

Exoplanet Science from NASA's Kepler Mission

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ASA Big Data Conference

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Outline

- Kepler mission overview
- Kepler's data
- From candidates to planets
- Exoplanet science with Kepler
- Kepler's future

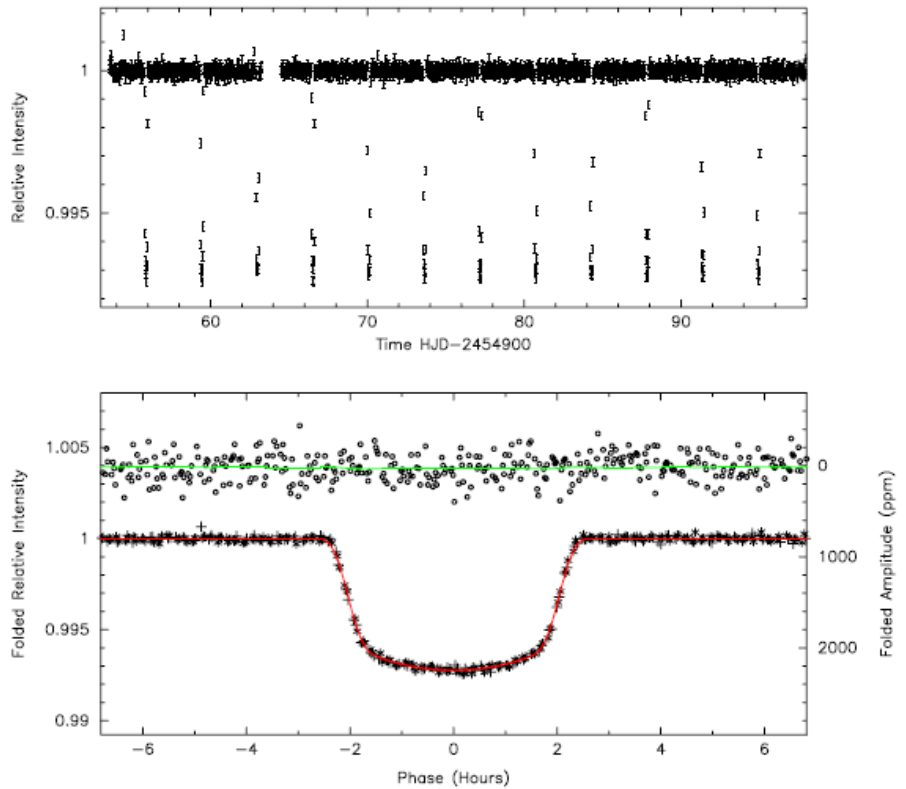
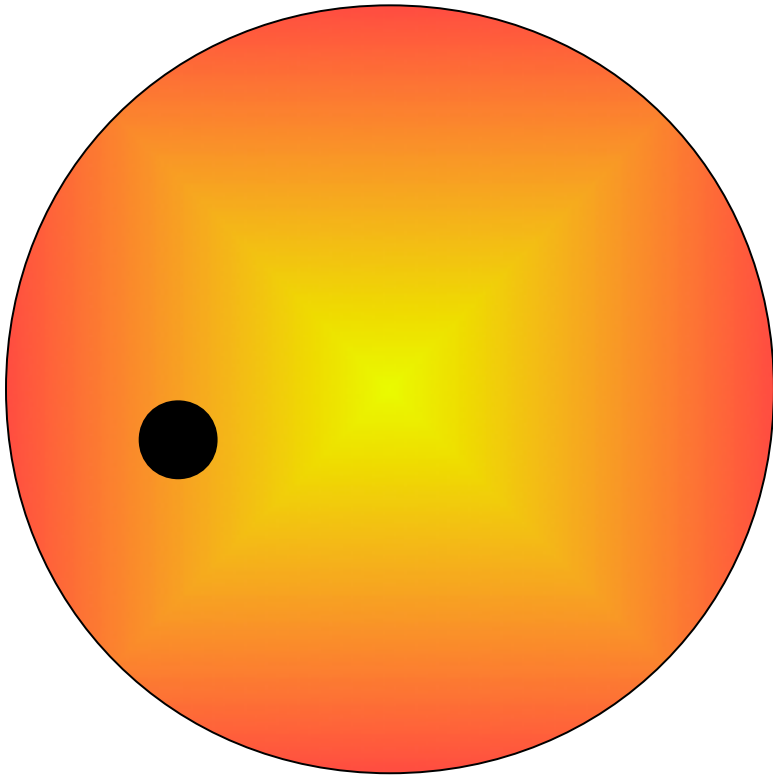
Kepler Mission Goals



- 1) Determine the frequency of terrestrial and larger planets in or near the habitable zone of a wide variety of spectral types of stars.
- 2) Etc.

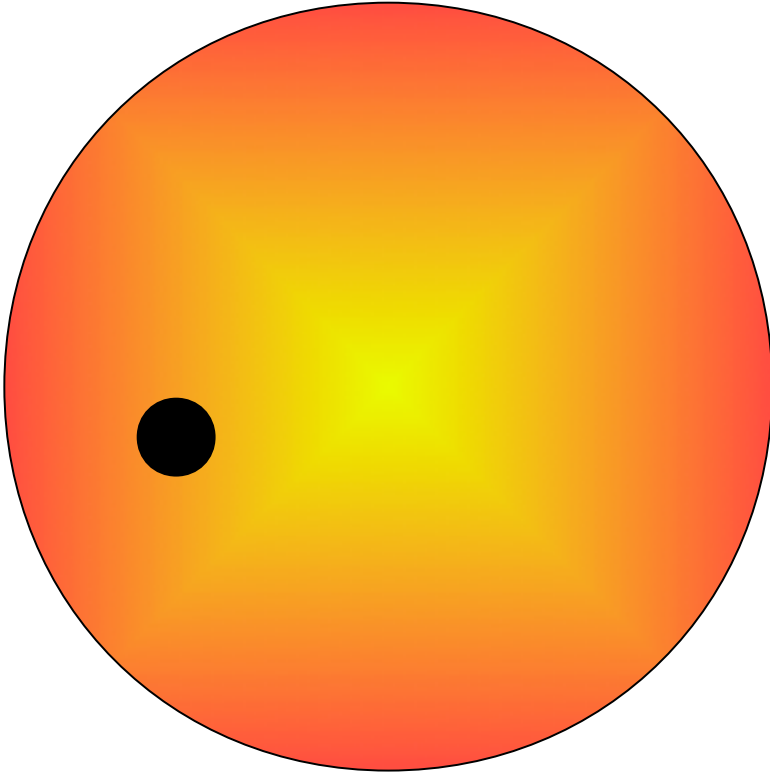
Planet Finding Methods

Planetary Transits

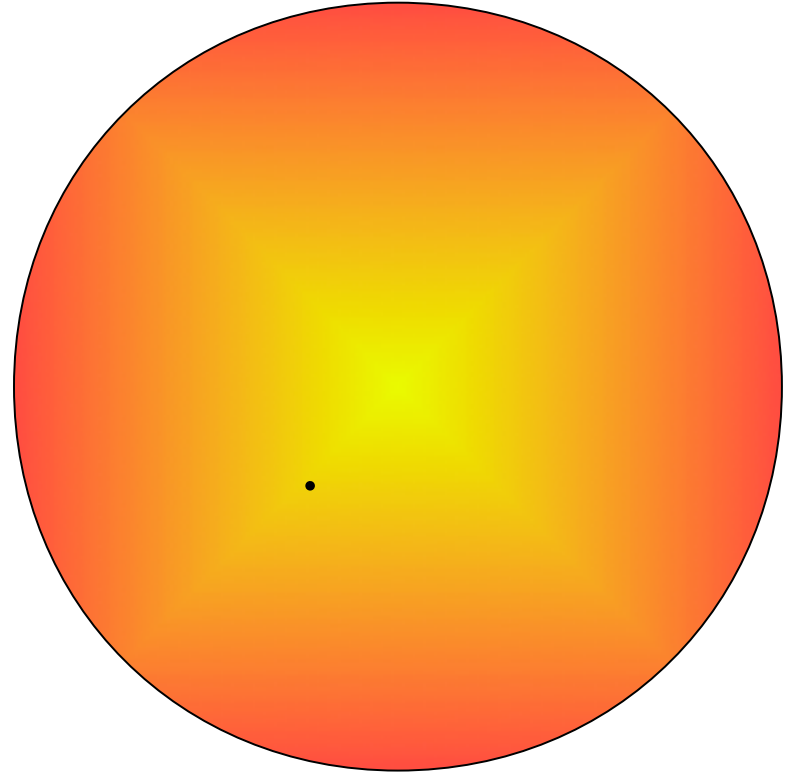


Planet Finding Methods

Planetary Transits



Jupiter: 1 part per 1000



Earth: 1 part per 100,000

From one “Goldilocks” to Another

1) Spacecraft Size:

- Too large → over budget
- Too small → not enough precision

2) Target List:

- Too few → statistical sample too small
- Too many → loss of data due to downlink time

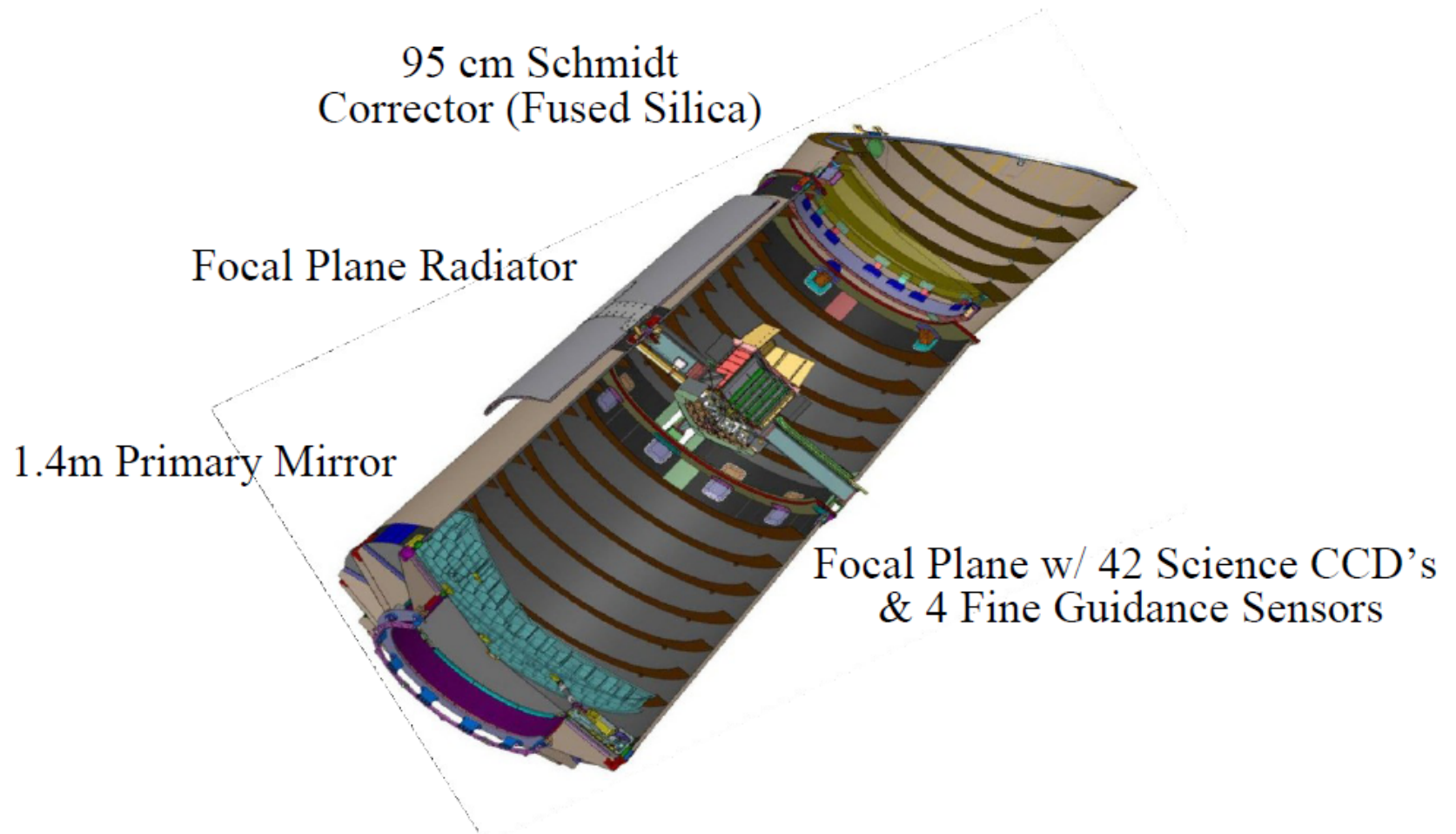
3) Field of View:

- Too dispersed → statistical sample too small
- Too crowded → confusion from background stars

4) Observing Cadence:

- Too fast → loss of data due to downlink time
- Too slow → planet transits are no longer visible

Kepler Spacecraft



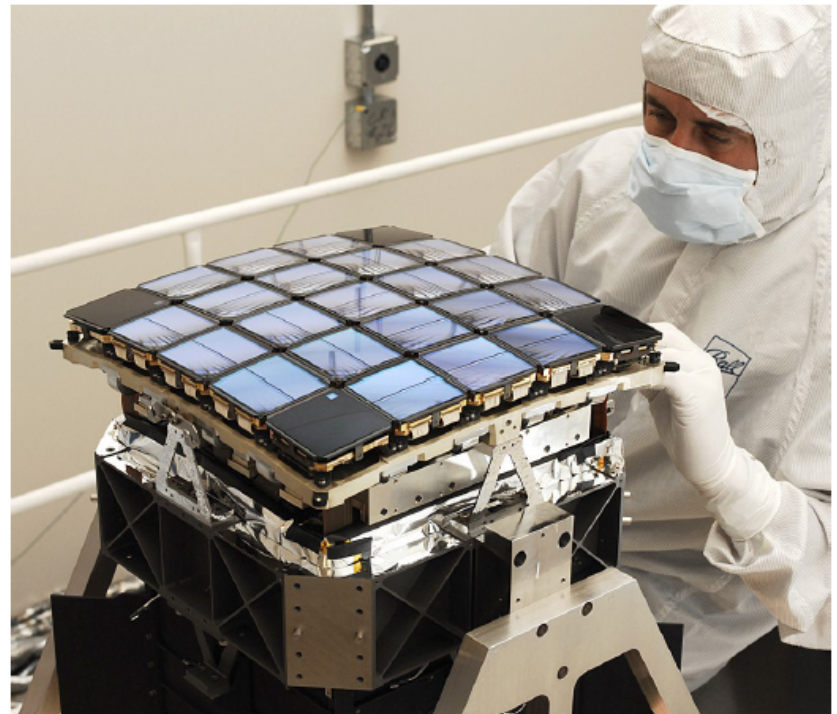
Kepler Photometer

50 micromagnitudes in 6 hours
30 minute cadence

Continuously monitor
~150,000 target stars

Images are de-focused

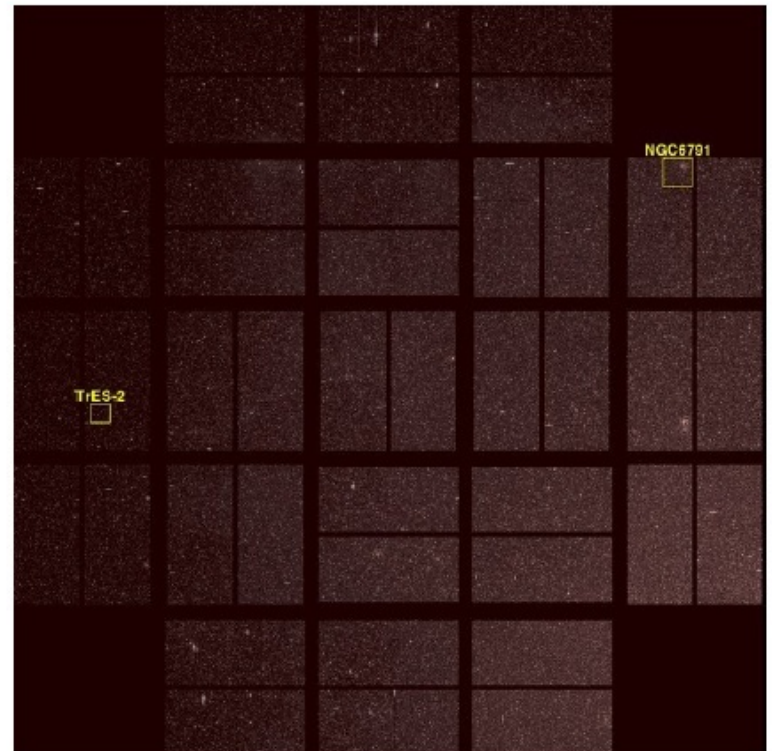
Only target pixels are
sent back to Earth



