ARIEL as a powerful machine for exomoon/Trojan detection and TTVs

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Key points

ARIEL InfraRed Spectrometer (AIRS), R = 30 – 200 between 1.95 and 7.8 μm.

Fine Guidance Sensors (FGS), 3 photometric channels, between 0.5 and 1.2 μm and low resolution NIR spectrometer from 1.2 – 1.95 μm.

+ Cadence of up to 5 Hz, simultaneously at multiple wavelengths.
+ Targeting bright stars will lead to high SNR signal.
+ Uninterrupted observation of transit, out-of-transit and phase-curves.

Key points

ARIEL InfraRed Spectrometer (AIRS), R = 30 – 200 between 1.95 and 7.8 μm.

Chromatic light-curves from the spectra

Fine Guidance Sensors (FGS), 3 photometric channels, between 0.5 and 1.2 μm and low resolution NIR spectrometer from 1.2 – 1.95 μm.

High precision photometry at zero cost

+ Cadence of up to 5 Hz, simultaneously at multiple wavelengths.
+ Targeting bright stars will lead to high SNR signal.
+ Uninterrupted observation of transit, out-of-transit and phase-curves.

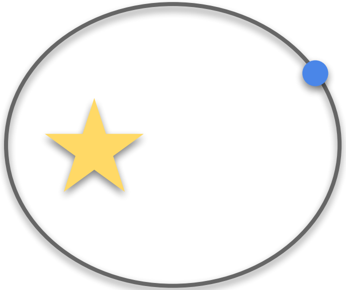
Outstanding sampling of the light curve

timing, ingress/egress, and deformations

IR photometry: less contribute from limb darkening and stellar activity

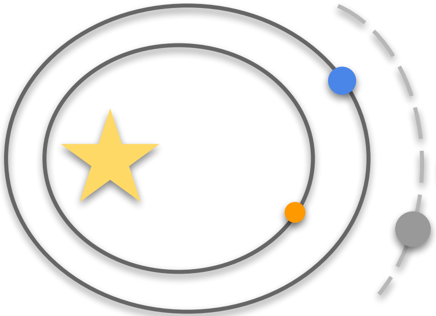
Transit Timing Variation (TTV)

2-body system



P = const
Linear Ephem.

multiple-planet system



$P \neq$ const
mutual interaction
among planets

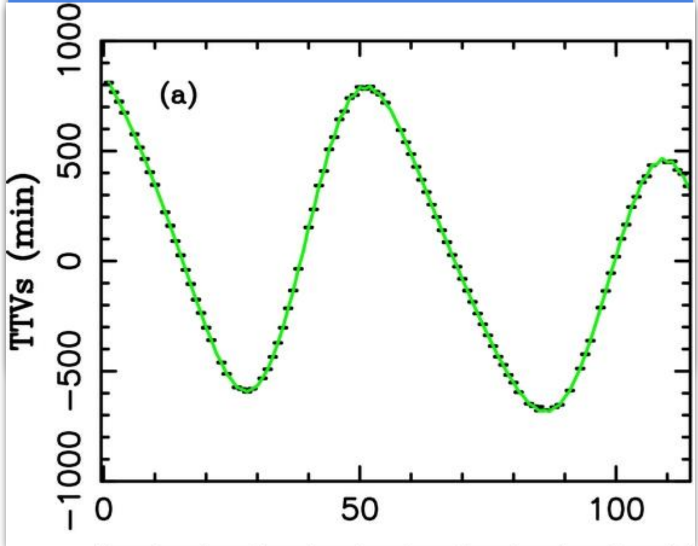
Transit Timing Variation (TTV)
w.r.t
Linear Ephemeris
$$TT_{lin} = TT_{ref} + P \times N$$

& Transit Duration Variation (TDV)

