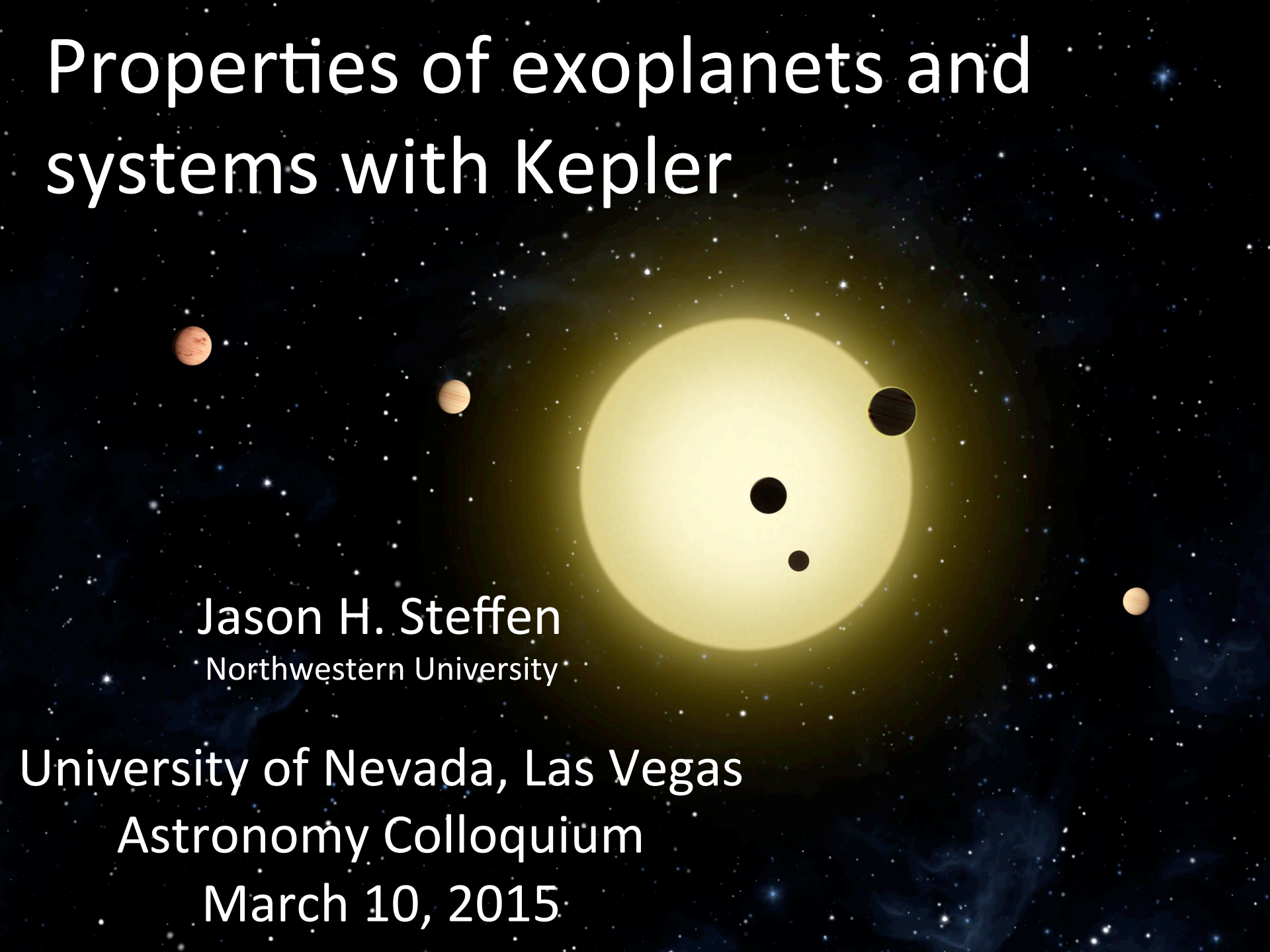
Properties of exoplanets and systems with Kepler



Jason H. Steffen
Northwestern University

University of Nevada, Las Vegas
Astronomy Colloquium
March 10, 2015

Collaborators

Eric Agol, Josh Carter, Dan Fabrycky, Eric Ford, Matt Holman, Andrew Howard, Daniel, Juntof-Hutter, Dave Latham, Jack Lissauer, Geoff Marcy, Tsevi Mazeh, Jerry Orosz, Fred Rasio, Billy Quarles, Darin Ragozzine, Jason Rowe, Francesca Valsecchi, William Welsh, Kepler Science Team

Graduate Students:
Jason Hwang, Sam Hadden, Robert Morehead

Undergraduate Students:
Lauren Barmore, Emily Ellinger, David Lee, Remy Millman, David Rice

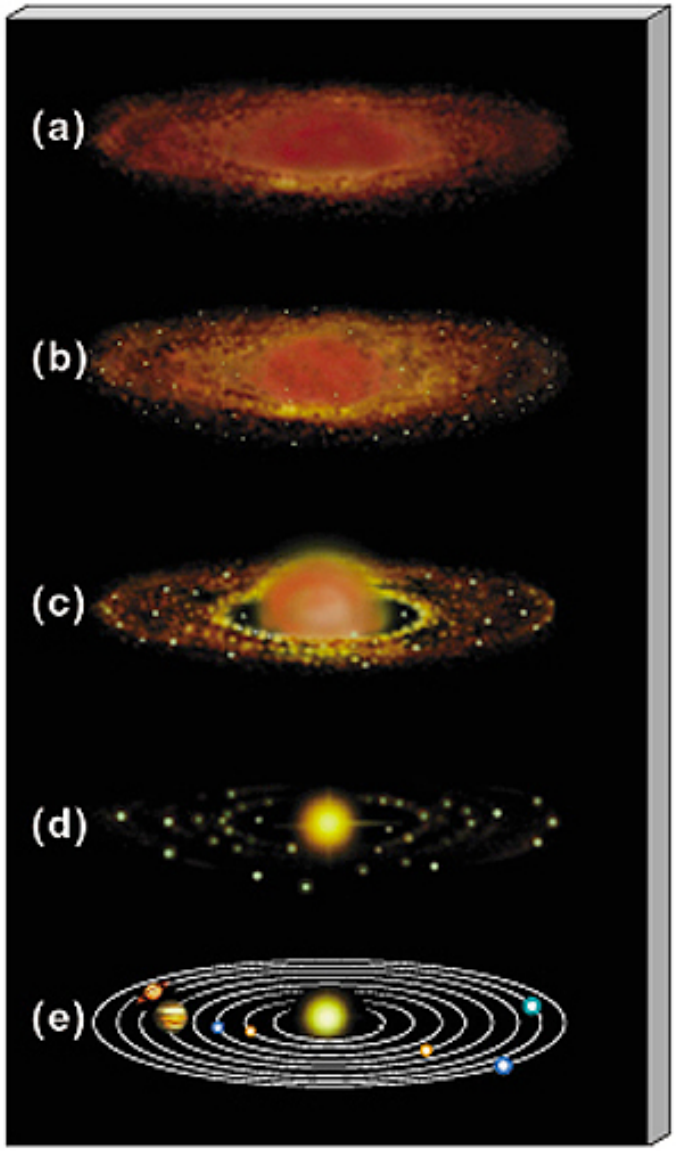
Funding through NASA's Kepler Participating Scientist Program and NASA's Origins Program

Theory of Planet Formation

Kant

Laplace

Nebular theory of planet formation is largely unchanged after more than 200 years – planets form from a gaseous disk.



Solar System Data

```
Revised: Dec 12, 2013                Neptune                                  899

PHYSICAL DATA (update 2009-May-26):
 Mass (10^24 kg)          =   102.41          Density (g/cm^3)          =  1.638
 Equat. radius (1 bar) = 24766+-15 km         Polar radius (km)         = 24342+-30
 Volumetric mean radius= 24624+-21 km         Flattening                =  0.0171

 Rotation period          = 16.11+-0.01 hr    Rot. rate(10^-4 rad/s)    =  1.083
 m = w^2a^3/GM            =  0.02609          Hydrostatic flat., fh     =  0.01804
 Inferred rot. period     = 16.7+-1.4 hr      ks = 3*J2/m               =  0.407
 Mom. of inert. I/MRo^2=                      I/MRo^2 (upper bound)     =  0.239
 Rocky core mass (Mc/M)=                      Y factor (He/H ratio)     =  0.235+-.040

 GM (km^3/s^2)            = 6,835,107         GM 1-sigma (km^3/s^2)     = +-15
 Equ. grav, ge (m/s^2)    = 11.15             Pol. grav, gp (m/s^2)     = 11.41+-0.03

 Geometric albedo         =  0.41             Visual magnitude V(1,0)= -6.87
 Vis. mag. (opposition)= +7.84                Obliquity to orbit        = 29.56 deg
 Sidereal orbit period    = 164.79132 yr      Sidereal orbit period     = 60190.029 d
 Mean daily motion        = 0.006020076dg/d Mean orbit velocity         = 5.4778 km/s

 Atmos. temp. (1 bar)     =  72+-2 K          Heat flow/mass (x10^7)    =  2 erg/gm*s
 Planetary Solar Const    =   1.47 W/m^2      Dipole tilt/offset        = 47deg/0.55Rp
 Escape velocity (km/s)=  23.5                Mag.dip.mom(gauss-Rp^3)= 0.133
 Aroche(ice)/Rp           =  2.98             Hill's sphere rad., Rp    = 4700
```