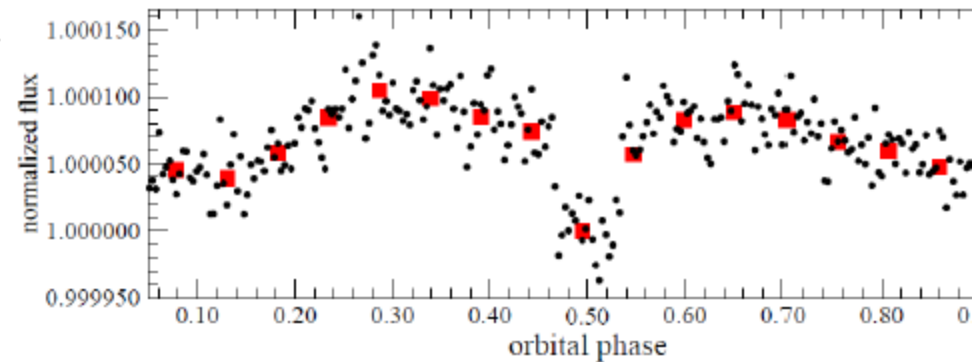
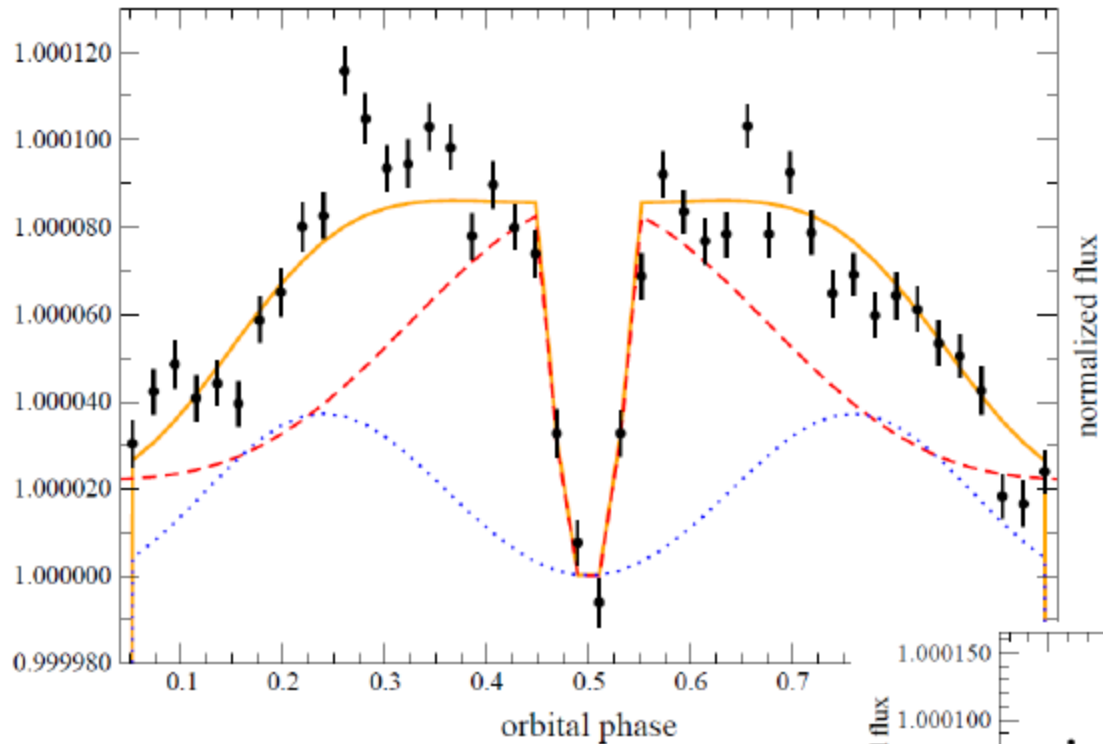
Kepler Field of View

~100 square degrees

First light image



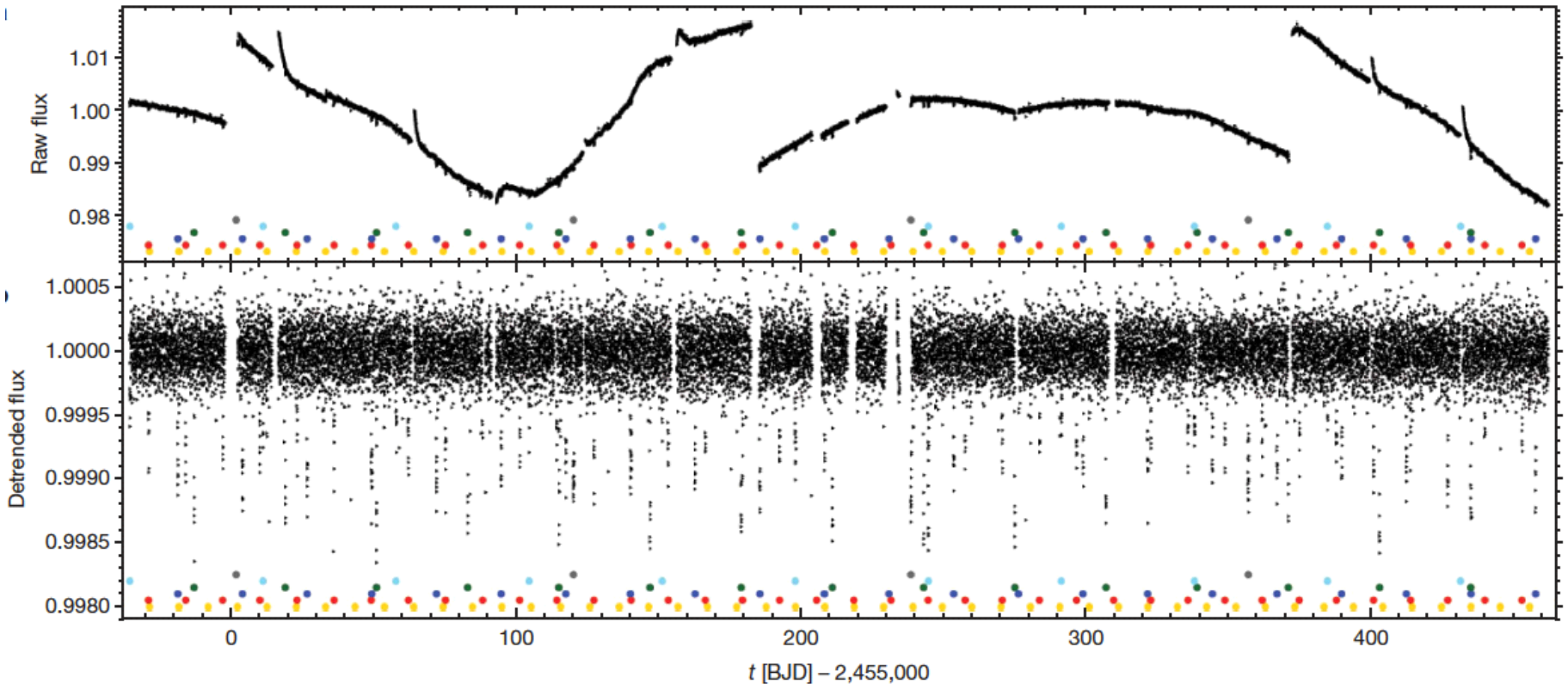
So, how good are these data?