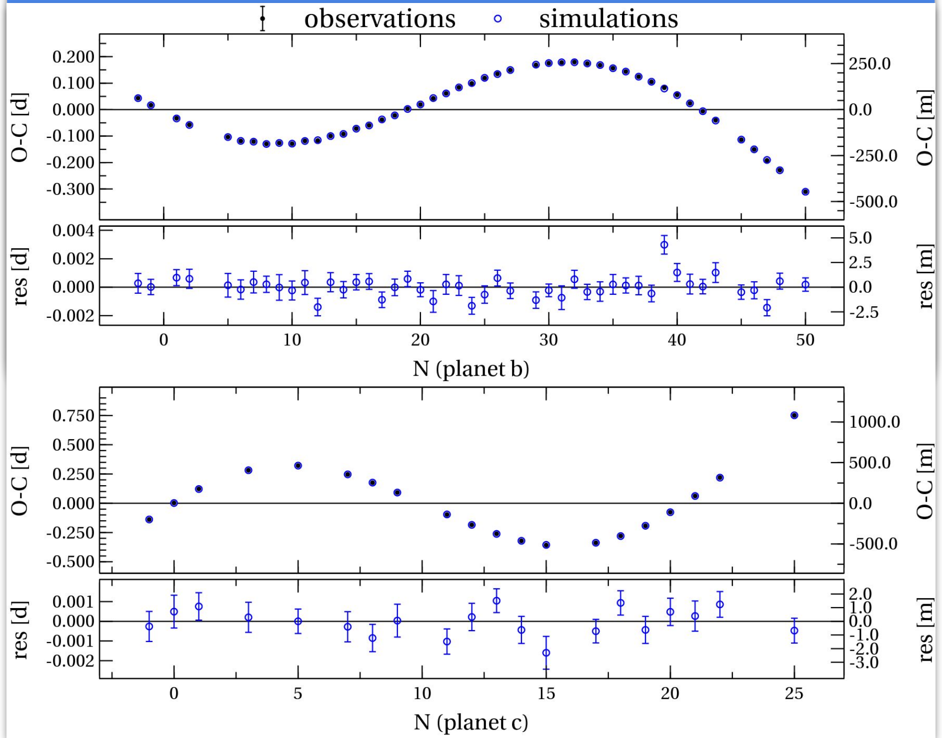
Agol+ 2005; Holman & Murray 2005

Transit Timing Variation (TTV)

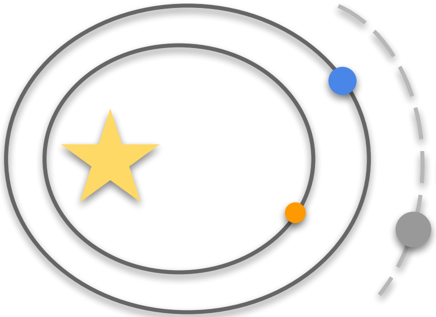
KOI-142.01 – King of TTVs
close MMR 2:1
Nesvorný+ 2013



Kepler-9 – 2 transiting planets
close MMR 2:1 => anticorrelated TTV