Solar System Ephemeris, JPL

Solar System Data

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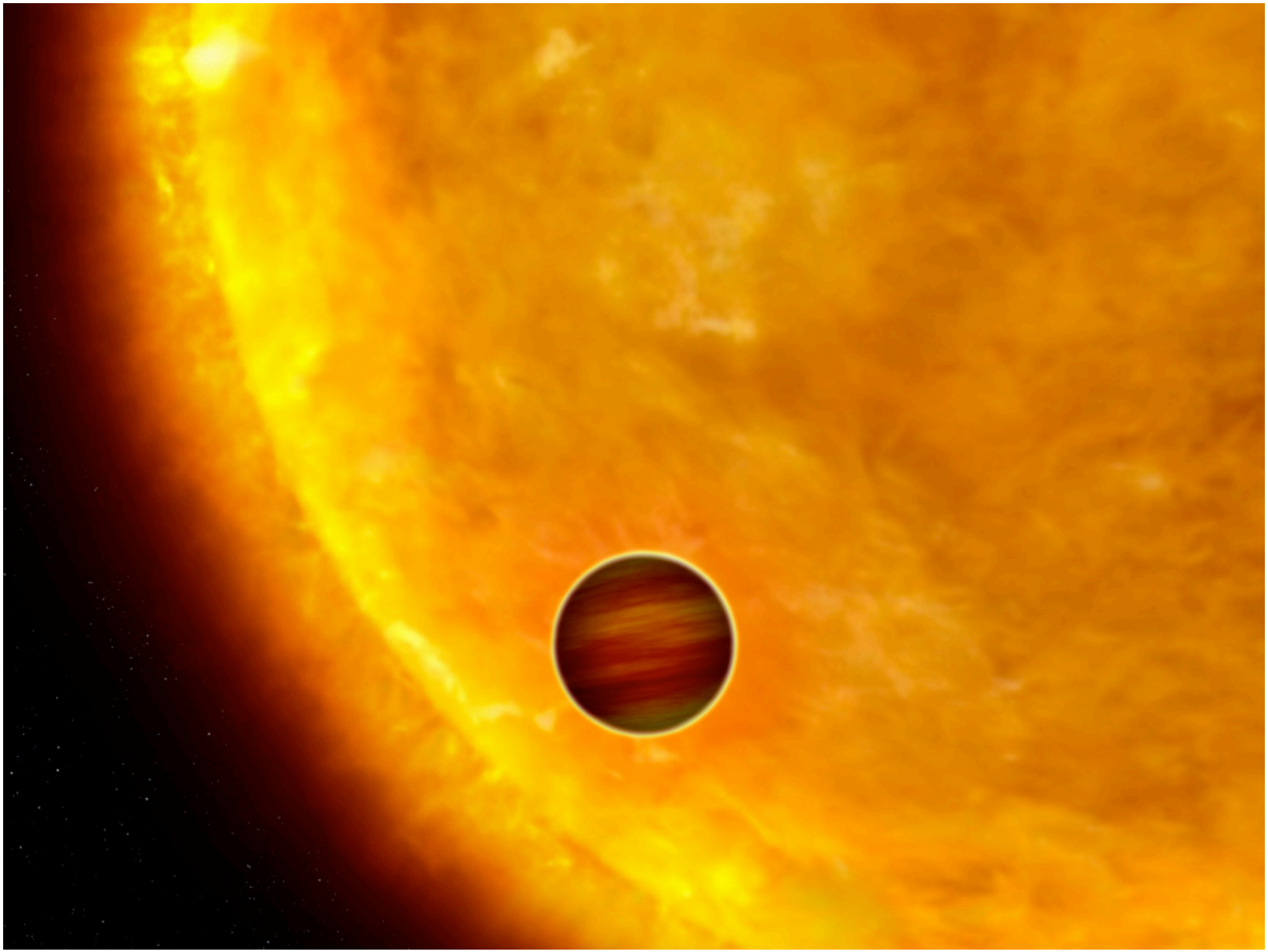
```

Solar System Ephemeris, JPL

Given our knowledge of the solar system, what role can exoplanets play?

1995



1995

1800 Confirmed planets

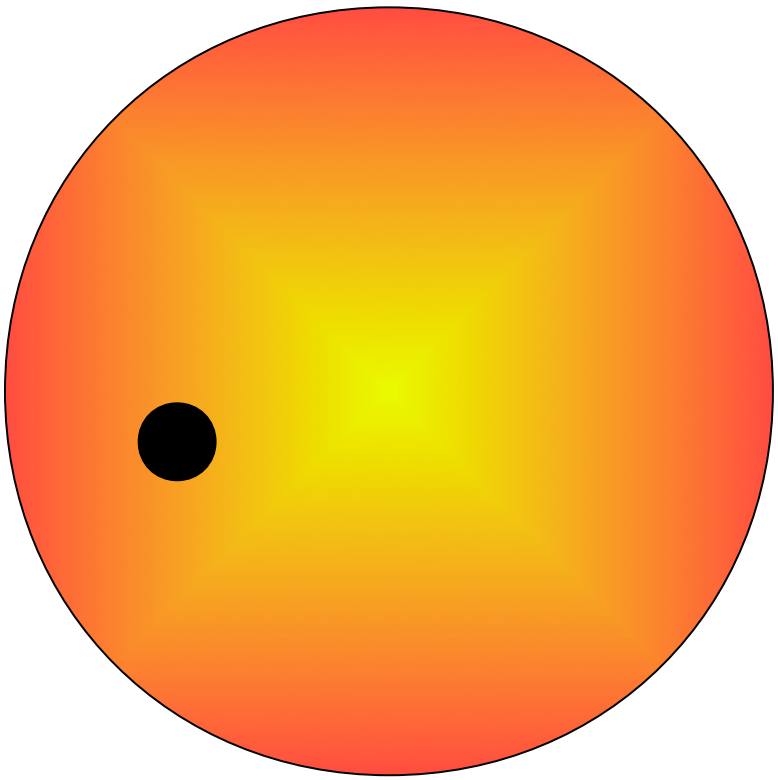
(about ½ from Kepler)

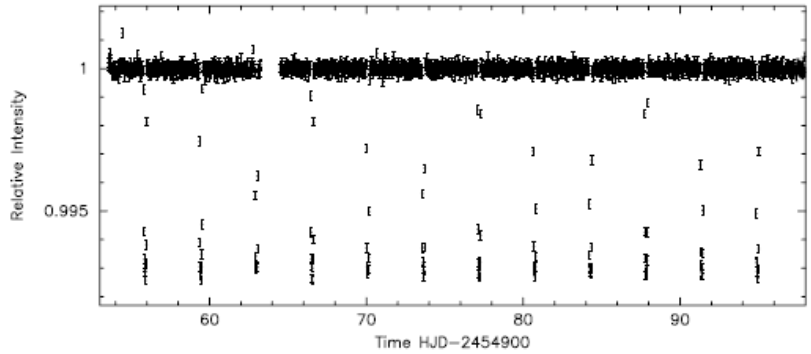
4200 Planet Candidates

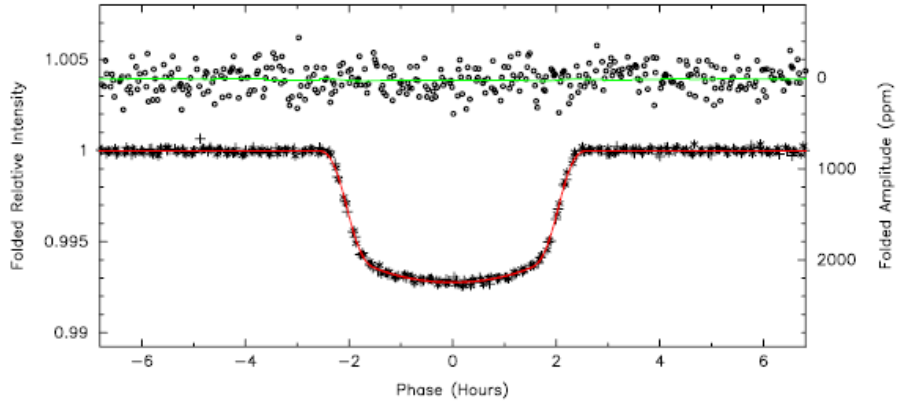
(from Kepler)

Planet Finding Methods

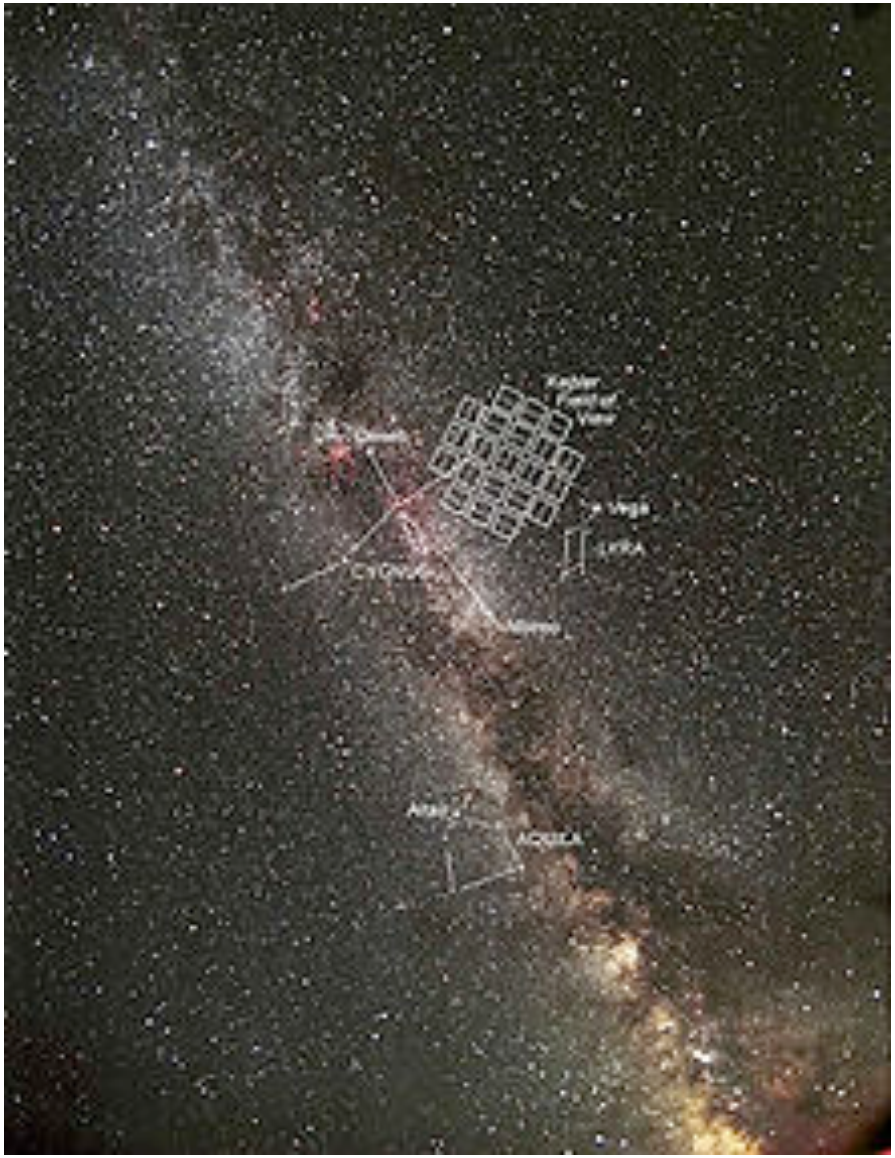
Planetary Transits

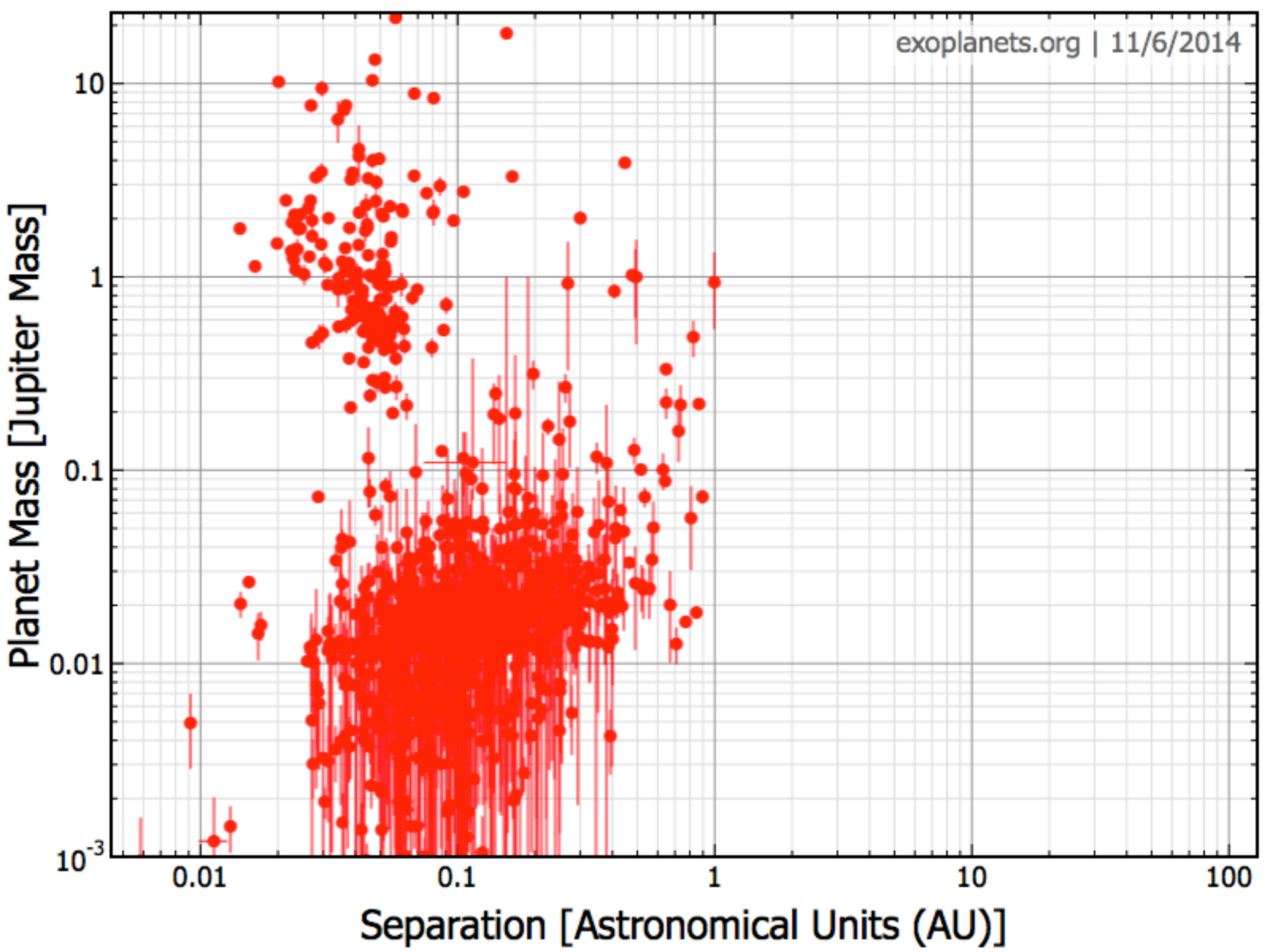


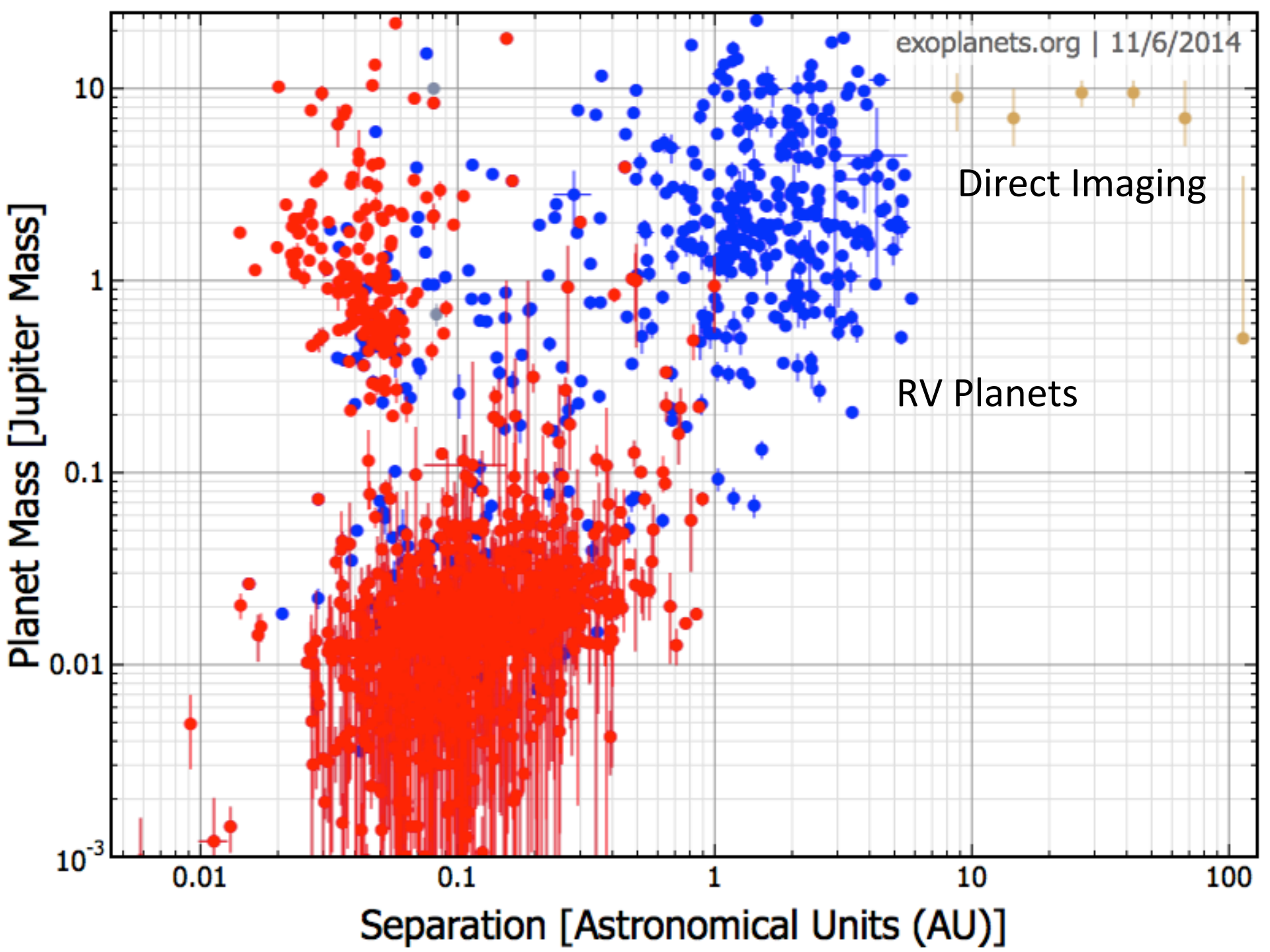




NASA’s Kepler Mission

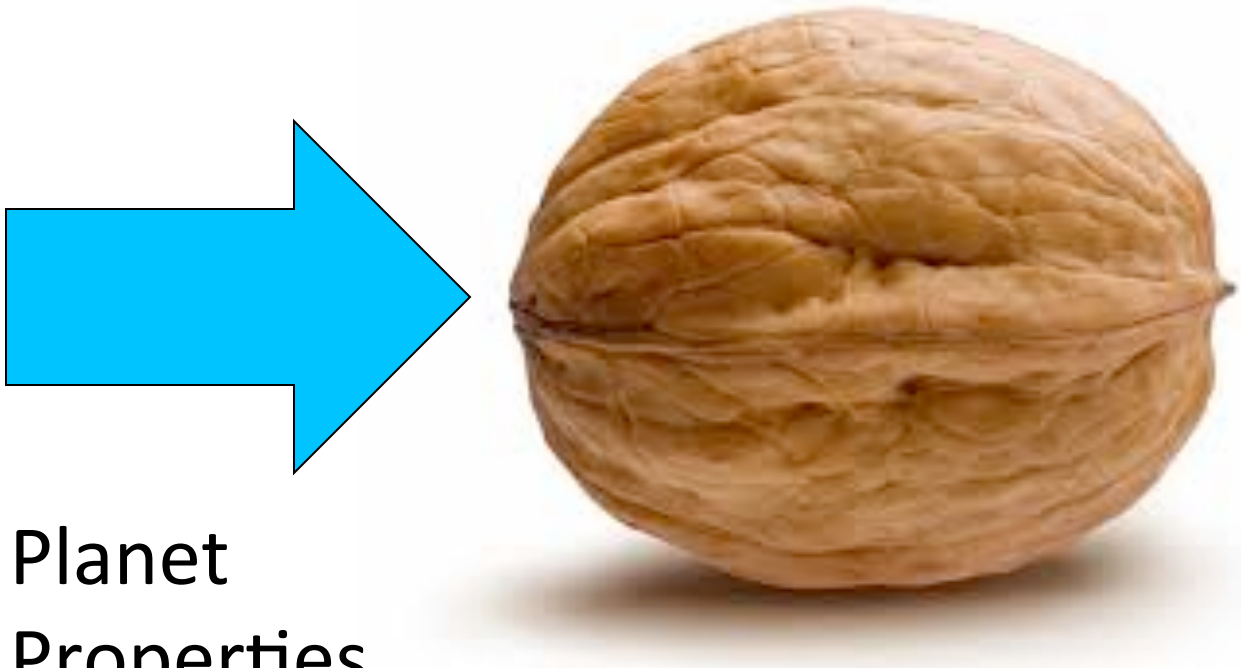



exoplanets.org | 11/6/2014
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]


exoplanets.org | 11/6/2014
Direct Imaging
RV Planets
Planet Mass [Jupiter Mass]
Separation [Astronomical Units (AU)]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100

Planet Formation

Planet Formation

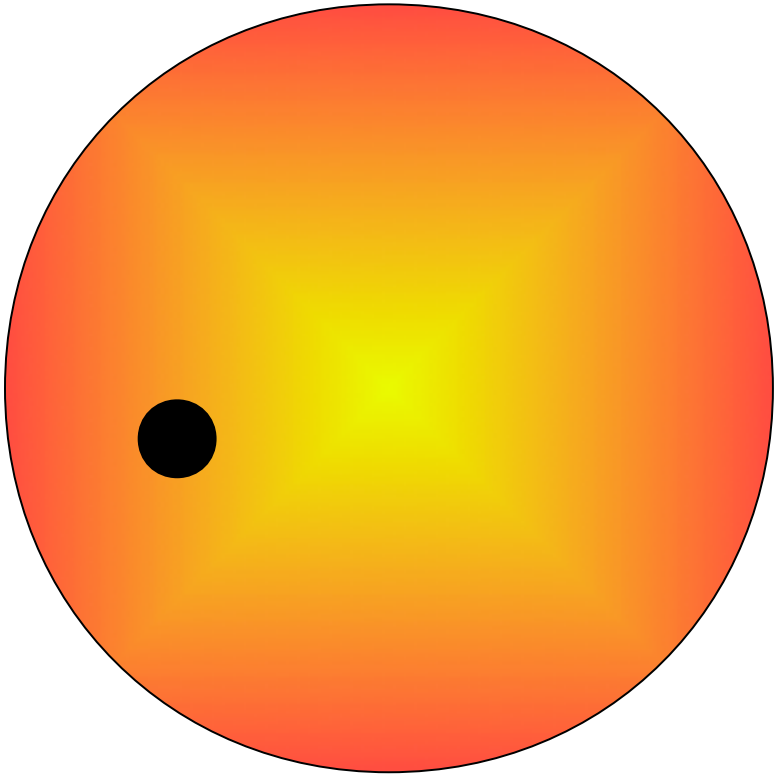


Planet
Properties

Planet Formation

The Value of Transiting Planets

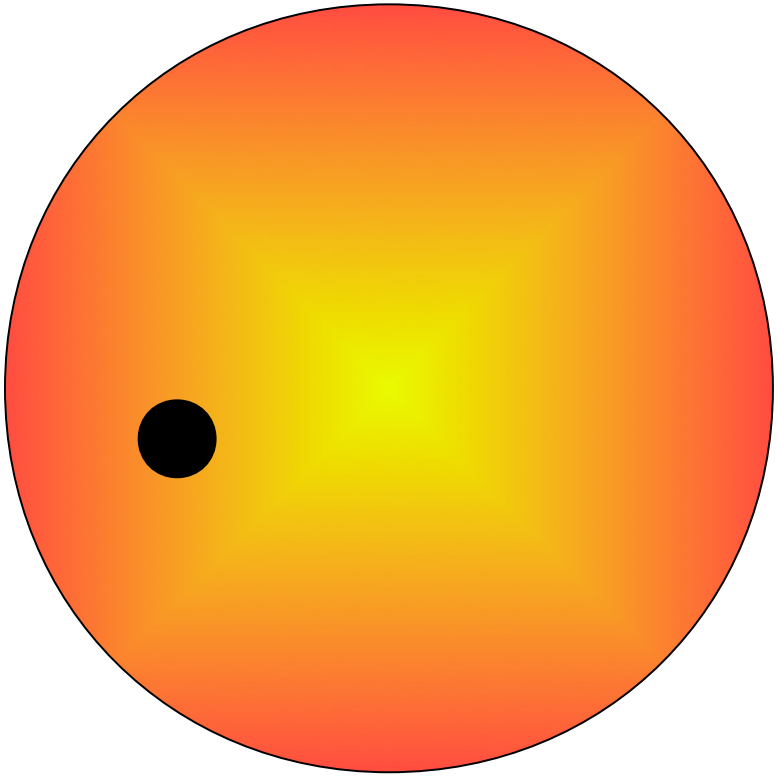
(among other things)



- Measurement of orbital inclination (mass)

The Value of Transiting Planets

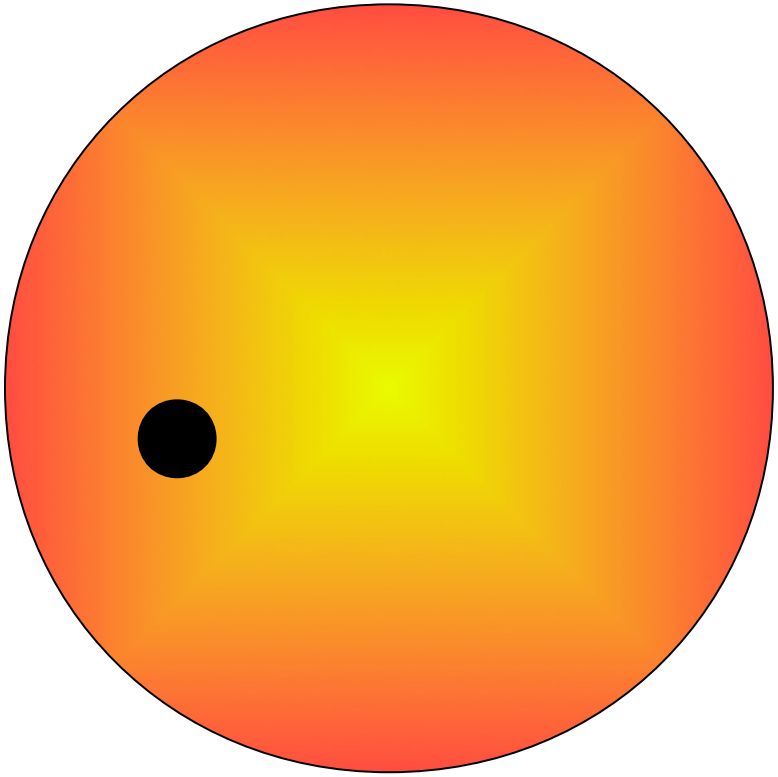
(among other things)



- Measurement of orbital inclination (mass)
- Measurement of the planet size (density)

The Value of Transiting Planets

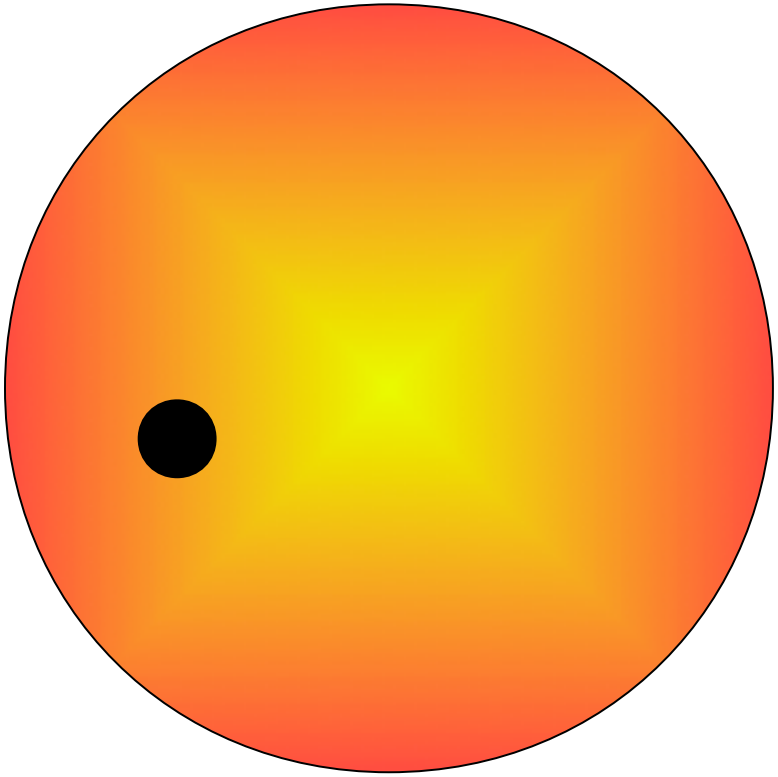
(among other things)



- Measurement of orbital inclination (mass)
- Measurement of the planet size (density)
- Precision of orbital phase ~0.0001 (dynamics)

The Value of Transiting Planets

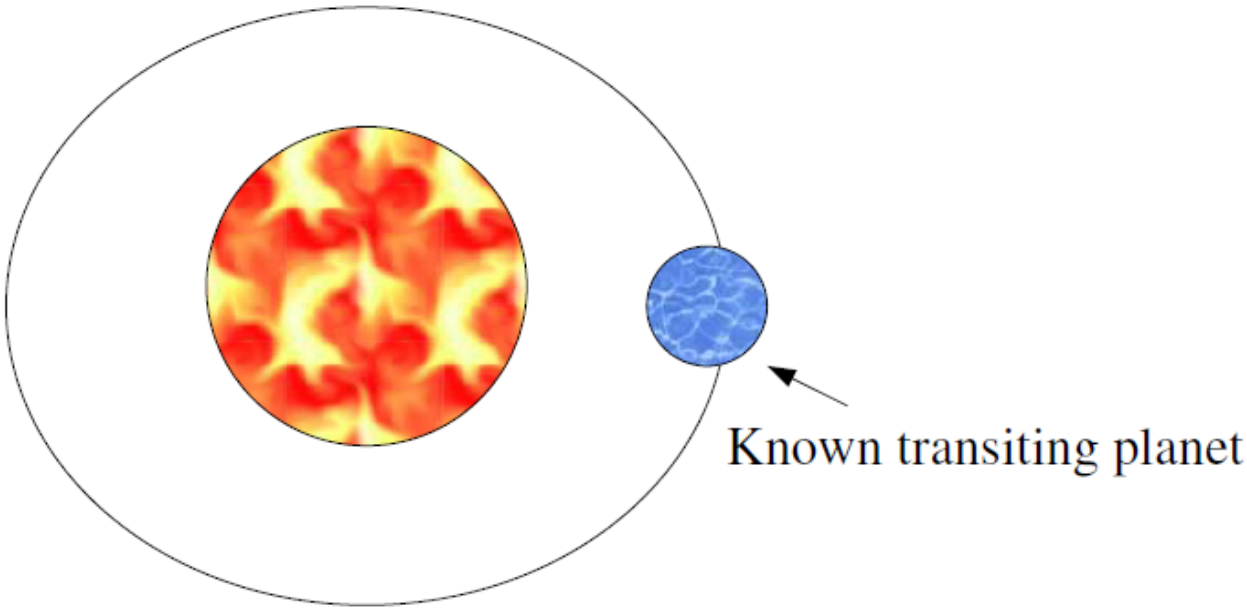
(among other things)



- Measurement of orbital inclination (mass)
- Measurement of the planet size (density)
- Precision of orbital phase ~0.0001 (dynamics)
- Measurement of orbital obliquity (environment and history)

Dynamics with Transiting Planets

Transit Timing Variations

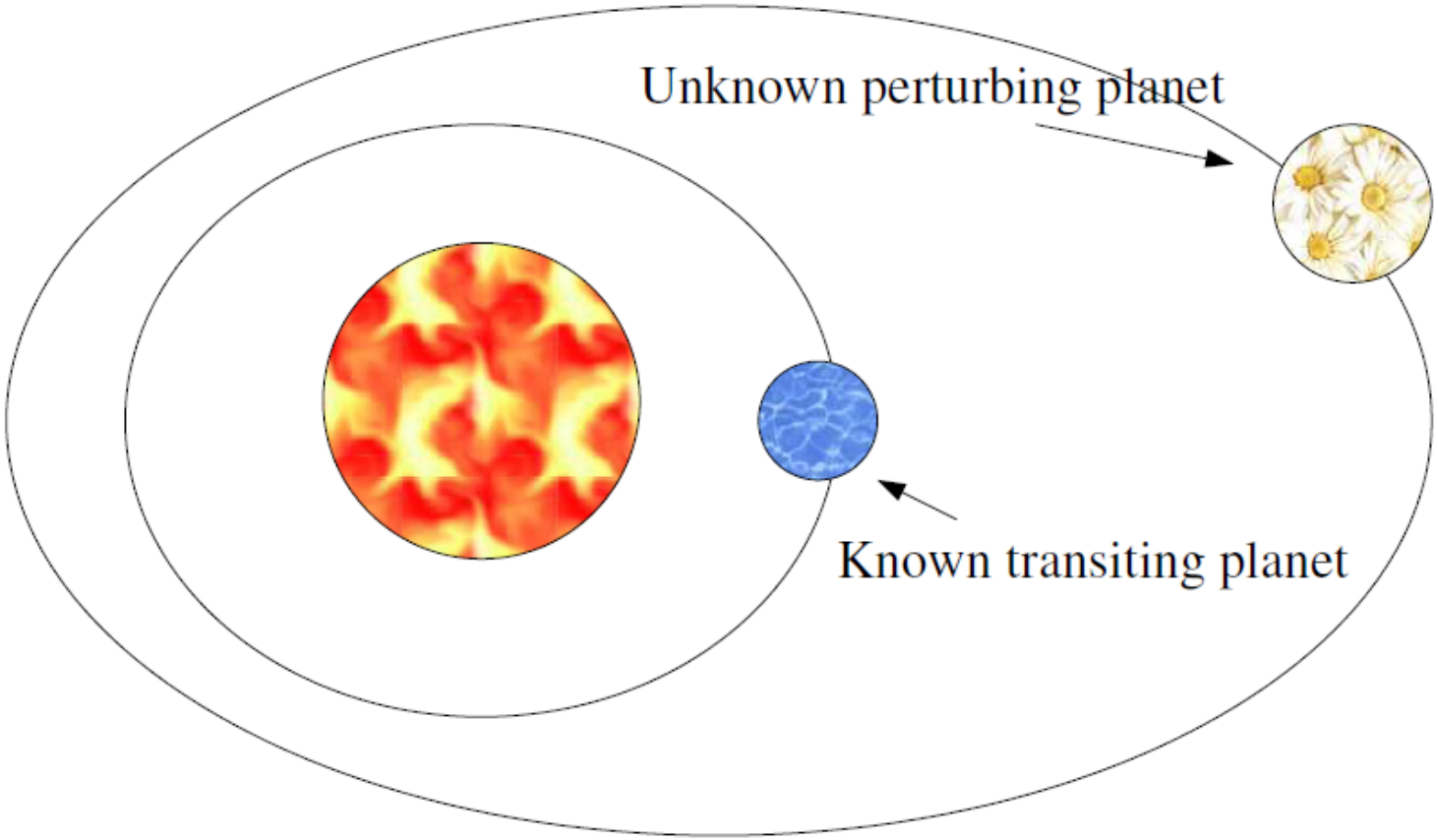


Transit times are equally spaced.

Agol, Steffen, Sari, Clarkson (2005), Holman and Murray (2005)

Dynamics with Transiting Planets

