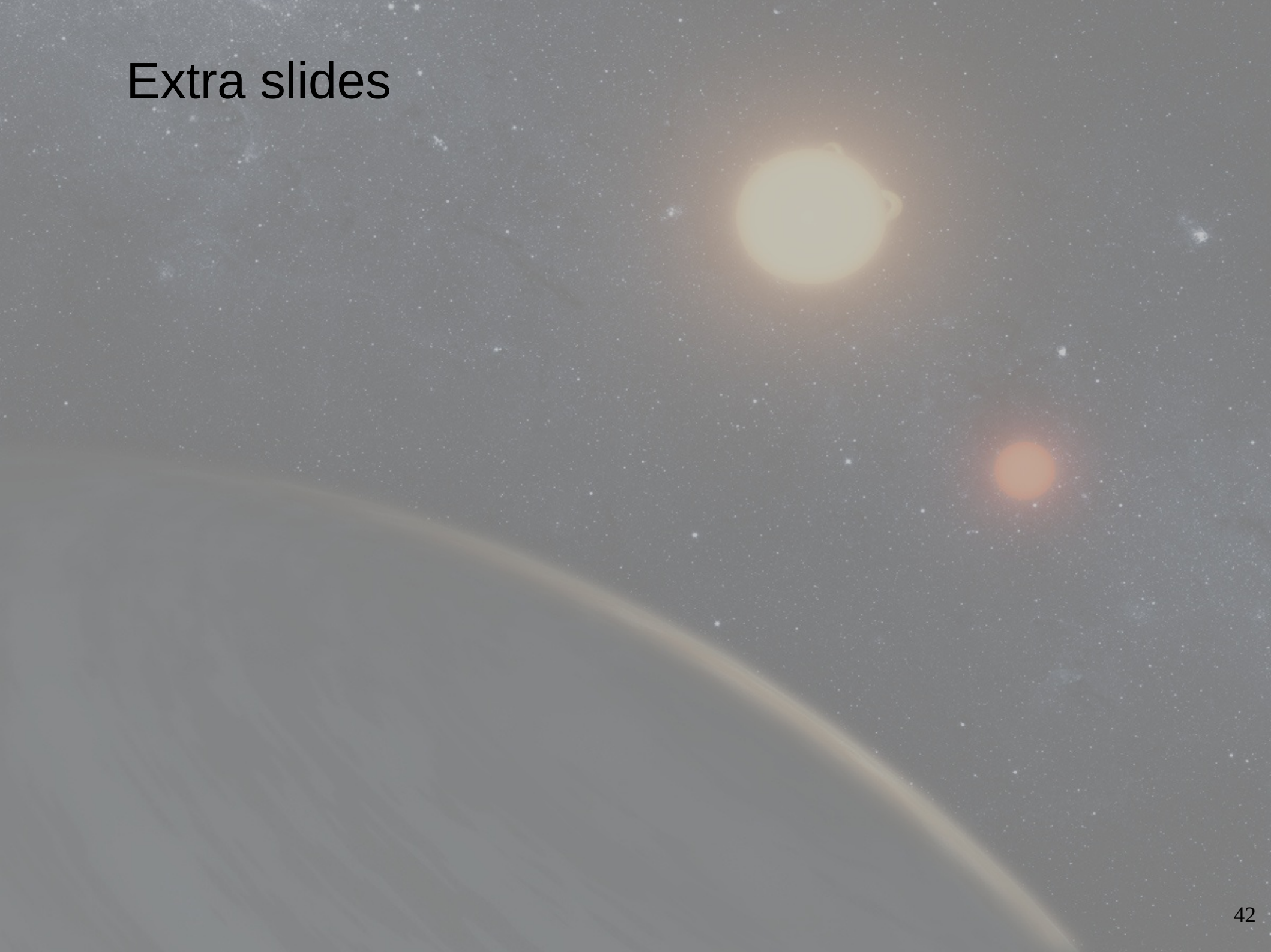
- Combination of literature data
- Reduction and analysis of 793 h observational data of 12 telescopes
- 400 new variable stars
- Follow-up for two transit candidates
 - false-positives
- Follow-up of young eclipsing binaries
 - characterising the system properties

Future work

- Own observations for membership of stars in Trumpler 37
- Binning of the light curves → more transit signals?

