KESPRINT: High-precision mass and radius determination of K2 planets

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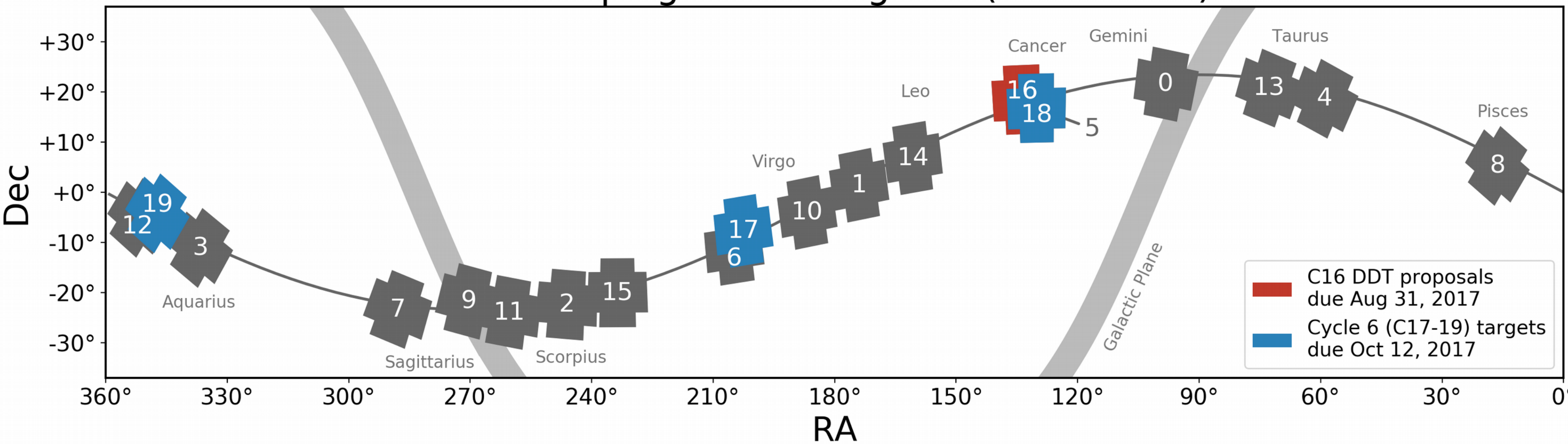
Thursday 7th, Sep 2017 – PLATO Mission Conference

The K2-project

K2 Campaigns 0 through 19 (2014-2018)



~80 days long campaigns along the ecliptic

~20,000 stars/field

~several open clusters are observed

- pixel files are public, light curve production teams

~photometric noise is ~80 ppm/hr (V=10),
worse than original Kepler's 29 ppm/hr (V=10)

DLR

KESPRINT: KEST + ESPRINT (since 2016 Sep 12, 32 members)

IAC (Spain):
R. Alonso
H. Deeg
D. Nespral
G. Nowak
E. Pallé
J. Arranz

Uni. Aarhus (Denmark): Simon Albrecht

Uni. Leiden (NL): V. Van Eylen

Chalmers Uni. (Sweden):
M. Fridlund
C. Persson

DLR (Berlin):

J. Cabrera
Sz. Csizmadia
A. Erikson
P. Eigmüller
H. Rauer
A. Smith

TLS (Tautenburg)

A. Hatzes (PI)
E. Guenther

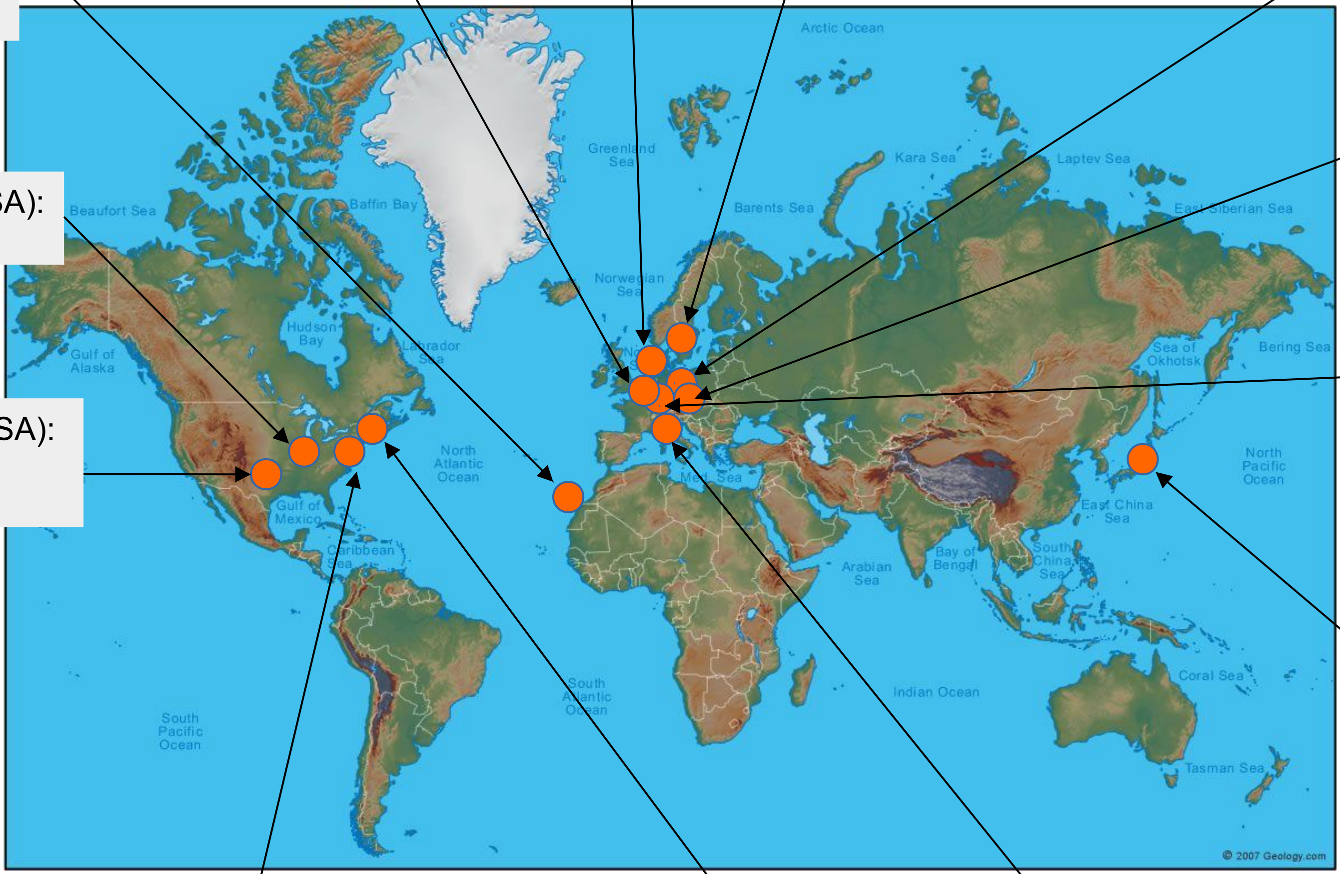
Uni. Ohio (USA):
M. Johnson

McDonald (USA):
W. Cochran
M. Endl

RIU (Cologne)

S. Grziwa
J. Korth
M. Pätzold

Japan:
TIT: T. Hirano
NAOJ: M. Fukui
Uni. Tokyo:
J. Livingston,
N. Narita



Princeton (USA): J. Winn

MIT (USA): Fei Dai

Uni. Torino (Italy): D. Gandolfi
O. Barragán

KEST: K2 Exoplanet Science Team (~2014)
ESPRINT: Equipo de Seguimiento de Planetas Rocosos Intepretando sus Transitos (~2014)

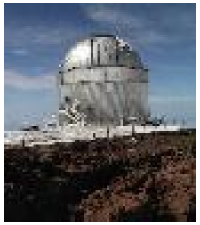
Facilities, pipelines and light curves used

K2

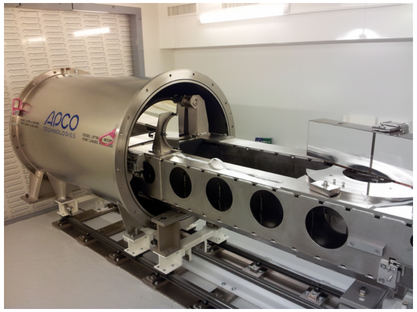
Pipelines:
RIU (Cologne) pipeline (S. Grziwa)
DLR (DLR, Eigmüller, Smith, Cabrera)
K2phot (Leiden, V. Van Eylen)

Light curve factory teams public LC:
EVEREST
Vanderburg

Softwares:
BLS, DST, EXOTRANS, ExoFast, TLCM, TRADES, SME, etc.

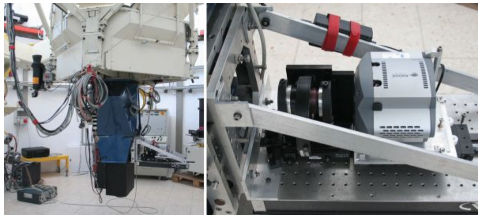


ALFOSC-NOT
FIES-NOT (2.6m)

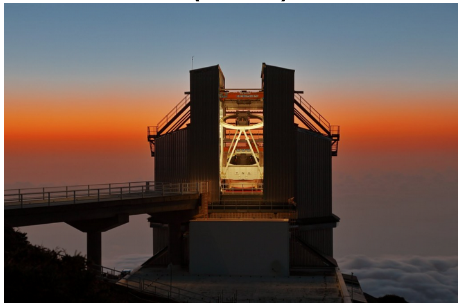


HARPS
HARPS-N

McDonald 2.7m (Tull)