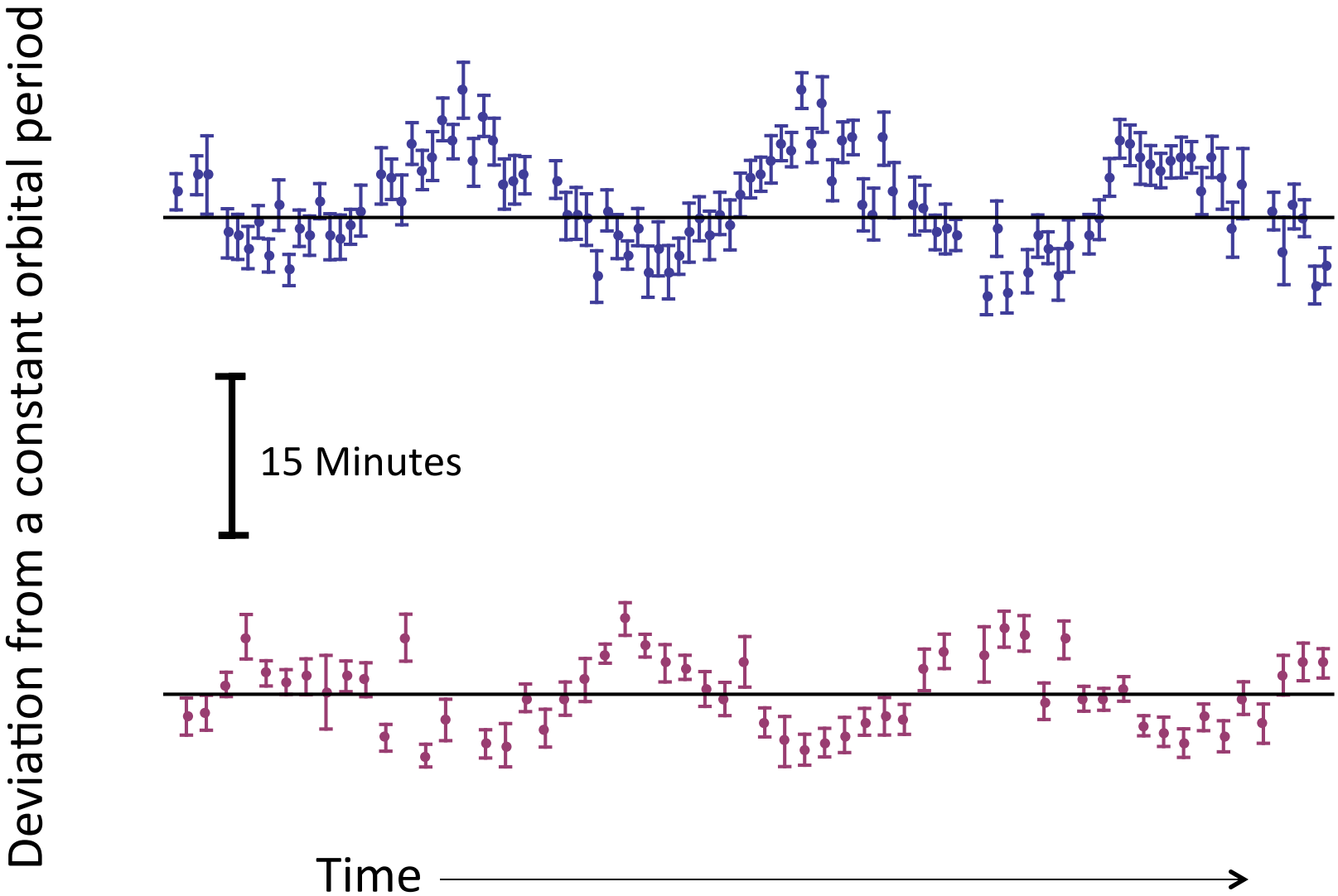
Transit Timing Variations



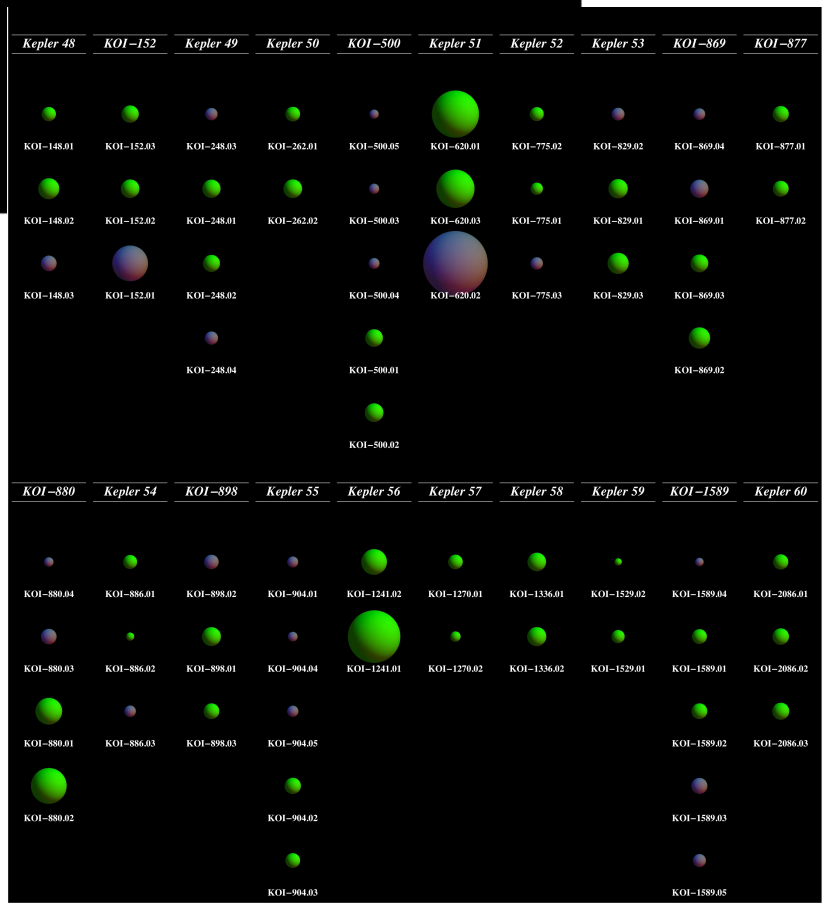
Transit times are <u>NOT</u> equally spaced.

Agol, Steffen, Sari, Clarkson (2005), Holman and Murray (2005)

Transit Timing Variations

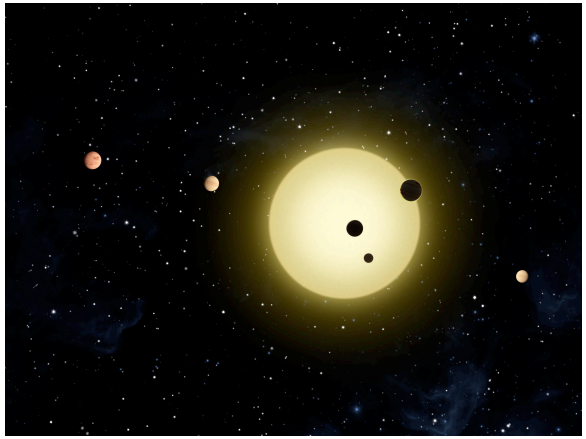


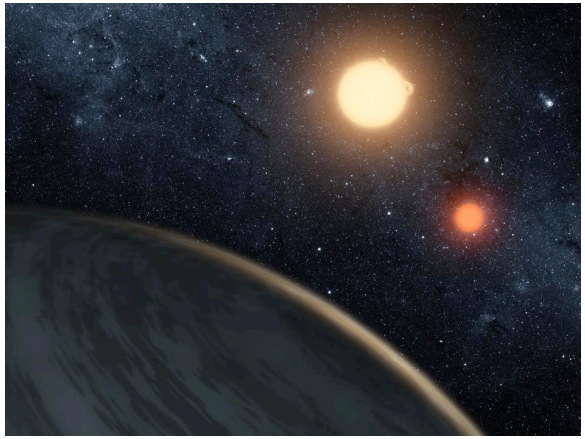
Kepler 23 — 32, 48 — 60

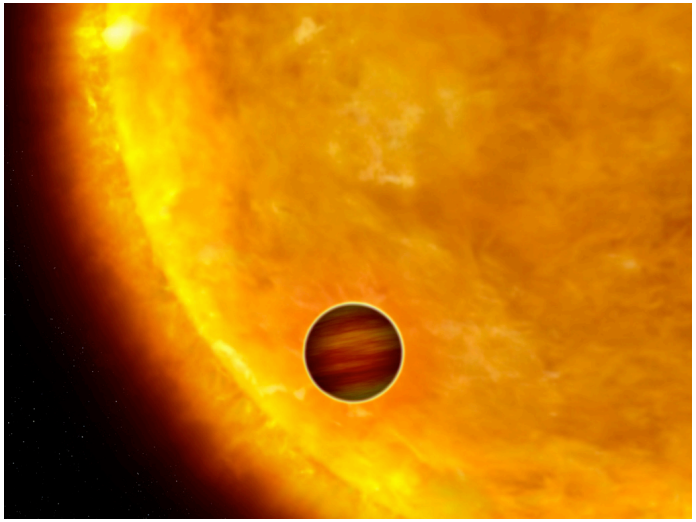


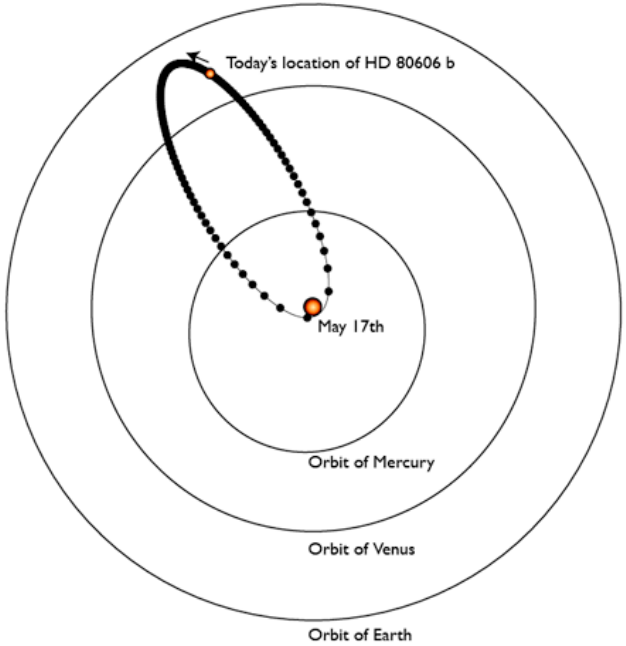
Ford et al. (2012a), Steffen et al. (2012a), Fabrycky et al. (2012a), Steffen et al. (2013a), Xie (2012)

Planetary System Characterization

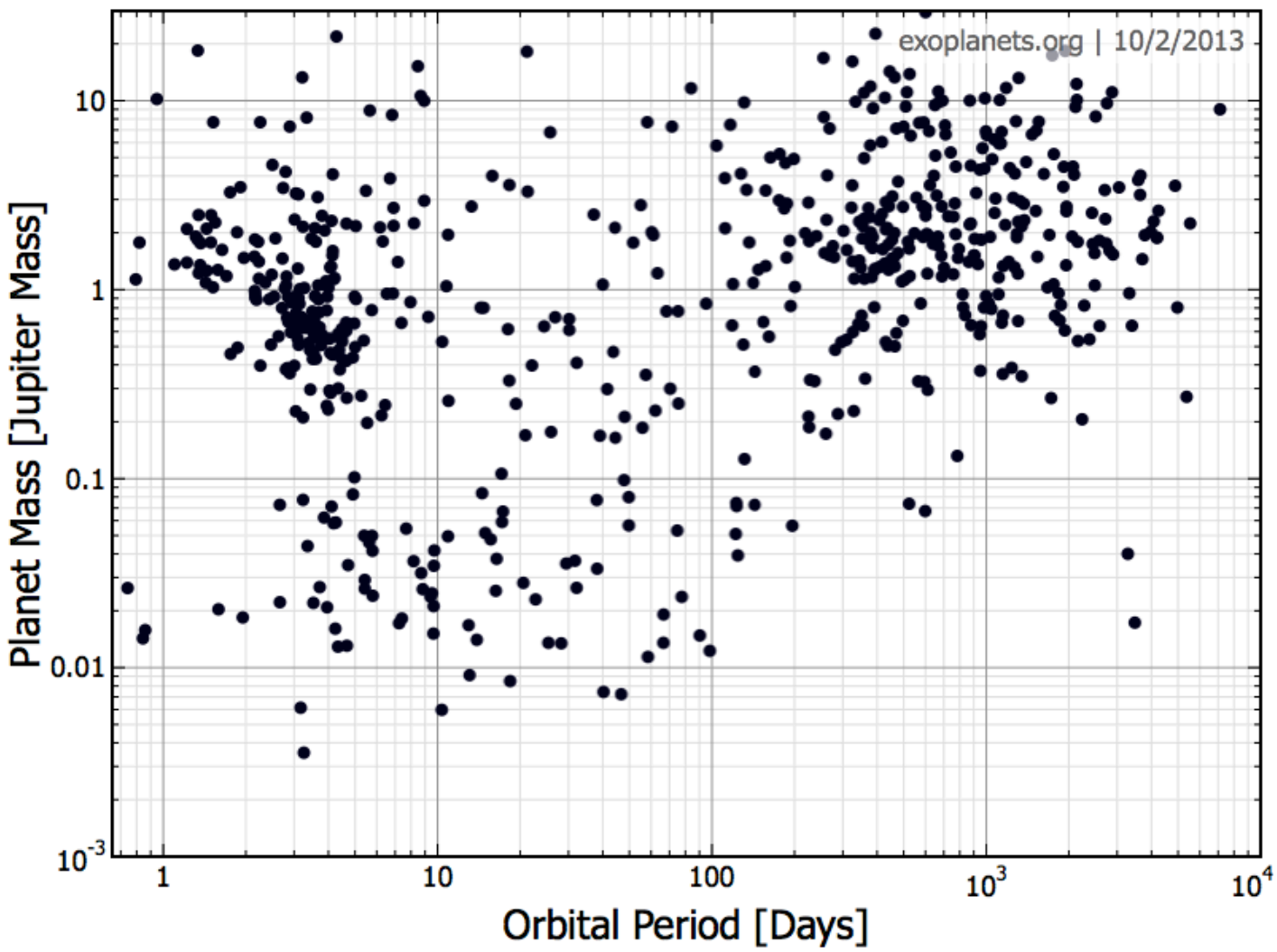








Systems with a Hot Jupiter



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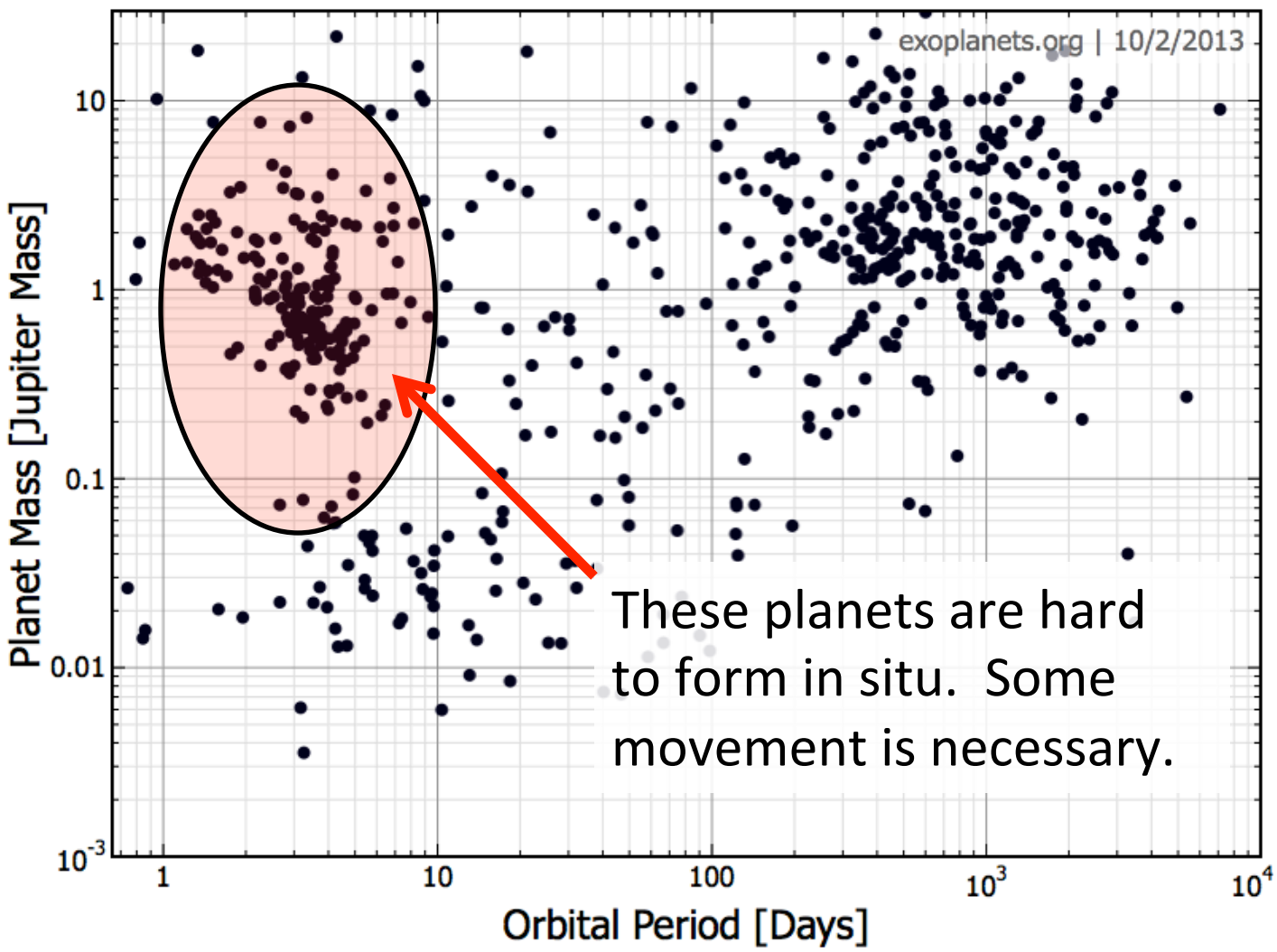
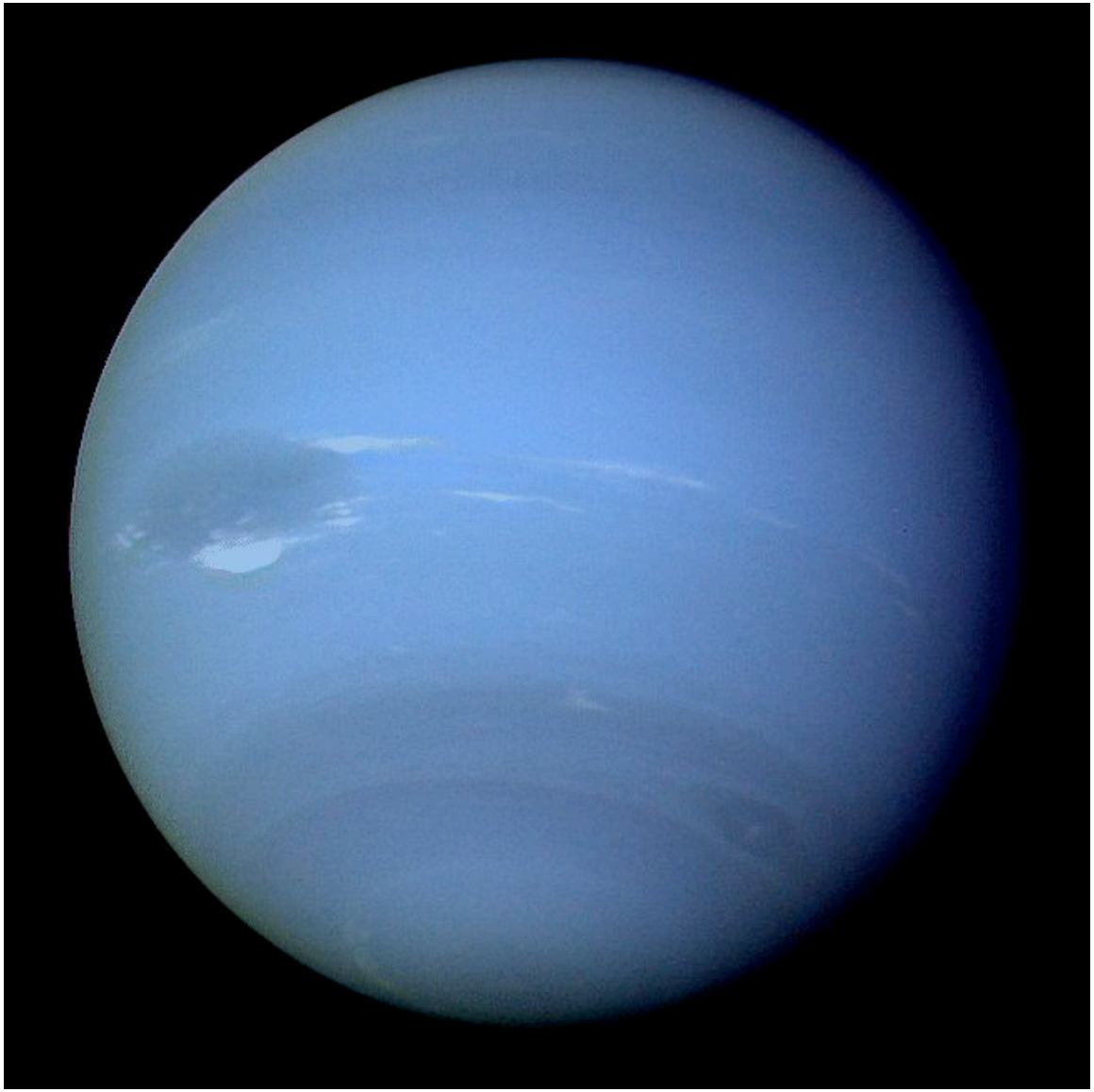
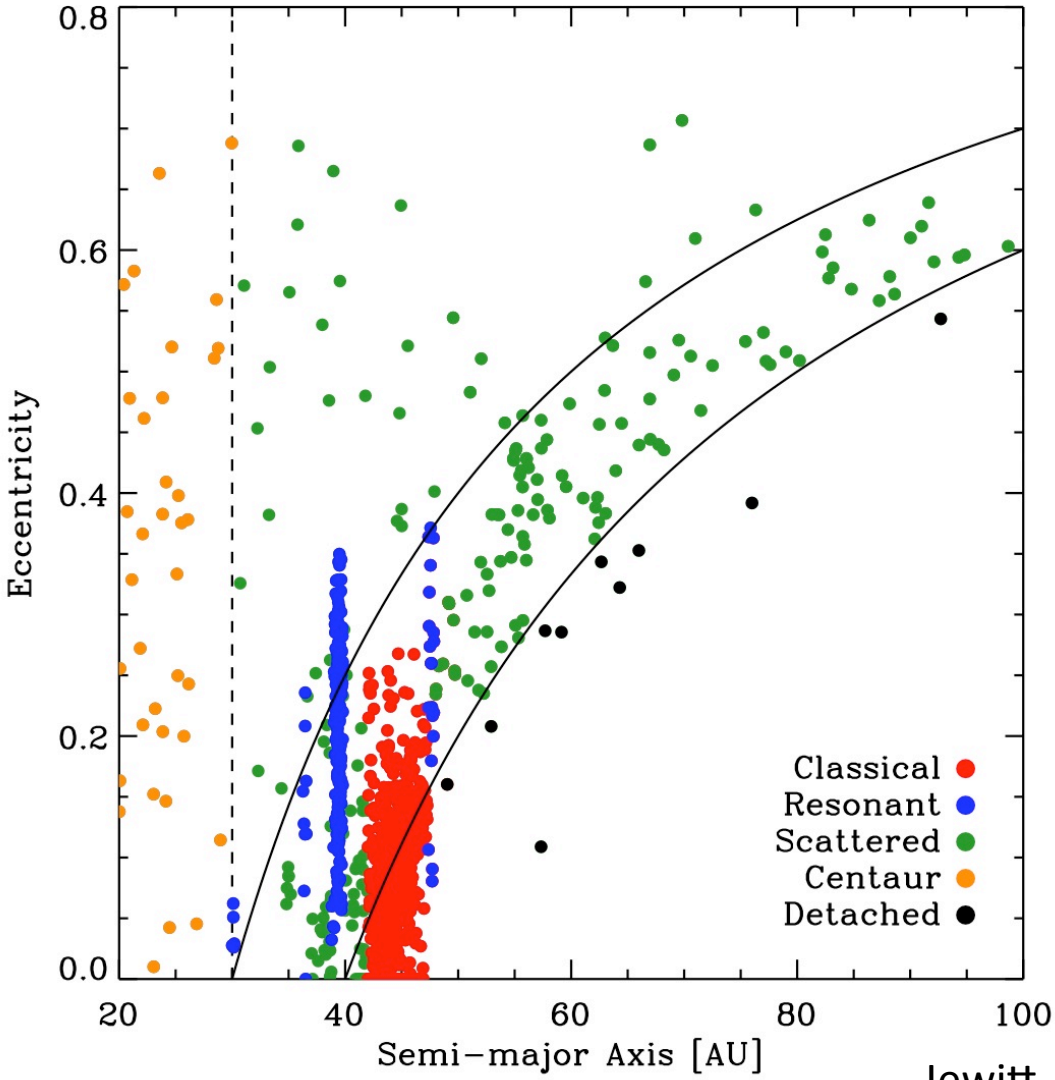


An issue in the Solar System



Planet Migration in the Solar System

Discoveries of TNOs show an excess of objects near mean-motion resonance with Neptune.



Jewitt

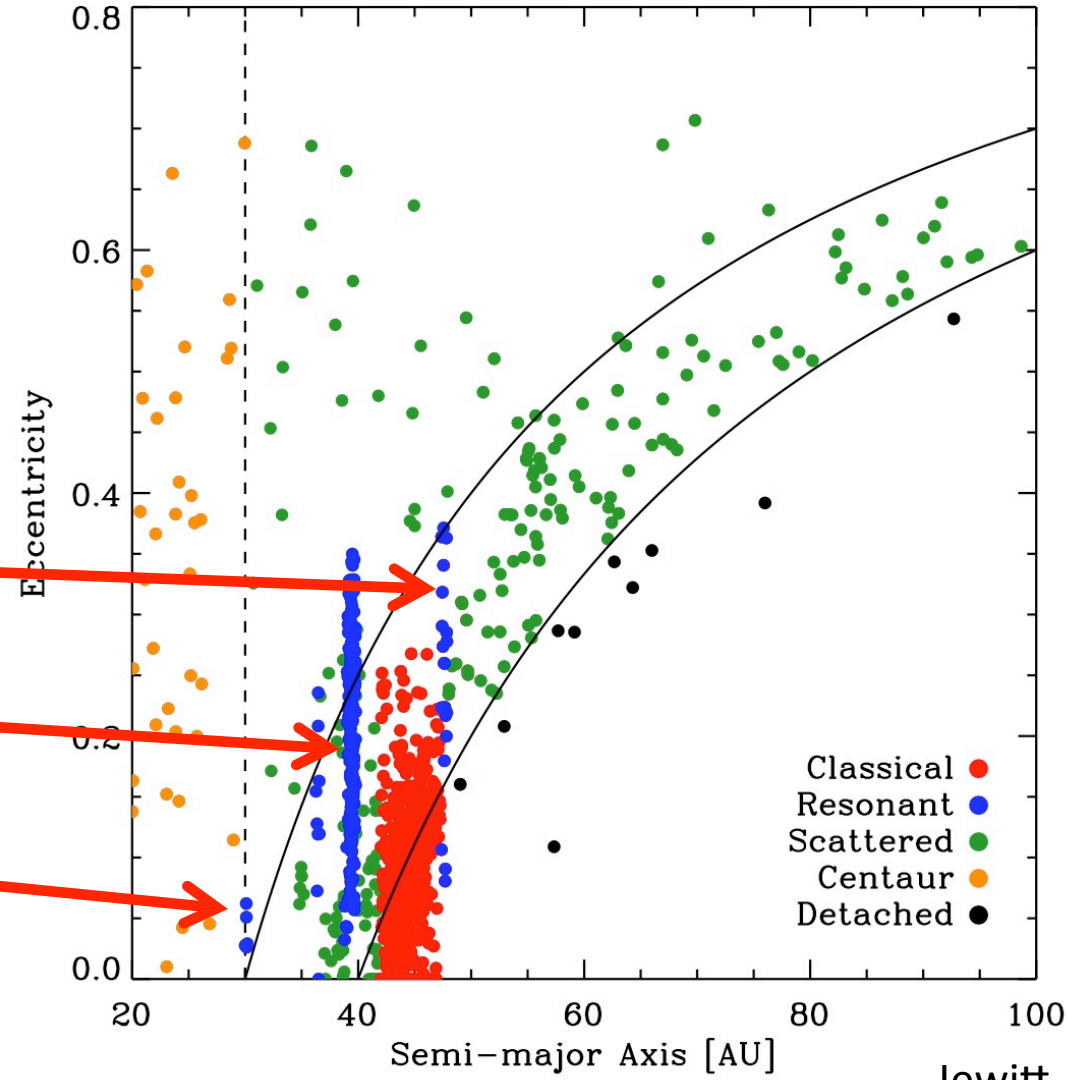
Planet Migration in the Solar System

Discoveries of TNOs show an excess of objects near mean-motion resonance with Neptune.

2:1

3:2

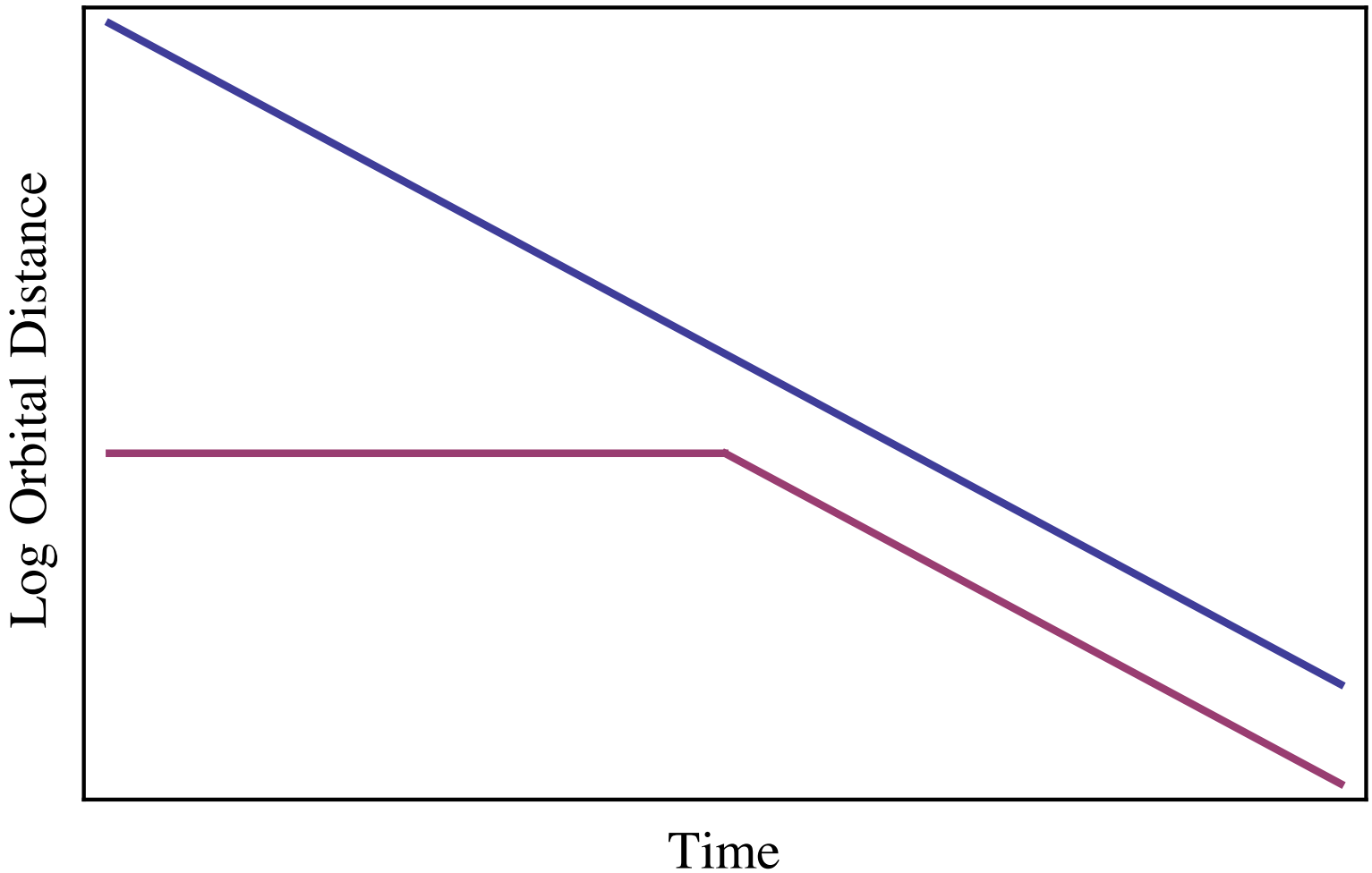
1:1



Jewitt

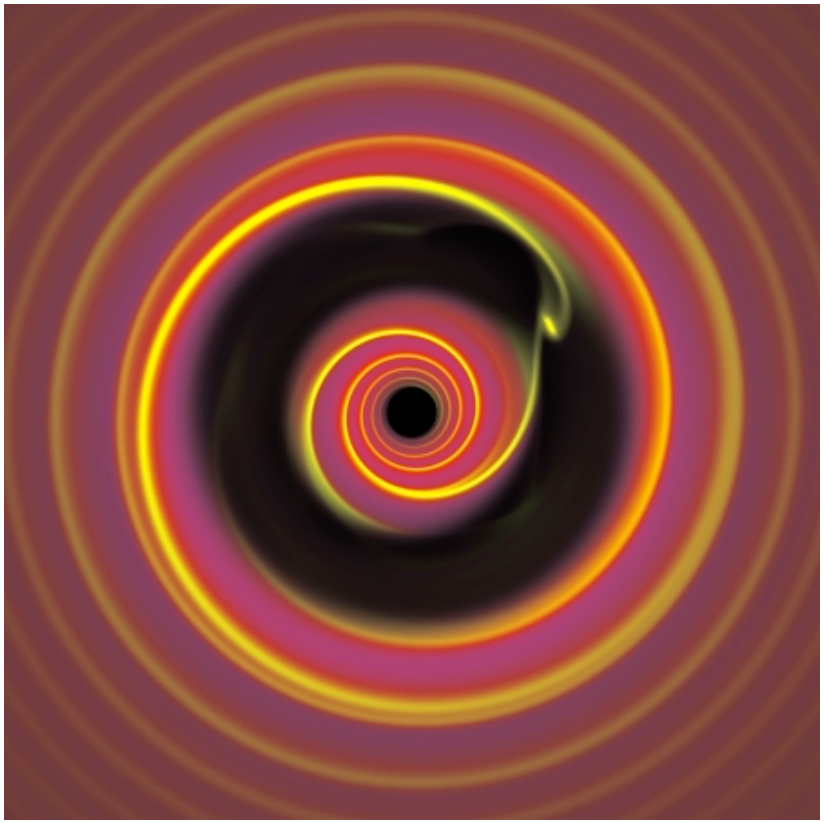
A Signature of Disk Migration

Mutually migrating bodies become trapped in mean-motion resonance



The movement of Hot Jupiters

Peace and Harmony



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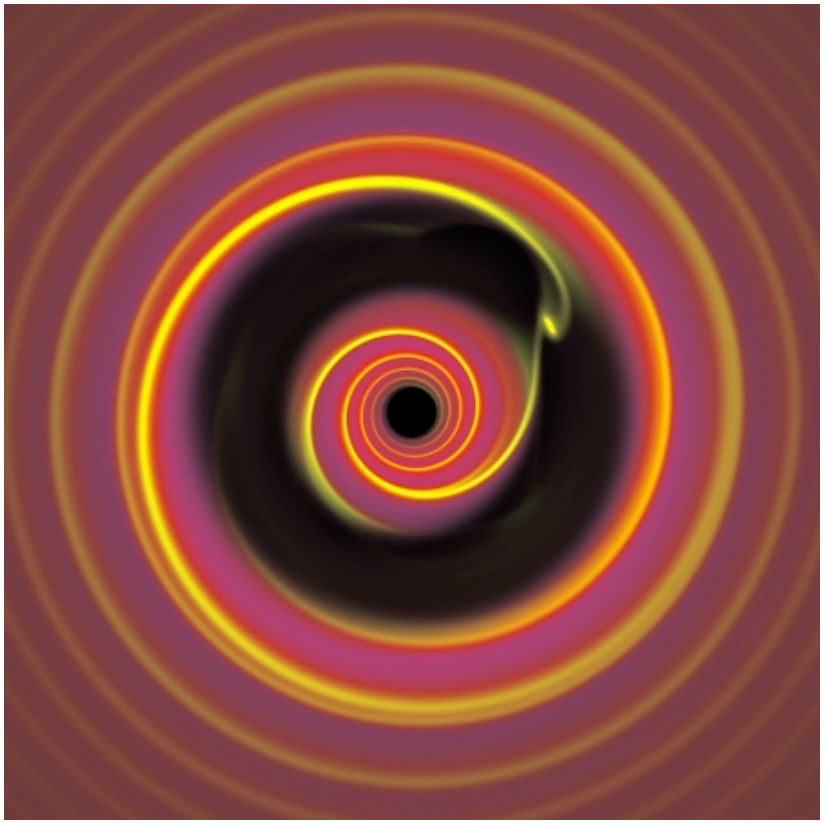
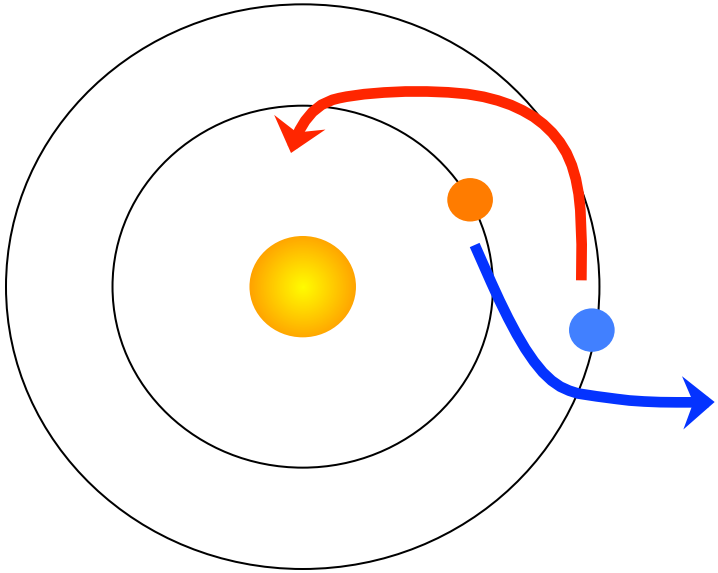


Violence and Mayhem



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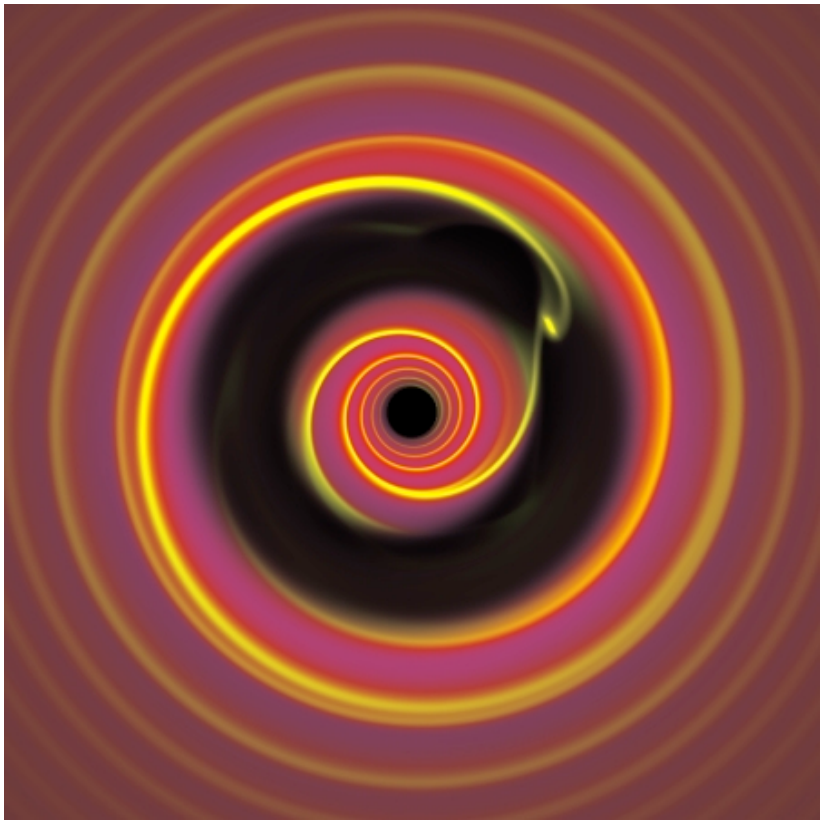

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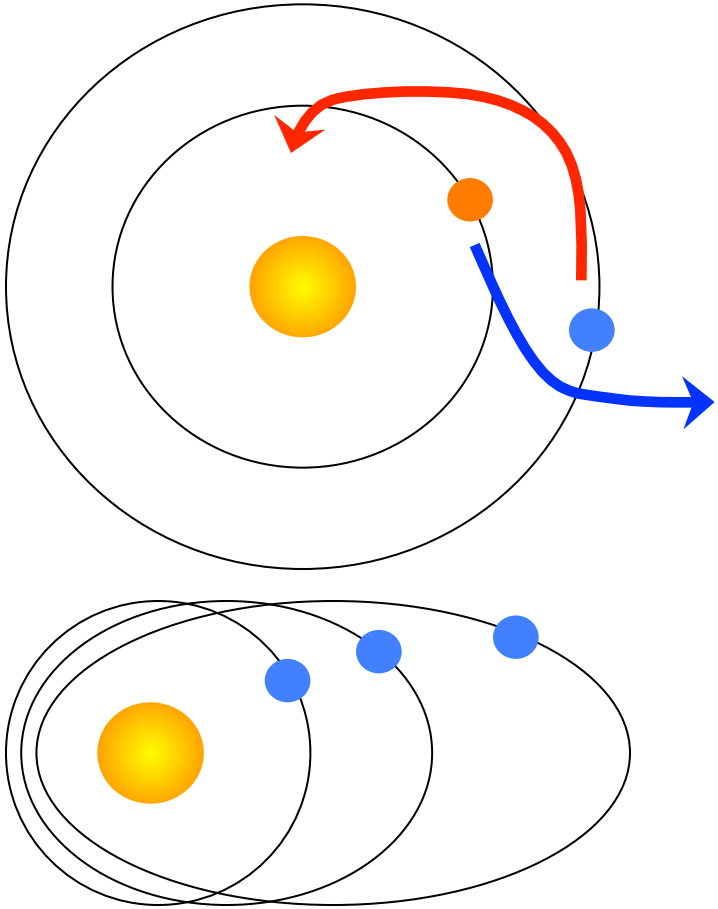
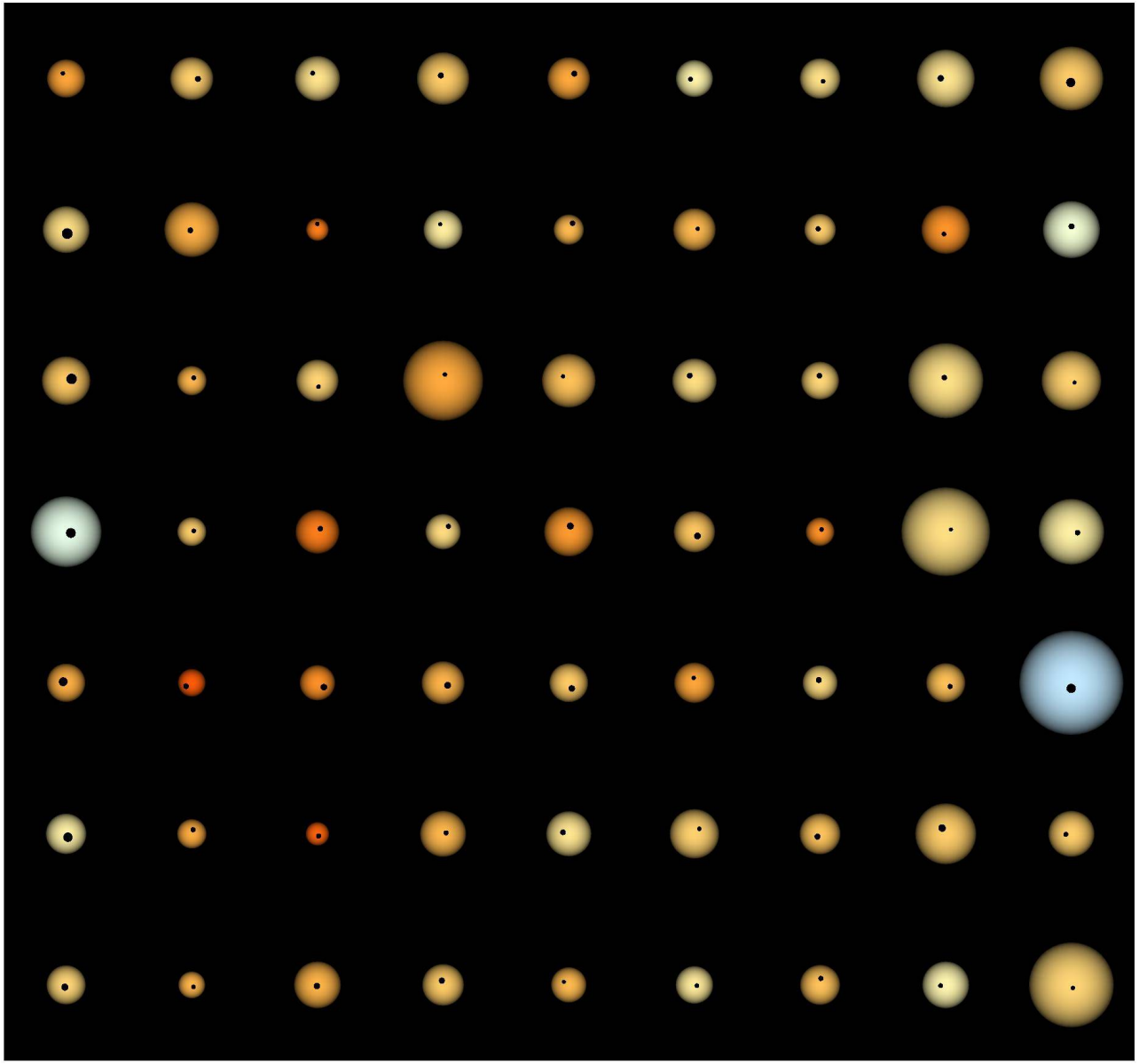
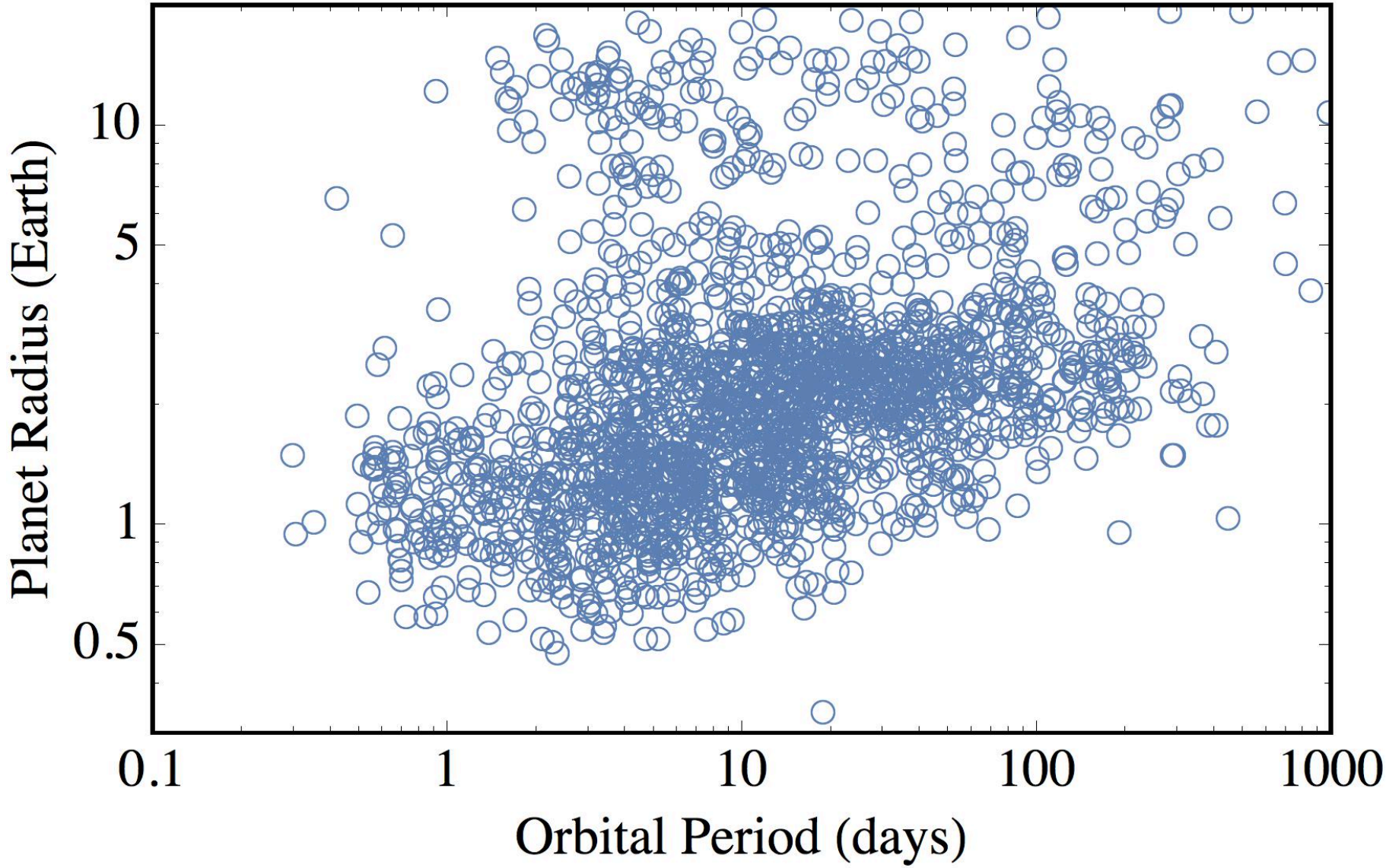


63 Hot Jupiter Systems from Kepler

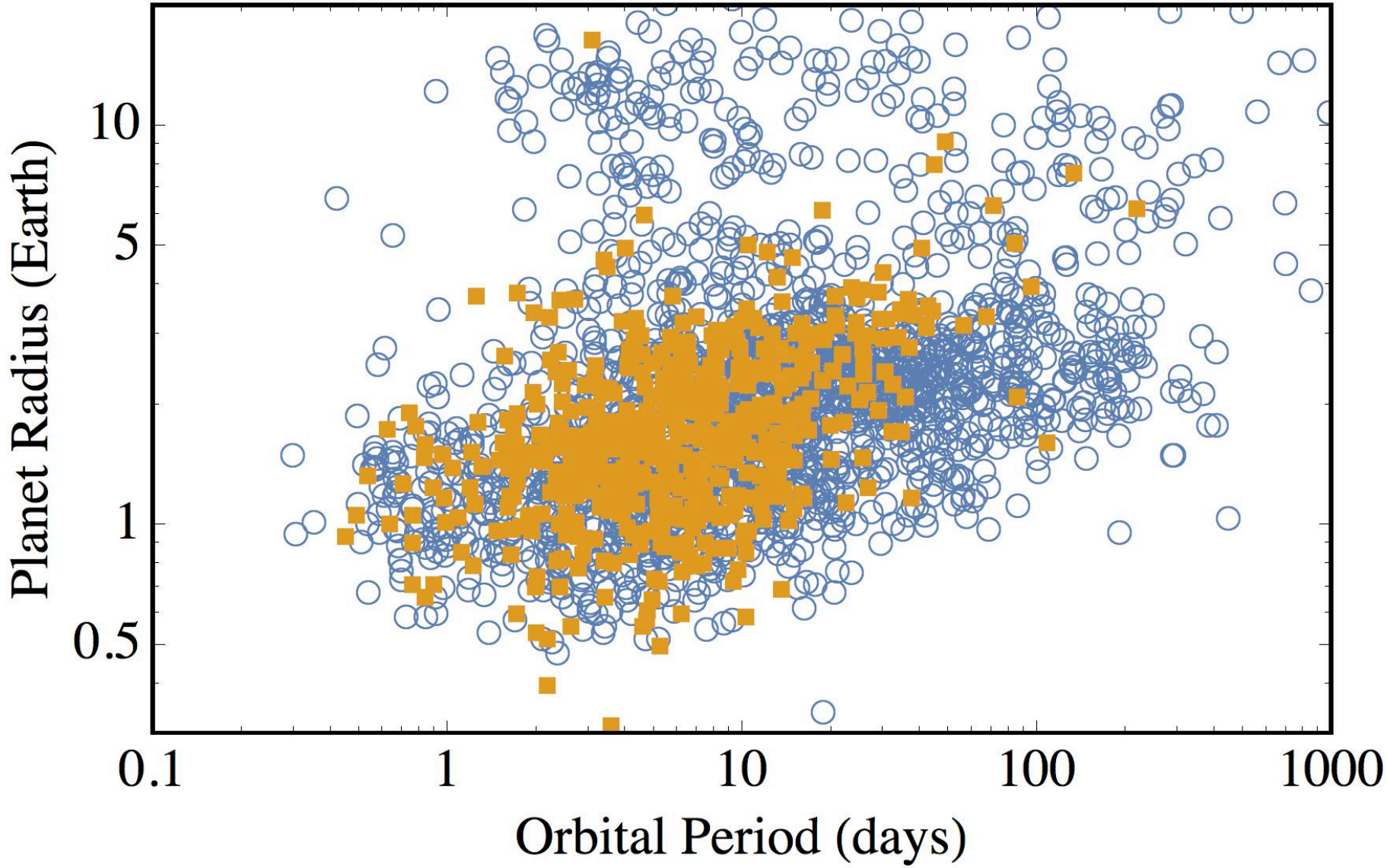


Steffen et al. (2012)

Kepler Singles



Kepler Singles and Multis



Kepler's Hot Jupiter Systems

- No evidence for additional transiting planets

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- Observed multiplanet systems in adjacent samples
