Detecting Terrestrial Planets in Transiting Planetary Systems

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Planet Formation

How massive is the protoplanetary disk?

How long does it take to make a planet?

What is the lifetime of a disk?

Why are there hot Jupiters?

How can I make hot Jupiters?

What is going to happen to Anna Nicole's baby?

Why are some of the eccentricities of distant planets so big?

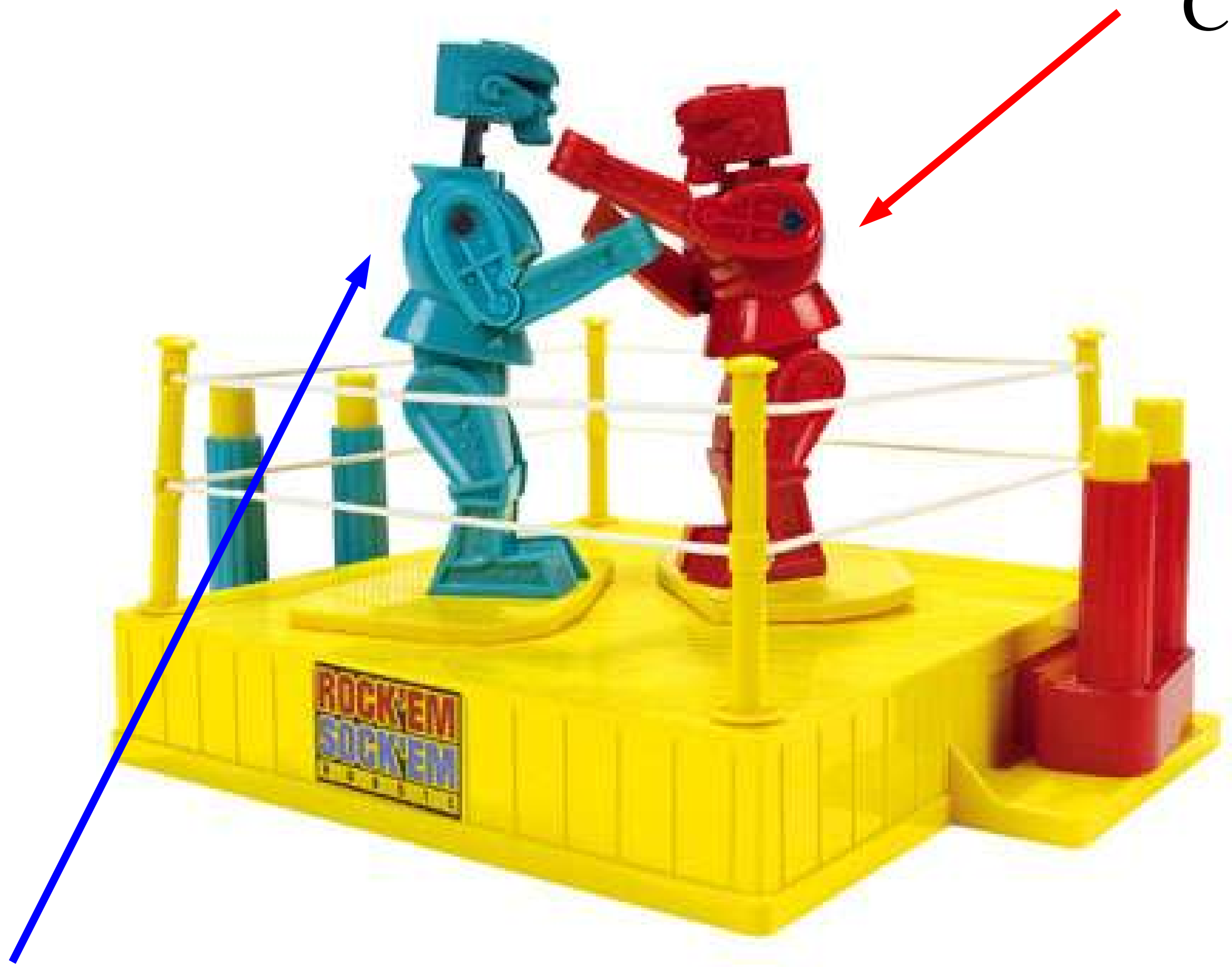
Planet Formation

Planet Formation

Gravitational Instability

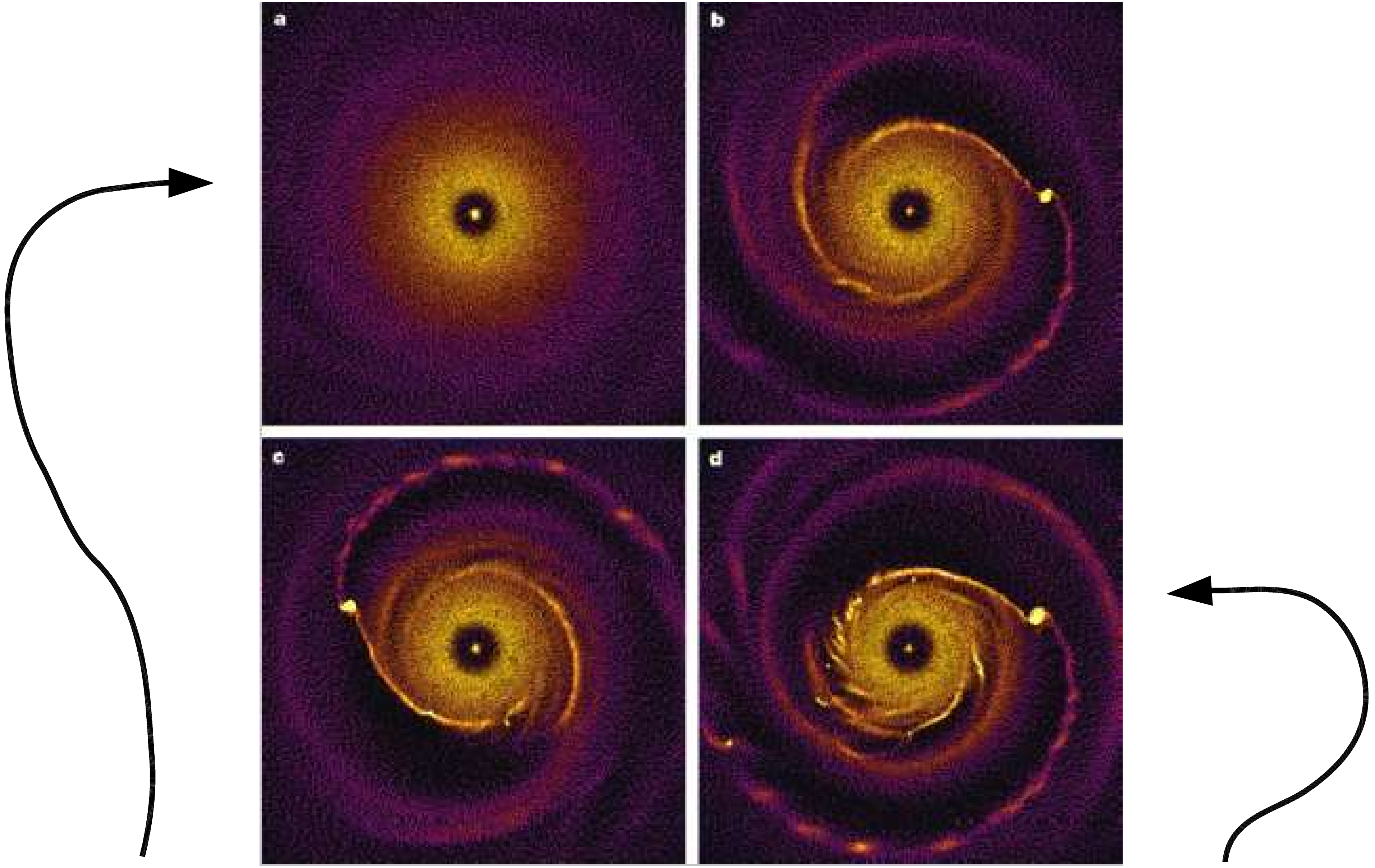
Planet Formation

Core Accretion



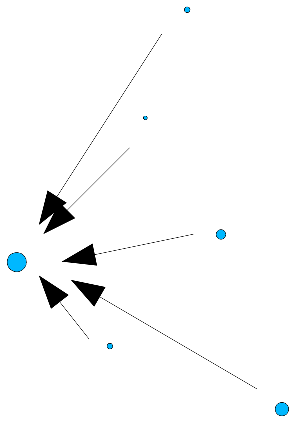
Gravitational Instability

Gravitational Instability



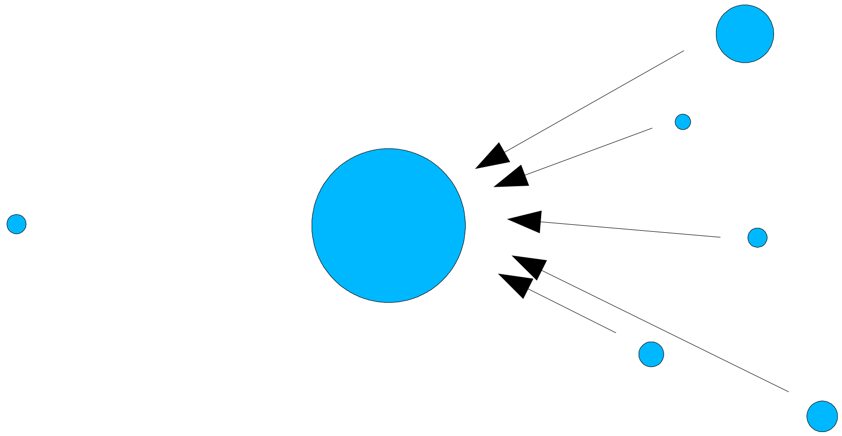
Start with initial disturbances. End with gas giant planets.

Core Accretion



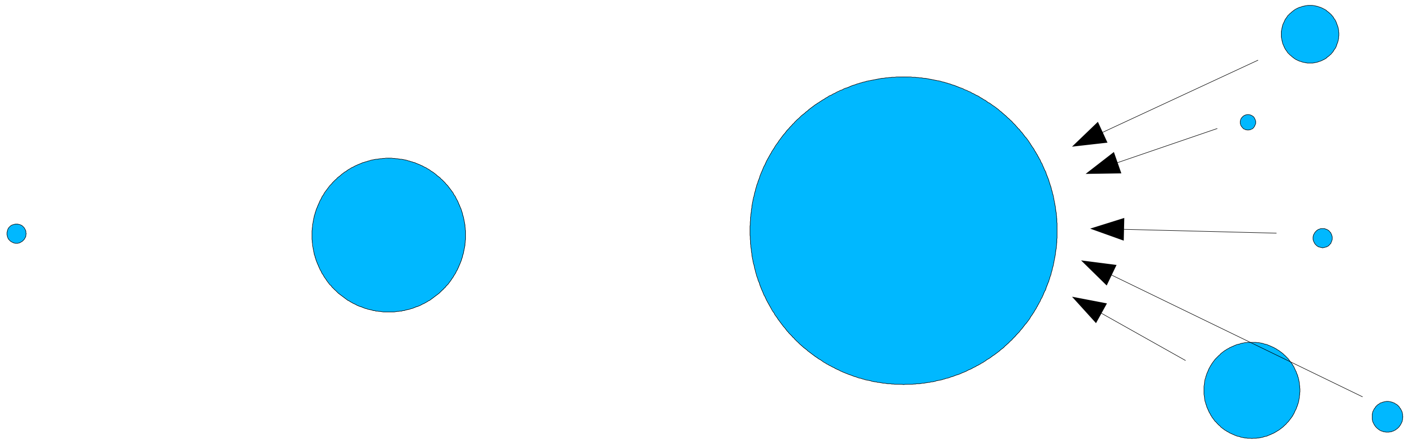
Start with small objects that accrete other small objects.