FastCam 1.5m CST



3,6 m TNG

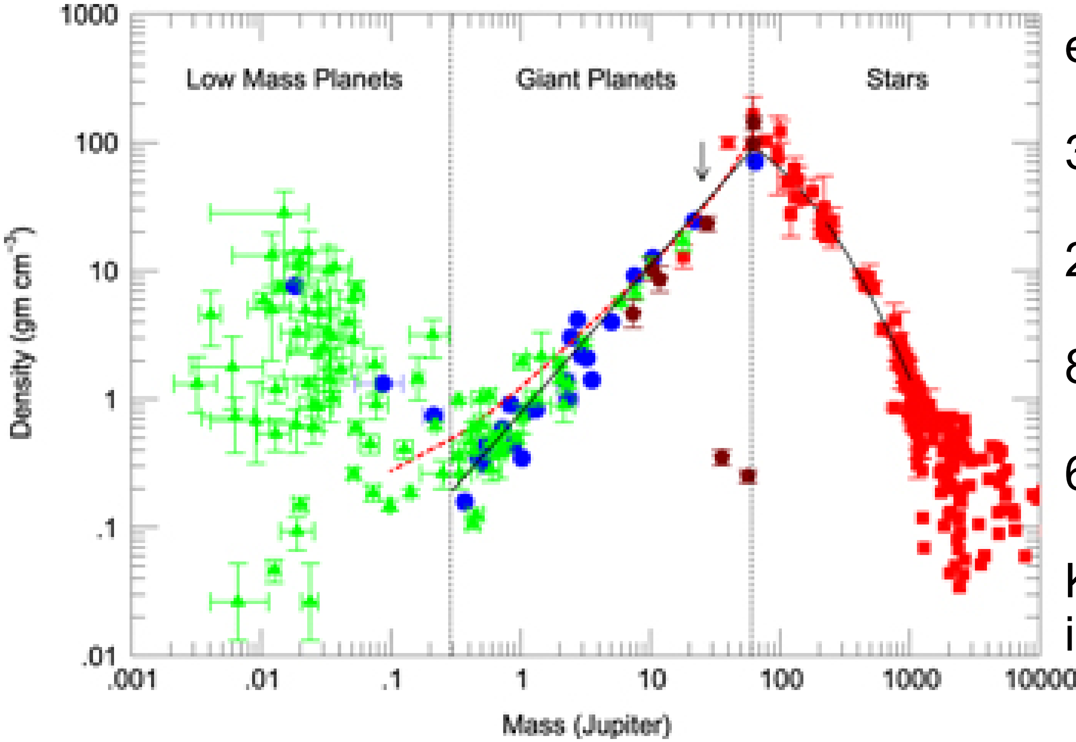
Keck 10m / NIRC2 / HIRES

Subaru (8m, imaging HiCIAO, IRCS, RV with HDS)

PFS (6.5m Magellan)
NESSI/WIYN (imaging, 3.5m)

DLR

Motivation: planet diversity and keep our community together between CoRoT and PLATO (meantime: Kepler, K2, CHEOPS, TESS)



From Hatzes & Rauer (2015, ApJ)

exoplanet.eu (2 Sep 2017):

3664 confirmed planets

2132 without mass

865 with mass(xsini), but without radius

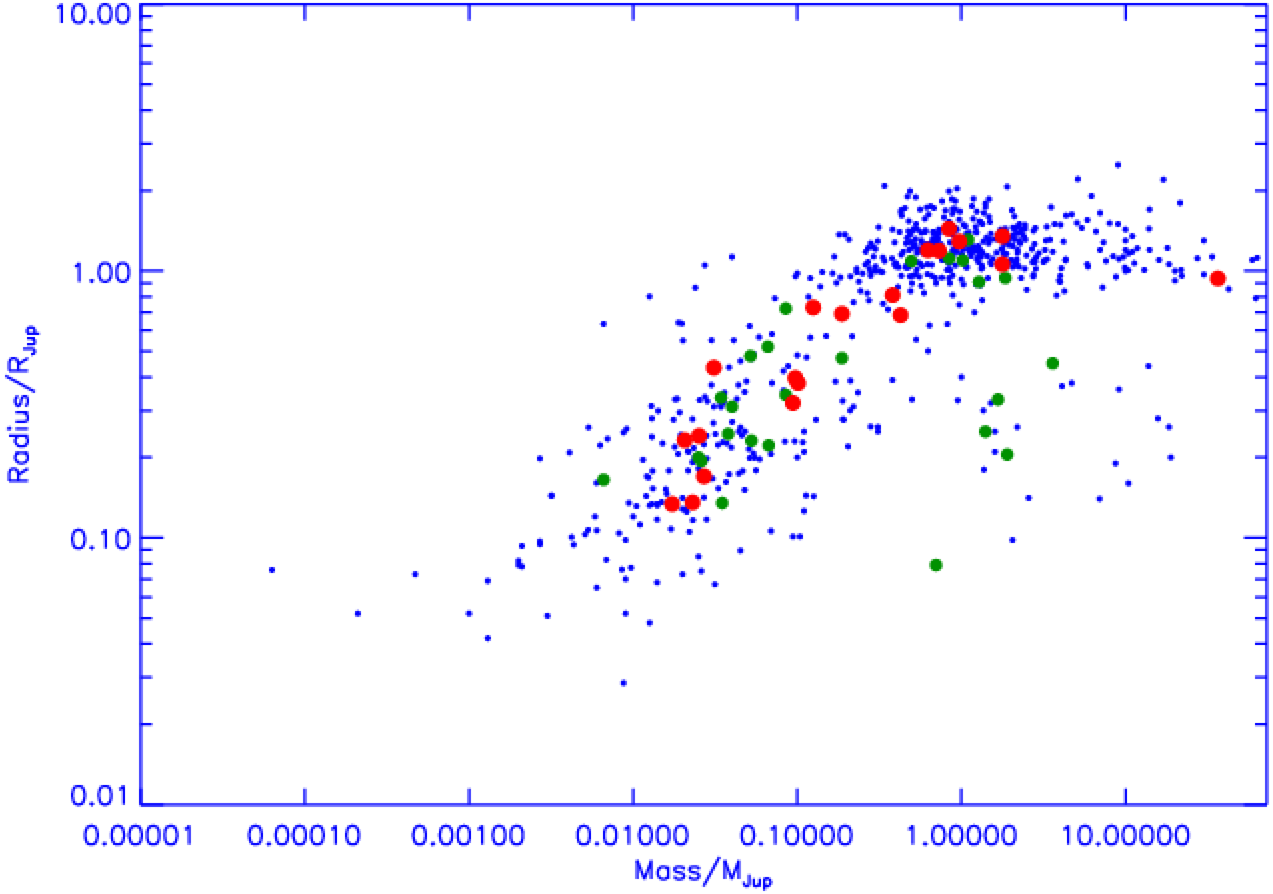
667 with mass and radius (all methods)

K2 planet tables have 155 planets, including ca. ~25 already known ones / other designations (e.g TRAPPIST) – see also talk by J. Cabrera

K2 produced 41 records with M+R (other K2-planets are without mass or without radius)

K2 planets on the mass-radius diagram

Blue: all planets with all methods
Green: K2-planets, masses with all methods (TTV and RV)
Red: measured by KEST/ESPRINT/KESPRINT: 20 out of 41 (49%) (2 TTV+RV and 18 RV)



In the following slides former KEST and ESPRINT measurements are merged with later KESPRINT ones and only KESPRINT is mentioned. Upper limits are not discussed here.

KESPRINT mass refinement - 0.

K2-19bc mass determinations

Detected and studied by: Armstrong et al. (2015), Barros et al. (2015), Montet et al. (2015), Sinukoff et al. (2016. planet d, 2.5d), Dai et al. (2016)
Our work on it: Nespral et al.(A&A, 2017)

Star: 5250 ± 70K

Planet: hot Jupiter

P	~ 7.9 days	~11.9 days
e =	$0.023(^{+0.23}_{-0.024})$	0.183-0.42
M =	54.4 (±8.9) M_E	$7.5\ (^{+3.0}_{-1.4})\ M_E$

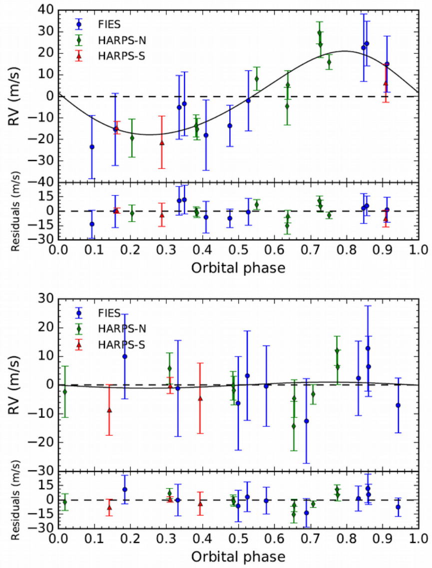
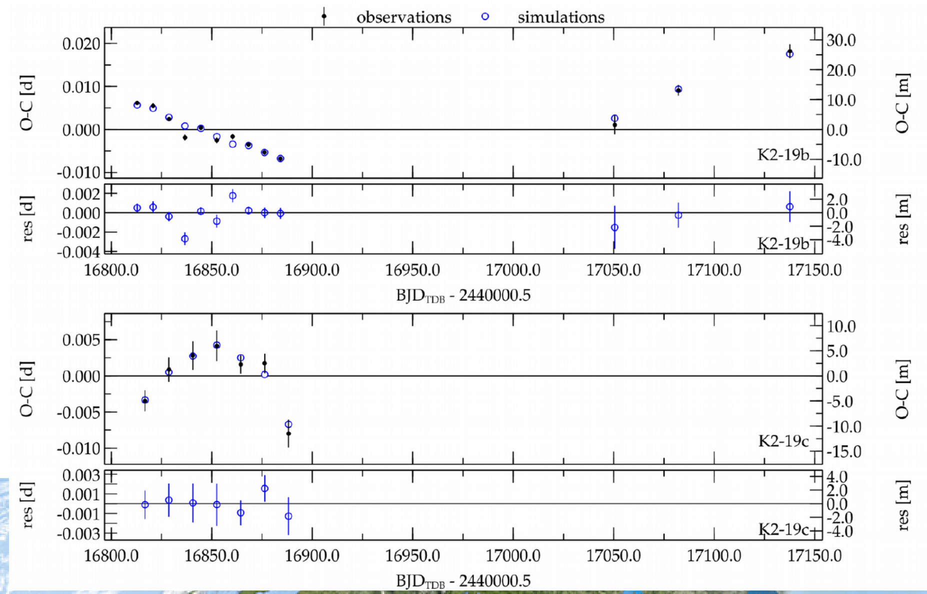