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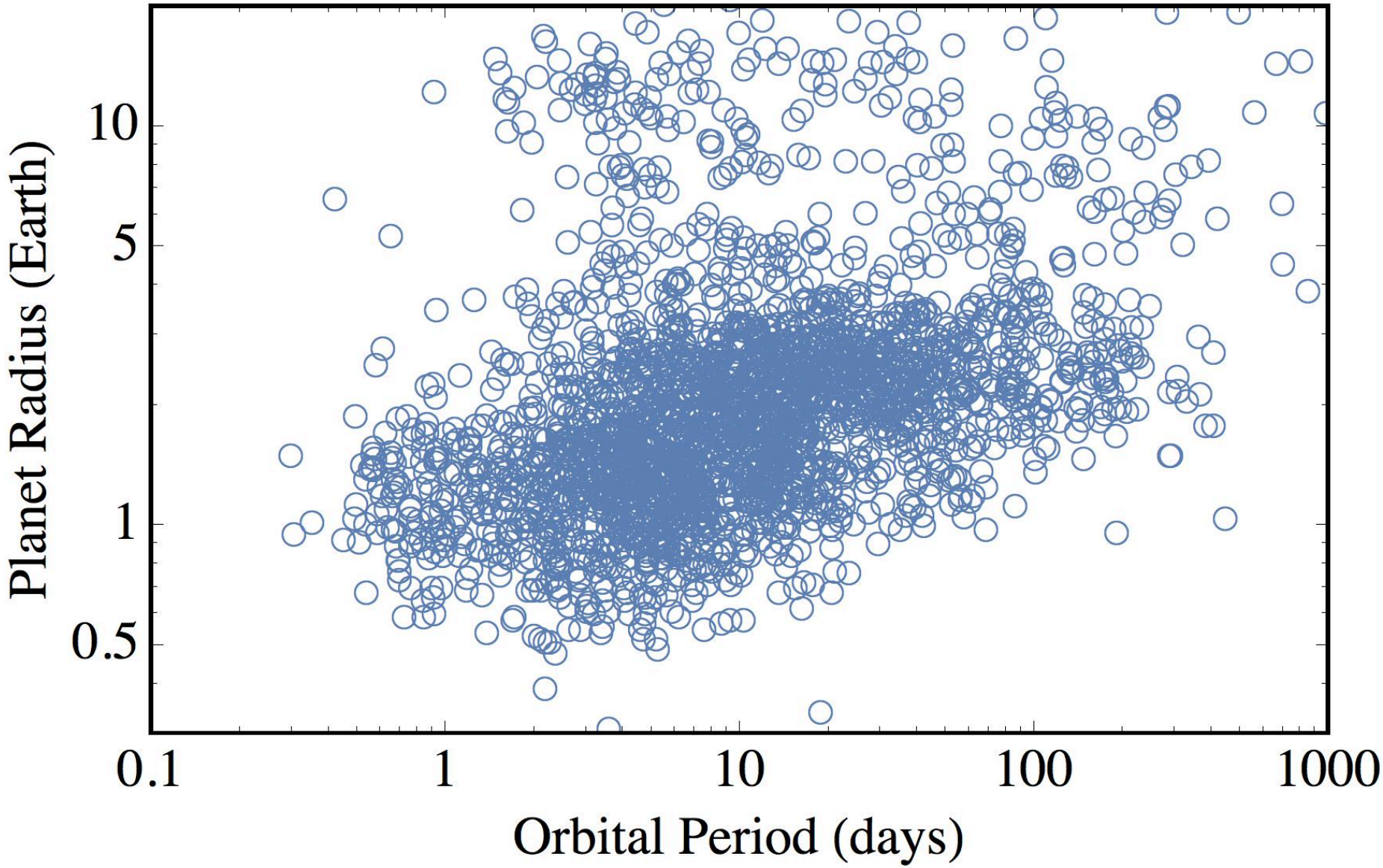
- Hot Jupiters are lonely – Violence and Mayhem likely cause

All Kepler Candidates



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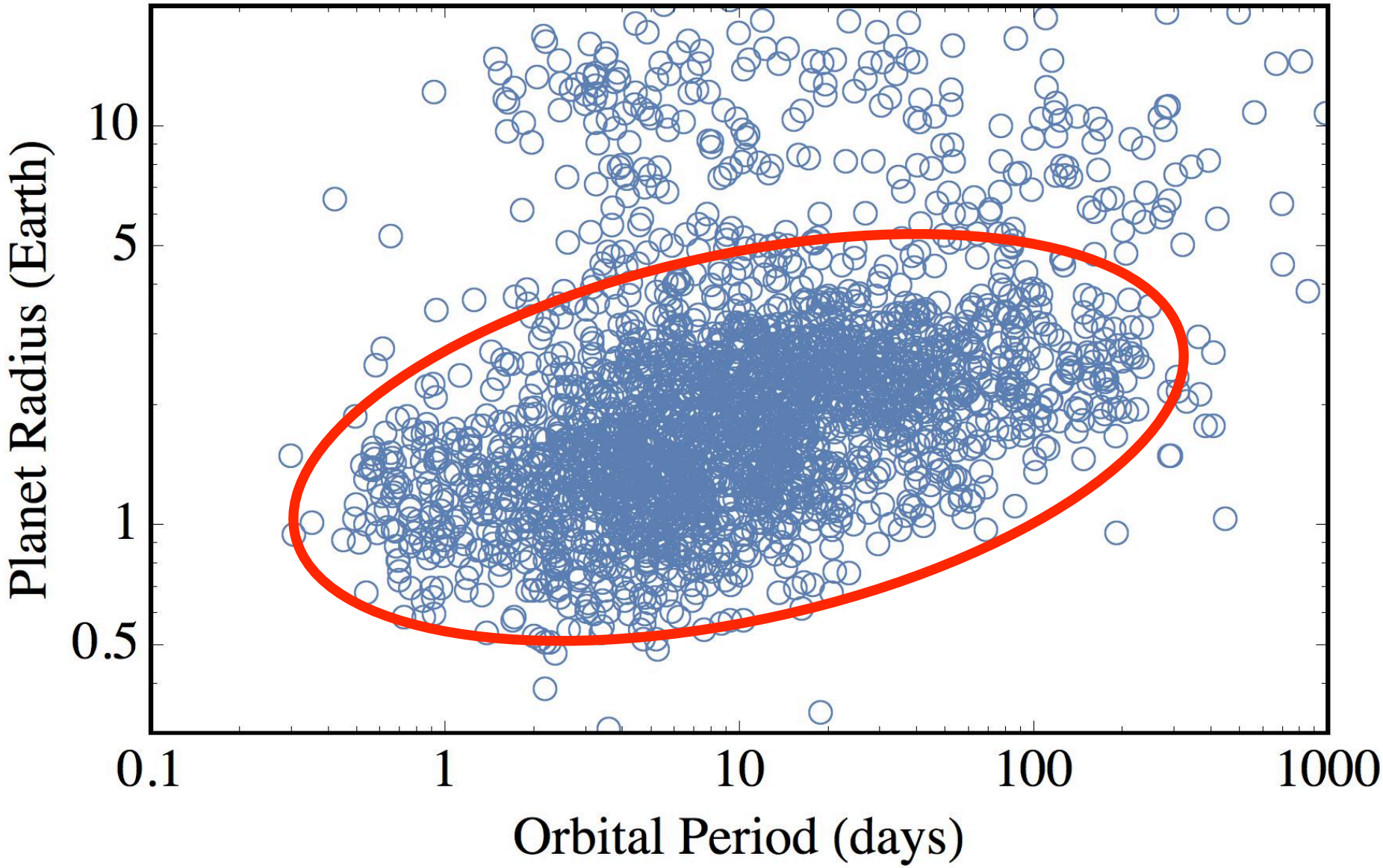
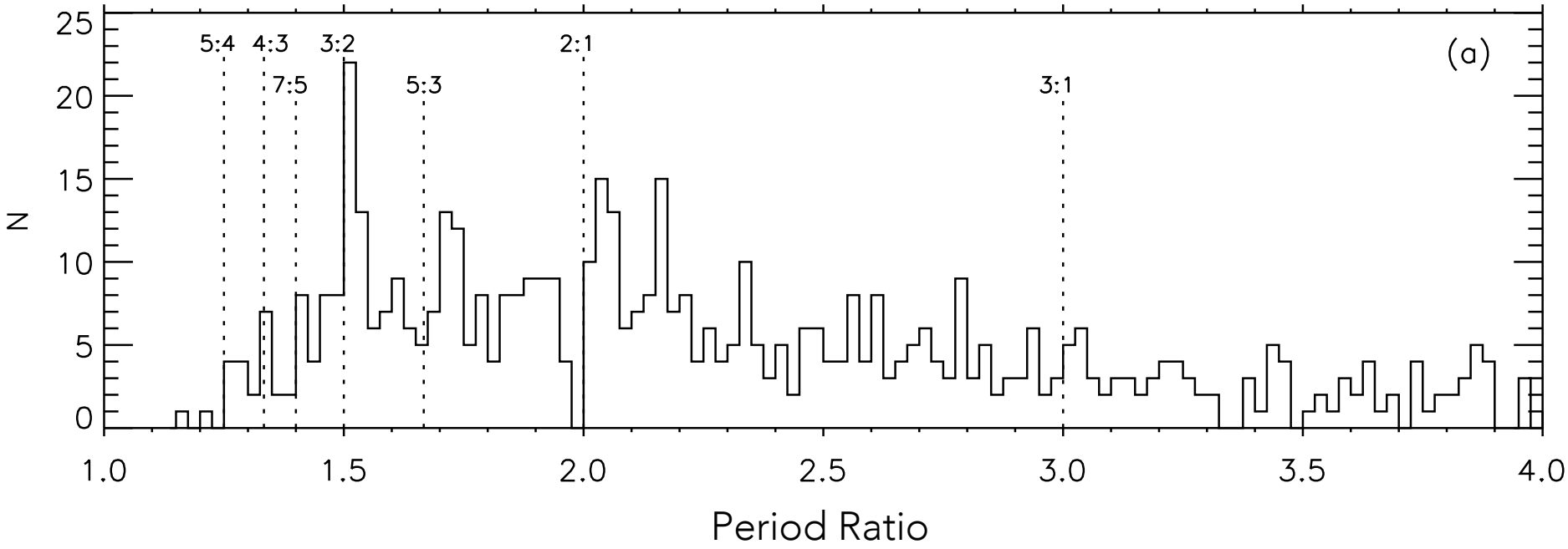


How the other 99% live

Architectures of Multiplanet Systems

Distribution of orbital period ratios



Fabrycky et al. (2014)

Architectures of Multiplanet Systems

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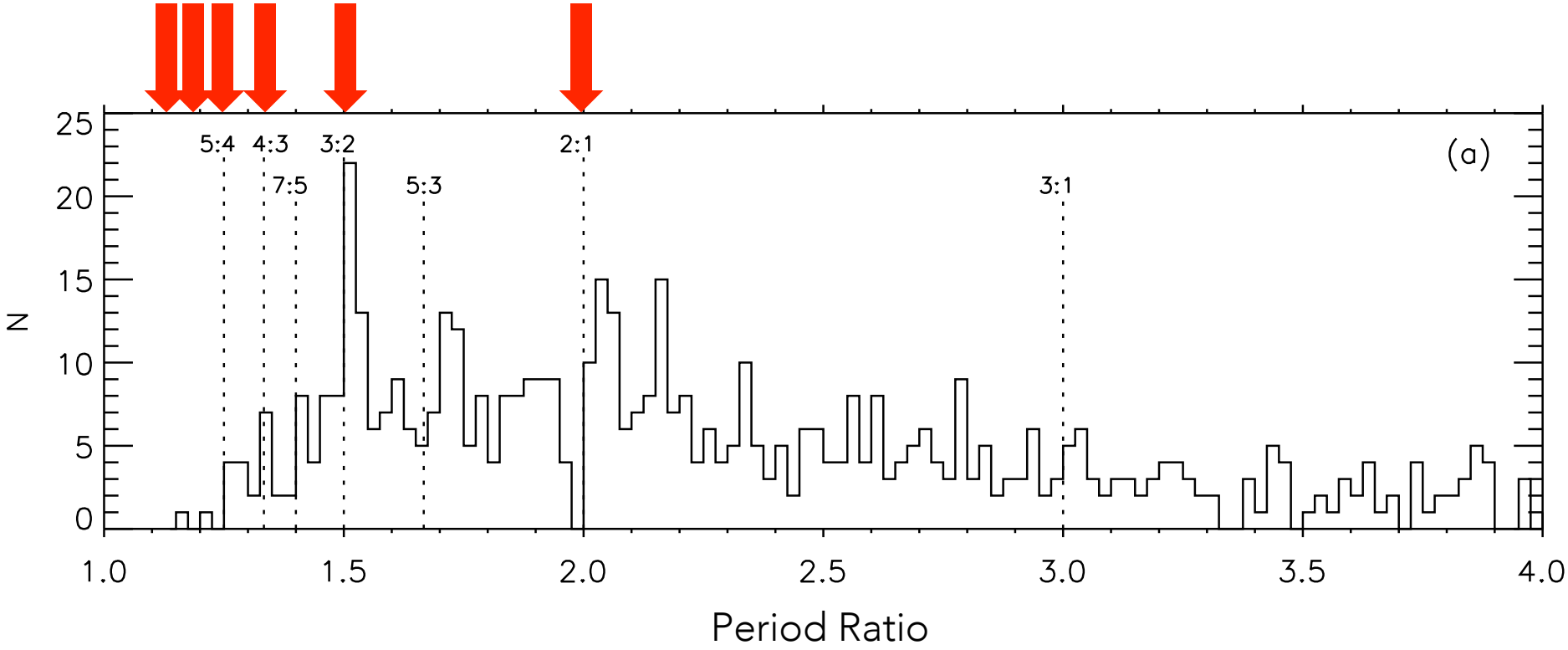
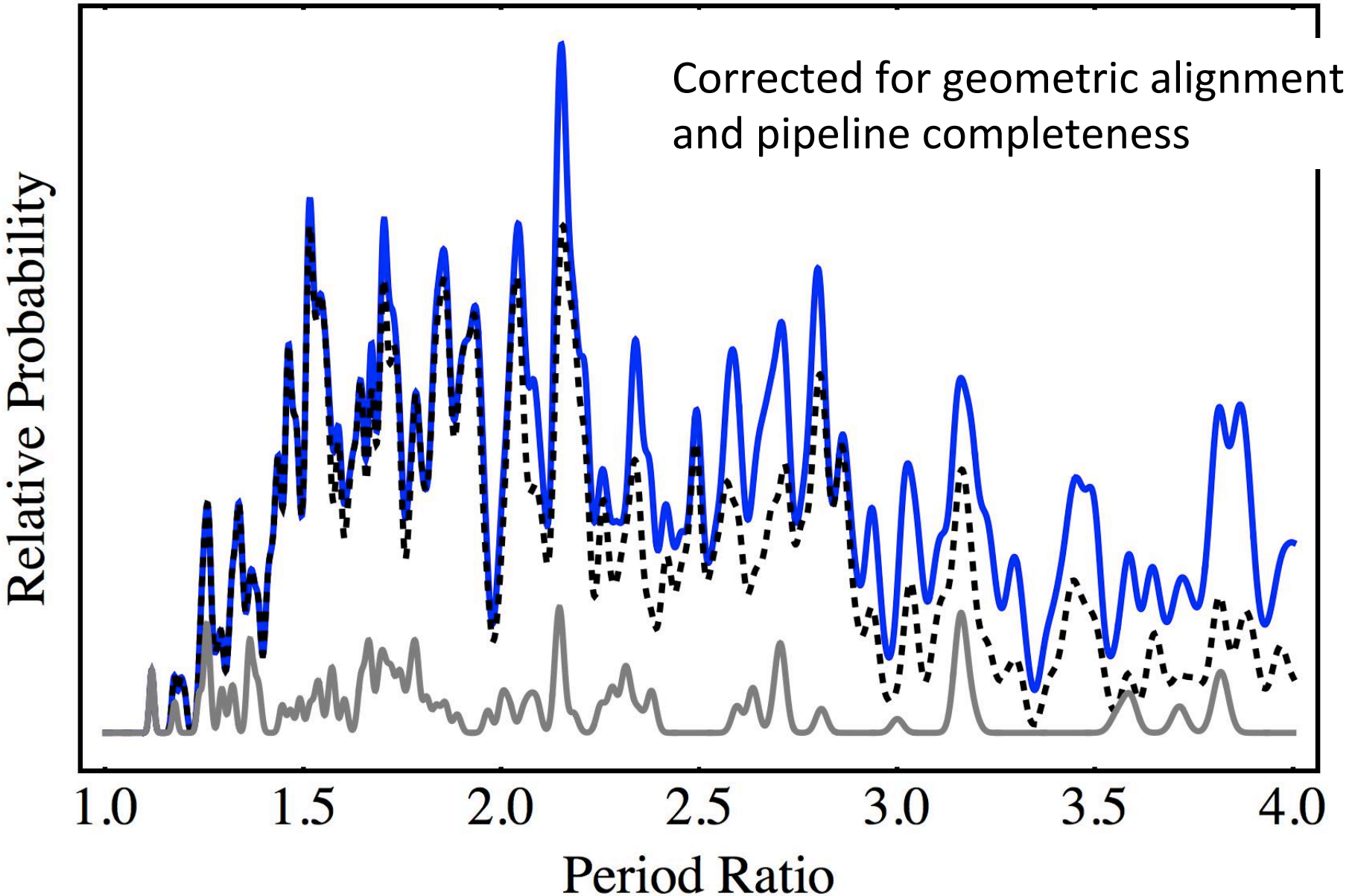


Fabrycky et al. (2014)

Corrected Distribution of Period Ratios



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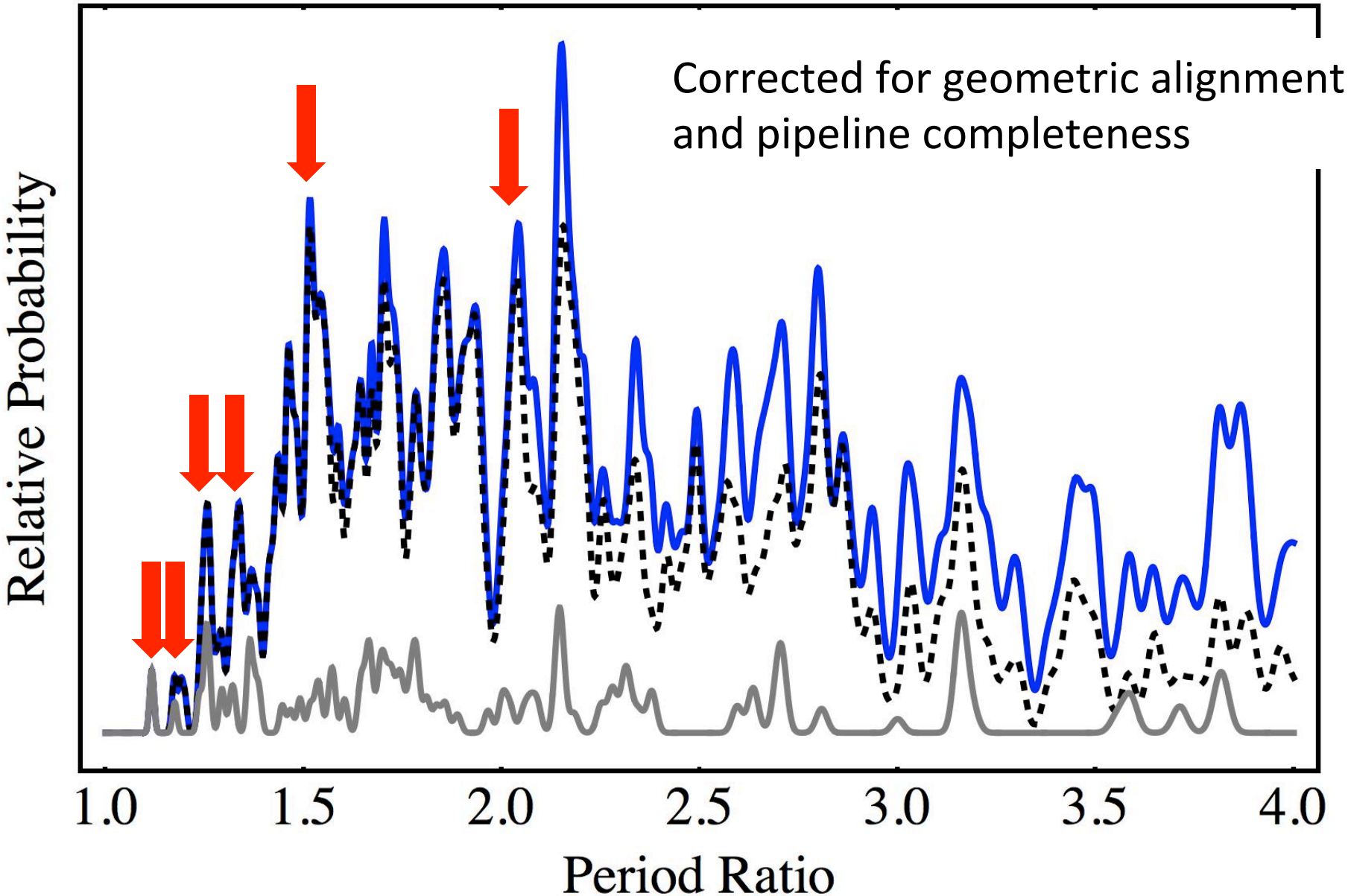
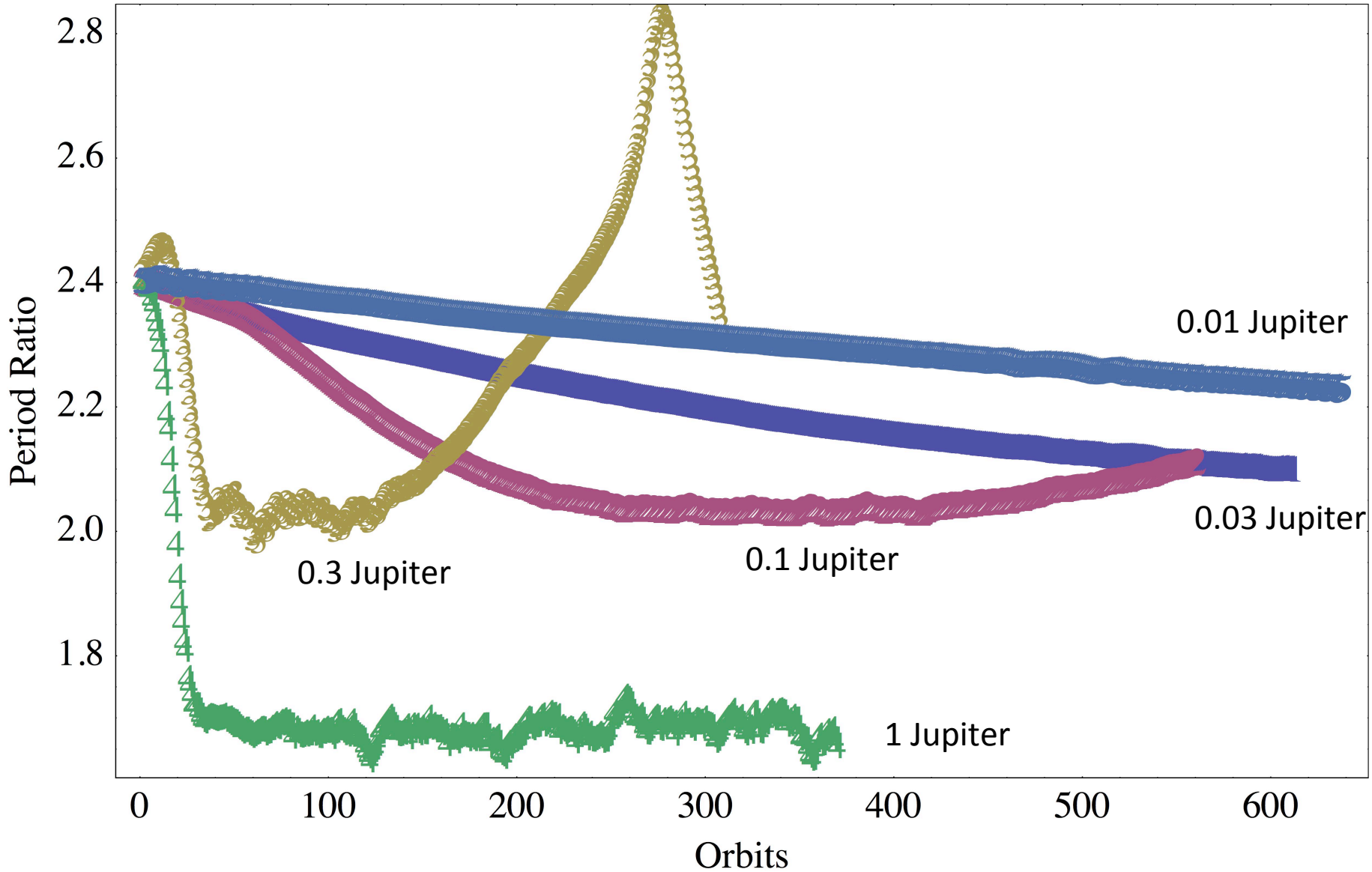


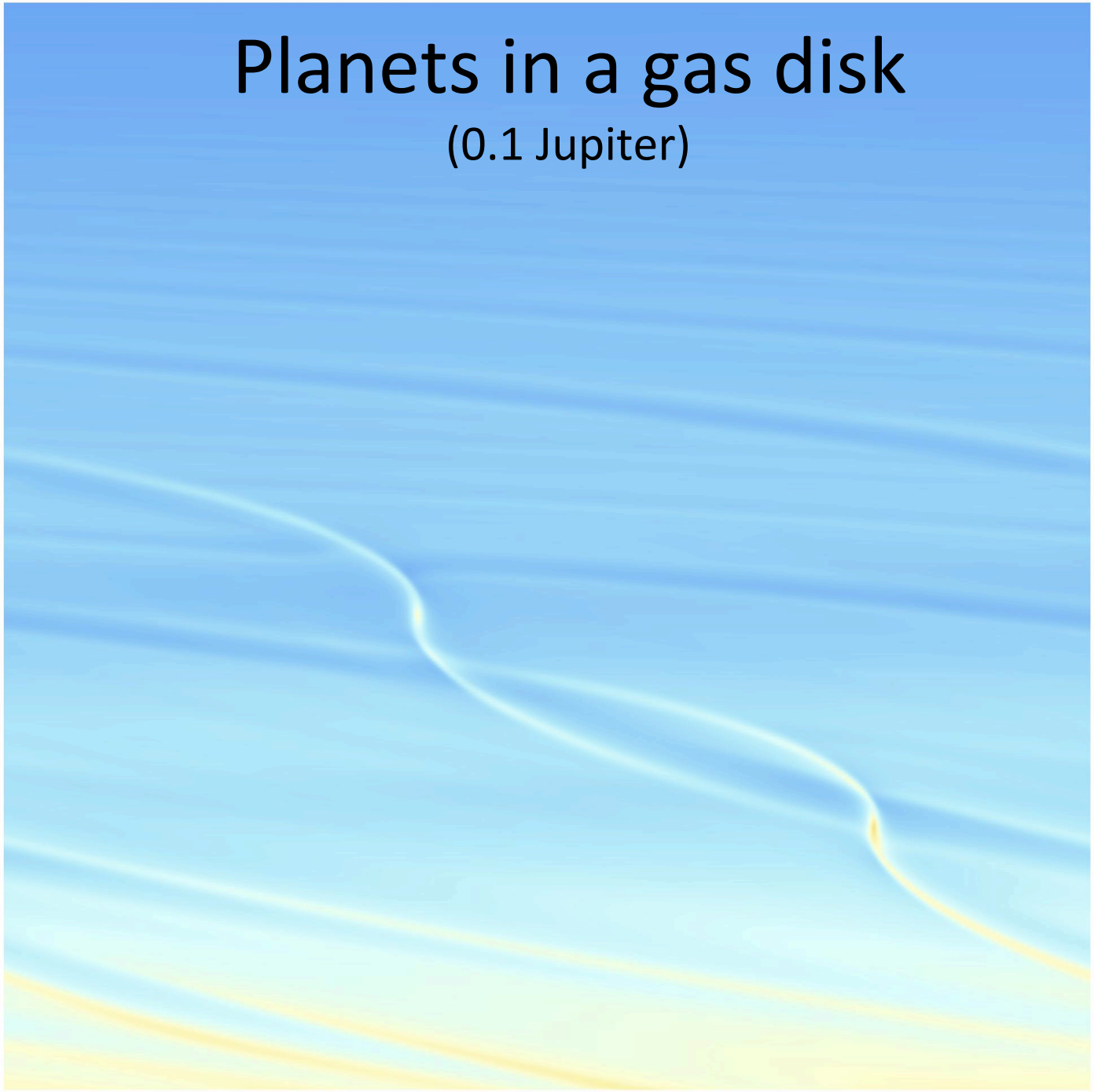
Planets in a gas disk



Emily Ellinger Northwestern

Planets in a gas disk

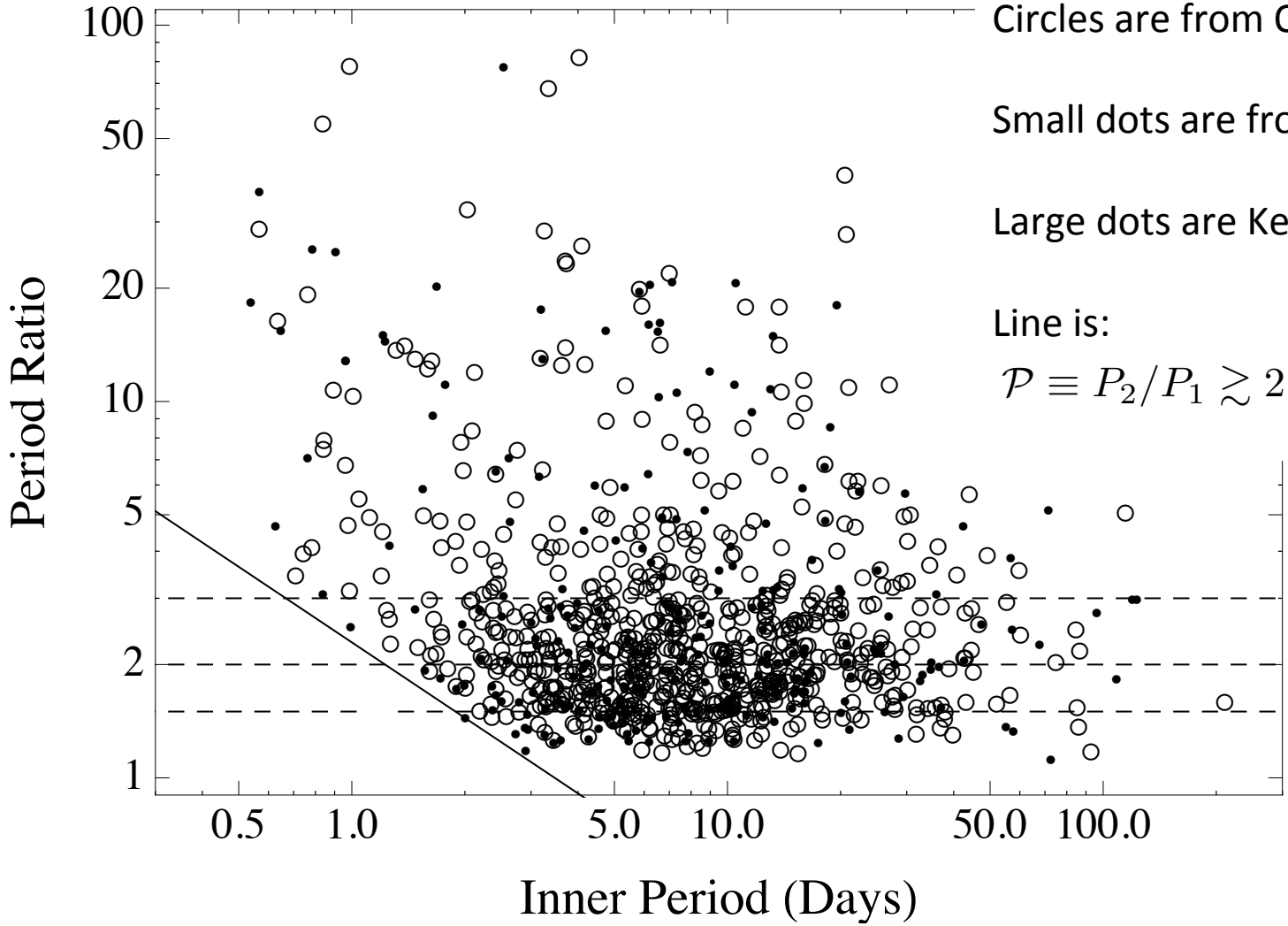
(0.1 Jupiter)



Planets in a gas disk

(1 Jupiter)

Architecture as a Function of Size



Circles are from Q8

Small dots are from Q12

Large dots are Kepler-42

Line is:

$$\mathcal{P} \equiv P_2/P_1 \gtrsim 2.3(P_1/\mathrm{day})^{-2/3}$$

Steffen & Farr (2013c)

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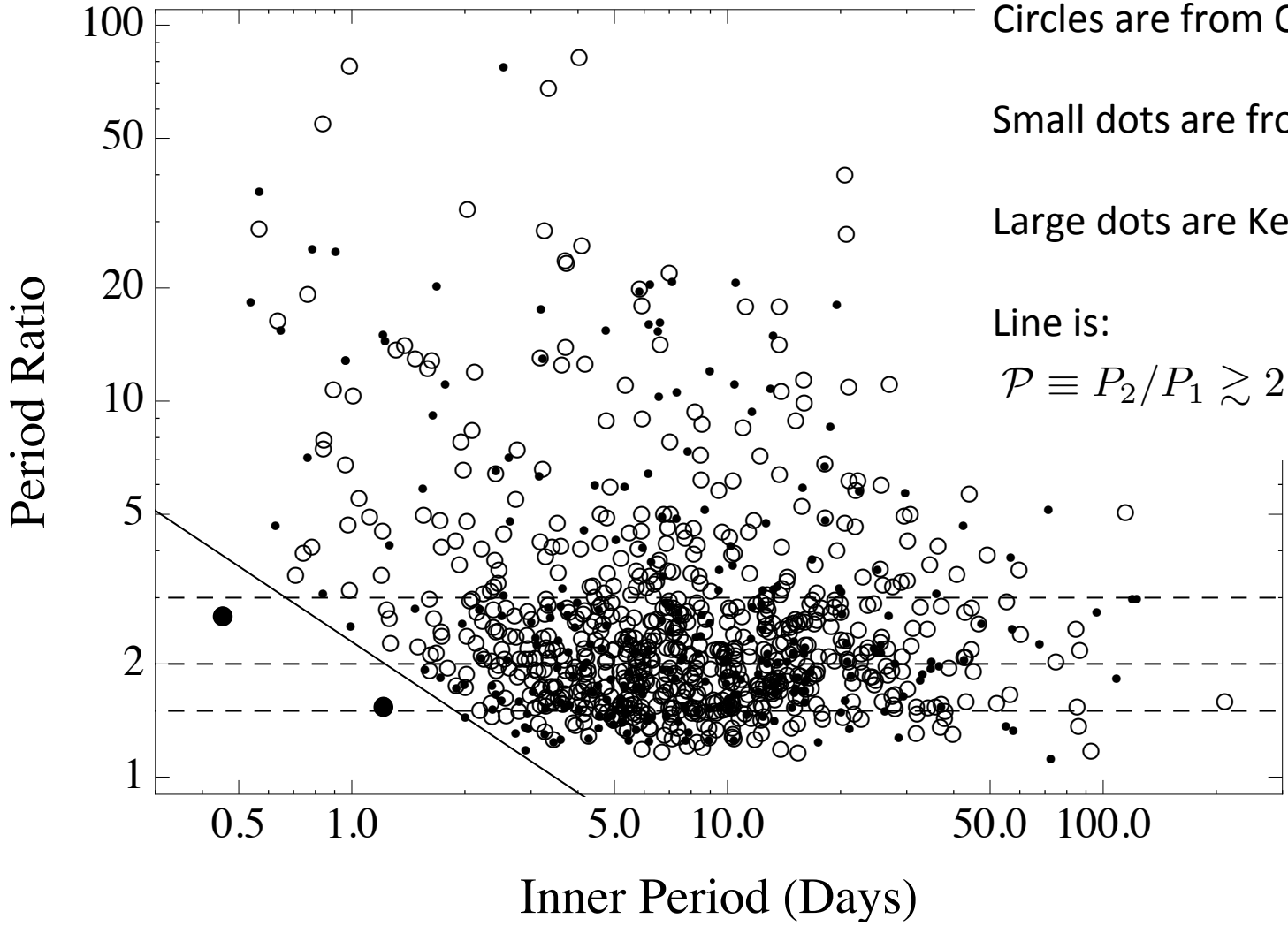

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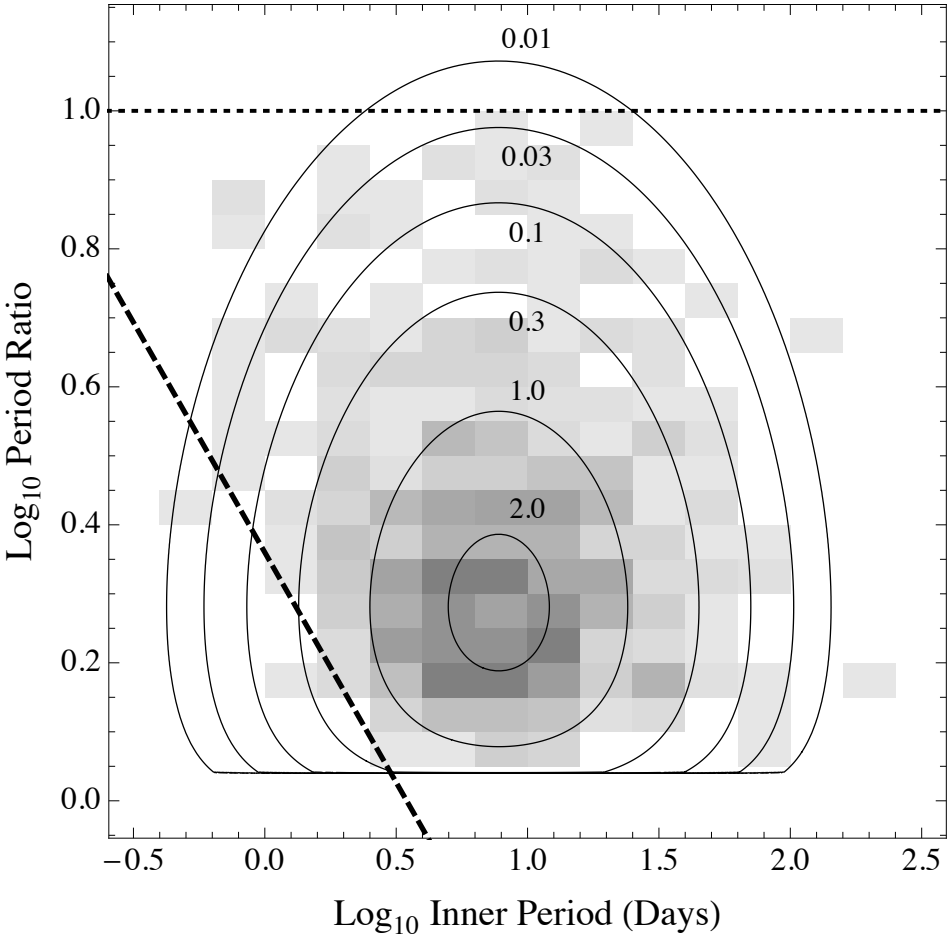

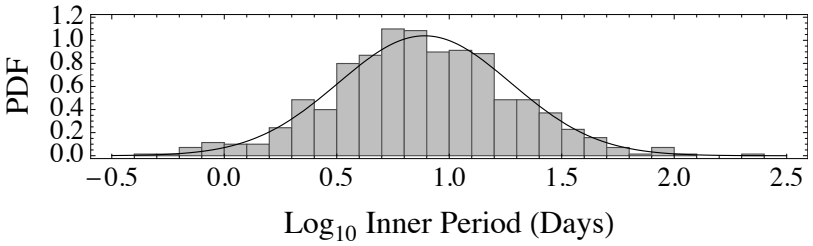

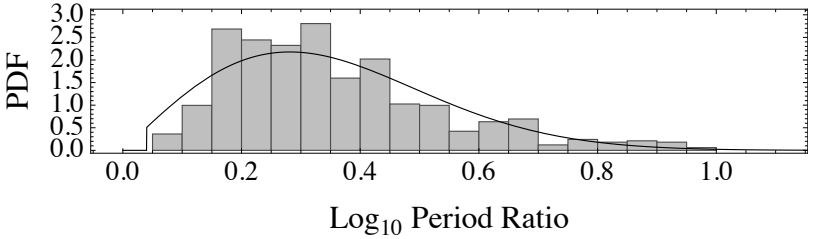

Predict 17.5 ± 5 planet pairs below the dashed line.

Observe two such pairs ($p \approx 0.001$), both in the same system.

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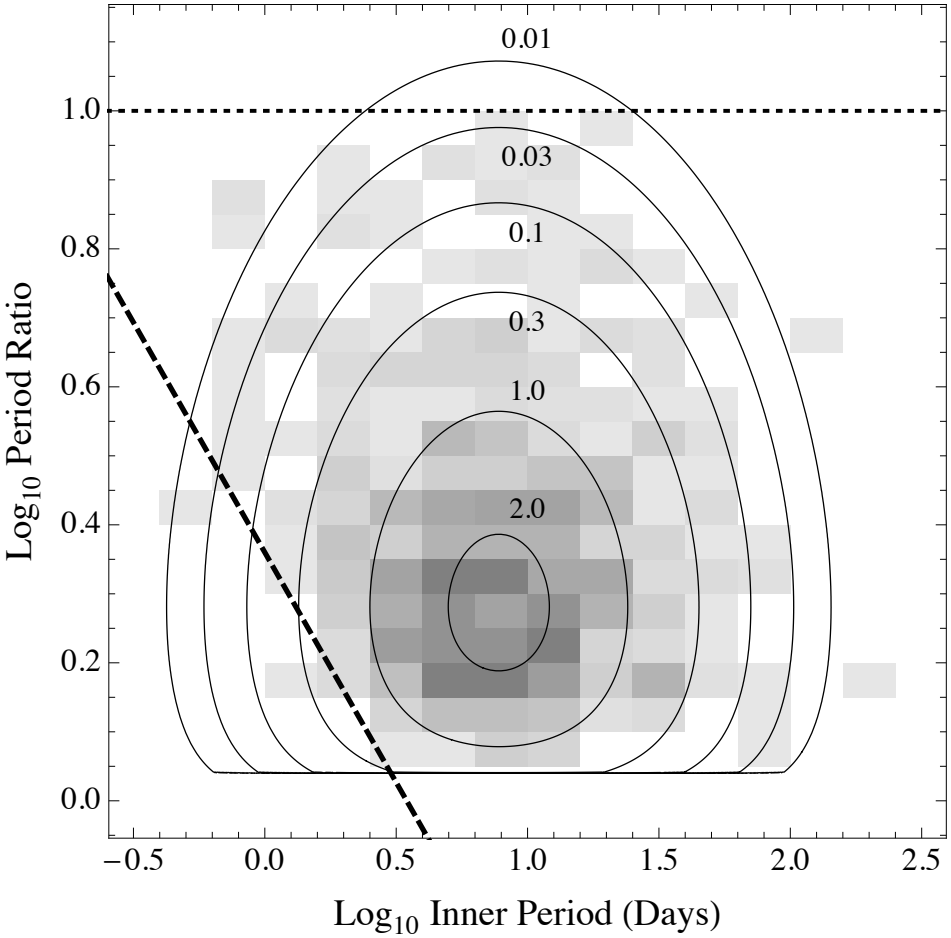

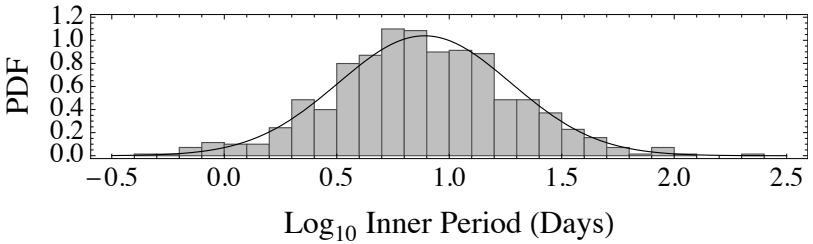

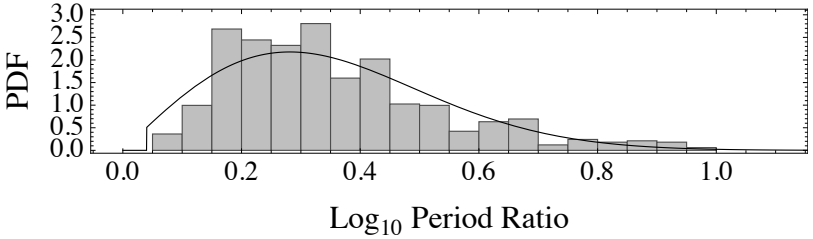

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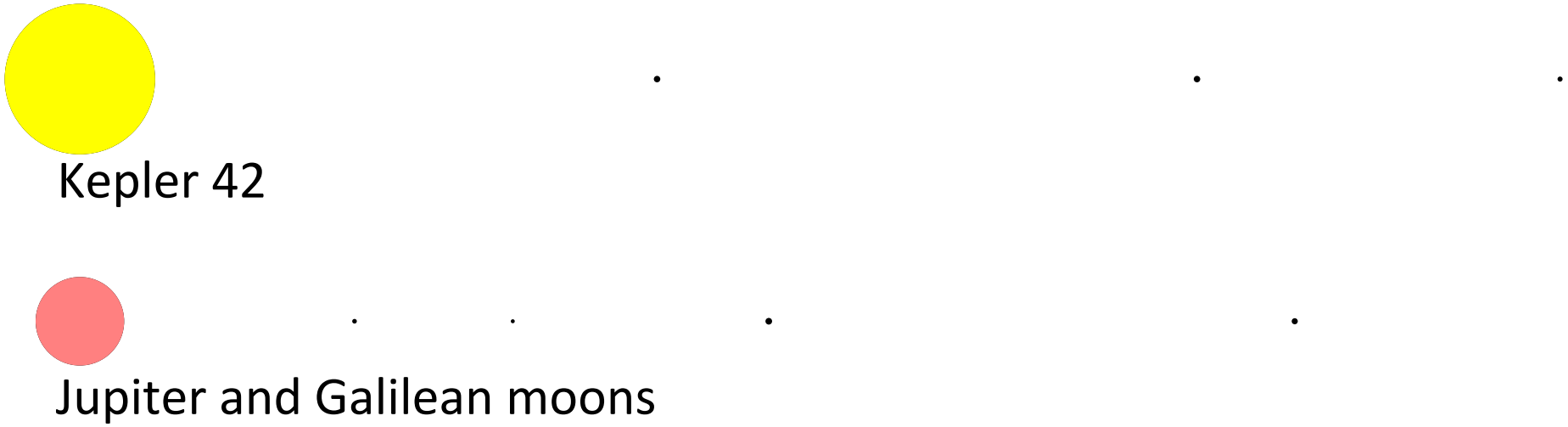
Some additional physics must be included to explain this feature.

Steffen & Farr (2013c)

Kepler 42, Jupiter, and Mercury



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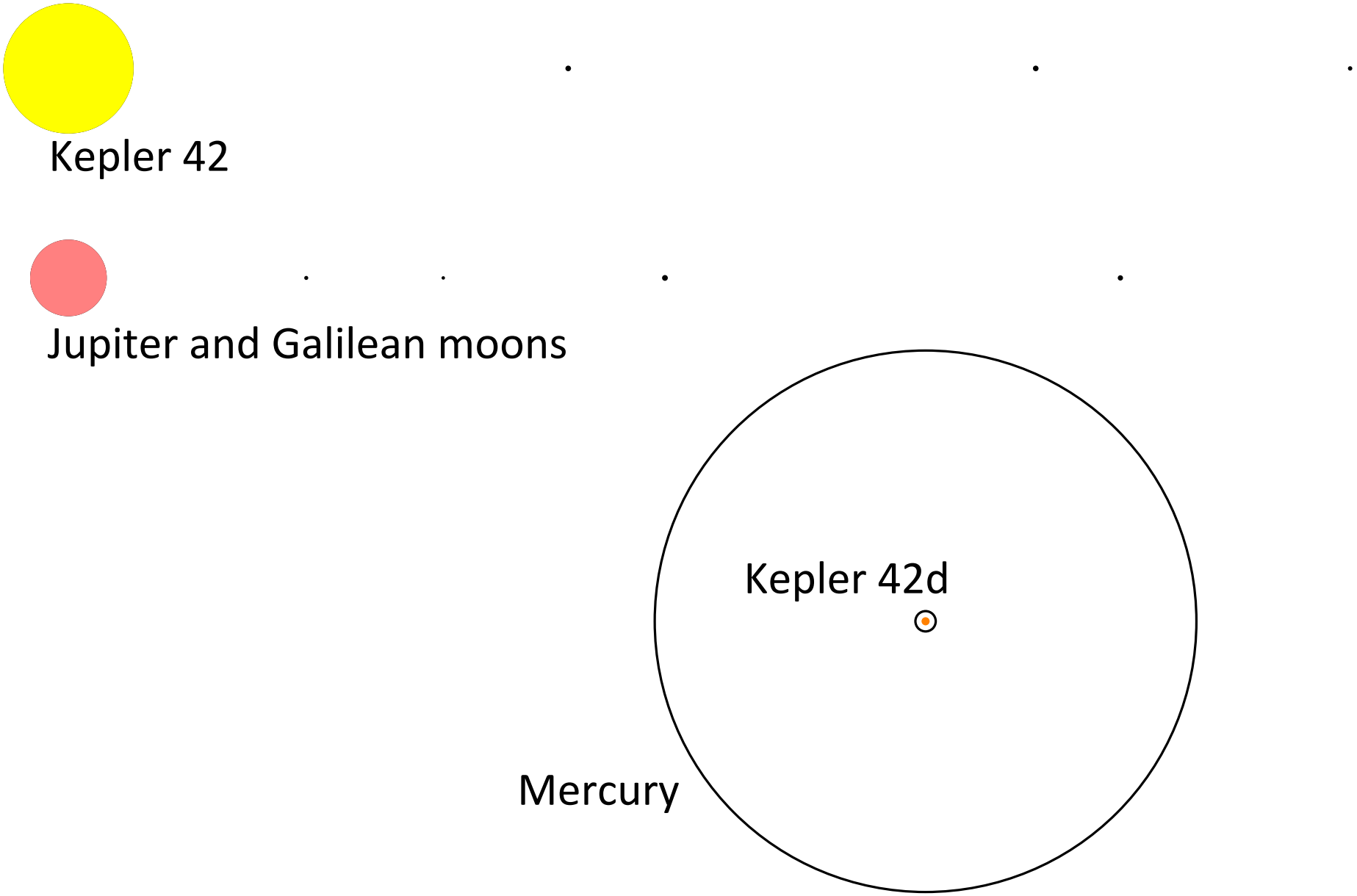
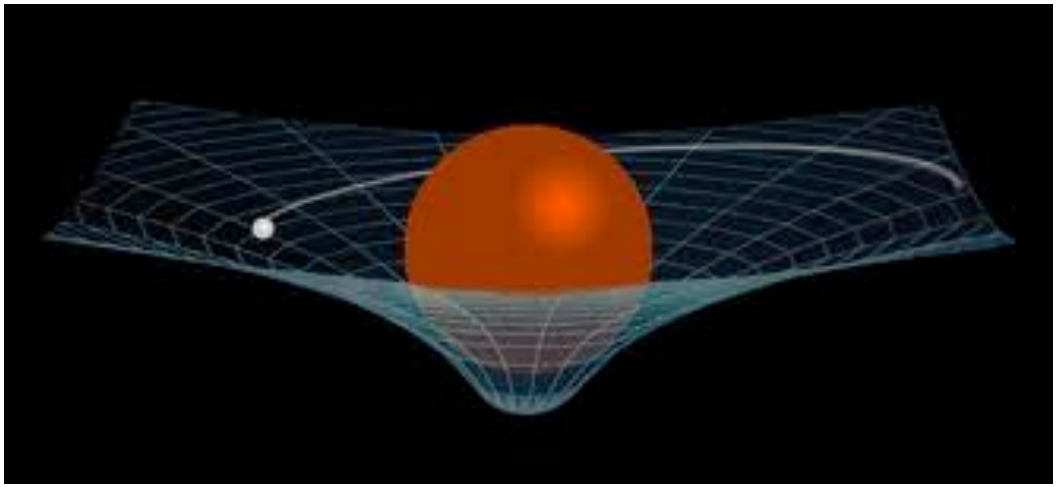
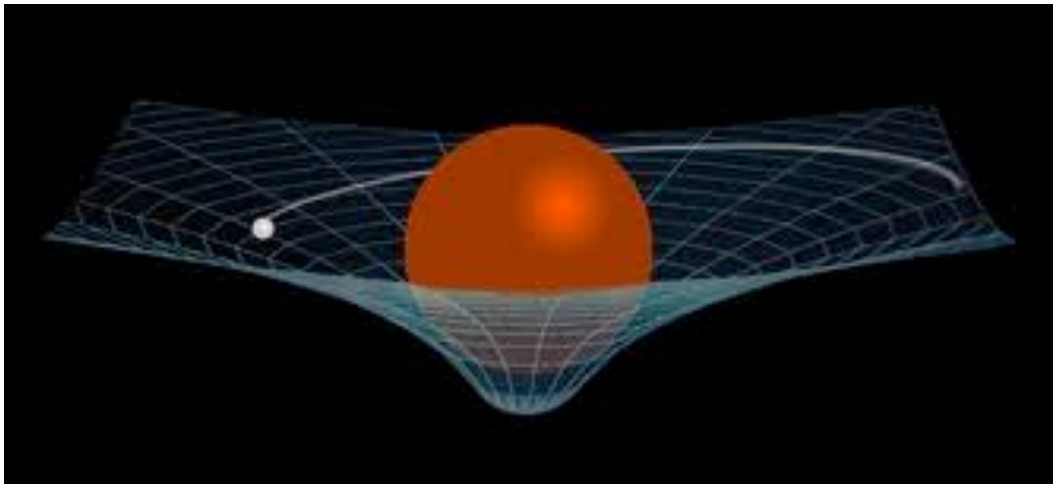


