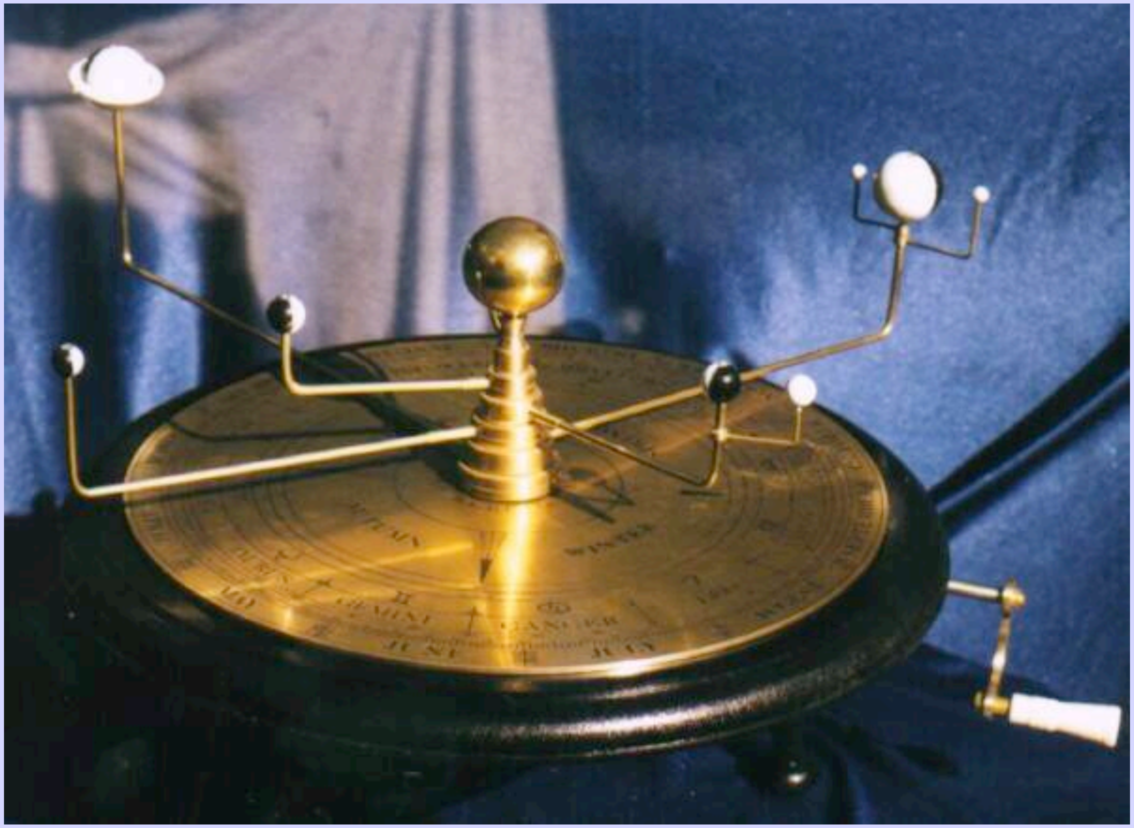
Transit Timing

Matthew J. Holman
Harvard-Smithsonian
Center for Astrophysics

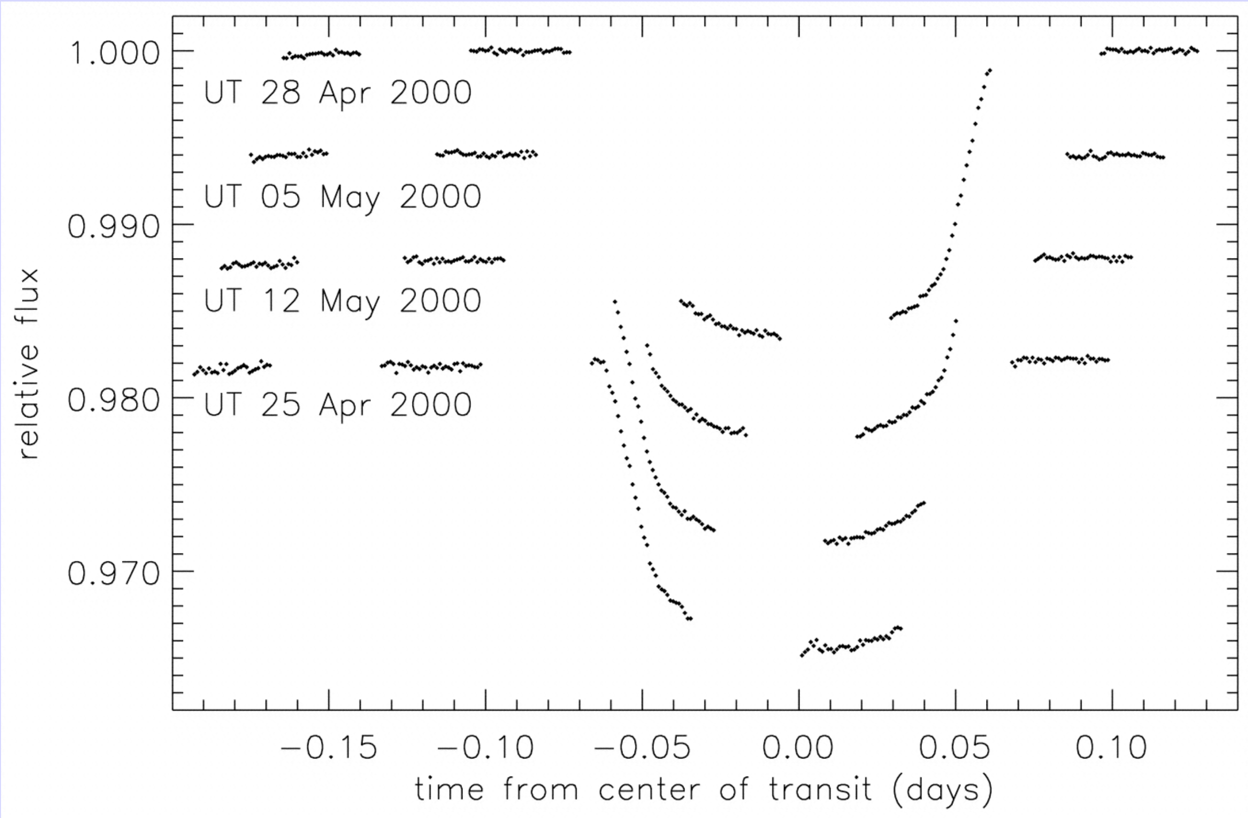


Outline

- Transit method and its observables
- Using transit timing to detect other planets
- The Transit Light Curve (TLC) Project
- Summary

Transit Observables

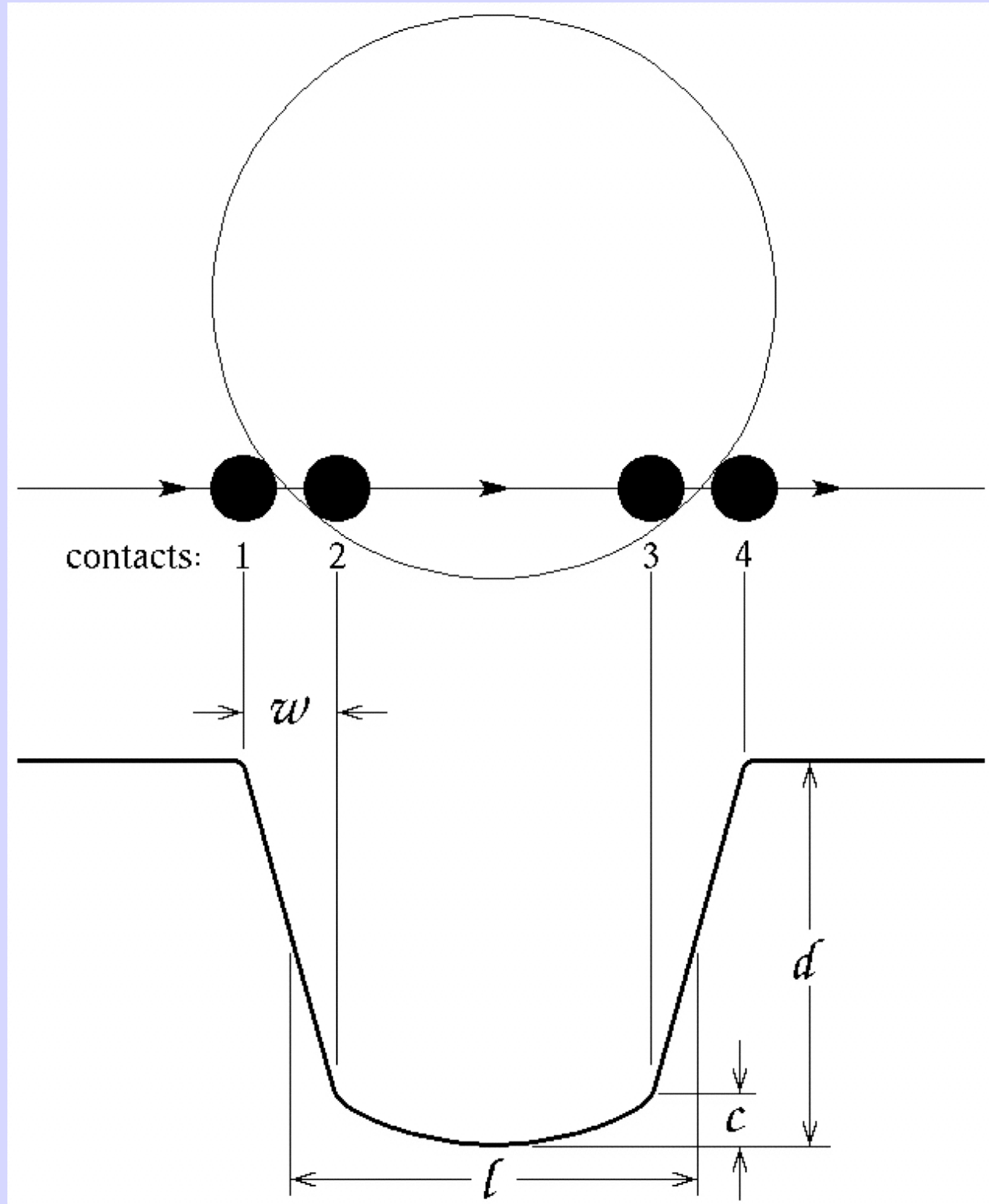
- Times of transit center
- Duration of transits
- Depth of transits
- Shape of transits



HD 209458b
HST/STIS photometry
Brown et al (2001)

Transit Observables

- Times of transit center
- Duration of transits
- Depth of transits
- Shape of transits



HD 209458b
HST/STIS photometry
Brown et al (2001)

Orbit variations affect transit timings

- The intervals between successive transits of a planet on a fixed Keplerian orbit are constant.
- But the intervals will gradually change for orbits that precess due to the oblateness of the central star, general relativity, or the presence of other mass in the system (Miralda-Escude 2002).
- Tidal dissipation will alter the semimajor axis and eccentricity of a close-in planet, thereby changing the transit timings (Sasselov 2003).
- HOWEVER, the short-term interactions with other planets can have an even more important influence on the intervals between successive transits. This has been suggested for HD209458b (Bodenheimer et al 2004).

Orbit variations affect transit timings

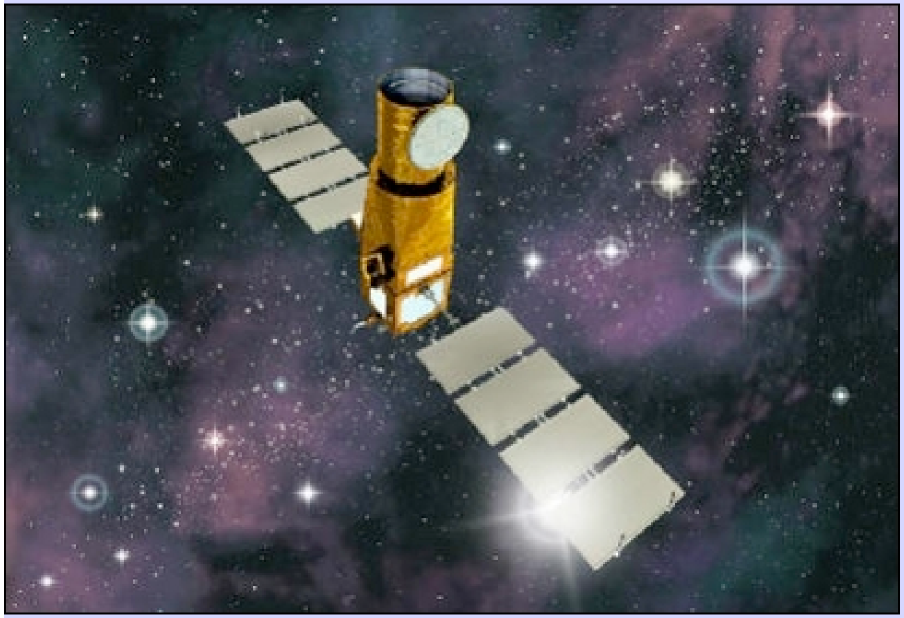
• Many of the theoretical aspects of the Transit Timing Variations (TTV) method have been worked out in a series of theory papers.