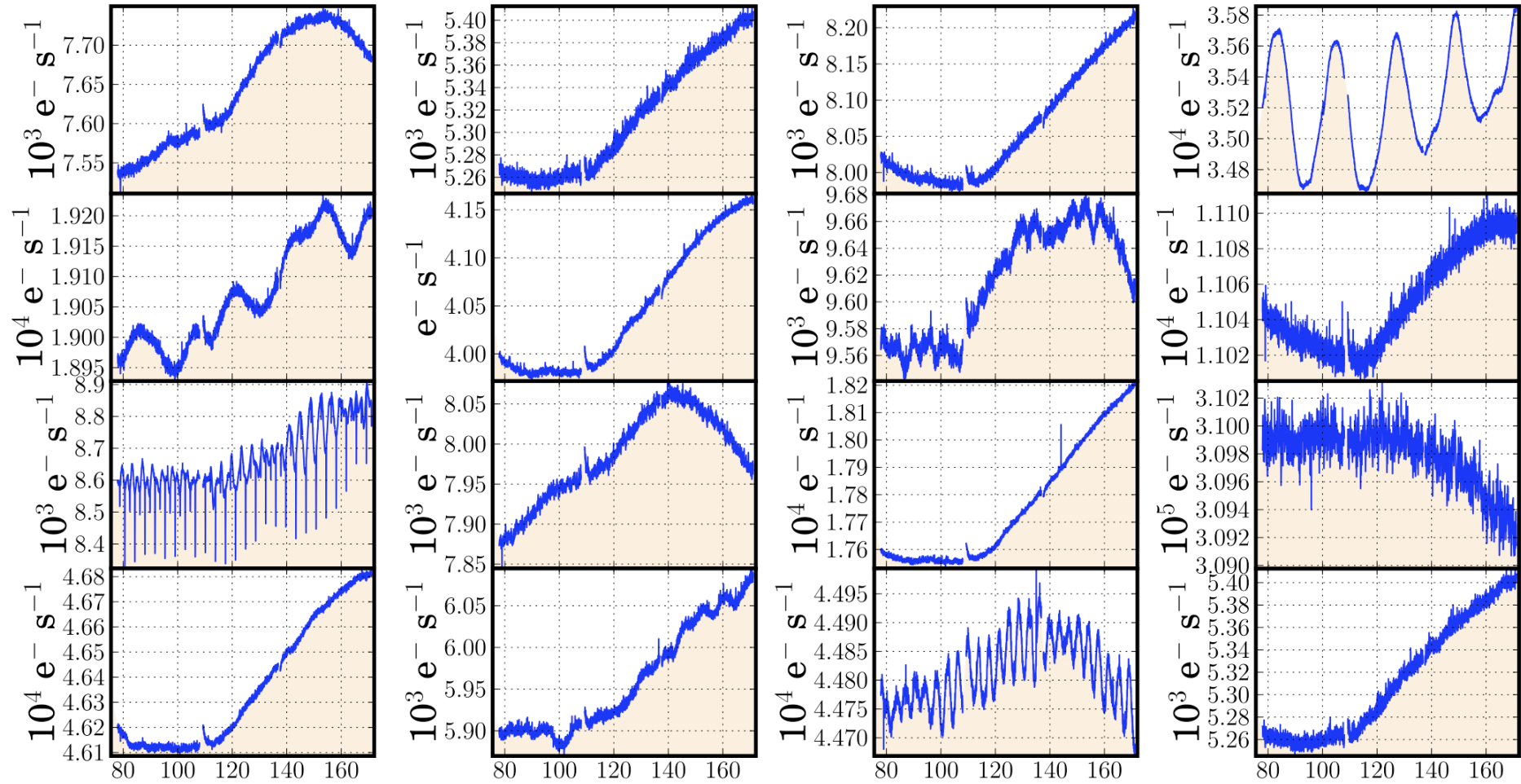
THE DISCOVERY OF ELLIPSOIDAL VARIATIONS IN THE *KEPLER* LIGHT CURVE OF HAT-P-7

WILLIAM F. WELSH, JEROME A. OROSZ

It's not all fun and games

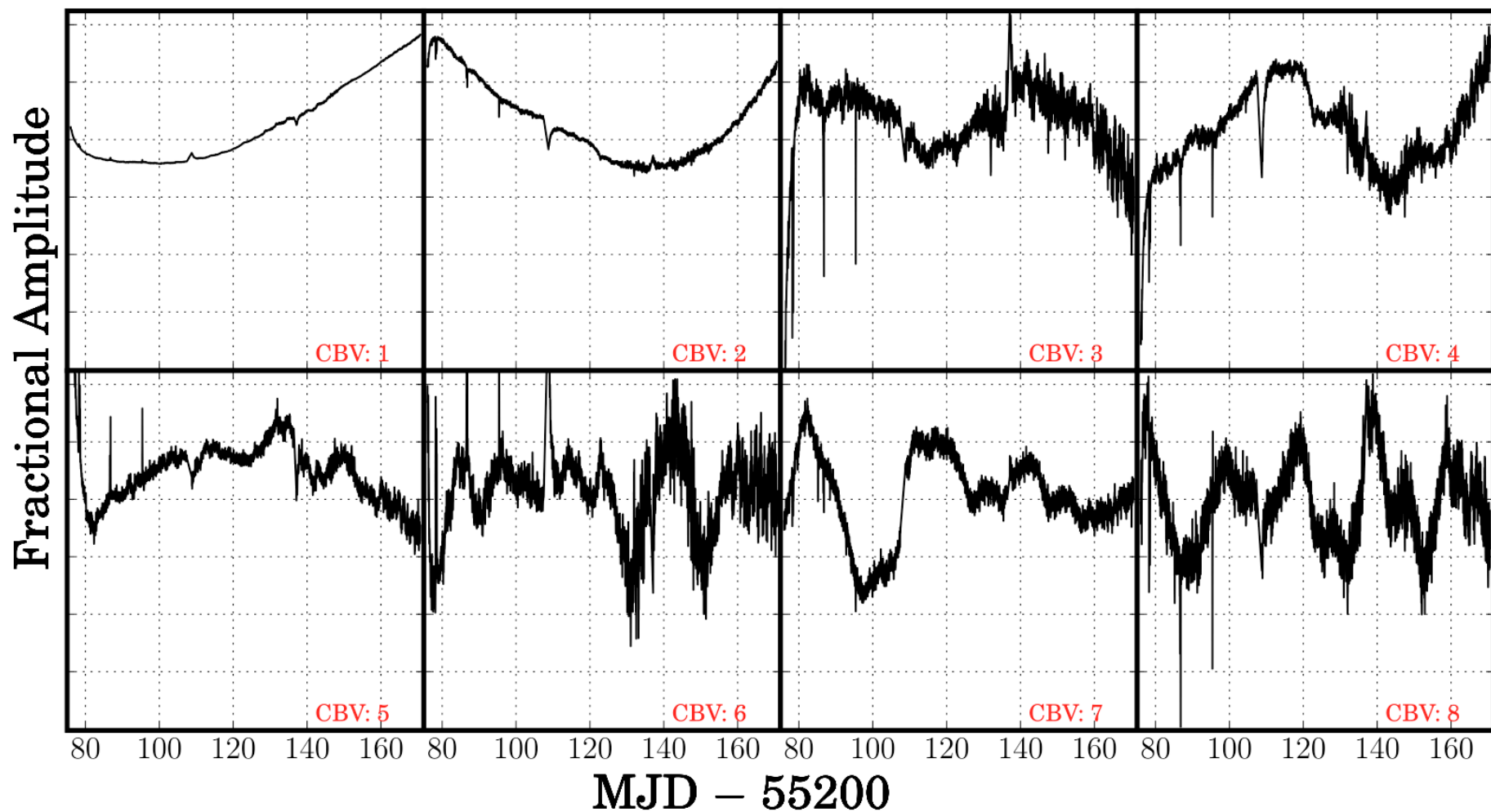


Raw Time Series

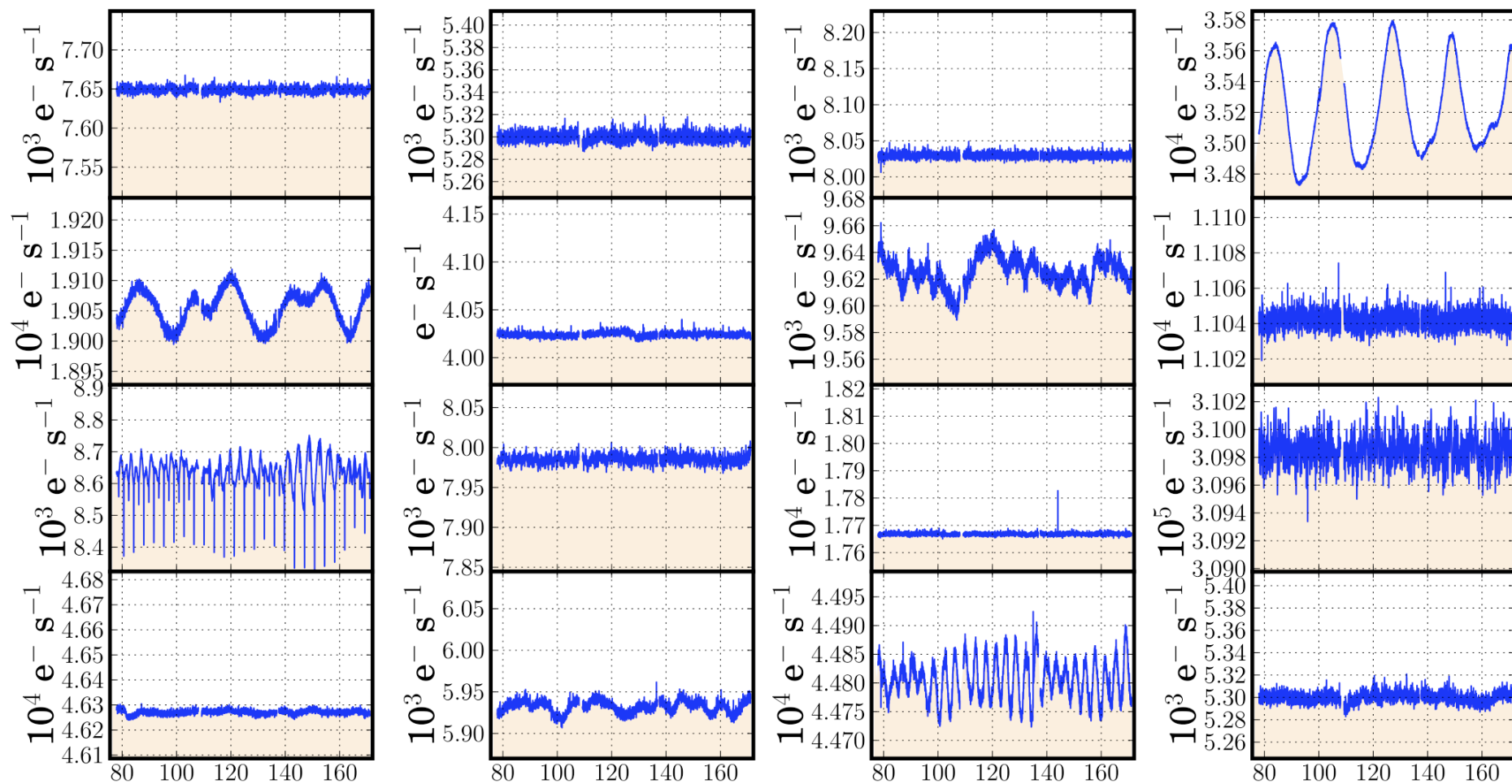


BJD - 2455200

Cotrending Basis Vectors

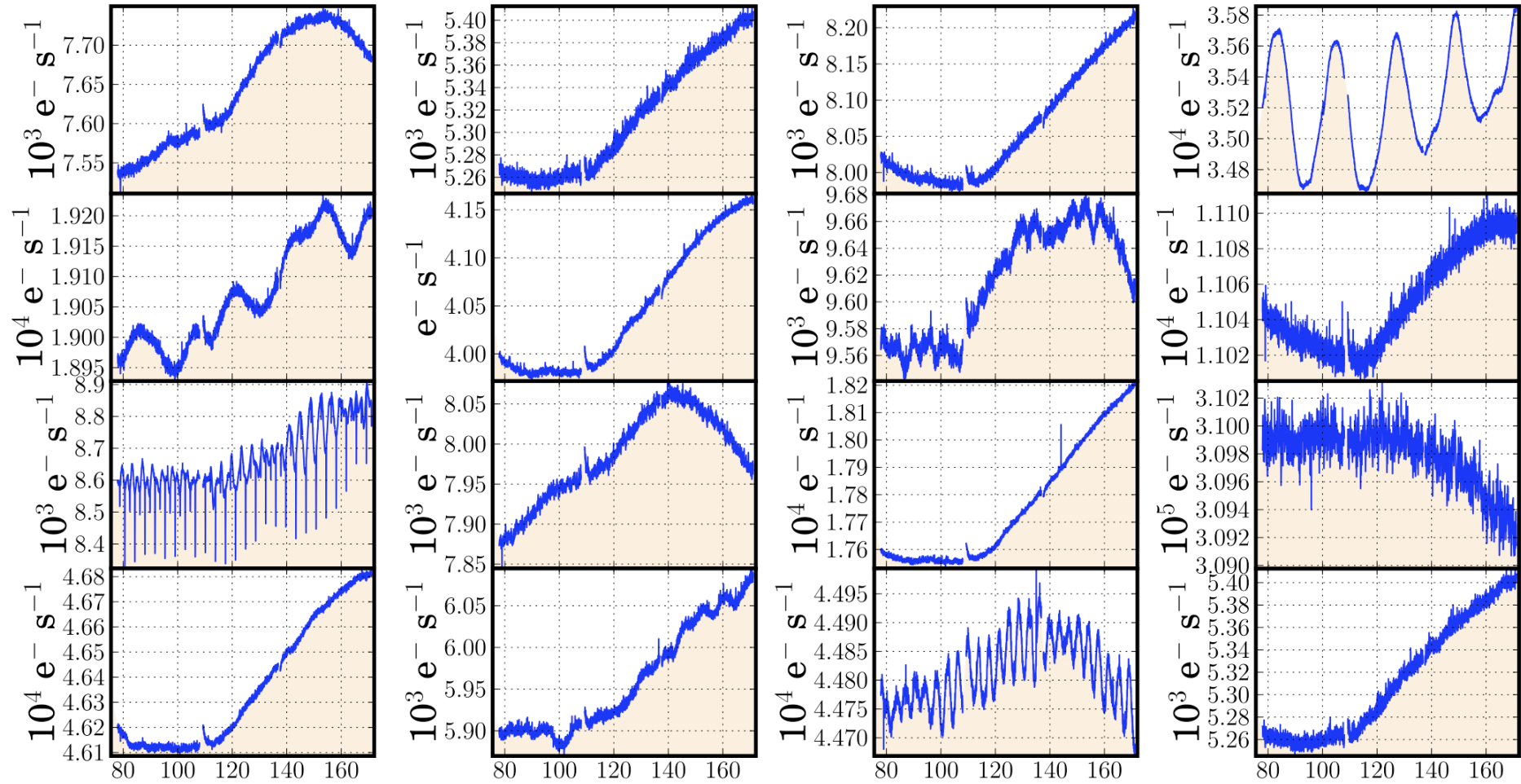


Corrected Time Series



BJD - 2455200

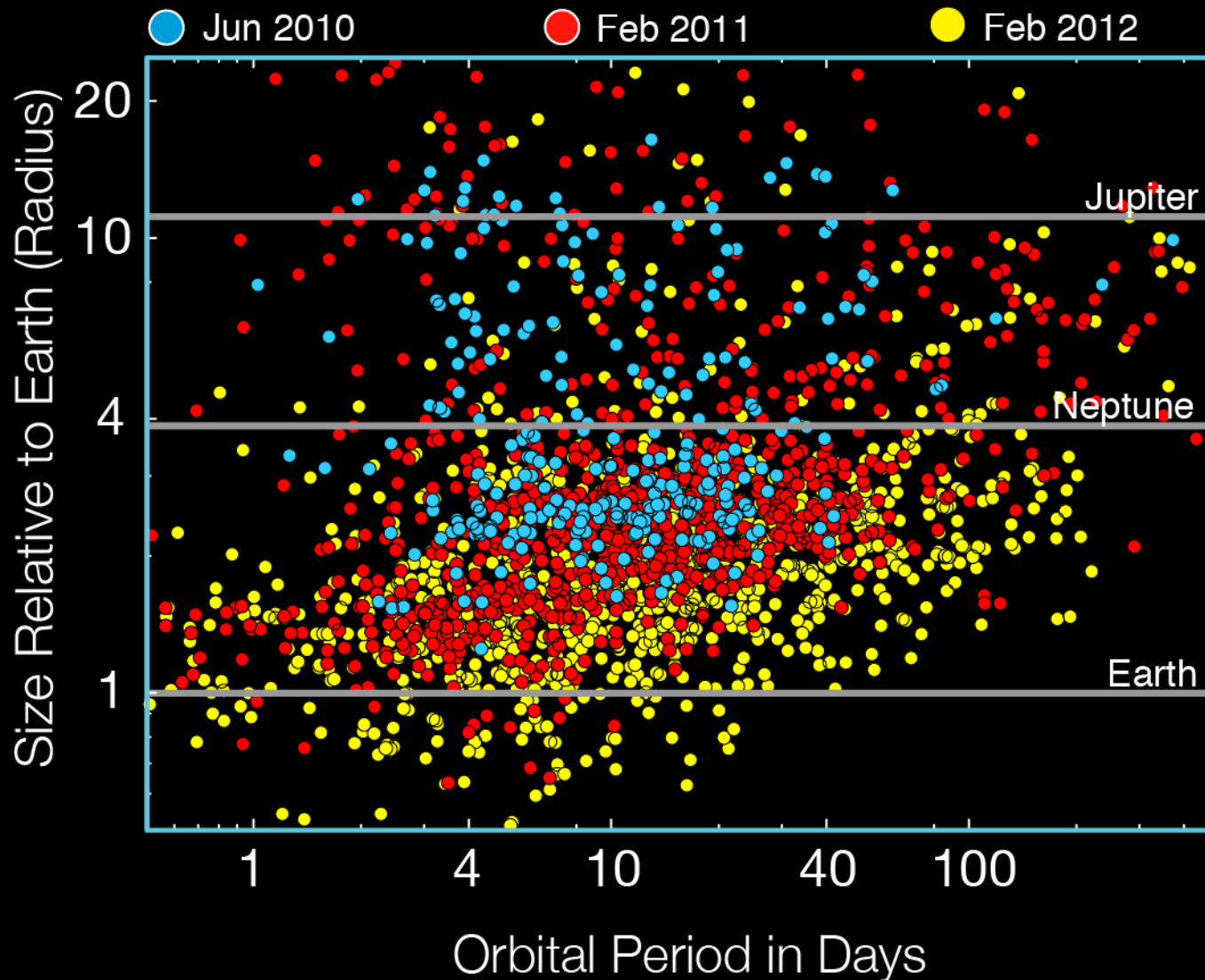
Raw Time Series



BJD - 2455200

Planet Candidates

As of February 27, 2012



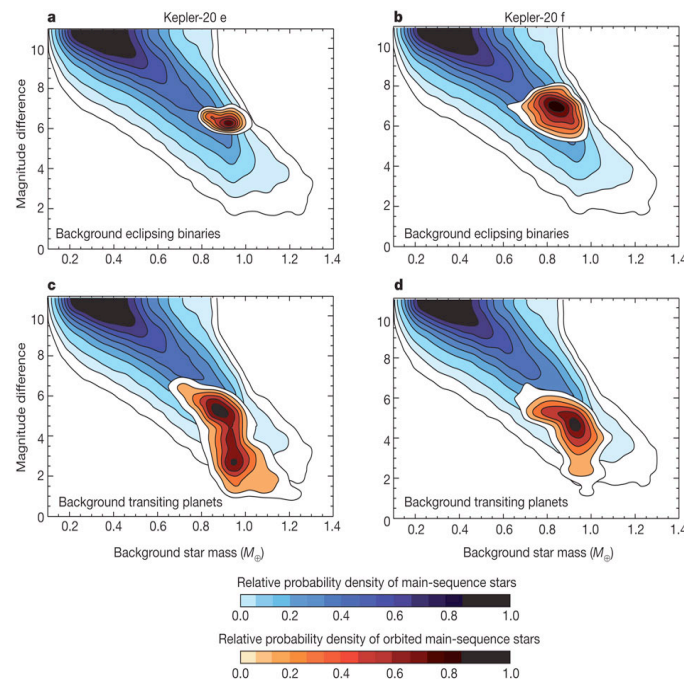
From Candidate to Planet

Validation: demonstrate the planet nature of a candidate
by eliminating alternative explanations

Confirmation: demonstrate the planet nature of a candidate
through a dynamical constraint on its mass

Planet Validation

The least massive planets do not produce large dynamical signals.