Borsato+ 2014



Transit Timing Variation (TTV)



P ≠ const
mutual interaction among planets

Transit Timing Variation (TTV)
w.r.t
Linear Ephemeris
$$TT_{lin} = TT_{ref} + P \times N$$

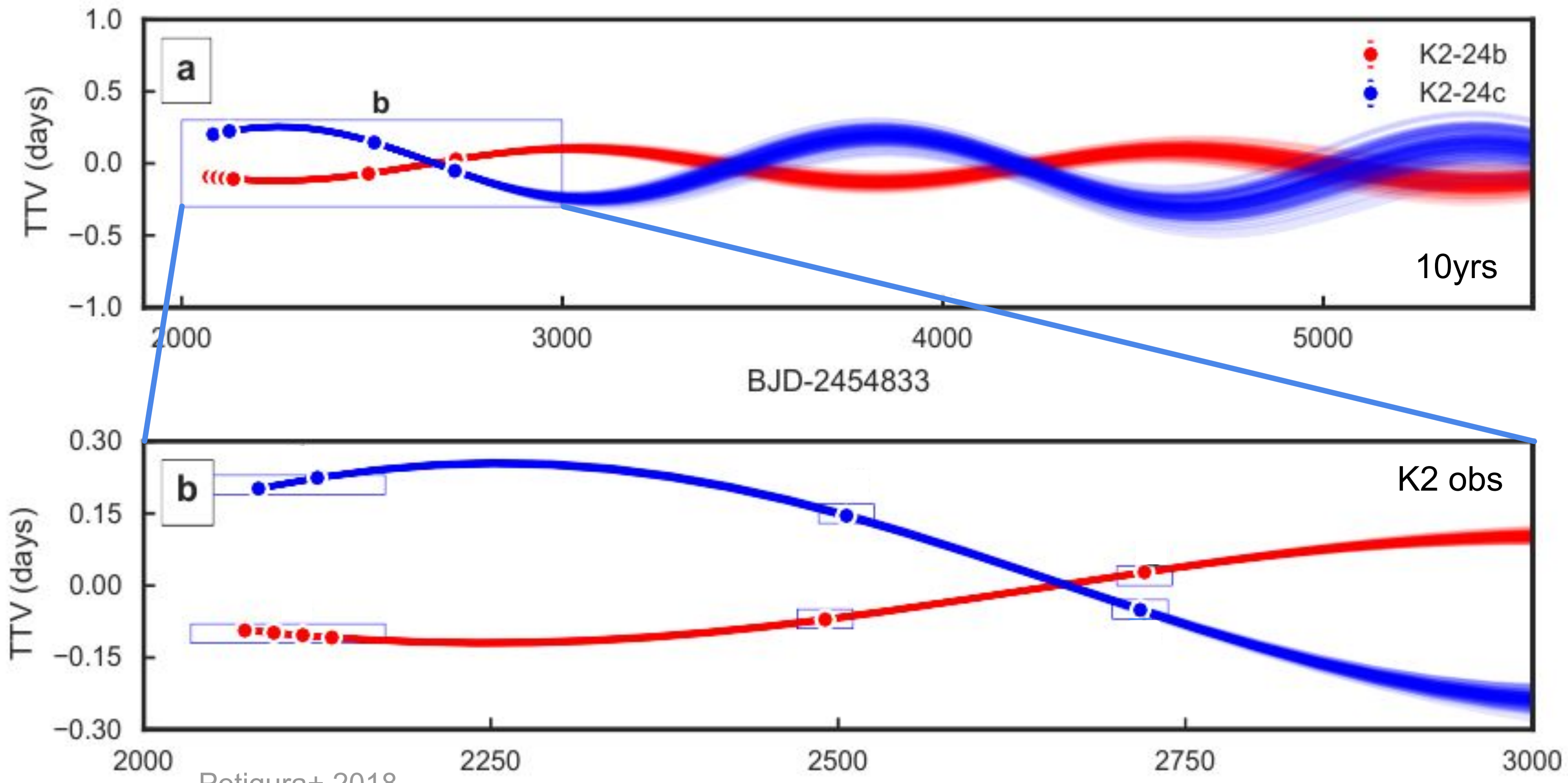
Establish **planetary nature** of transiting planets