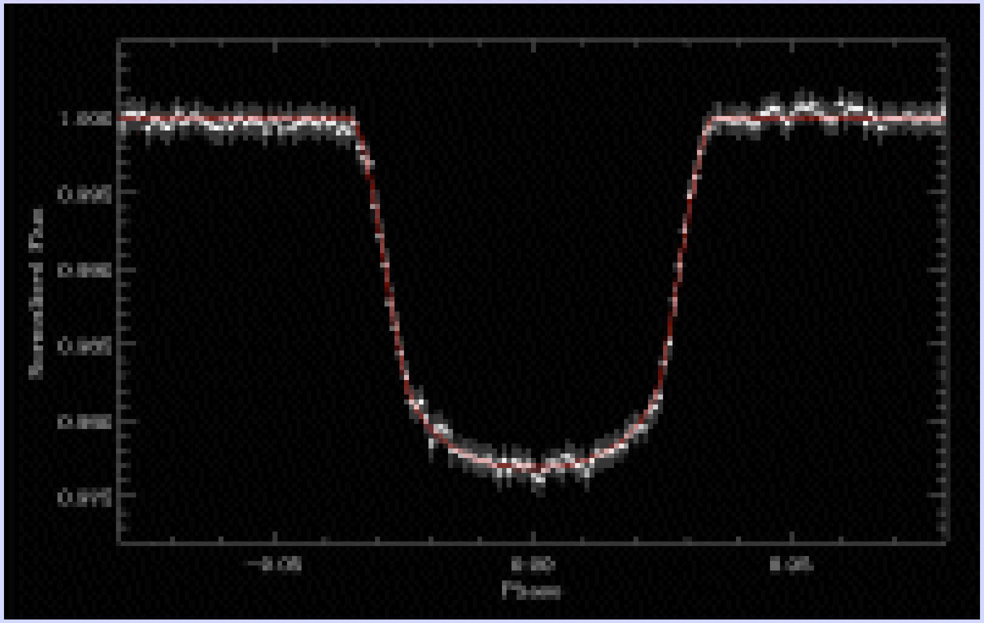
Holman & Murray 2005 **Science** 307, 1288
Agol, Steffen, Sari, and Clarkson 2005 **MNRAS** 359, 567

Heyl & Gladman 2007 **MNRAS** 377, 1511 (long-term variations)
Ford & Holman 2007 **ApJ** 664, 51 (Trojans planets)
Simon et al. 2007 **A&A** 470, 727 ("Exomoons")

• The method has already been applied to specific systems
TrES-1: Steffen & Agol 2005 **MNRAS** 364, 96
HD 209458b: Agol & Steffen 2007 **MNRAS** 374, 941
HD 209458b: Miller-Ricci 2007 (submitted)

The CoRoT Mission

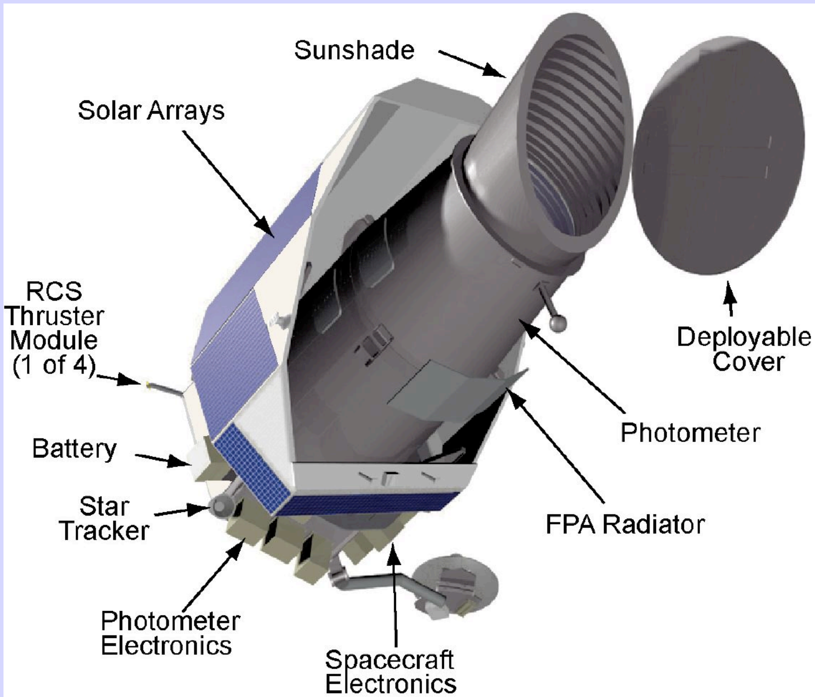


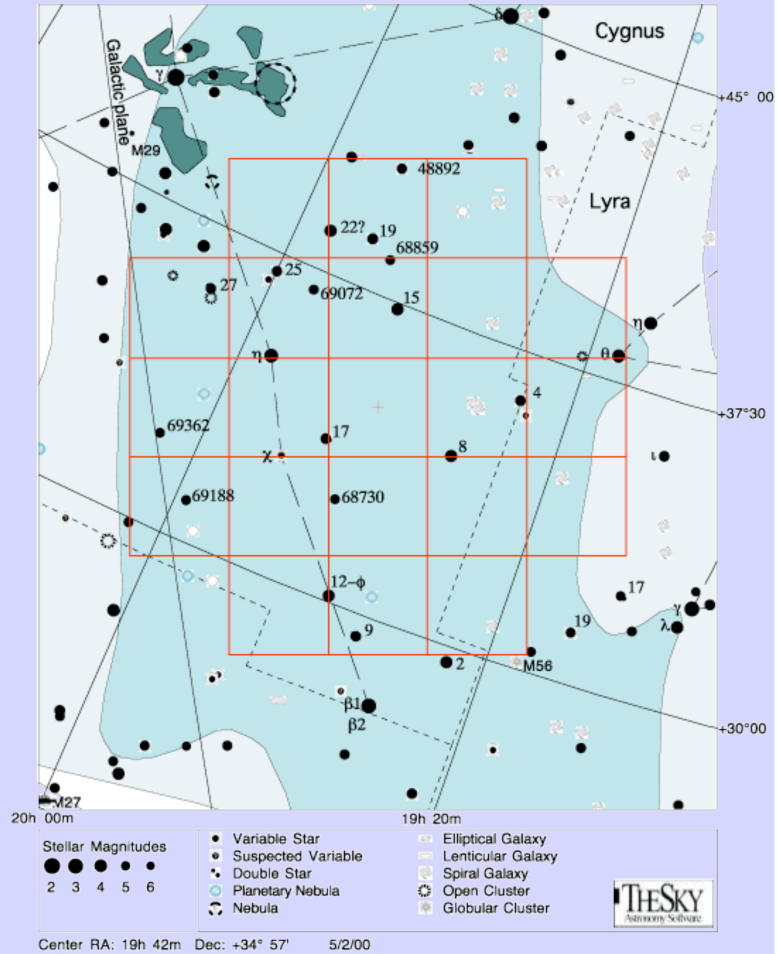


CoRoT-Exo-1b

Suzanne Aigrain's talk today

The Kepler Mission

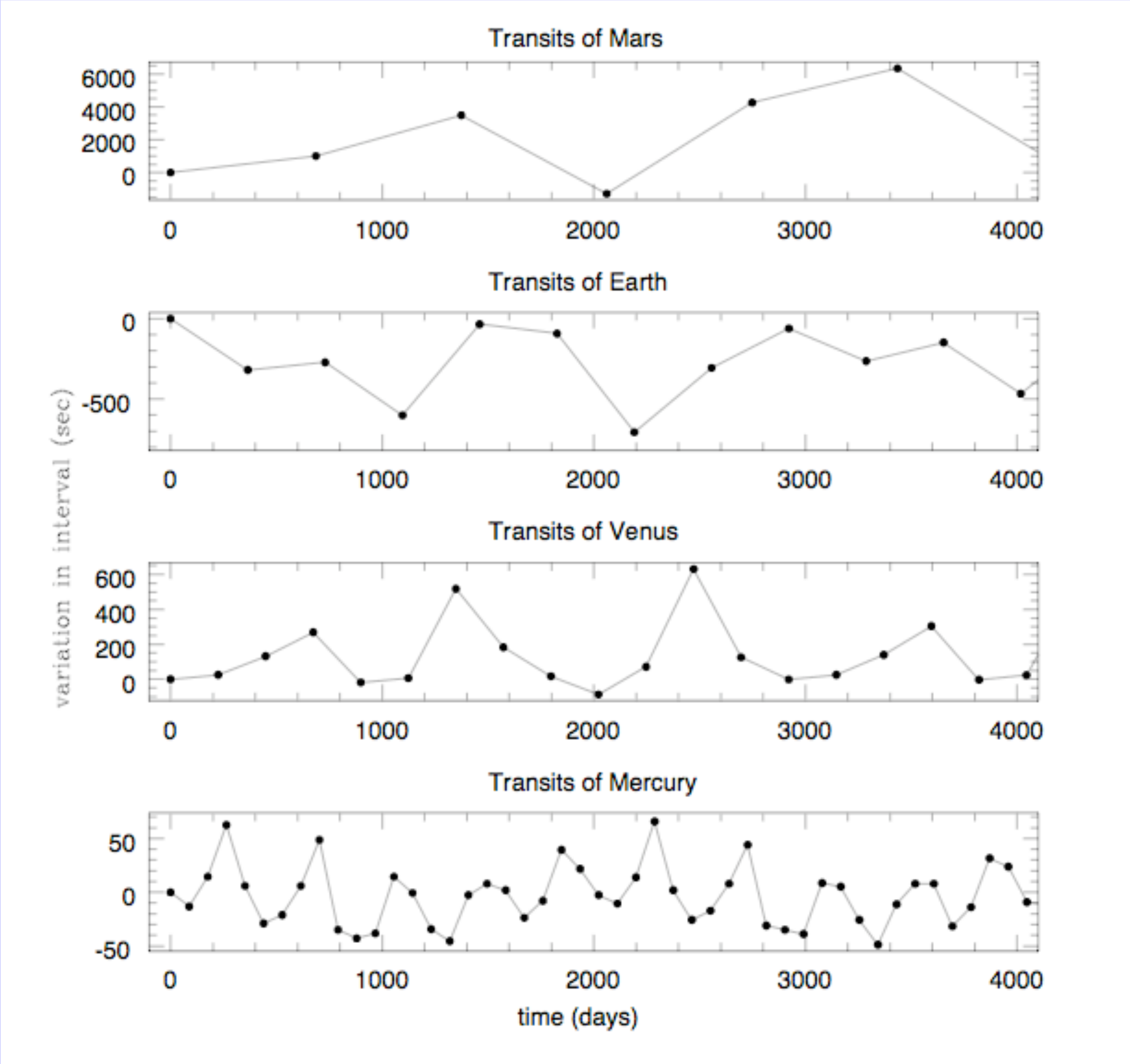




Bill Borucki's talk today

Our Solar System

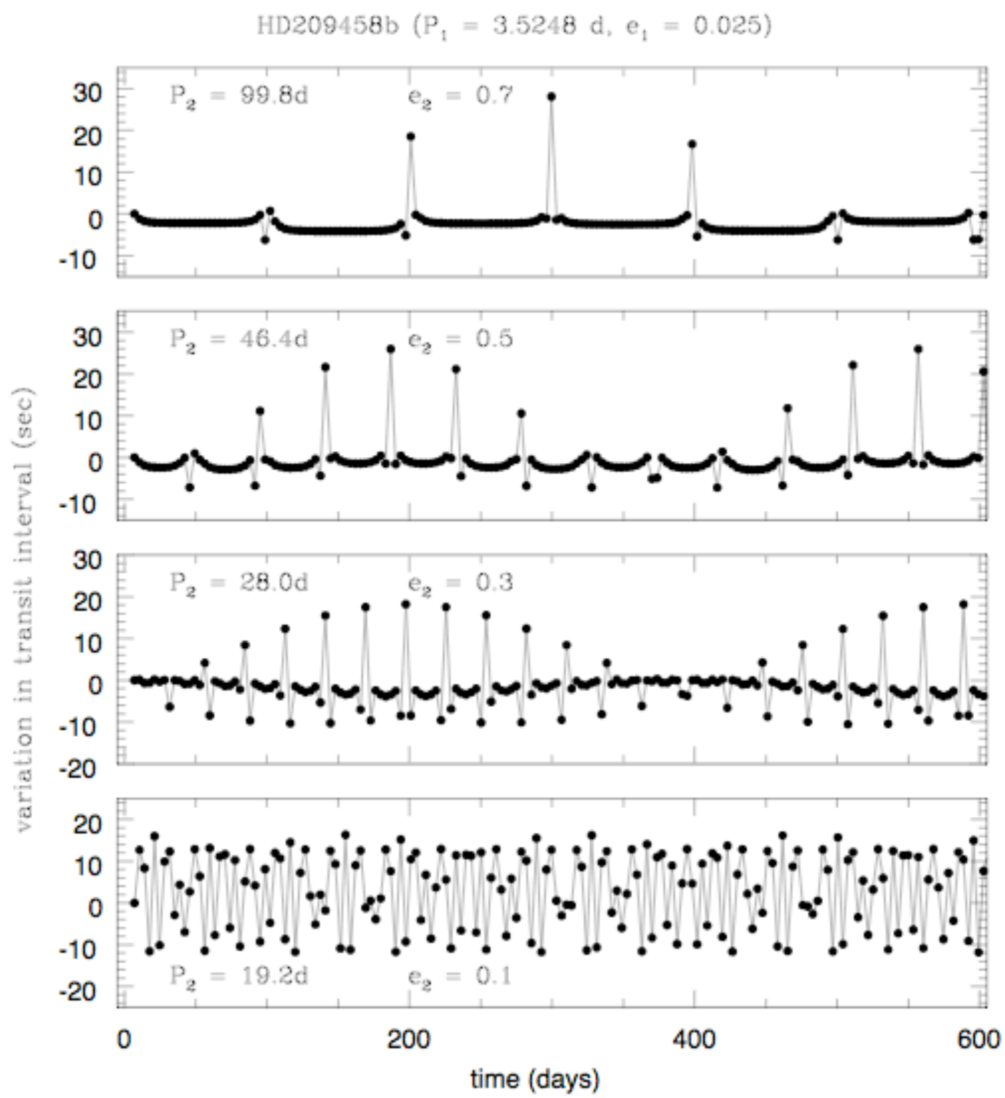
Variation in the time between successive transits, recorded by a distant observer in the plane of each planet.



HD209458b with a hypothetical additional planet

Method

- Three-body problem (star and two planets, co-planar)
- $M_2 = M_J$
- Numerical integration of the heliocentric equations of motion
  - Bulirsch-Stoer numerical integrator
  - Relative energy error $dE/E \sim 10^{-12}$
- Iteratively search for times of transit center
- Calculate interval between successive transits



Not a traditional O-C plot.