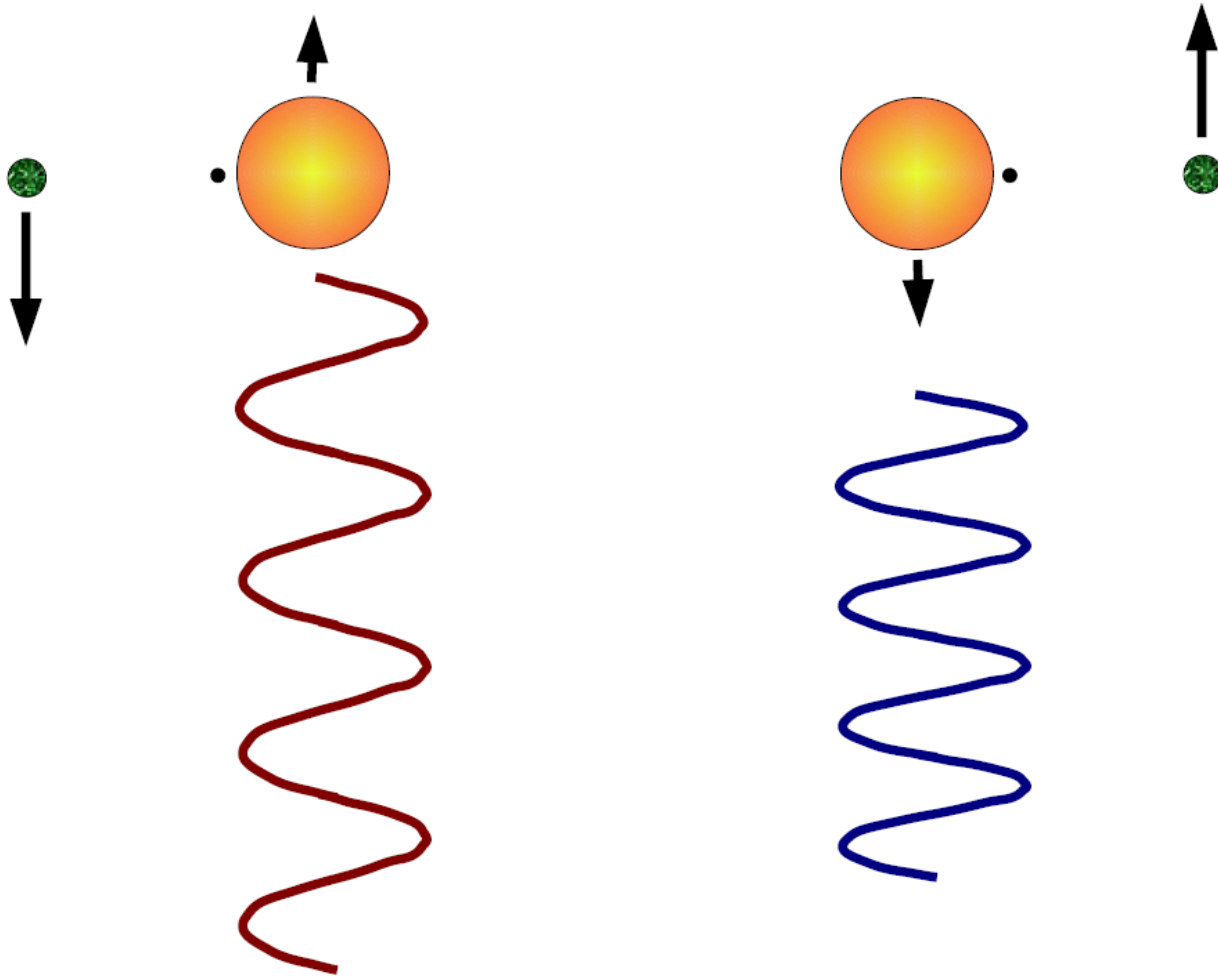


Alternative explanations, such as background eclipsing binaries, or background transiting planet, must be eliminated.

The smallest planets that Kepler discovers will use this approach.

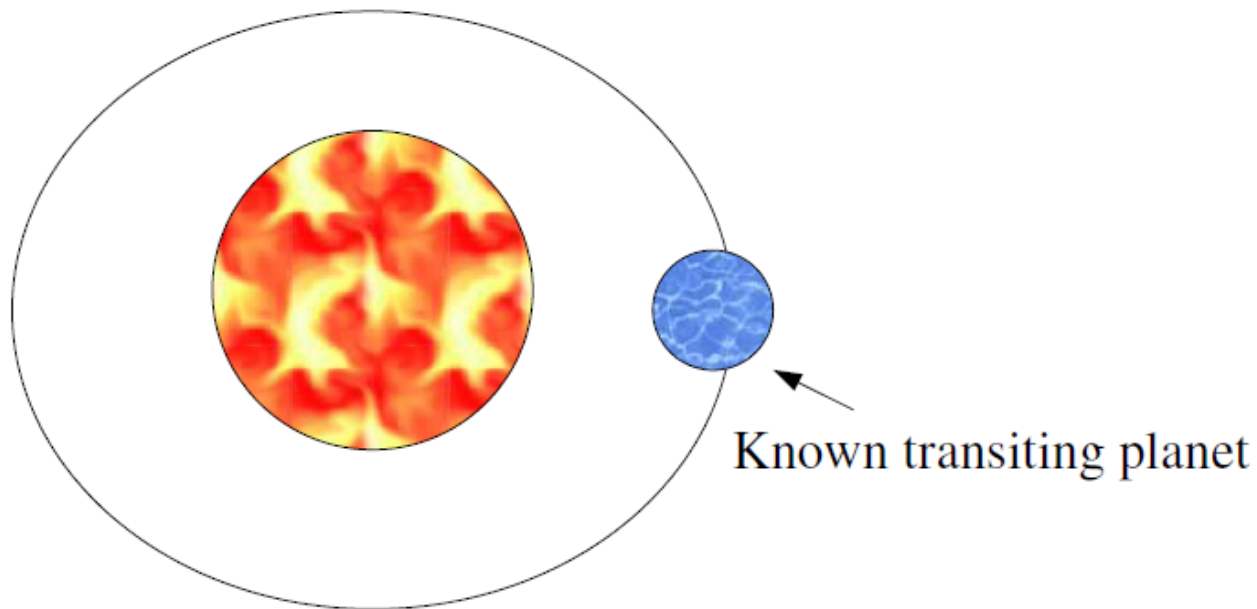
Planet Confirmation

Radial Velocity



Planet Confirmation

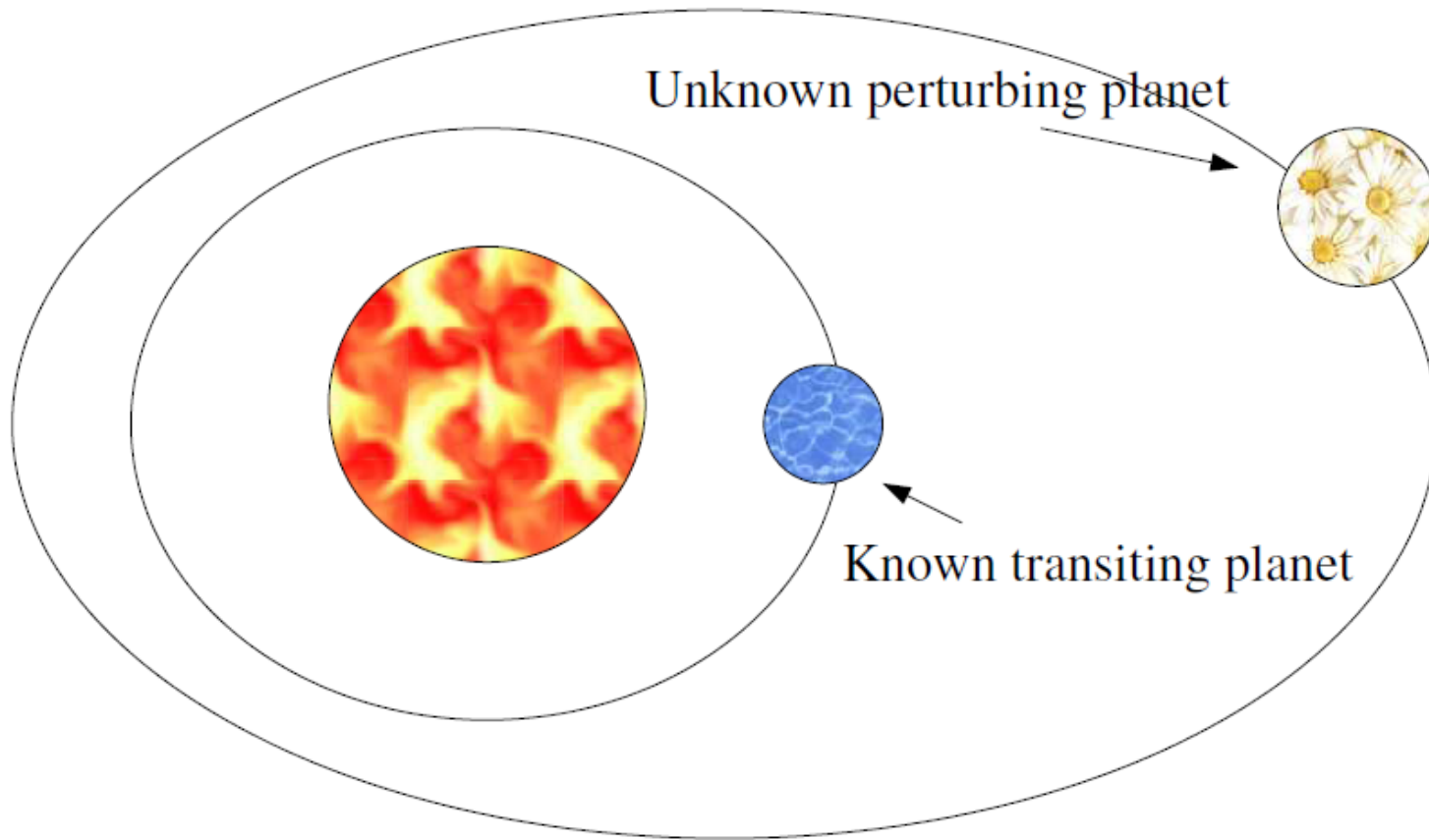
Transit Timing Variations



Transit times are equally spaced.

Planet Confirmation

Transit Timing Variations



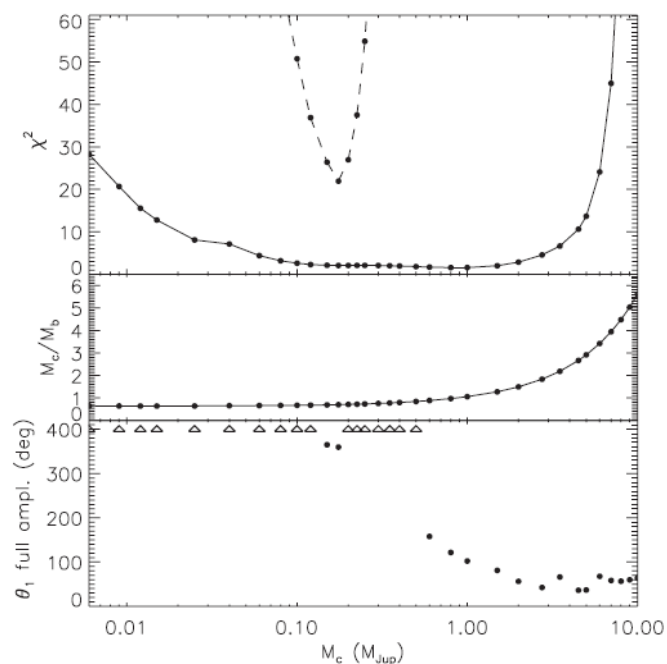
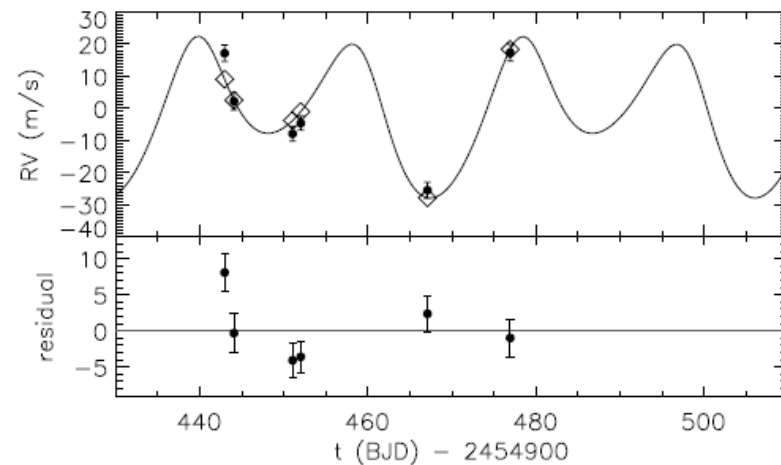
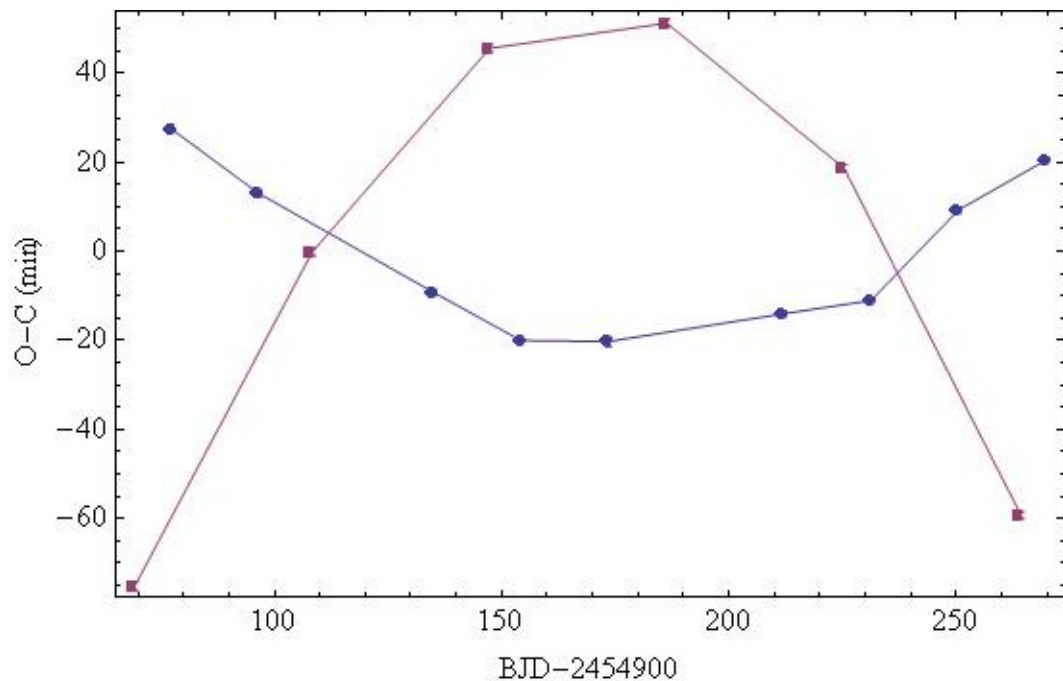
Transit times are NOT equally spaced.

