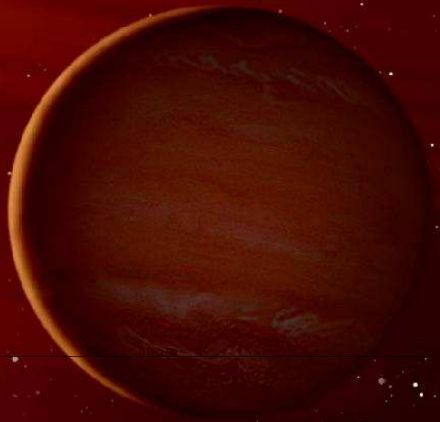
Exoplanet Detection through Timing

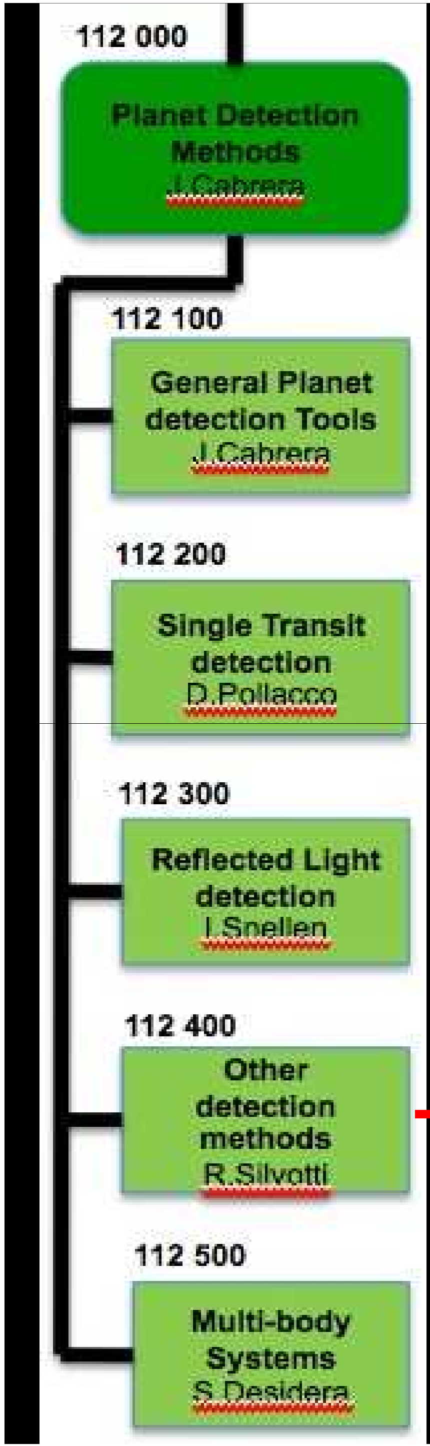


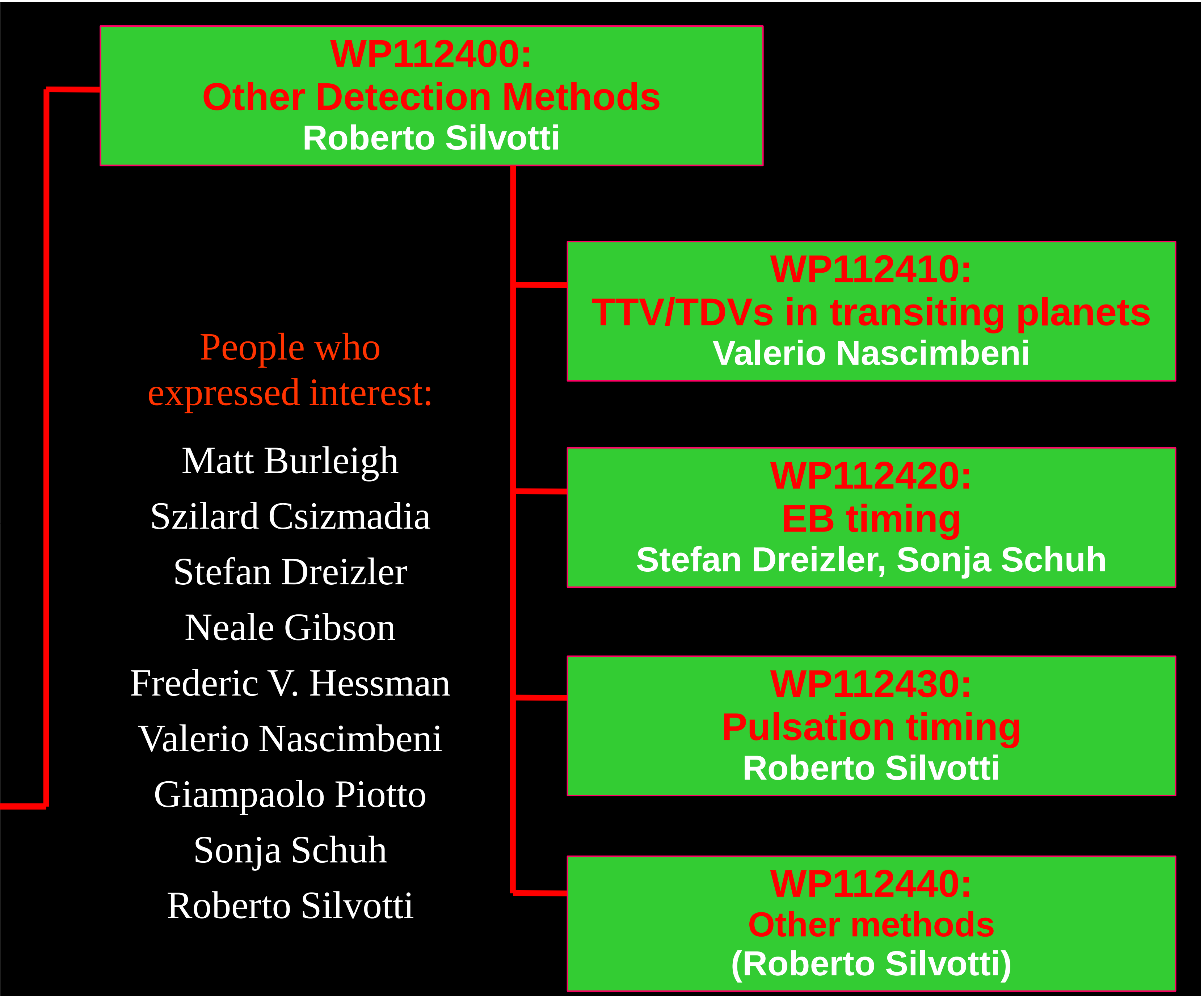
Roberto Silvotti

INAF - Osservatorio Astronomico di Torino

and the WG112400 team

PLATO Science Conference, Berlin, 24-25 February 2011





WP112400:
Other Detection Methods
Roberto Silvotti

People who expressed interest:

Matt Burleigh

Szilard Csizmadia

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Valerio Nascimbeni

Giampaolo Piotto

Sonja Schuh

Roberto Silvotti

WP112410:
TTV/TDVs in transiting planets
Valerio Nascimbeni

WP112420:
EB timing
Stefan Dreizler, Sonja Schuh

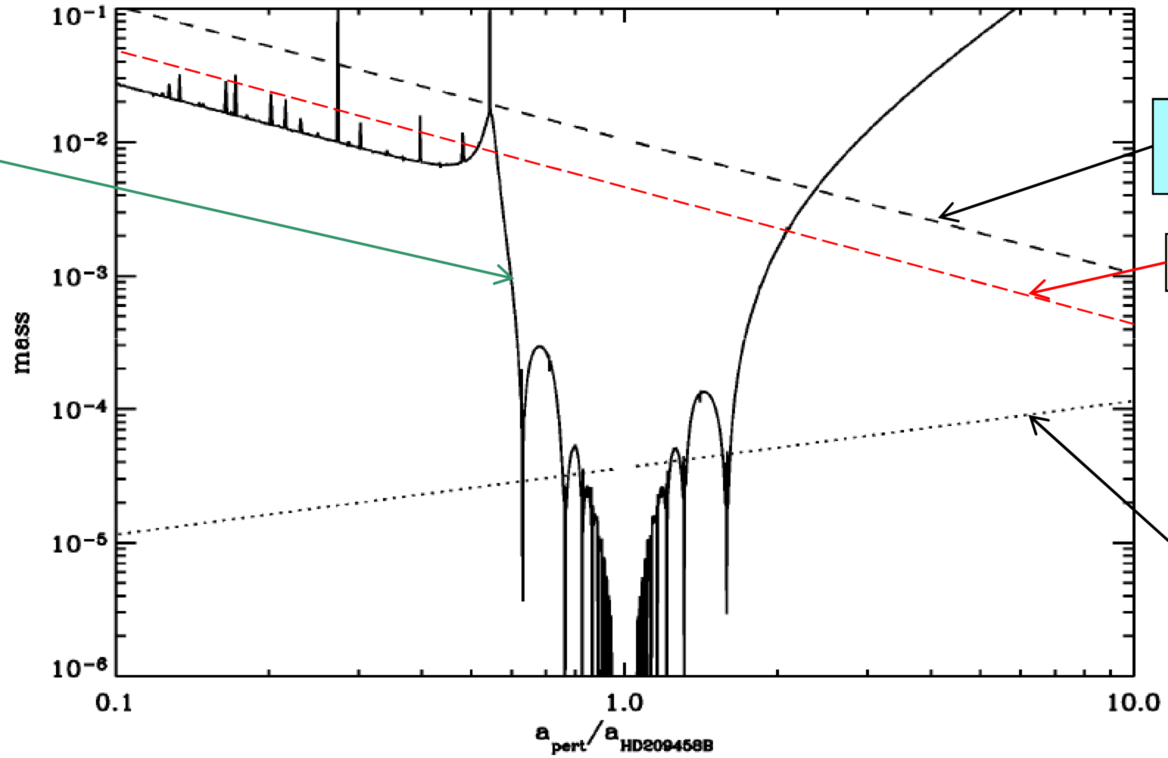
WP112430:
Pulsation timing
Roberto Silvotti

WP112440:
Other methods
(Roberto Silvotti)

TTVs are a powerful method to detect low mass planets (not necessarily transiting) from the transit time variations of transiting planets

The solid line represents a perturber mass sufficient to cause a TTV ampl. of 100 s (10σ) on HD 209458 b (P=3.5 d) assuming $M_{trans}=6.7\times10^{-4}\ M_{SUN}$ and both planets on circular orbits.