Timing variations vs Period and Eccentricity

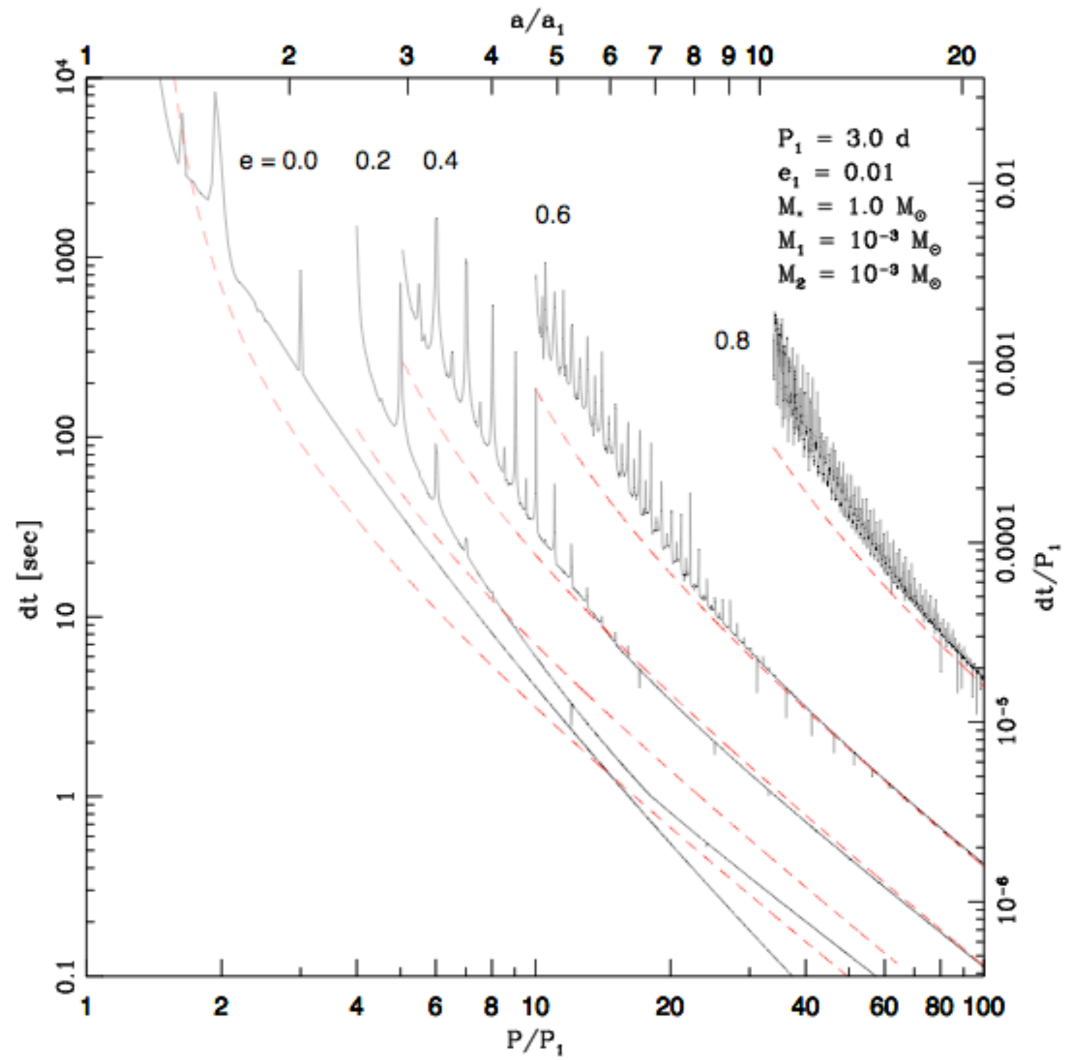
$1\ M_J$ transiting planet
$1\ M_J$ perturber
Co-planar

Analytic approximation:

$$\Delta t \sim \frac{45}{16\pi}\left(\frac{M_2}{M_*}\right) P_1 \alpha_e^3 \left(1-\sqrt{2}\alpha_e^{3/2}\right)^{-2}$$

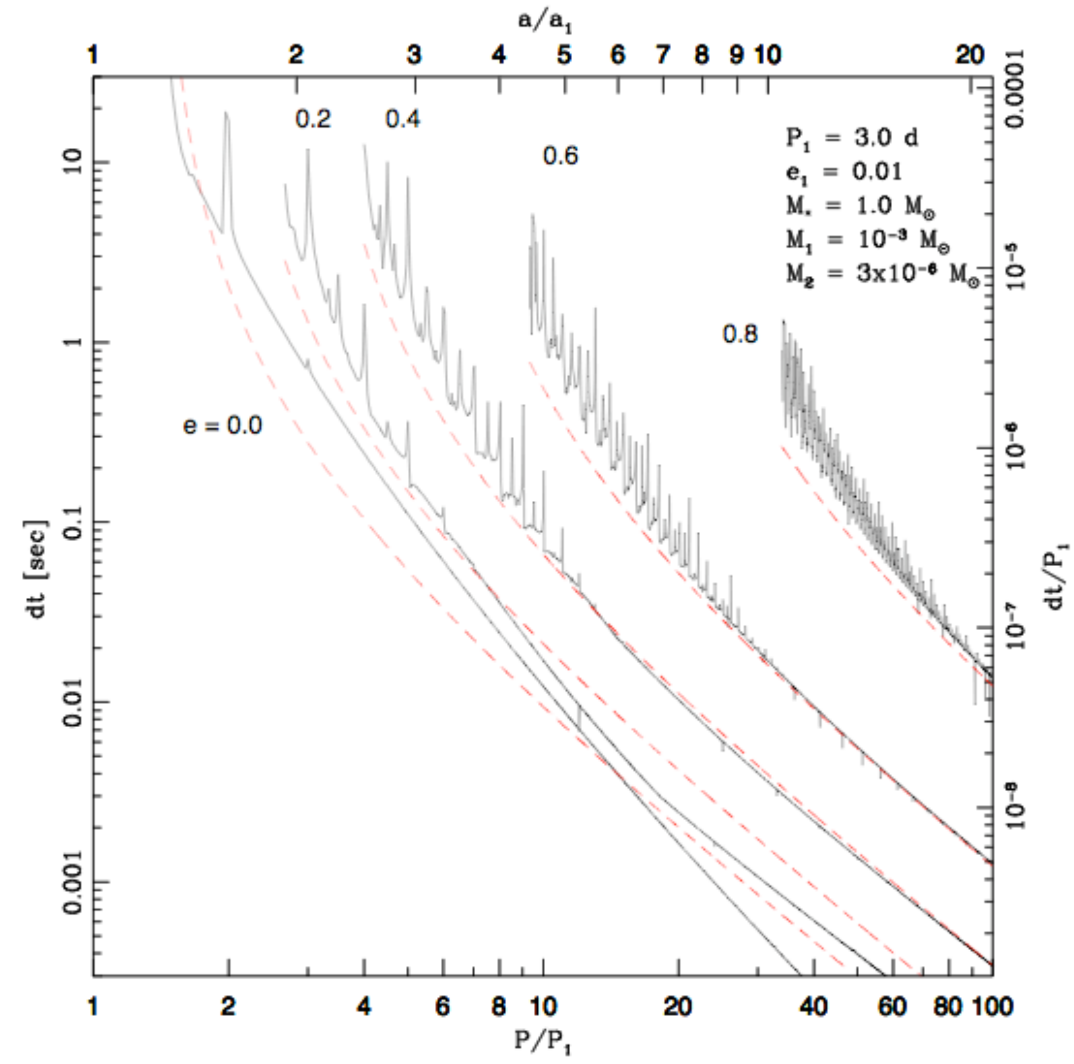
$$\alpha_e = \frac{a_1}{a_2(1-e_2)}$$

- Linear in M_2
- Inversely proportional to M_*
- Factor of P_1
- Factor of $(P_1/P_2)^2$



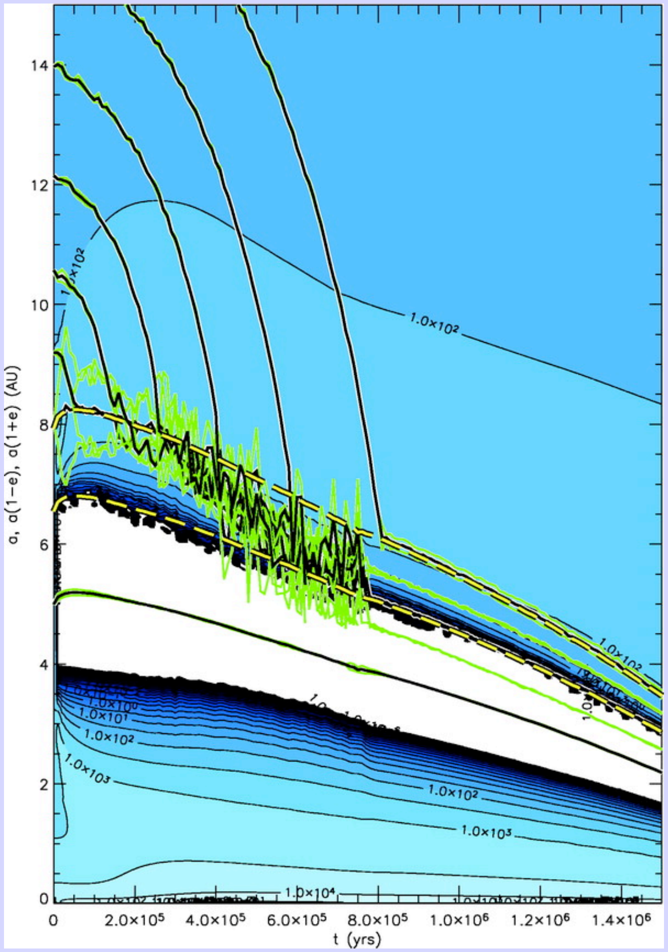
Timing variations vs Period and Eccentricity