Low probability for transiting planets in one open cluster
→ observation of several clusters with YETI

Extra slides



Observations



View Finder

Focus:	Cassegrain
Diameter:	10"
Focal length:	2250 mm
f/D:	9
Camera	CTK/CTK-II

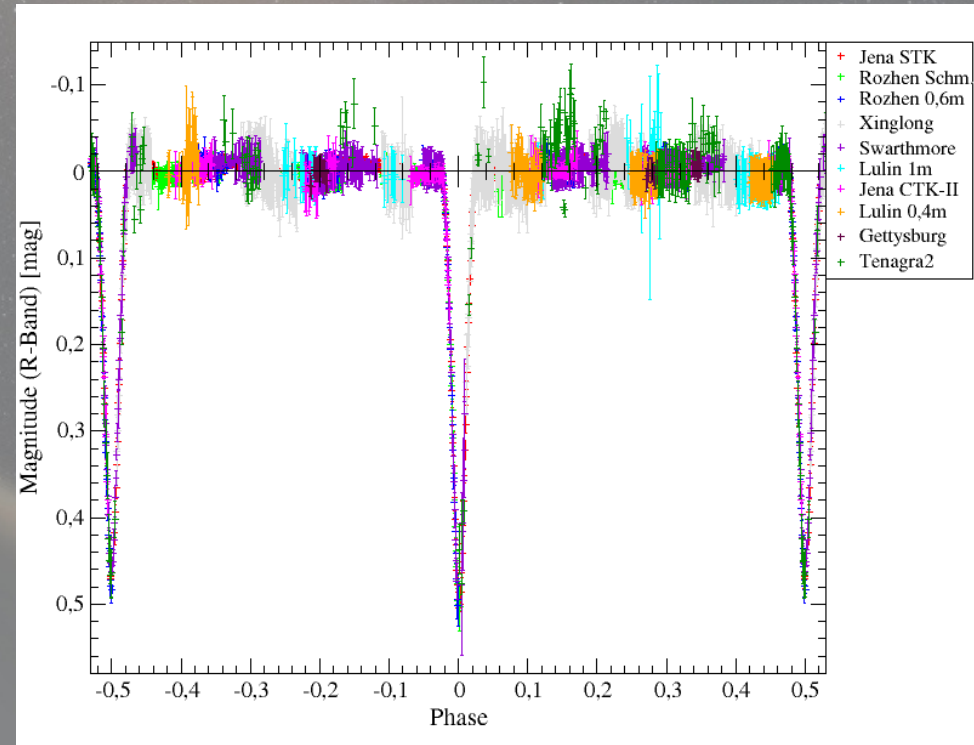
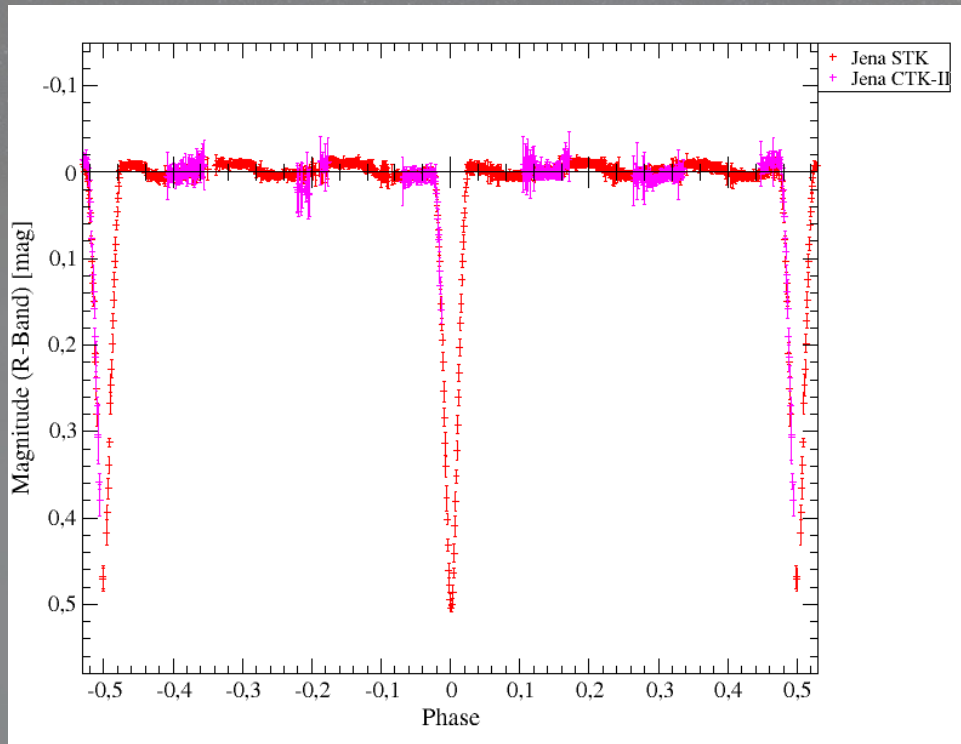
Telescope