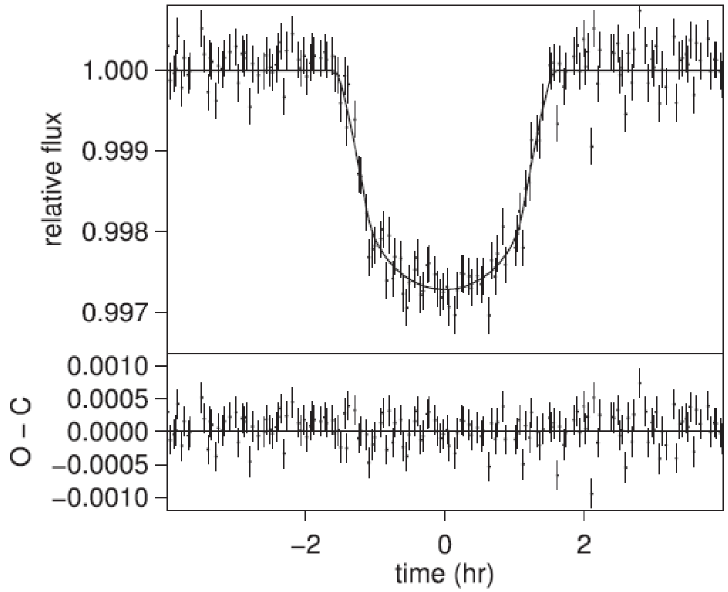
Fig. 1. FIES (blue circles), HARPS-N (green diamonds) HARPS-S (red triangles) RV measurements of K2-19 and Keplerian fits (solid line), phase folded to the orbital period and time of first transit of K2-19b (upper figure) and K2-19c (lower figure). For K2-19c, the fitted RVs from K2-19b have been removed. All RVs, fits and residuals (in smaller sub-panels) are shown following the subtraction of the systemic velocities from the three instruments (Table 2)

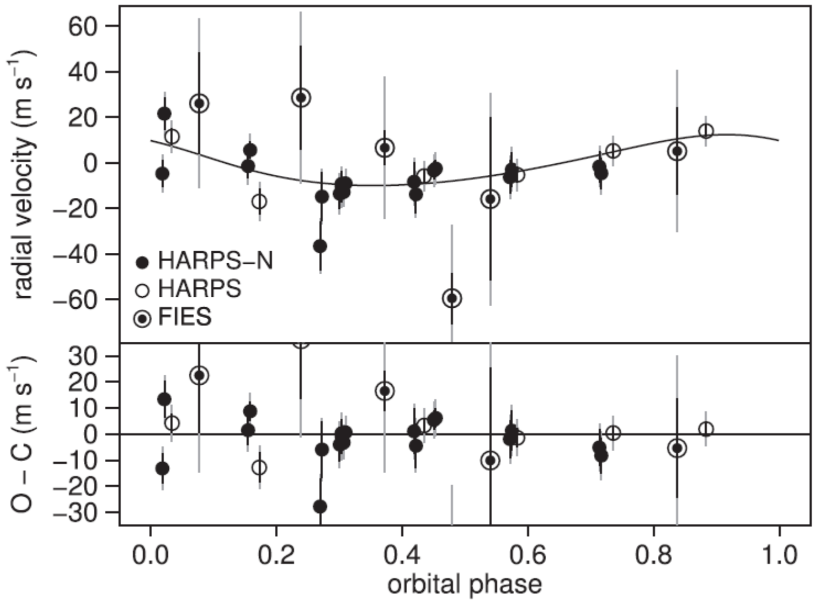


KESPRINT mass measurements – I., II., III, IV.

K2-27b, K2-34b, K2-39b, K2-105b

(K2-27: Hirano et al. 2016a ApJ; K2-34: Hirano et al. 2016b ApJ; K2-39: Van Eylen et al. 2016, AJ; K2-105: Narita et al. 2017, PASJ)





K2-27b LC and RV. Figures are from Hirano et al. (2016a). K2-27b and K2-39b were studied by Petigura et al. (2016), Rvs too. K2-34b was also reported by Lillo-Box et al. (2016)

KESPRINT-detections V., VI.

K2-29b, K2-30b

Johnson et al.
(ApJ, 2016)

K2-29:	K2-30:
Star: K1V	G6V
Planet: hot Jupiter	
P ~ 3.3 days	~4.1 days
e = 0.084 ($^{+0.032}_{-0.023}$, 3.6σ)	0
M = 0.613 ($^{+0.027}_{-0.026}$) M_J	0.579 ($^{+0.028}_{-0.027}$) M_J
R = 1.000 ($^{+0.071}_{-0.067}$) R_J	1.039 ($^{+0.050}_{-0.051}$) R_J
ρ = 0.76 ($^{+0.17}_{-0.14}$) g/cm^3	0.64 ($^{+0.98}_{-0.80}$) g/cm^3

K2-29b:

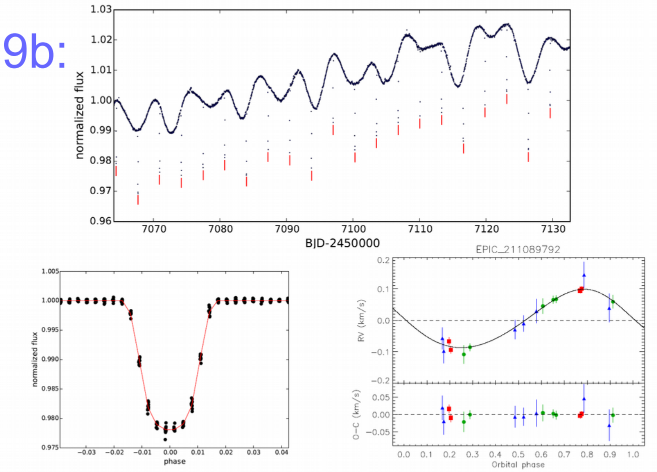
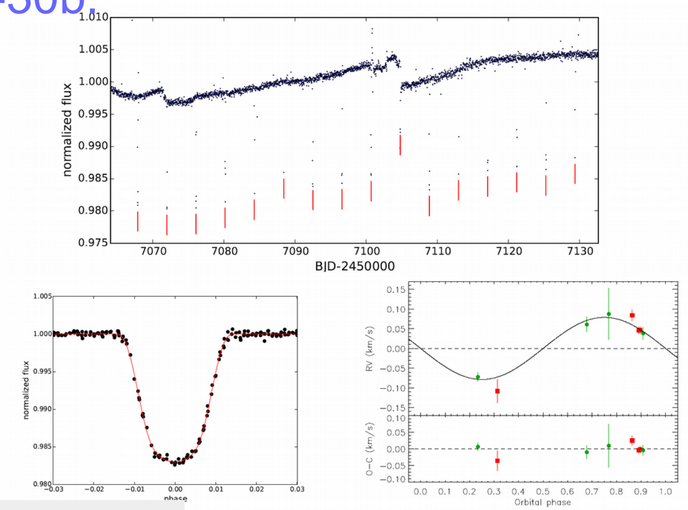


Figure 1. Top: light curve for K2-29, produced using the pipeline of Vanderburg & Johnson (2014). Times of transits are marked by vertical red bars. Note the large variability due to the stellar rotation. Bottom left: phase-folded light curve for K2-29. The best-fit model is overplotted in red. The clustering in the phase-folded data is due to the fact that the planetary orbital period (3.2589265 ± 0.0000015 days) is very close to 156 *Kepler* 30 minute long cadence periods (3.25 days). Both the full and phase-folded lightcurves have been corrected for the contaminating flux of the nearby source, as described in the text. Bottom right: phase-folded RVs for K2-29, following the subtraction of the systemic velocity and FIES-TS23 RV offset listed in Table 3. HARPS-N data are shown with red squares, FIES with green circles, and McDonald with blue triangles.

K2-30b:



, produced using the pipeline of Vanderburg & Johnson (2014). Times of transits are marked by … in the light curve due to instrumental systematics are visible. Bottom left: phase-folded light curve … otted in red. We excluded the data from the 10th transit from this figure (and from the fit) due to … ght: phase-folded RVs for K2-30, following the subtraction of the systemic velocity and FIES-TS23 … data are shown with red squares and FIES with green circles.

K2-29b was detected in S-WASP (W-152b) by Santerne et al. (2016), reported on the same day.
K2-30b was also reported on the same day by
Lillo-Box et al. (2016) and weeks later by Brahm et al. (2016).

KESPRINT-detections VII., VIII.

K2-31b, EPIC 218916923b

K2-31b:	EPIC:
Grziwa et al. (ApJ, 2016)	Barragán et al. (MNRAS, under review)
Star: G7V	K0V
Planet: hot Jupiter	warm Jupiter
P ~ 1.3 days	
e = 0.0	
M = 1.774 (±0.079) M_J	0.381 (±0.045) M_J
R = 0.71-1.41 R_J	0.812 (±0.030) R_J
ρ = 0.78-6.14 g/cm^3	0.88 ± 0.14 g/cm^3

These two: nobody else :-) (yet?)
K2-31b: it is grazing!
→ Oshagh et al. (2015): lack of grazing ones

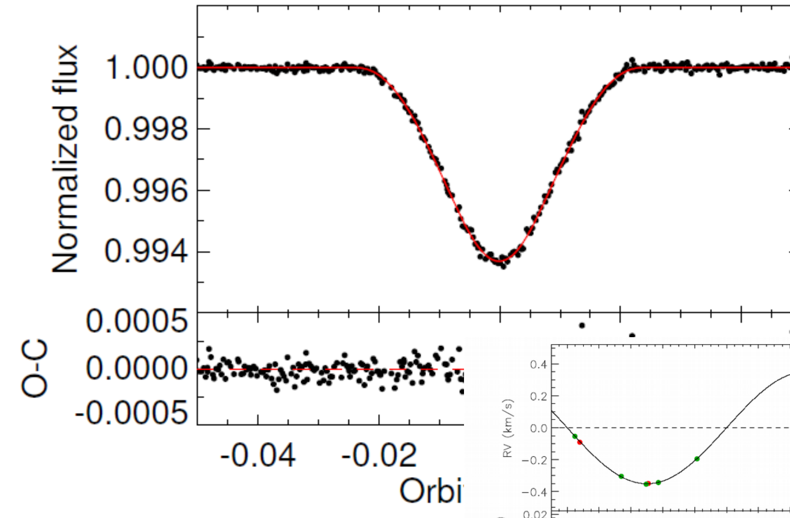


Figure 2. *Upper panel*: Phase-f
K2-31b and an exemplary best-
Lower panel: Residuals to the tr

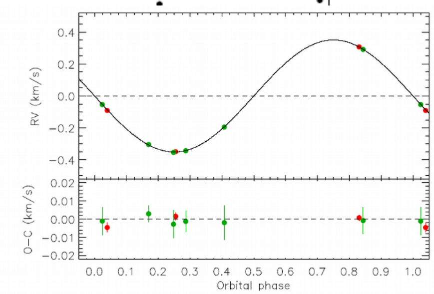


Figure 3. *Upper panel.* Phase-folded FIES (green points) and HARPS (red points) RVs of K2-31 and Keplerian fit to the data. *Lower panel.* Radial velocity residuals.