1 M_J transiting planet
1 M_E perturber

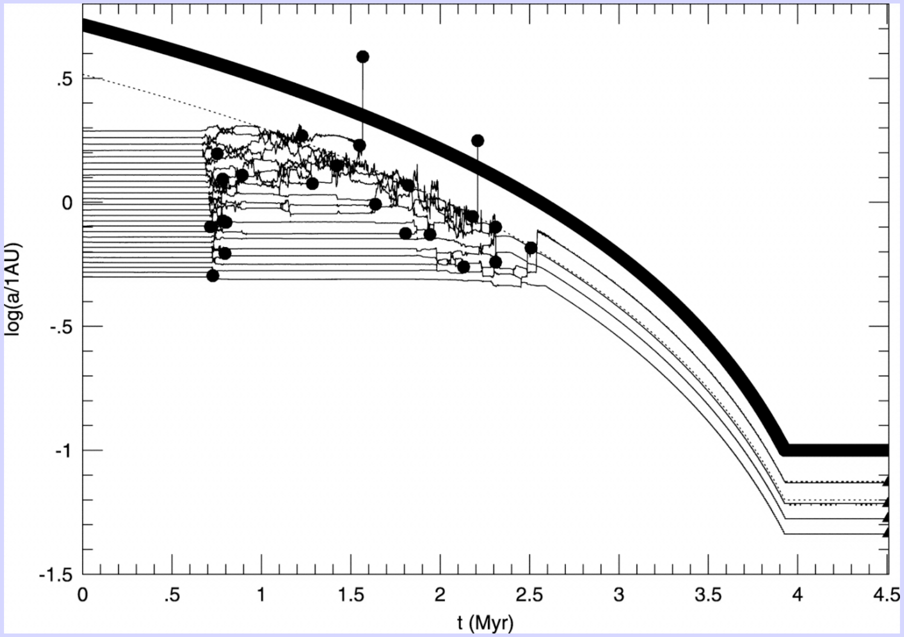


Resonant planets are not uncommon

GJ 876b & c	1:2
HD 82943b &c	1:2
55 Cnc b&c	1:3



Thommes 2005



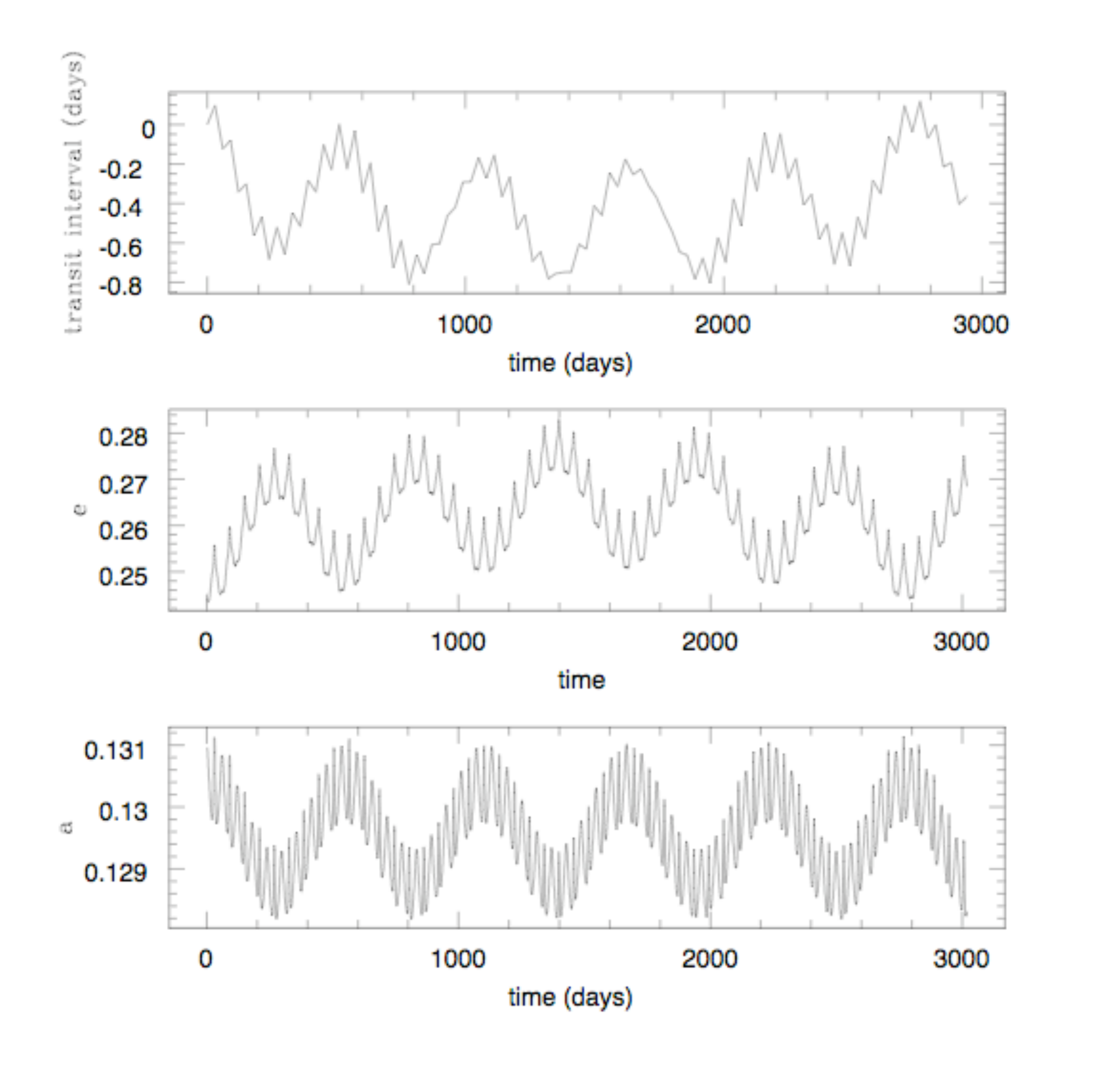
Zhou et al 2005

Extreme case of GJ876: planets in resonance

Transit interval variation

Eccentricity

Semimajor axis



Transit timing of Trojan planets

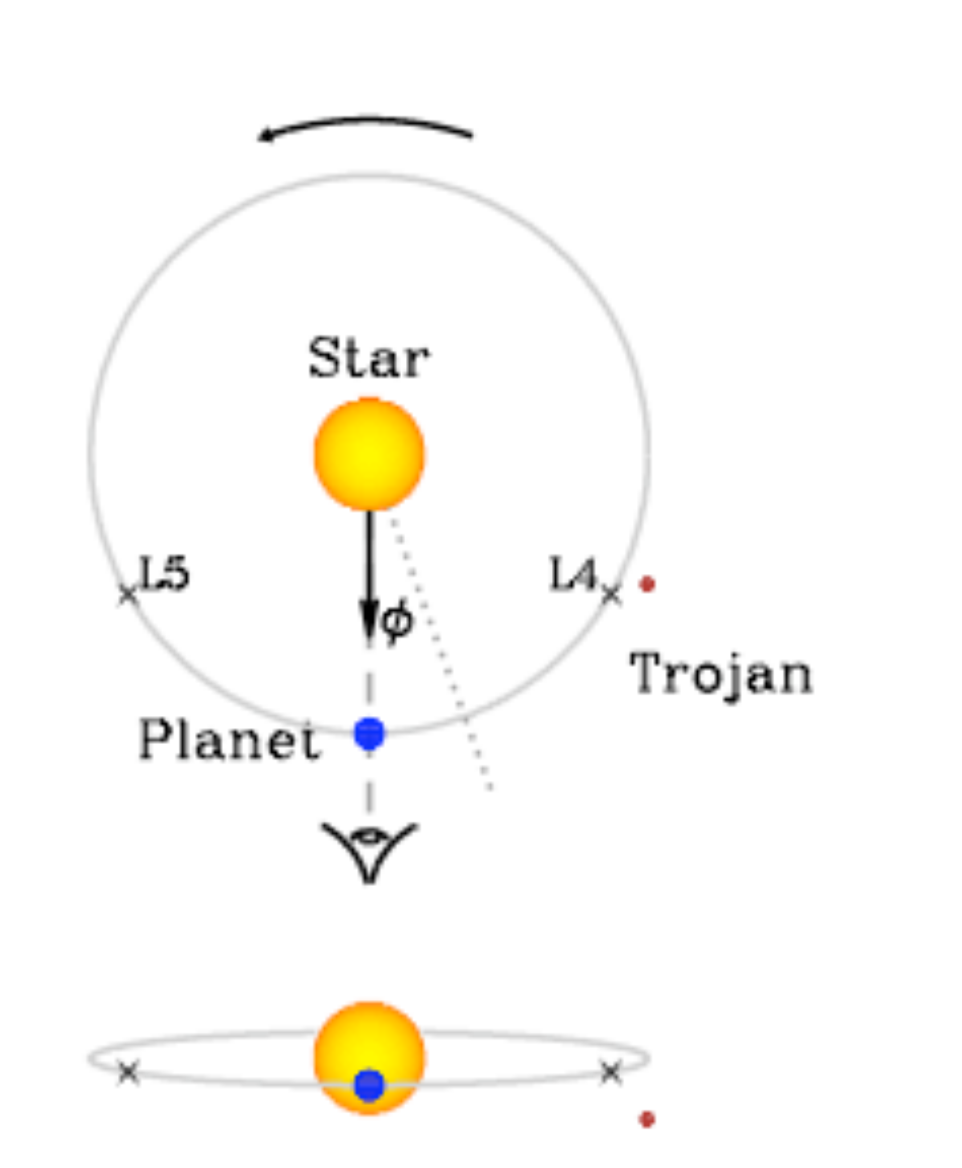
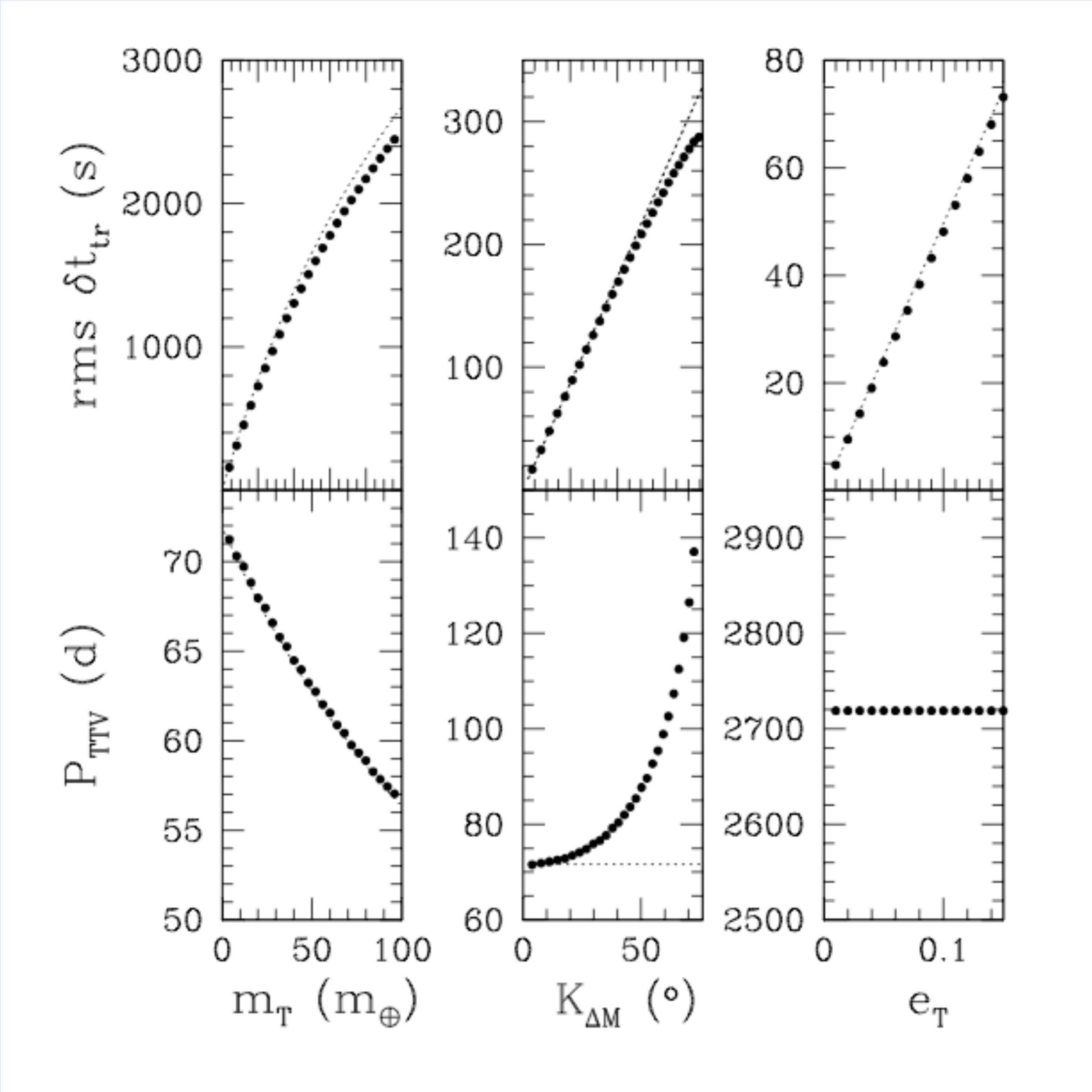


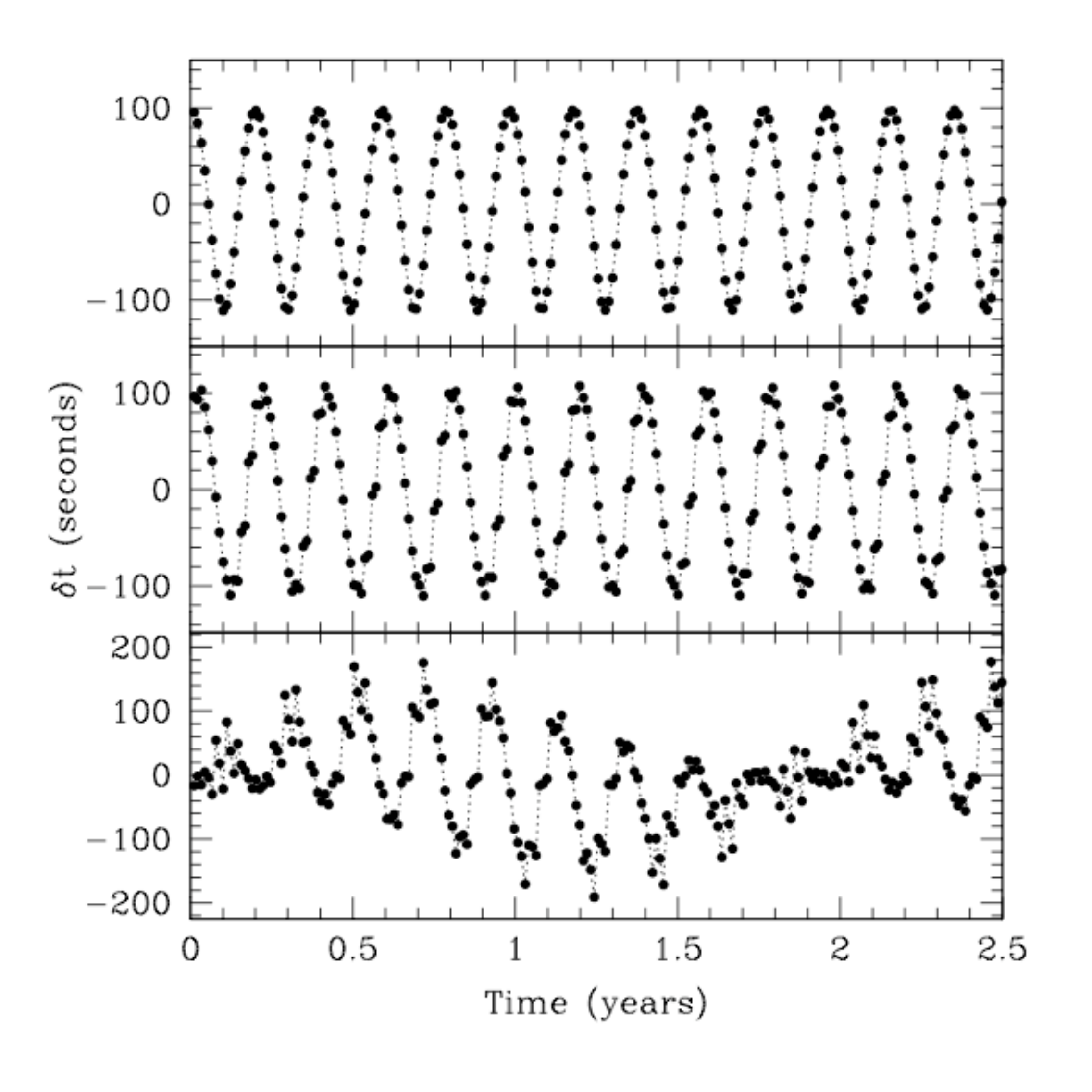
Figure from
Ford & Gaudi 2007

Transit timing of Trojan planets



Ford & Holman 2007

Comparison of TTV signals



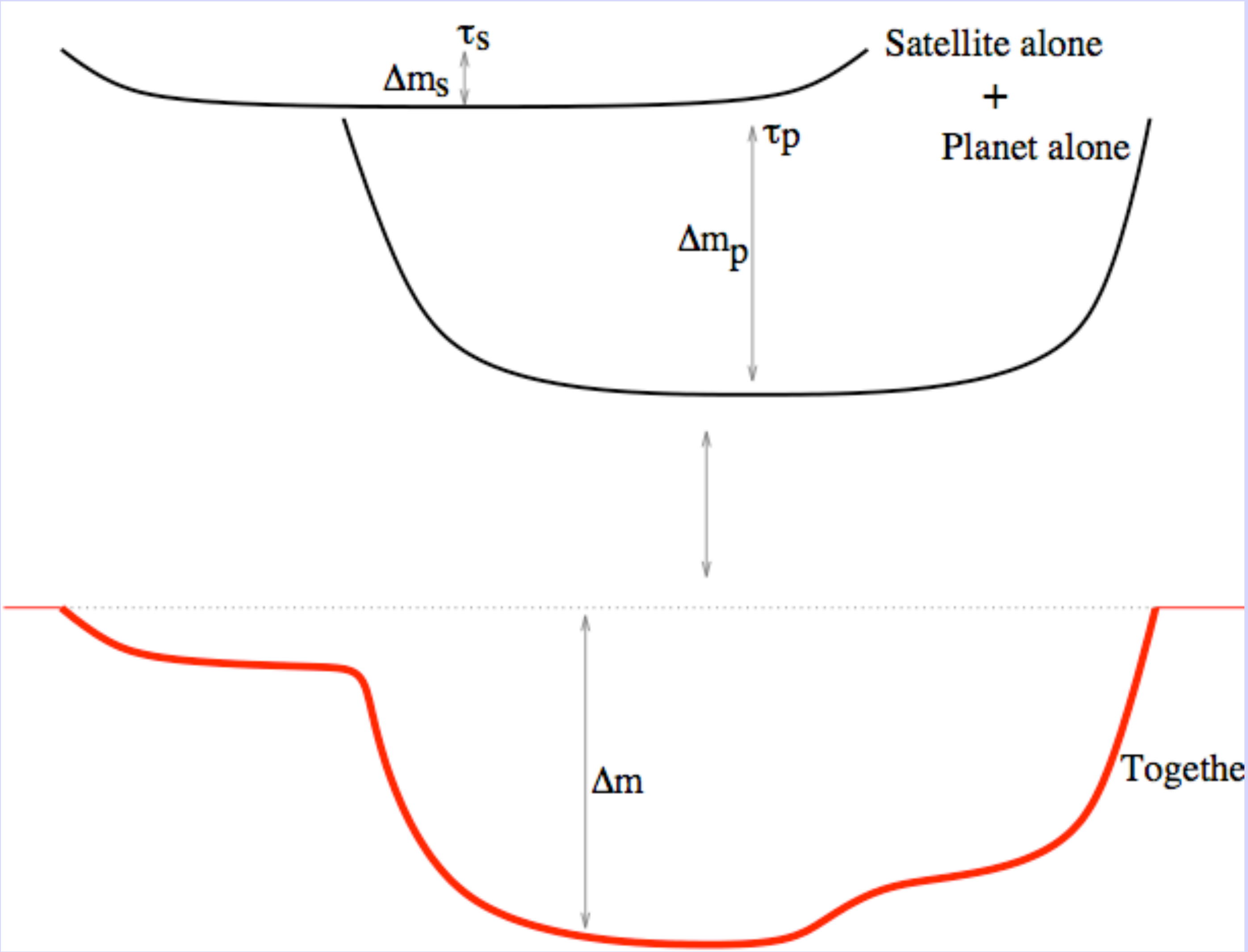
1 M_E Trojan

28 M_E in exterior 2:1

5 M_E in interior 3:2

Ford & Holman 2007

Transit timing of "Exomoons"



Simon et al. 2007

Double Transiting Systems

- If one sees transits of one planet in a multiple planet system, what is the probability of seeing transits of a second planet?
- Can obtain estimates of masses and radii of both planets
- This allows estimates of the densities of the planets, without radial velocity measurements.