- multi-planet system characterisation
- **mass** of the perturber (perturbers if more than one planets)
- orbital **parameter determination** and degeneracy breaking

architecture characterisation: ~MMR, formation and evolution processes

complementary to RV for mass determination

Importance of the TTV baseline



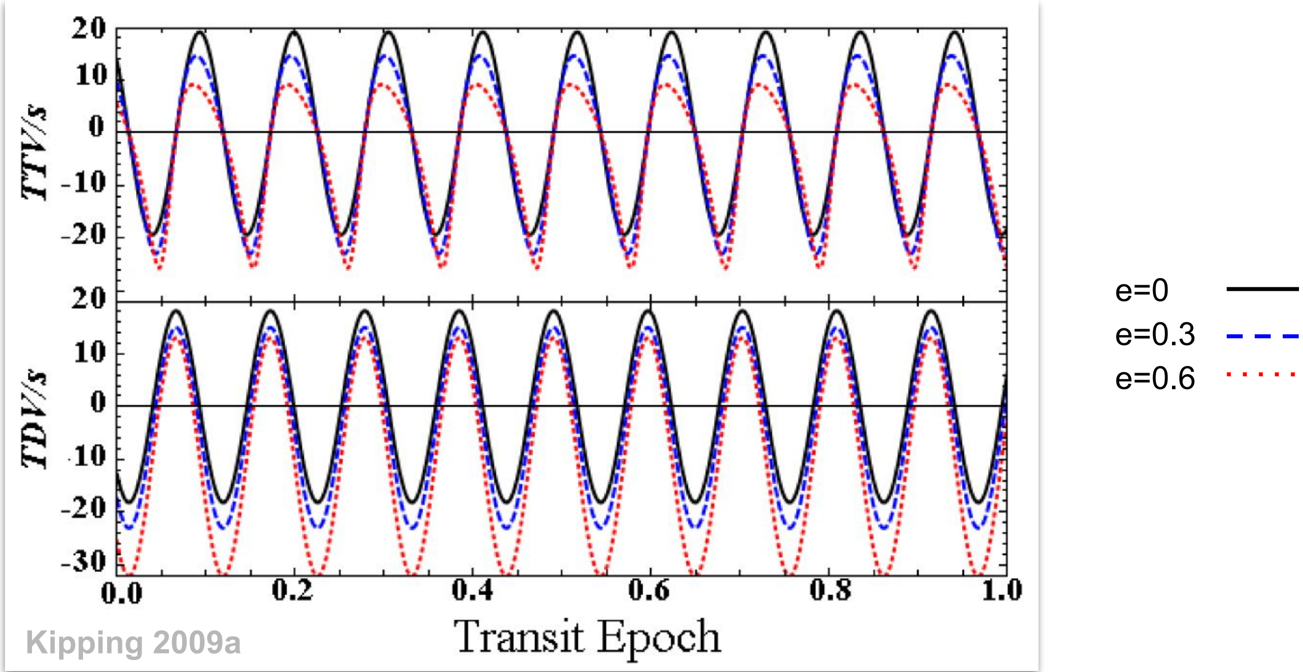
Petigura+ 2018

Exomoon - TTV/TDV & transit features

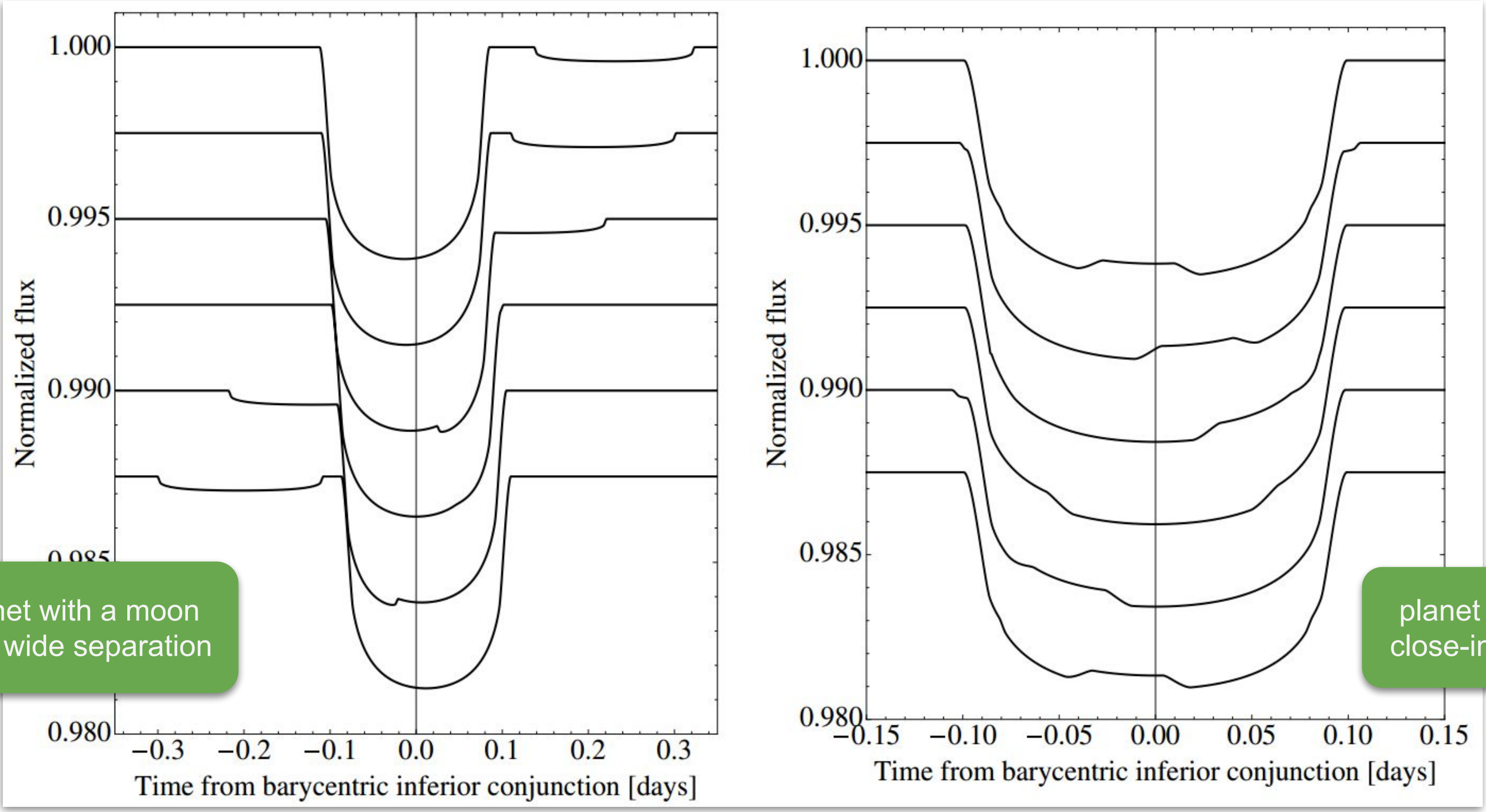
$A_{TTV} \propto a_s M_s$
$A_{TDV} \propto M_s / a_s^{-1/2}$
Kipping 2009a