Physics Beyond the Standard Model



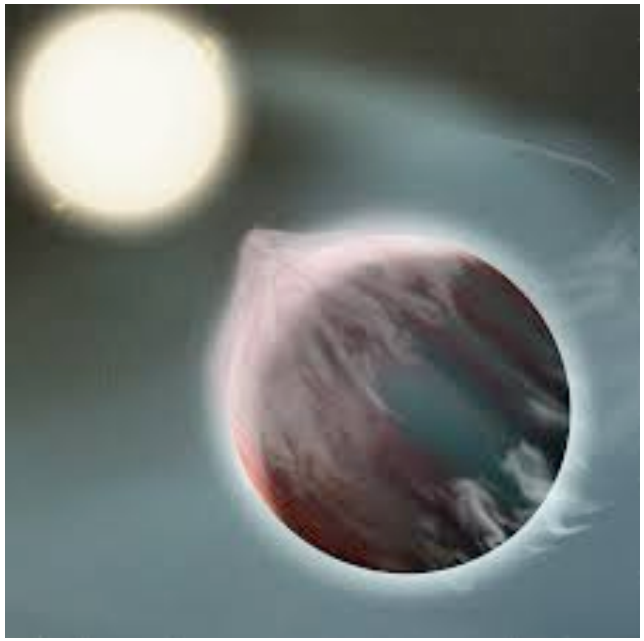
Relativity

Physics Beyond the Standard Model



Relativity

Tides



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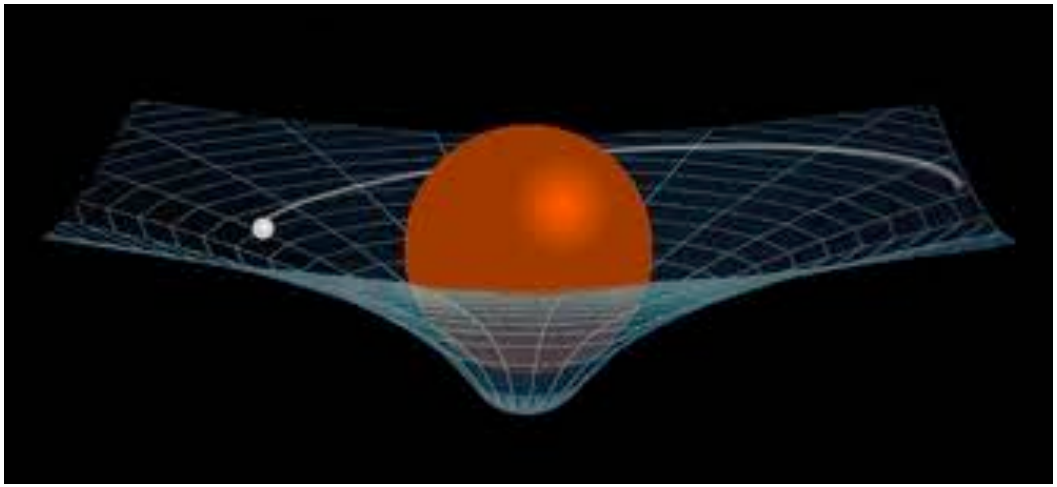

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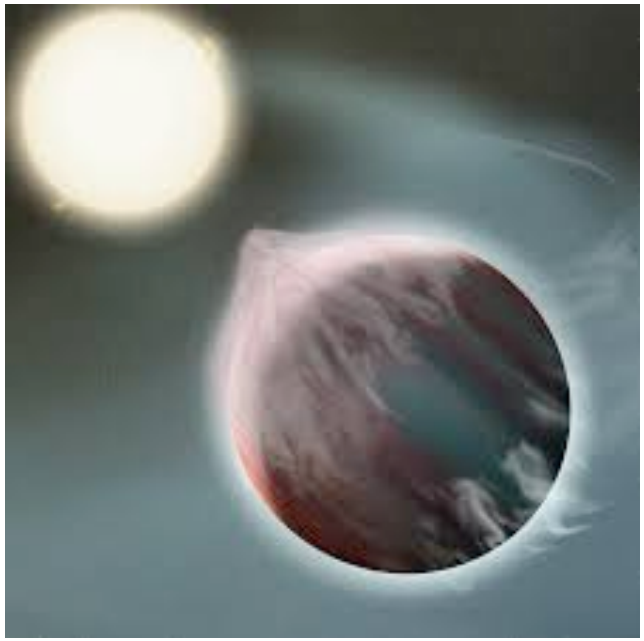
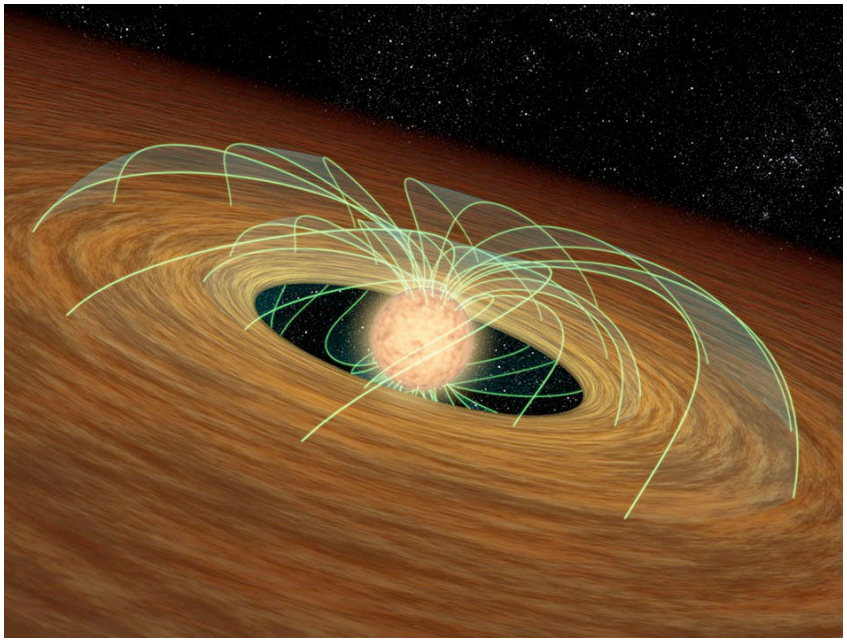


Magnetic Fields



Architecture of Kepler Systems

- Most systems are consistent with high multiplicity and missing planets

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- There is "physics beyond the standard model" as orbital periods decrease
- Significant excess of planet pairs near a period ratio of 2.2 (Not a ratio one would naturally predict.)

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Limitations of Kepler:

- Sensitivity falls off rapidly for P > 400 days
- Mutual inclinations prevent many detections
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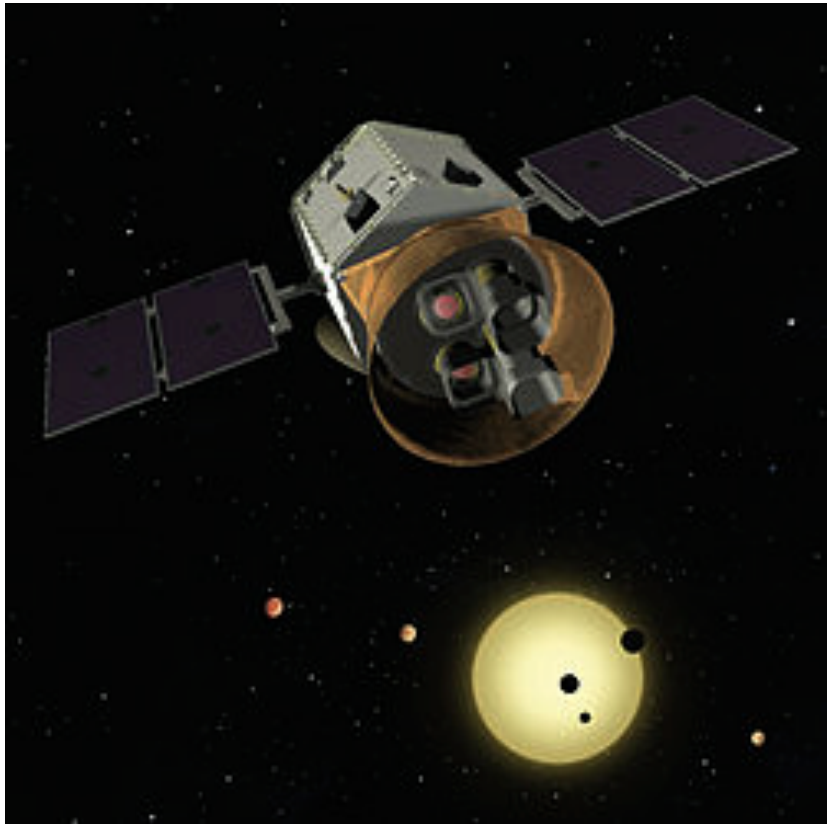

NASA's TESS Mission

Whole System Architectures

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Advantages of TESS:

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However:

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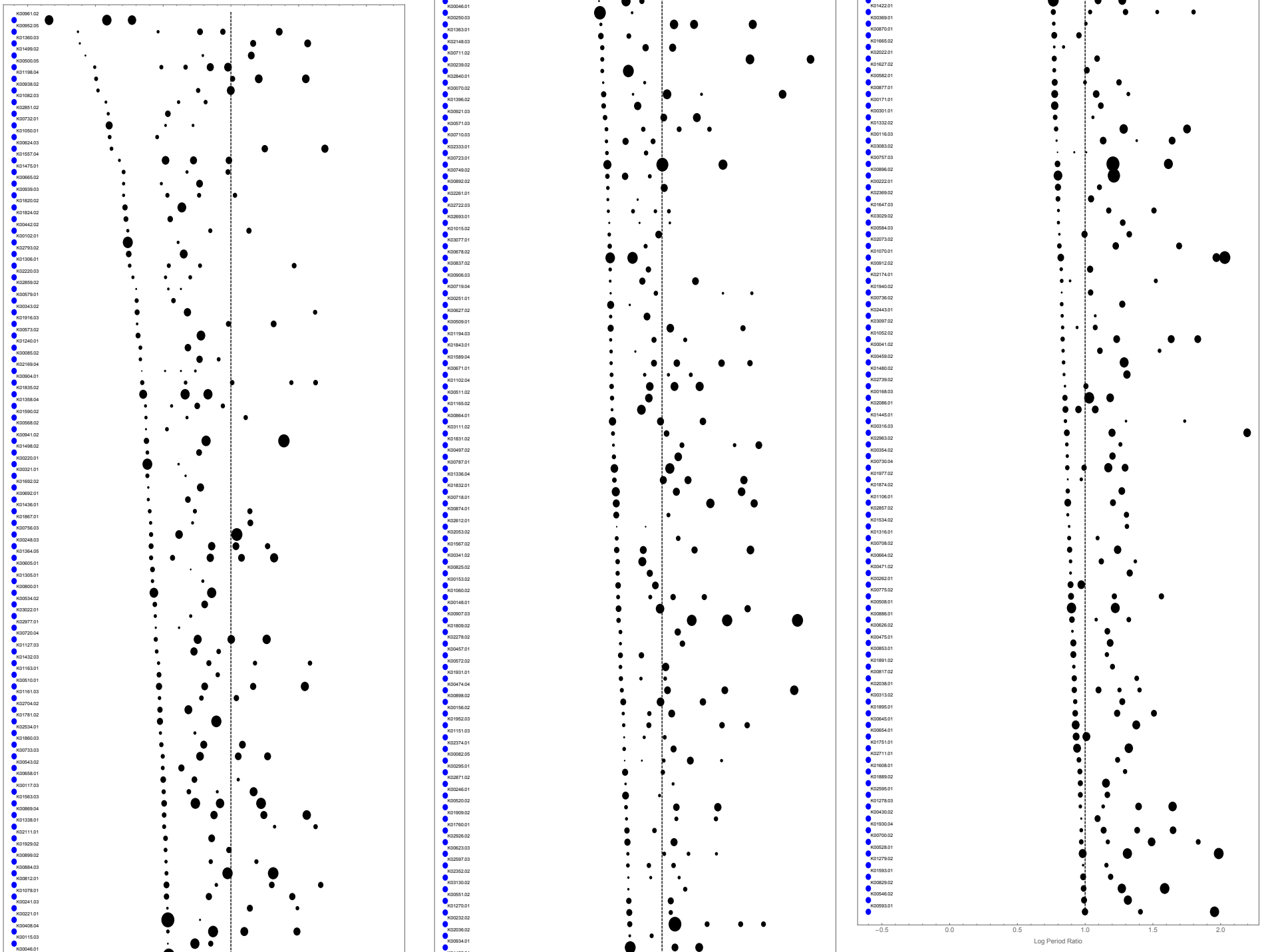
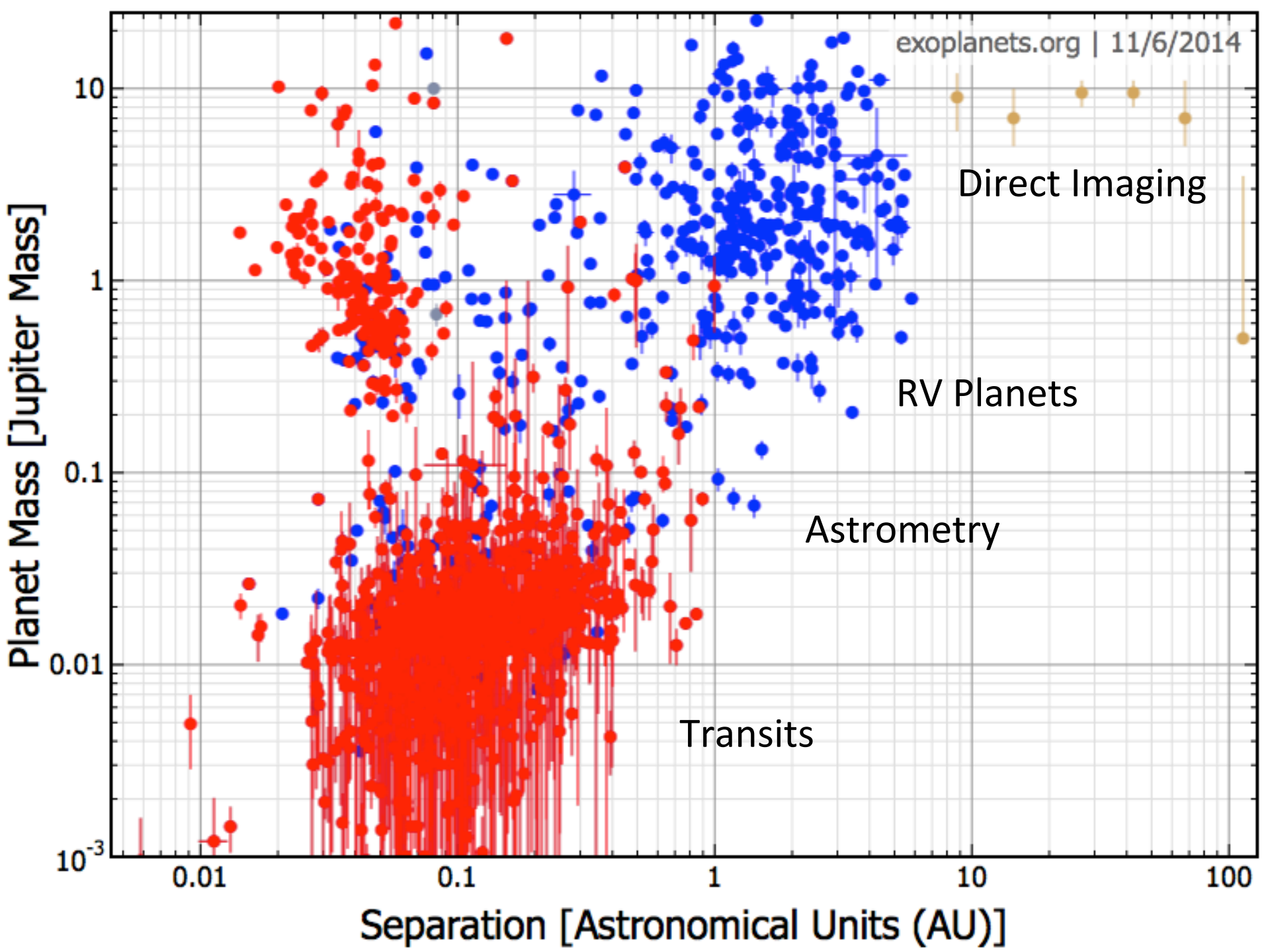
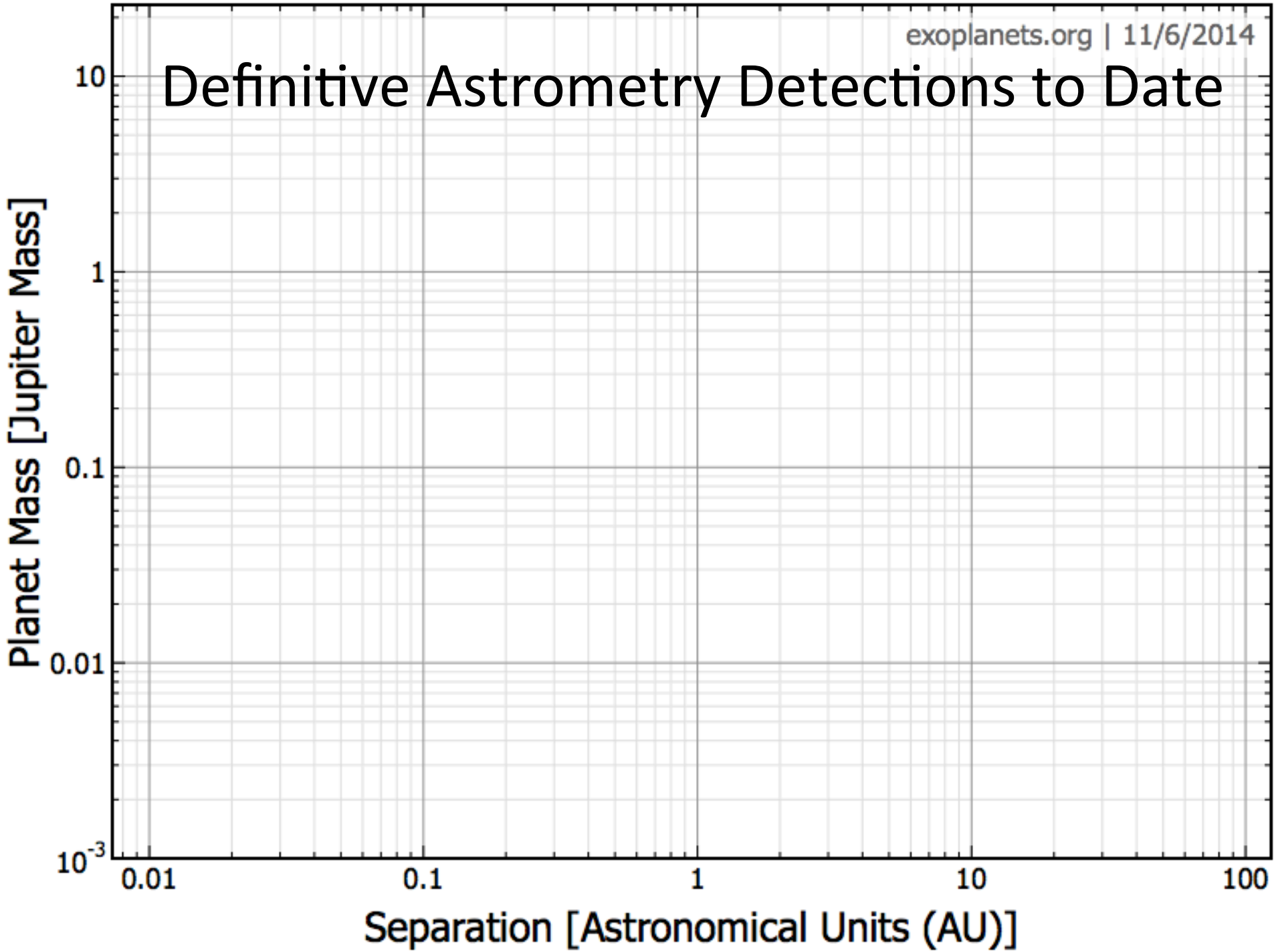
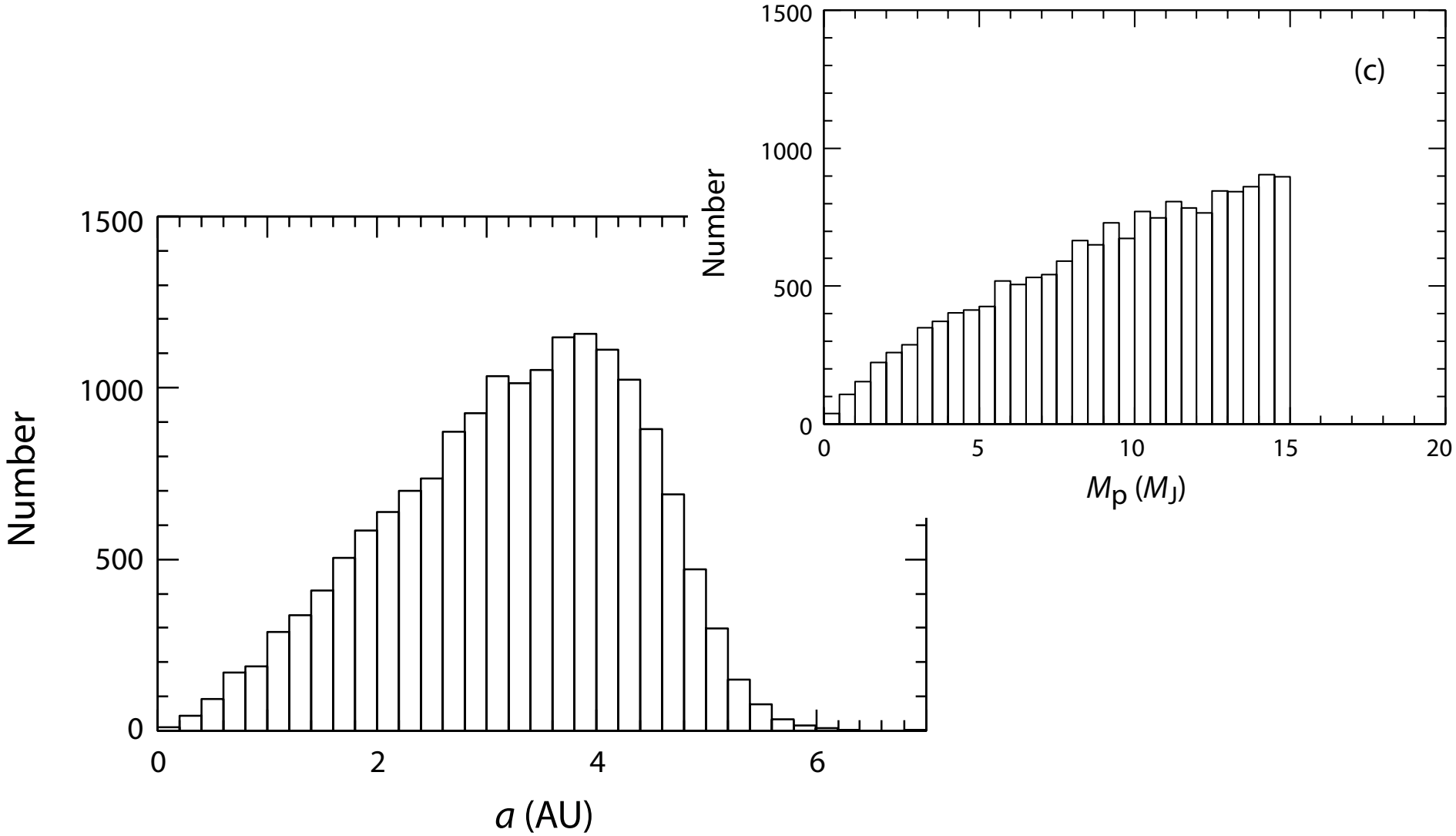

−0.5
0.0
0.5
1.0
1.5
2.0
Log Period Ratio


exoplanets.org | 11/6/2014
Direct Imaging
RV Planets
Astrometry
Transits
Planet Mass [Jupiter Mass]
Separation [Astronomical Units (AU)]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100

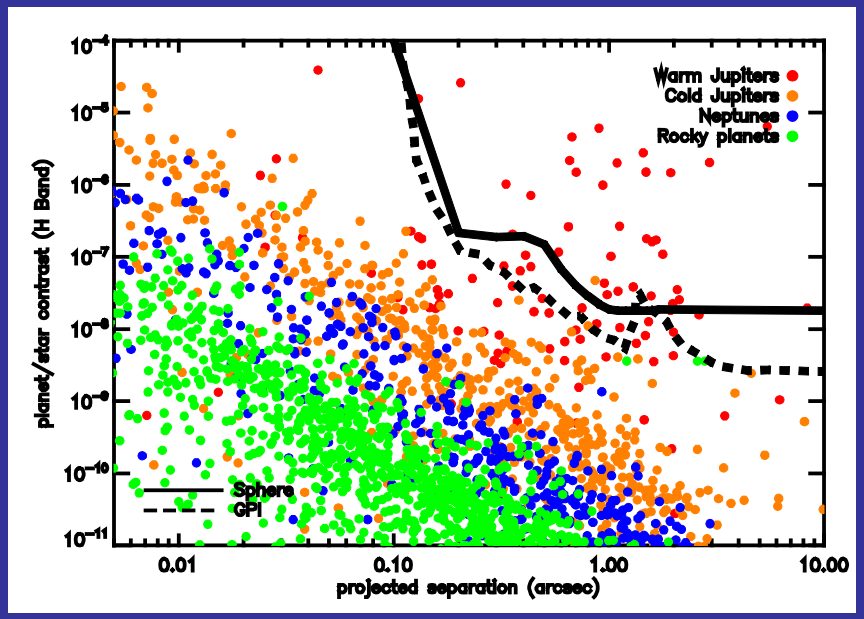

exoplanets.org | 11/6/2014
Definitive Astrometry Detections to Date
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]

Predicted Astrometry Detections from GAIA

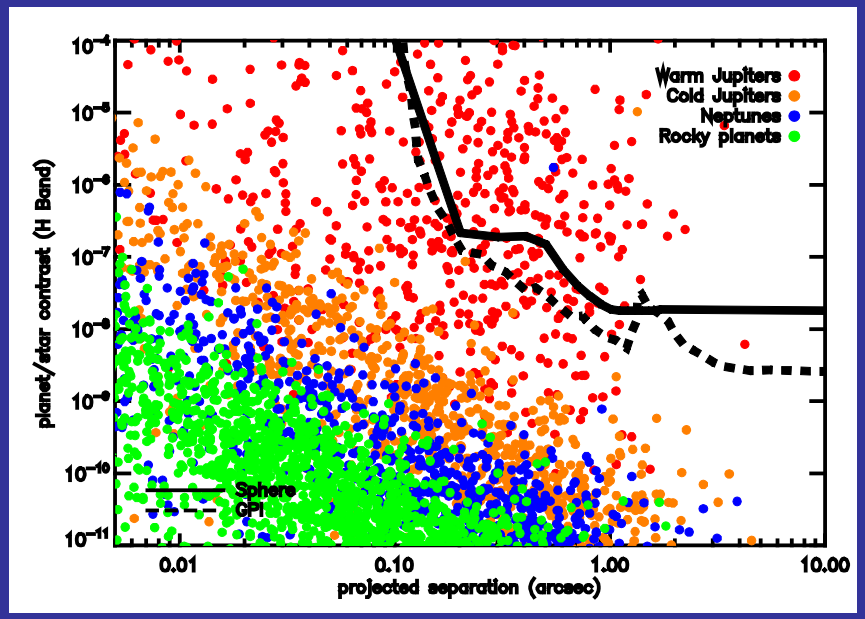


Perryman, Hartman, & Bakos (2014)

Planets observable with Sphere and GPI (2013-)



Nearby stars (<20 pc)



Young stars (<5 10^8 yrs)

➔Tens of young giant planets at rather large separations

Slide stolen from R. Gratton

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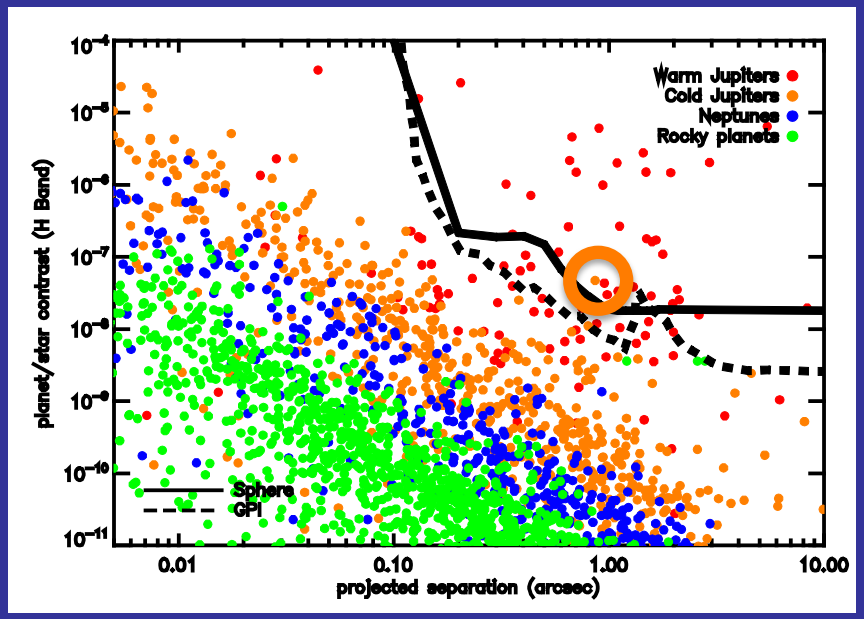