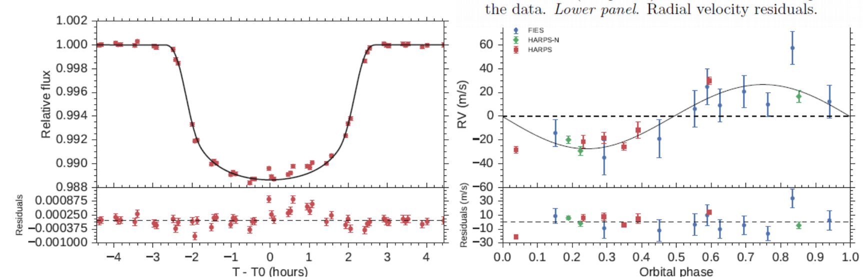
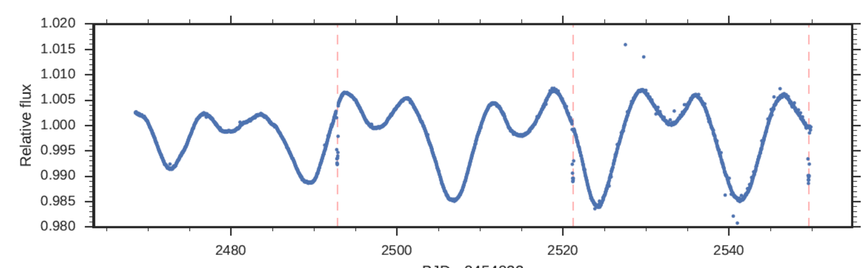


Figure 3. *Left panel*: Transit light curve folded to the orbital period of C7_6923b and residuals. The red points mark the binned *K2* data and their error bars. The solid line mark the re-binned best-fitting transit model. *Right panel*: Phase-folded FIES (blue circles), HARPS-N (green diamonds) and HARPS (red triangles) RV measurements of C7_6923 and best fitting orbit (solid line), following the subtraction of the systemic velocities as measured from each instrument. The error bars have not been corrected by the stellar jitter



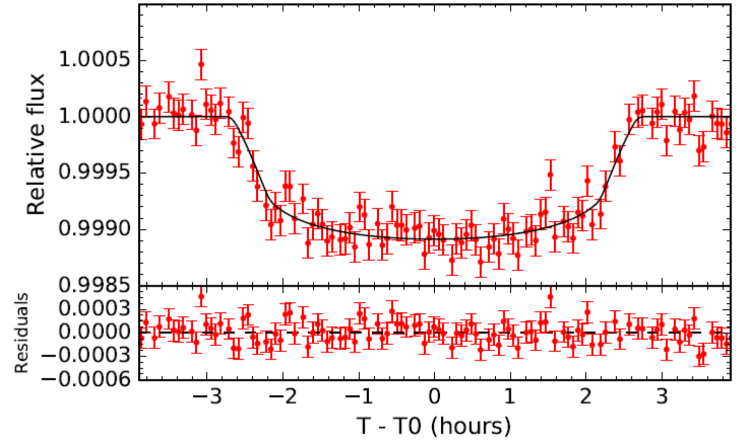
K2-98b

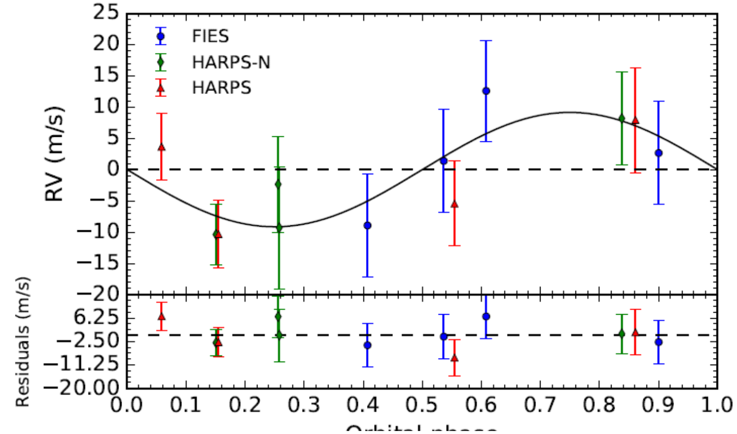
K2-98b: Barragán et al.
(ApJ, 2016)

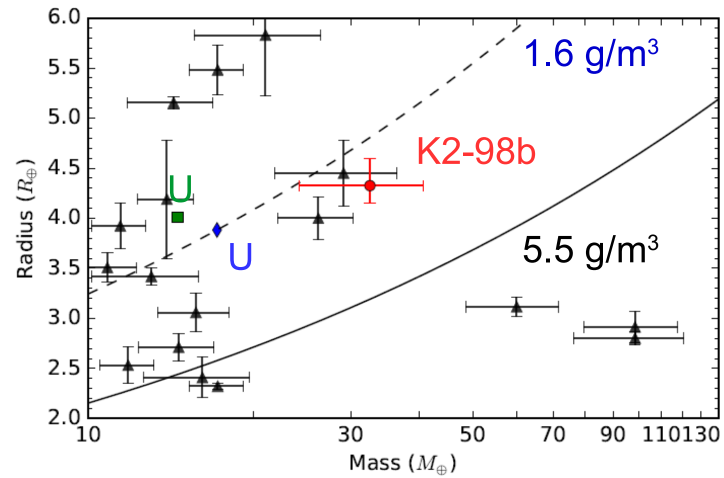
Star: F8V

Planet: Neptune
P ~ 10 days
e = 0.0
M = 32.1 (±8.1) M_{Earth}
R = 4.3 ($^{+0.3}_{-0.2}$) R_{Earth}
ρ = 0.78-6.14 g/cm^3

No other publ. yet. Planet will be engulfed ~3 Gyrs.
Neptune-sized objects with mass and radius better than ~25%:







DLR

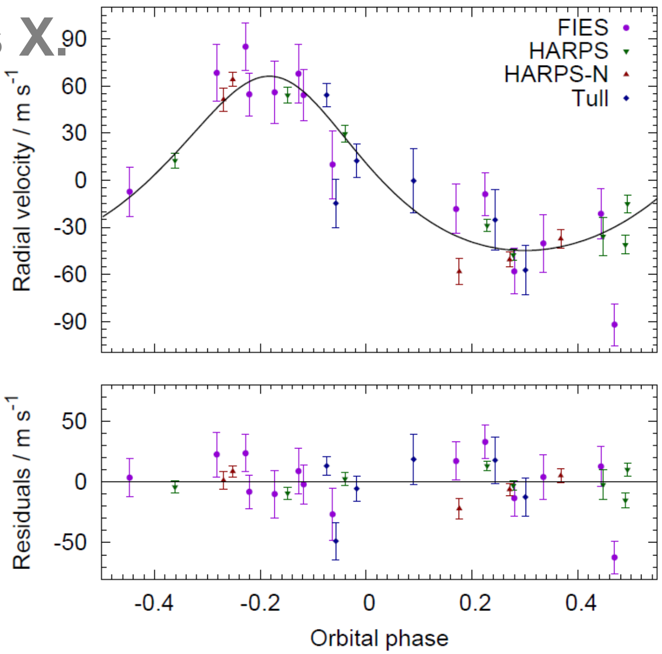
KESPRINT-detections X.

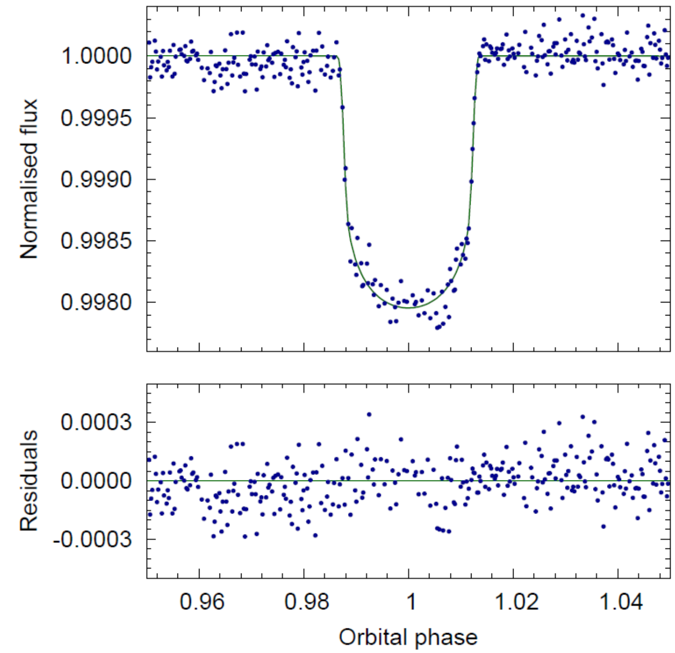
K2-99b

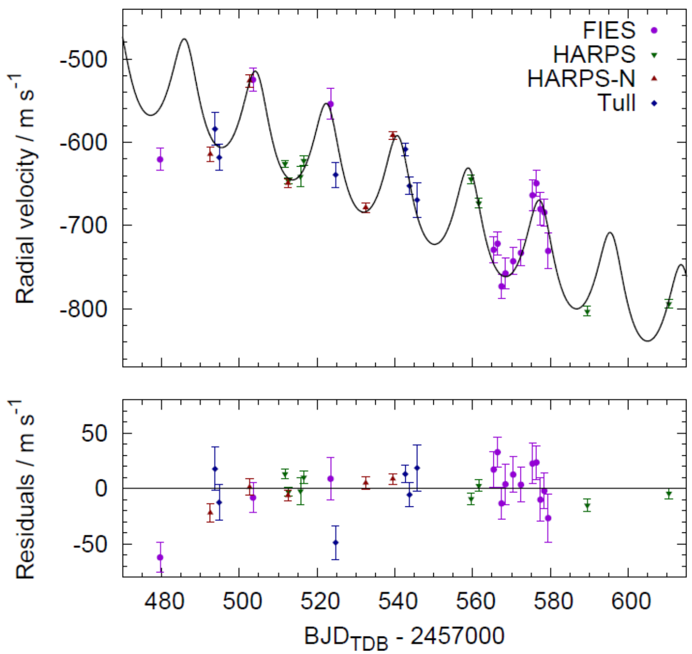
Smith et al.
(MNRAS, 2017)