Core Accretion



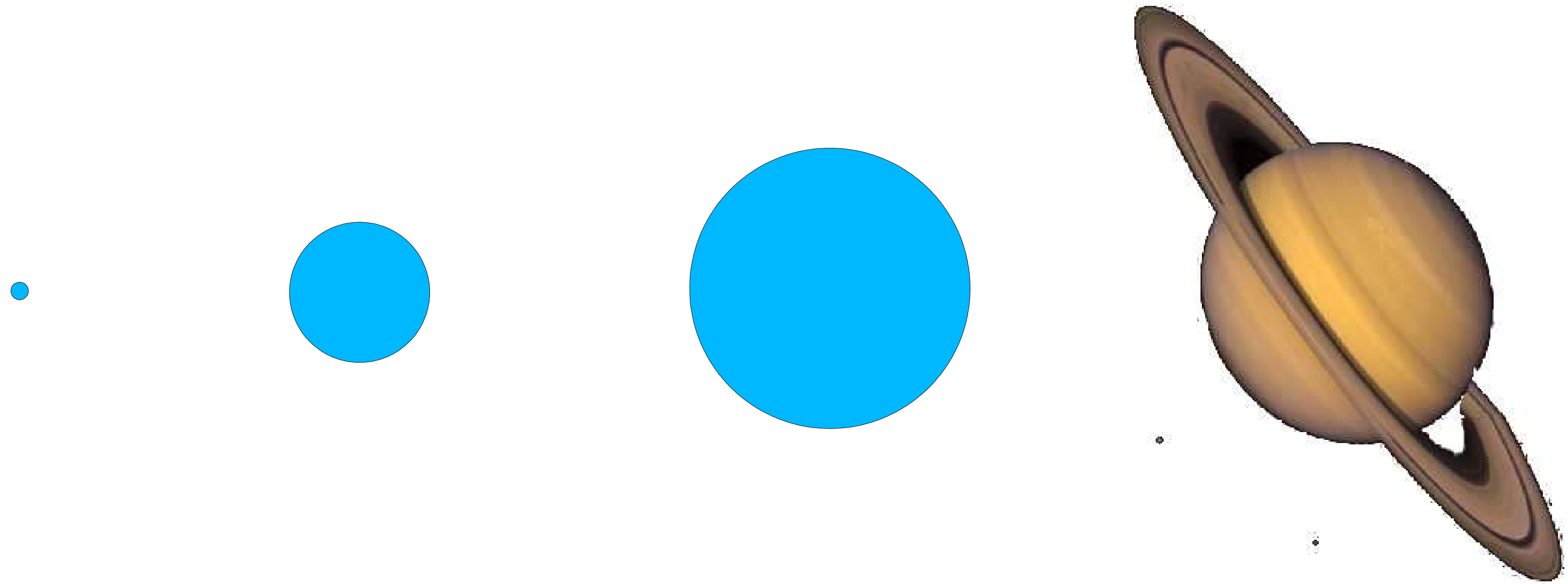
and other small objects.

Core Accretion



and other not so small objects.

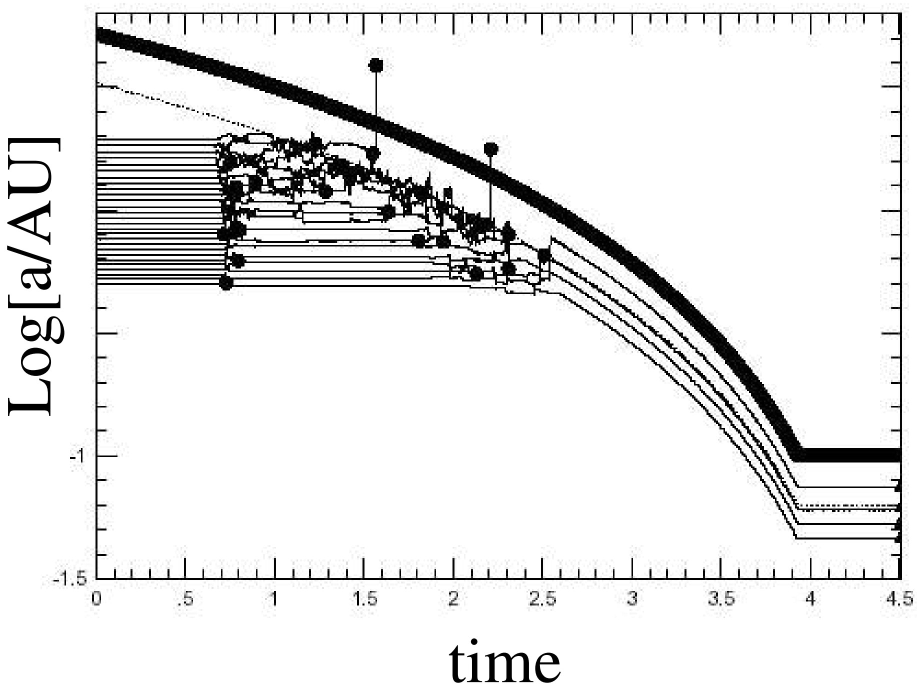
Core Accretion

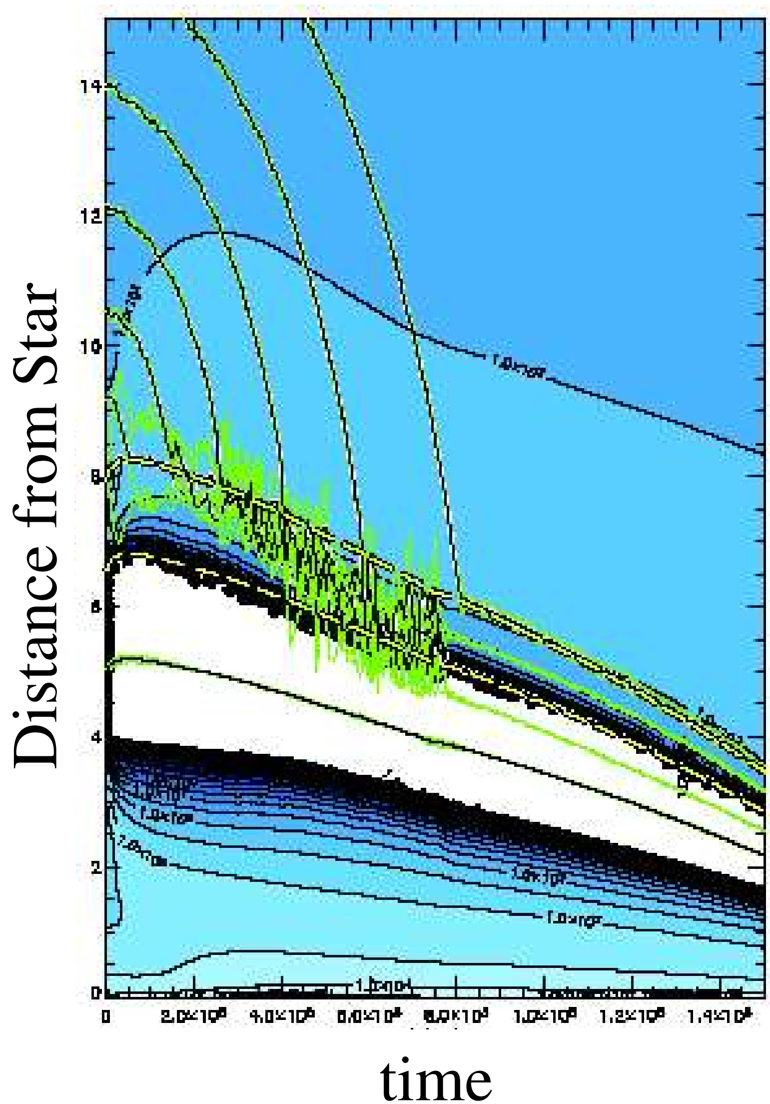


to make a planet

Tell Tale Sign

Core accretion predicts small, resonant planets.