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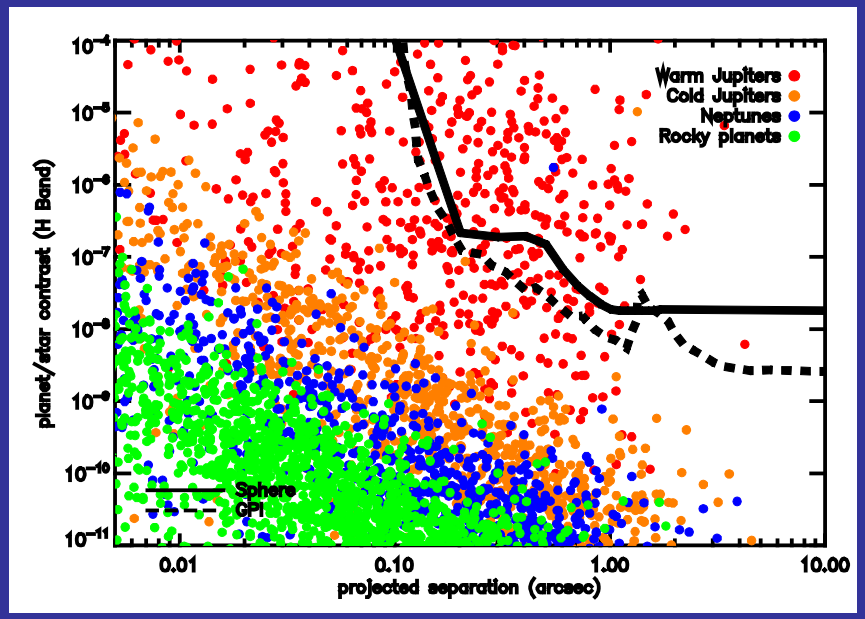

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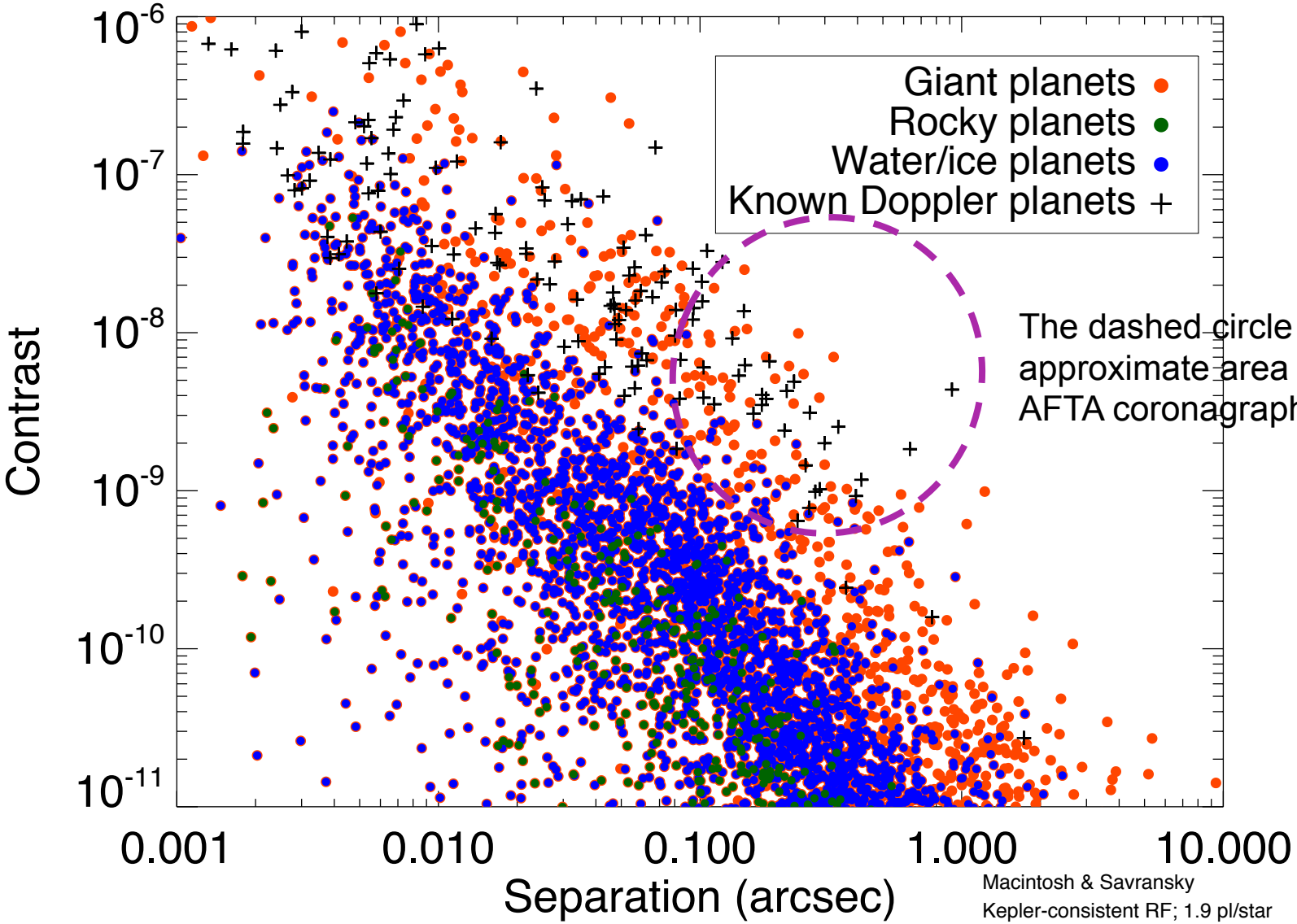
Simulated Planets within 30 pc



The dashed circle indicates the approximate area of WFIRST-AFTA coronagraph sensitivity

Macintosh & Savransky
Kepler-consistent RF; 1.9 pl/star
Main sequence non binary stars

TESS A & D Working Group

Measurement and Interpretation of Whole System Architectures

- Coordinate Transit, RV, Astrometry, Direct Imaging measurements
- Identify additional planets at a wide range of periods
- Constrain additional planets at a wide range of periods
- Measure orbital eccentricity and inclinations
- Interpret results in terms of formation and dynamical evolution
- Measure ephemerides to predict transits

What now?

- Only ε of the science has been done on the Kepler data
- New pipeline and vetting processes being completed

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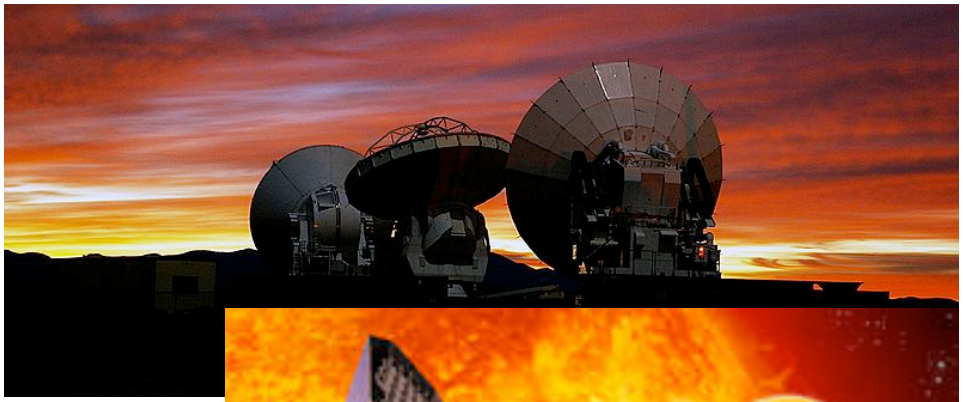
- Continue the analysis of existing data, now through Quarter 17
- Understand the cause of the observed anomalies
- Prepare for anticipated data from planned missions

What now?



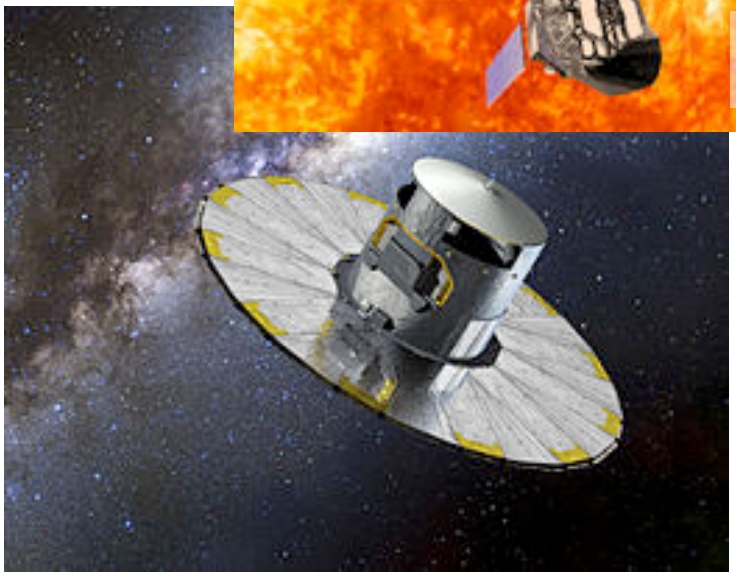
ALMA

PLATO

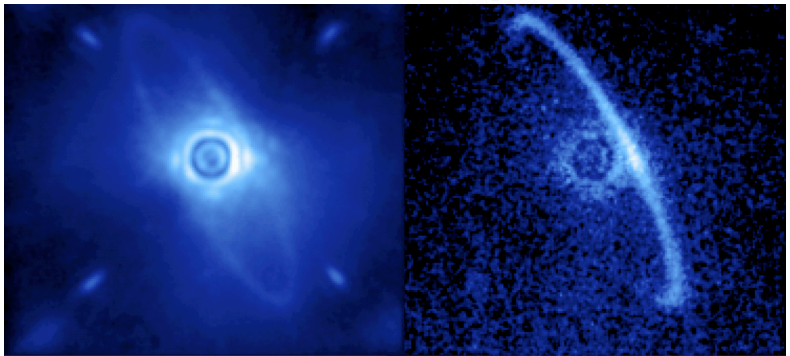
TESS

WFIRST

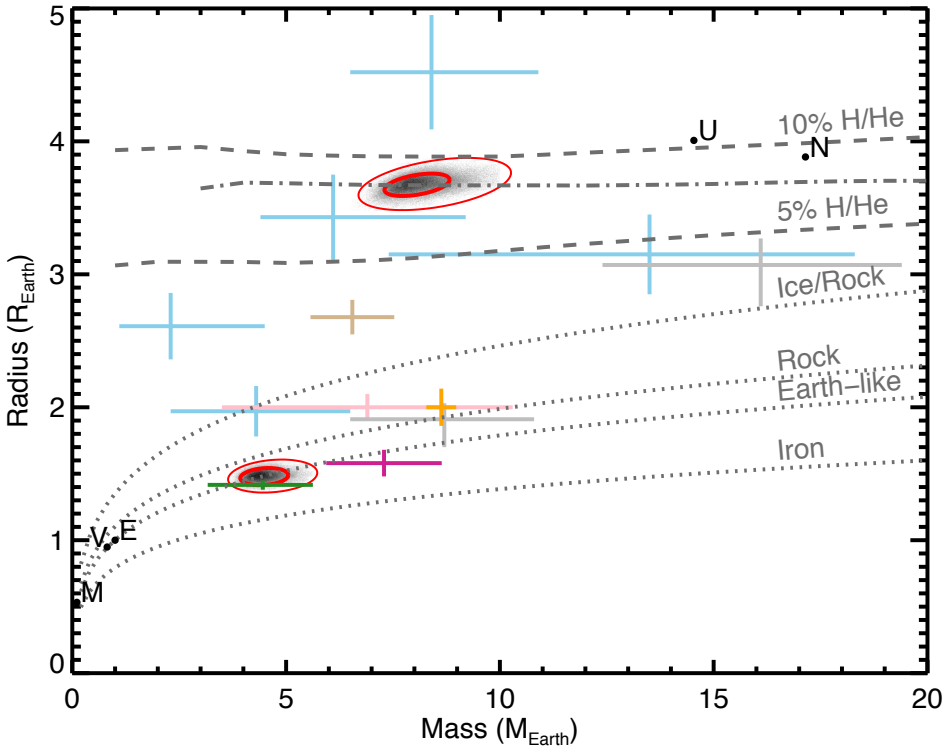
GAIA



GPI

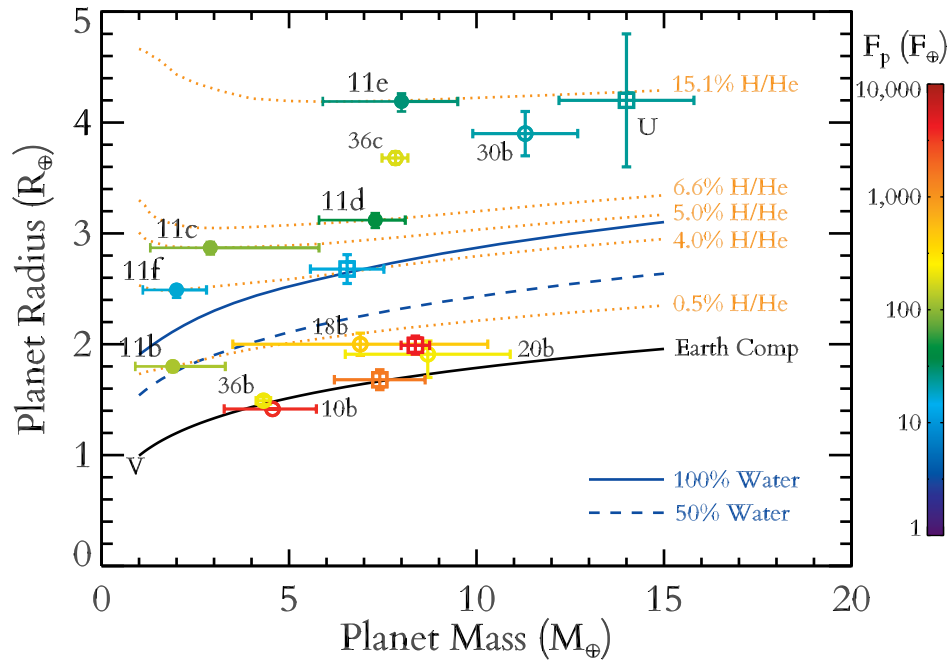


Planet Properties with Kepler



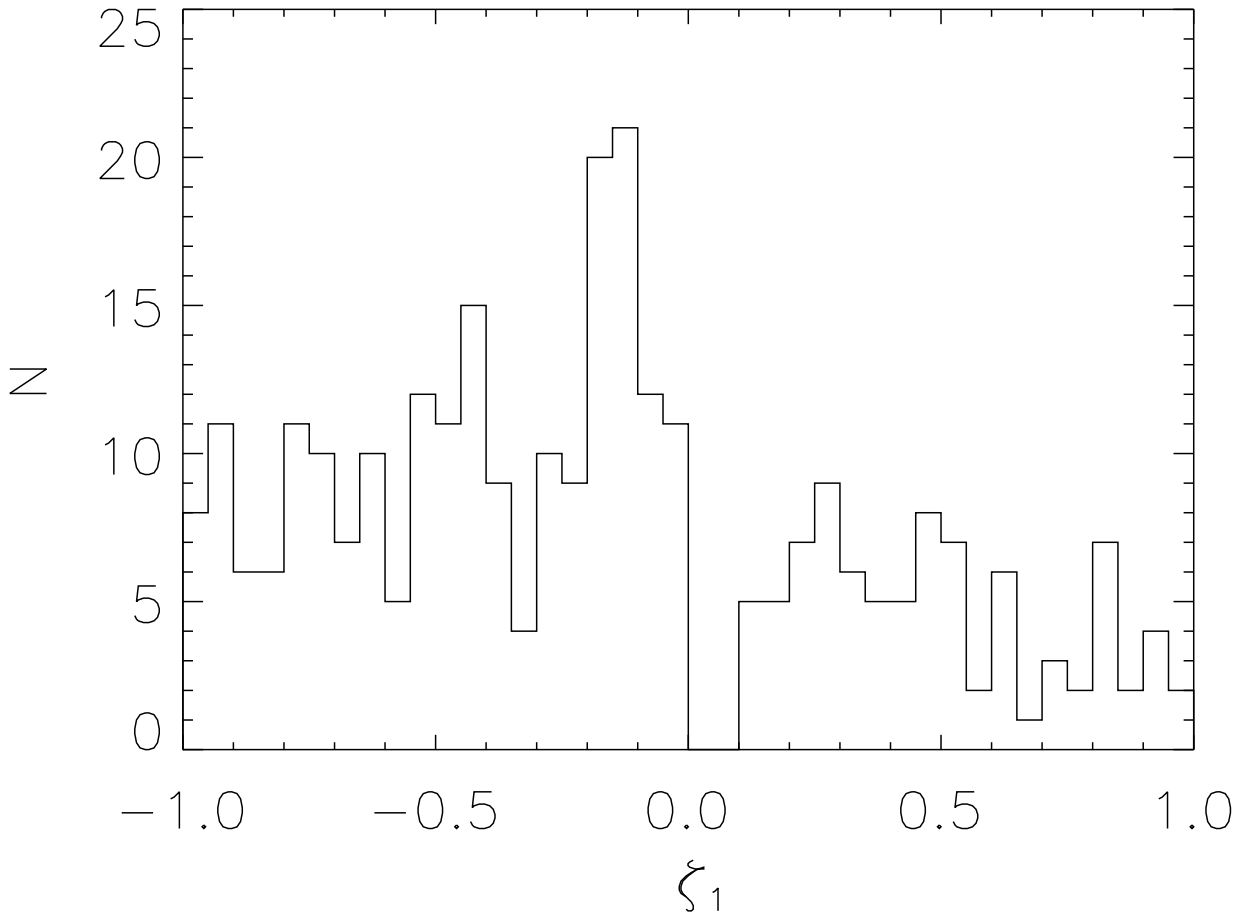
Kepler-36
Carter, Agol, et al. 2011

Kepler-11
Lissauer et al. (2013)



Architectures of Multiplanet Systems

"Stacking" the first-order resonances

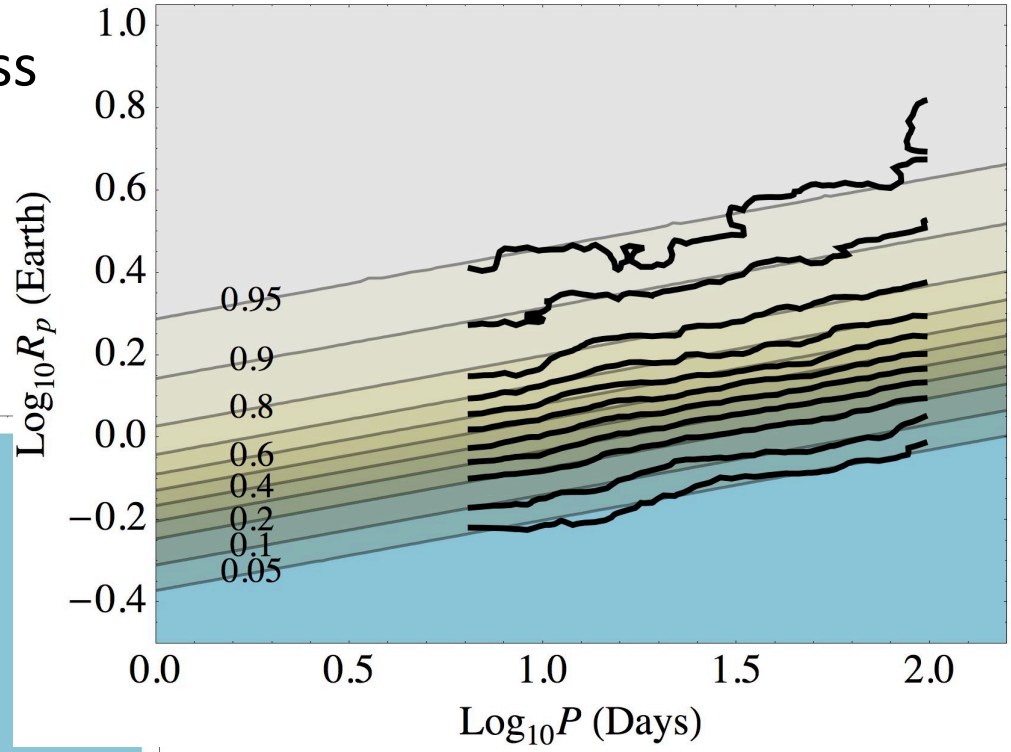


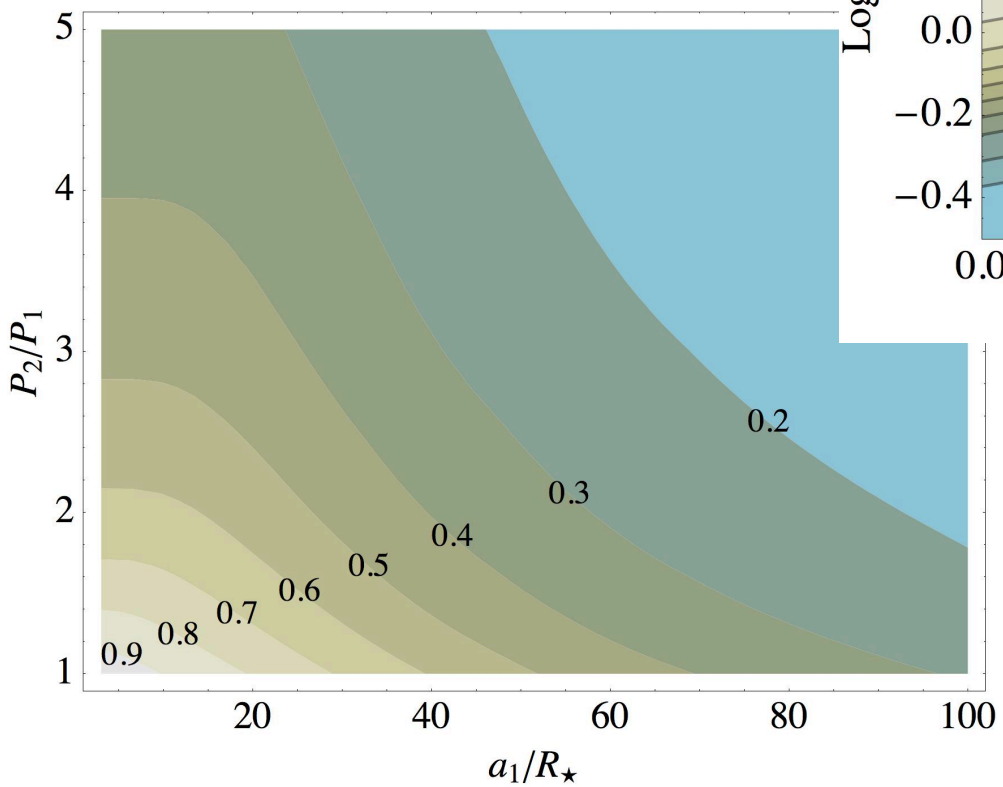
$$\zeta_1 = 3\left(\frac{1}{\mathcal{P}-1} - \mathrm{Round}\left[\frac{1}{\mathcal{P}-1}\right]\right)$$

Fabrycky et al. (2012)

Effects to Consider

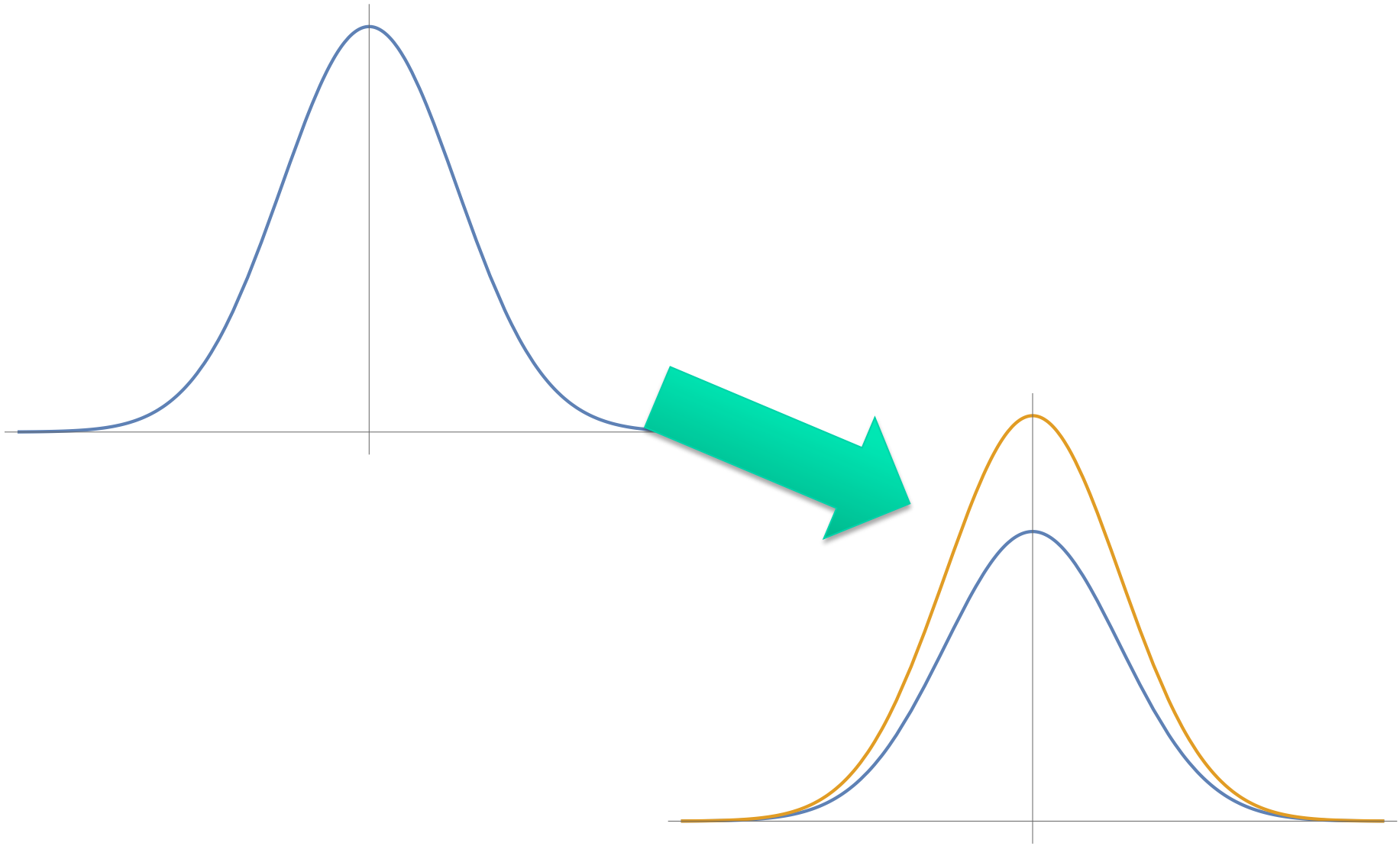
Pipeline Completeness





Geometric Transit Probability

Modified Kernel Density Estimate



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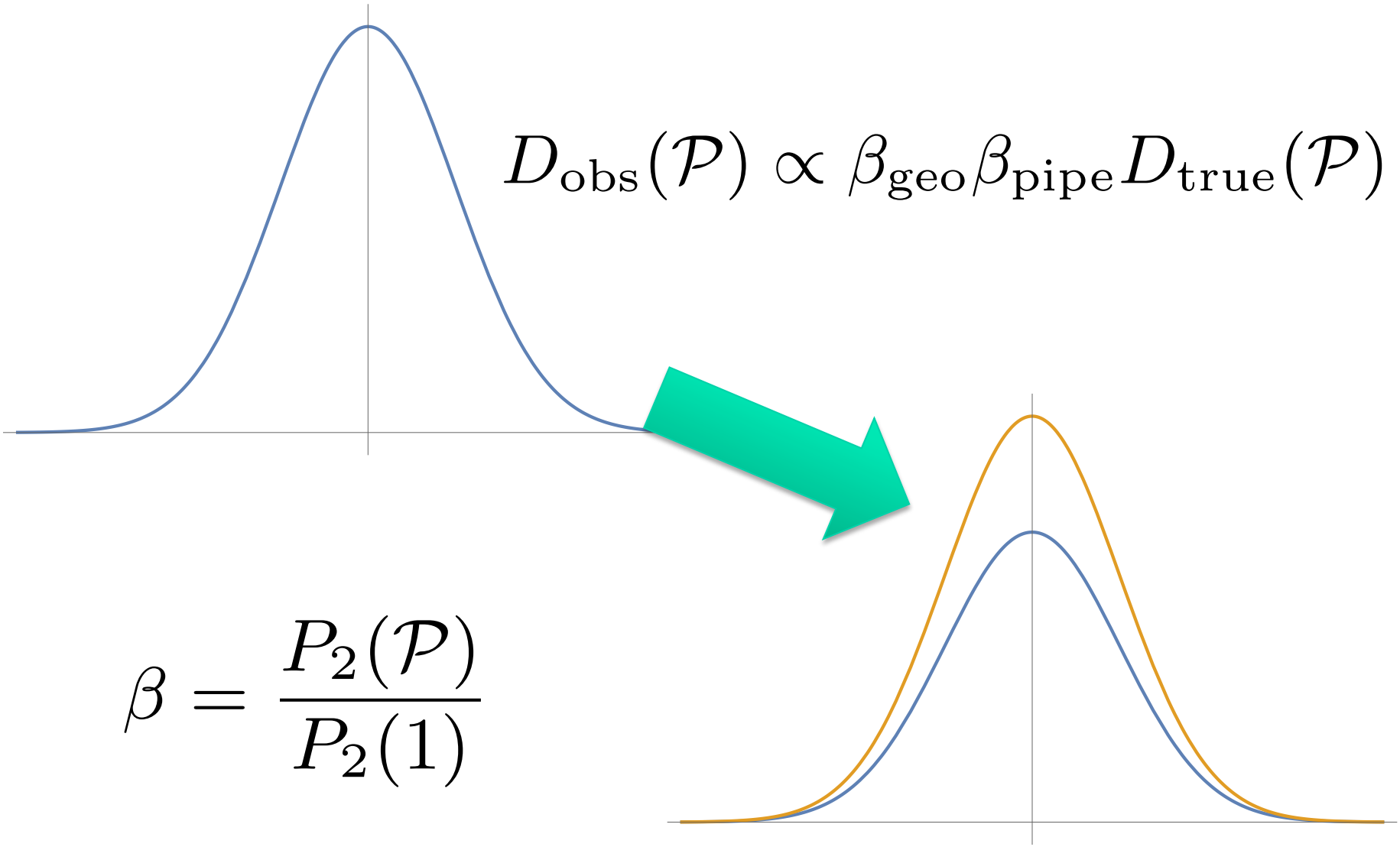
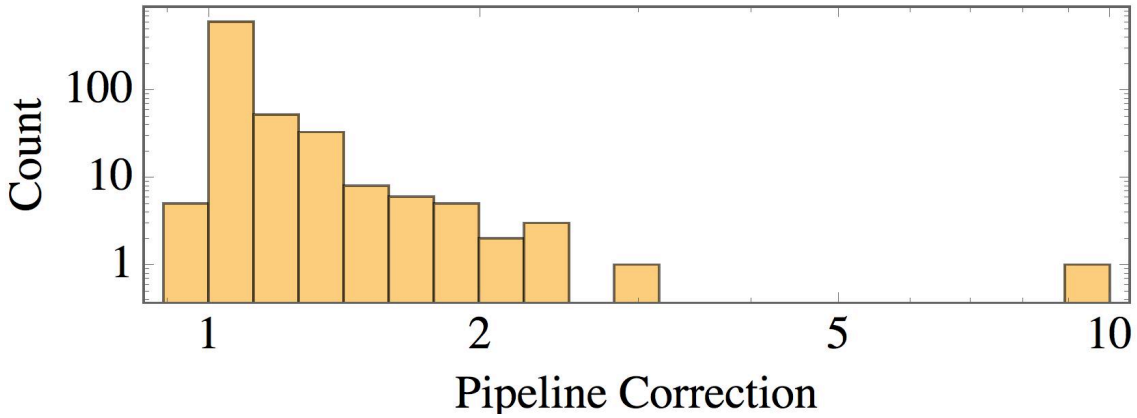