- Co-planar Orbits

$$P_{t_2} = a_1/a_2$$

- Mutually inclined orbits, with the inner planet transiting the center of the star.

$$P_{t_2} = \frac{2}{\pi} \arcsin\left(\frac{R_*}{a_2 \sin i'}\right)$$

i' = mutual inclination of the two planets
Assumes $\sin i' > R_*/a_2$, otherwise transits of the second planet are certain.

For $R_* = R_\odot$, $i' \sim 5°$, and $a_2 \sim 1$ AU,

$P_{t_2} \sim 10\%$.

(also David Koch's 1995 DPS abstract and poster)

Detection limits

$$\frac{\sigma_{t_c}}{t_T} \sim (\Gamma t_T)^{-1/2} \rho^{-3/2} (1-\beta^2)^{-1/4}$$

σ_{t_c} = error in measurement of transit center
t_T = transit duration
Γ = stellar photon count rate
$\rho = R_p/R_*$
β = impact parameter (in stellar radii)
Assumes photon noise limited observations

For Kepler ($D = 0.95$ m, broad filter):
$\Gamma = 7.8 \times 10^8\ 10^{-0.4(V-12)}\ \mathrm{hr}^{-1}$

- For a hot Jupiter orbiting a $V = 12$ solar-type star, ($\rho \sim 0.1$, $t_T \sim 3\mathrm{hr}$):

→ $\sigma_{t_c} \sim 10$ s

- For an Earth-sized planet in a 1-year orbit about a $V = 12$ solar-type star, ($\rho \sim 0.01, t_T \sim 13\mathrm{hr}$):

→ $\sigma_{t_c} \sim 500$ s

For Magellan ($D = 6.5$ m, broad filter):
$\Gamma = 3.7 \times 10^{10}\ 10^{-0.4(V-12)}\ \mathrm{hr}^{-1}$

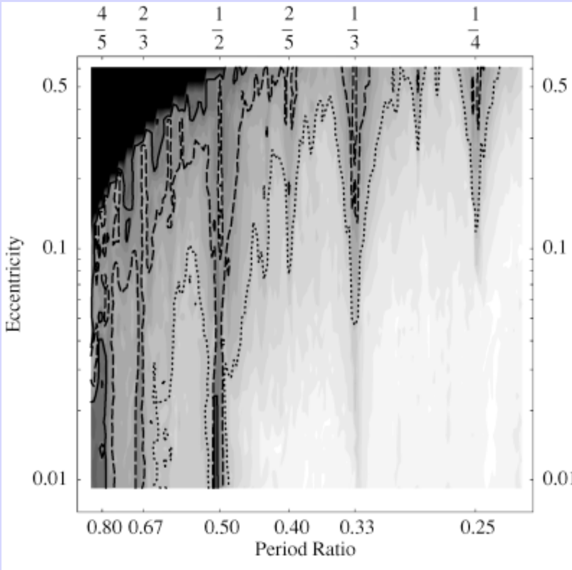
- For a hot Jupiter orbiting a $V = 12$ solar-type star, ($\rho \sim 0.1$, $t_T \sim 3\mathrm{hr}$):

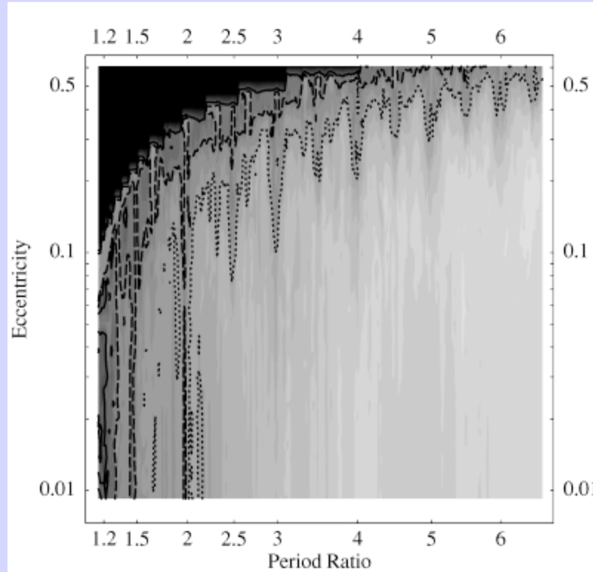
→ $\sigma_{t_c} \sim 1$ s

Requires control of systematic effects

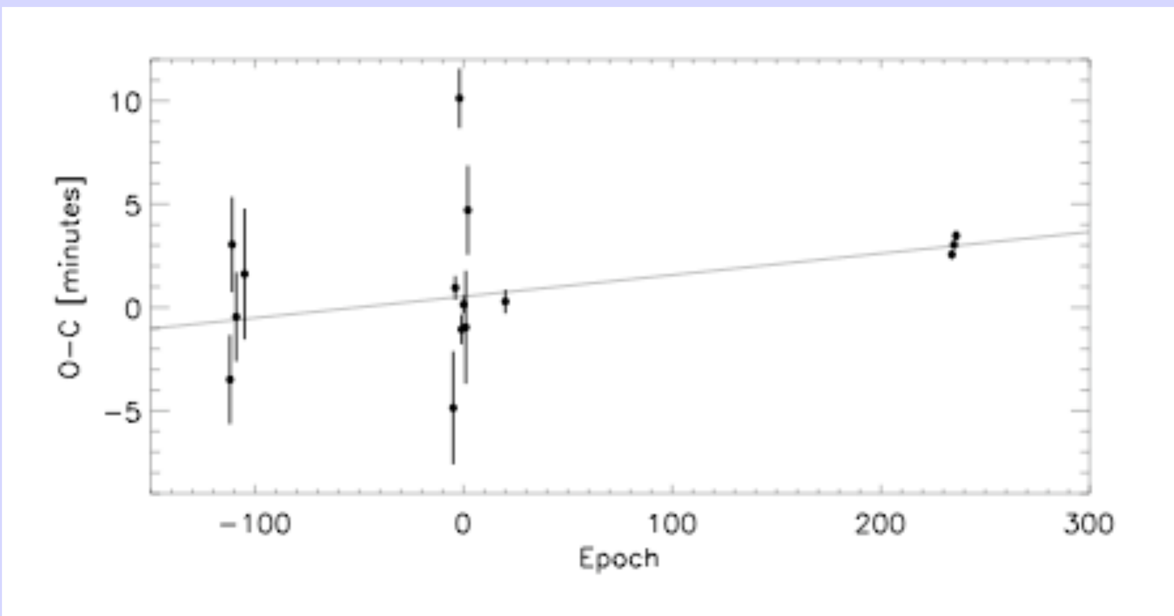
What can we do while we wait for results from CoRoT and Kepler?

We can use existing ground-based observations: TrES-1



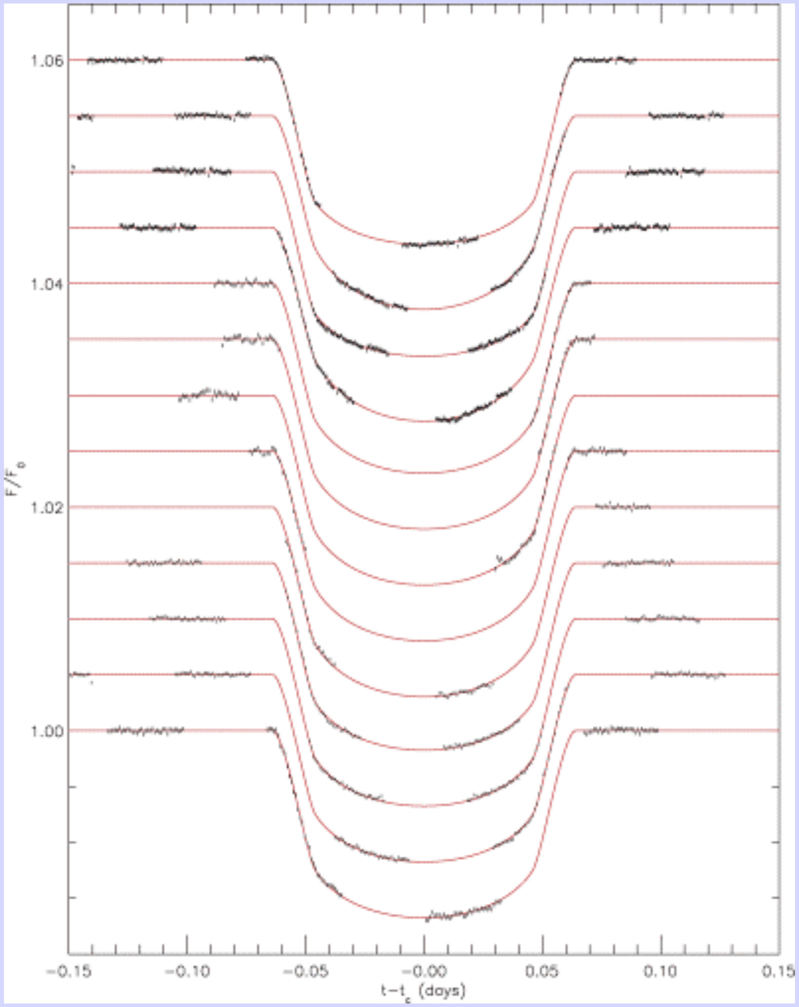


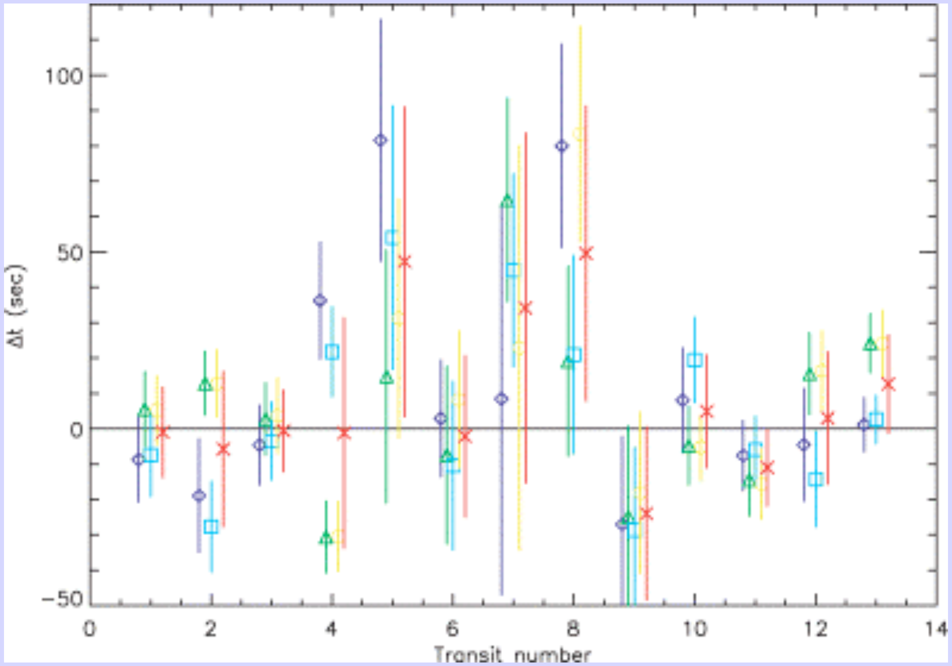
Steffen & Agol 2005



Winn, Holman, Roussanova 2007

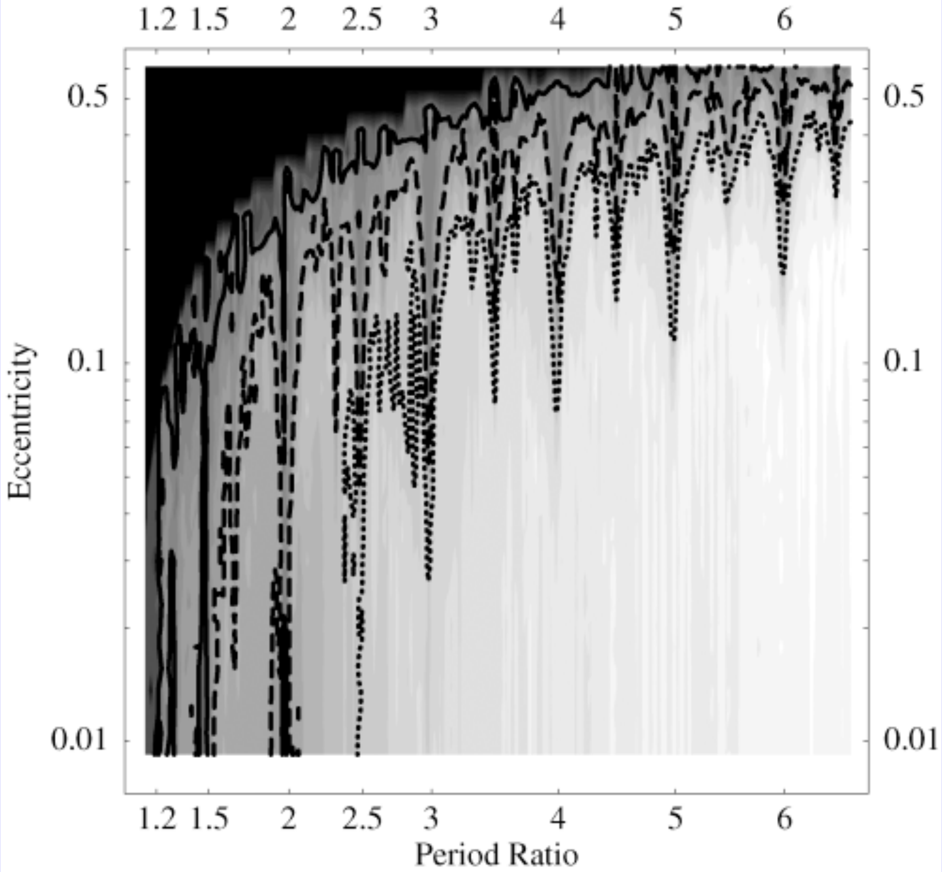
We can use existing space-based observations: HD 209458b