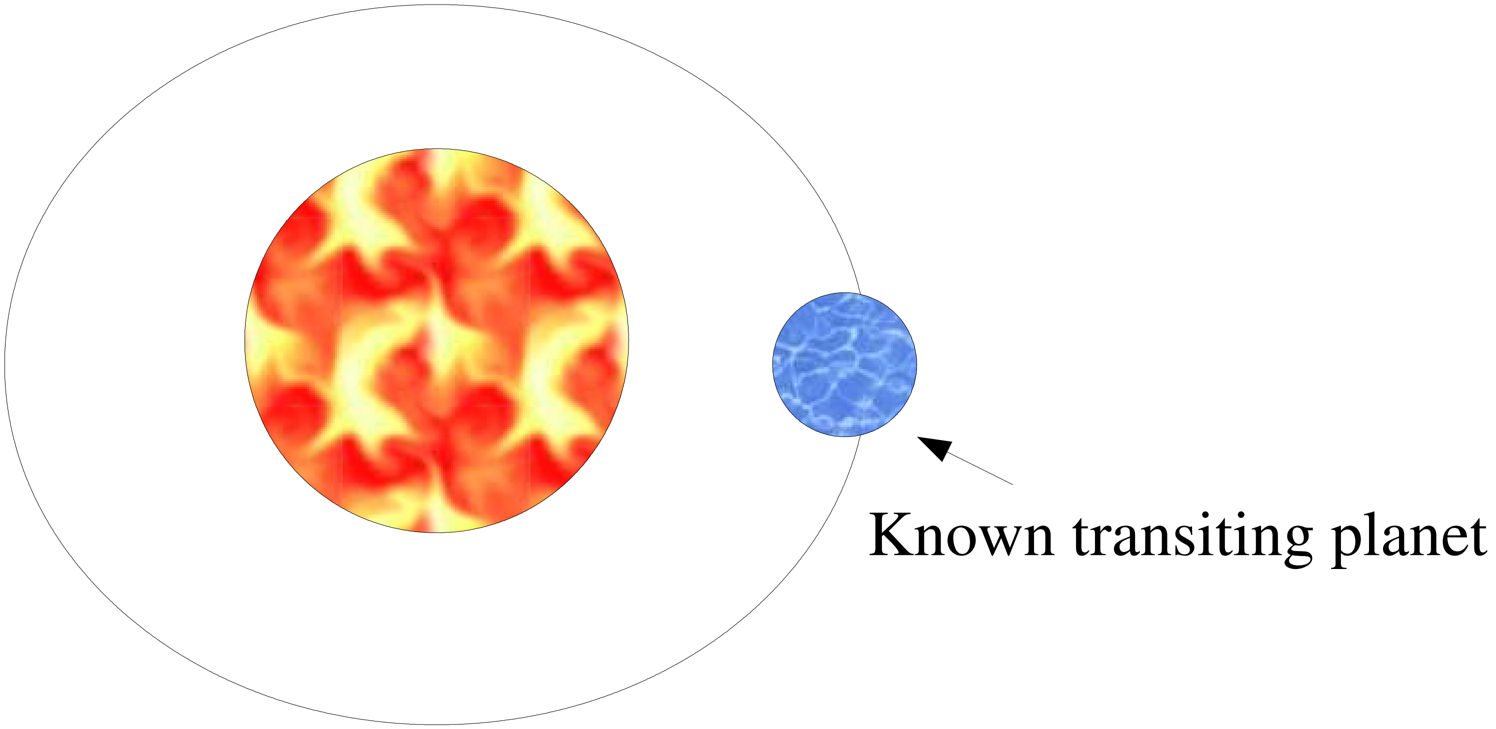




Zhou et al 2005

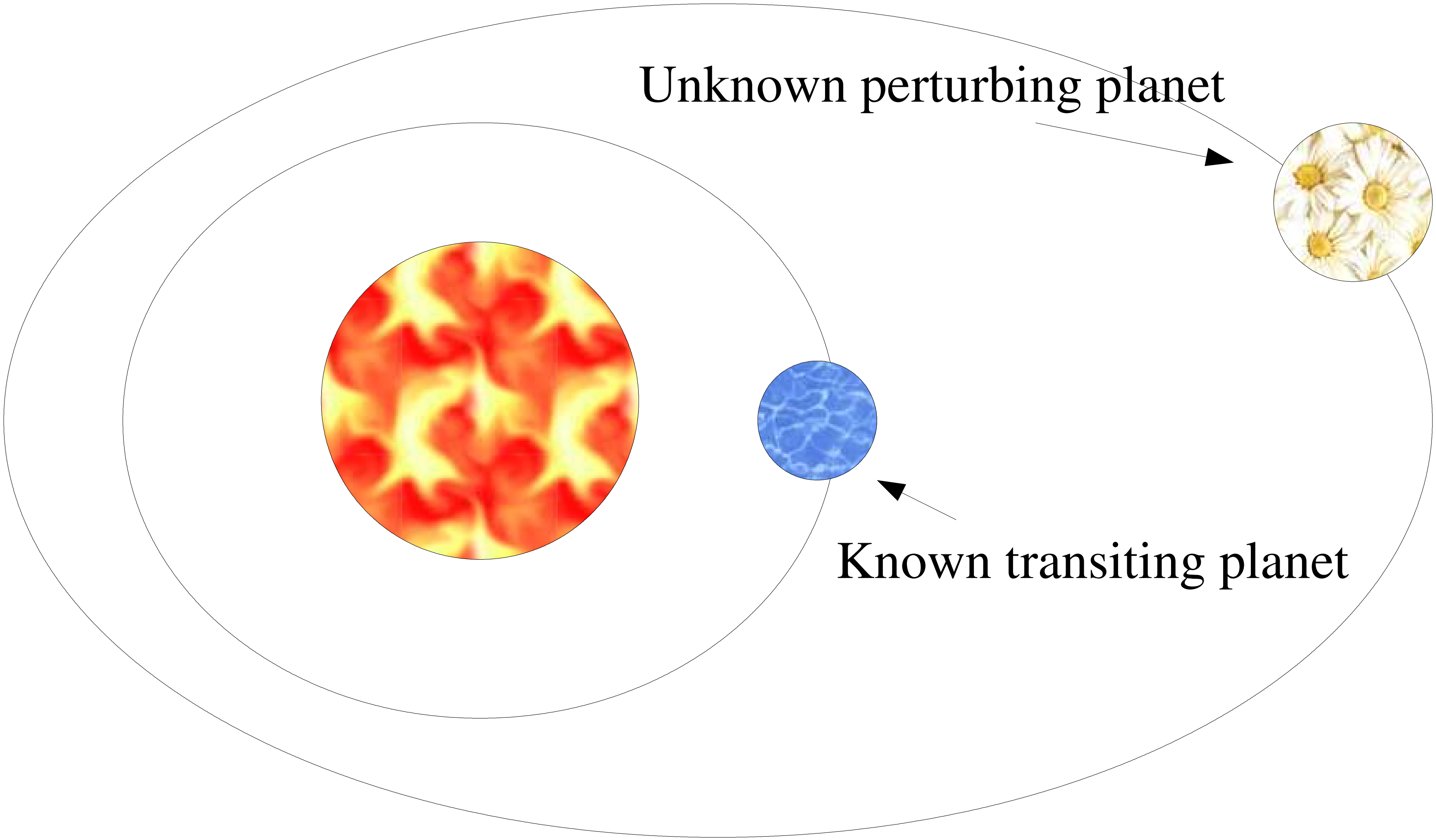
Thommes 2005

Transit Timing Variations



Transit times are equally spaced.

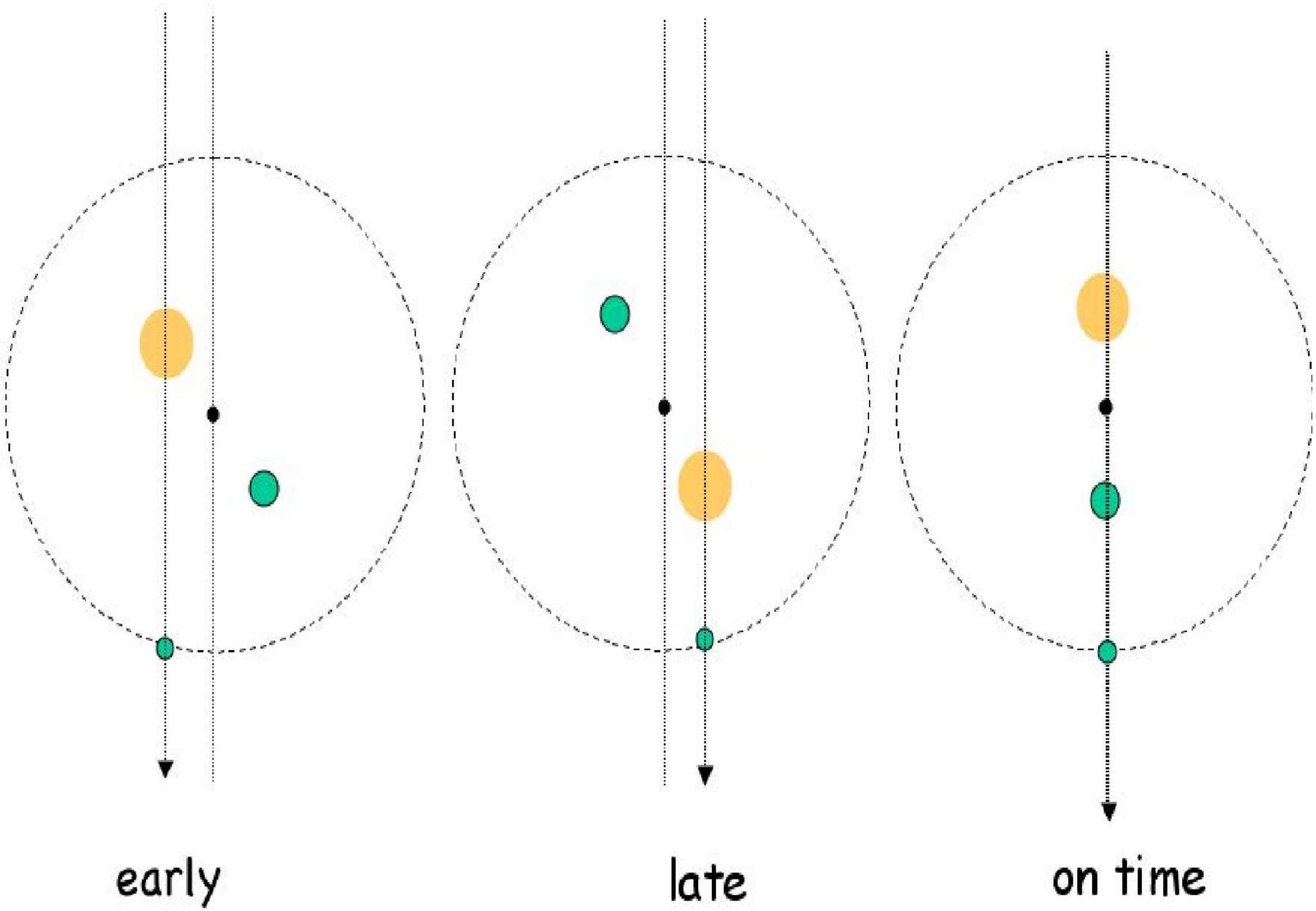
Transit Timing Variations



Transit times are <u>NOT</u> equally spaced.

Transit Timing Variations

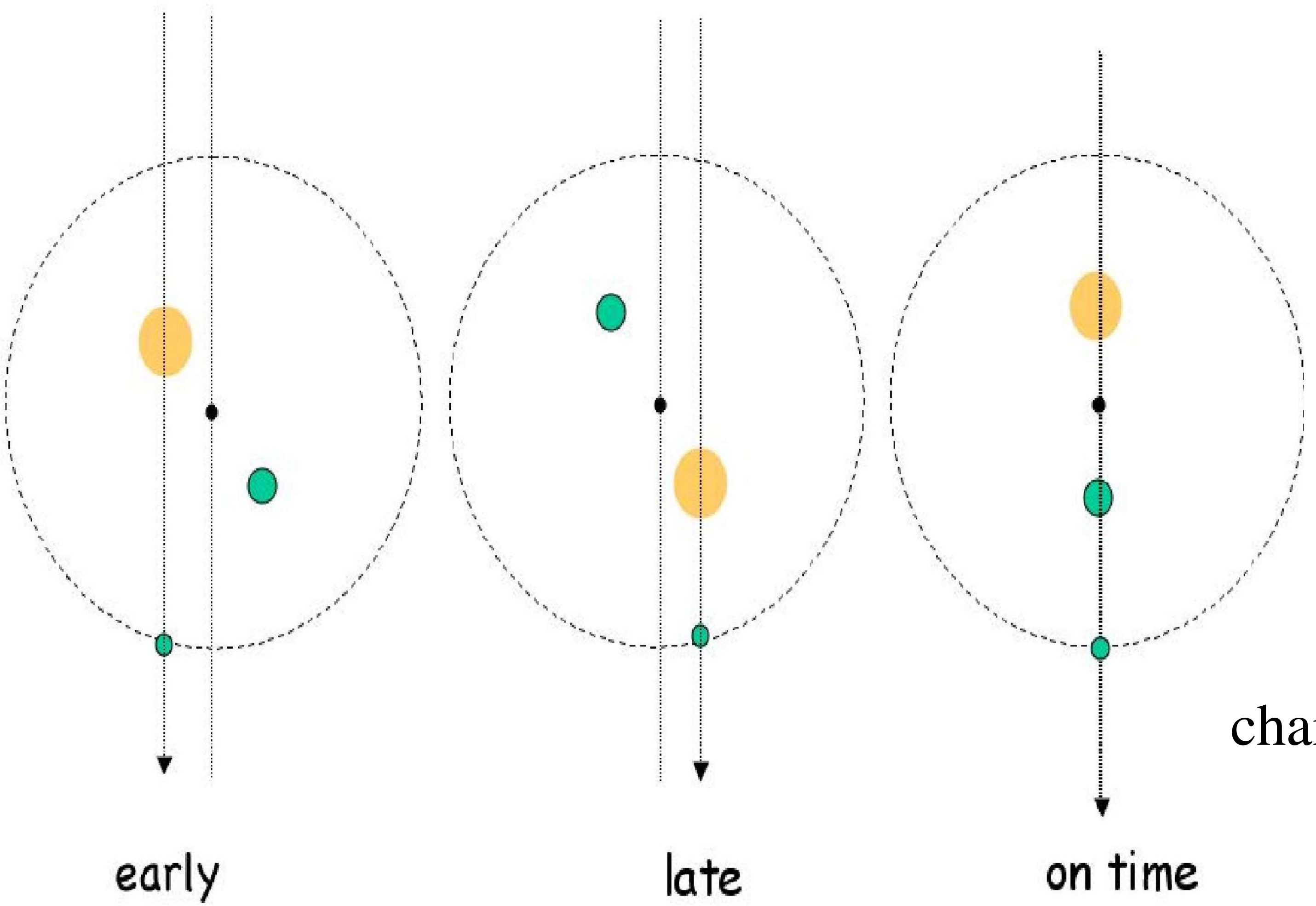
The TTV Poster Child



$$\sigma_t \sim \left(\frac{P_2}{a_2}\right)\left(\frac{m_1 a_1}{m_0}\right)$$

Transit Timing Variations

The TTV Poster Child



characteristic velocity

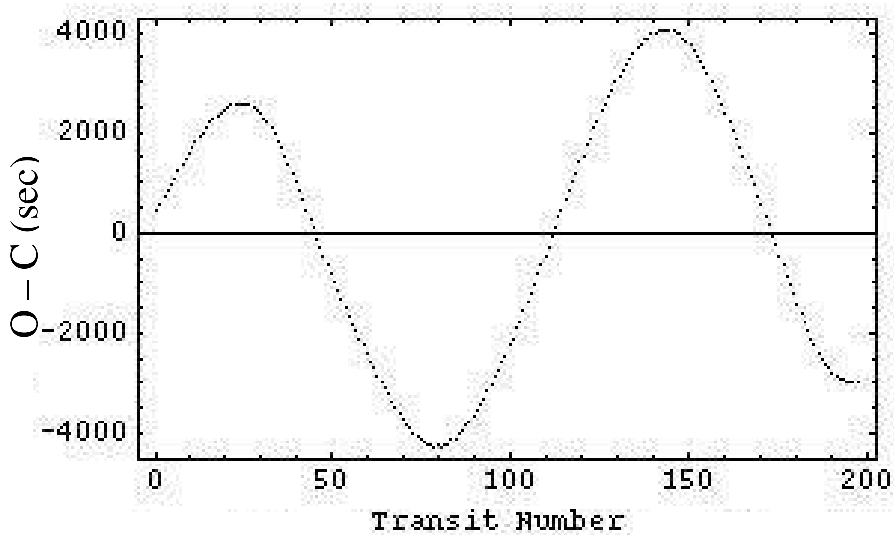
$$\sigma_t \sim \left(\frac{P_2}{a_2}\right)\left(\frac{m_1 a_1}{m_0}\right)$$

characteristic displacement

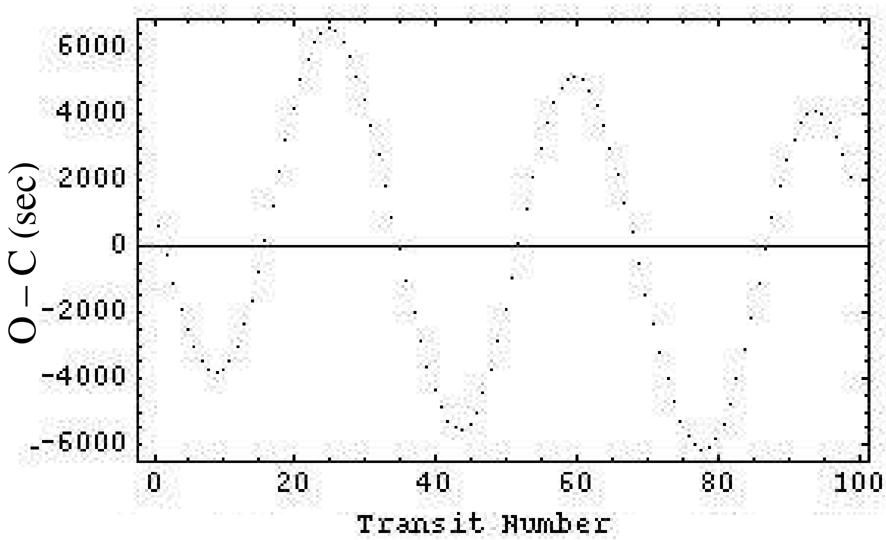
Transit Timing Variations

Sample signal for a resonant, 0.1 Jupiter-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