(Agol et al 2005)



astrometry limit (10σ) with σ_A=1 μas

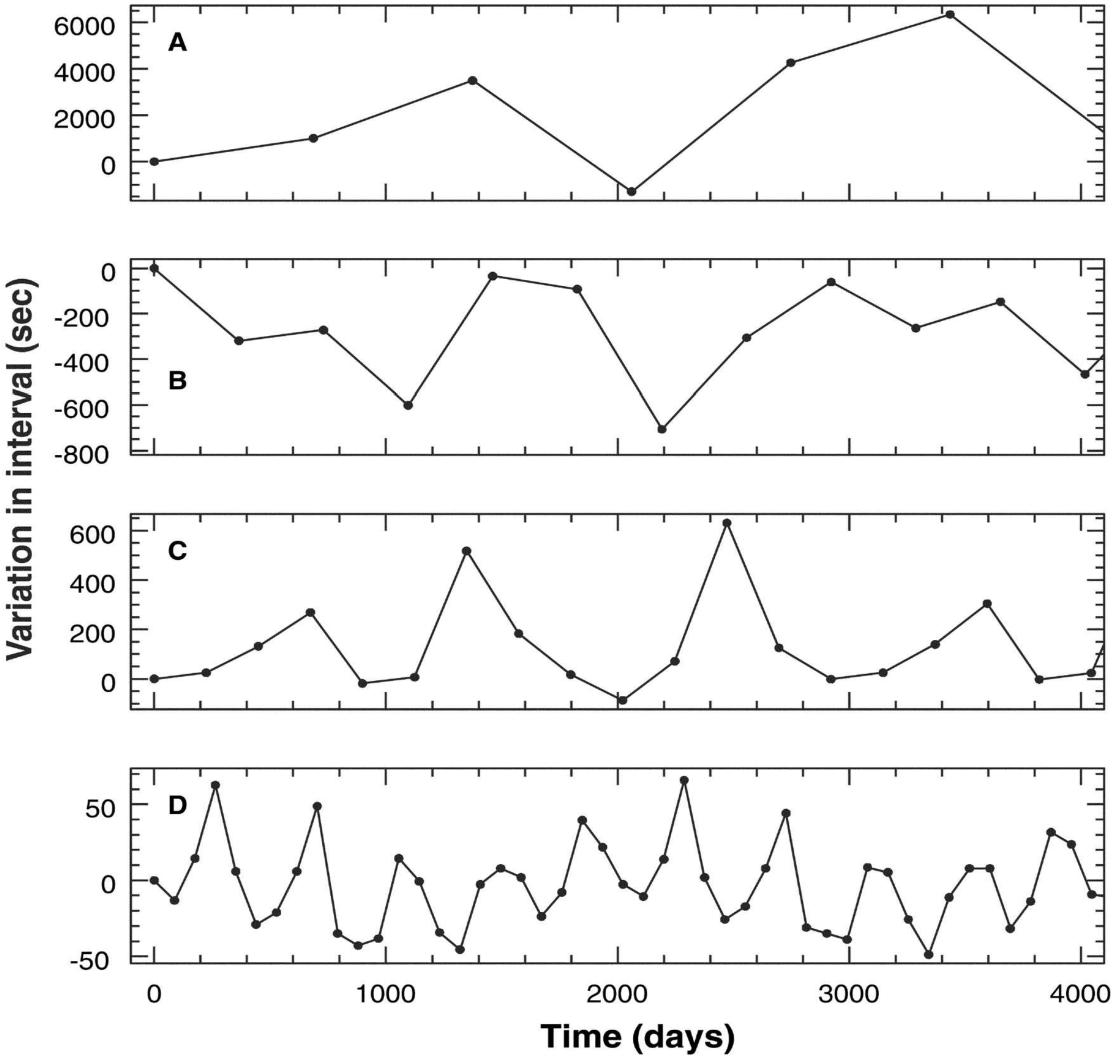
GAIA (3σ)

RV limit (10σ) with σ_{RV}=0.5 m/s

Figure 7. Mass sensitivity of various planet detection techniques to secondary planets in HD 209458. The vertical axis is the perturbing planet's mass in units of $M_\odot$. The horizontal axis is the period ratio of the planets. The solid line is for the transit timing technique, the dashed line is astrometric, and the dotted line is the radial velocity technique.

TTVs of solar-system terrestrial planets

(Holman & Murray 2005)



MARS

EARTH

VENUS

MERCURY

There are various possible configurations.

Following Agol et al. 2005:

1) Interior perturbing planets with much smaller periods

2) Exterior perturbing planets on eccentric orbits with much larger periods

2a) Both planets on circular orbits with arbitrary period ratio but not in resonance

2b) Planets on initially circular orbits in resonance

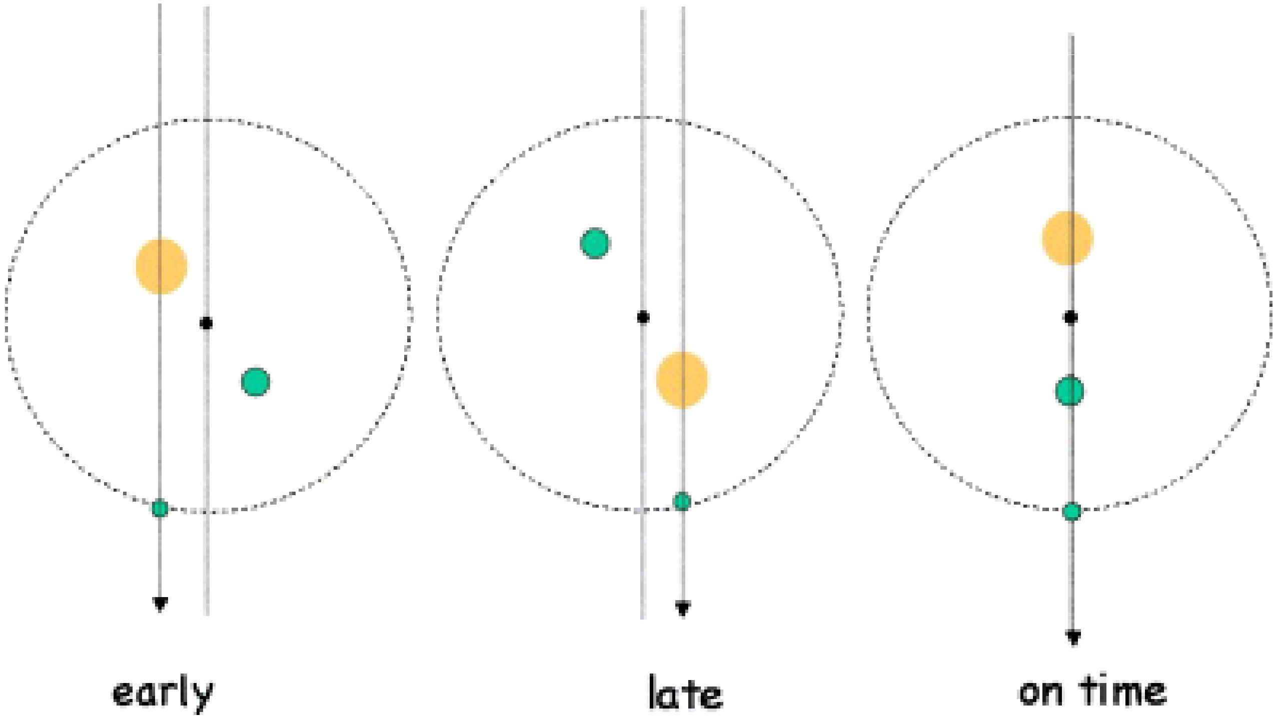
Moreover the potential of TTVs increases further in case of multi-transiting planets (e.g. Kepler -11) or, even more, in case of overlapping transits.

1) Interior perturbing planet with much smaller period:

Planet-planet interactions are negligible and the main effect is due to the reflex motion of the star:

$$\delta t_{max} \cong (M_{in}/M_\star)\,(a_{in}/2\pi a_{out})\,P_{out} \cong 15\text{ min for } 1\,M_J,\ 1\,M_{SUN},\ a_{out}=5a_{in},\ 1\text{ yr}$$

$$\cong 3\text{ s} \quad \text{for } 1\,M_E$$



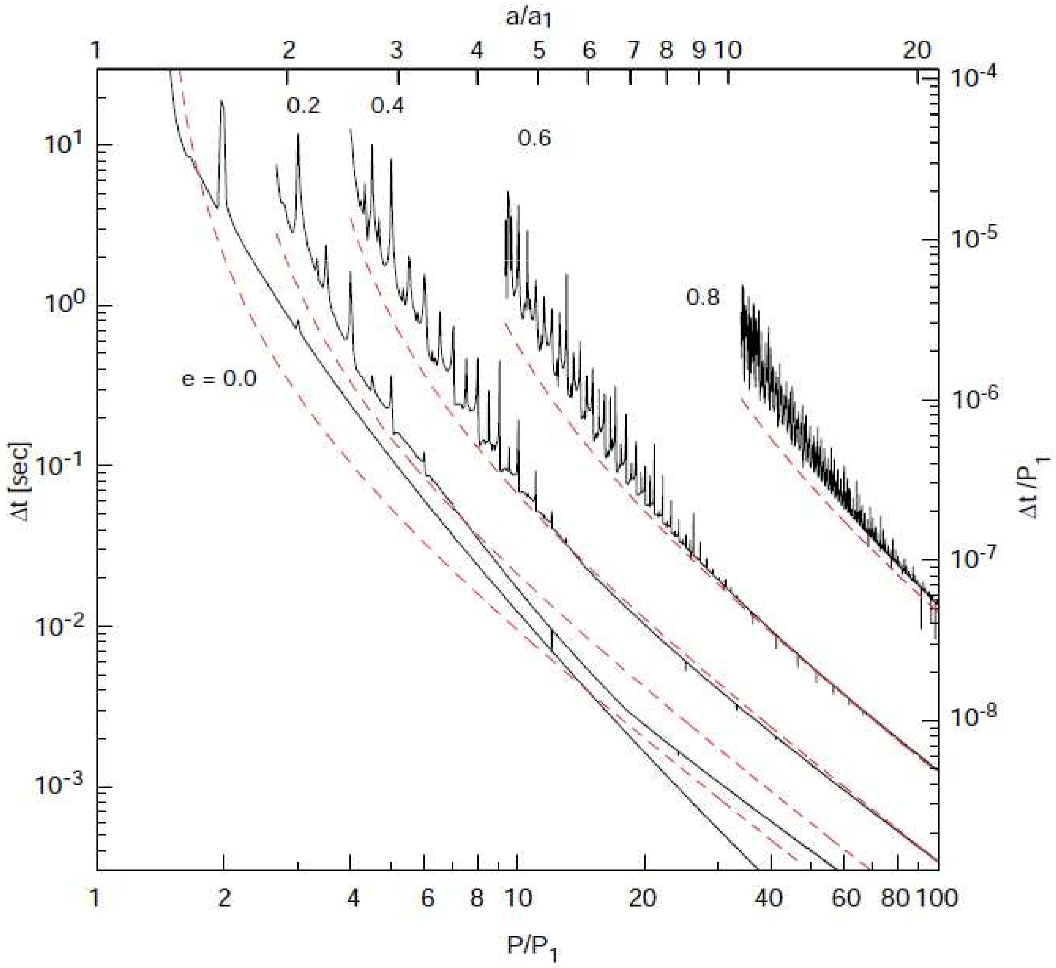
2) Exterior perturbing planet on eccentric orbit with much larger period:

An exterior planet changes the period of the internal planet and TTVs are given by

$$\delta t \sim (M_{out}/M_{\star})\, e_{out}\, (a_{in}/a_{out})^3\, P_{out}$$

Right: TTVs on a planet with P_{in}=3 d, e=0.01, M_{in}=1M_J, induced by an external planet with **M_{out}=1M_E** ($M_{\star}$=1M_{SUN}) for different period (or semimajor axis) ratios and different eccentricities (from Holman & Murray 2005). The two planets are assumed to be coplanar. The black lines show the maximum TTVs from numerical simulations, while the red dashed lines are an analytical solution (eq.1 of Holman & Murray 2005).

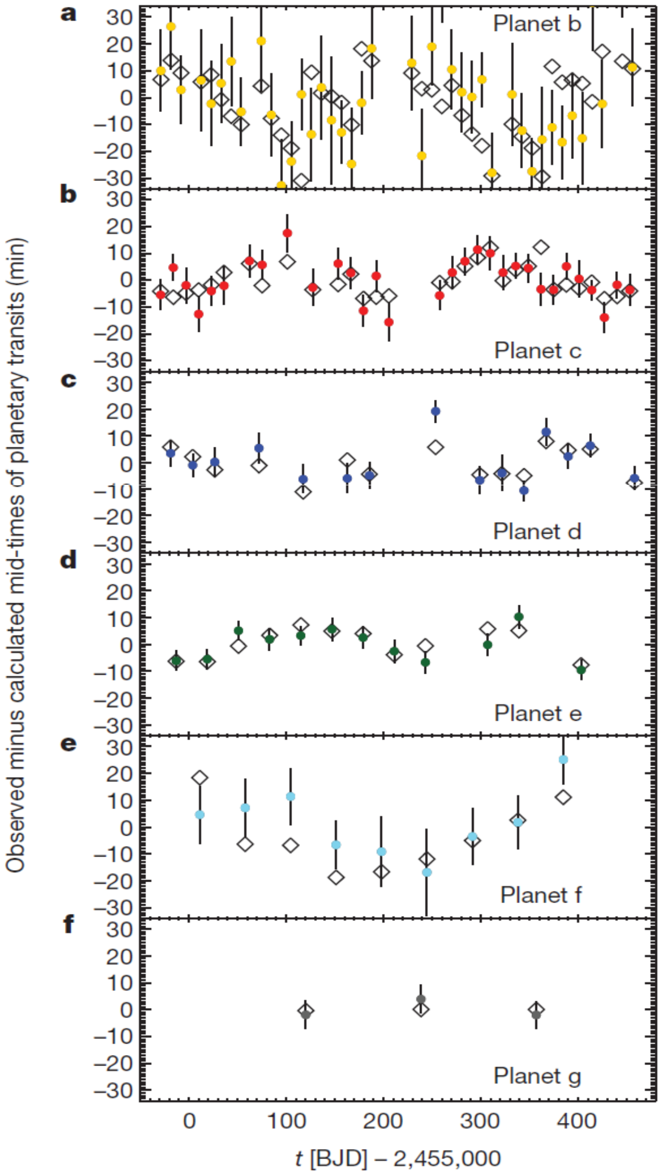
The figure clearly shows that the maximum effect is obtained when the two planets are in resonance.