M_s & a_s determined
$\phi_{TDV} = \phi_{TTV} + \pi/2$
Kipping 2009a

hypothetical
$1M_\oplus$ exomoon
around GJ436b



Exomoon - TTV/TDV & transit features

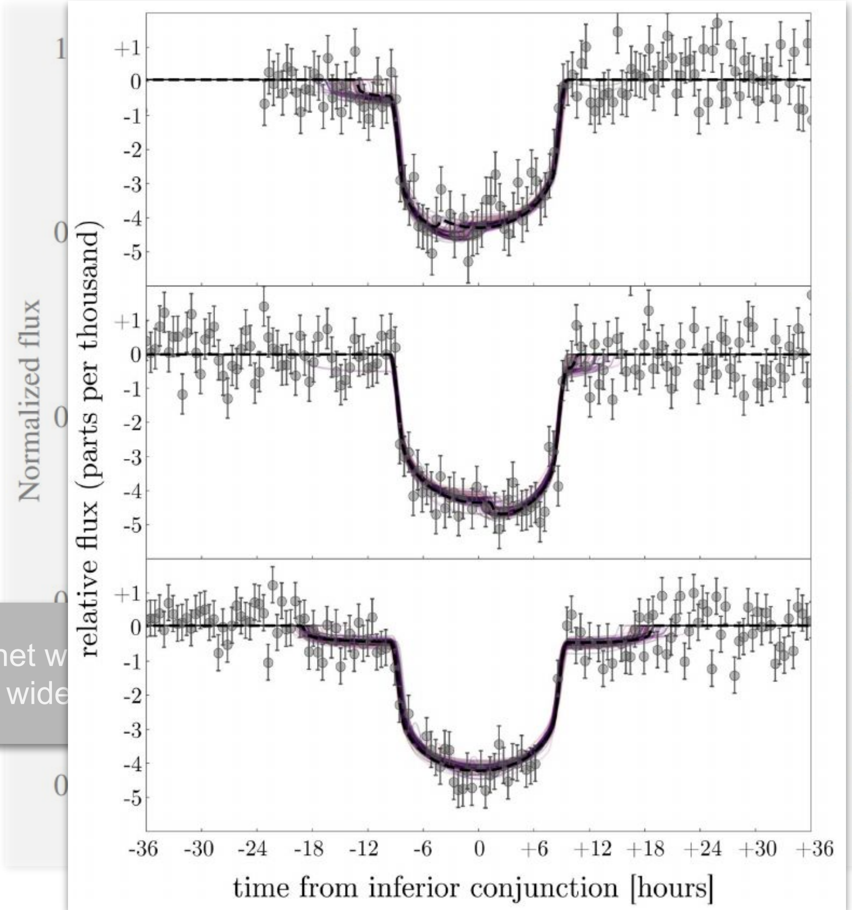


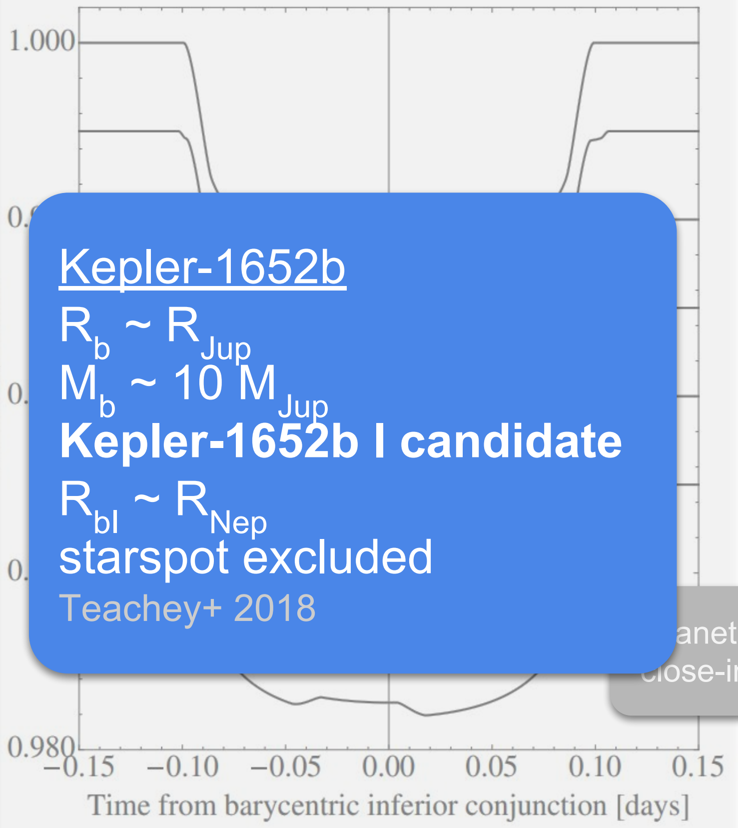
planet with a moon on a wide separation

planet with a close-in moon

Kipping+2012

Exomoon - TTV/TDV & transit features





planet w
on a wide

anet with a
close-in moon

Kepler-1652b

$R_b \sim R_{Jup}$

$M_b \sim 10\ M_{Jup}$

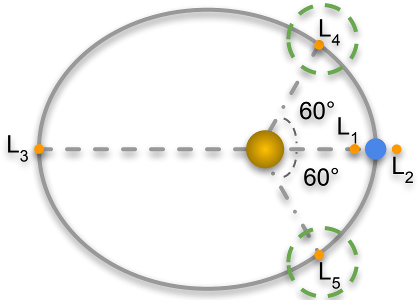
Kepler-1652b I candidate

$R_{bI} \sim R_{Nep}$

starspot excluded

Teachey+ 2018

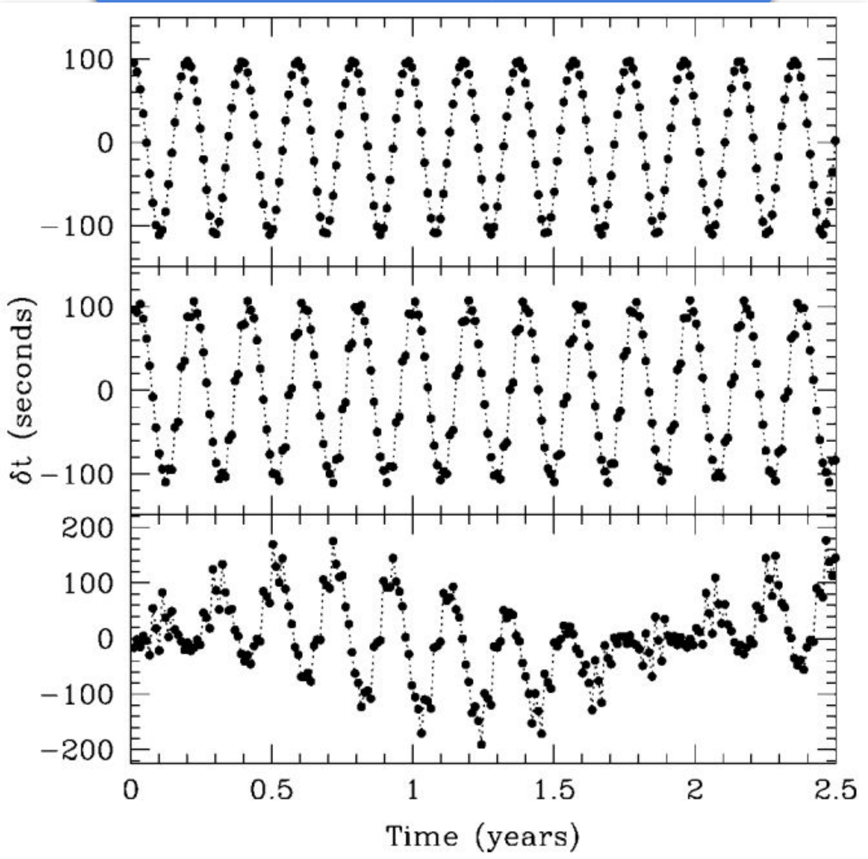
Trojans



Transit detection:
if small mutual-inclination
&
large radii

shift ΔT of the TT_{LC} & TT_{RV}

TTV on $M=0.5M_{Jup}$, P=4.09 d



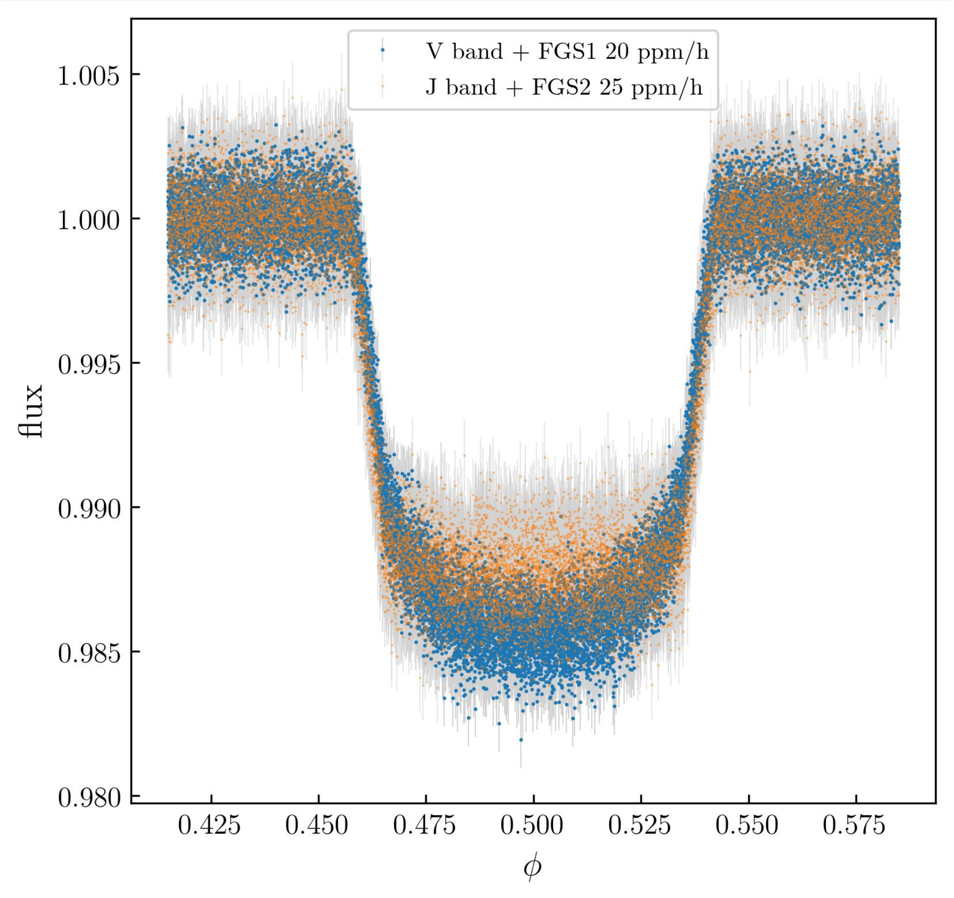