Focus:	Schmidt / Nasmyth
Diameter:	60 cm / 90 cm
Focal length:	1800 mm / 13500 mm
f/D:	3 / 15
Camera	STK

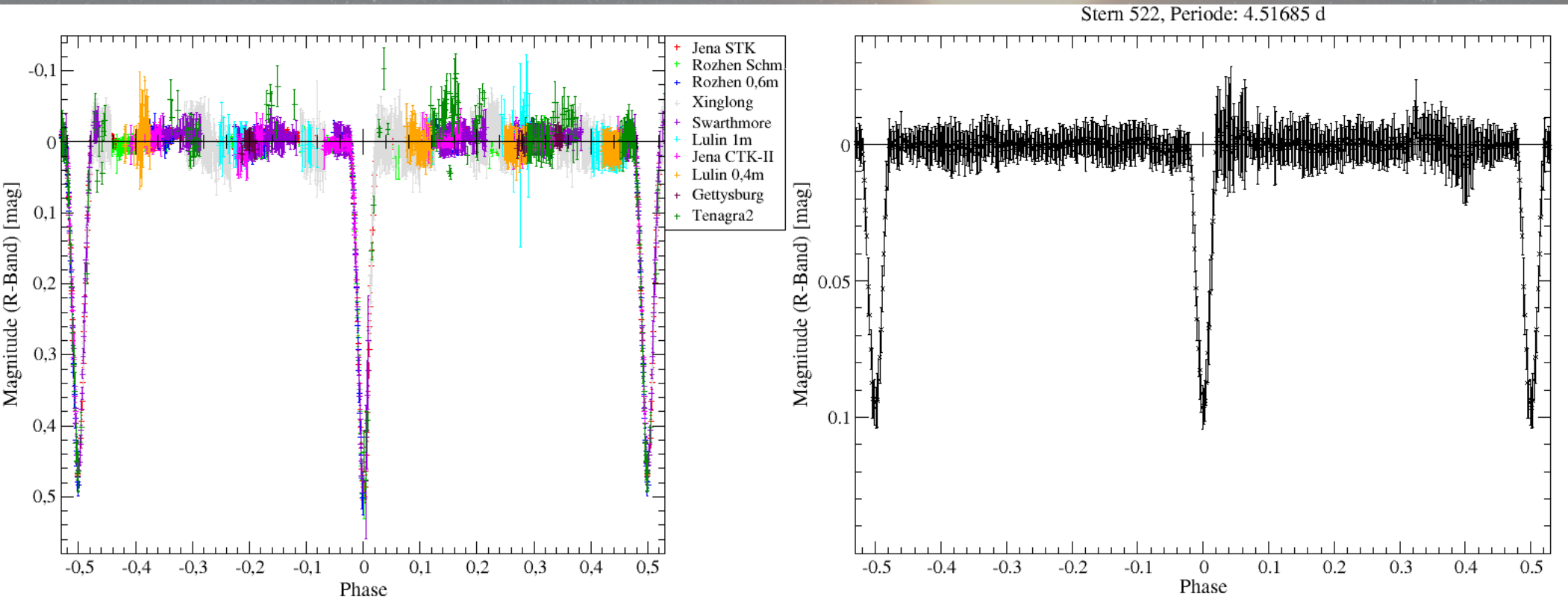
Guide Scope

Focus:	Refractor
Diameter:	10"
Focal length:	3000 mm
f/D:	15
Camera	RTK

Star 118 Jena / YETI

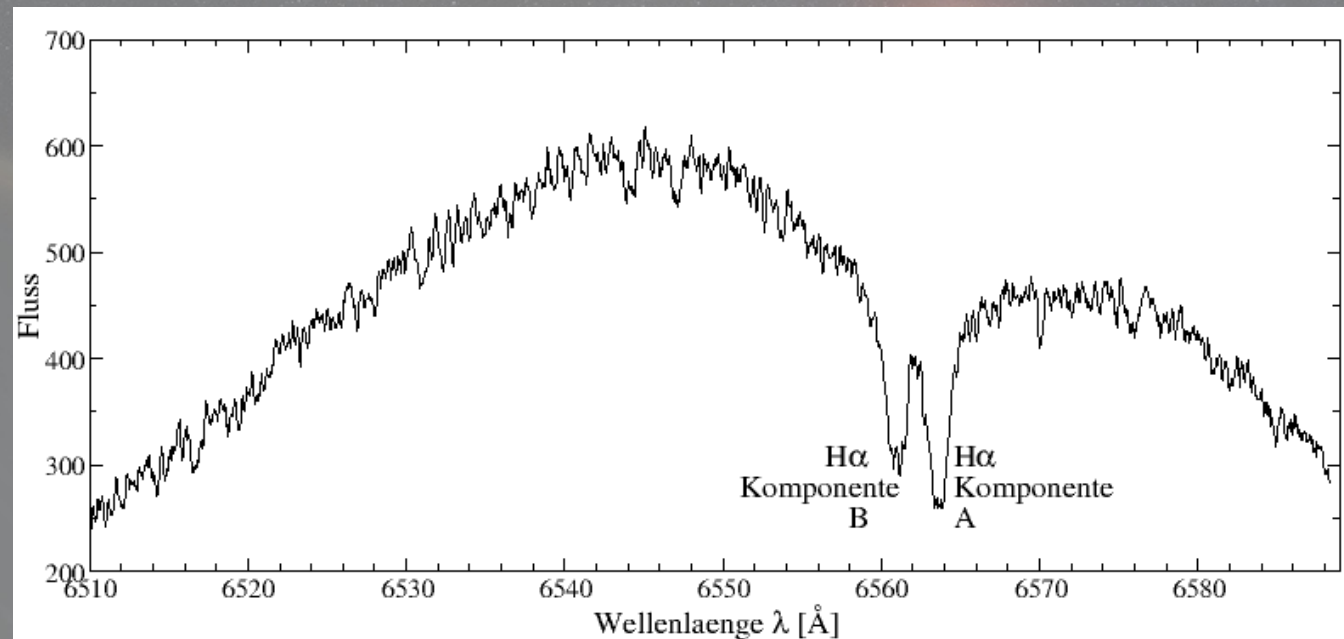


Light curves of the eclipsing, double lined binaries



Doubled lined young eclipsing binaries

- High resolution HIRES or HDS spectra
- Cross correlation with PHOENIX NextGen2 model spectra:
Simultaneous use of two model spectra
 - stellar parameters of both components: T_{eff} , $\log g$, $v \sin i$
 - orbital parameters: radial velocity
- Simultaneous modelling of light curves and radial velocities with PHOEBE
 - Masses, radii
- Comparison with star formation models