Kepler 9



Holman et al. 2010

A first definitive TTV detection, Kepler 9

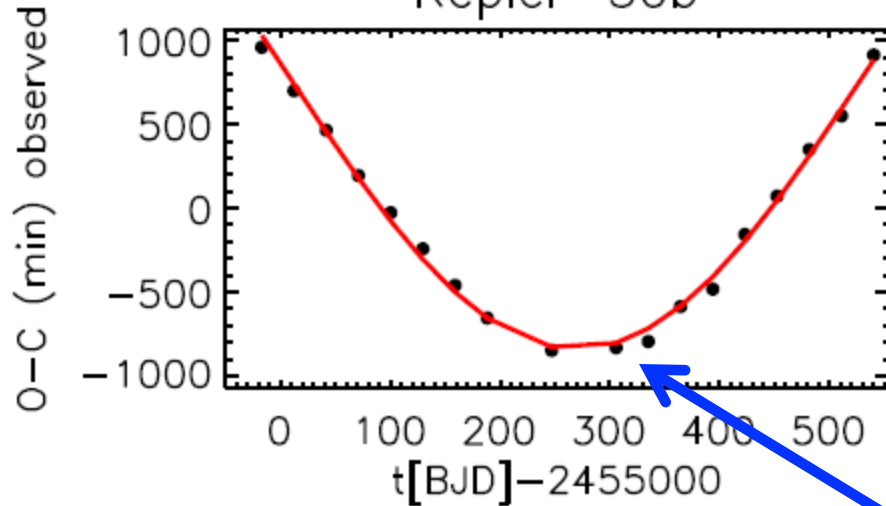


Kepler-9: A System of Multiple Planets Transiting a Sun-Like Star, Confirmed by Timing Variations

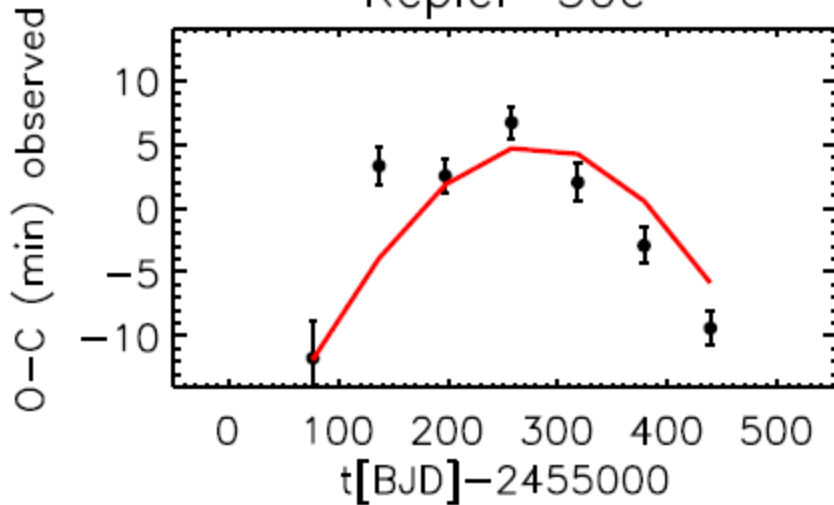
Matthew J. Holman,^{1*} Daniel C. Fabrycky,¹ Darin Ragozzine,¹ Eric B. Ford,² Jason H. Steffen,³ William F. Welsh,⁴ Jack J. Lissauer,^{5,6} David W. Latham,¹ Geoffrey W. Marcy,⁷ Lucianne M. Walkowicz,⁷ Natalie M. Batalha,⁸ Jon M. Jenkins,⁹ Jason F. Rowe,^{5,20} William D. Cochran,¹⁰ Francois Fressin,¹ Guillermo Torres,¹ Lars A. Buchhave,^{1,11} Dimitar D. Sasselov,¹ William J. Borucki,⁵ David G. Koch,⁵ Gibor Basri,⁷ Timothy M. Brown,^{13,21} Douglas A. Caldwell,^{5,9} David Charbonneau,¹ Edward W. Dunham,¹⁴ Thomas N. Gautier III,¹⁵ John C. Geary,¹ Ronald L. Gilliland,¹⁶ Michael R. Haas,⁵ Steve B. Howell,¹⁷ David R. Ciardi,¹¹ Michael Endl,¹⁰ Debra Fischer,¹⁸ Gábor Fűrész,¹ Joel D. Hartman,¹ Howard Isaacson,⁷ John A. Johnson,¹⁹ Phillip J. MacQueen,¹⁰ Althea V. Moorhead,² Robert C. Morehead,² Jerome A. Orosz⁴

Planet Confirmation with TTVs

Kepler-30b



Kepler-30c



Some systems show very large TTVs.

This is a problem if you are nominally looking for strictly periodic signals and need to stack multiple transits in order to detect a small planet.

Less Intensive Planet Confirmation

Criterion for planethood:

- an object has the mass of a planet

Less Intensive Planet Confirmation

Criterion for planethood:

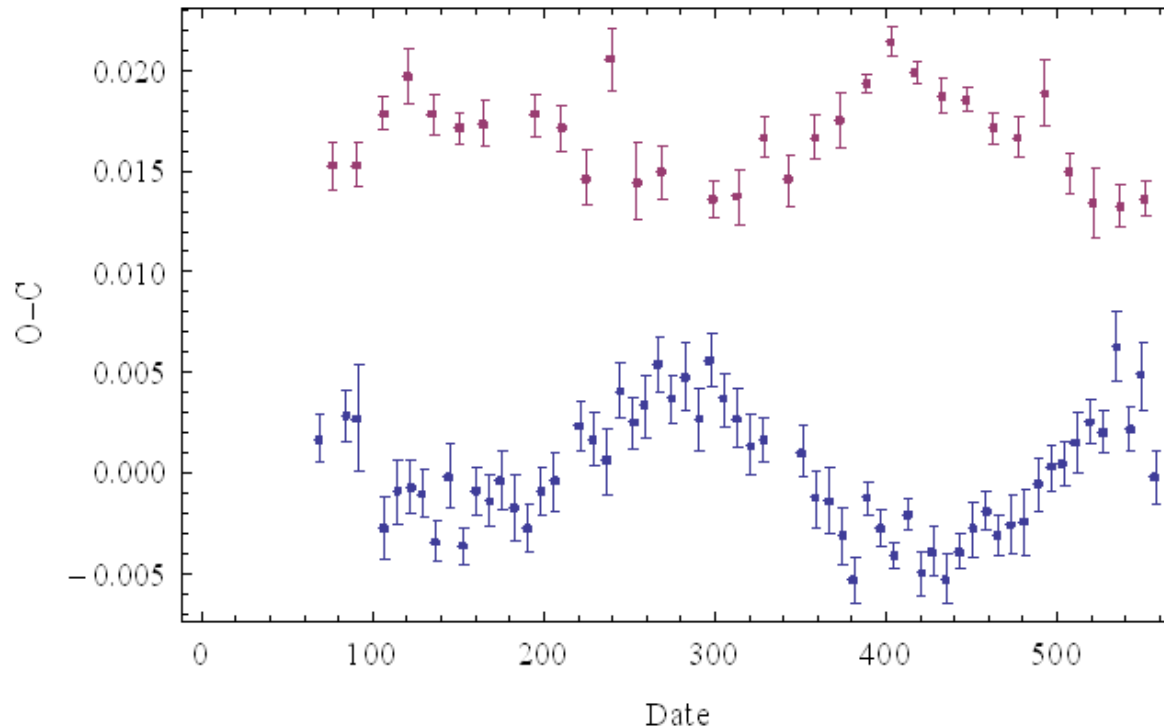
- an object has the mass of a planet

In a multitransiting system:

- use TTVs to show that two candidates are in the same system
- use dynamical stability to show that their masses are planetary

Kepler 18 (KOI 137)

Dynamical interactions within the system
cause changes in orbital period.



Anticorrelated TTVs expected from conservation laws.

Demonstrates with high confidence that this is a single system.
(This is a sufficient criterion, but not necessary.)

Kepler 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33



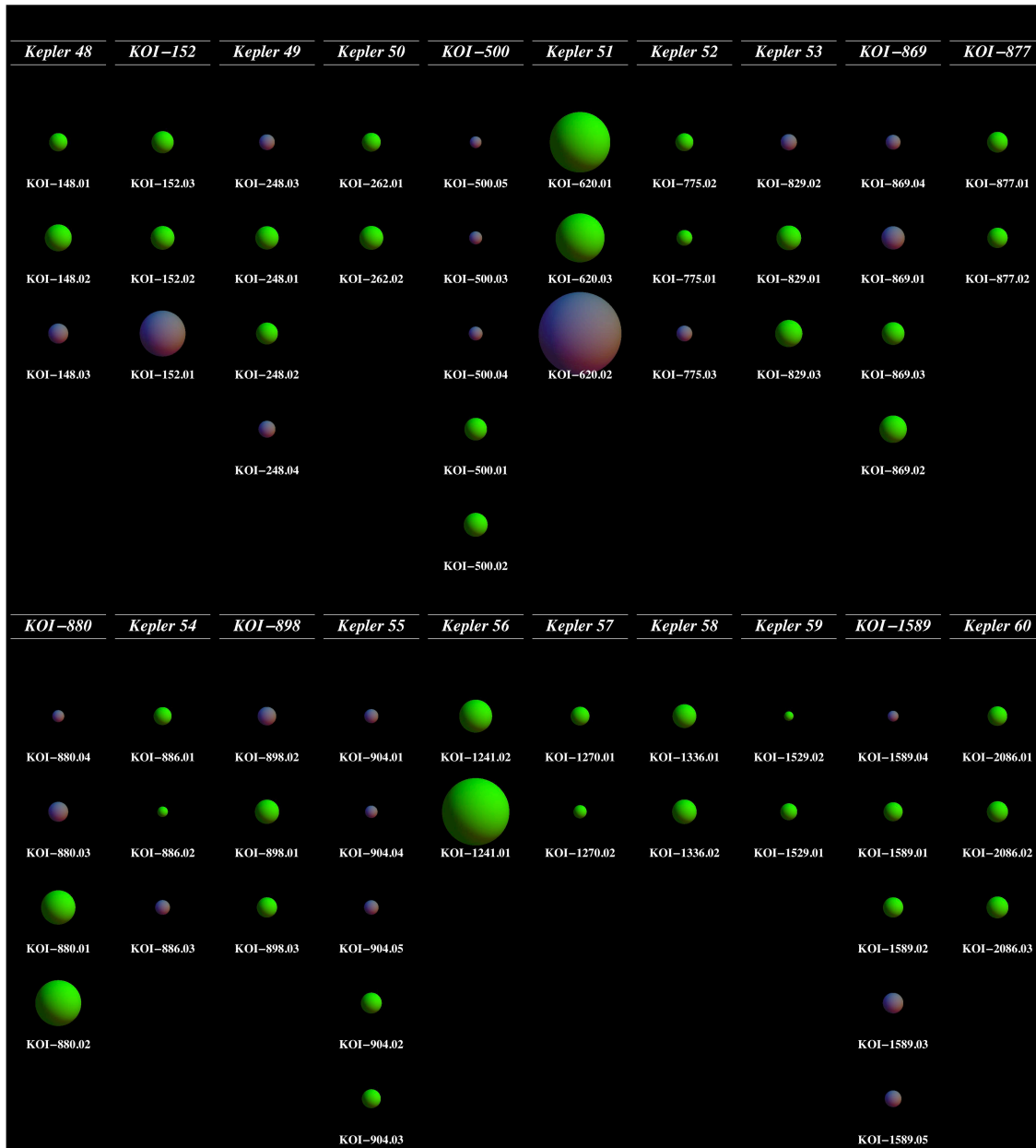
Blue: Solar System

Red: Known planets in multi-transiting systems

Gray: KOIs in multi-transiting systems

Green: Newly confirmed planets

Kepler 48 — Kepler 60 (and a few others)



Two independent papers confirm 41 planets in 20 multiplanet systems.

Steffen et al. (2012e)

Xie (2012)

Exoplanet Science

Kepler 36

Large TTVs required the development of a new search algorithm.

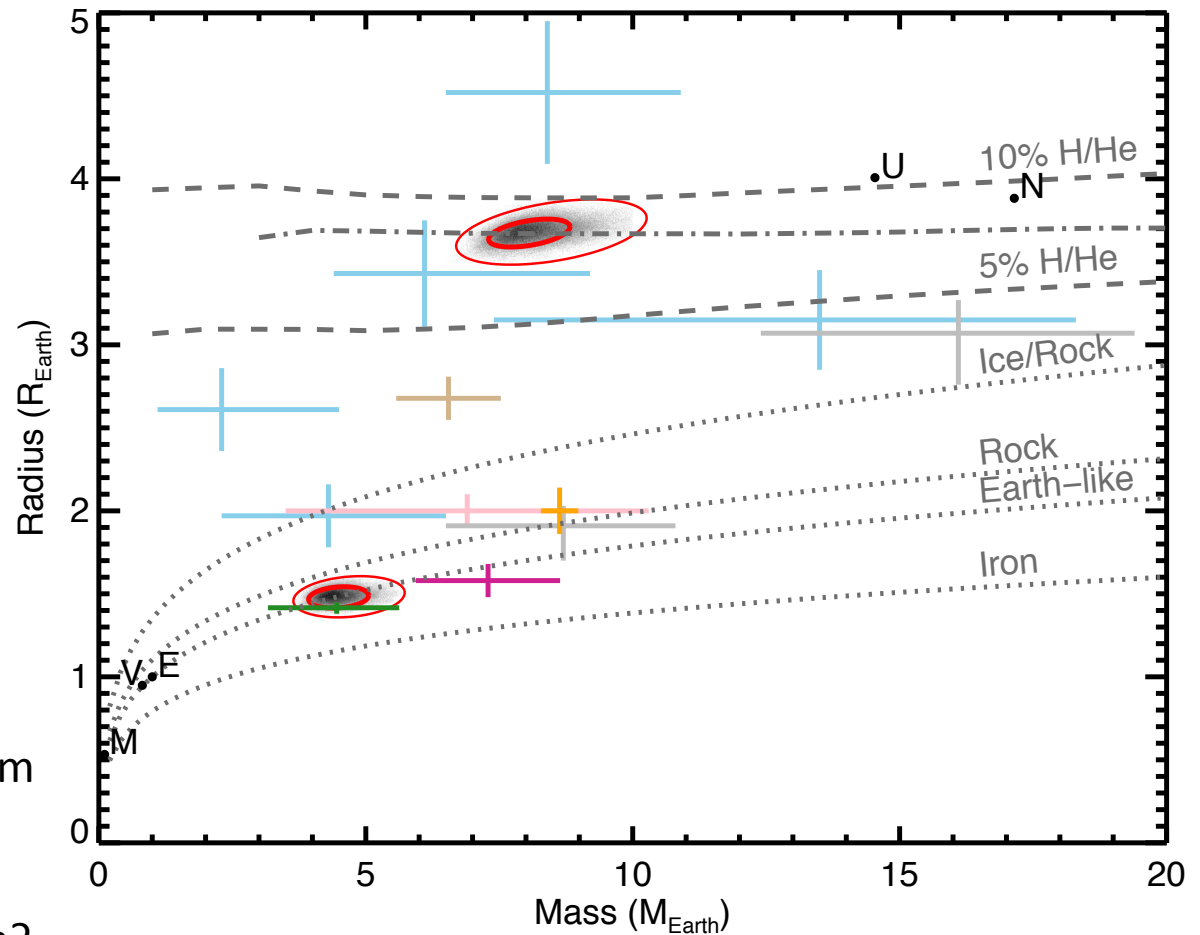
These two planets are very near the 7:6 mean-motion resonance—their orbital distances are 10% different.