Trojan
M_T = 1 M_{Earth}

Planet out 2:1 MMR
M_P = 28 M_{Earth}
P_P = 8.7 d

Planet in 3:2 MMR
M_P = 4.8 M_{Earth}
P_P = 5.91 d

eg. Ford & Gaudi (2006); Ford & Holman (2007); Giuppone+ (2012); Janson (2013); Fabrycky+ (2014); Leleu+ (2017)

LC examples & TT precision



test WASP-76b West+ (2016)

V = 9.5

$R_\star = 1.73\ R_\odot$

$R_b = 1.83\ R_{Jup}$

$P_b = 1.81$ d

$T_{41} = 3.7$ h

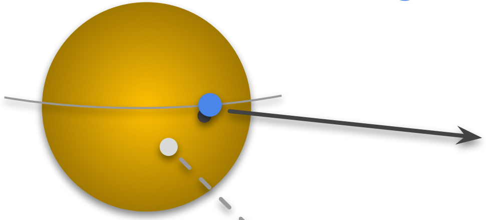
texp = 1.5s

$\sigma_{TT} = 100. / SNR_{transit}$ min

Mazeh+ 2013; Holczer+ 2016

$\sigma_{TT,FGS1} = 4.4$ s | $\sigma_{TT,FGS2} = 6.2$ s

Stellar activity & starspots



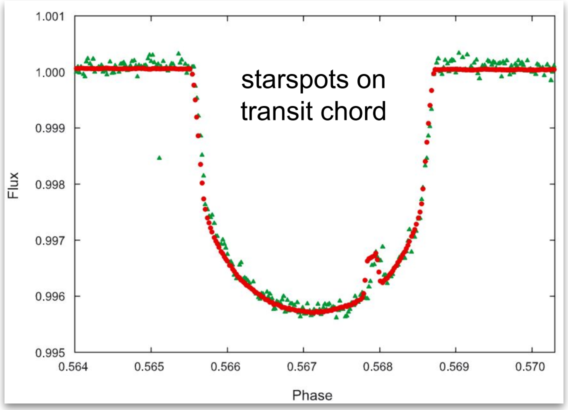
dark/bright starspots/plagues on(out) transit chord

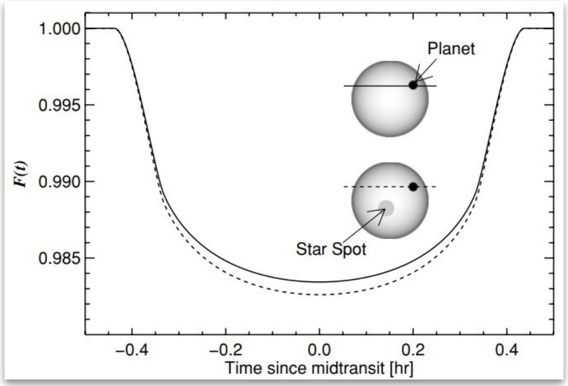
↓

smaller/larger transit depth δF

↓

smaller/larger planet radius R_p





Activity in NIR
(Reiners+ 2010)

decreases up to a factor of 10 for low temperature contrast (~200k)

decreases factor < 10 for larger temperature contrast

simultaneous optical-NIR observations provide strong constraints on **spot properties**

eg. Czesla+ 2009; Reiners+ 2010; Carter+ 2011; Oshagh+ 2013, 2014, 2015; Morris Brett+ 2018; Oshagh 2018

What do we need to know?

What is the **exposure/sampling time**?

Access to **ARIELsim** & simulate a **few targets with different characteristics**:

- magnitude, $R_\star$, spectral type
- R_p, period, temperature
- given number of transits (observing baseline coverage)

to compute:

- SNR(transit) in different bands
- error on the transit time, σ_{TT} (analytically and transit fit)
- possible TTV/TDV signals for different perturbers