The potential of the systems with multiple transits

TTVs are not only an indirect detection method: they are also a **validation** and **characterization** tool !

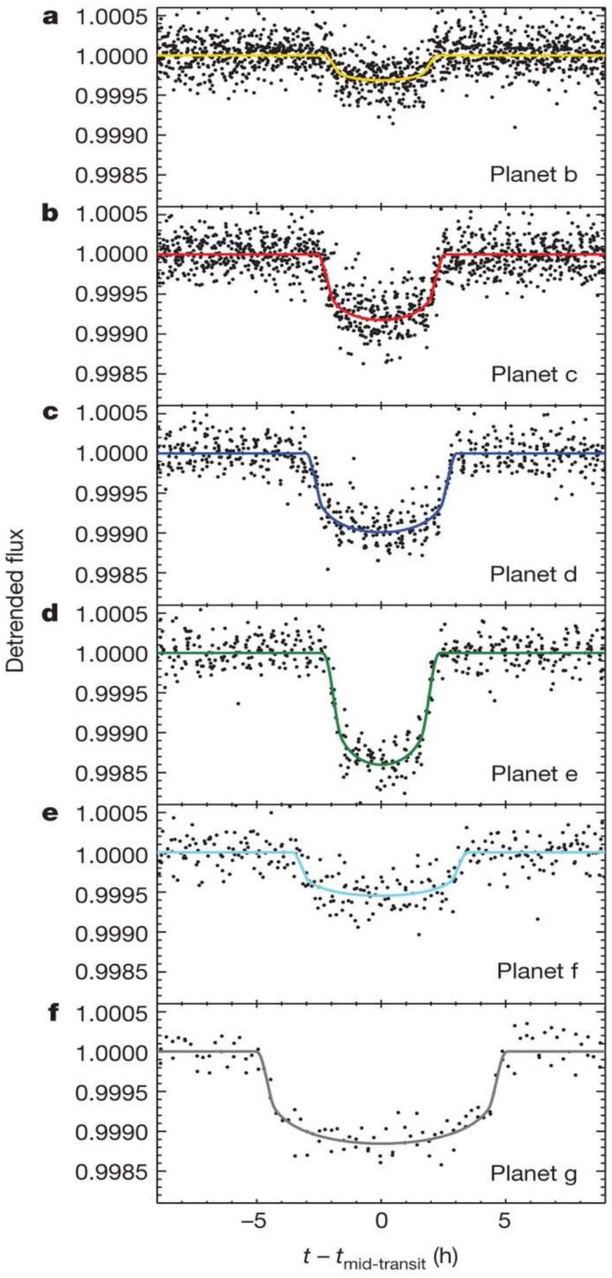
Low-mass planets tend to cluster in multiple systems, and Kepler is revealing tens of stars with candidate multiple transiting planets, many locked in MMR (Lissauer et al. 2011, arXiv:1102.0543). The detection of a **mutual TTV** allow us to validate both planets and to measure their masses without expensive or unfeasible RV follow-ups.



Kepler-11 is a six-planet system, whose five inner members were validated only with TTV analysis (Lissauer et al. 2011, Nature 470, 53).

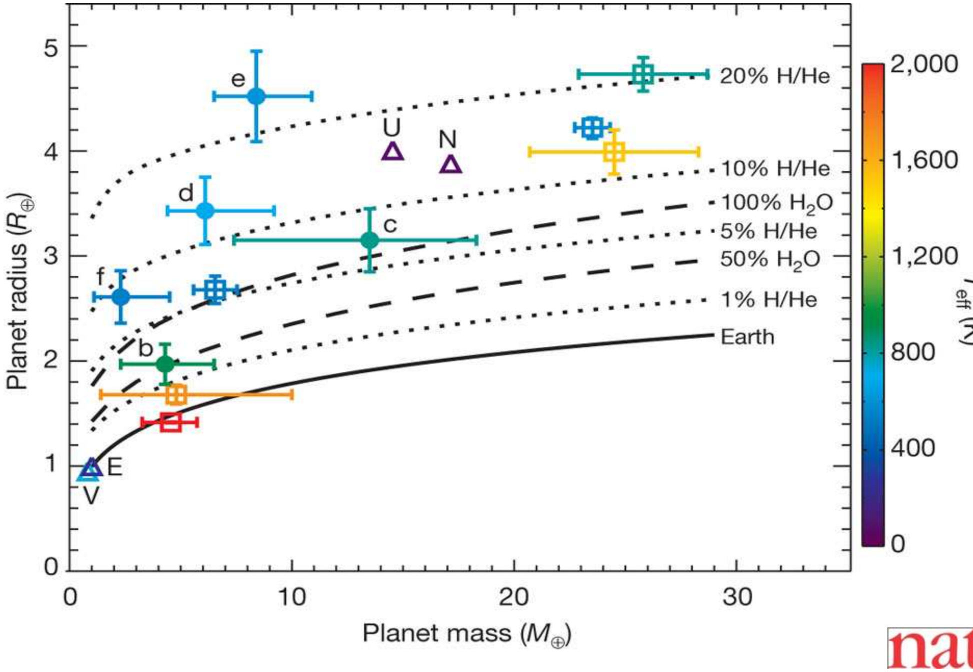
This is a great opportunity also for Plato, which will take advantage of an optimal time sampling from the two “fast” telescopes.

Kepler-11 *(Lissauer et al. 2011)*



Left: detrended data shown phased at the period of each transit signal and zoomed to an 18-h region around mid-transit.

Bottom: mass-radius relation ship of Kepler-11b to Kepler-11f. Other transiting extrasolar planets in this size range are shown as open squares, representing, in order of ascending radius, Kepler-10b, CoRoT-7b, GJ 1214b, Kepler-4b, GJ 436b and HAT-P-11b. The triangles (labelled V, E,Uand N) correspond to Venus, Earth, Neptune and Uranus, respectively.



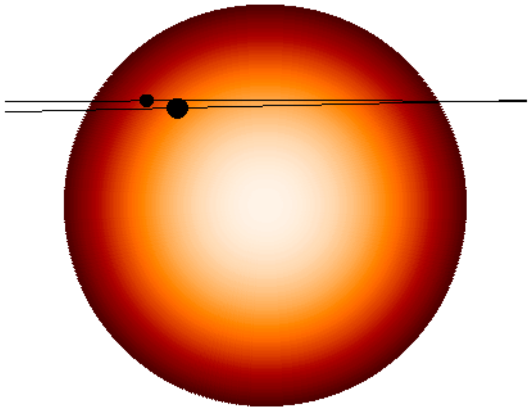
nature

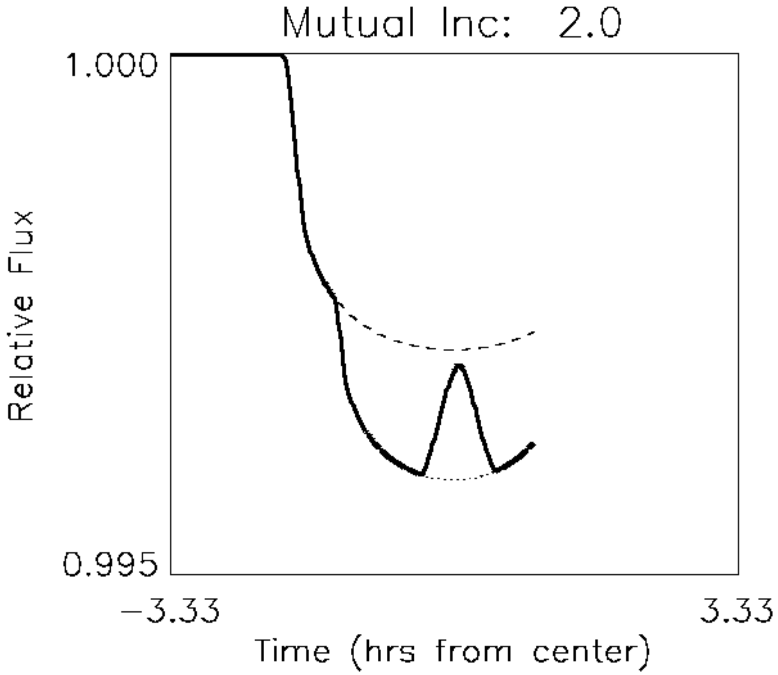
Overlapping double transit

(from Ragozzine & Holman 2010)

When one planet crosses over the other, it is possible to measure also the

mutual inclination





Animation from:

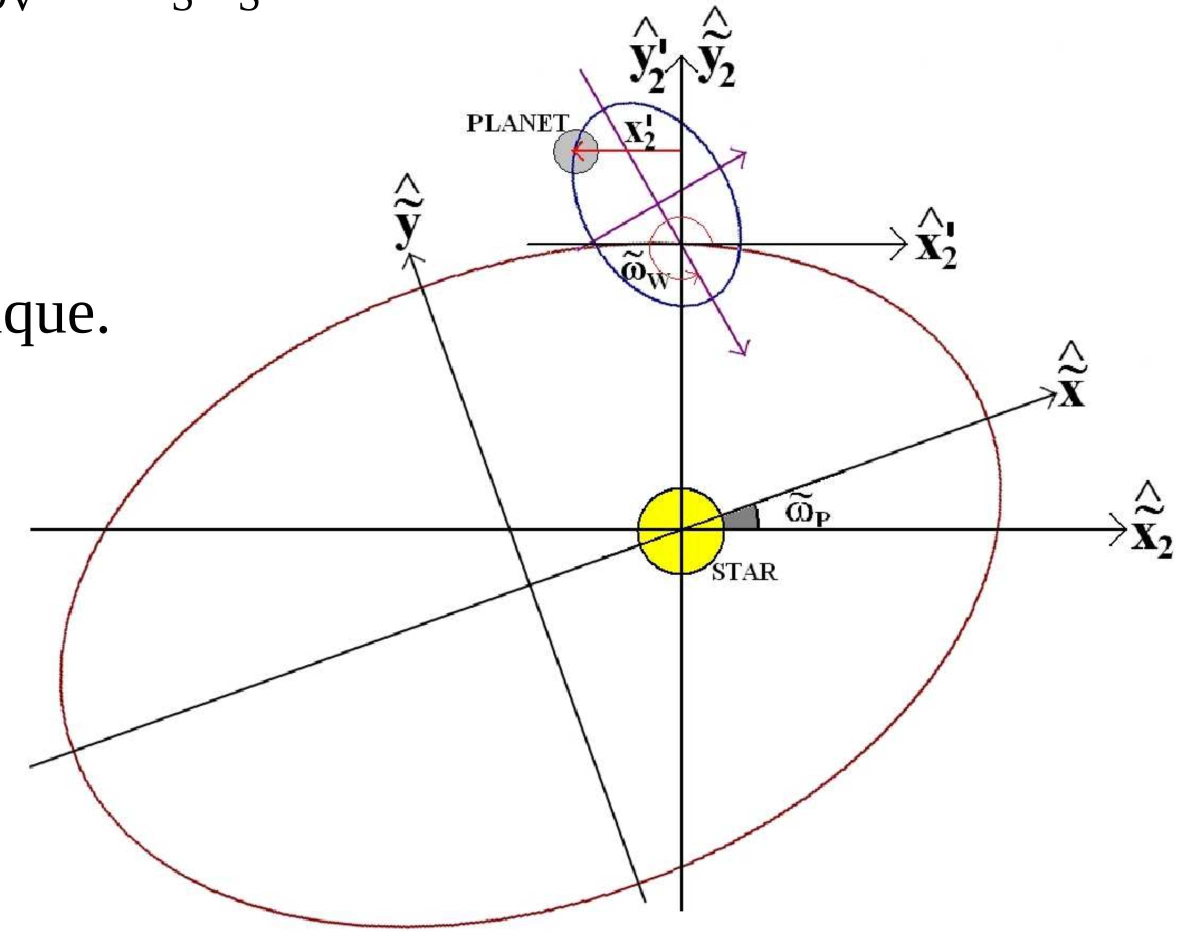
https://www.cfa.harvard.edu/~dragozzi/meanim.gif