Their densities differ by nearly a factor of 10.

Deck et al (2012) showed that this system undergoes short-term dynamical chaos.

How do you make such a system?

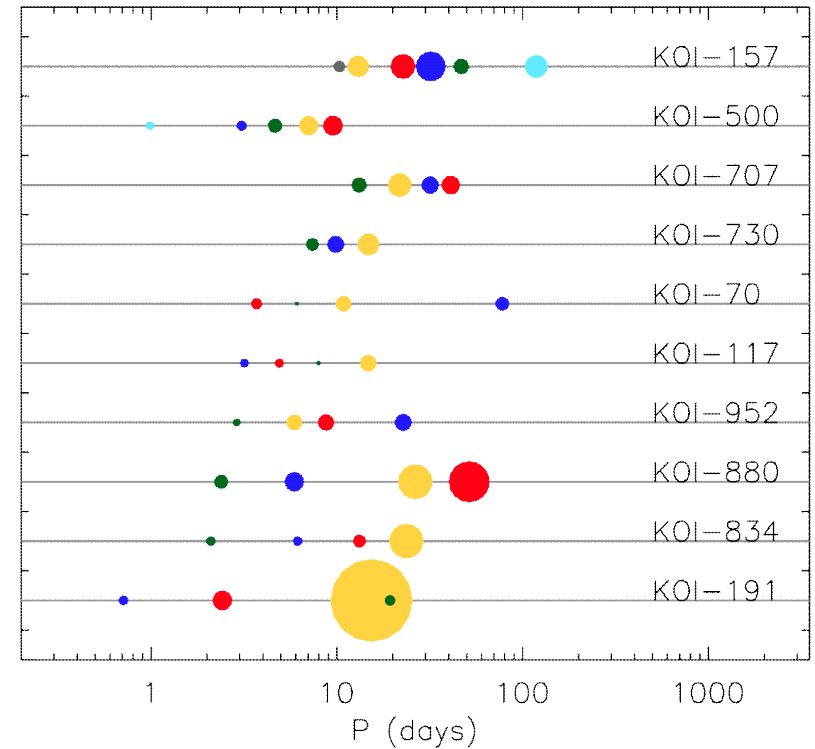
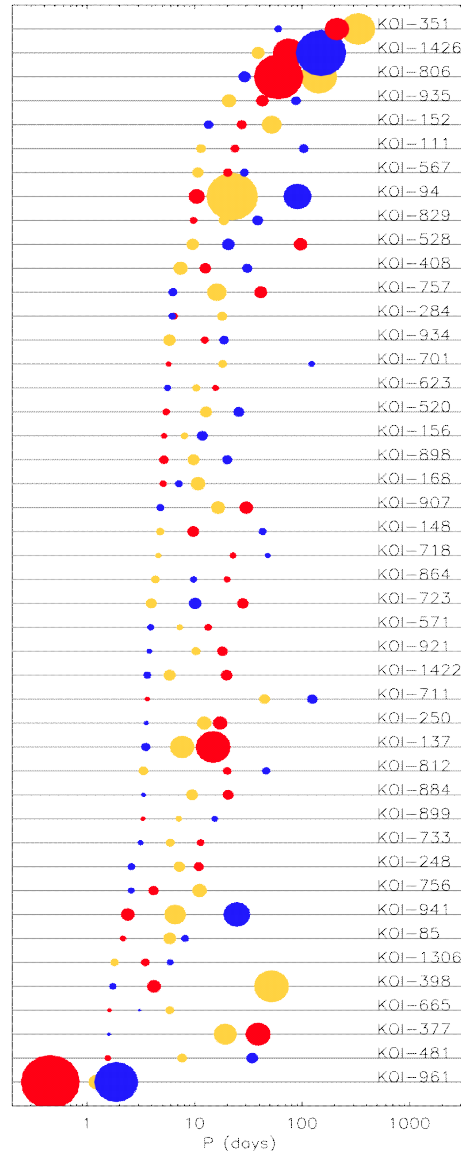
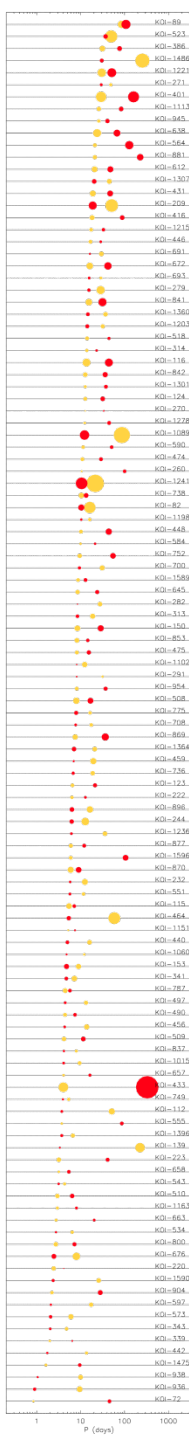
Good question.



Kepler 36

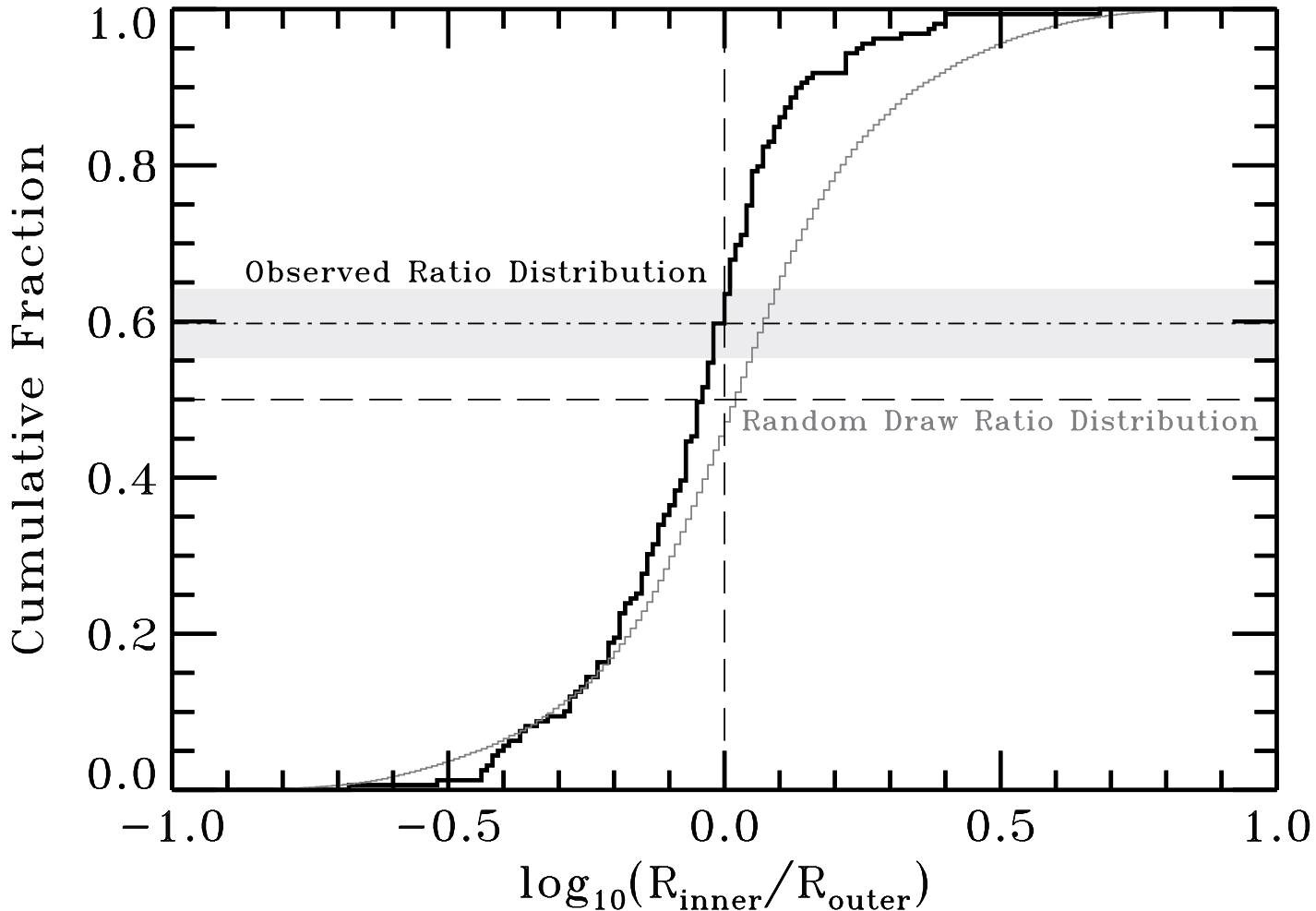


Multiple Candidate Systems



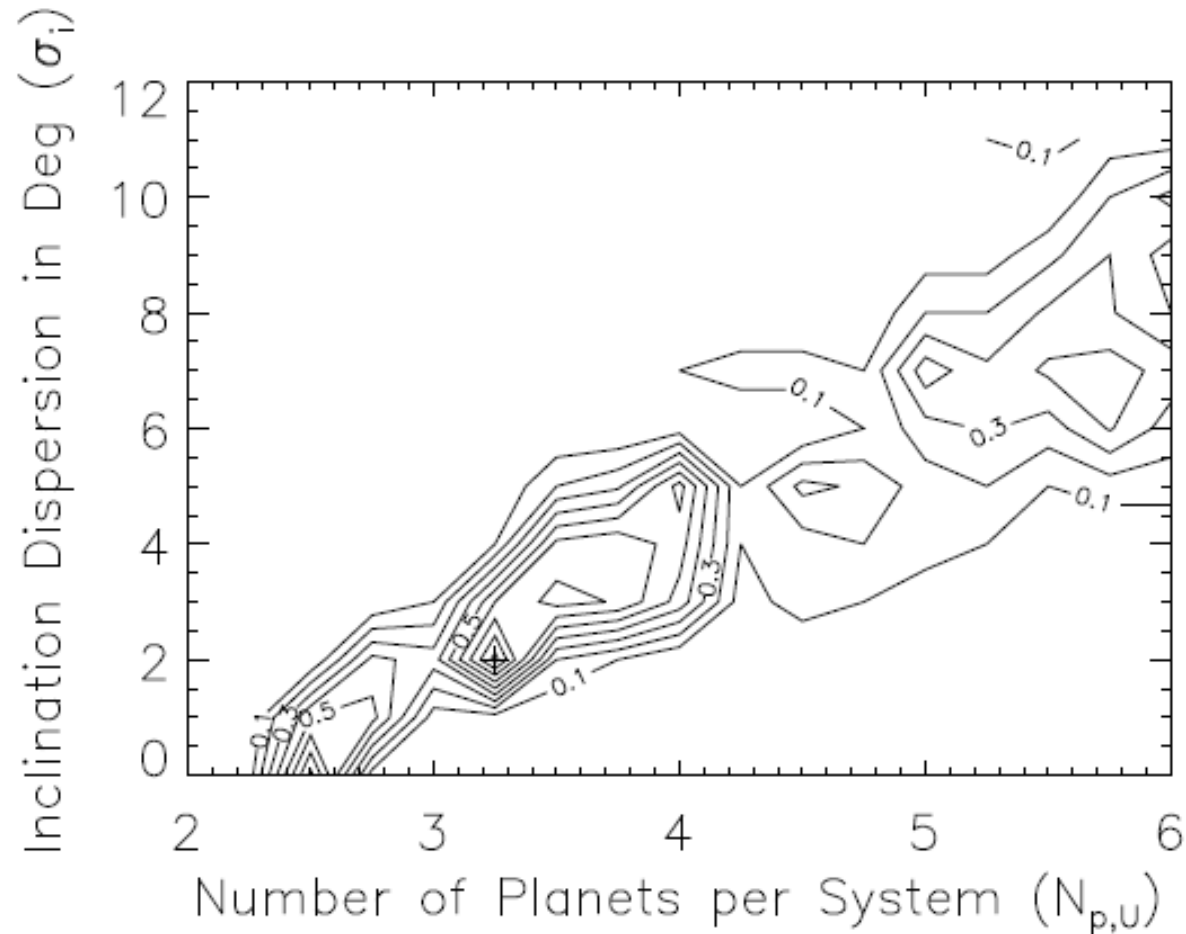
Lissauer et al. (2011)

Candidate Radius Comparison



CDF of candidate radius ratio (outer/inner) – Jupiter/Saturn is 0.08, Venus/Earth is -0.02.
(Ciardi et al. 2013)

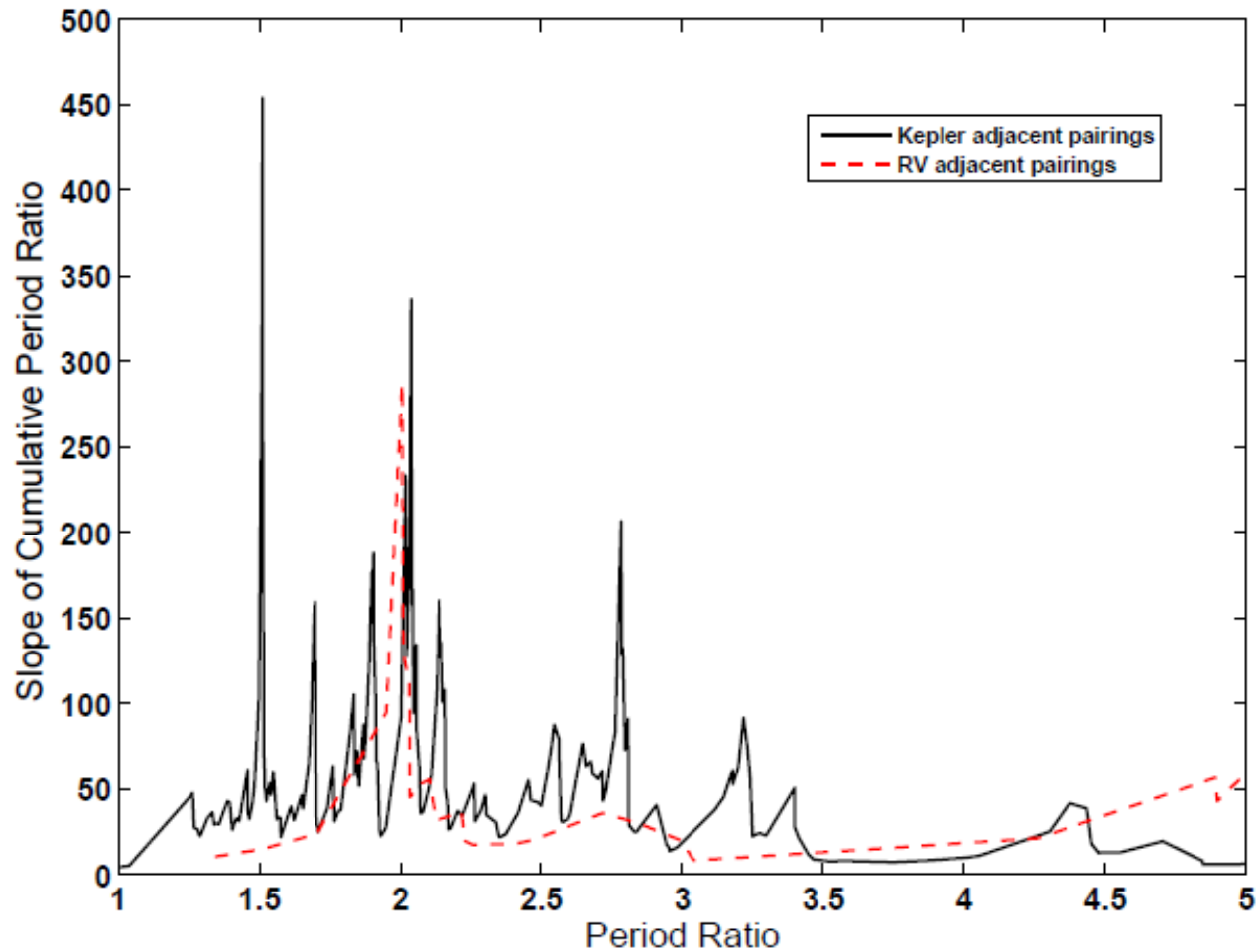
Inclination Distribution



Probability for Kepler to find the candidate population vs inclination and number of planets