Star: F8V

Planet: hot Jupiter
P ~ 18.3 days
e = 0.19±0.04
M = 0.97 (±0.09) M_J
R = 1.29 (±0.05) R_J
ρ = 0.78-6.14 g/cm^3







No other publ. yet. Metal-rich host star [Fe/H]=0.2.
Eccentric, RV-drift followed-up
Smith et al (in prep): ~500 days, 10 M_J

K2-99c

Smith et al.
(MNRAS, 2017)

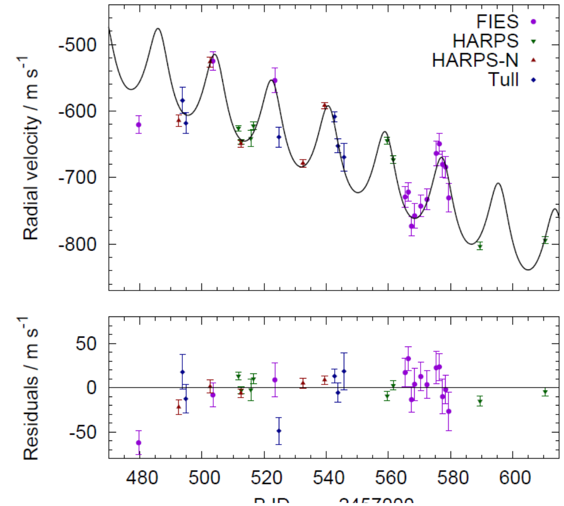
Star: F8V

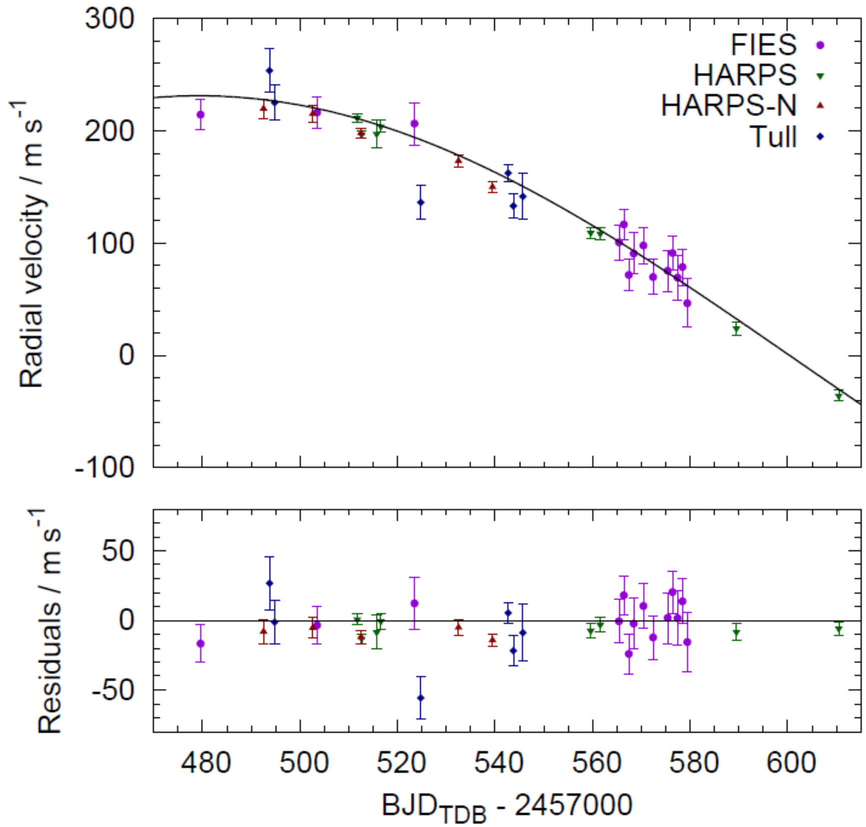
2nd planet: cold giant planet

No transit was observed

Full orbit will come soon!

How lonely are the hot Jupiters?





KESPRINT-detections XI.

K2-60b

Eigmüller et al.
(MNRAS, 2017)

> Planet K2-60b has been recently reported as a planet candidate by Crossfield et al. (2016) and validated using high resolution imaging by Schmitt et al. (2016). However, the planet has not been characterized before in terms of mass and bulk density.

Star: G4V

Planet: warm Jupiter
P ~ 3.0 days
e = 0.0
M = 0.426 (±0.037) M_J
R = 0.683 (±0.037) R_J
ρ = 1.7 ± 0.3 g/cm^3

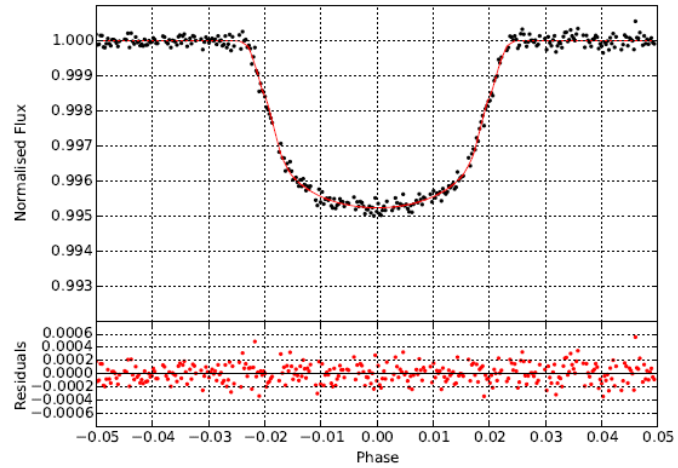


Figure 5. Phase folded light curve and best fitting transit model (red line) of K2-60b. Residuals to the fit are shown in the lower panel.

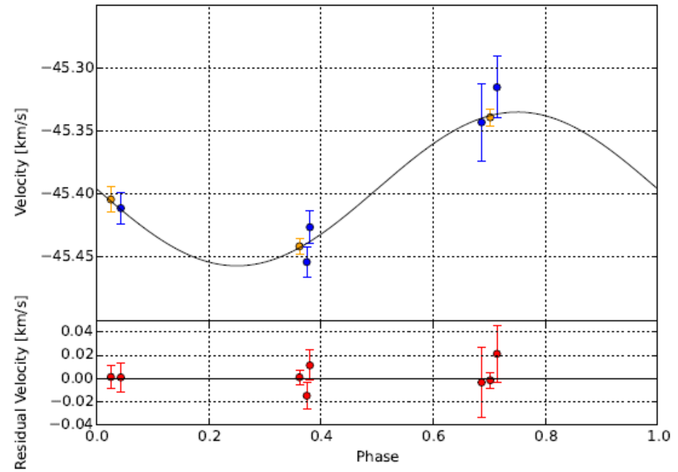


Figure 6. FIES (blue circles) and HARPS-N (orange circles) RV measurements of K2-60b and best fitting circular model. Residuals to the fit are shown in the lower panel.

DLR

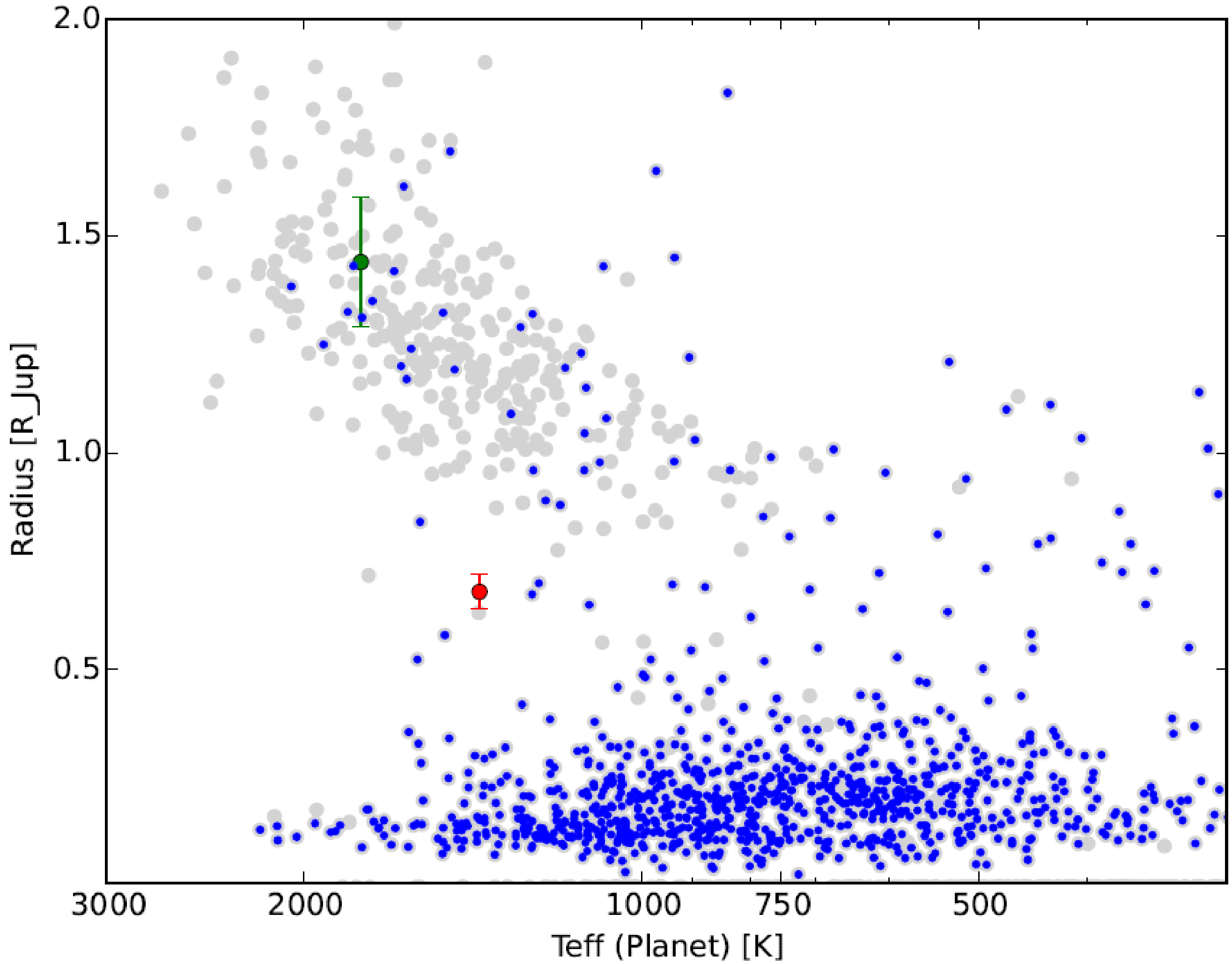


Figure 9. Planet radius over its orbit-averaged effective temperature. The gray dots show all planets. The blue dots mark planets that have been detected by the Kepler spacecraft (Kepler mission or K2 mission). The red dot denotes K2-60b and the green dot C7_8514b. The exoplanet data are taken from Extrasolar Planets Encyclopaedia (www.exoplanets.eu).