TDVs: another observable to detect exomoons

and break the degeneracy on M_S and a_S:

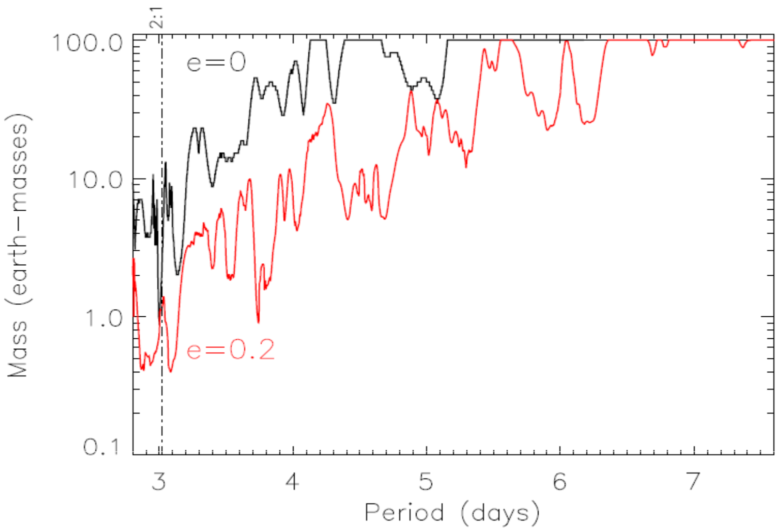
$\delta_{TTV} \propto M_S \, a_S$ while $\delta_{TDV} \propto M_S \, a_S^{-1/2}$

TDV has a $\pi/2$ phase difference to the TTV signal, making it an excellent complementary technique.



(Figure from Kipping 2009)

Measuring TTVs in CoRoT-1b (Csizmadia et al. 2010, A&A 510, A94)



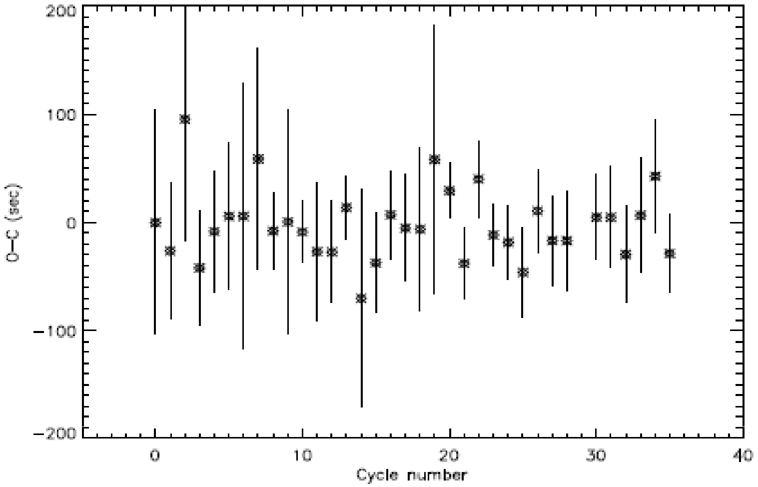
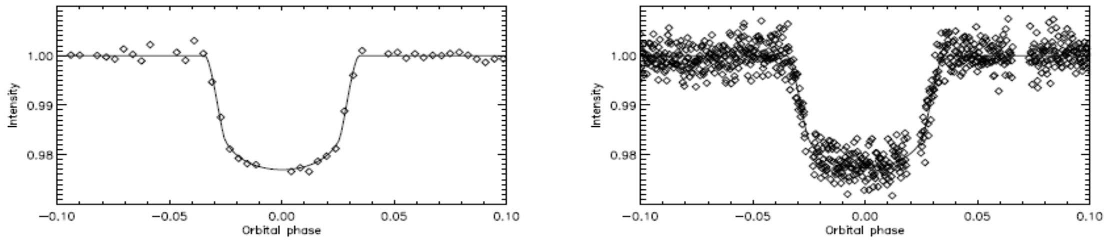
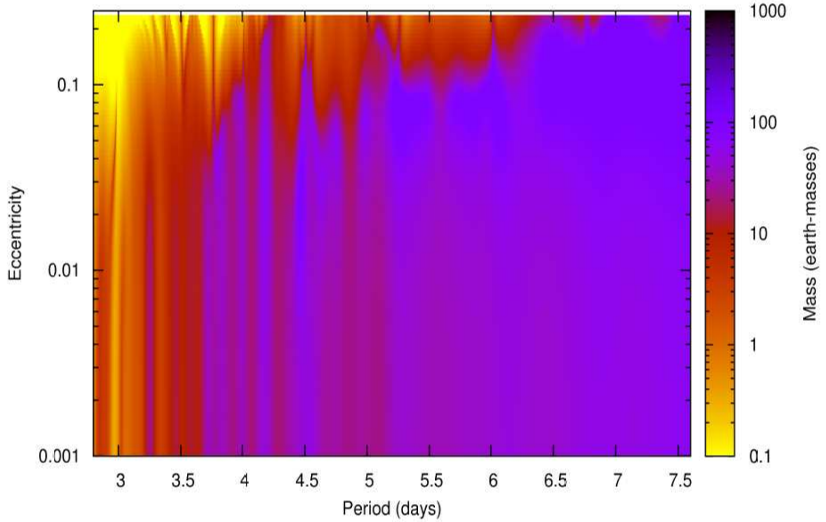


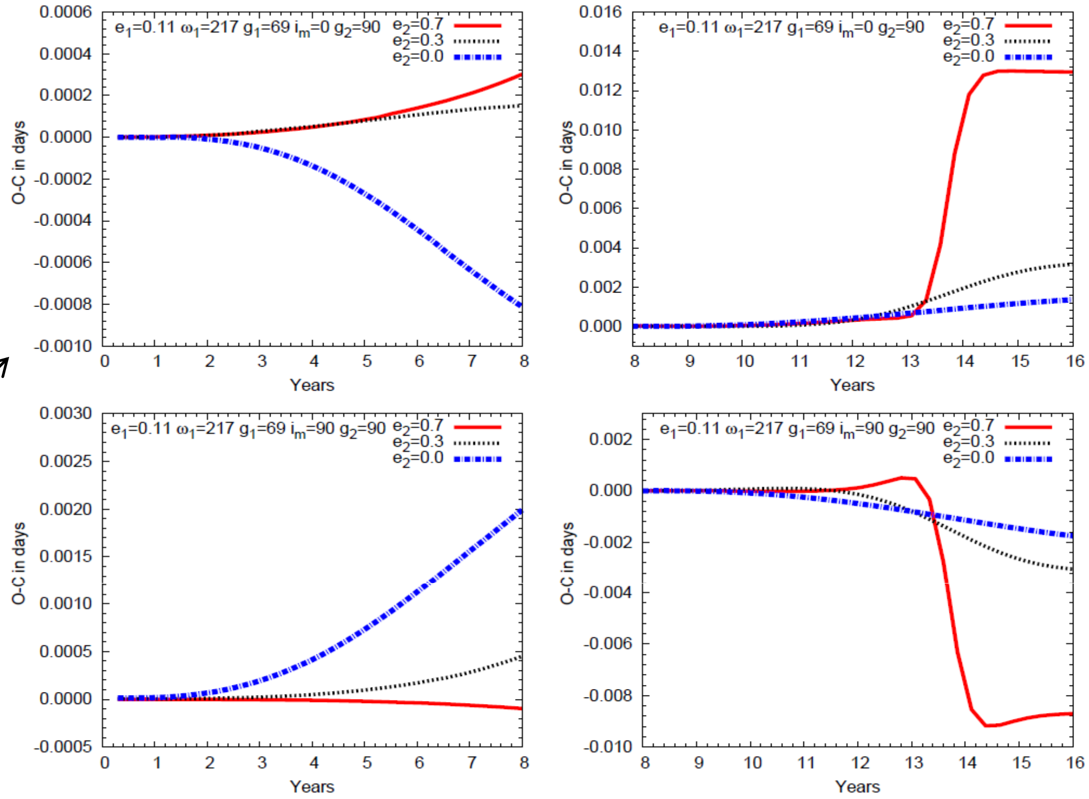
Fig. 4. Maximum allowed mass of a hypothetical perturbing object as a function of its orbital period for excentricities e=0 and 0.2. The 2:1 mean motion resonance is indicated.



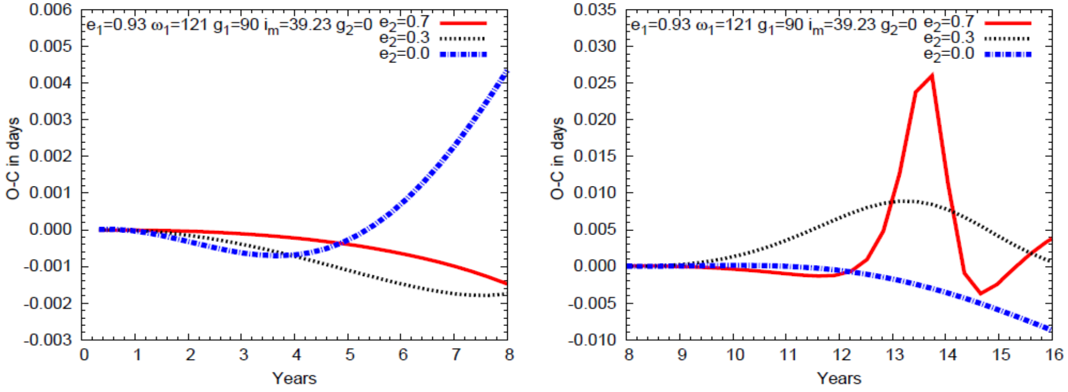


O-C predictions for an hypotethical third body (P=27 years, M=5Mjup) orbiting:

CoRoT-9b (P=95 d, e=0.11)



HD 80606b (P=111 d, e=0.93)



(Borkovits, Csizmadia et al. 2011)

The light travel time effect

$$\tau = \frac{a}{c}\,\frac{m_p \sin i}{M_\star + m_p} \overset{m \ll M}{\cong} 0.5\,\frac{[a/\mathrm{AU}]\,[m_p/m_{\mathrm{JUP}}]\sin i}{[M_\star/M_{\mathrm{SUN}}]}\ \mathrm{sec}$$

where a can be obtained from Kepler’s 3^d law:

$$a = \left[\frac{G}{4\pi^2}\,(M_\star + m_p)\,P_{\mathrm{ORB}}^2\right]^{1/3}$$

Post-RGB planets

Planet name	**M sini [M_{Jup}]**	***a* [AU]**	**P [yr]**	**e**	**Evolut. phase of the parent star**	**Detection method**	**References**
PSR 1257+12 b PSR 1257+12 c PSR 1257+12 d	M≅6 e-5 M≅0.014 M≅0.012	0.19 0.36 0.46	25.262 d 66.5419 d 98.2114 d	0 0.0186 0.0252	pulsar	timing (radio signal) timing (radio signal) timing (radio signal)	Wolszczan & Frail 1992 Konacki & Wolszczan 2003
PSR B1620-26 b	2.5	23	100		pulsar+WD in GC	timing (radio signal)	Thorsett et al. 1994 Sigurdsson et al. 2003
WD0137-349 b	M≅55	0.375 R_{sun}	1.927 h		WD	RVs	Maxted et al. 2006
GD66 b?	2.4 (M<7)	2.75	5.7	0	puls. WD (DAV)	timing (pulsations)	Mullally et al. 2008, 2009
GD356?	M<12		>2.7 h		magnetic WD	inferred from Zeeman splitting	Wickramasinghe et al. 2010
V391 Peg b	3.2	1.7	3.2	0	EHB (puls. sdB)	timing (pulsations)	Silvotti et al. 2007
HW Vir b HW Vir c	19.2 8.5	5.3 3.6	15.8 9.1	0.46 0.31	EHB (ecl. sdB+M)	timing (eclipse) timing (eclipse)	Lee et al. 2009
HS0705+6700 b	39.5	< 3.6	7.15		EHB (ecl. sdB+M)	timing (eclipse)	Qian et al. 2009a
HD 149382 b?	M≅8-23	5-6.1 R_{sun}	2.391 d		EHB (sdB)	RVs	Geier et al. 2009 Jacobs et al. 2010
HIP 13044 b	1.25	0.116	16.2 d	0.25	RHB (extragal. orig.?)	RVs	Setiawan et al. 2010
NN Ser b NN Ser c	6.9 2.3	5.4 3.4	15.5 7.7	0 0.2	pre-CV (ecl.WD+M)	timing (eclipse) timing (eclipse)	Qian et al. 2009b Beuermann et al. 2010a Hessman et al. 2010
DP Leo b	6.05	8.2	28.0	0.39	CV (eclips. polar)	timing (eclipse)	Qian et al. 2010a Beuermann et al. 2010b
QS Vir b	M≅6.65	4.2	7.86	0.37	CV (hybernat. ecl.)	timing (eclipse)	Qian et al. 2010b