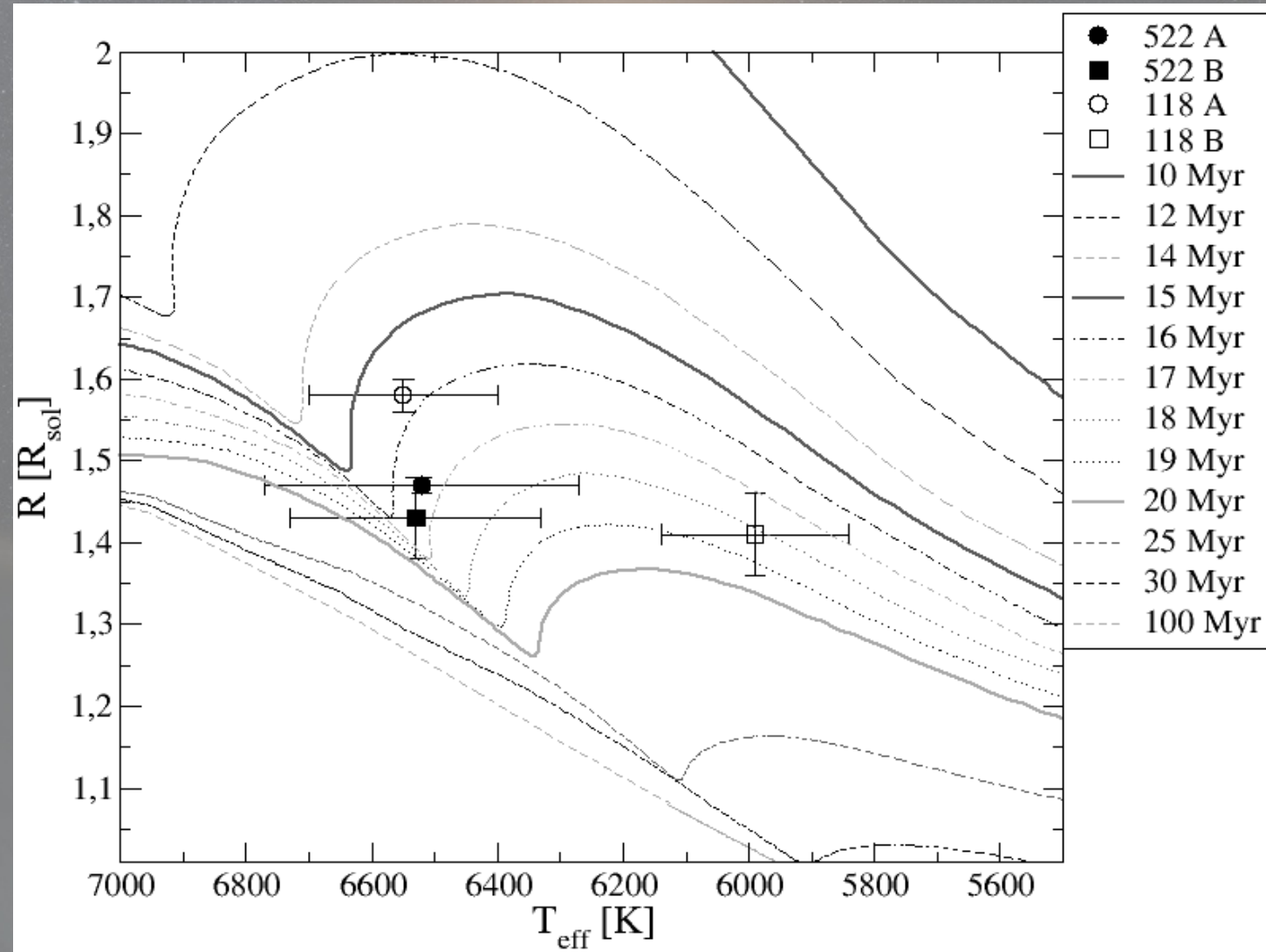
HDS spectrum of star 522

HIRES: High Resolution Echelle Spectrograph at the Keck telescope,
HDS: High Dispersion Spectrograph at the Subaru telescope.
PHOEBE: Physics Of Eclipsing BinariEs

Comparison of measured parameters with stellar models

- Components of system 118 don't have same age in models
- Age of both systems too high for membership in Trumpler 37

Observational data:
118: young, foreground
522: young, high membership probability



Isochrones from Tognelli et al. 2011

Parameters of the eclipsing, double lined binaries

118 System:

Period [d]	6,004907 ± 0,000001	
γ [km/s]	-37,603 ± 0,022	
Component	A	B
T_{eff} [K]	6450 ± 150	5990 ± 150
$M [M_{\odot}]$	1,39 ± 0,02	1,30 ± 0,01
$R [R_{\odot}]$	1,58 ± 0,02	1,41 ± 0,05
Spectral type	F4 ... F7	F9 ... G2
EW (Li) [mÅ]	15 ± 8	36 ± 3
r [pc]	281 ± 68	

→ young foreground star

522 System:

Period [d]	4,51685 ± 0,00002	
γ [km/s]	-12,0268 ± 0,0008	
	A	B
T_{eff} [K]	6520 ± 250	6530 ± 200
$M [M_{\odot}]$	1,30 ± 0,01	1,24 ± 0,01
$R [R_{\odot}]$	1,47 ± 0,01	1,43 ± 0,05
Spectral type	F2 ... F8	F3 ... F7
EW (Li) [mÅ]	16 ± 7	28 ± 5
r [pc]	920 ± 270	

→ probably member in Trumpler 37

Distance from: $m_V - M_V = 5 \log\left(\frac{r}{10 \text{ pc}}\right) + A_V$, M_V aus Spectral type

Radial velocity Trumpler 37: (-15,3 ± 3,6) km/s (Sicilia-Aguilar et al. 2006)