2:1 – outer resonance



2:1 – inner resonance

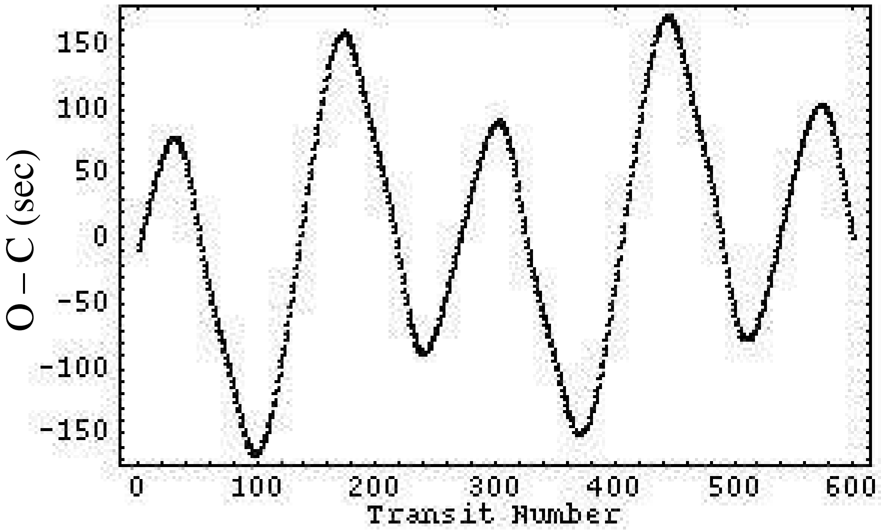


$$\delta t_{max} \sim \frac{P}{4.5j} \frac{m_{pert}}{m_{pert} + m_{trans}}$$

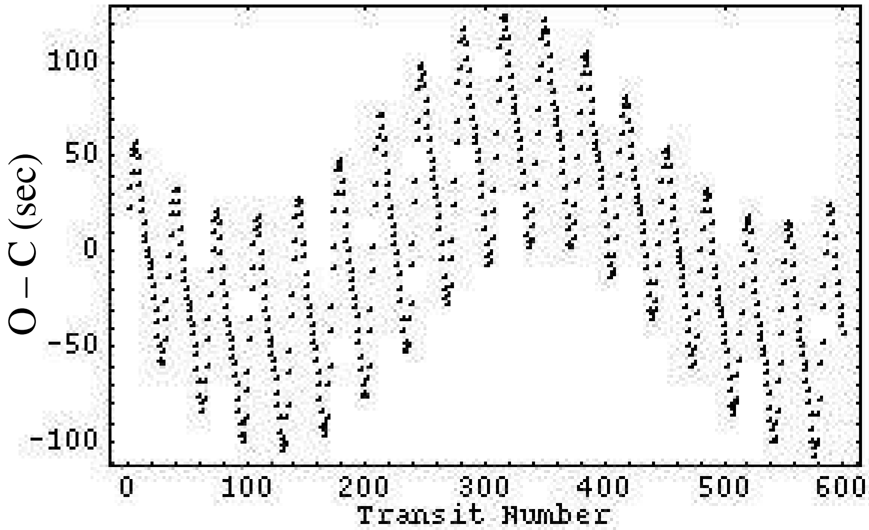
Transit Timing Variations

Sample signal for a resonant, Earth-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

2:1 – low eccentricity



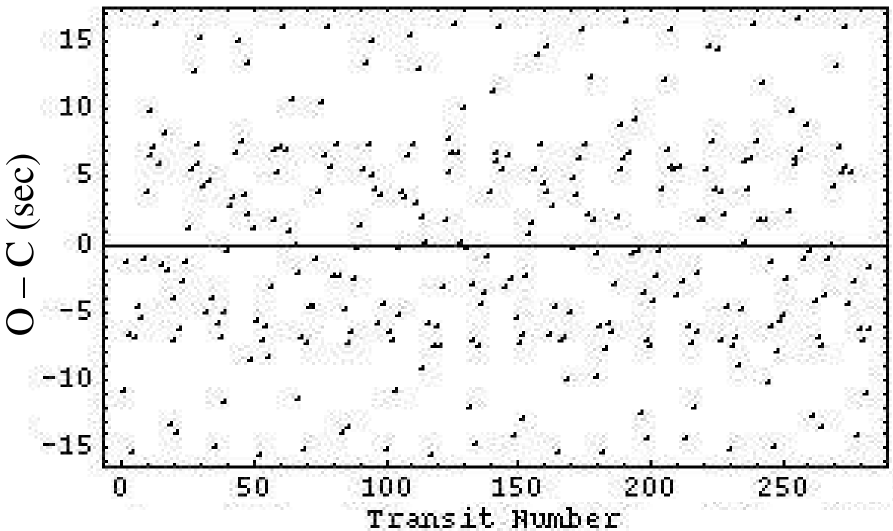
2:1 – high eccentricity



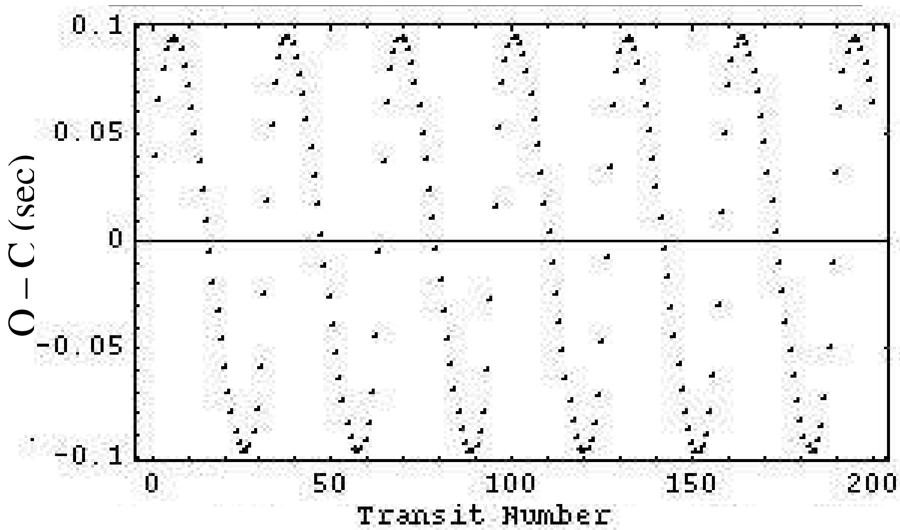
Transit Timing Variations

Sample signal for a non-resonant, 0.1 Jupiter-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

2:1 – semi-major axis ratio



10:1 axis ratio, high eccentricity

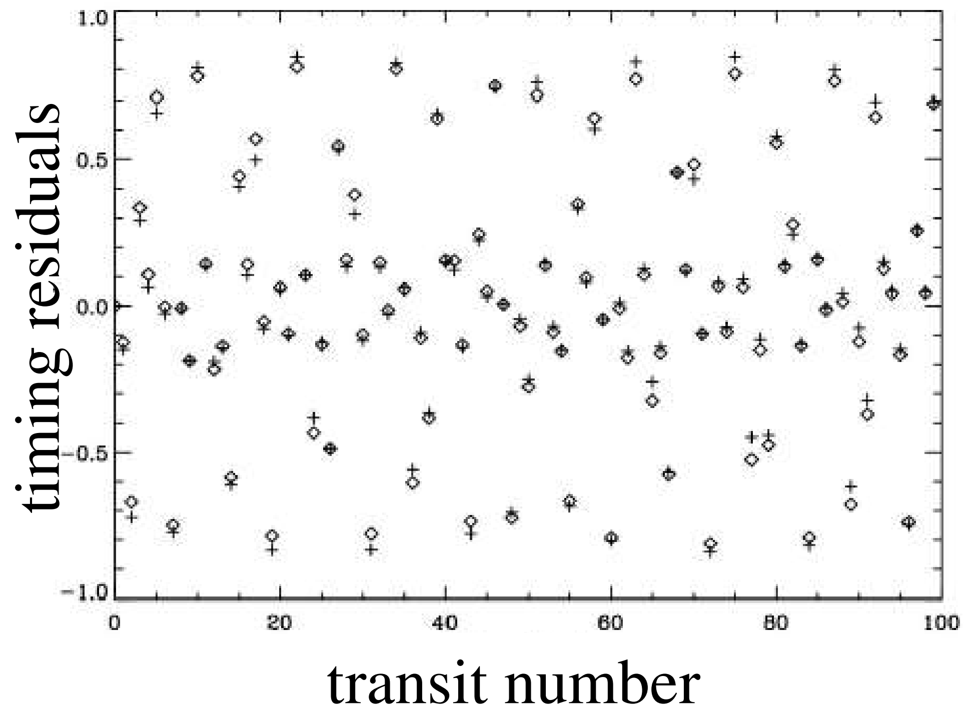


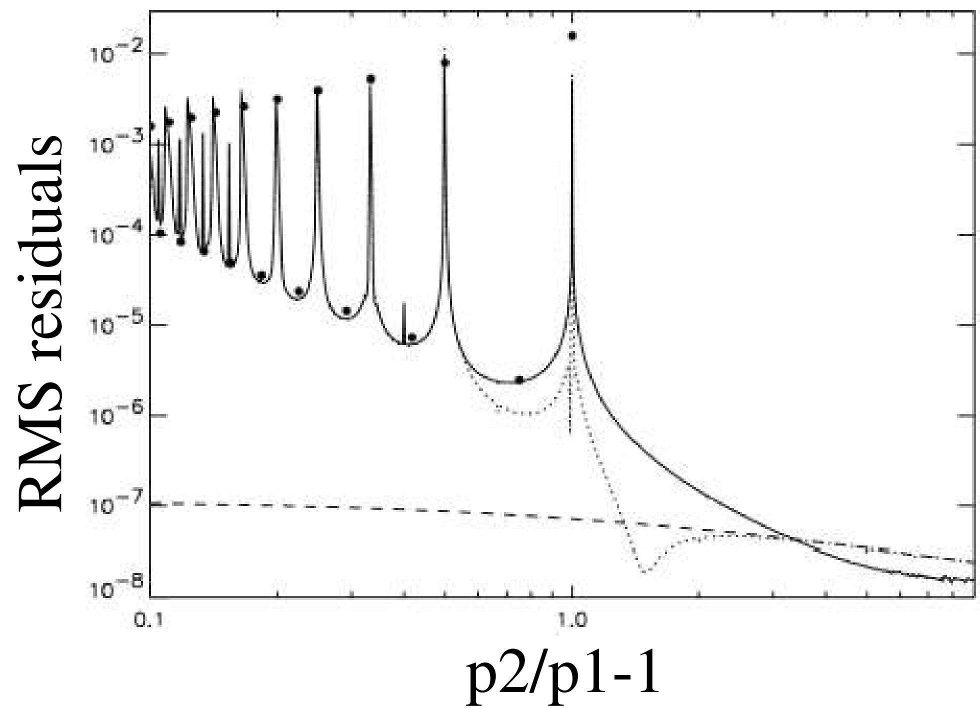
$\sigma_t \sim$ (Big, Messy Expression)

$$\sigma_1 \sim e_2 P_2 \left(\frac{m_2}{m_0}\right)\left(\frac{a_1}{a_2}\right)^3$$