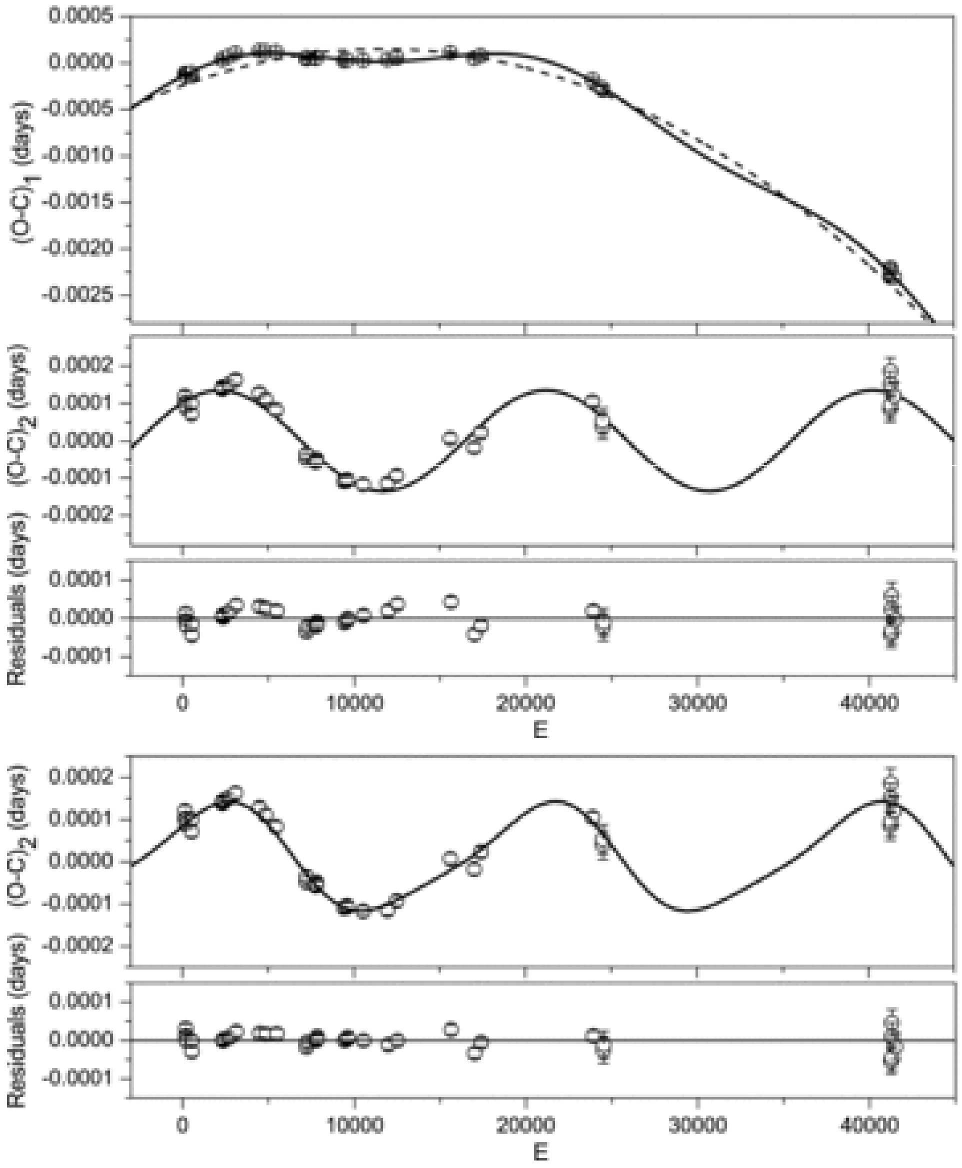
Planets orbiting wide binary WD+MS systems are not included (at least 3 such systems exist, Desidera e Barbieri 2007).
A few post-RGB BDs of particular interest are included (but the list of post-RGB BDs is not complete).

QS Vir b (eclipse timing)

Star:
hibernating CV

Planet:
$M = 6.7\ M_{Jup}$
$P = 7.9$ yr
$a < 4.2$ AU

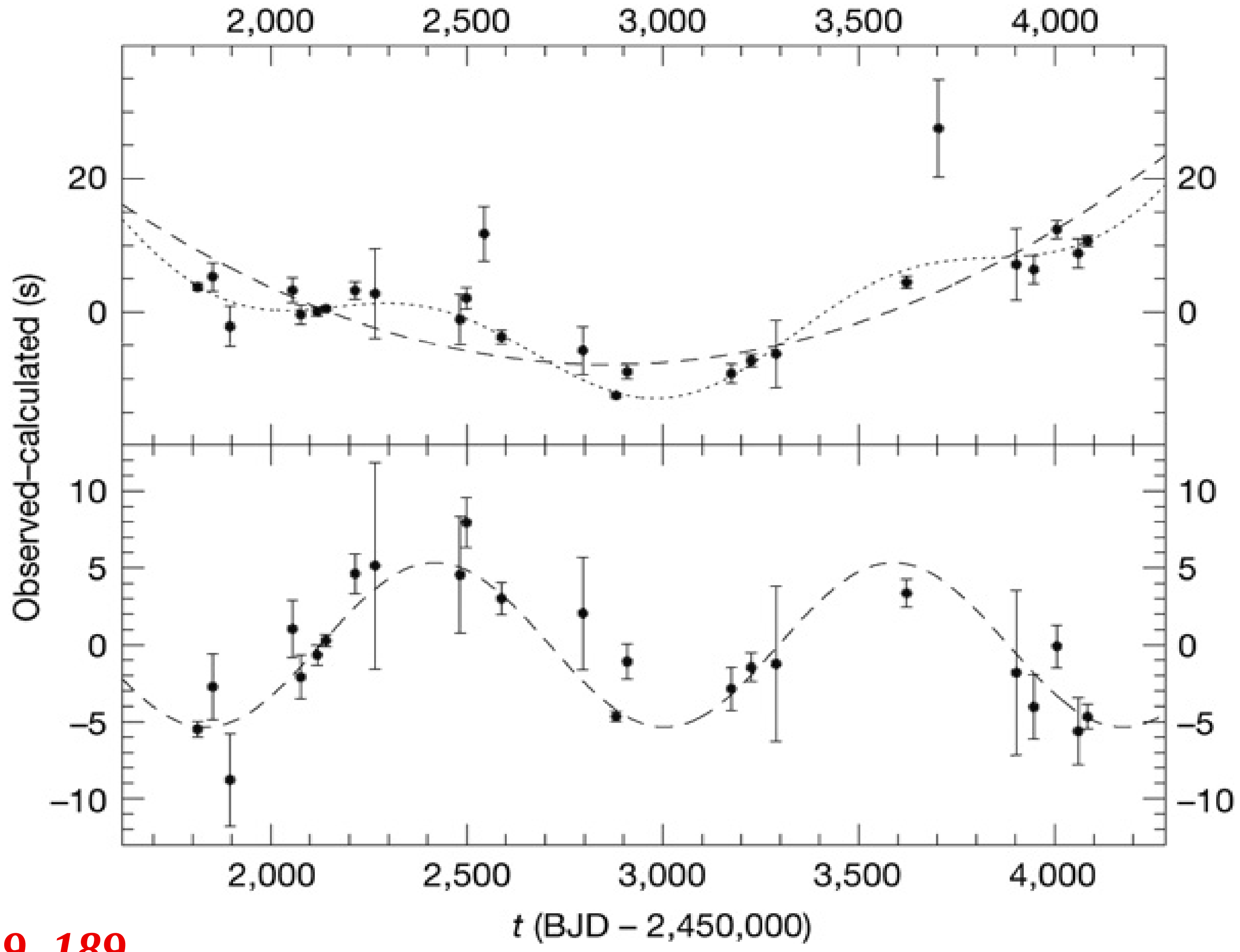
Qian et al. 2010b



The EHB sdB + giant planet system V391 Peg

Star:
single sdB pulsator

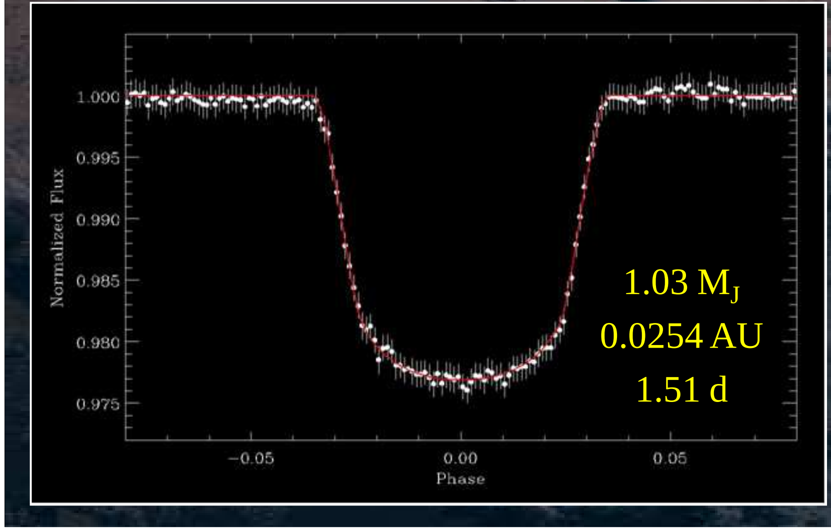
Planet:
$M_{min} = 3.3\ M_{Jup}$
$P = 3.2$ yr
$a = 1.7$ AU