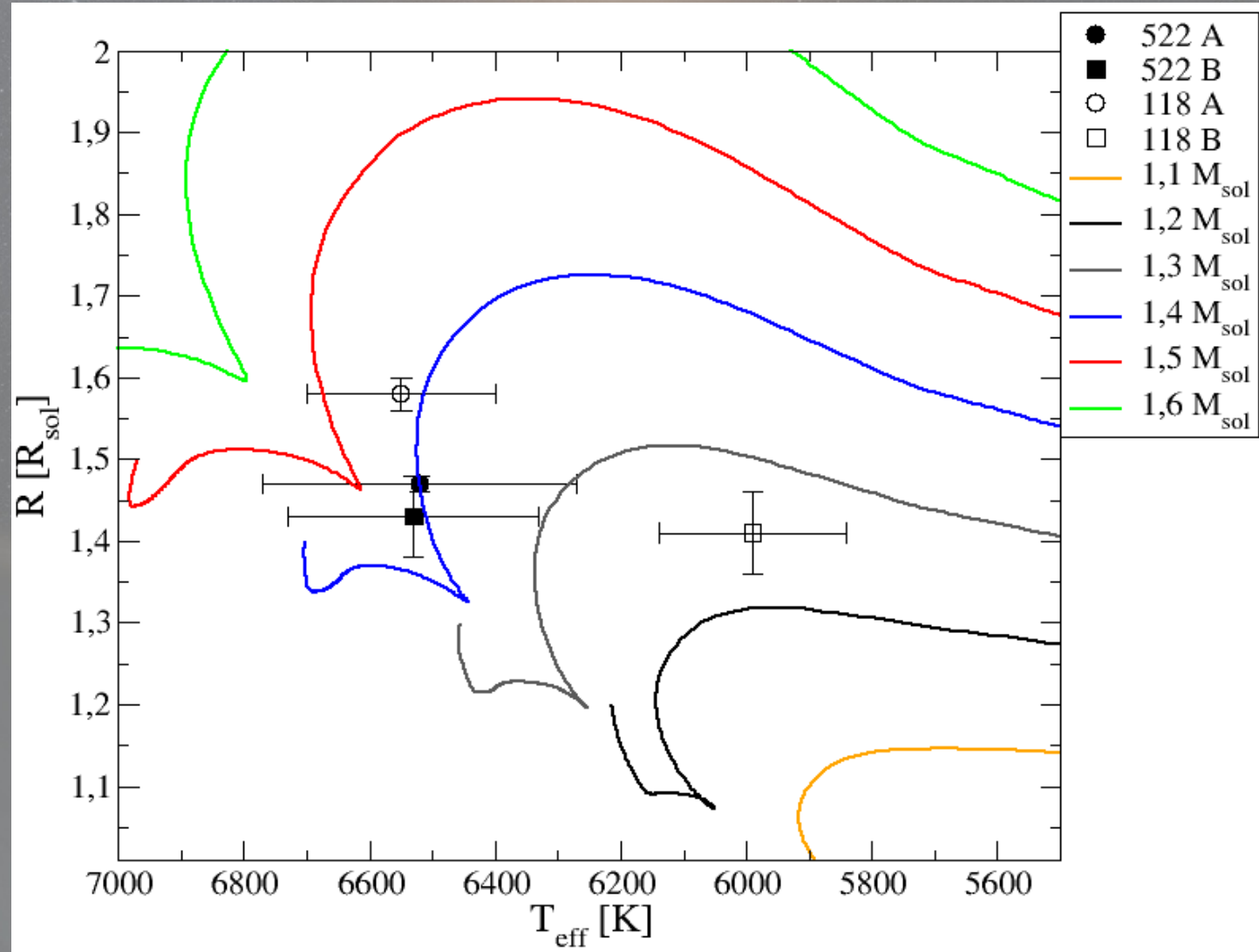
Comparison of measured parameters with stellar models

- Masses from model too high for system 522

Spectroscopic masses and radii:

	<u>118 A</u>	<u>118 B</u>
M [M_{\odot}]	1.39 (2)	1.30 (2)
R [R_{\odot}]	1.58 (2)	1.41 (5)

	<u>522 A</u>	<u>522 B</u>
M [M_{\odot}]	1.30 (1)	1.24 (1)
R [R_{\odot}]	1.47 (1)	1.43 (5)



Evolutionary tracks from Tognelli et al. 2011