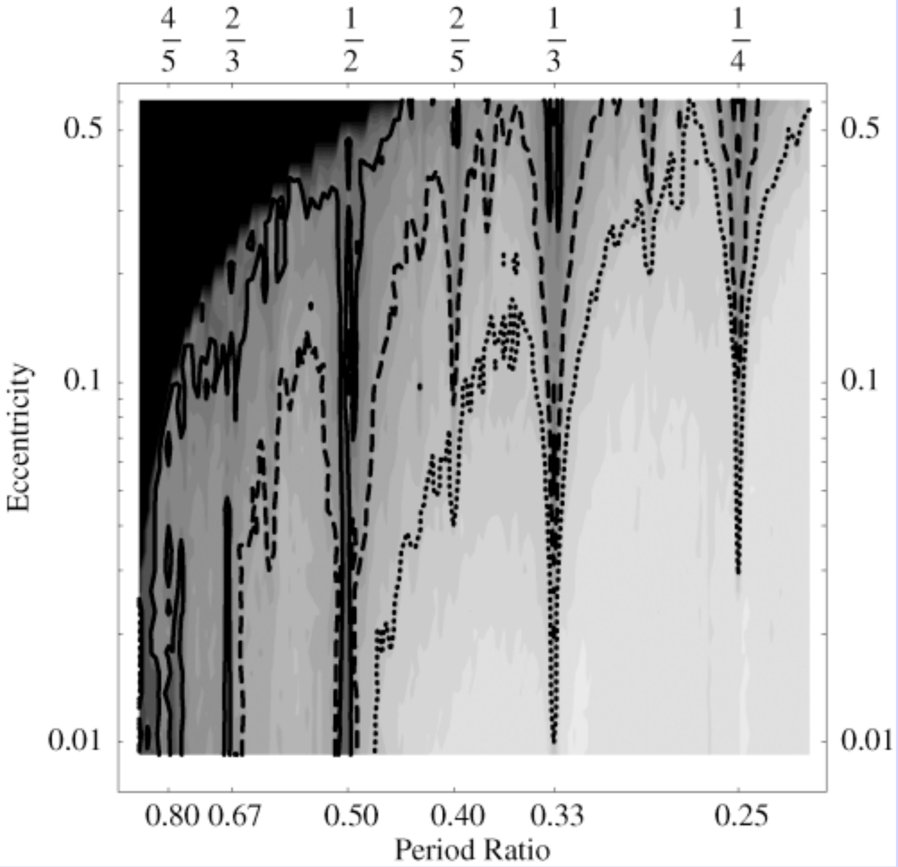




Agol & Steffen 2007

HD 209458b perturber mass limits



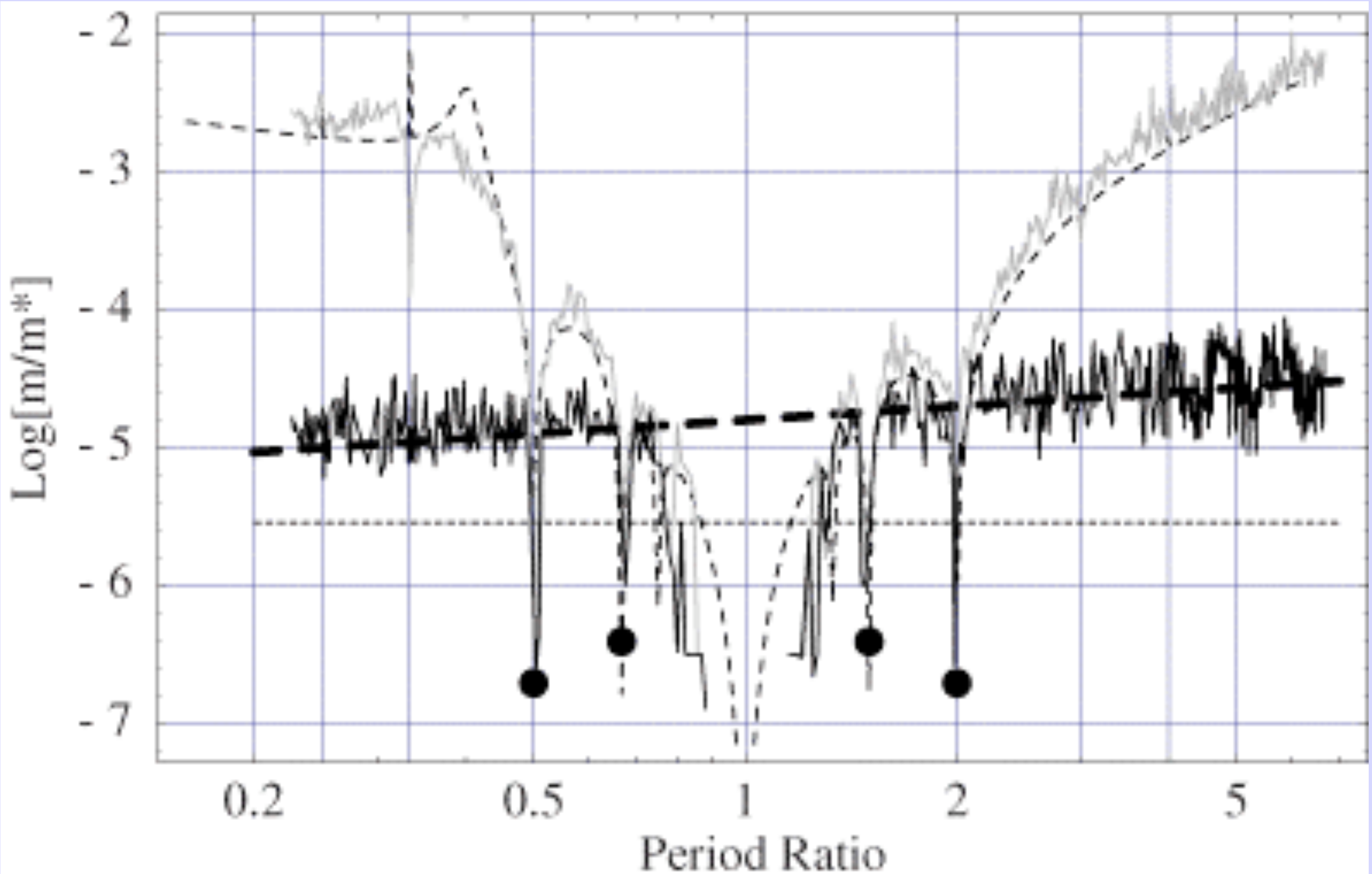


Interior perturber

Exterior perturber

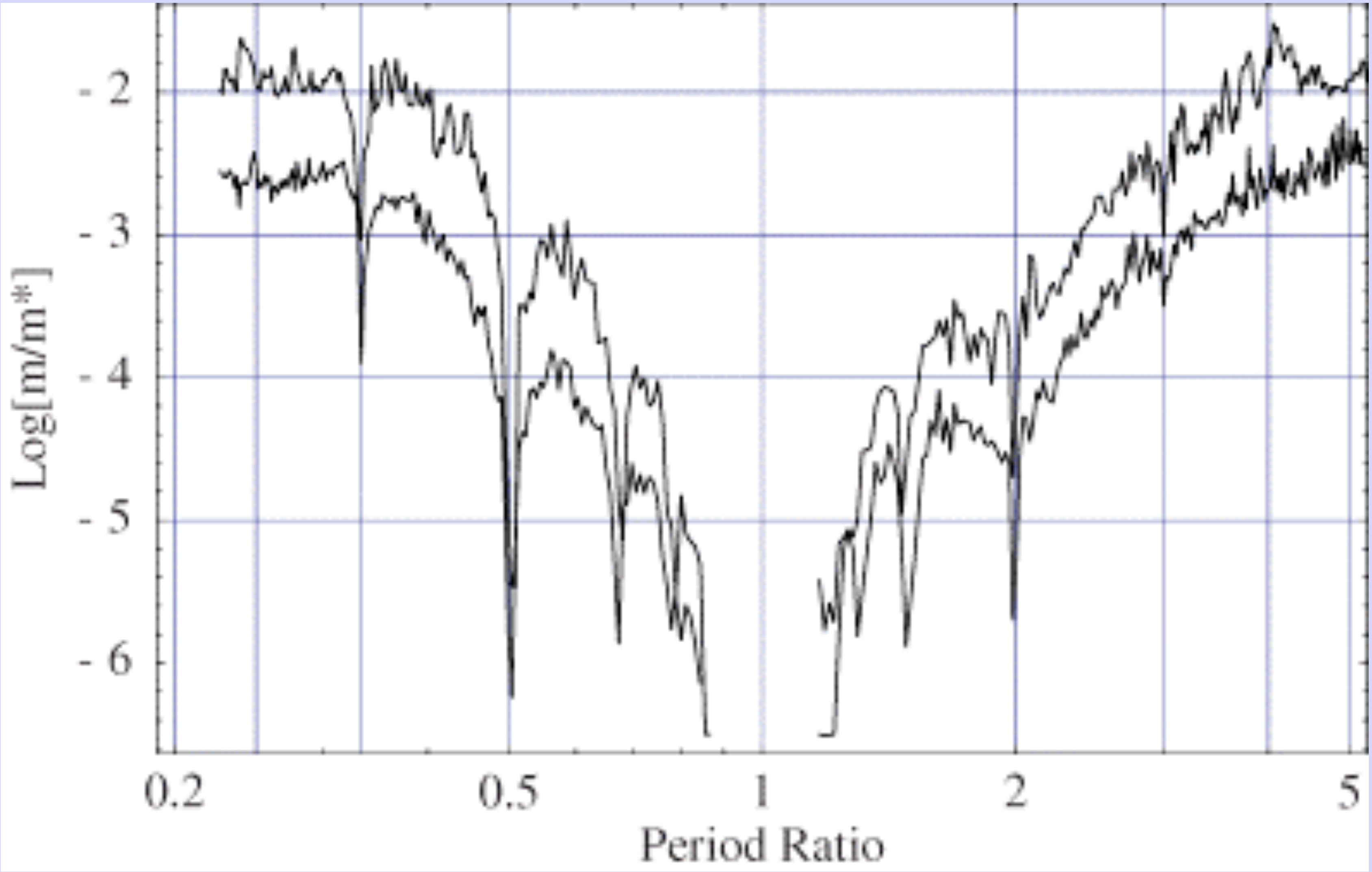
Agol & Steffen 2007

HD 209458b



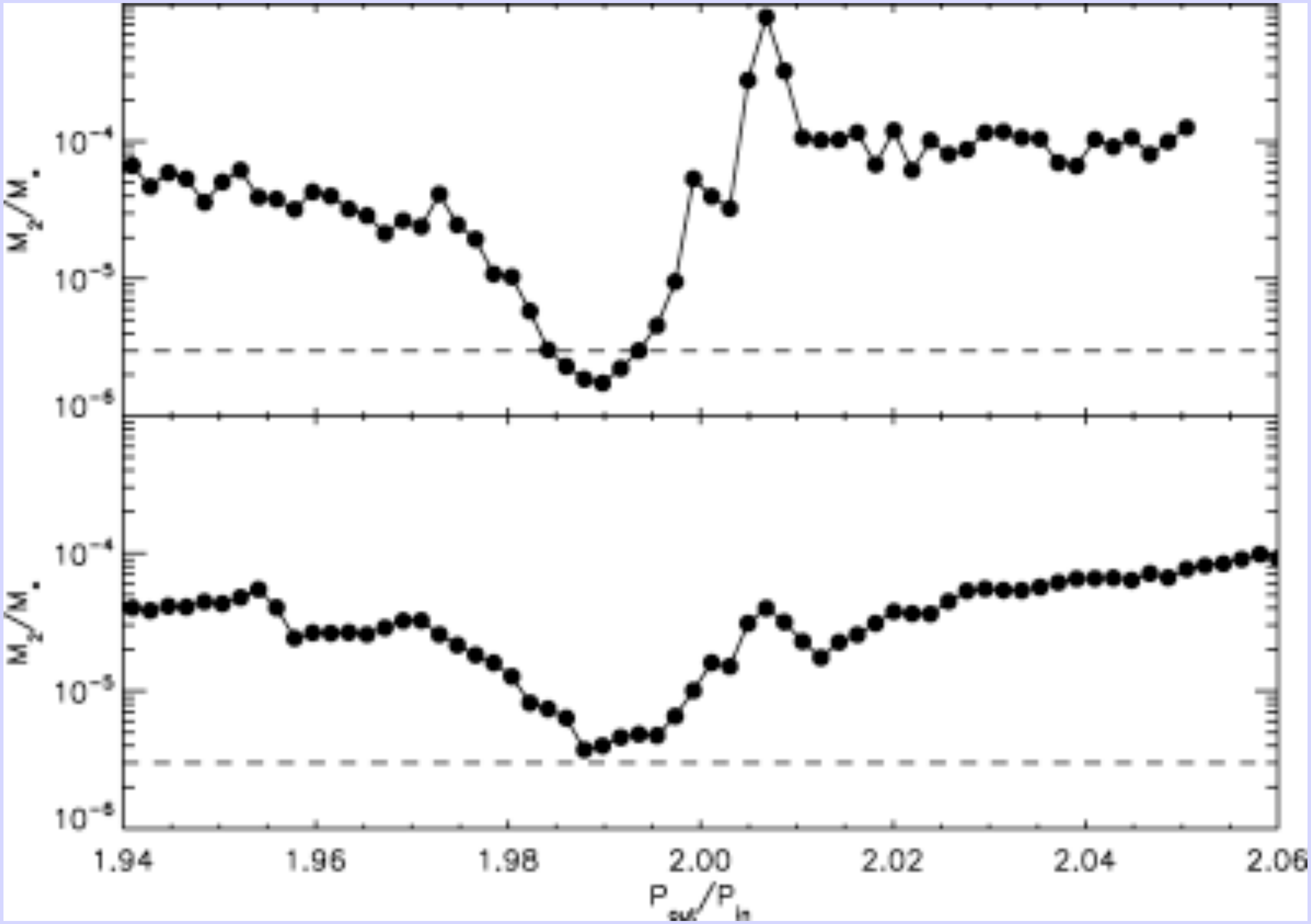
Agol & Steffen 2007

TrES-1 vs HD 209458b



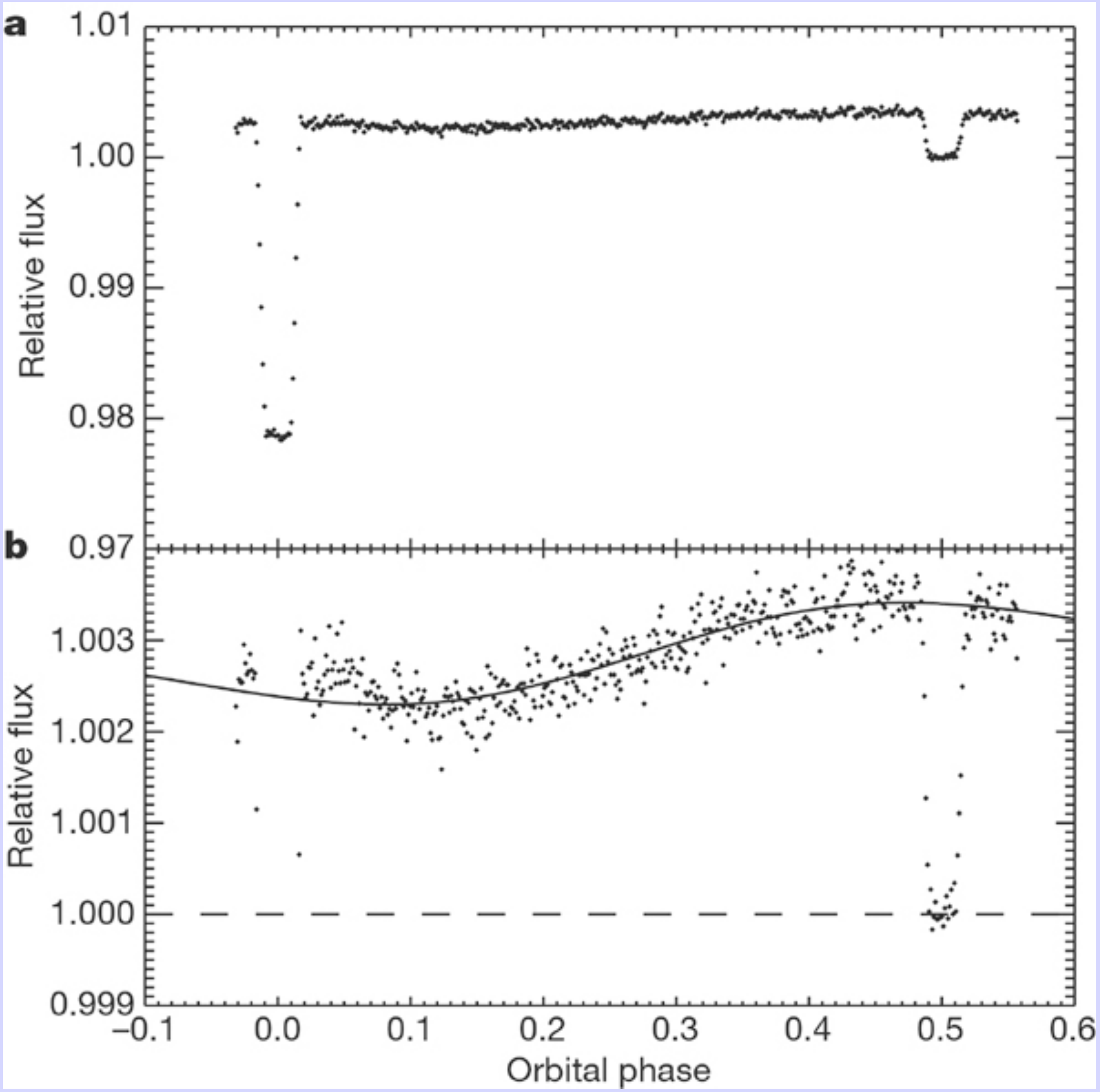
Agol & Steffen 2007

HD 209458b



Agol & Steffen 2007

Transit timing with Spitzer



Knutson et al 2007

HD 189733b

~6 sec timing precision for primary transit.

~24 sec timing precision for secondary eclipse.

Best achieved to date.

Eric Agol has a Spitzer program to observe 6 primaries and 6 secondaries of HD 189733b.

We can collect more ground-based data:
The Transit Light Curve Project

The Transit Light Curve (TLC) Project

Matthew J. Holman (CfA)
Joshua N. Winn (MIT)

Dave Latham (CfA)
Dave Charbonneau (CfA)
Gaspar Bakos (CfA)
Francis O'Donovan (Caltech)
Dimitar Sasselov (CfA)
Cesar Fuentes (CfA)
Joel Hartman (CfA)
Jose Fernandez (CfA)
Kris Stanek (OSU)
Scott Gaudi (OSU)

Tsevi Mazeh (Tel Aviv)
Avi Shporer (Tel Aviv)
Guillermo Torres (CfA)
Gil Esquerdo (CfA, PSI)
Mark Everett (PSI)
Anna Roussanova (MIT)
Andras Pal (Eotvos)
Wesley Fraser (U. Vic)
Lynne Jones (NRC Canada)
Carl Hergenrother (LPL)

The TLC Project:

We have initiated a long-term campaign to build a library of high-precision transit photometry.

The goals of the project are:

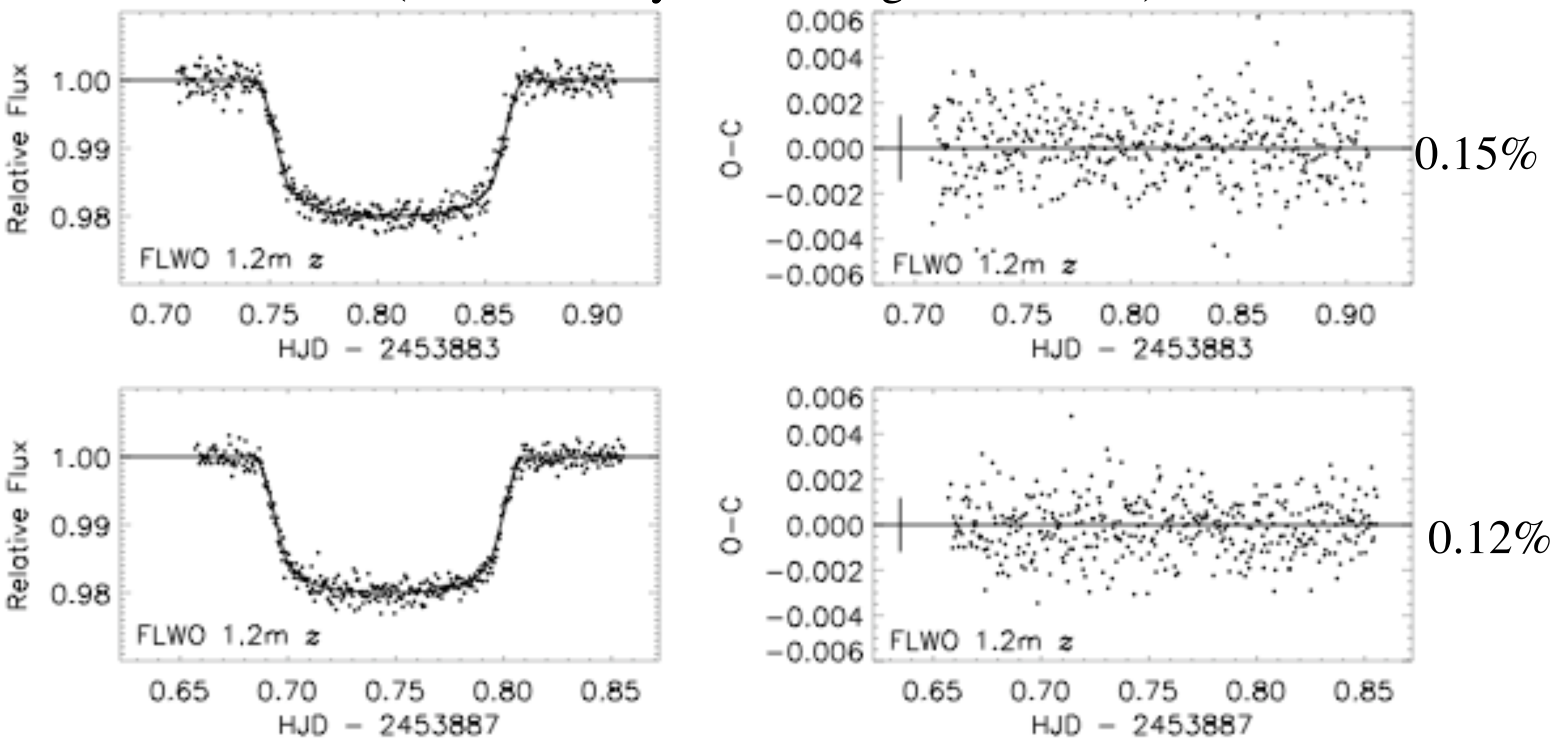
1. To refine the physical and orbital parameters of all suitable known transiting extrasolar planets.

2. To search for transit time variations that may result from the perturbation of other planets, precession, tidal dissipation, etc.

3. To search for stellar flux reflected from extrasolar planets near times of secondary eclipses to constrain the atmospheric properties of such planets.

TLC I: XO-1b (Holman et al. 2006)

XO-1b (discovered by McCullough et al. 2006)



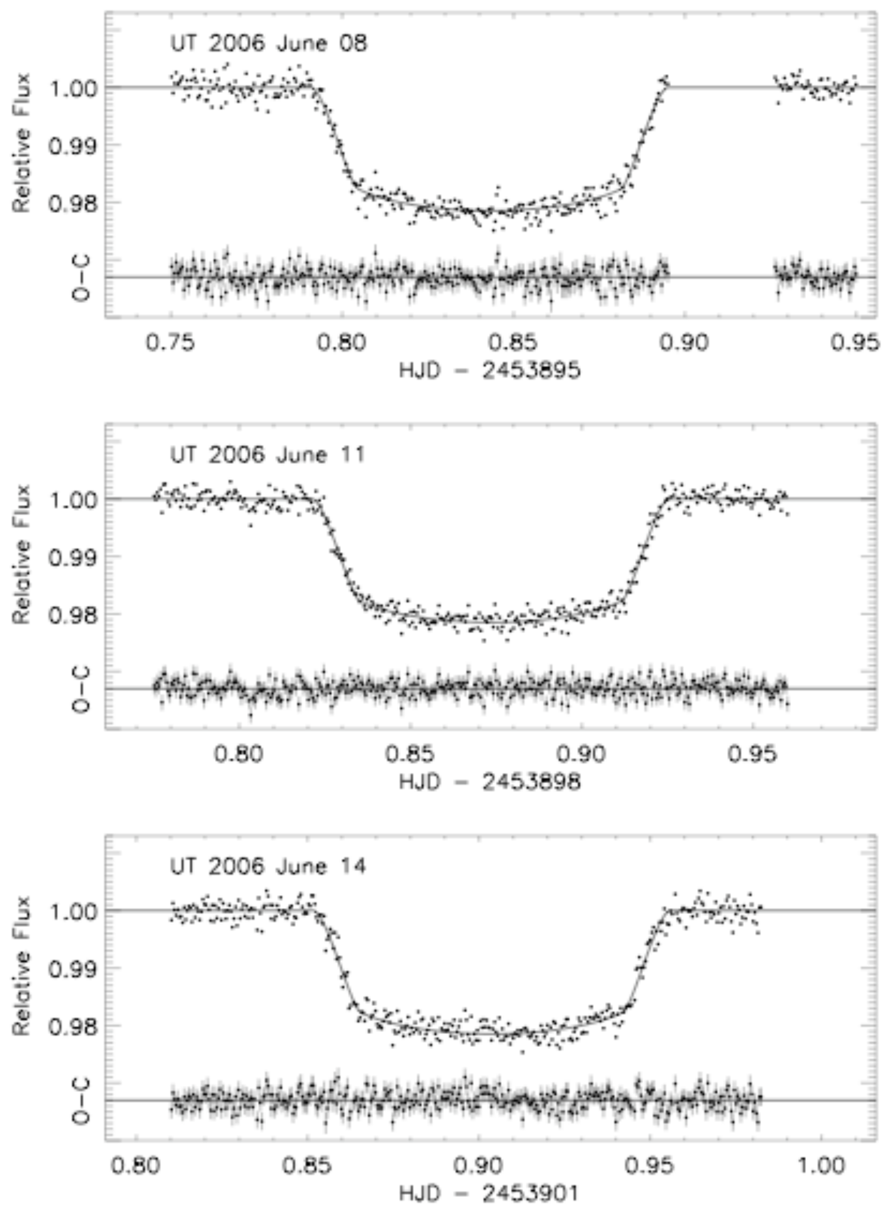
FLWO 1.2m, Keplercam z-band observations: 30 sec exposures, auto-guiding, 11.5 sec read/reset time
Aperture photometry with 4 nearby comparison stars of similar magnitude and color, differential extinction correction.

M_S = 1.00 +/- 0.03 M_{sun} assumed.
Uncertainties dominated by stellar mass.

R_P = 1.184 +0.025/-0.018 R_{jup}
R_S = 0.928 +0.018/-0.013 R_{jup}

Uncertainties in T_C unc. ~ 15-20 sec, comparable or better than with HST.

TLC III: TrES-1 (Winn, Holman, Roussanova 2007)



Keplercam z-band observations: 30 sec exposures, auto-guiding, 10 sec read/reset time
Aperture photometry with nearby comparison stars of similar magnitude and color, differential extinction correction.