Silvotti et al. 2007, Nature 449, 189

CoRoT

1st transit detection



1.03 M_J

0.0254 AU

1.51 d

Launch: Dec. 2006

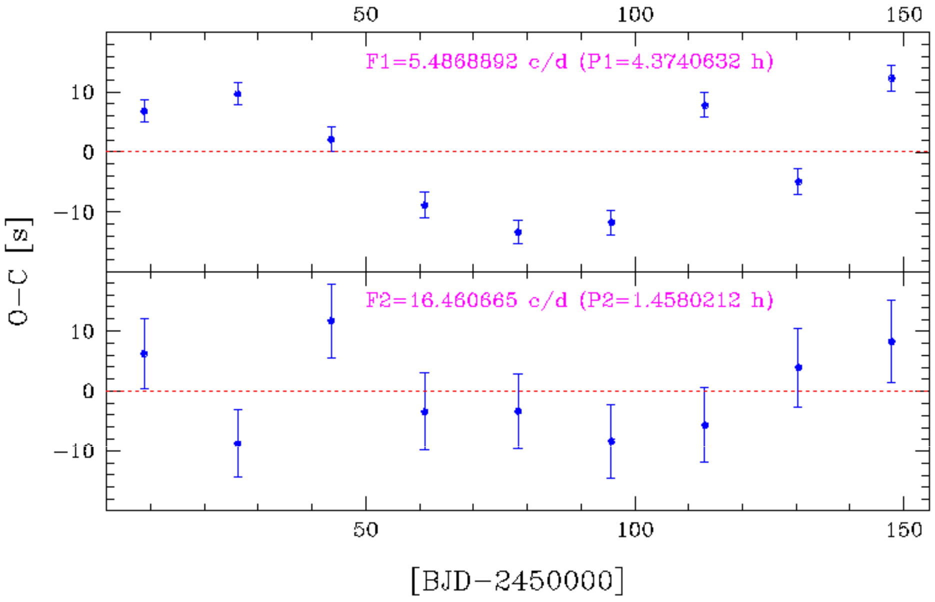
Mission: 6.25 yr

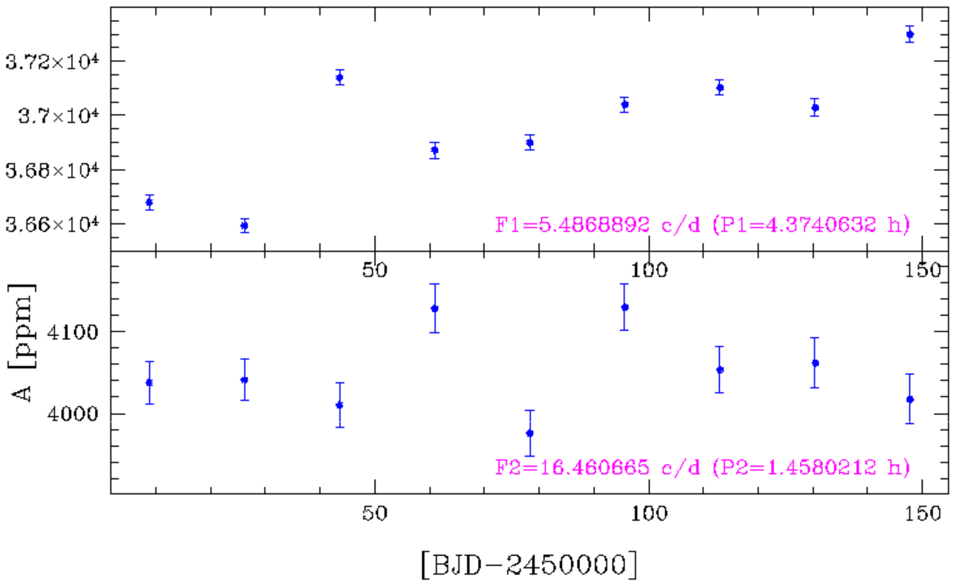
Area: 0.057 m^2

FOV: 4 deg^2

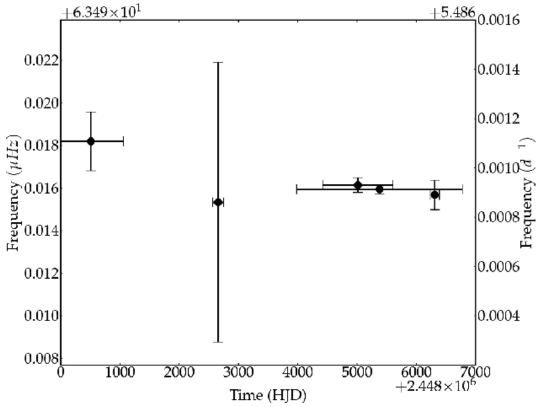
Tests on CoRoT data: **(1) the β Cephei star HD180642 (V1449 Aquilae)**

O-C diagram of the β Cephei star HD 180642 (V1449 Aquilae), V=8.29





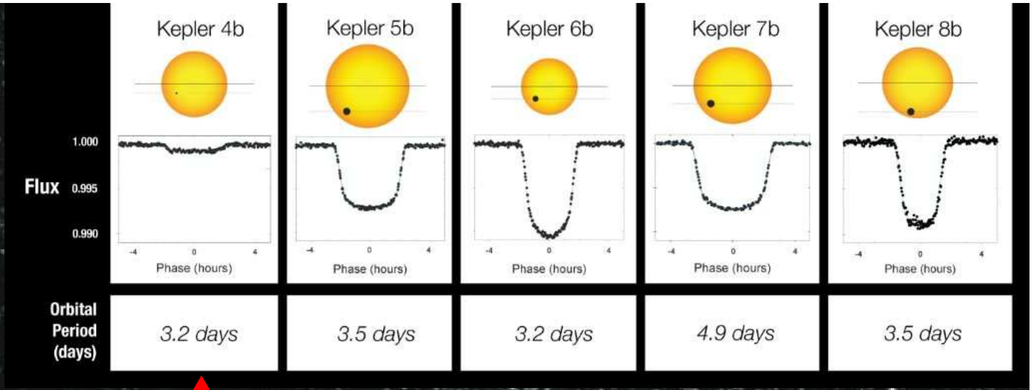
Each point represents about 17.4 days of a CoRoT long run of 156 days. The upper and lower panels were obtained from the frequencies at 5.487 c/d (or 4.374 hours, main pulsation mode) and 16.461 c/d (1.458 hours). The upper panel suggests an O-C variation of about 20 s in 2 months, which would translate into a value of dP/dT of about 4×10^{-9} s/s, while Degroote et al. (2009) obtained about 1.3×10^{-9} s/s from a direct measurement.

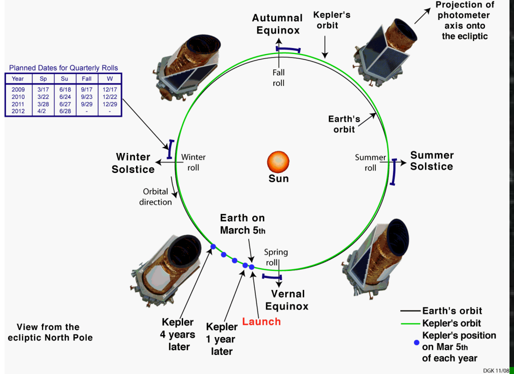


Silvotti et al. 2010

Degroote et al. 2009

Kepler





Planned Dates for Quarterly Rolls

Year	Sp	Su	Fall	W
2009	3/17	6/18	9/17	12/17
2010	3/22	6/24	9/23	12/22
2011	3/28	6/27	9/29	12/29
2012	4/2	6/28	-	-

$0.077\ M_J$

$0.357\ R_J$

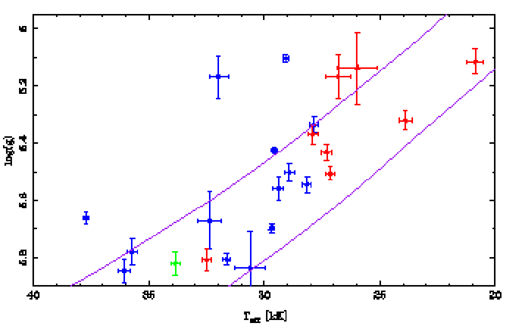
0.0456 AU

Launch: June 2009

Mission: 3.5 yr +

Area: 0.7 m^2

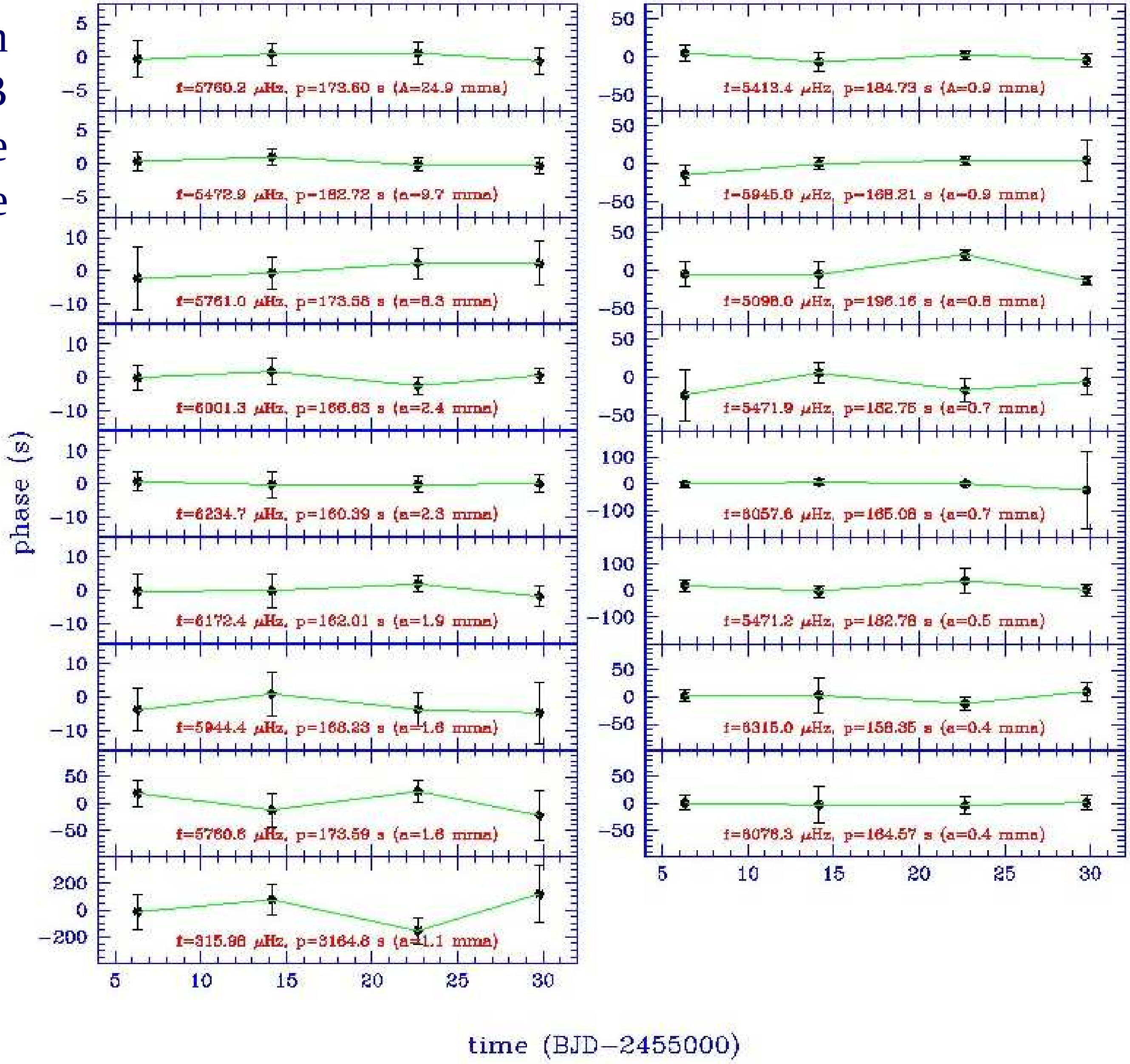
FOV: 111 deg^2



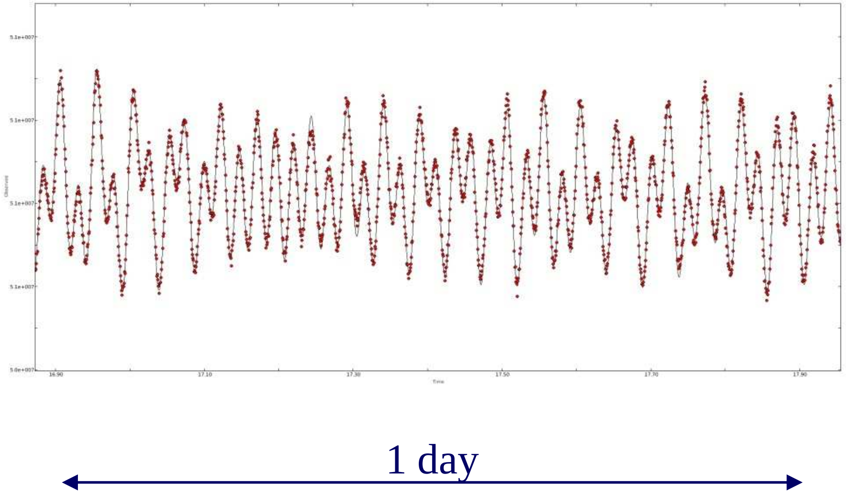
Preliminary tests on Kepler data: **(1) sdB (fast) pulsators**

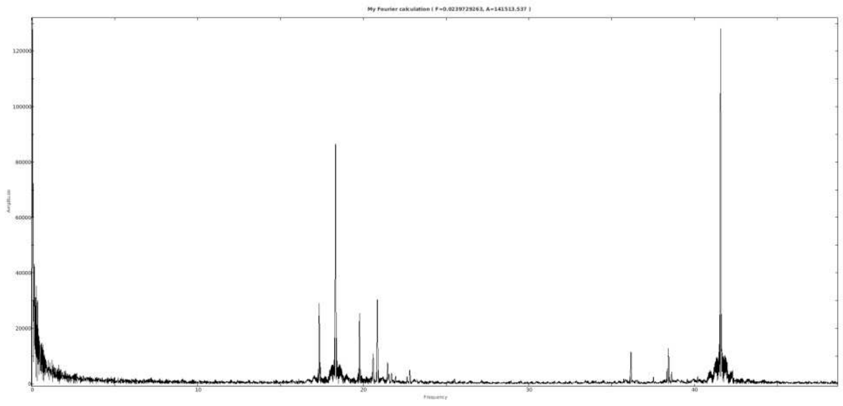
O-C plots of 17 pulsation periods of the short-period sdB pulsator kplr10139564 (see Kawaler et al. 2010 for more details).