From Eigmüller et al. (2017) - see also talk by Bourrier

DLR

KESPRINT-detections XII.

K2-107b

Eigmüller et al.
(MNRAS, 2017)

Star: F9IV

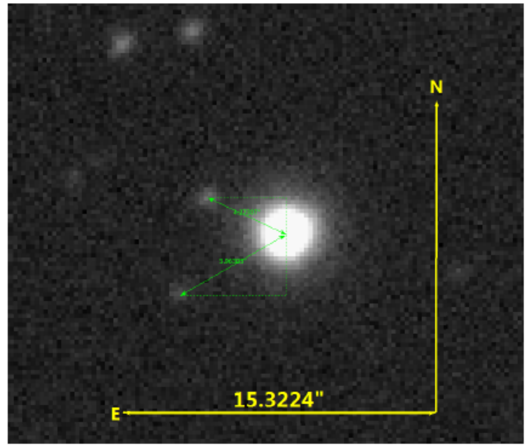


Figure 4. ALFOSC@NOT R-band image of C7_8514. W can resolve sources as close as 2″ to our target star. C7_851 and its two contaminants are marked with green circles.

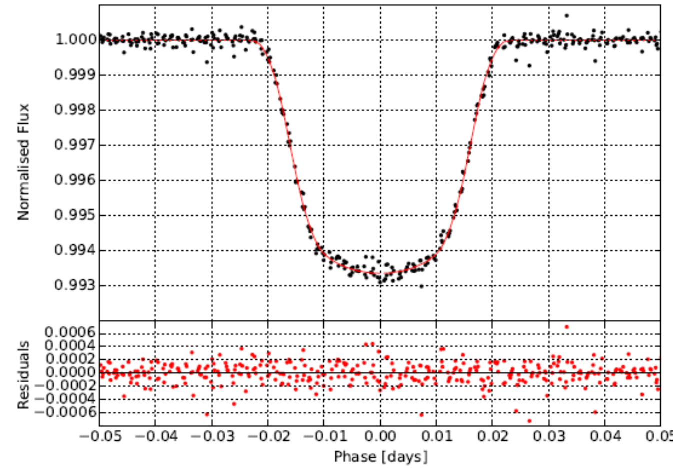


Figure 7. Phase folded light curve and the best fitting transit model (red line) of C7_8514b. Residuals to the fit are shown in the lower panel.

Planet: warm Jupiter (T_{eq} below 2000K)

P ~ 3.3 days

e = 0.0

M = 0.84 (±0.045) M_J

R = 1.44 (±0.030) R_J

ρ = 0.35 ± 0.1 g/cm^3

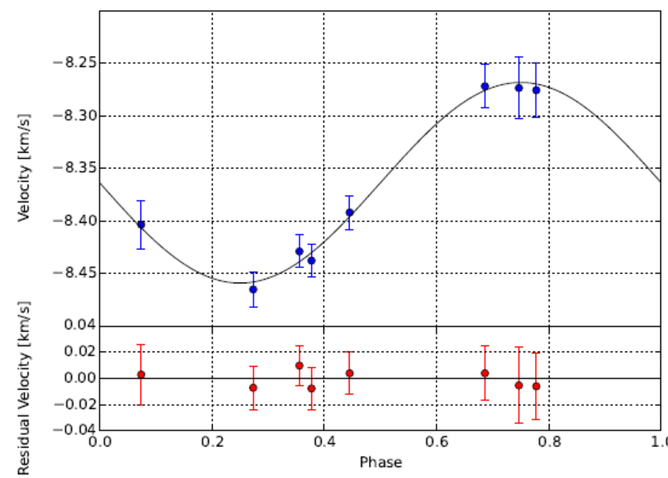


Figure 8. FIES RV measurements of C7_8514b and best fitting circular model. Residuals to the fit are shown in the lower panel.

DLR

KESPRINT-detections XIII.

K2-106b,c

Independently detected by Adams et al. (2017), only upper mass-limits are given there.

Günther et al.
(AJ, 2017)

Star: ~G0V

Object:

Planet b:	Planet c:
P ~ 0.6 days	13.3 days
e = 0.0	0.0
M = 7.7 (±0.8) M_{Earth}	6.79 (±2.29) M_{Earth}
R = 1.52 (±0.16) R_{earth}	2.59 (±0.23) R_{Earth}
ρ = 12 ± 3.5 g/cm^3	2.4 (±1.3) g/cm^3

Metal-rich and metal-poor planets

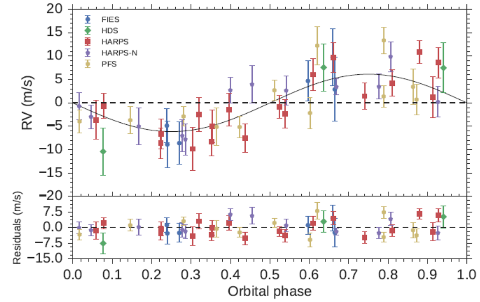


Fig. 2. Phase-folded RV-curve of K2-106 b after removing the signal from the other planet.

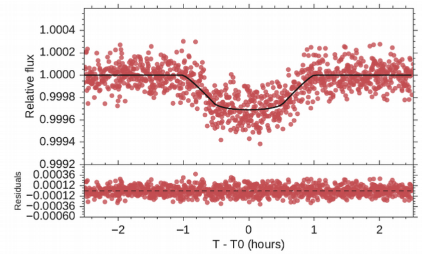


Fig. 6. Best-fit light curves to planet K2-106 b. Light curve is folded to the orbital period of the planet (Table 4).

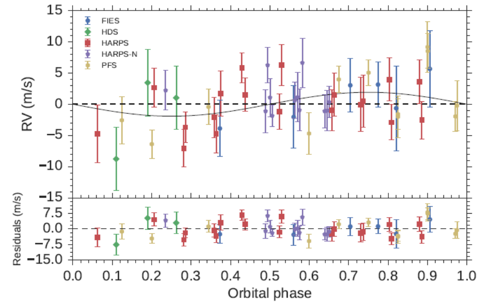


Fig. 3. Phase-folded RV-curve of K2-106 c after removing the signal from the other planet.

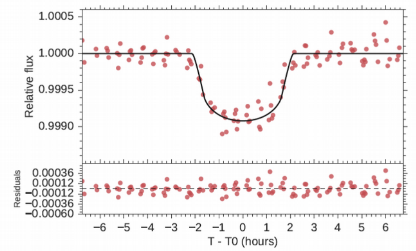


Fig. 7. Best-fit light curves to planet K2-106 c. Light curve is folded to the orbital period of the planet (Table 4).

DLR

EPIC219388192b

Nowak et al.
(AJ, 2017)

Star: ~G0V,
M = 1.01 ± 0.04 M_{sun}, R = 1.01 ± 0.03 M_{sun},
[Fe/H] = 0.03 ± 0.08
3.0 ± 0.25 Gyr (Curtis et al., 2013)

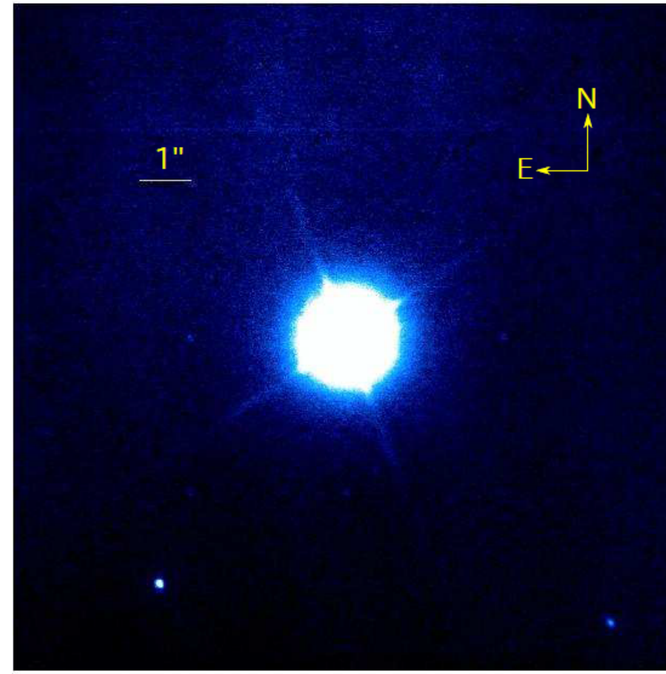
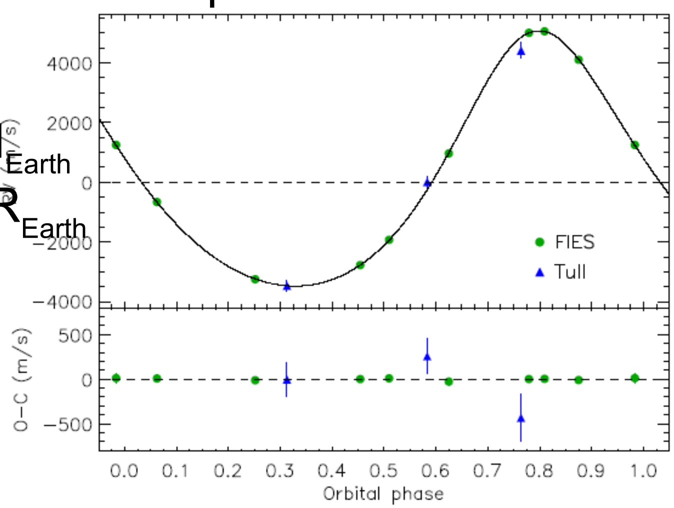
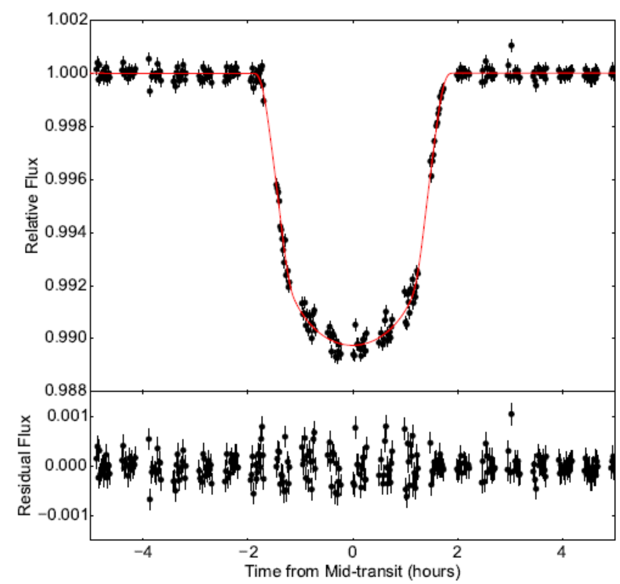