Transit Timing Variations

Comparison of Analytic and Numerical Results





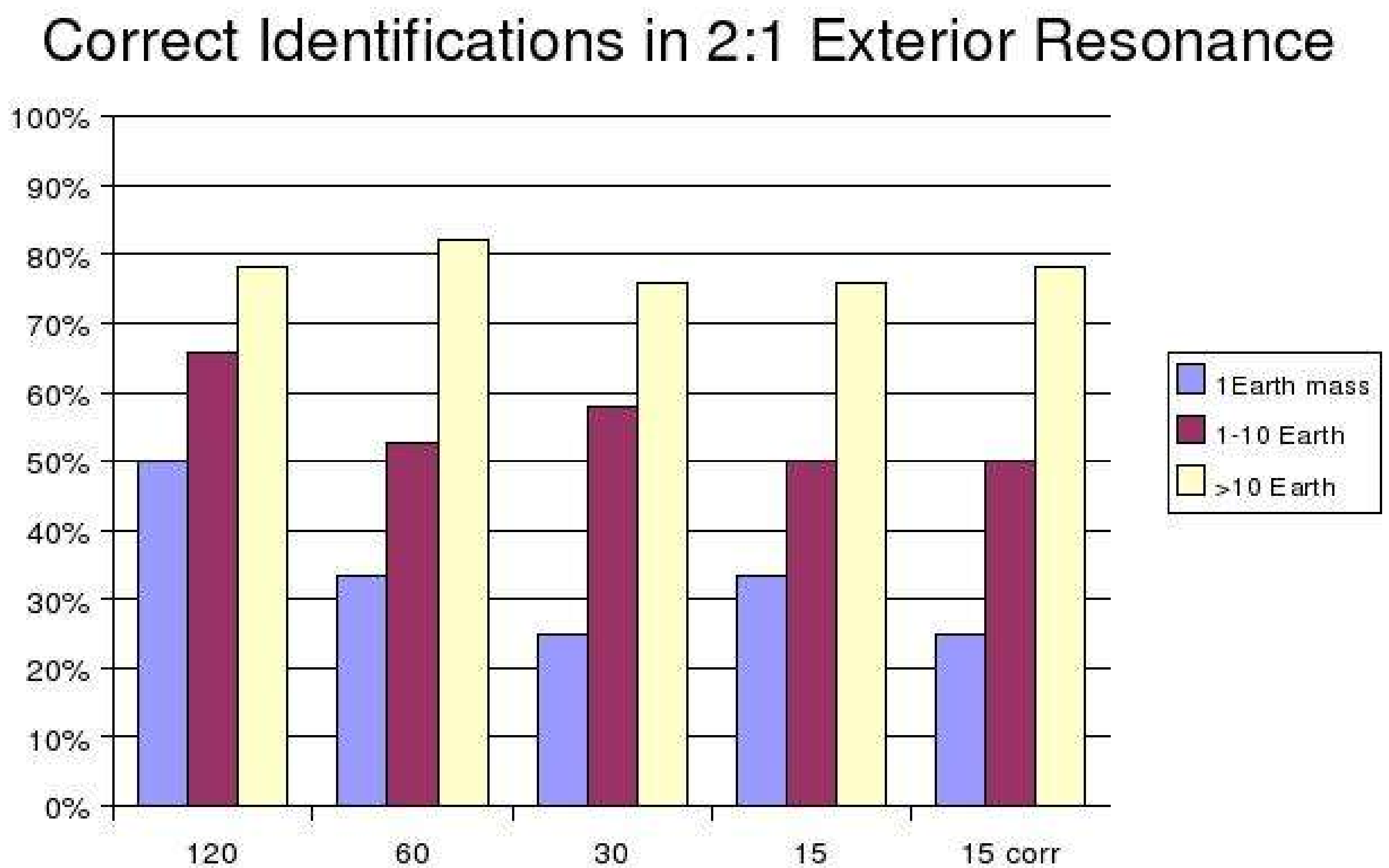
Signal increases with period of transiting planet, mass of perturber, and, particularly, proximity to mean-motion resonance.

Images from Agol et al 2005

Finding Simulated Planets

- 100 random systems
  - Transiting Jupiter on a 3-day orbit
  - Perturbing planet with mass between 0.3 and 300 Earth-masses
  - Eccentricities between 0.001 and 1
  - Coplanar orbits of random orientation
- All systems near the 2:1 exterior resonance
- Data spans 120 orbits – broken into 4 subsets of 120, 60, 30, and 15 random transits, and one of 15 correlated transits.
- White, Gaussian timing noise added equal to 5 seconds per day of the transiting planet period

Finding Simulated Planets

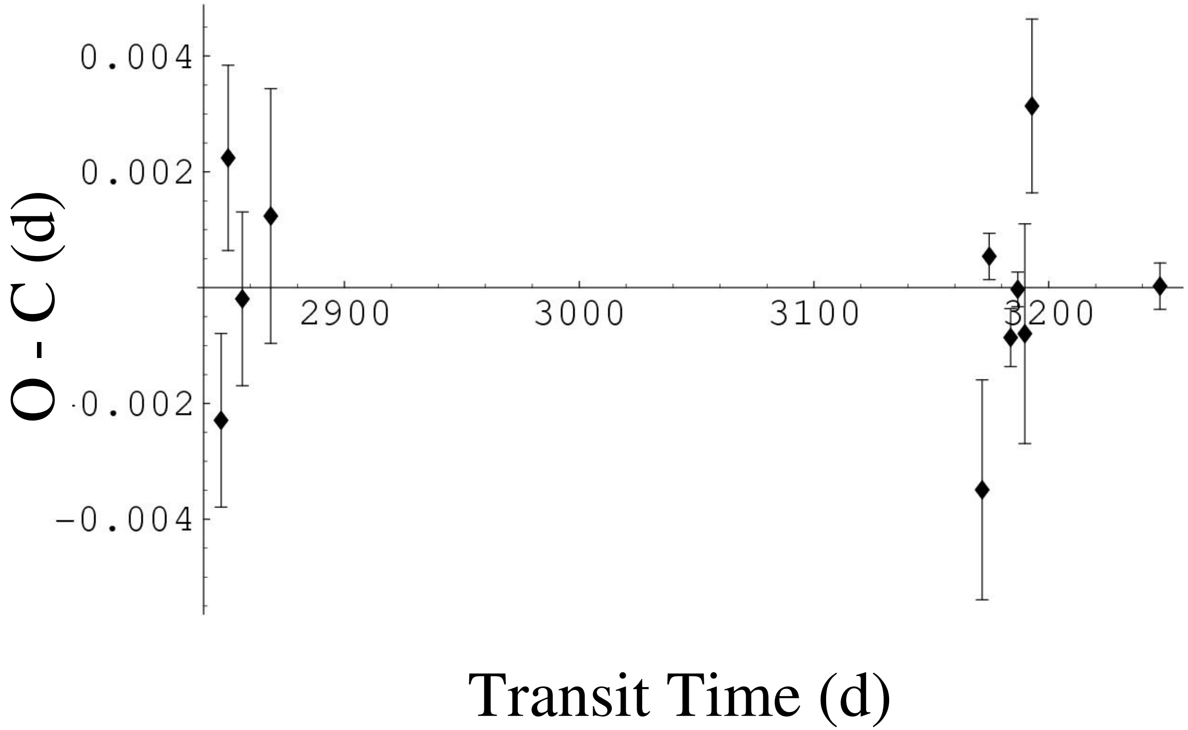


Number of Analyzed Transits

These results are for a coarse search with a no frills minimization algorithm.

Analyzing Real Data, Part 1

11 ground-based transits of the TrES-1 system



reduced $\chi^2 = 1.93$
mean $\sigma = 107.6$s
minimum $\sigma = 25.9$s
(1.2m Whipple)

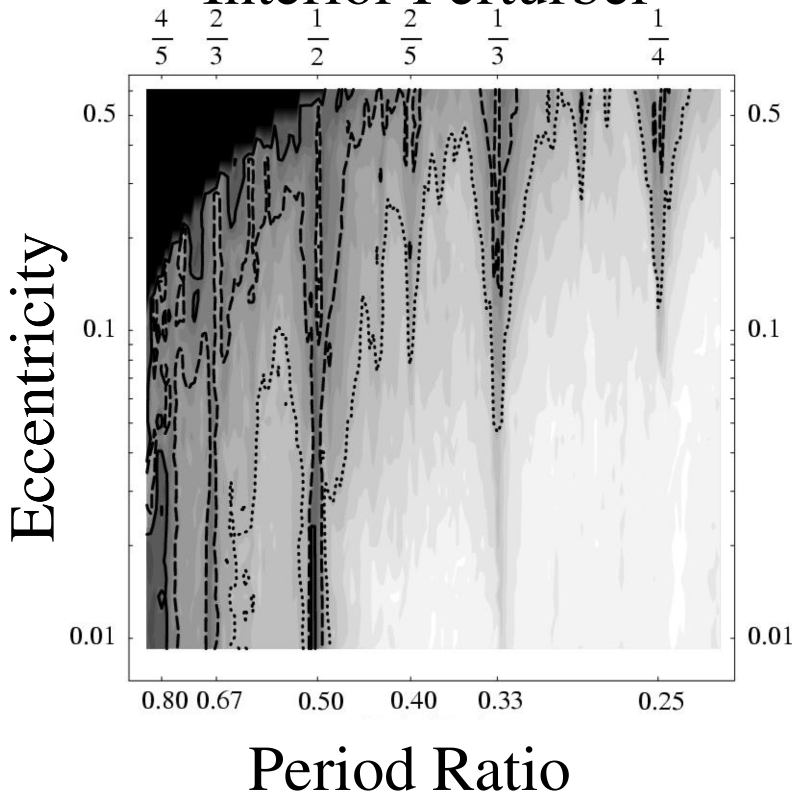
Data from Charbonneau et al. 2005

Results from Steffen & Agol 2005

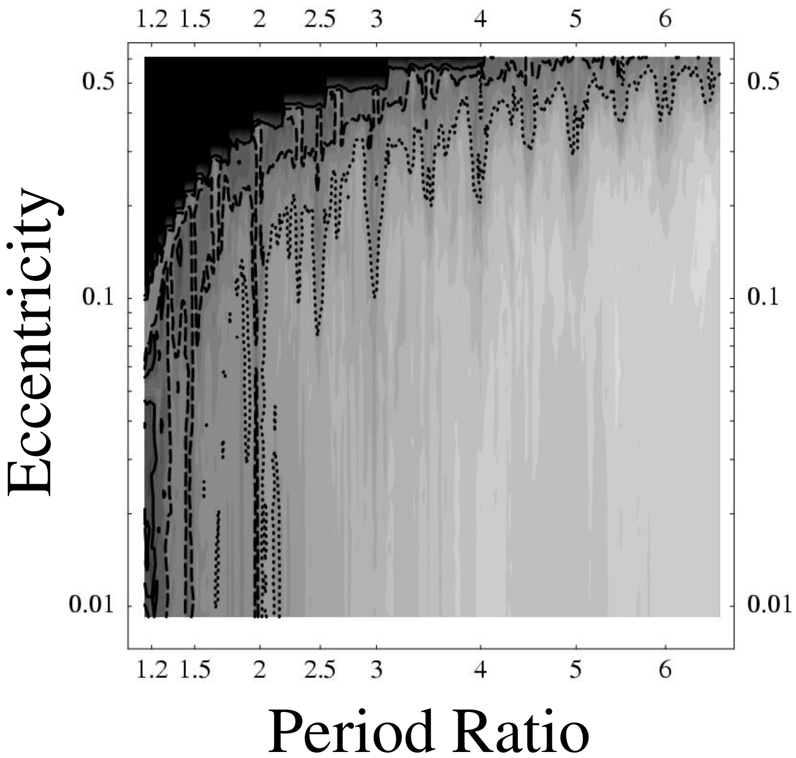
The TrES-1 System

Constraints on the Mass of a Secondary Planet

Interior Perturber



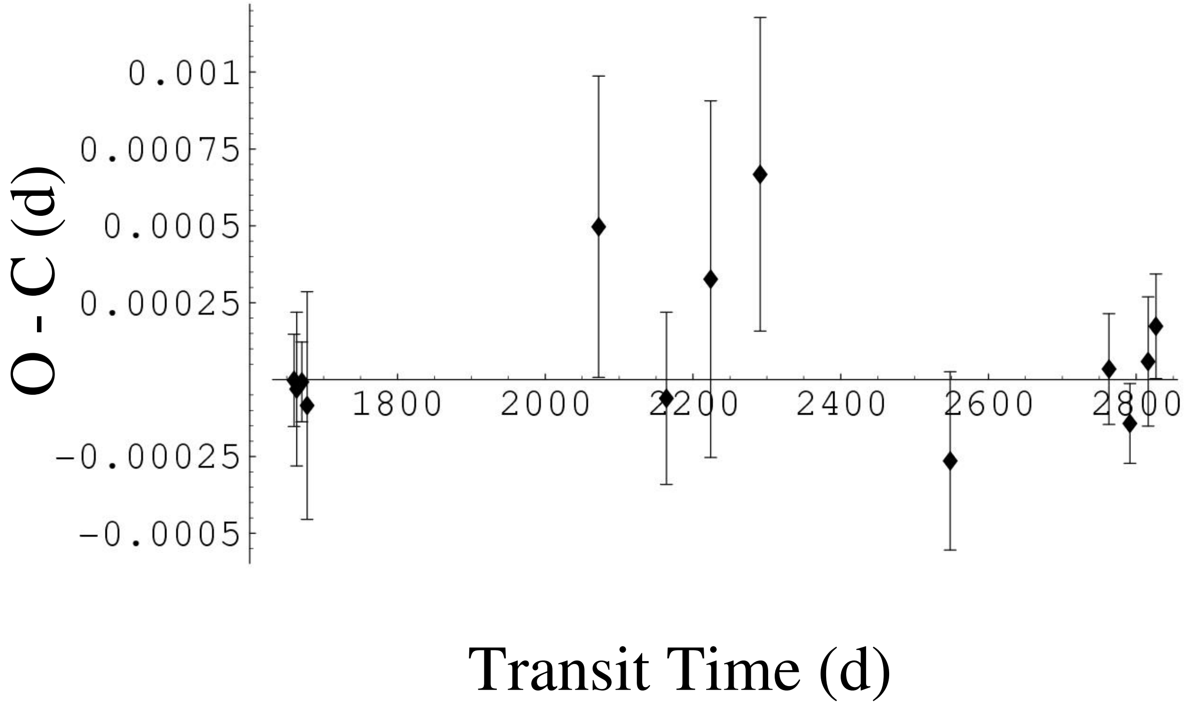
Exterior Perturber



Contours: 100, 10, and 1 Earth mass

Analyzing Real Data, Part 2

13 HST transits of the HD 209458 system



reduced $\chi^2 = 0.58$
mean $\sigma = 24.9$s
mean STIS $\sigma = 17.2$s
minimum $\sigma = 11.2$s