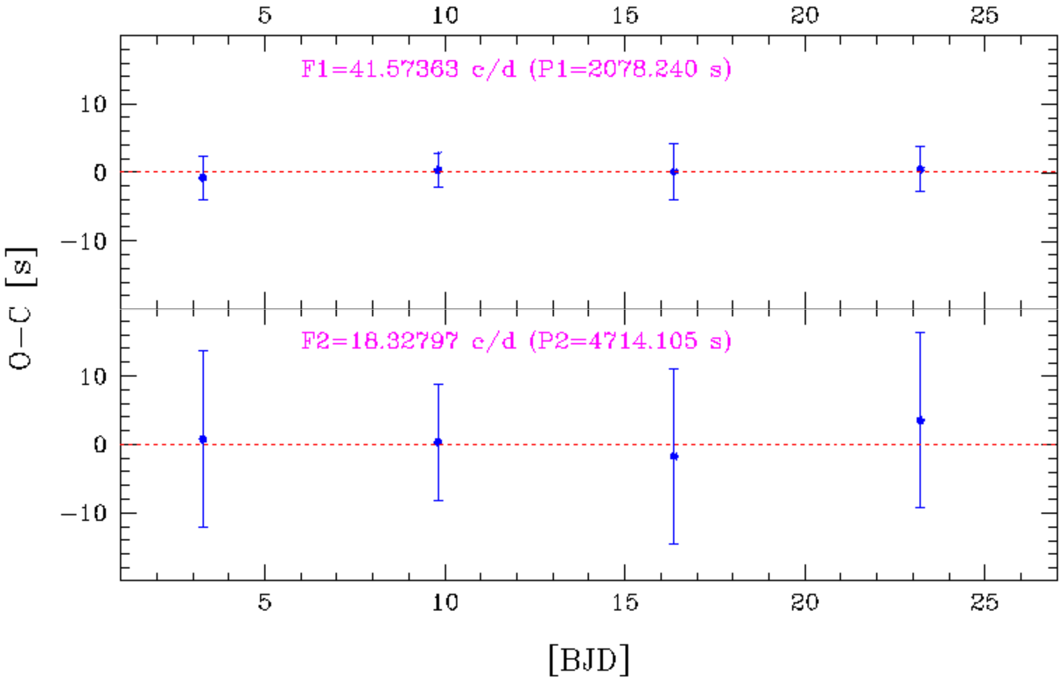
Each point represents about 5 days of short cadence data. The phase coherence of all these periods suggests that dP/dt could be measured for most of them in 3.5 yrs of the Kepler mission. The small error bars of the two periods with higher amplitude (173.60 and 182.72 s) allow to detect a planet of about 5 M_J at 1 AU from the star. Using longer subsets, this limit could be reduced to about 1.5 M_J.



Preliminary tests on Kepler data: **(3) Delta Scuti**

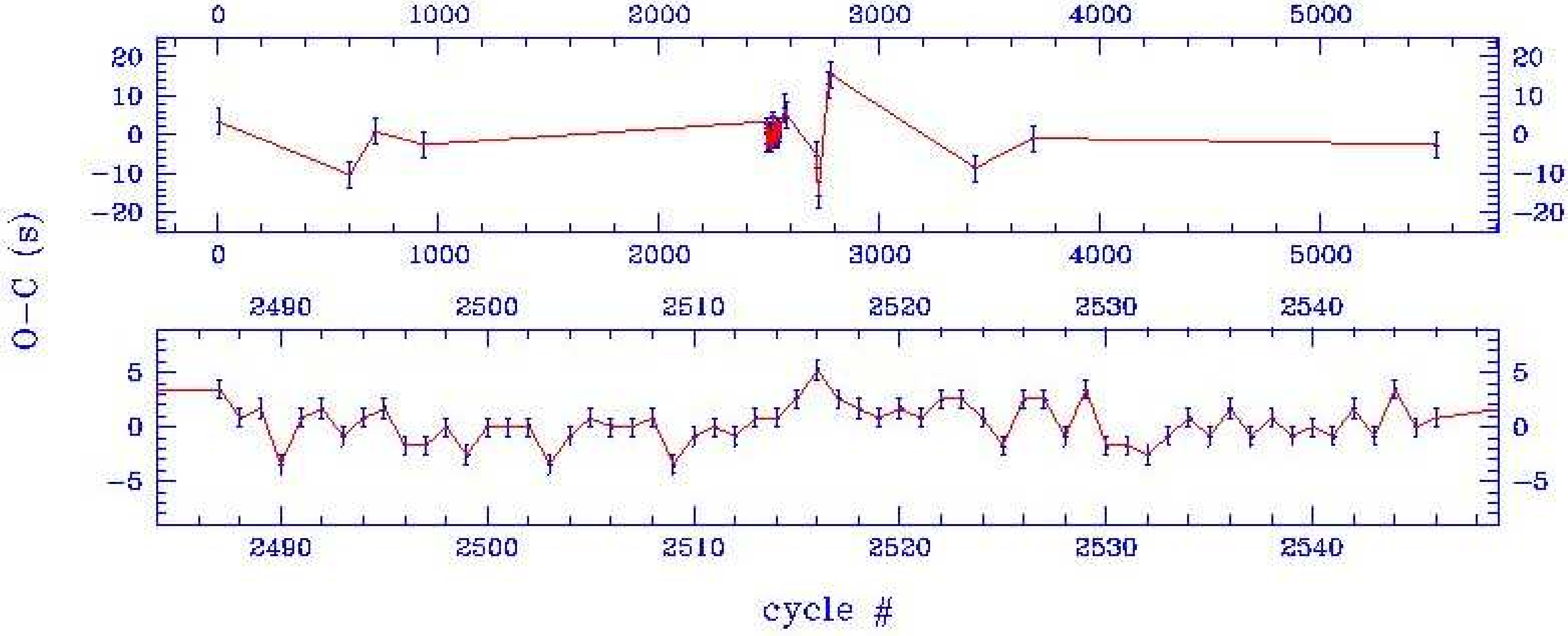






Each point represents about 1 week of short cadence data (sampling time of 1 minute)

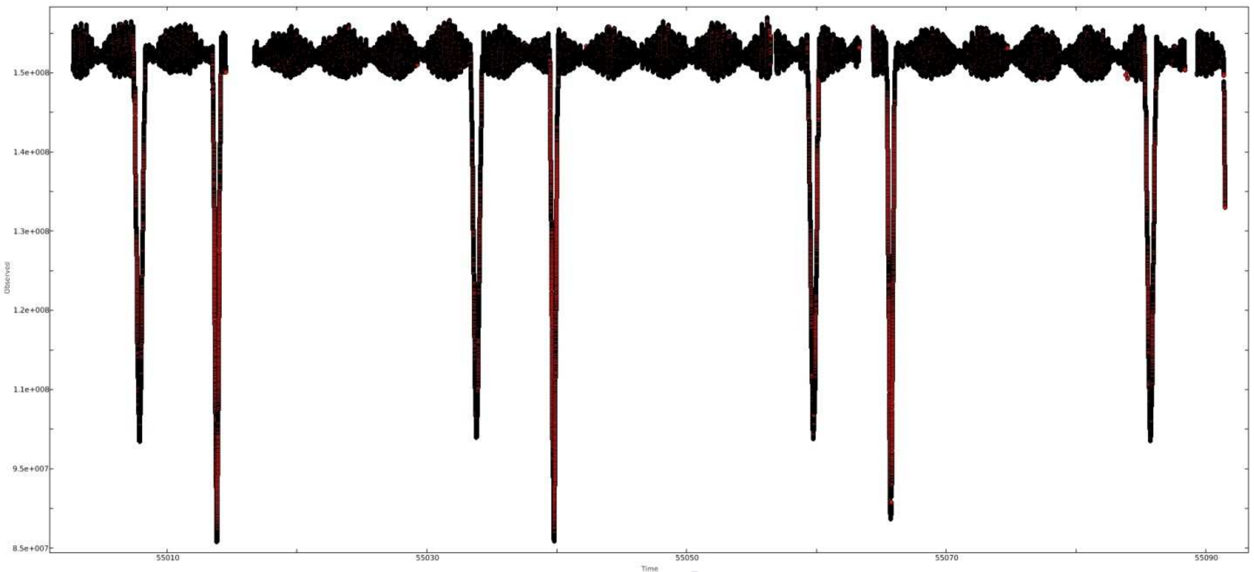
Preliminary tests on Kepler data: (4) pulsators in eclipsing binaries



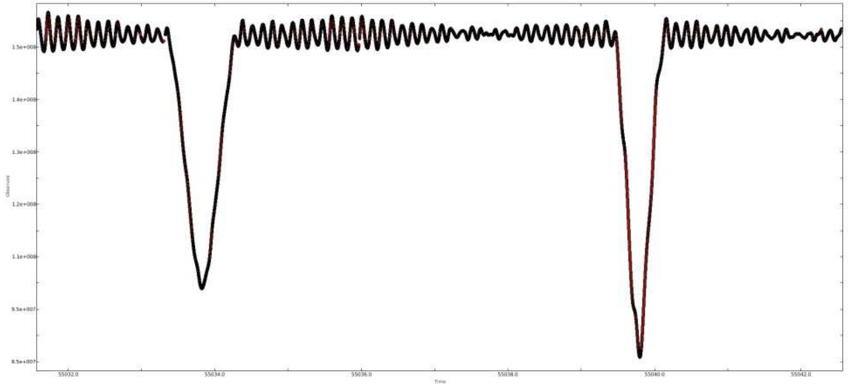
sdB+dM system 2M1938+4603 (see Østensen et al. 2010 for more details)

Preliminary tests on Kepler data: **(4) pulsators in eclipsing binaries**

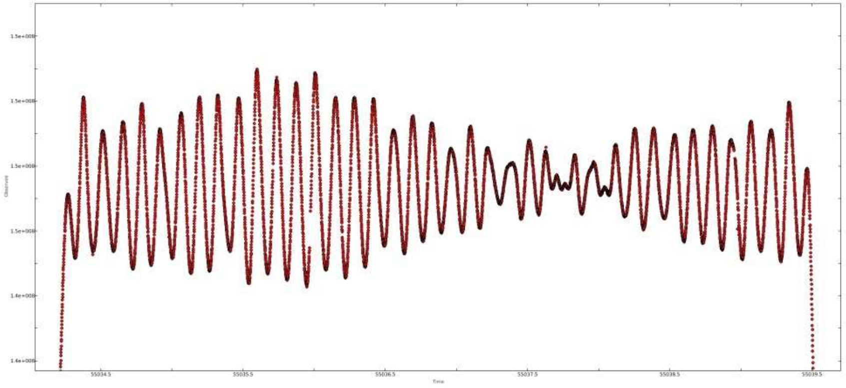
Eccentric eclipsing binary
with Delta Scuti pulsations:
V=9.25, Porb=25.95 d