Figure 3. Combined saturated image of EPIC 219388192 ob-

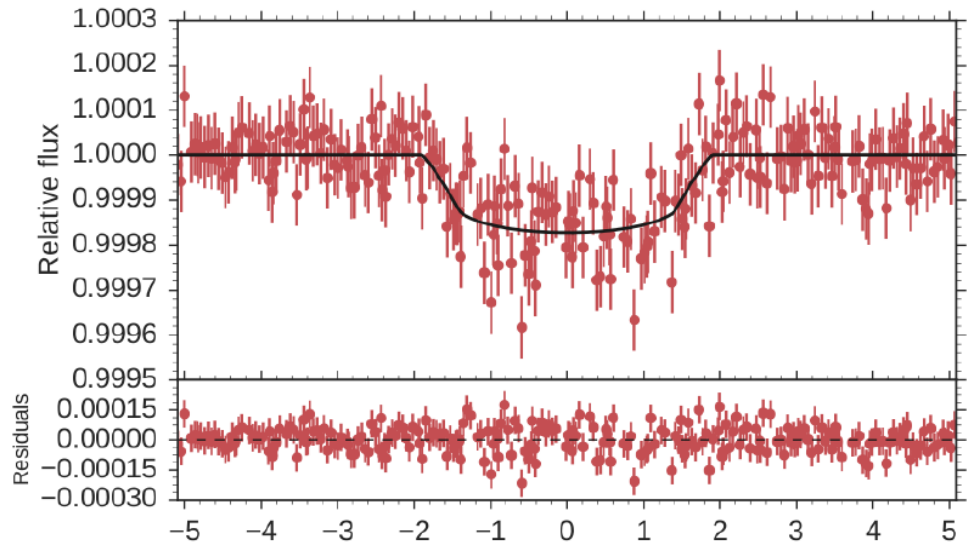
Object: brown dwarf in OC Ruprecht 147
P ~ 5.3 days
e = 0.0
M = 36.50 (±0.09) M_{Earth}
R = 0.937 (±0.042) R_{Earth}
ρ = 59 ± 8.1 g/cm^3





DLR

KESPRINT-detections XV.



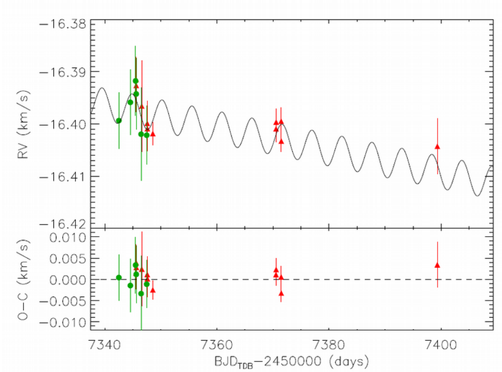
K2-111b

Fridlund et al.
(A&A 2017)

Star: 5730 ± 50 K, 10.8 ± 1.5 Gyrs

Object: SuperEarth, probably rocky
P ~ 5.3 days
e = 0.0
M = 8.6 (±3.9) M_{Earth}
R = 1.9 (±0.2) R_{Earth}

No other detection (yet)
Maybe member of the
Arcturus-stream
like Kepler-444?



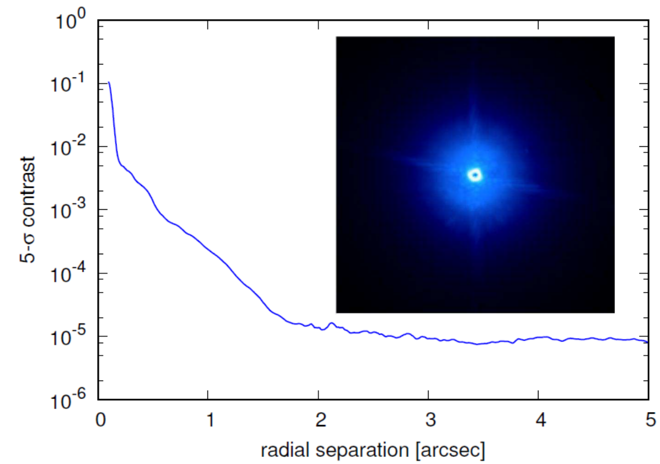


Fig. 3: 5σ flux contrast curve as a function of separation from EPIC 210894022. The inset displays the combined saturated H-band image of the target acquired with HiCIAO. The field-of-view is 4″ × 4″. North is up and East is to the left.

KESPRINT-detections XVI.

Planet b,c: Vanderburg et al. (2016) without mass-measurement
Planet d was characterised by Christiansen et al. (2017)

HD 3167b and c

Gandolfi et al. (submitted)

Star: K0V

Object:
M: 5.7 and 8.3 M_e
P:
0.96 and 29 days
R:
1.57 and 2.74 R_{ea}
Density:
8 and 2.2 g/cm^3

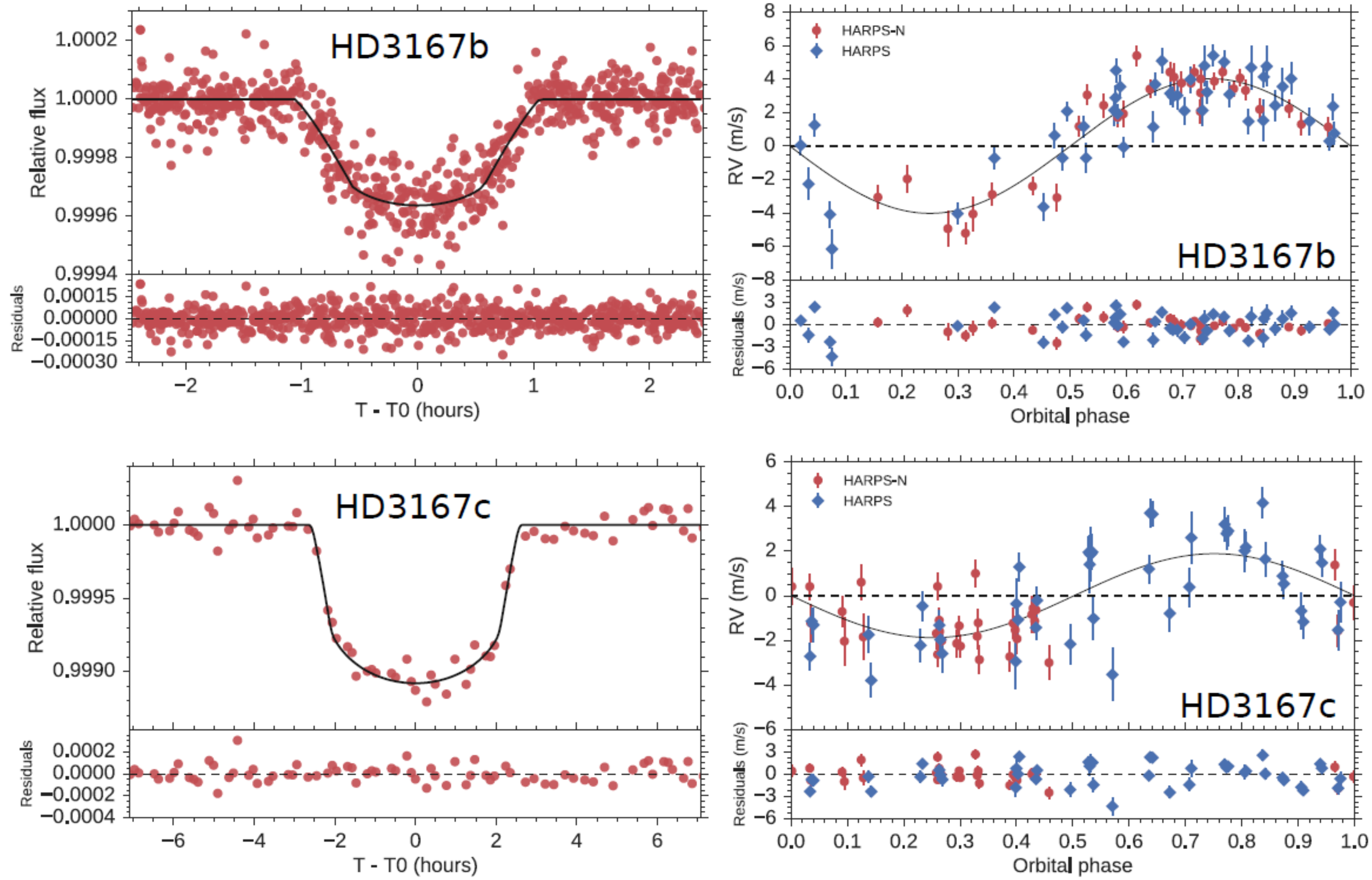


Figure 9. Transit light curves and RV curves of HD 3167 b (upper panels) and HD 3167 c (lower panels). The best fitting transit and Keplerian models are overplotted with thick black lines. The *K2* data points are shown with red circles (left panels). The HARPS and HARPS-N RV measurements are plotted with red circles and blue diamonds, respectively, along with their nominal uncertainties (right panels).

KESPRINT-detections XVII.