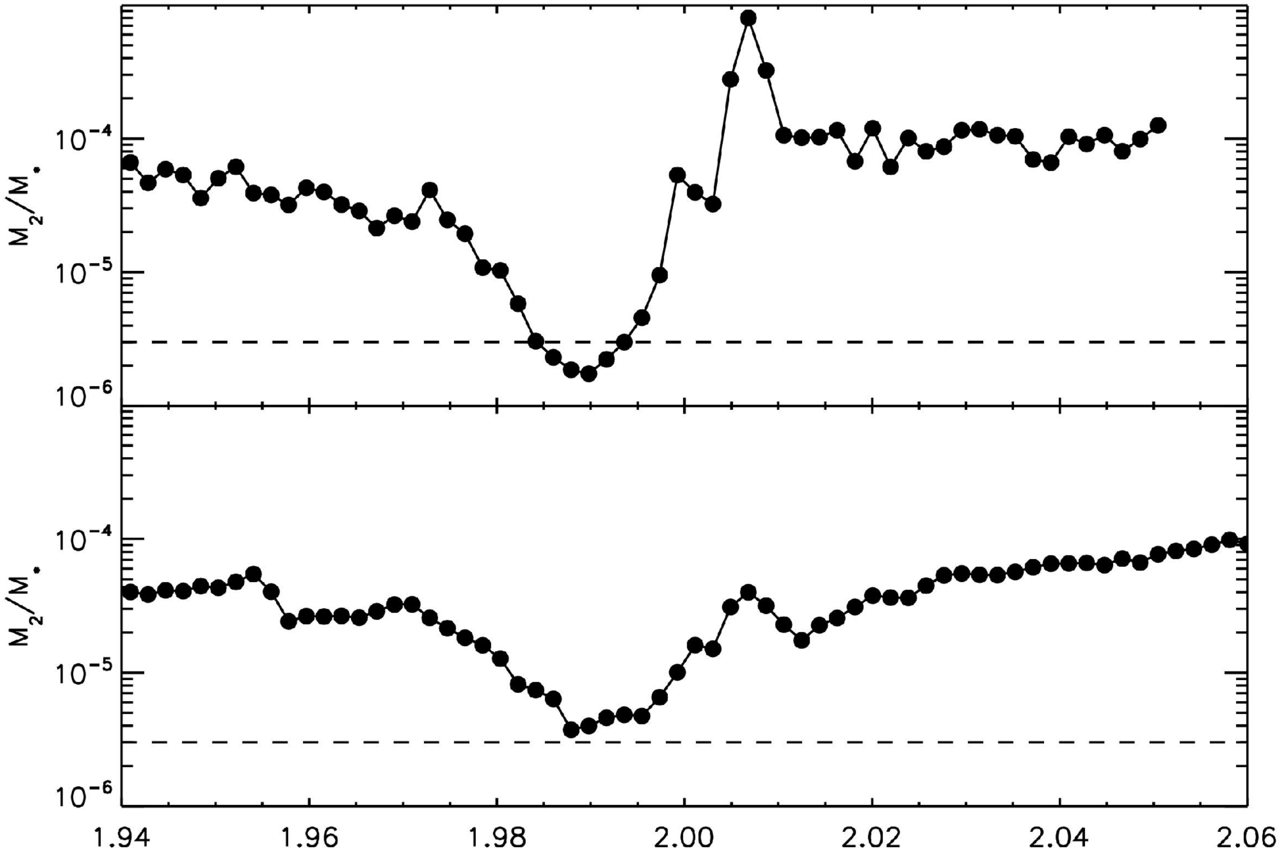
Data from Charbonneau et al. 2001, Brown et al. 2001, Schultz et al. 2004
Re-reduced and analyzed in Agol & Steffen 2007

The HD 209458 System

Maximum allowed mass of companion
in 2:1 resonance with any eccentricity

Interior Perturber

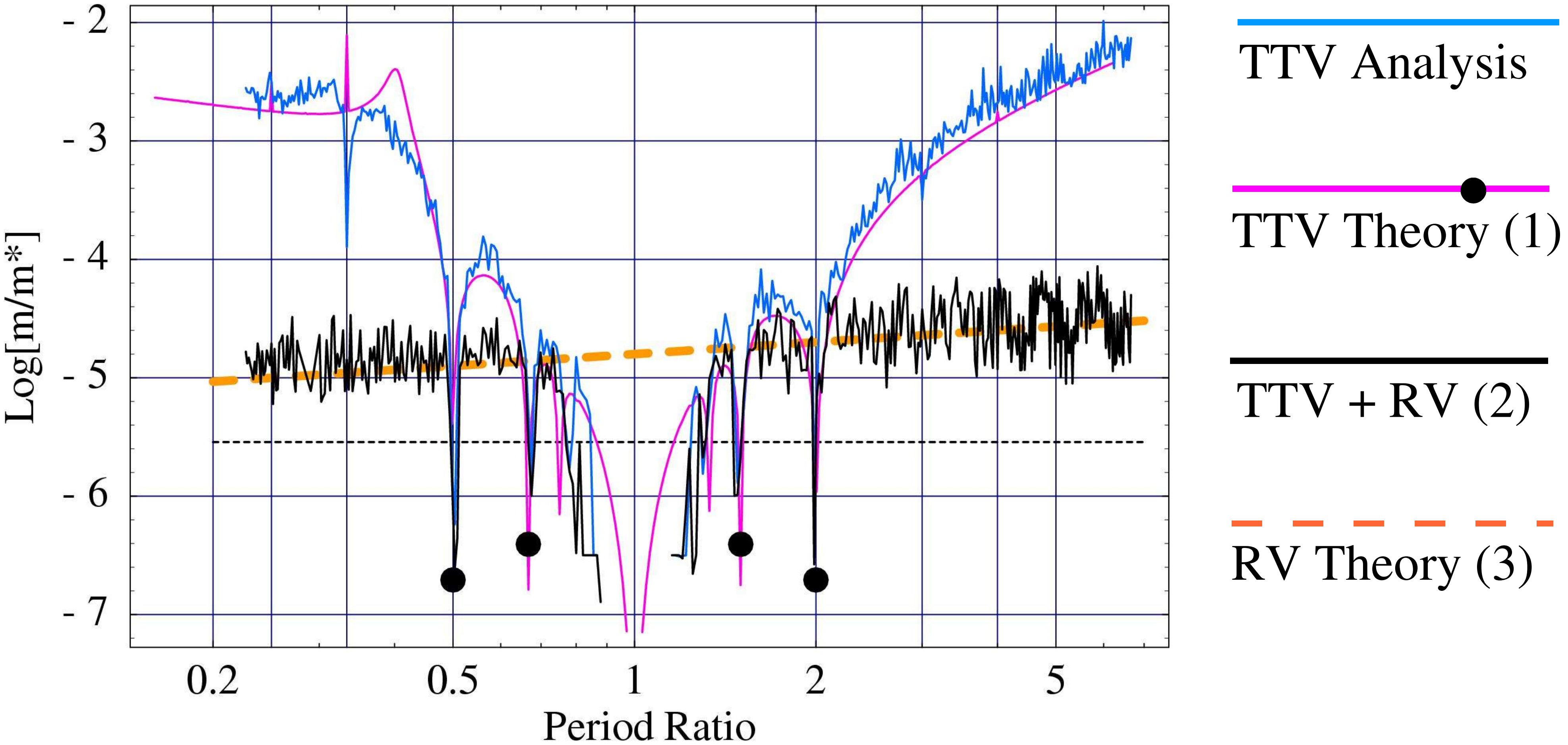
Exterior Perturber



Period Ratio

The HD 209458 System

Maximum allowed mass for companion in initially circular orbit



(1) Eqns. (A7-8) & (33) from Agol, Steffen, Sari, & Clarkson MNRAS 359, 567 (2005)

(2) RV measurements from Laughlin et al. ApJ 629, L121 (2005)

(3) Eqn. (2) from Steffen & Agol MNRAS 364, L96 (2005)

The Future of TTV

PASS, WASP0, ASAS-3, RAPTOR, TrES,
XO, HATnet, SWASP, Vulcan, RAPTOR-F,
BEST, Vulcan-S, SSO/APT, RATS, TeMPEST,
EXPLORE-OC, PISCES, ASP, OGLE-III,
STEPSS, INT, ONC, EXPLORE-N, EXPLORE-S,
KELT, ASEPS, Pan-Planets, MOST

The Future of TTV

PASS, WASP0, ASAS-3, RAPTOR, TrES,
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EXPLORE-OC, PISCES, ASP, OGLE-III,
STEPSS, INT, ONC, EXPLORE-N, EXPLORE-S,
KELT, ASEPS, Pan-Planets, MOST

and

CoRoT and Kepler

Science from TTV

1) Detect additional planets in transiting systems and determine the masses and radii of all bodies in them.

2) Determine the relative importance of Gravitational Instability and Core Accretion models of planet formation.

3) Constrain planetesimal masses and parameters of protoplanetary disk

4) Study the evolution of planetary systems, e.g. the effects of planet-planet scattering on eccentricity and inclination.

5) Interesting dynamical scenarios with strongly interacting systems.

Conclusions

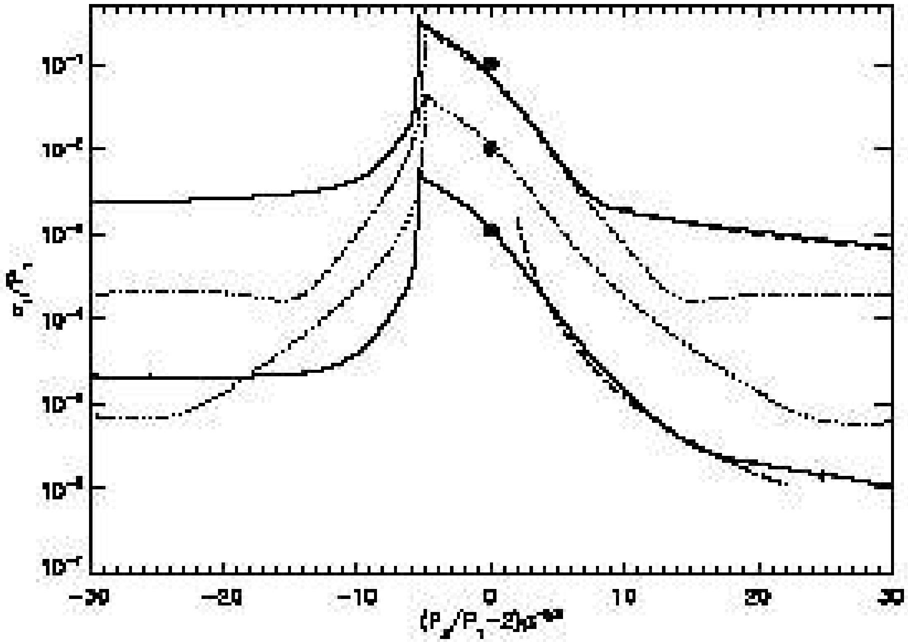
1) No low-order resonant ~Earth-mass planets in HD 209458 or TrES-1
   - Sensitivity to 0.2 Earth-masses in low-eccentricity orbits for HD 209458 and 0.7 Earth-masses in TrES-1
   - No comment on planet formation at this time.