(Solar system ~ 1.5 degrees)

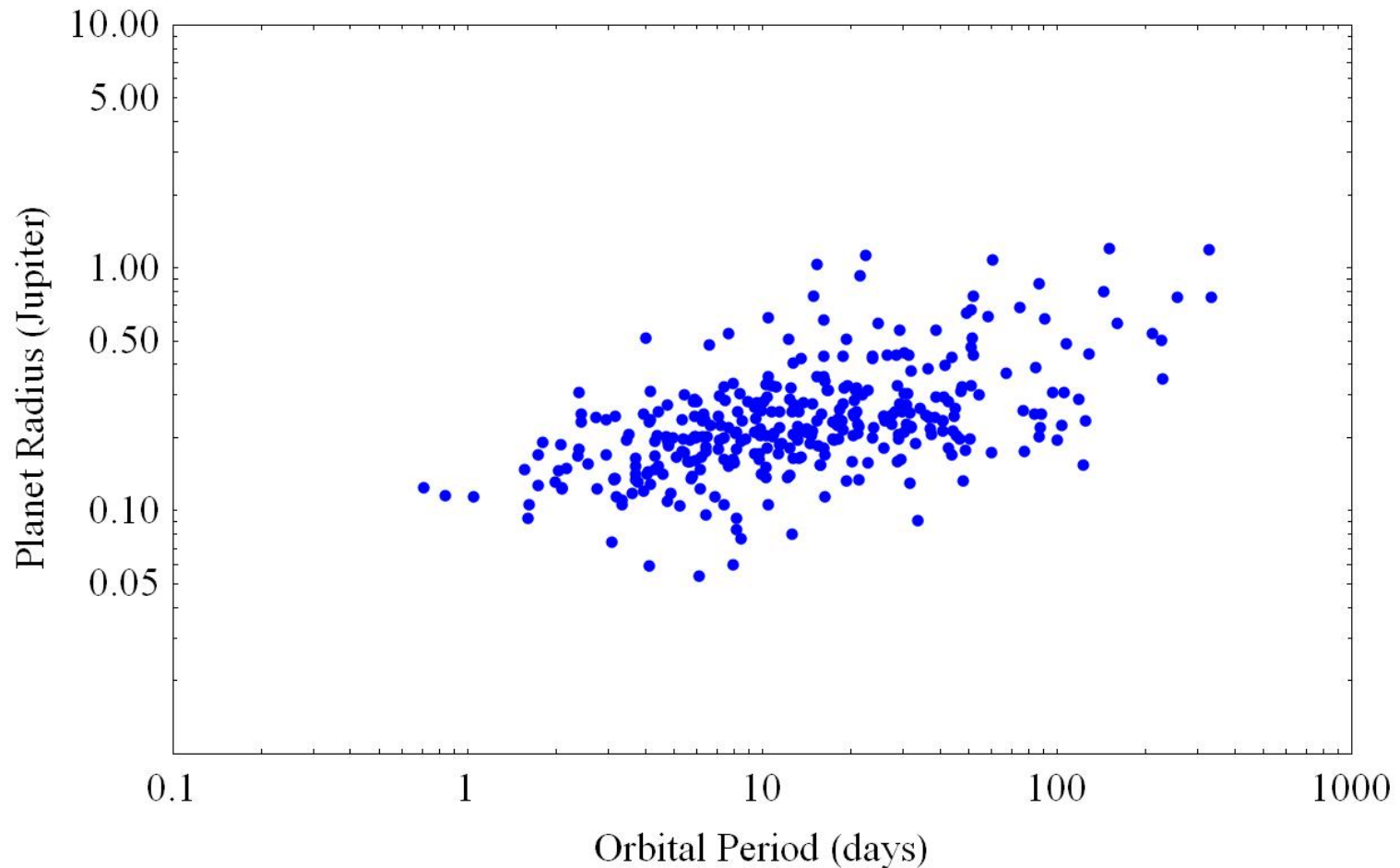
Resonance Proximity



Slope of the CDF in period ratio averaged over four adjacent candidates.

Different planet populations

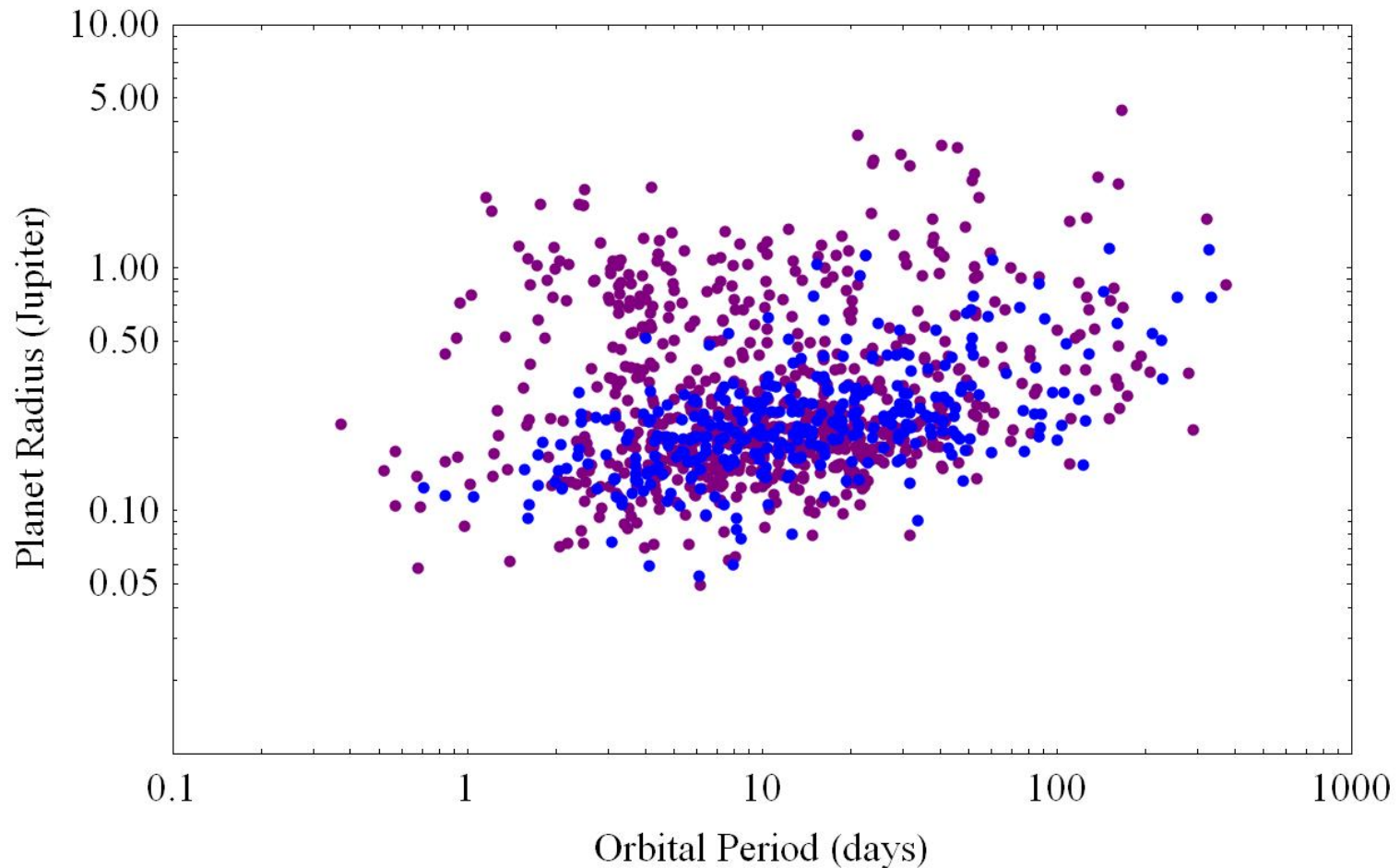
Multiple Candidate Systems



Teff > 4600K only

Different planet populations

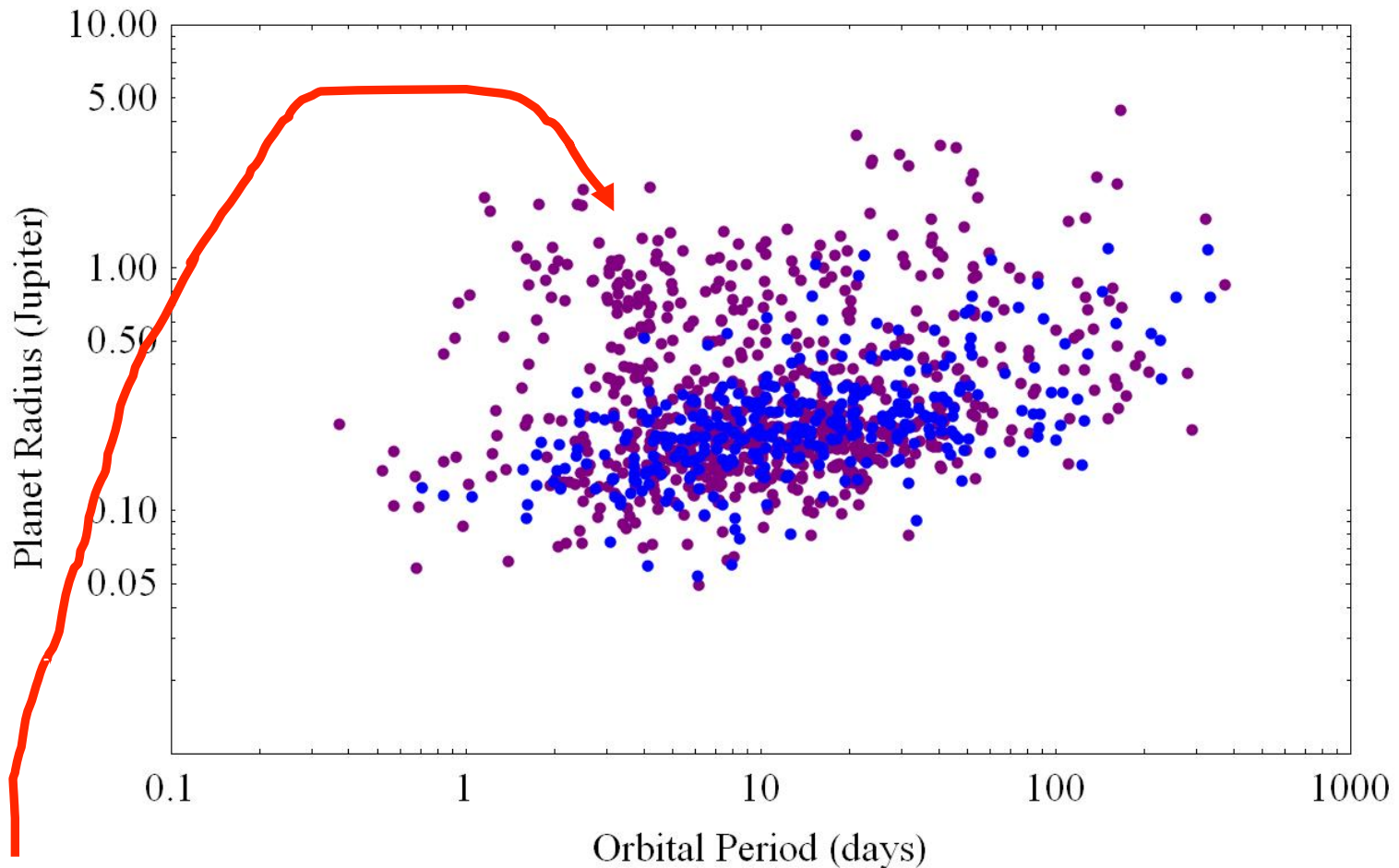
Multiple Candidate Systems and Single Candidate Systems



Teff > 4600K only

Different planet populations

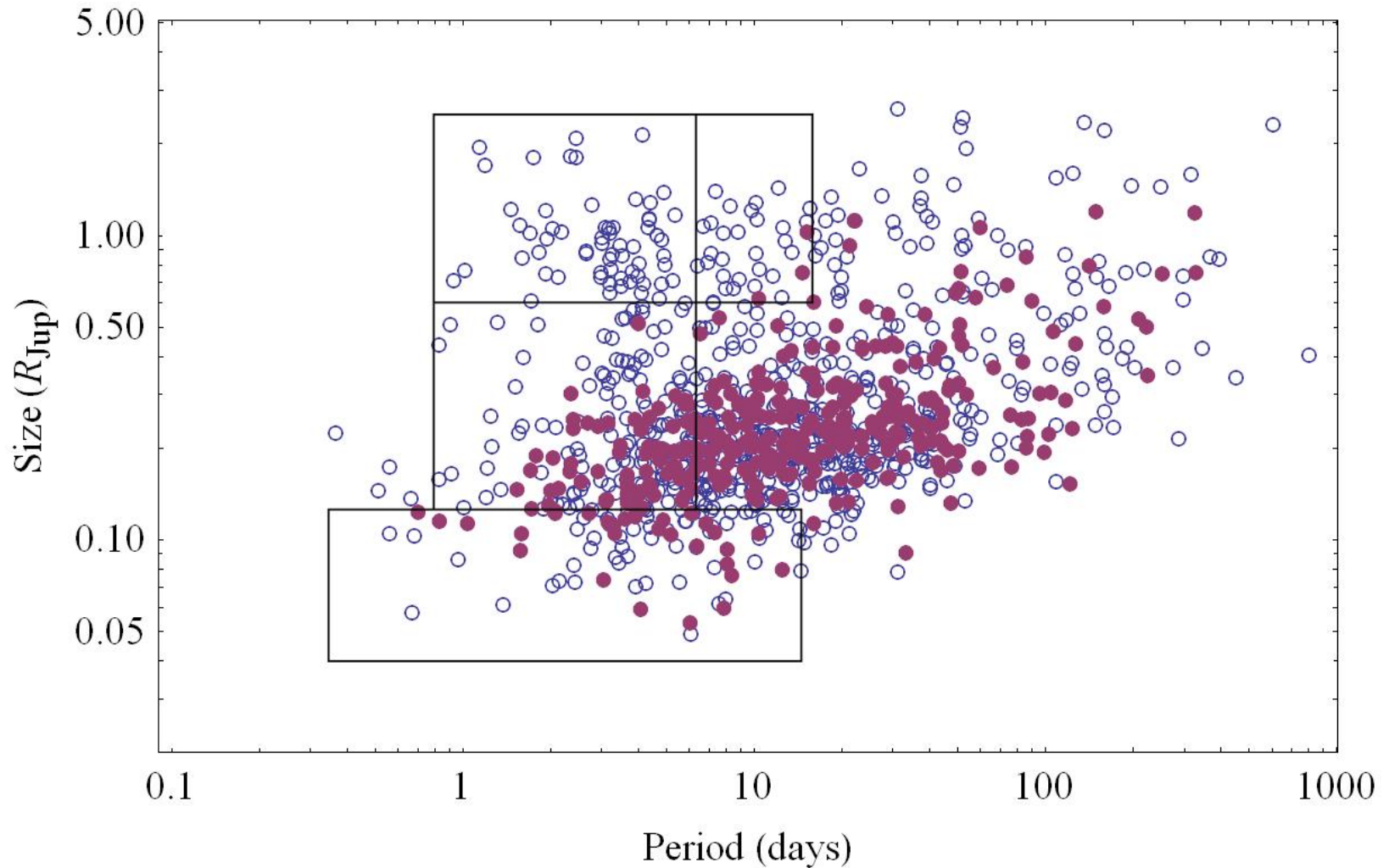
Multiple Candidate Systems and Single Candidate Systems



How do these planets get here?