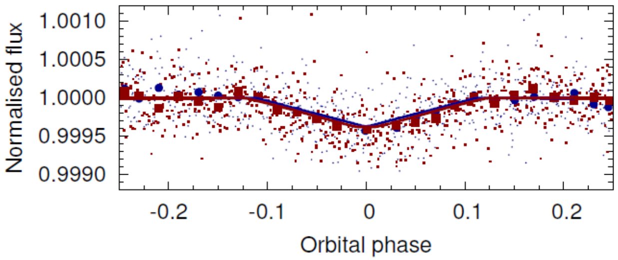


Figure 6. *K2* photometry, for odd-numbered transits (blue circles) and even-numbered transits (red squares), over-plotted with binned data (larger symbols). Our best-fitting transit models are also shown, in colours corresponding to the datapoints. No significant difference between odd and even-numbered transits is seen

EPIC 228813918 b:

an Earth-sized planet in a 4.3-hour orbit around an M-dwarf

Smith, Cabrera, Csizmadia et al.
(MNRAS, under review)

Star: M3V

Object: Earth, probably rocky
P ~ 4.3 hours
e = 0.0
M = 0.6-2.7 M_{Earth}
R = 0.89 (±0.09) R_{Earth}

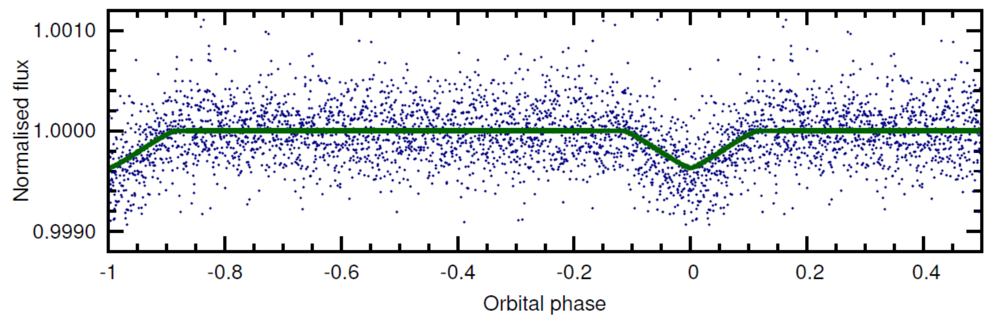


Figure 7. *K2* photometry, over-plotted with our best-fitting transit model, as described in 7.3. Note that the apparent 'V'-shape of the transit is caused by the cadence of the data (see Section 7.4 and Fig. 8).

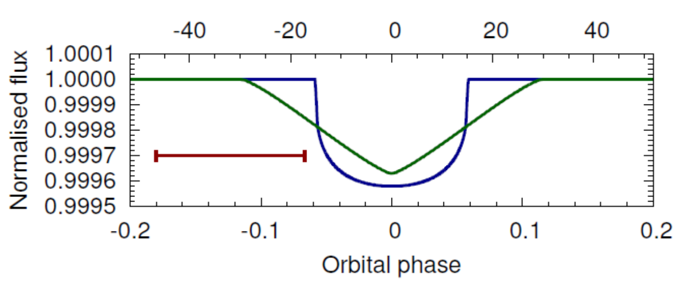


Figure 8. Comparison of our best-fitting model (green curve) with the same model if the exposure time were short (1 s, blue curve). The long-cadence *K2* data has the effect of making the transit longer, shallower, and more 'V'-shaped. The red bar indicates the duration of a single *K2* exposure.

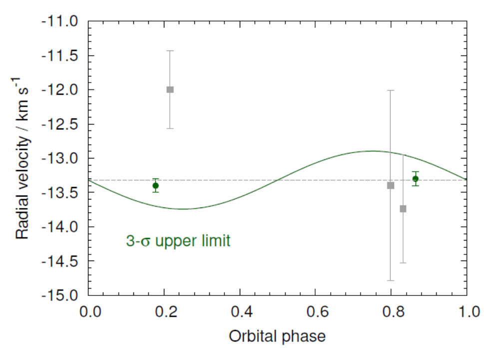
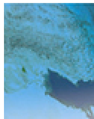


Figure 5. Keck/HIRES radial velocities (green circles) and 1-σ error bars, over-plotted with a model (solid line) with K = 423 m s^{-1}, corresponding to the 3-σ upper limit to K. The Subaru/IRCS radial velocities are shown as grey squares, but are not used to calculate the upper limit to K. The dashed line represents the systemic radial velocity, γ.



DLR

KESPRINT-detections XVII.

EPIC 228813918 b:

an Earth-sized planet in a 4.3-hour orbit around an M-dwarf

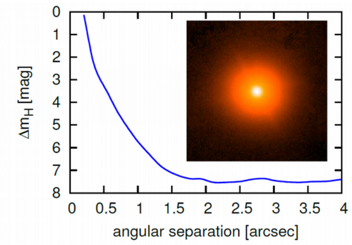


Figure 3. Contrast curve calculated from the saturated Subaru/IRCS adaptive optics image. The curve is a 5-σ upper limit to the difference in H-band magnitudes between the target and a putative neighbouring object, as a function of angular separation. Inset: the 4″× 4″ Subaru/IRCS image.

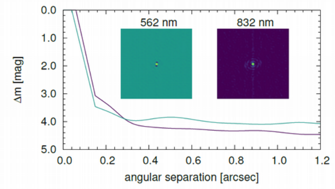


Figure 4. Contrast curves calculated from our WIYN/NESSI speckle images (inset). The green curve corresponds to the 562 nm image, and the purple curve to the 832 nm image. Each of the reconstructed images is ≈ 1.2″ × 1.2″ in size.

6 RADIAL VELOCITY CONSTRAINTS

6.1 Expected amplitude of RV signal

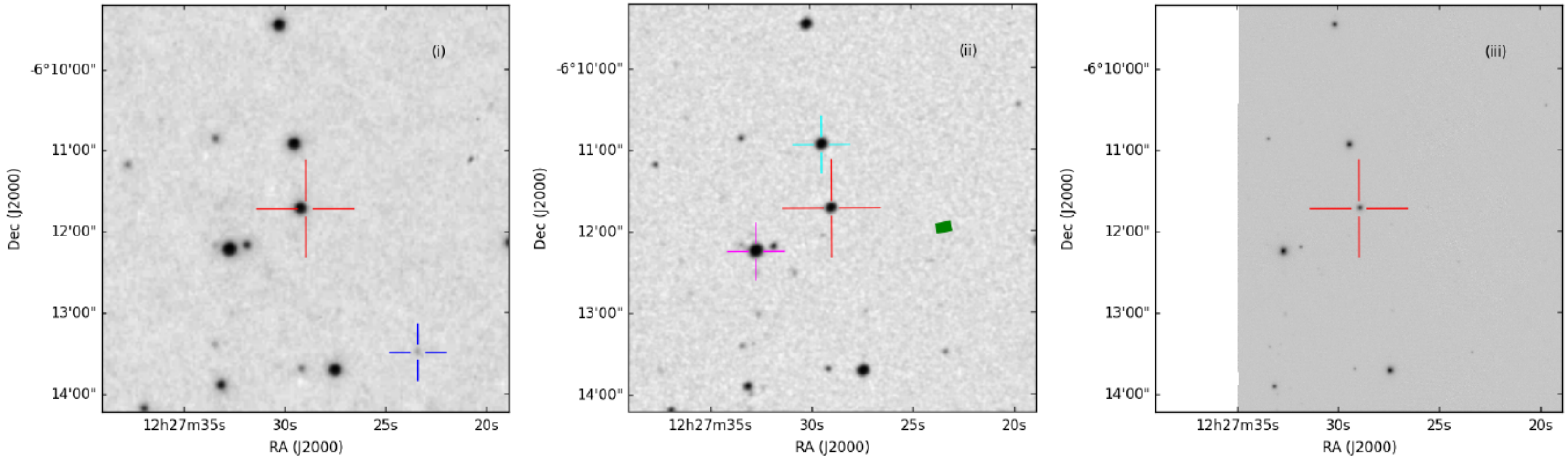


Figure 2. Archival images of EPIC 228813918, demonstrating its proper motion over nearly six decades. The images are from (i) 1954, (ii) 1992, and (iii) 2012. Each image is 5′ by 5′, and in each case North is up and East is to the left. The position of EPIC 228813918 (J2000 epoch) is indicated with a red reticle. The blue reticle in the leftmost panel indicates the position of the star used to determine the limiting magnitude of the image (see Section 5.1 for full details). The arbitrarily-positioned green rectangle in image (ii) indicates the size of the photometric aperture used by Vanderburg & Johnson (2014) to extract the flux of EPIC 228813918. The cyan (NE of target) and magenta (SE of target) reticles in image (ii) indicate the positions of EPIC 228814238 and EPIC 228813721, respectively. The provenance and dates of observation for these images are given in Table 4.

SUMMARY:

PhD/Post-doc positions in Exoplanet Field:
http://www-astro.physik.tu-berlin.de/exoplanet-diversity/

(1) KESPRINT contributes to have well measured masses and radii from the K2 projekt: discoveries and follow-up RV-masses.

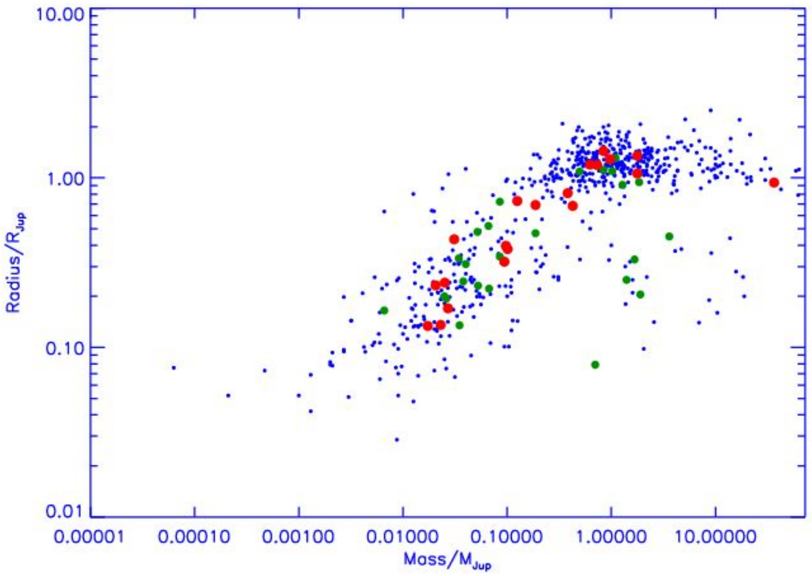
(2) Several more planets and masses will come.

(3) Improvement of eccentricites and masses: RV-work and its coordination

(4) K2 can probe the 0.1-1 Jupiter-radius range with 80 days of observations.

(5) K2/Kepler is a good template for PLATO-simulations: **PLATO will have brighter targets and better time-resolution!!!**

Many thanks for the TACs!



Blue: all planets with all methods
Green: K2-planets, masses (TTV and RV)
Red: measured by KESPRINT (TTV and mostly RV)