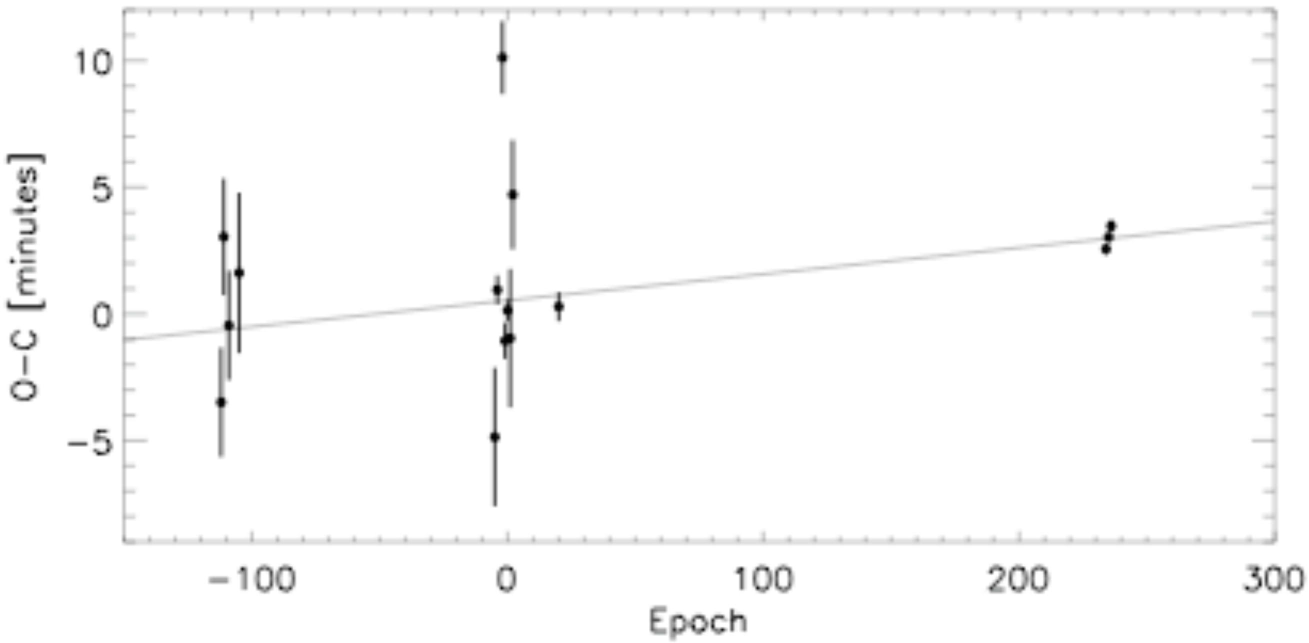
Mild a priori constraint on limb darkening coefficients.

T_C uncertainties ~ 15 sec.

R_P = 1.085 +/- 0.029 R_{jup}
R_S = 0.812 +/-0 .020 R_{jup}
M_S = 0.89 +/- 0.05 M_{sun} assumed.

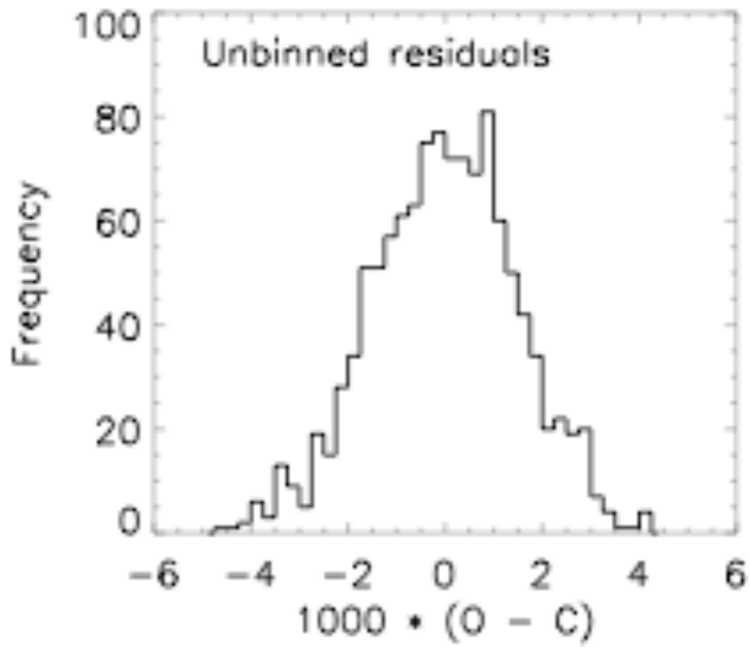
Uncertainties dominated by stellar mass.

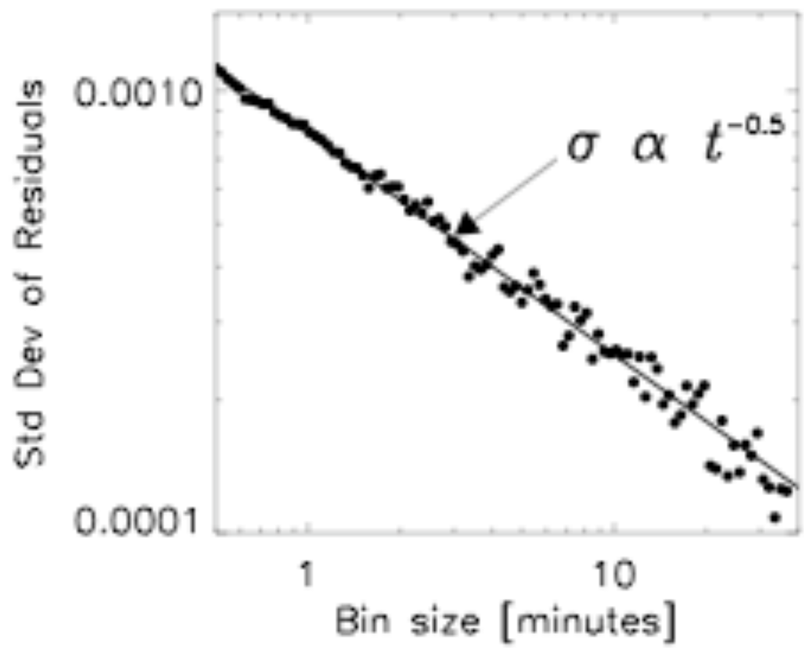
TrES-1



T_C uncertainties ~ 10-15 sec

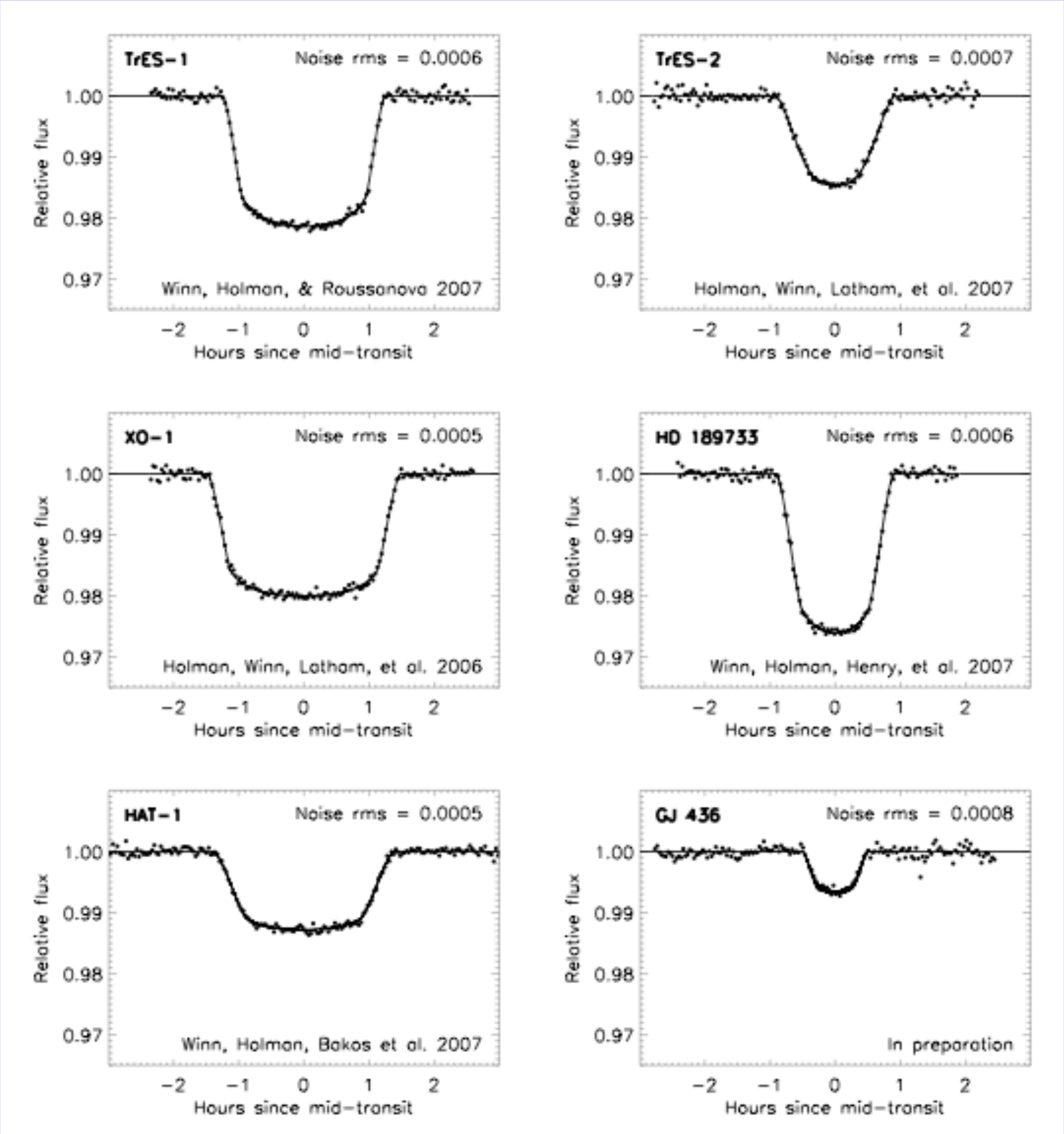
TrES-1





The KeplerCam data are remarkably free of systematic errors!

The TLC Project



What is the TLC Project doing right?

KeplerCam has rapid readout and excellent cosmetic properties.

For moderately bright (V~10-12) northern hemisphere targets we have

- Plenty of signal and little scintillation in 30 sec exposures with 1.2-m.
- Numerous nearby comparison stars of similar magnitude and color.
- Good sampling of the PSF.
- Good resolution of the 4 points of contact in z band.
- Apparent lack of significant systematic errors (for many targets).

We are able to obtain and schedule, through the formal TAC process and informal trading and collaboration, multiple nights of observation near the time of announcement.

High-precision, high cadence photometry allows us to fit for the radius of the star and planet, assuming only the stellar mass.

We can re-use spacecraft to observe transiting planets

Fact Sheet

EPOCh

Extrasolar Planet Observations & Characterization

...using the Deep Impact Spacecraft

Mission Overview

EPOCh exploits the CCD camera on Deep Impact to observe extrasolar planets transiting three bright stars, measuring reflected light from the planets, searching for transits of additional planets, and searching for rings and moons. EPOCh can detect terrestrial planets in these systems, as small as three Earth masses, by measuring perturbations in the times of the giant planet transits. EPOCh also measures our Earth in a global synoptic view, at both visible and IR wavelengths, validating models used to study extrasolar terrestrial planets.

EPOCh provides an opportunity for significant high visibility science results during early check-out of the spacecraft, immediately following Earth gravity assist in December 2007. EPOCh observations will occur from Jan - May, 2008, and are 100% compatible with an extended mission to comet Boethin or other target selected by NASA.

EPOCh does not build or launch any hardware; it uses the Deep Impact Flyby spacecraft exclusively.

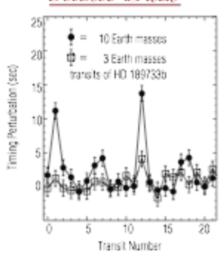
Science Objectives

- Observe multiple transits of the giant planets HD149026b, 189733b and 209458b
- Search for additional transiting planets, especially "hot Earths"
- Search for non-transiting massive terrestrial planets, via timing perturbations of the giant planet transits
- Search for rings and moons associated with the giant planets
- Detect reflected light from 189733b and 209458b, thereby:
  - -- measuring cloud properties
  - -- determining the bond albedo, with implications for the existence and nature of heat transport by strong zonal winds

Characterize the Earth as an extrasolar planet analog, providing ground truth for future imaging of extrasolar earths:

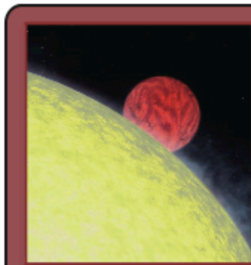
- Measure the empirical characteristics of the Earth in a global synoptic view
- Validate the Virtual Planetary Laboratory as a tool for understanding extrasolar earths

Science Data



Instrument Characteristics

Technology Development	Not Applicable
Science Payload	Deep Impact High Resolution Instrument Already operational
Spacecraft Characteristics	Deep Impact Flyby Spacecraft Already in orbit
Anticipated Launch Vehicle	Already launched
DSMS Infrastructure Usage	34-meter DSN at 200 kbps
Curatorial Services	Not Needed
Significant Contributions	None



EPOCh Measures Reflected Light at Secondary Eclipse

EPOCh Searches for Super-Earth-Mass Terrestrial Planets Orbiting Nearby Stars

EPOXI selected!

A'Hearn (DIXI PI)
Deming (EPOCH PI)

Charbonneau (CfA)
Holman (CfA)
Kuchner (GSFC)
Lisse (JHU)
Livengood (GSFC)
Pedelty (NASA)
Richardson (GSFC)
Schutz (NASA)
Seager (DTM)
Veverka (Cornell)
Wellnitz (U. MD)

Drake Deming's talk today

We propose new space missions:
There is an Announcement of Opportunity
for NASA Small Explorer Missions

Summary of Transit Timing

- The presence of one or more additional planets in transiting systems can lead to variations in the times, durations, and light curve shapes of transits.
- Many of these variations will be detectable with Kepler, CoRoT, EPOXI/EPOCh, or ground-based telescopes, allowing one to detect the presence of additional planets in transiting systems.
- More theoretical work is needed:
  - The non-co-planar case, including transit durations and depths.
  - The inverse problem of determining the the perturbing planet's orbit and mass.
  - More detailed work on the observational limits.
- There is an opportunity to propose new Small Explorer Missions.