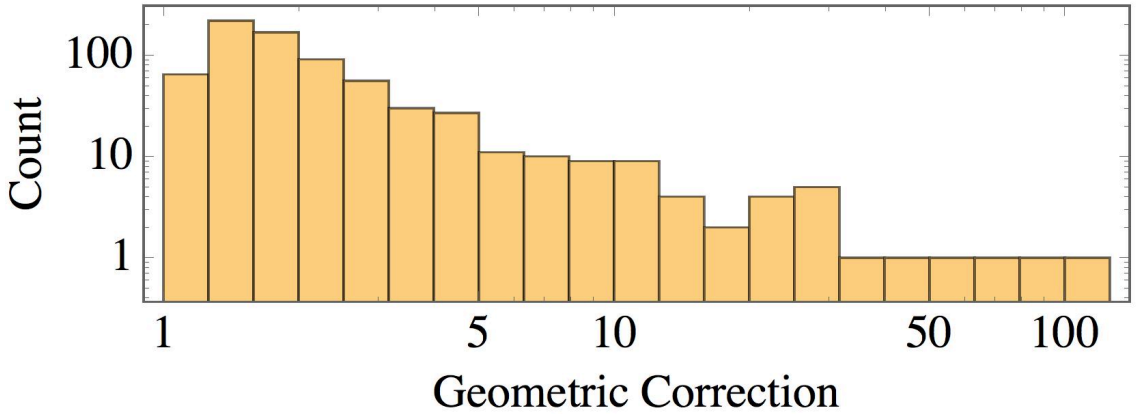


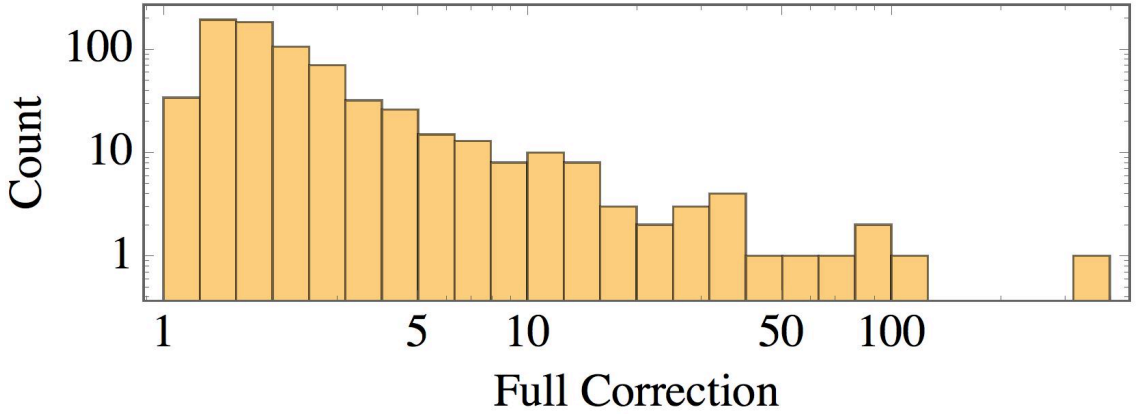
$$D_{\mathrm{obs}}(\mathcal{P}) \propto \beta_{\mathrm{geo}} \beta_{\mathrm{pipe}} D_{\mathrm{true}}(\mathcal{P})$$

$$\beta = \frac{P_2(\mathcal{P})}{P_2(1)}$$

Combined Corrections

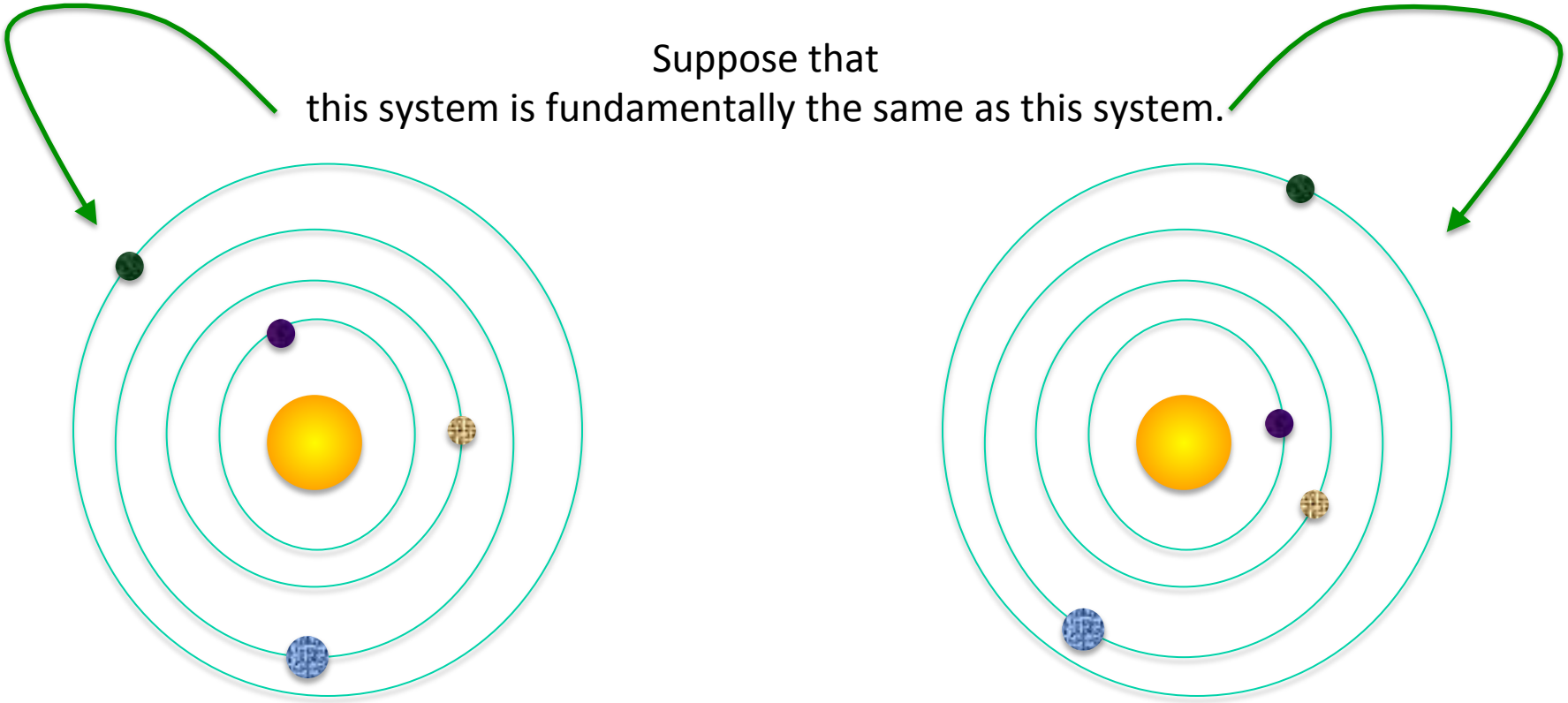






A Thought Experiment

Suppose that
this system is fundamentally the same as this system.



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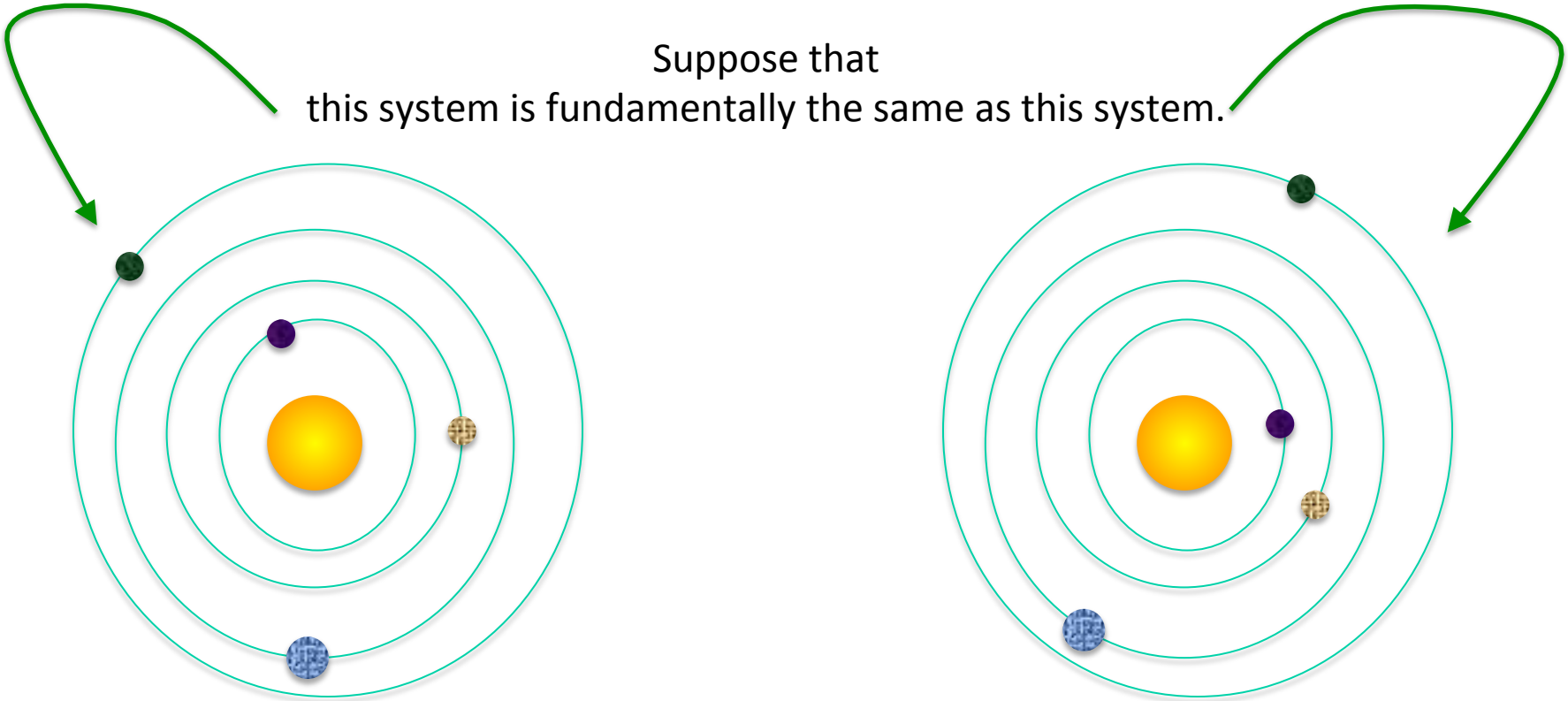
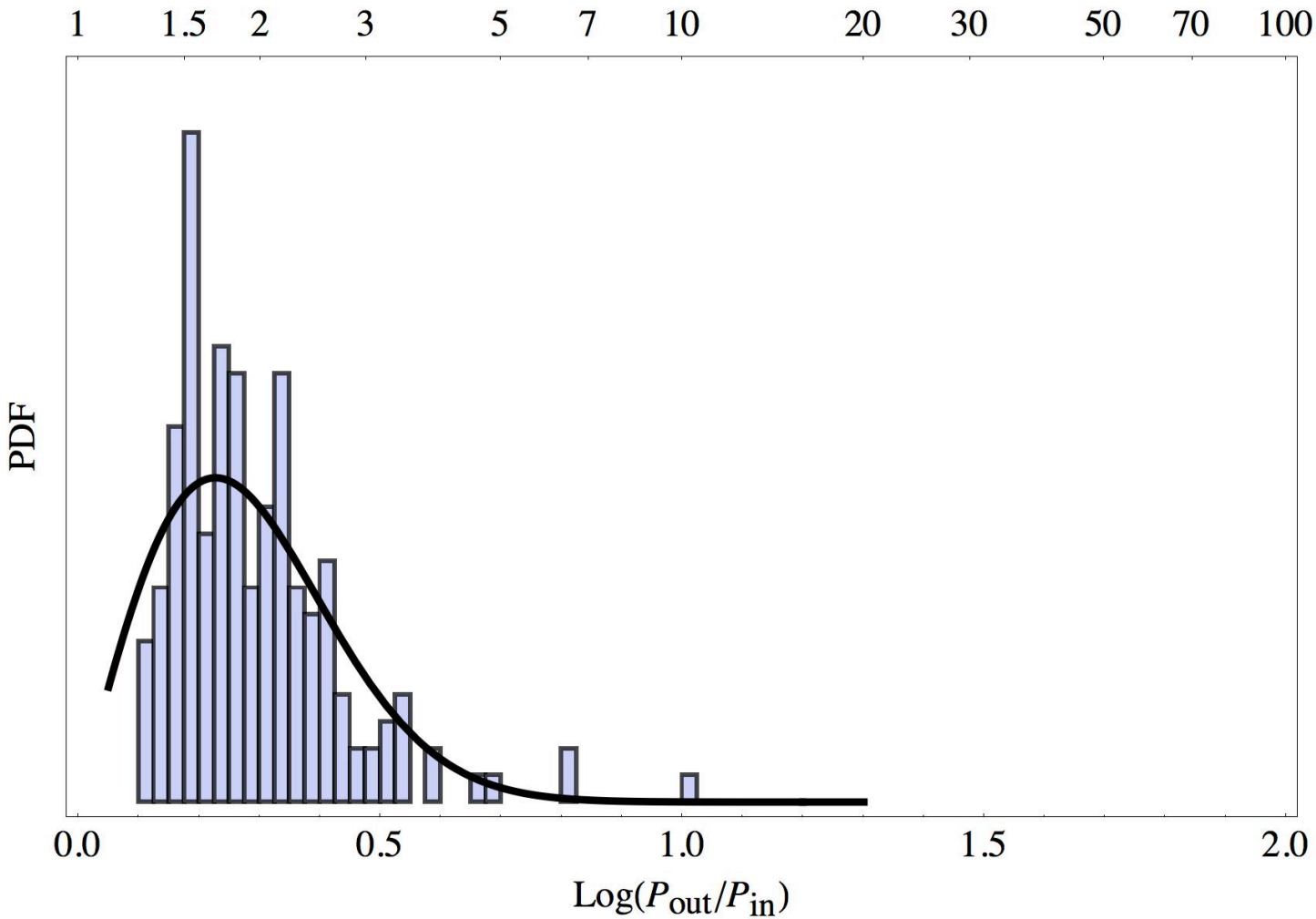


Except that the planets happen to have slightly different mutual inclinations.

Period Ratio Distribution of Adjacent Pairs

Systems with four or more planets.



Steffen (2013b)

Period Ratio Distribution of Adjacent Pairs

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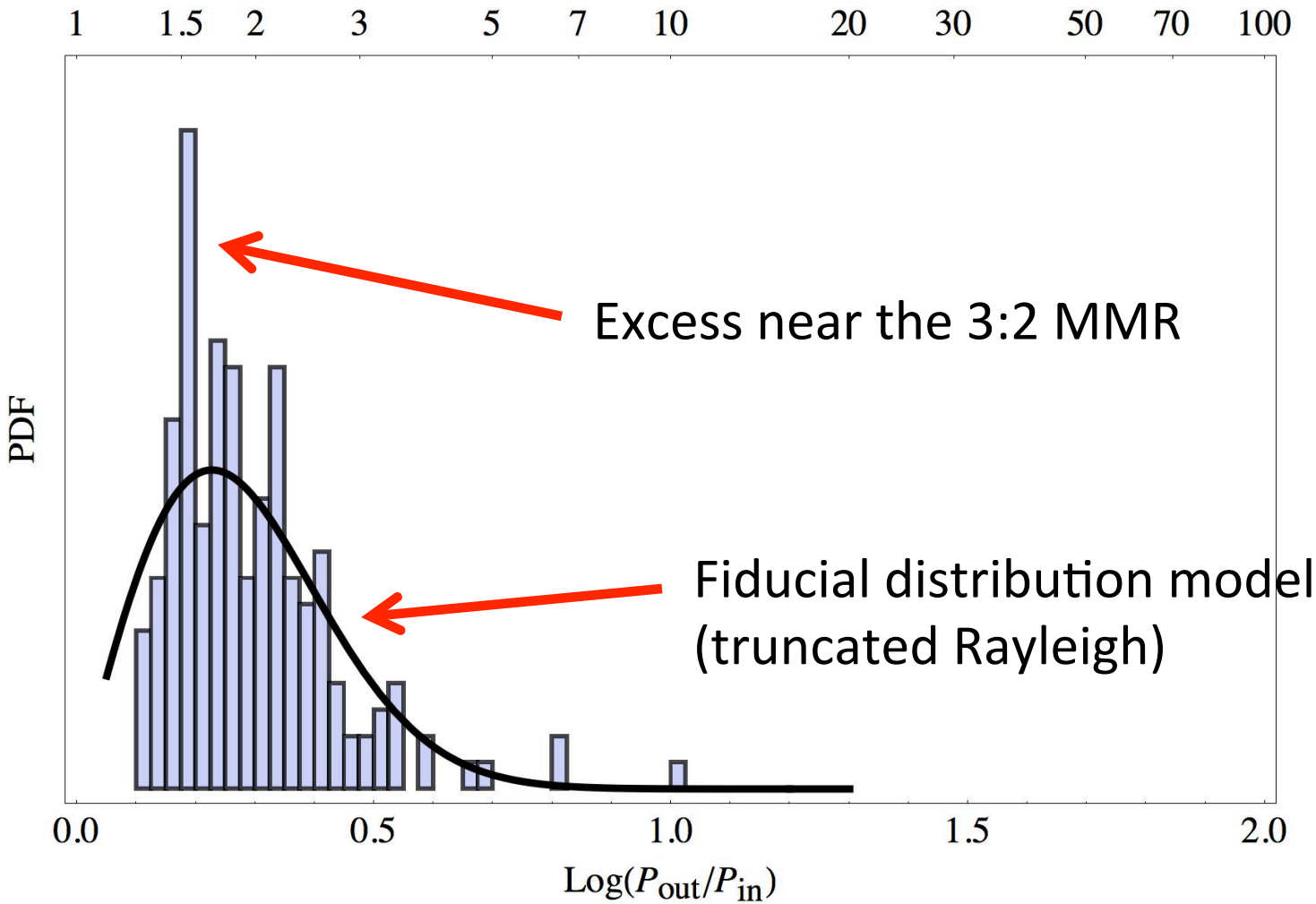
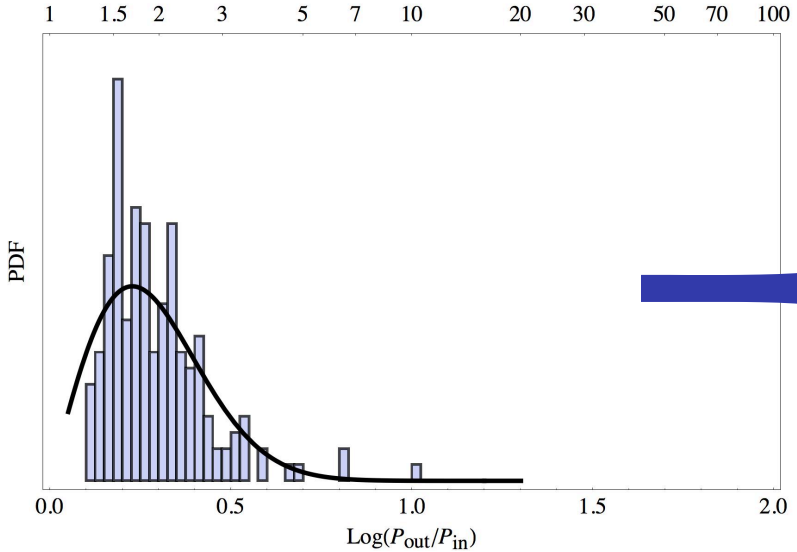


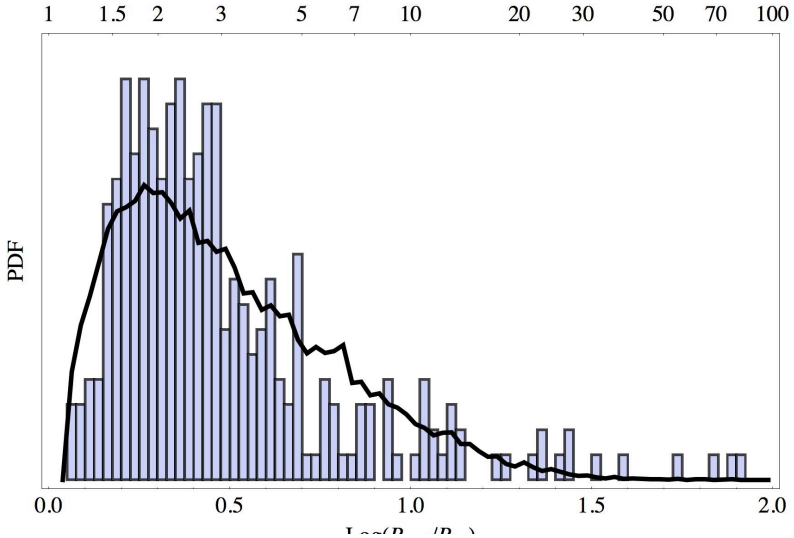
Steffen (2013b)

Period Ratio Distribution of Adjacent Pairs

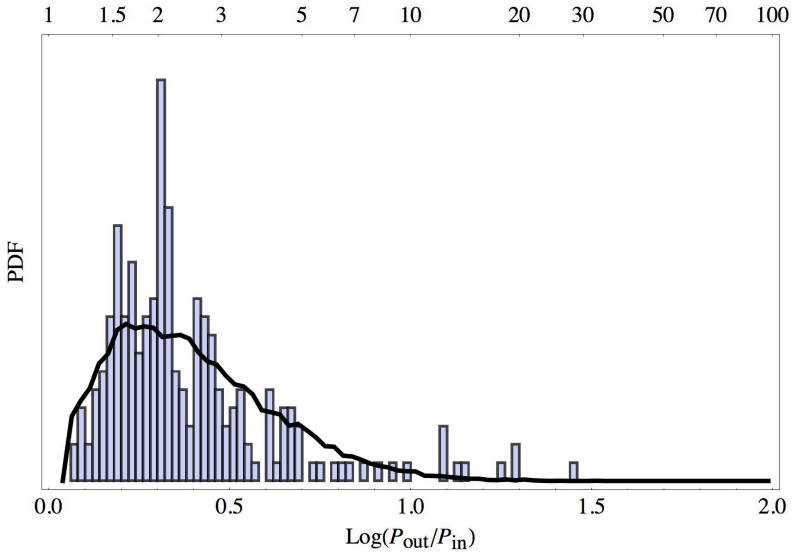
4+ planets



2 planets



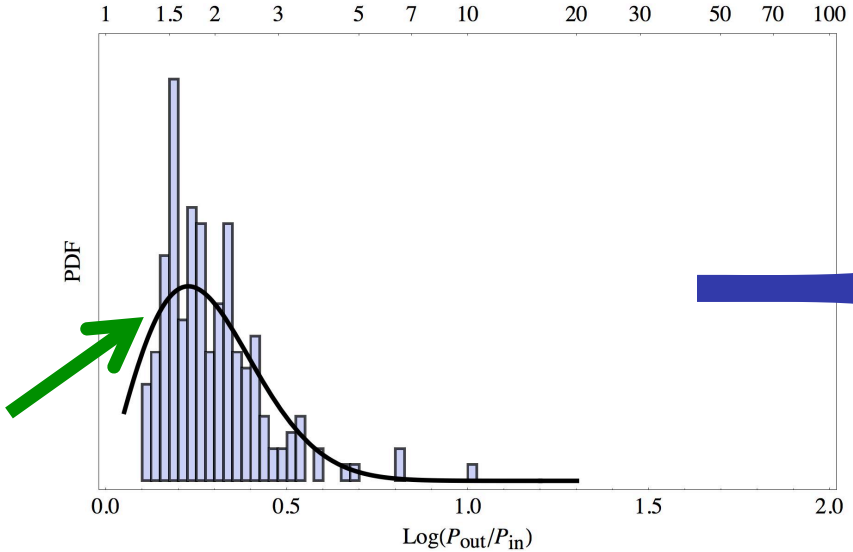
3 planets



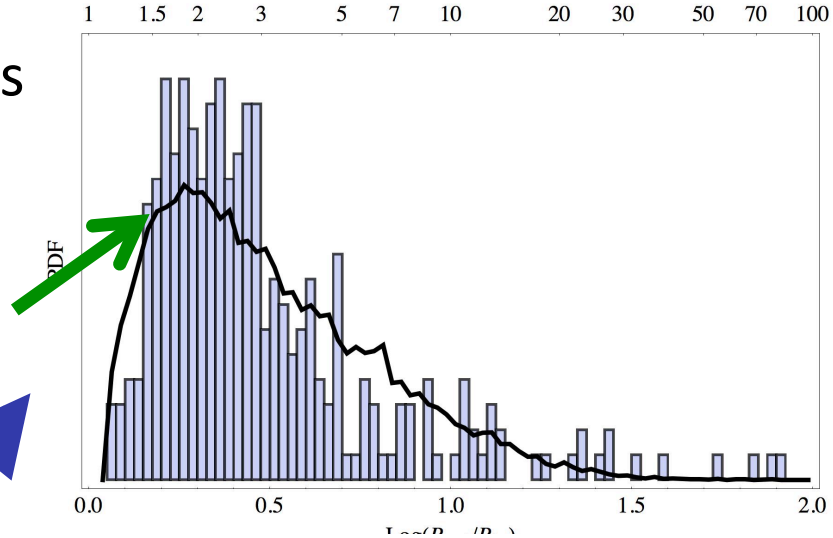
Steffen (2013b)

Period Ratio Distribution of Adjacent Pairs

4+ planets



2 planets



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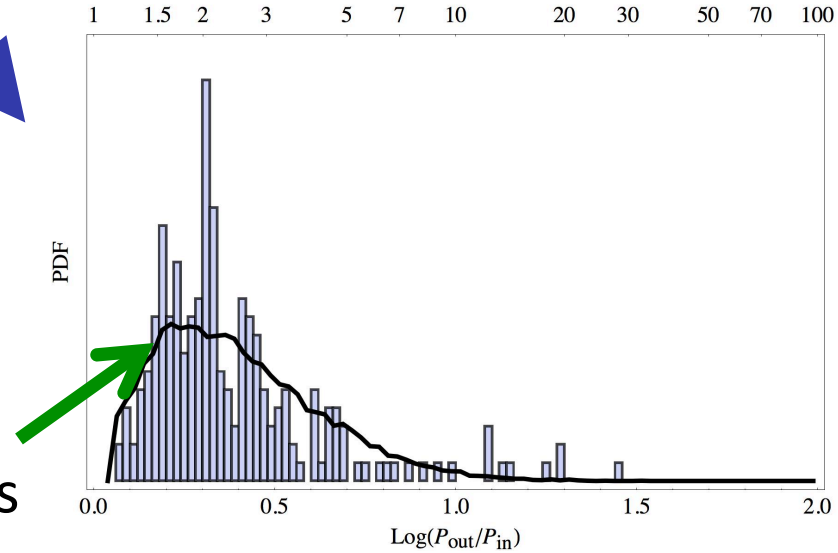

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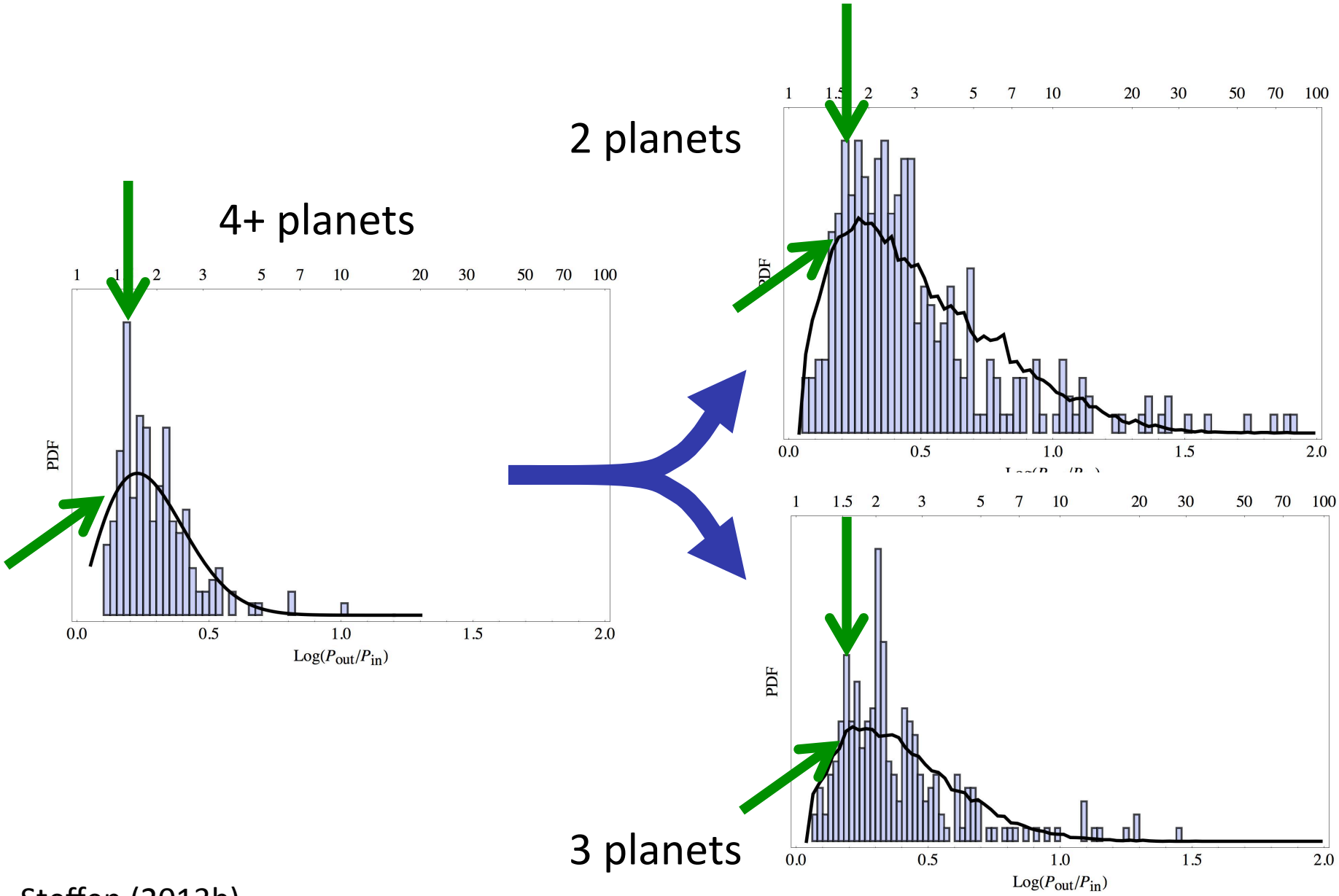

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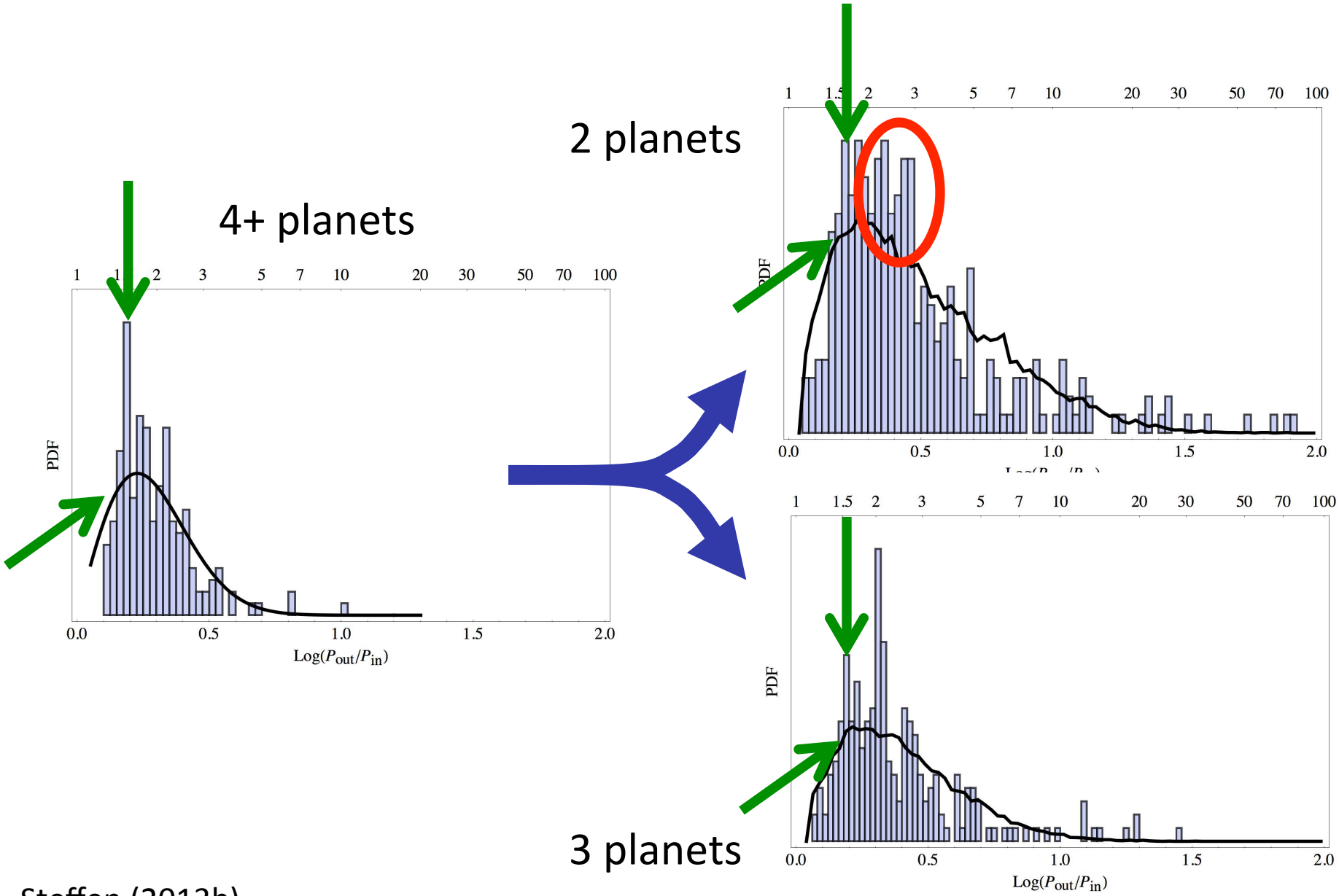

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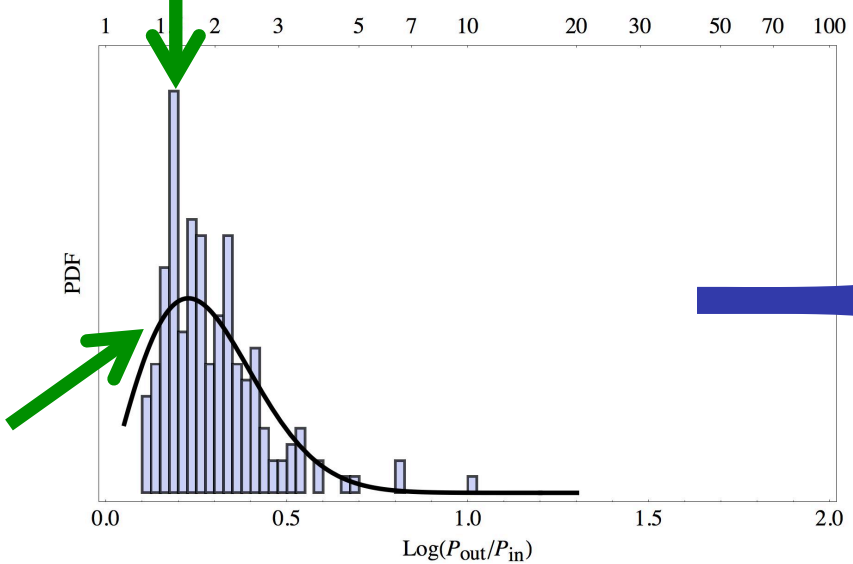

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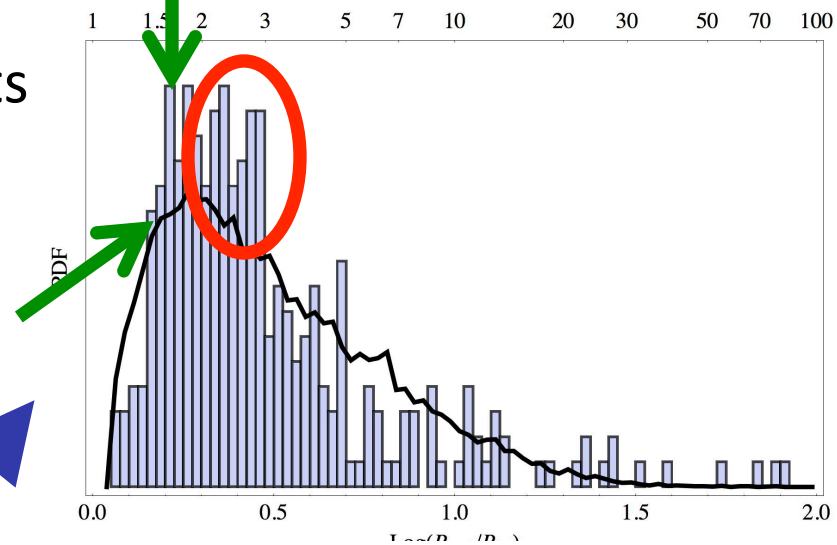

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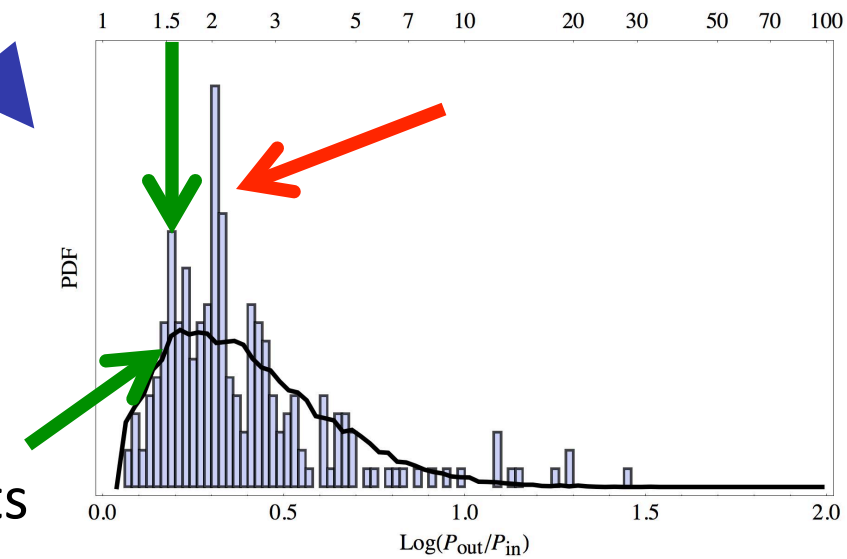
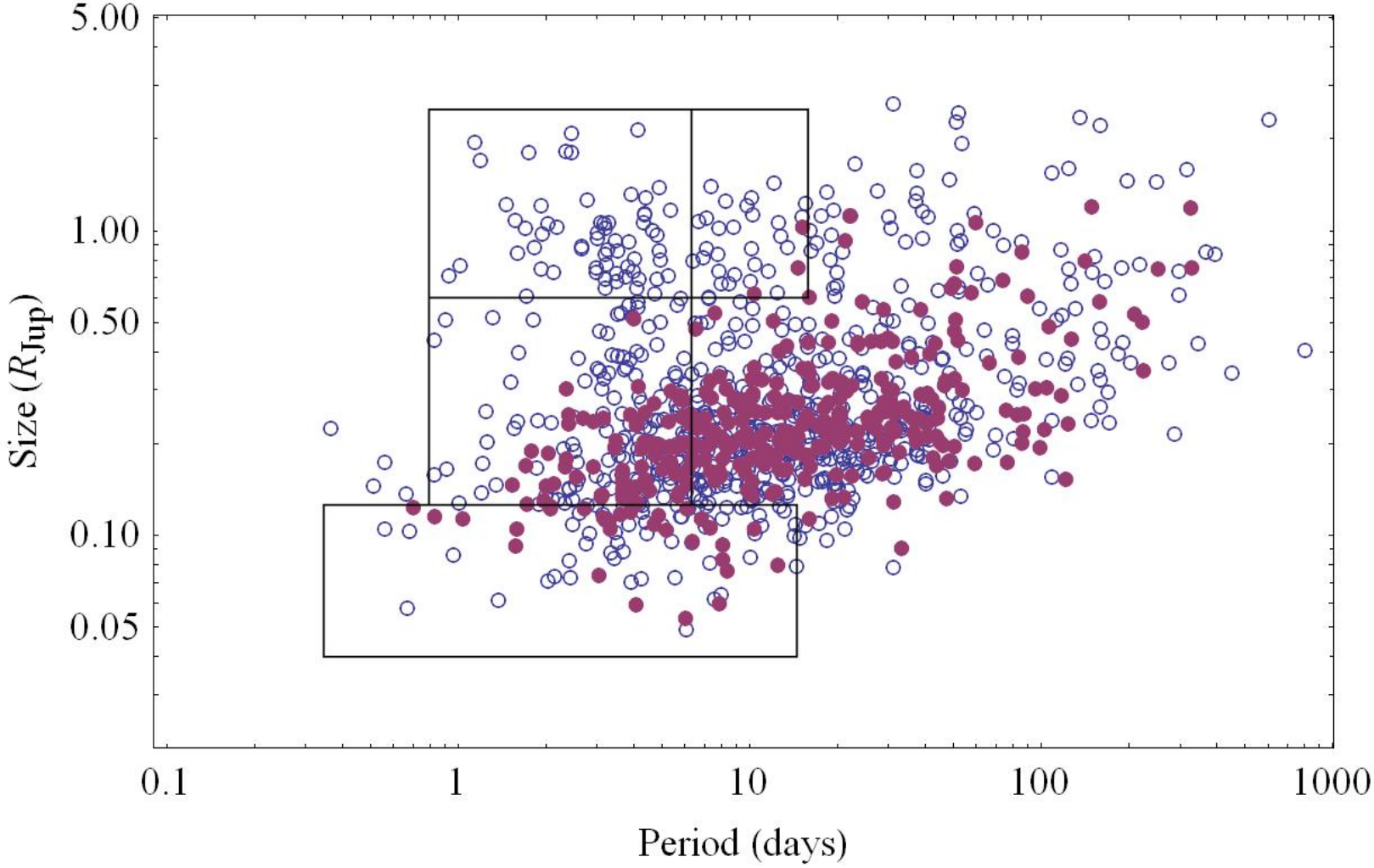


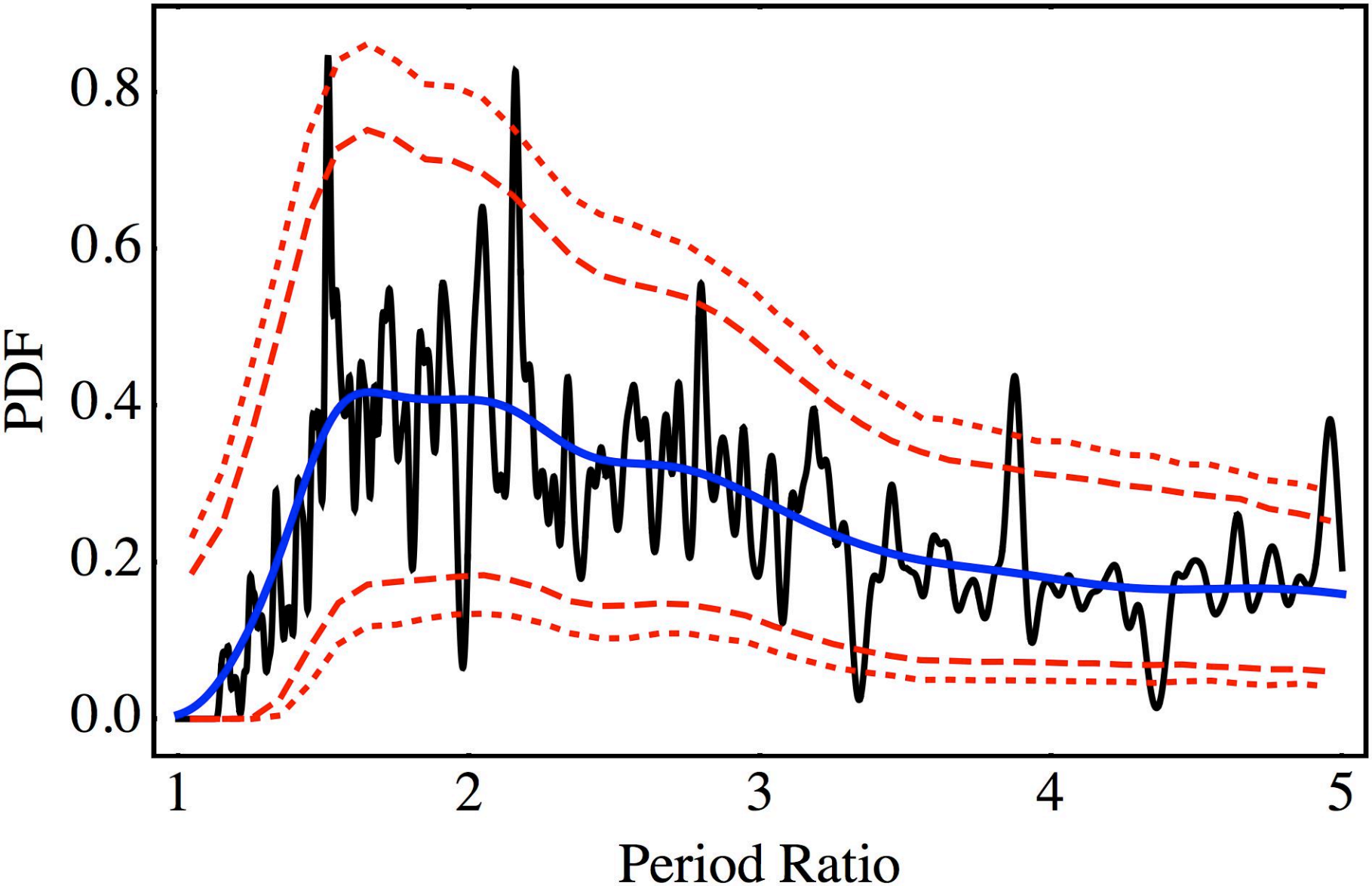
Steffen (2013b)

Analysis of Kepler's Hot Jupiters

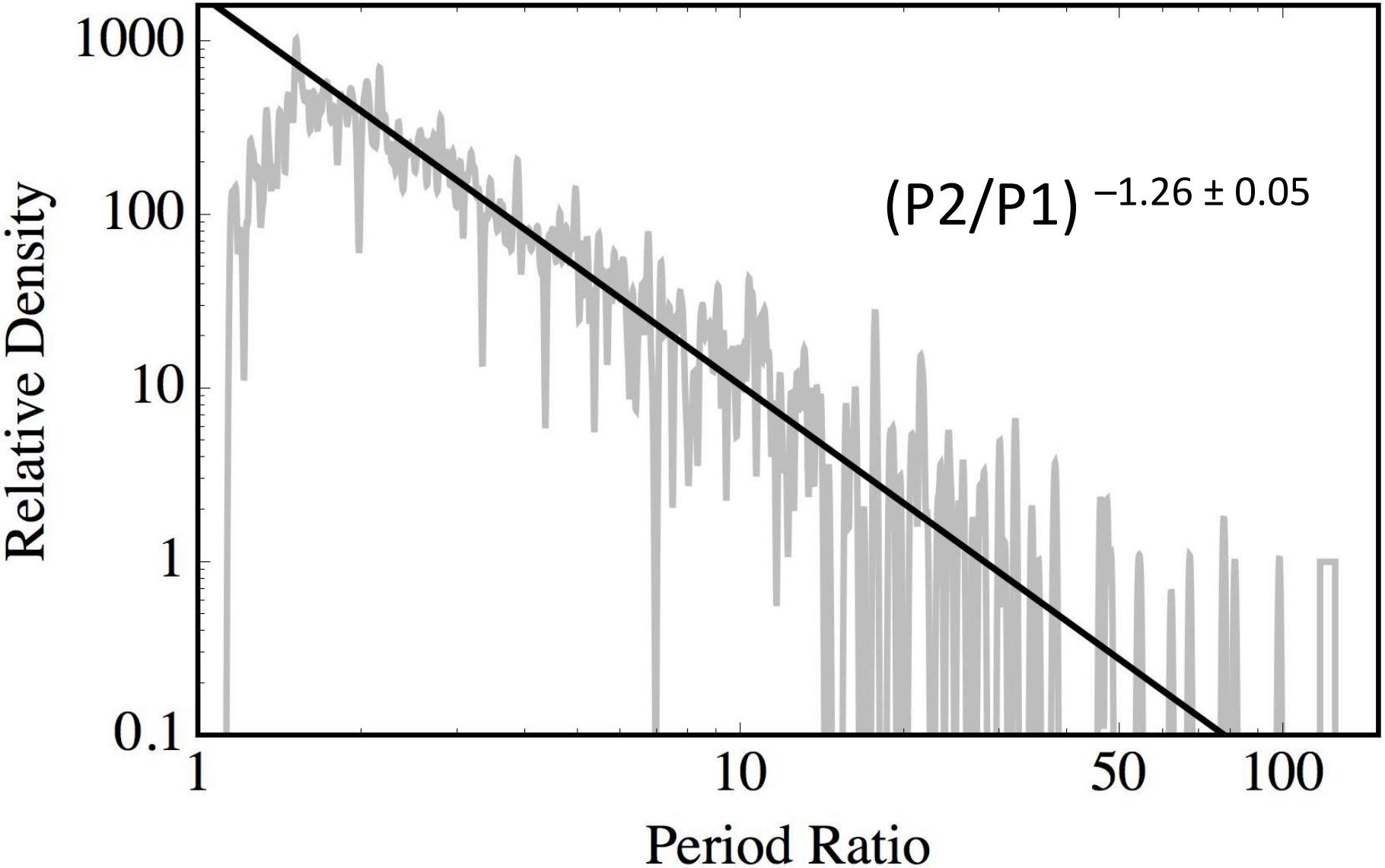


Steffen et al. PNAS (2012b)

Resulting Period Ratio Distribution



Distribution Tail



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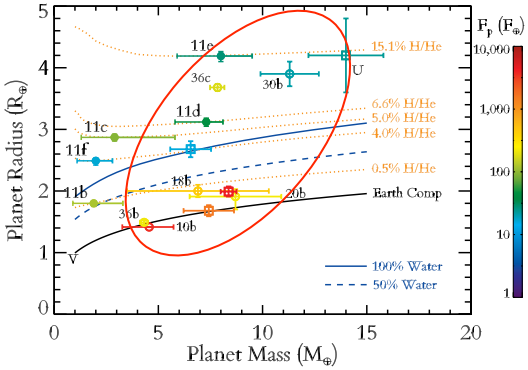