~3 months

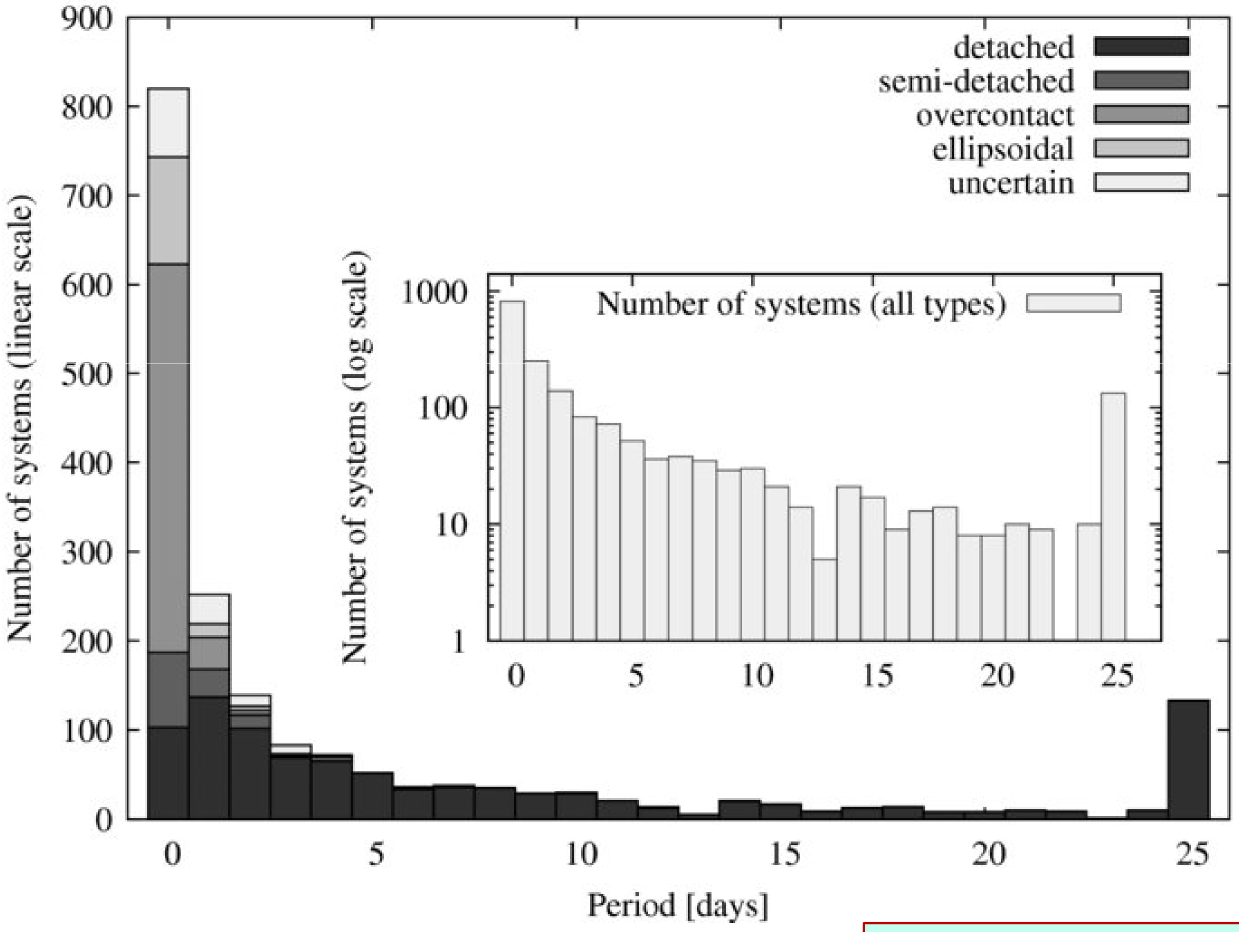


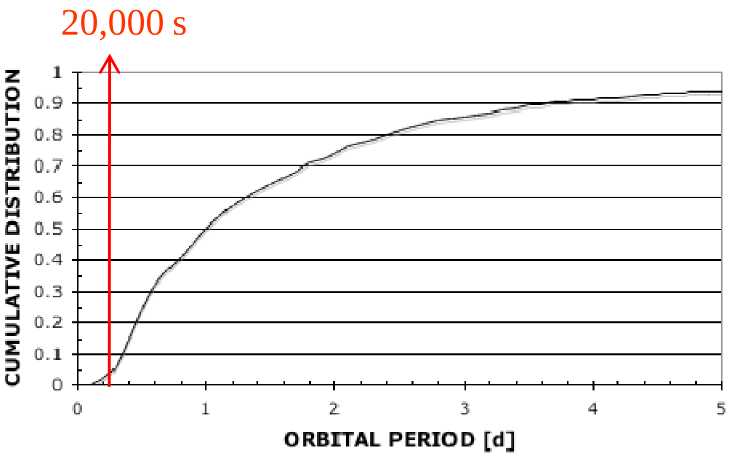
~10 d



~5 d

Kepler in the first 44 days of operation has observed 1832 EBs (Prša et al. 2010)





ASAS binaries:

Scaling on Kepler first results, PLATO could observe about 10,000 EBs.

For 5% of them with shorter periods high time resolution (25 s) would be useful to reduce the minimum detectable planetary mass by a factor √2.

See Stefan Dreizler's talk for more details

Timing errors

For a *pulsating star* with period P and amplitude A, the timing error σ_τ is given by:

$$\sigma_\tau = \frac{P}{2\pi}\left(\frac{2}{N}\right)^{1/2}\frac{\sigma_I}{A} = \frac{P}{2\pi}\,\frac{\sigma_A}{A}$$

(Breger et al. 1998, Montgomery & O'Donoghue 1998, Silvotti et al. 2006)

where σ_I is the photometric (relative intensity) error and N is the number of data points.

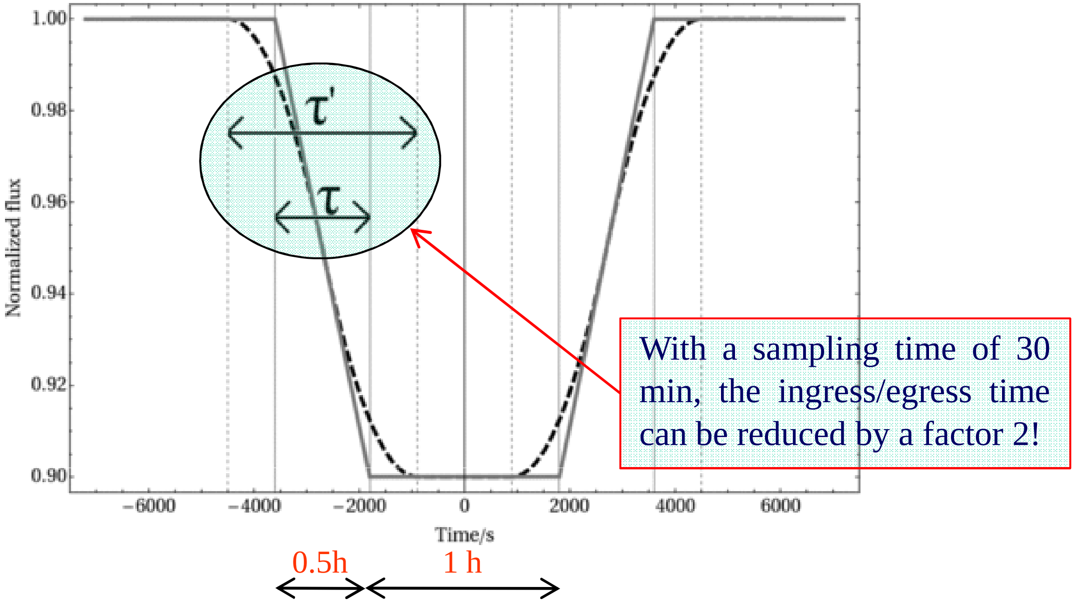
Similarly, the timing error for an *eclipsing binary* is:

$$\sigma_\tau = \frac{T_{ecl}}{2\,(N_{ecl})^{1/2}}\,\frac{\sigma_I}{(1-\Delta I)}$$

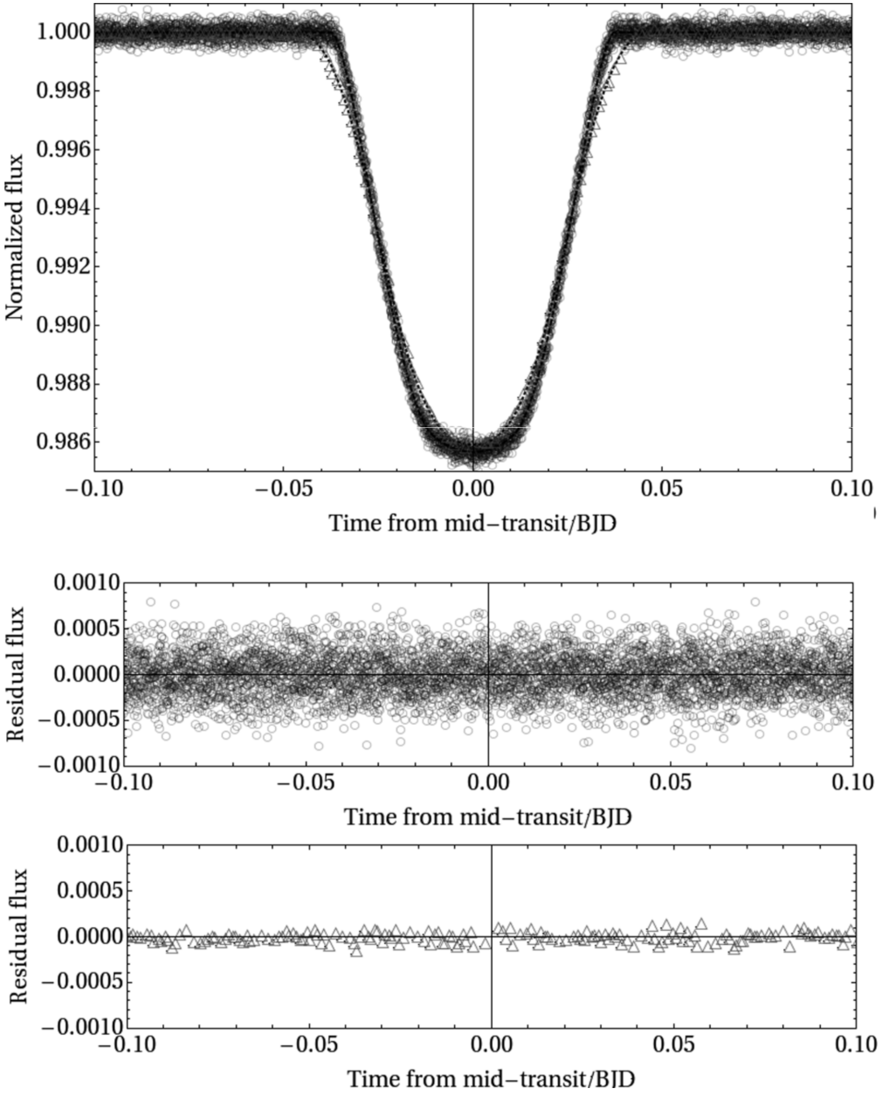
(Doyle & Deeg 2002 assuming a simple model of triangular eclipse)

where T_{ecl} is the eclipse duration from 1st to last contact, $(1-\Delta I)$ is the eclipse relative depth ($I=1$ out of eclipse) and N_{ecl} is the number of data points taken during T_{ecl}.

Morphological light-curve distortions due to finite integration time (from Kipping 2010)



With a sampling time of 30 min, the ingress/egress time can be reduced by a factor 2!



Right: comparison between Kepler SC (circles) and LC (triangles) data and their overlaid best fits (dashed line and dotted line respectively). The smearing effect of LC data is clearly visible.

When using numerical integration techniques, the retrieved light-curve parameters are consistent BUT

1) their errors remain larger for LC data

2) LC fit leads to very poorly constrained limb darkening coefficients

Summary (1)

Timing techniques are proving to be a very powerful tool .

- TTV/TDVs allow not only to detect low-mass planets but also to measure masses and mutual inclinations and study stability and dynamics in multi-transiting systems like Kepler-11 !

- EB and pulsation timing have just started to explore post-RGB planetary system evolution and the next 1-2 years will show what is the real potential of these techniques from space. WD planets (and WD seismology) are not (and will not be) covered by CoRoT/Kepler.

Summary (2)

For all timing techniques a high time resolution (HR) is essential.

To have the original 25s PLATO sampling on ~2,000 (and possibly more) best targets (imagettes) is important and the 2.5s resolution of the fast telescopes is a big opportunity for a few bright targets.

What could help:

- to keep the maximum level of flexibility on selecting HR targets;
- if onboard computing resources + telemetry allow to increase these numbers, 12×N new HR light curves (+ centroids) is better than N new imagettes.

Thank you !