Teff > 4600K only

Different planet populations



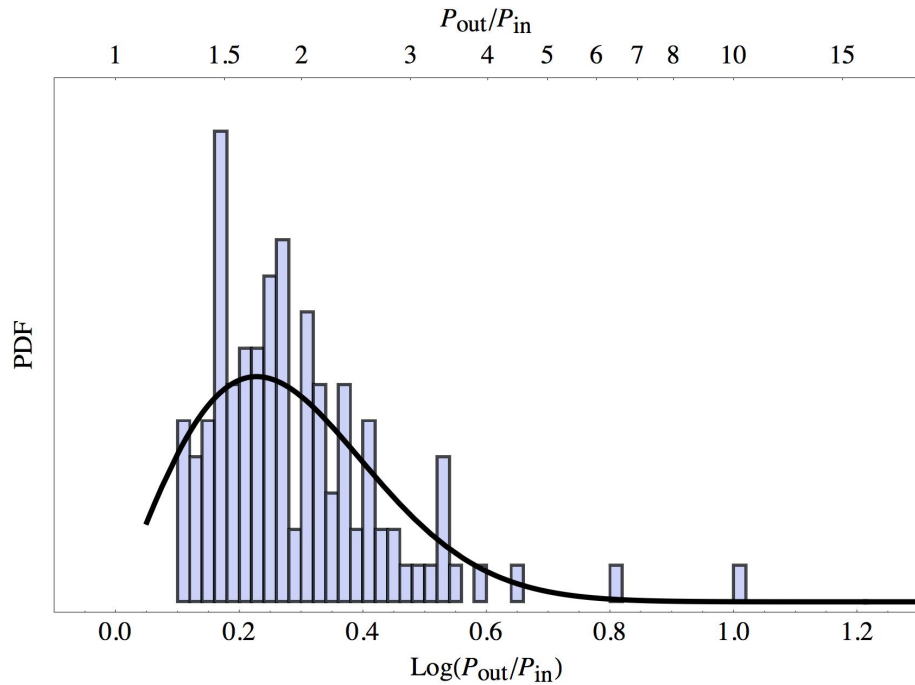
Steffen et al. (2012b)

A 7x9 grid of 63 spheres, each with a black dot in the center. The spheres vary in size and color (orange, yellow, white, blue) against a black background. The colors and sizes are distributed across the grid, with some spheres being significantly larger or smaller than others, and some being blue while most are orange or yellow.

Hot Jupiter Systems

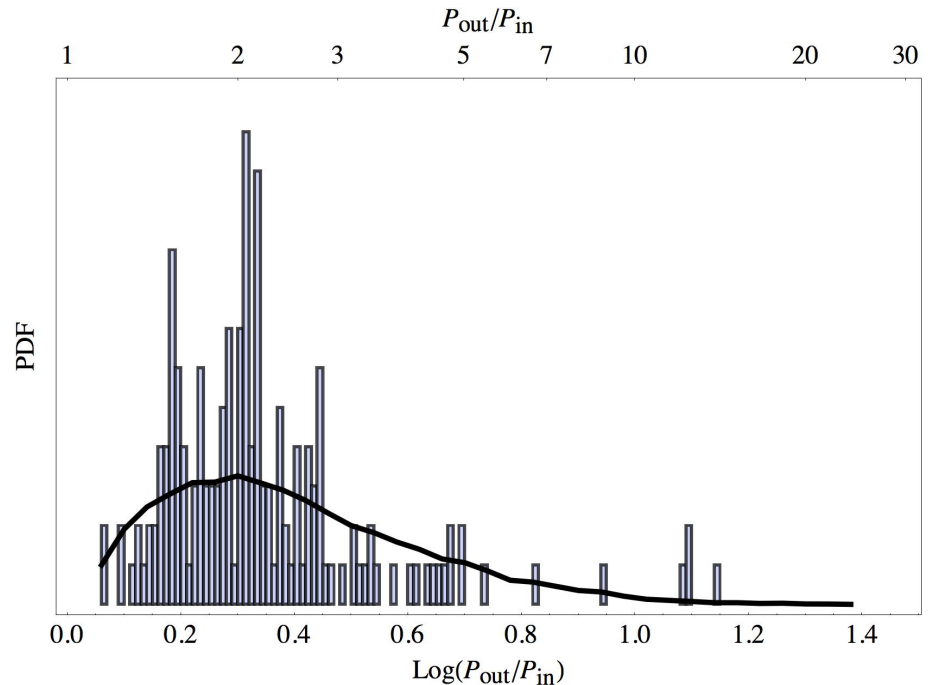
- No known multiple planet systems
- No evidence for companions with TTVs
- No evidence for high inclination perturbers
- Known multiple systems in adjacent samples
- Observed TTV signals in adjacent samples
- Hot Jupiters are really lonely

Other System Architectures

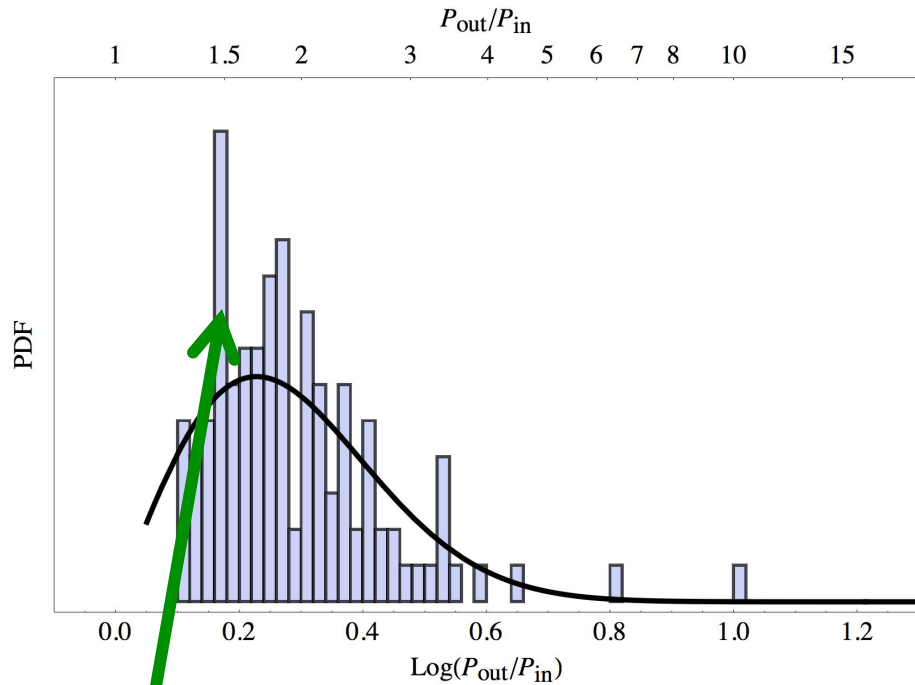


Systems with 4 or more planets

Systems with 3 planets



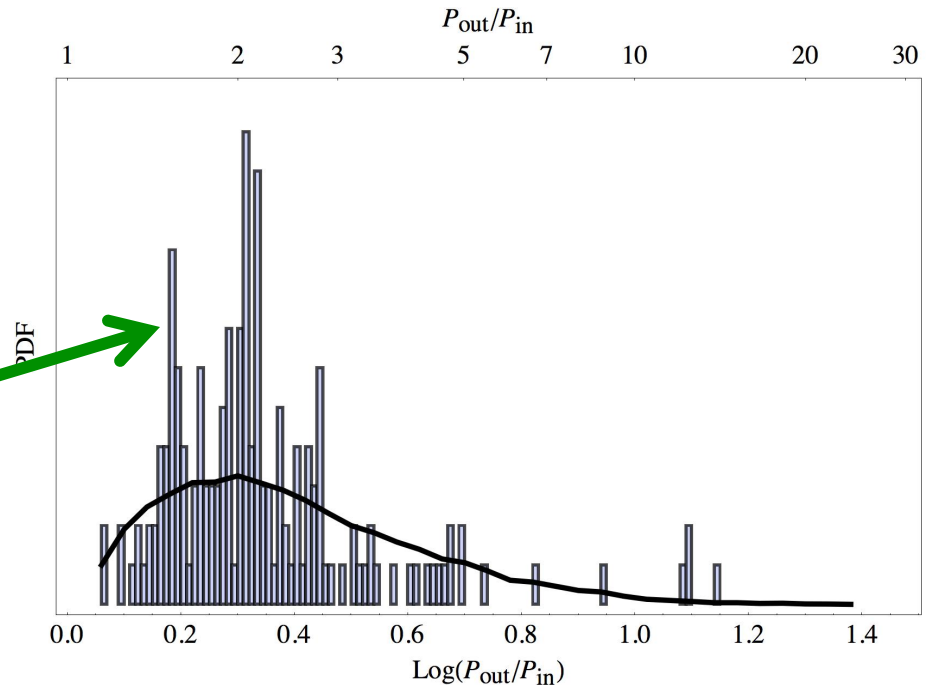
Other System Architectures



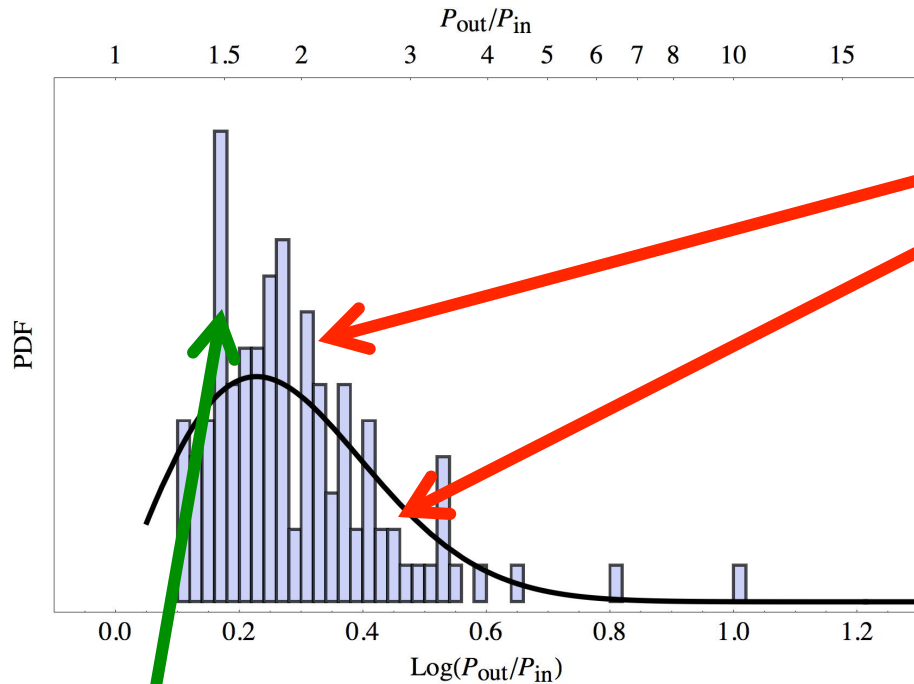
Systems with 4 or more planets

Same feature

Systems with 3 planets



Other System Architectures

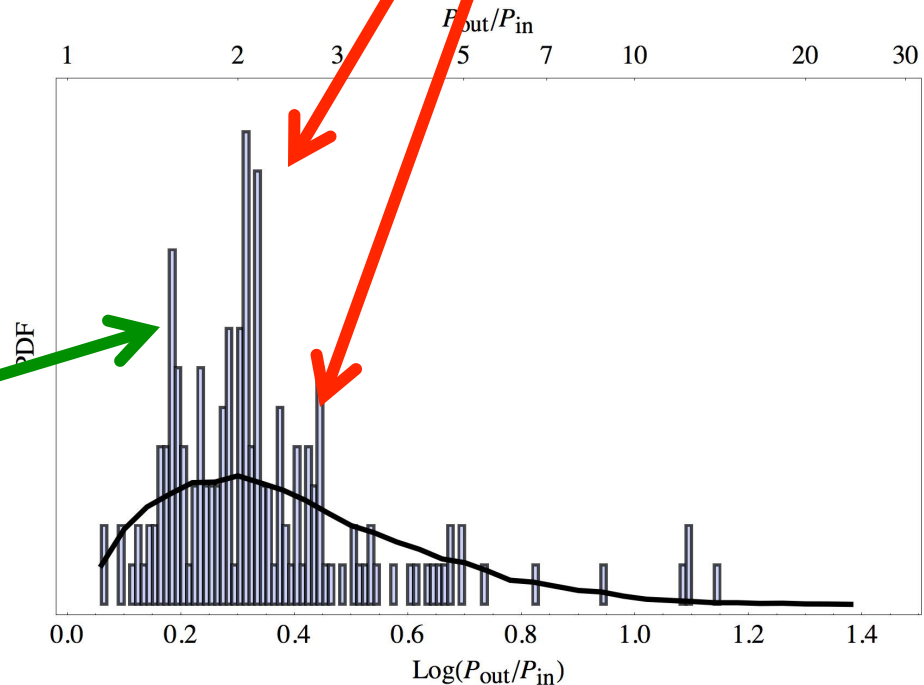


Systems with 4 or more planets

Same feature

Not the same features

Systems with 3 planets



Kepler Future

- Kepler is moving into new regimes
 - Longer periods
 - Smaller candidates
 - More transits
 - Habitable Zones for larger stars
- Important constraints on planet formation through dynamical interactions and geometry
- TTVs are proving an important component for planet confirmation and characterization
- Spacecraft able to operate for several more years
 - Mission was extended earlier this year

Kepler Future