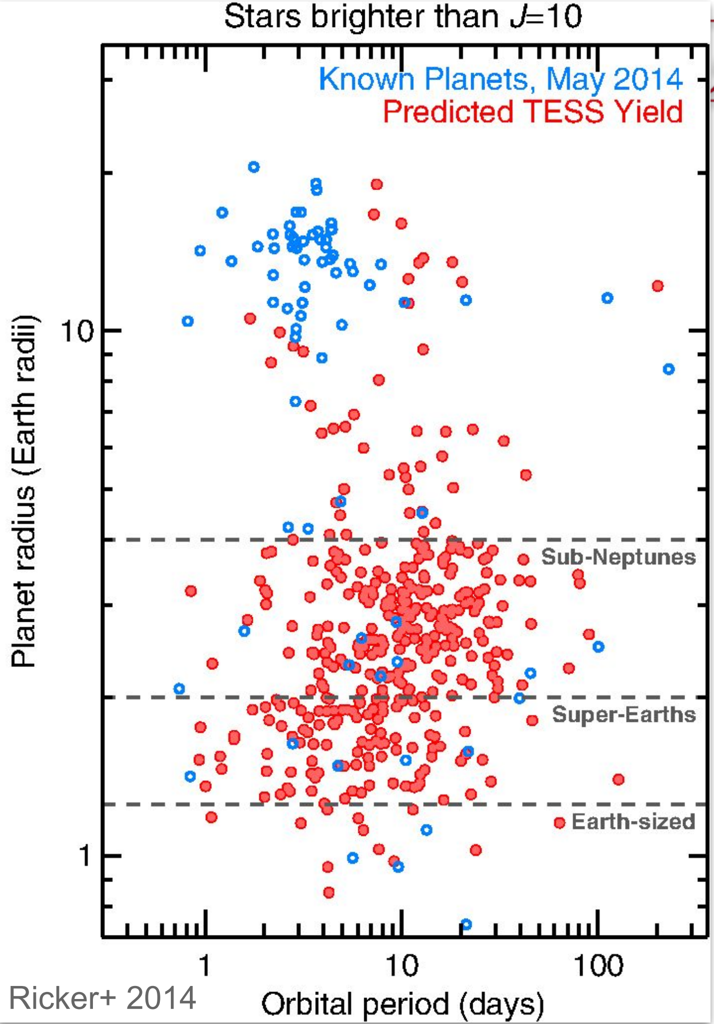
\+ stellar activity models

Target selection

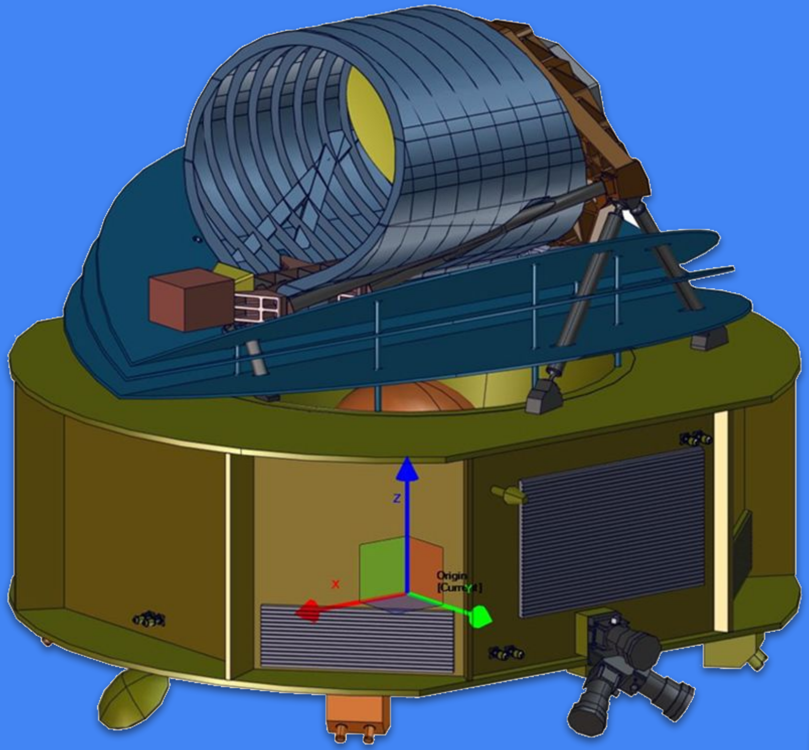
Extend known multiple-planet system around bright stars from K2 and TESS

Warm-Jupiters (P~10-200 d):

- larger orbit increases possibility of stable exomoons and Trojans
- > 50% in Kepler data are in multiple-planet systems (Huang+ 2016)



Ricker+ 2014



Thank you!

Stellar activity & starspots

Oshagh 2010 Characteristics of astrophysical "noise" signals in RV and photometric exoplanet searches

Noise source	Timescale	RV ($m\,s^{-1}$)	Photometry (ppm)	Treatment
Oscillations	5–15 min	0.2–3	100–300	**RV:** at least 15 min exposure **Photometry:** binning the light curve into 15-min bins after detection of transit signal
Granulation	15 min to 24 hr	1–30	50–500	**RV:** three measurements per night with 1–2 h separation and averaging them **Photometry:** binning the light curve into 1-h bins after detection of transit signal
Magnetic activity	Several days	1–200	50–10,000	**RV:** finding correlation between measured RVs and activity indicators; if any correlation found, remove RV jitter by modeling **Photometry:** model out-of- and in-transit portions of light curve