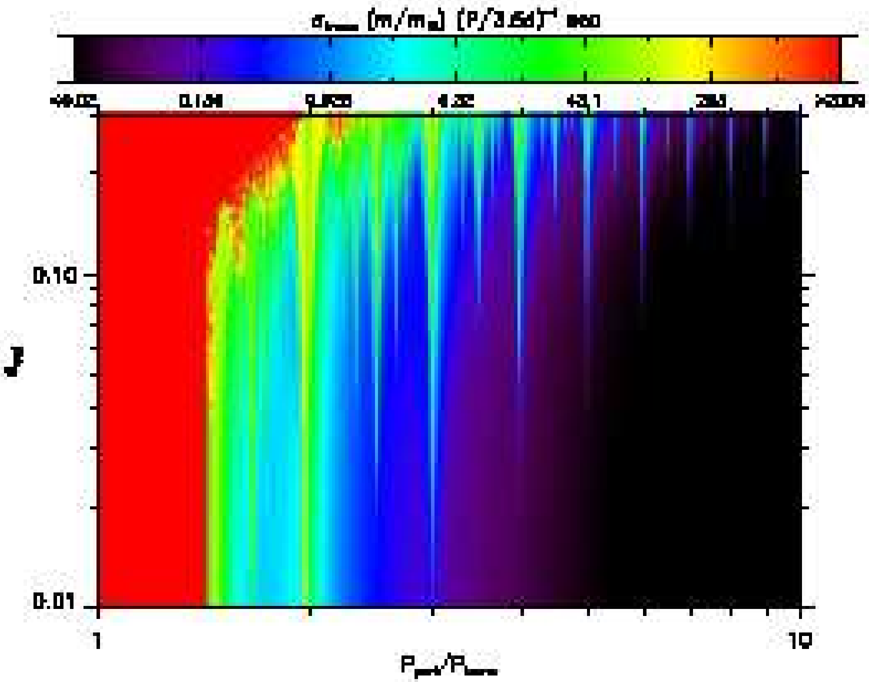
2) Most resonant systems are detectable with TTV
   - at least 2/3 of systems identified with as few as 15 transits

3) Many transit surveys are running and planned.
   - precursor science for larger missions (e.g. TPF)
   - additional science for each new system

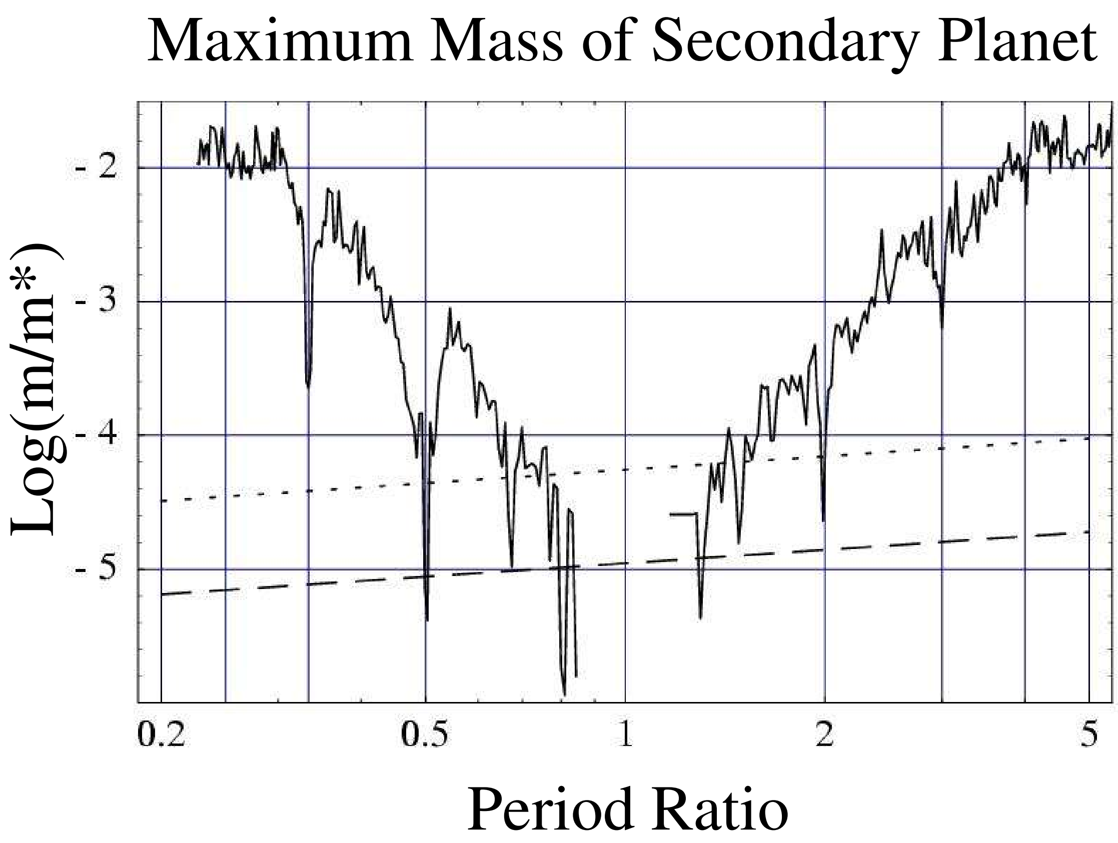
4) TTV's sensitivity to resonant planets can test planet formation theories

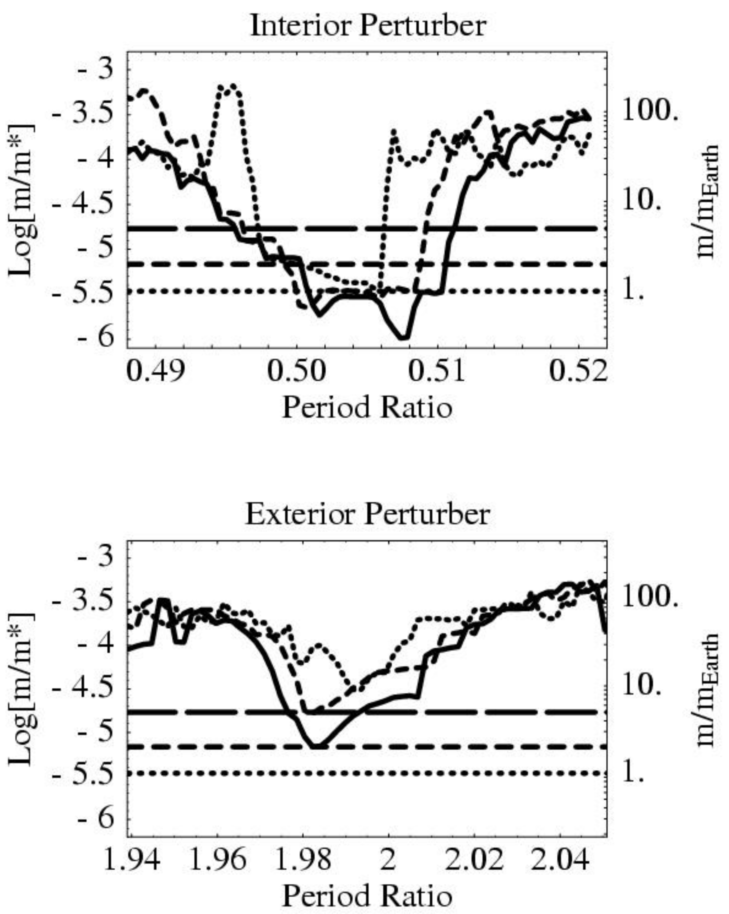
Bonus Feature: More on the Signal





Bonus Feature: TrES-1





Dotted: 5 m/s RV limit

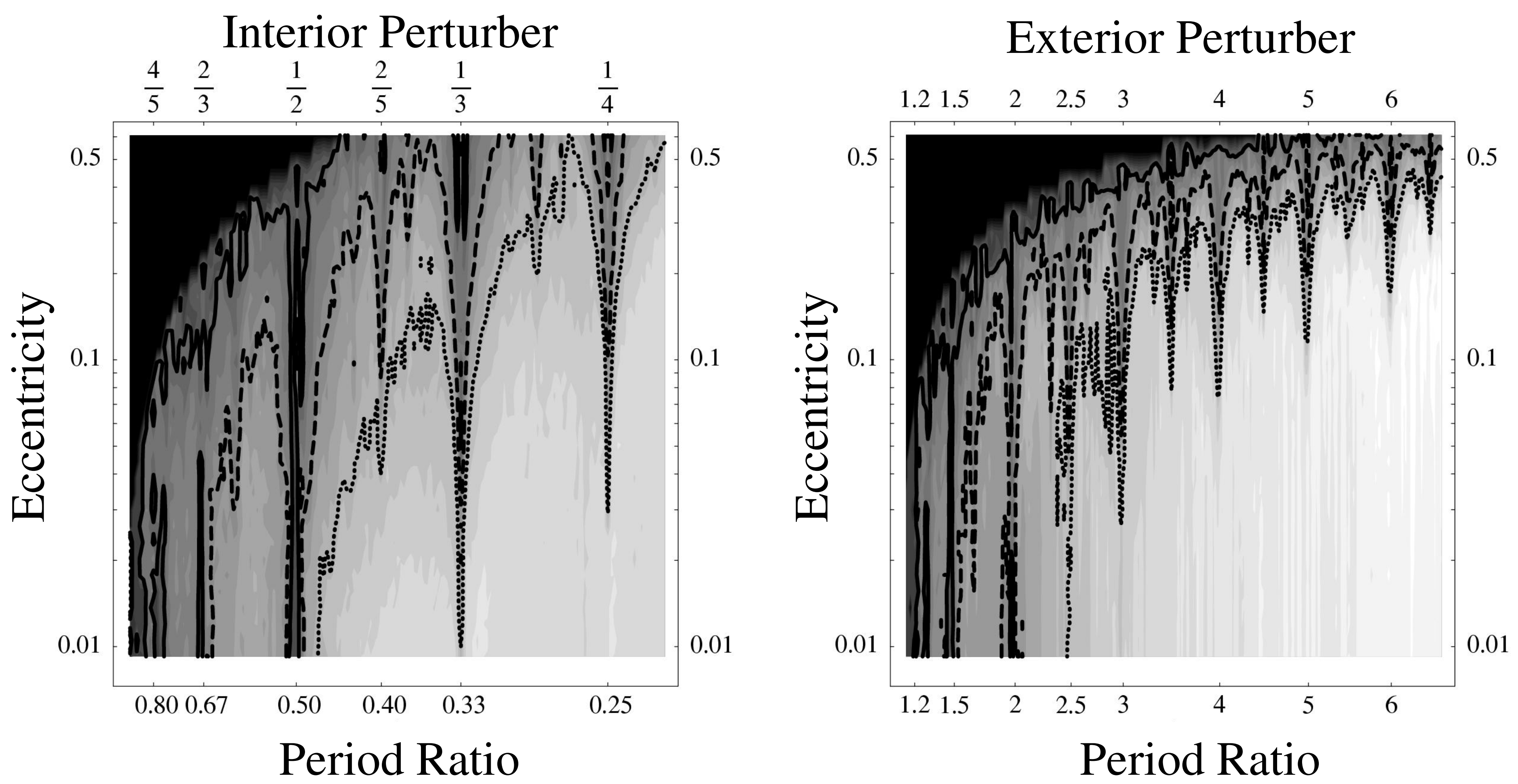
Dashed: 1 m/s RV limit

Eccentricity: 0.05

Horizontal Lines: 1, 2, 5 Earth mass

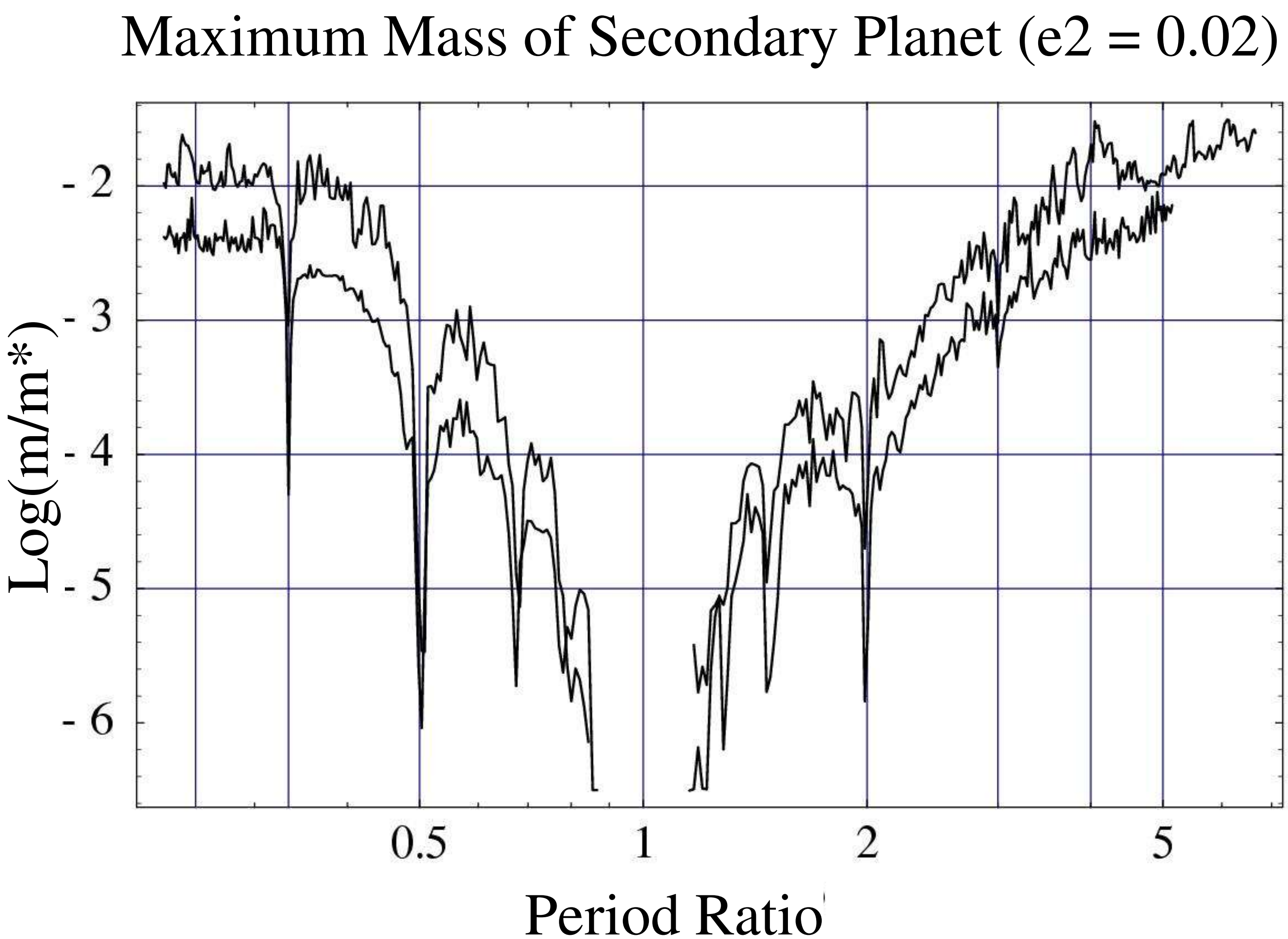
Bonus Feature: HD 209458

Maximum allowed mass of companion for HD 209458



Contours: 100, 10, and 1 Earth mass

Bonus Feature: Ground vs. Space



Upper curve:

TrES-1

11 transits

108s mean timing error

26s smallest error

Lower curve:

HD209458

13 transits

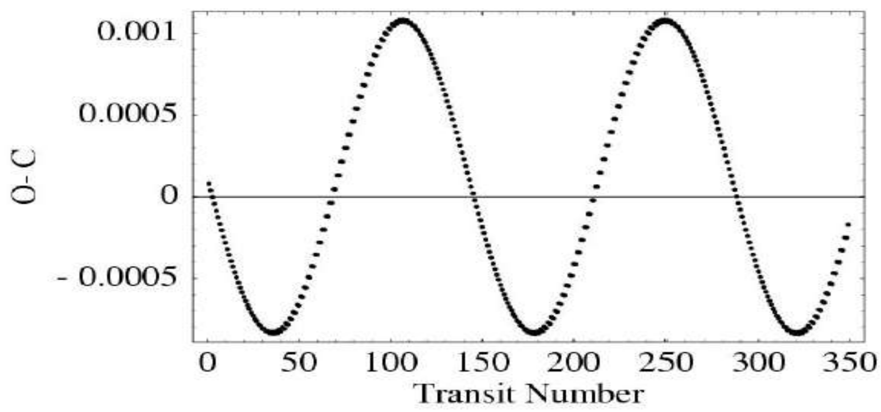
25s mean timing error

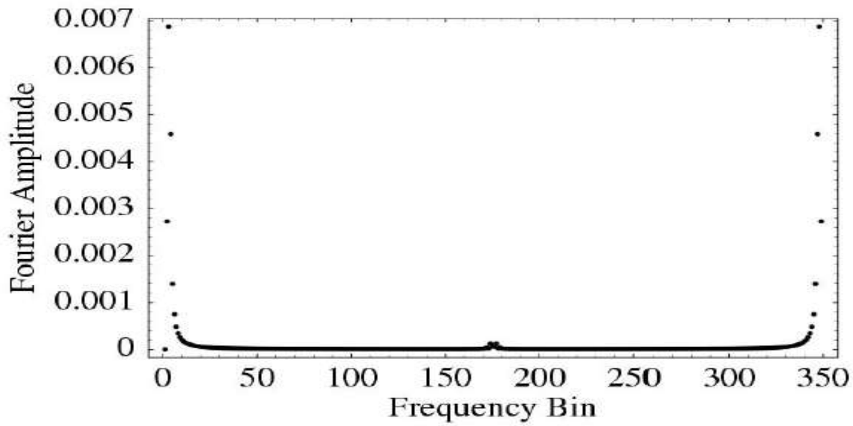
17s STIS mean error

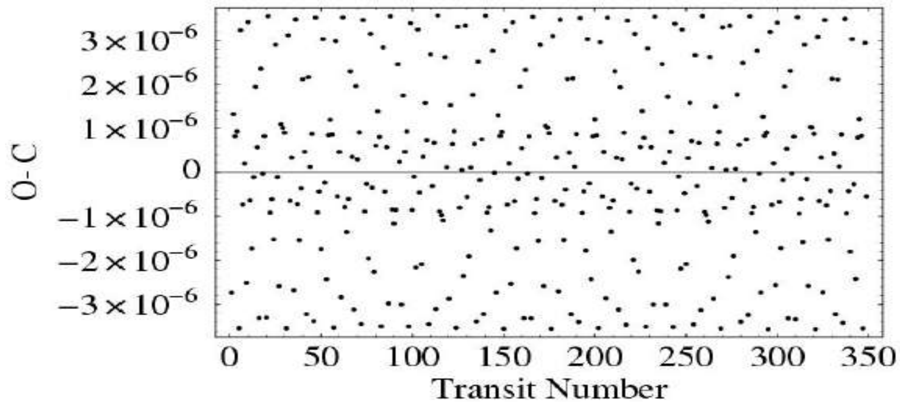
10s smallest error

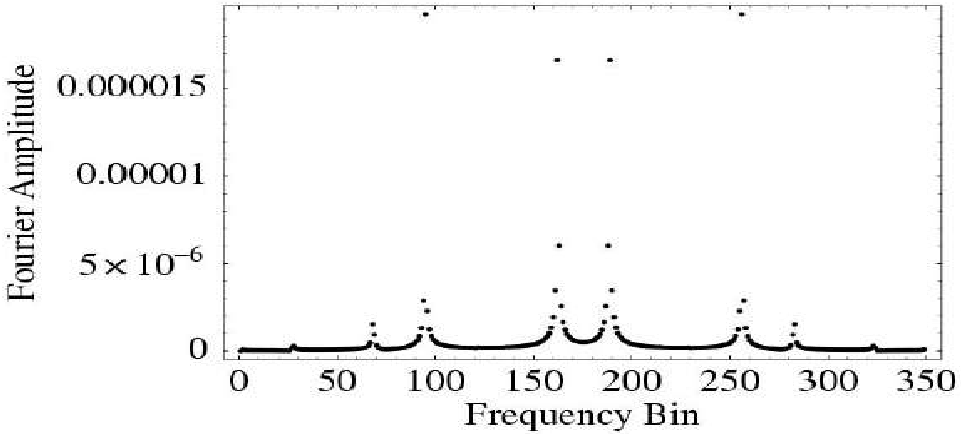
TrES-1 results from Steffen & Agol, MNRAS 364, L96 (2005)

Bonus Feature: Fourier Space

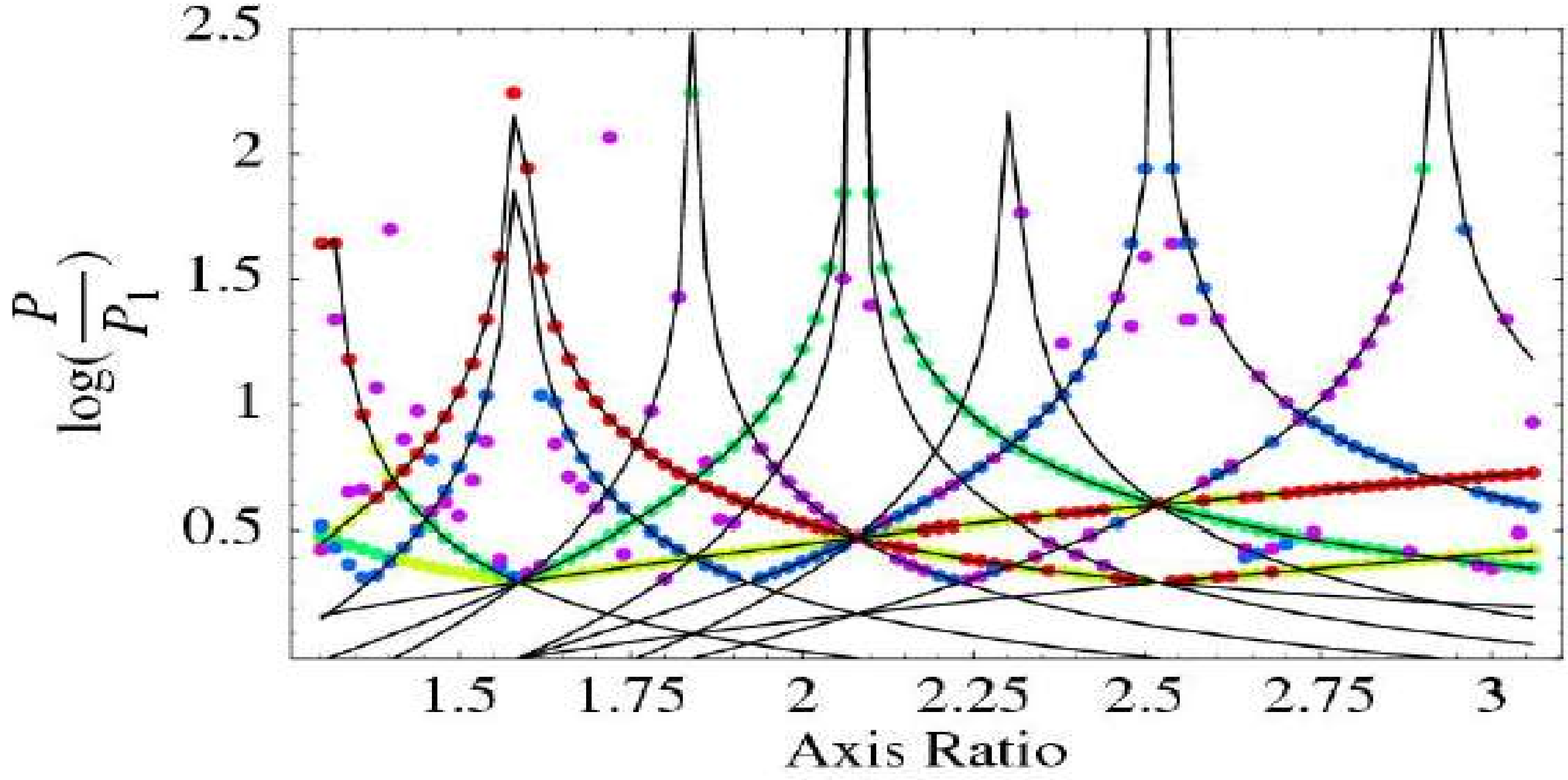








Bonus Feature: Fourier Space



$$\frac{P_{\rm peak}}{P_{\rm trans}} = \frac{P_{\rm pert}}{iP_{\rm trans} - jP_{\rm pert}}$$