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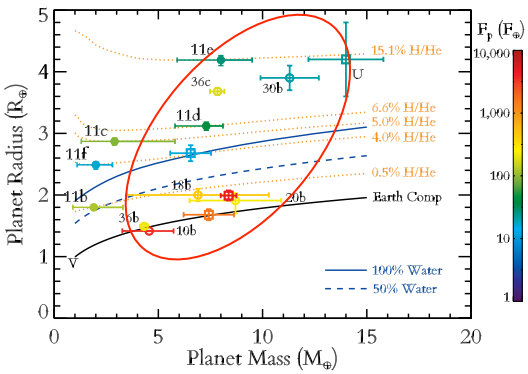

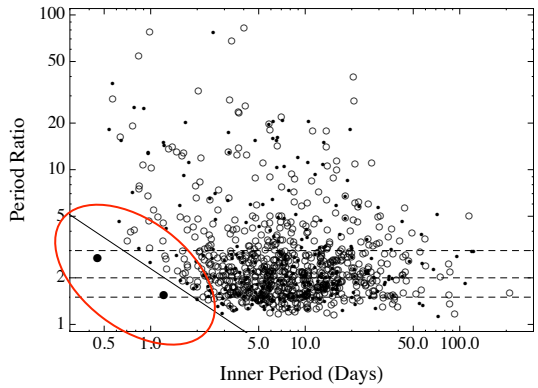

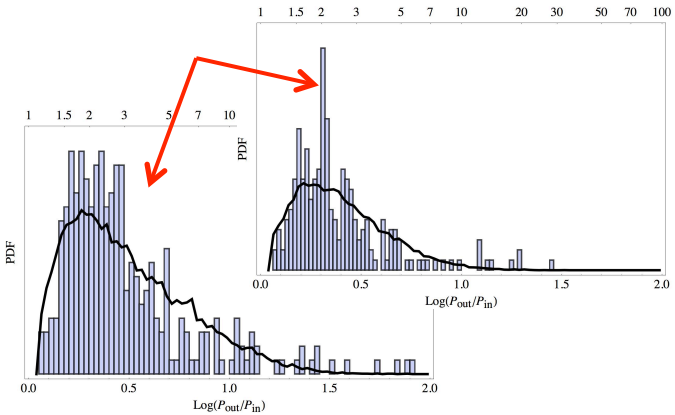

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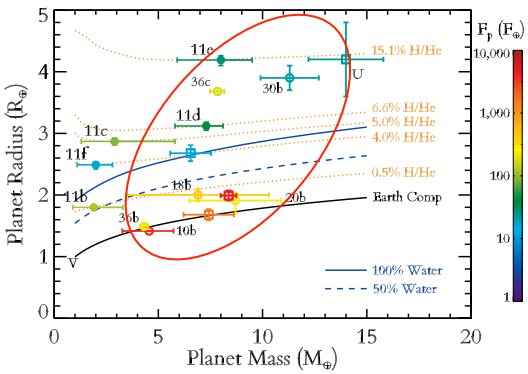

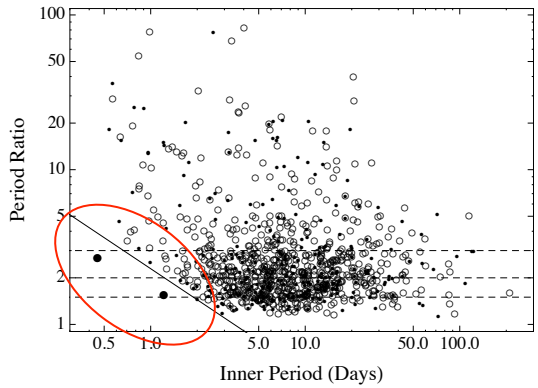

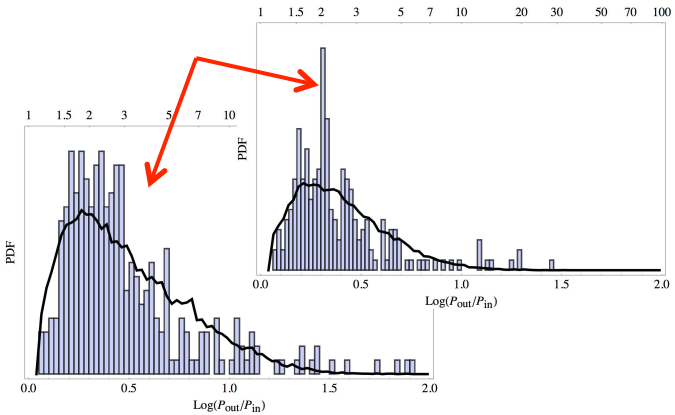

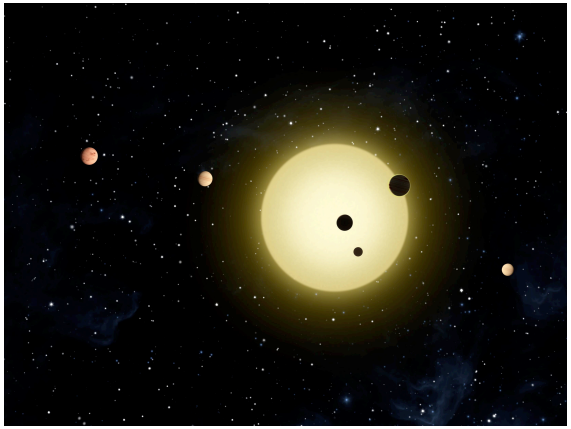

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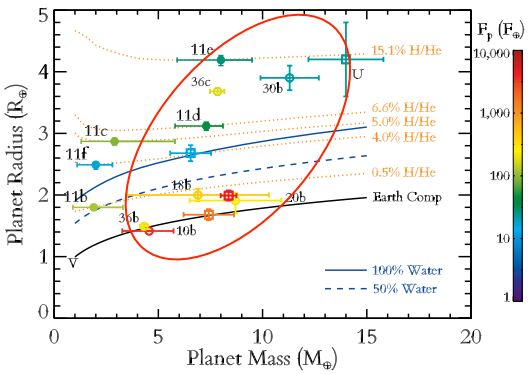
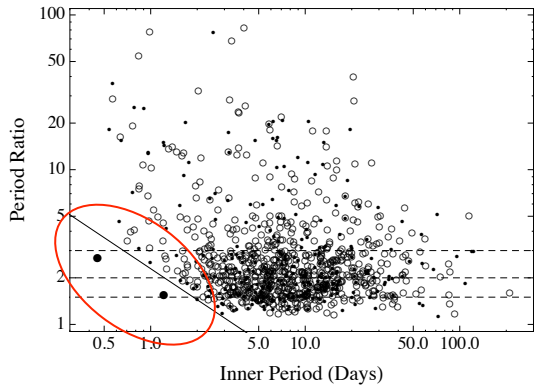
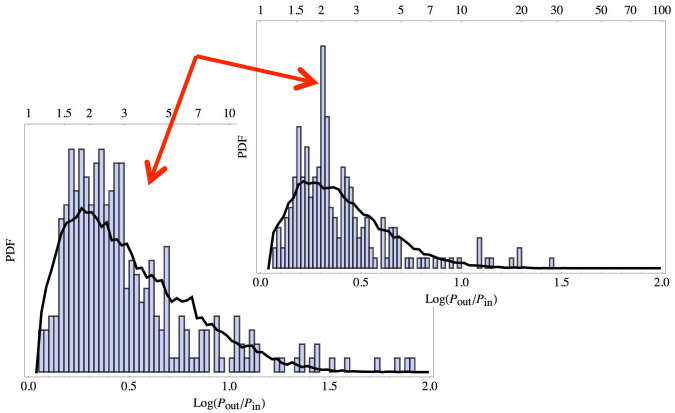
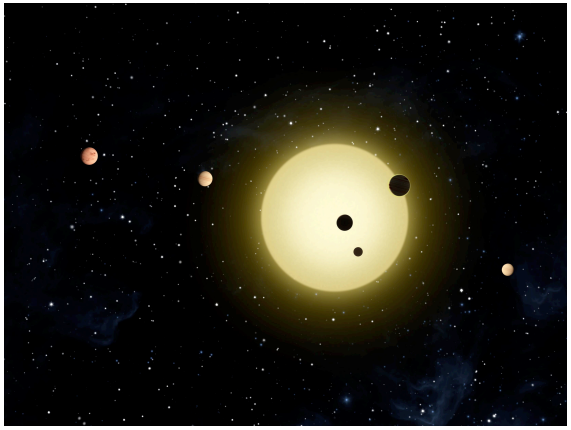
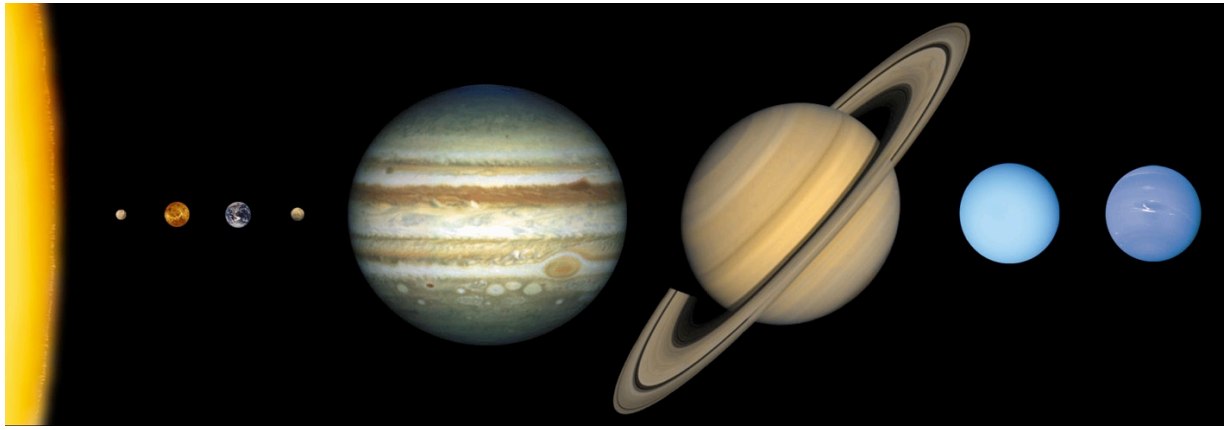


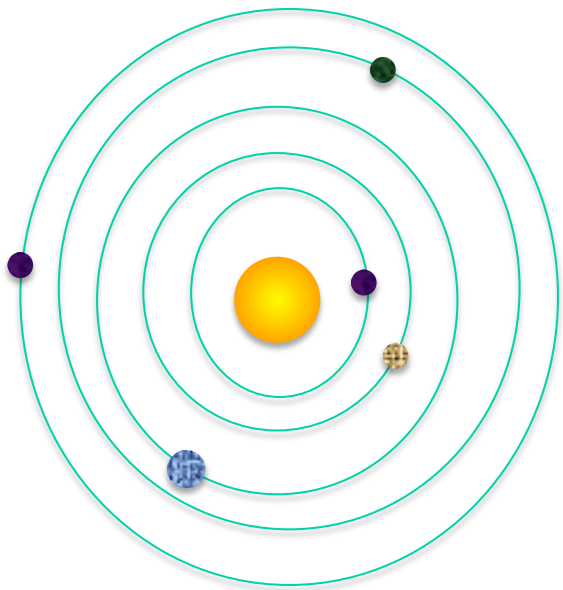








Some possibilities being pursued



Hwang, Steffen, & Rasio (in prep)

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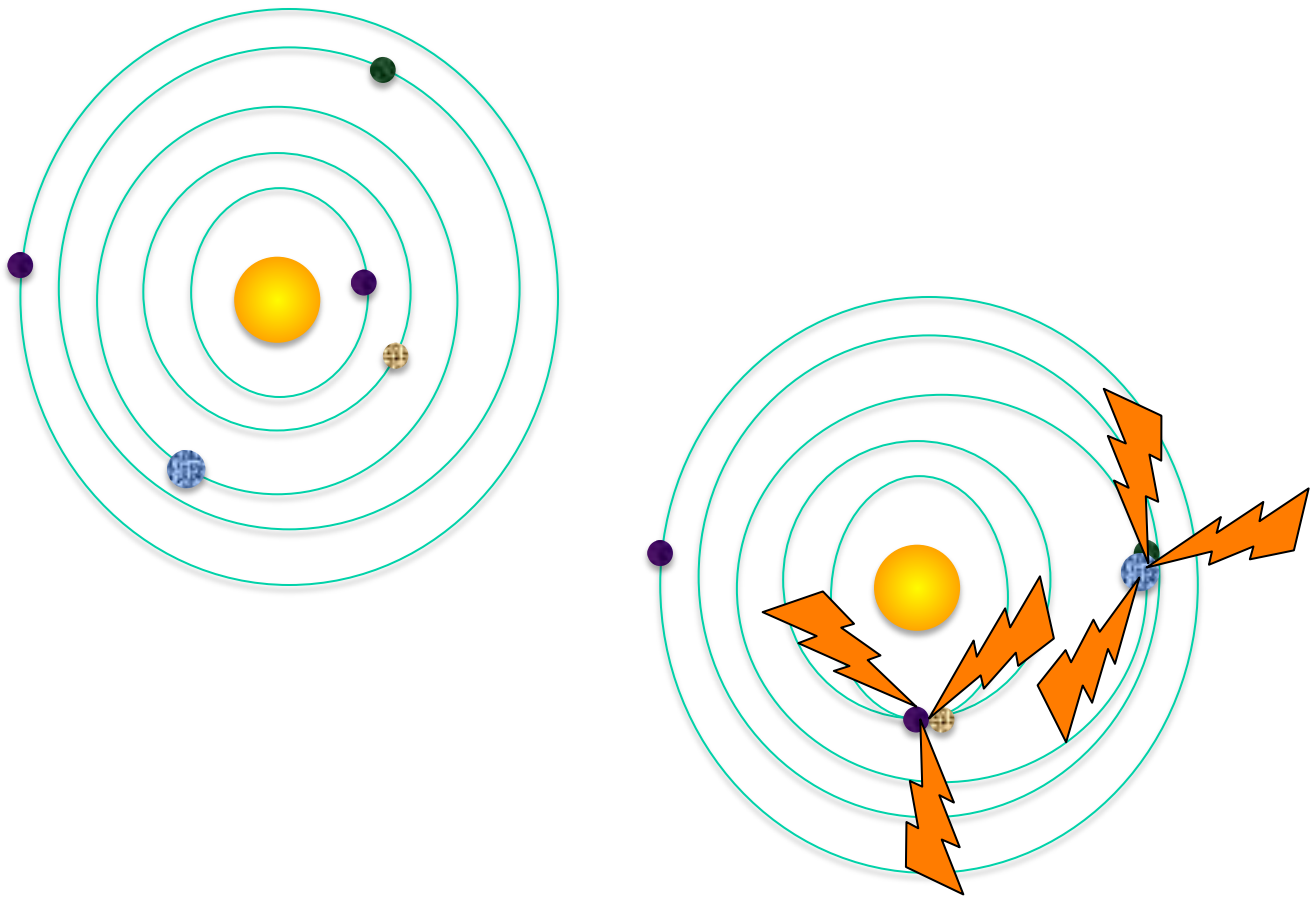

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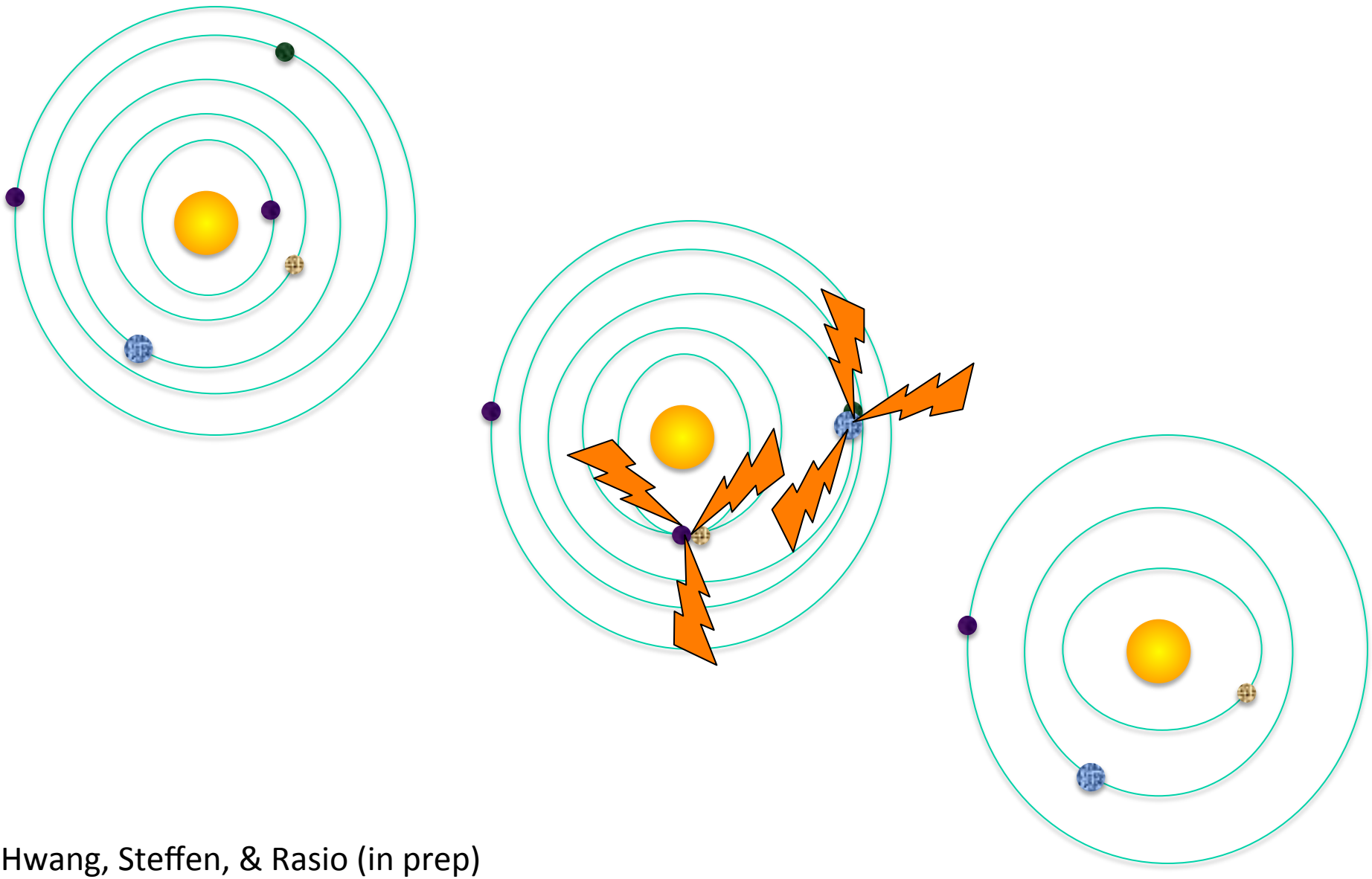

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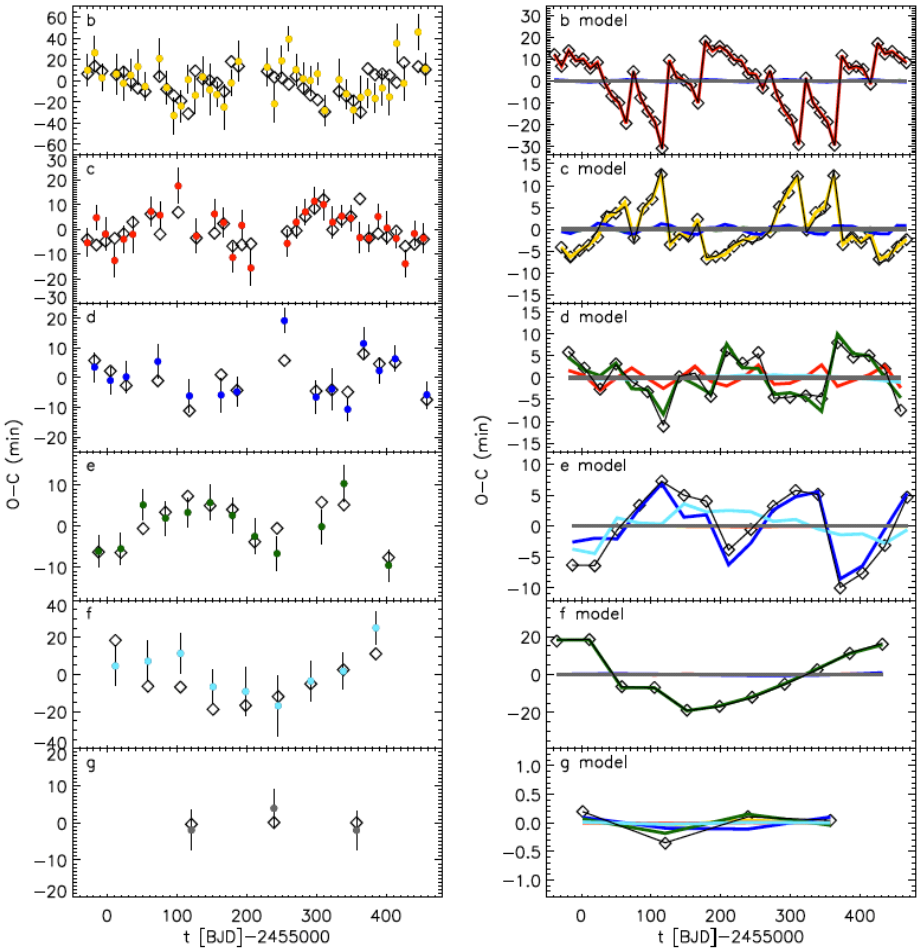
TTVs for Planet Characterization

Kepler 11



Lissauer et al. (2011)

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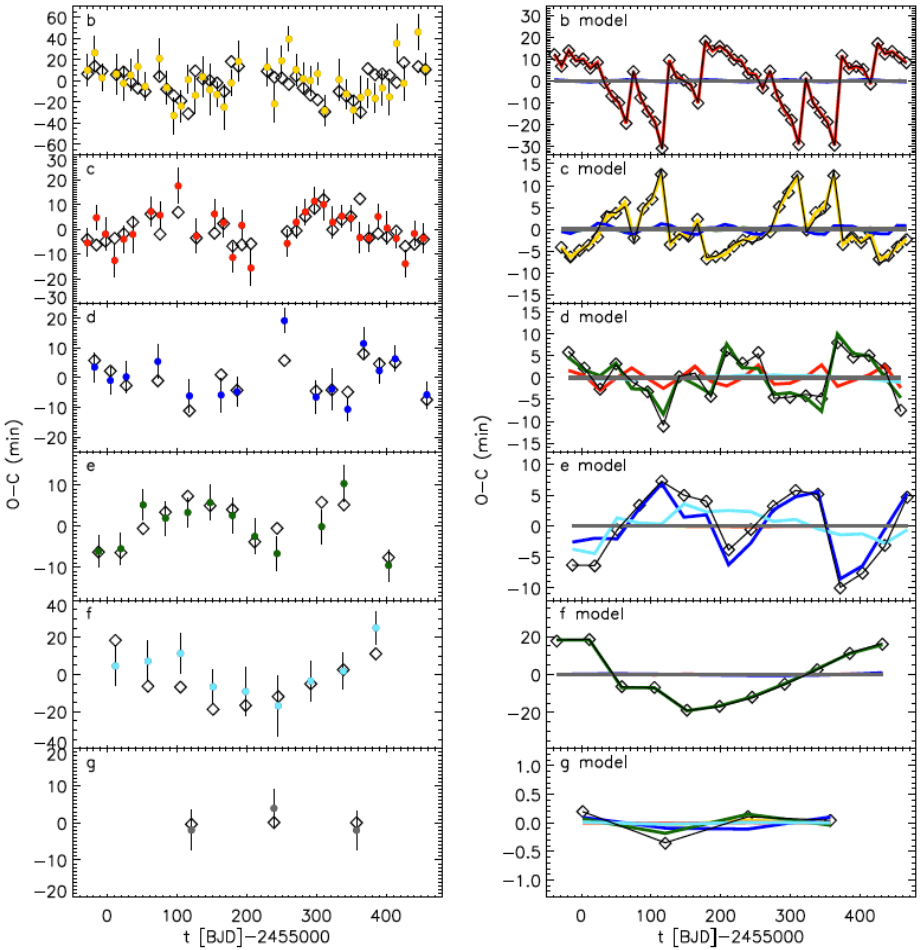
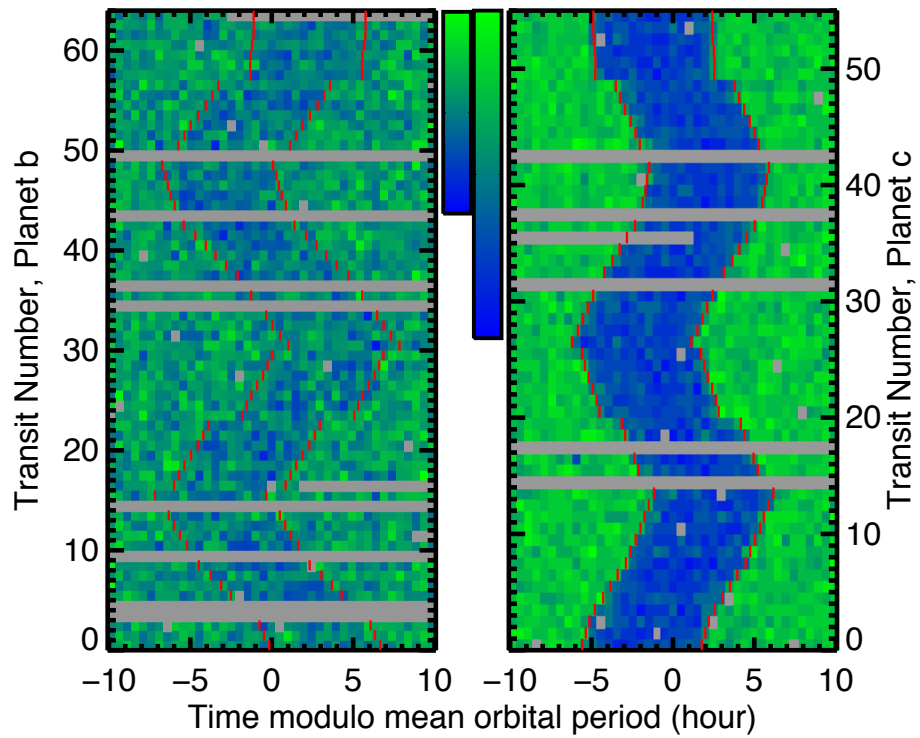


Lissauer et al. (2011)

Kepler 36



Carter, Agol, et al. (2012)

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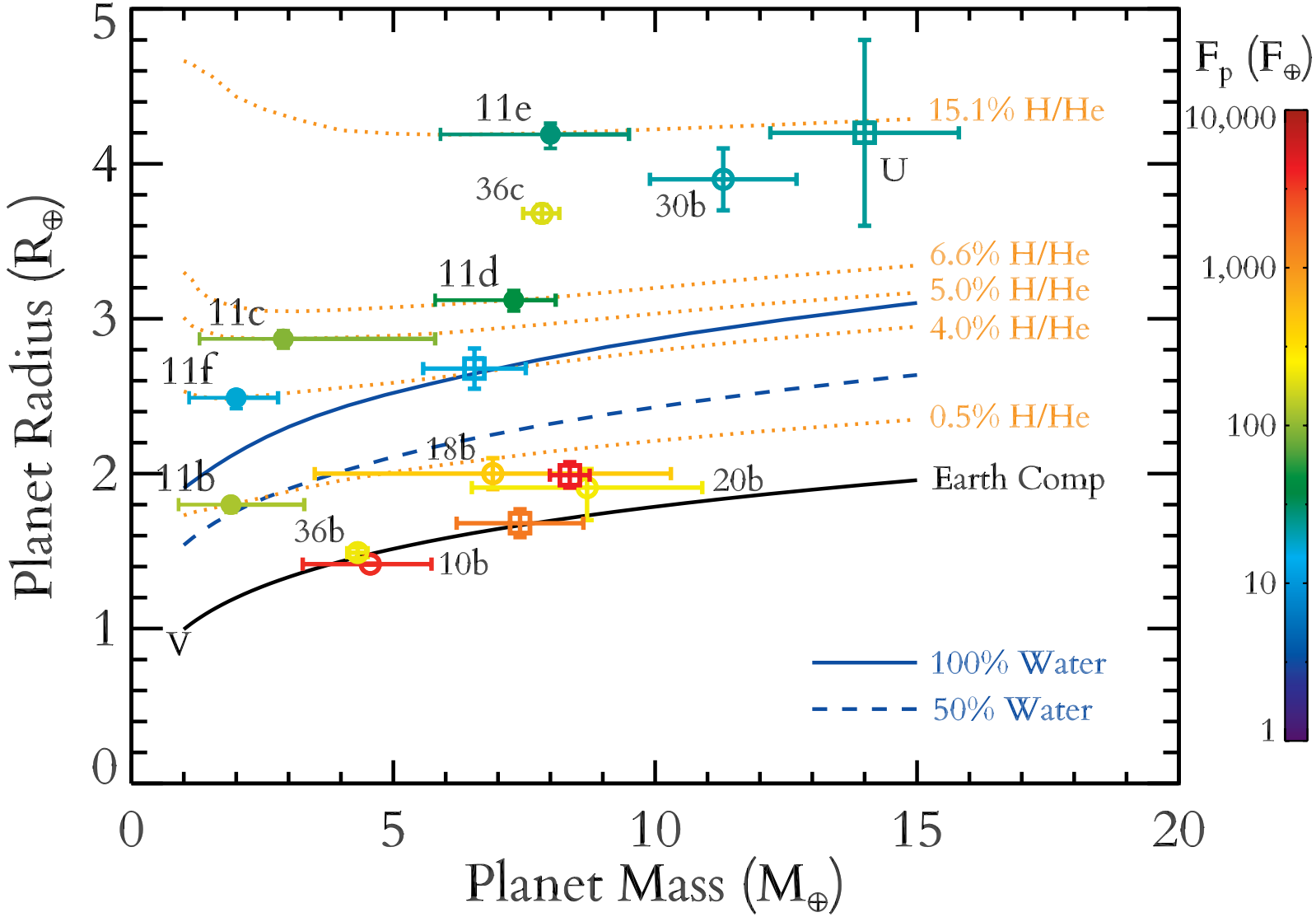

Lissauer et al. (2013)

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- Most of the Kepler planets have masses and sizes that are not present in our solar system
- Many Kepler planets are much closer together than planets in the solar system
- Planets seen by Kepler are well inside the "snow line" which planet formation theories must address

Multibody/TTV Working Group

Jack Lissauer (chair), Jason Steffen (chair), Eric Agol, Dan Fabrycky, Eric Ford, Tsevi Mazeh, Jerry Orosz, Darin Ragozzine, Jason Rowe, William Welsh

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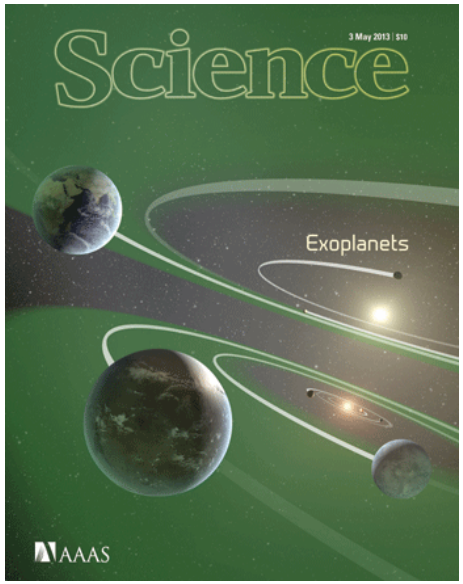
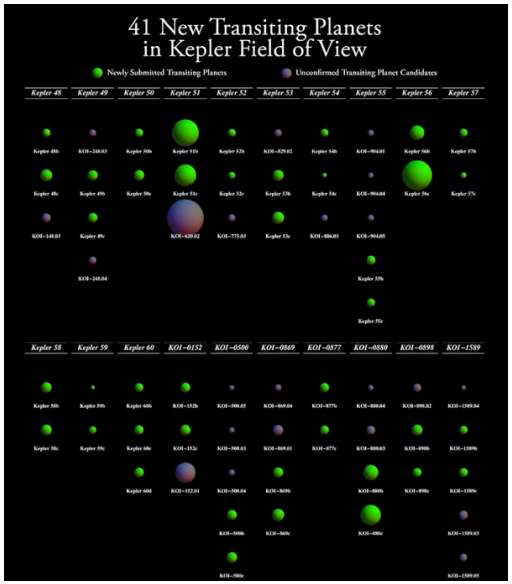
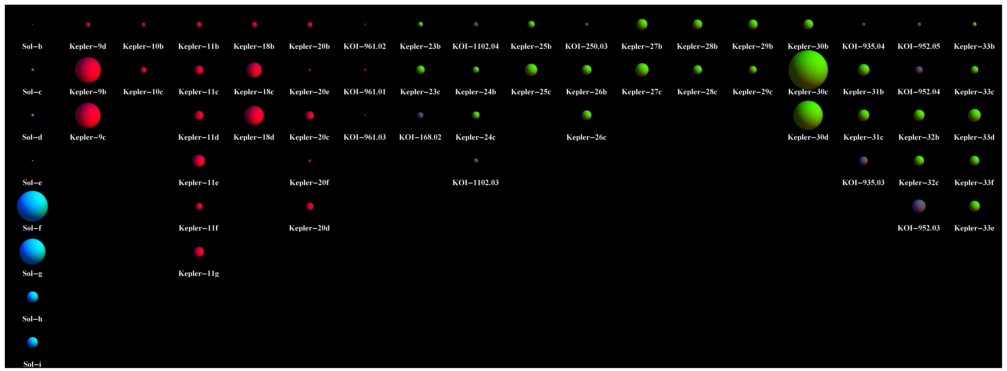
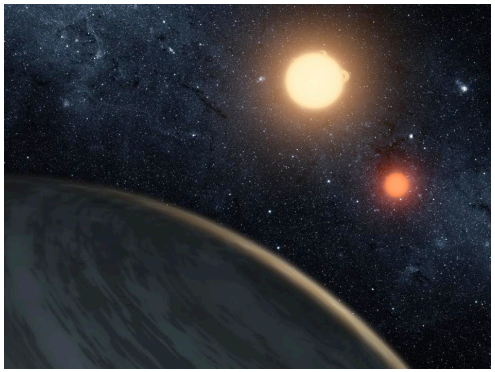
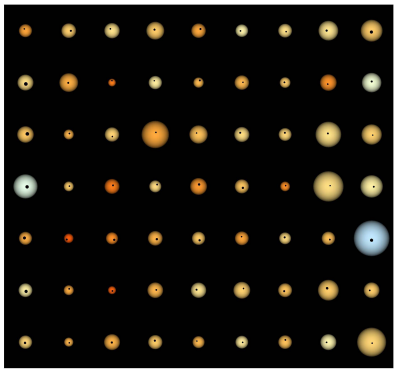


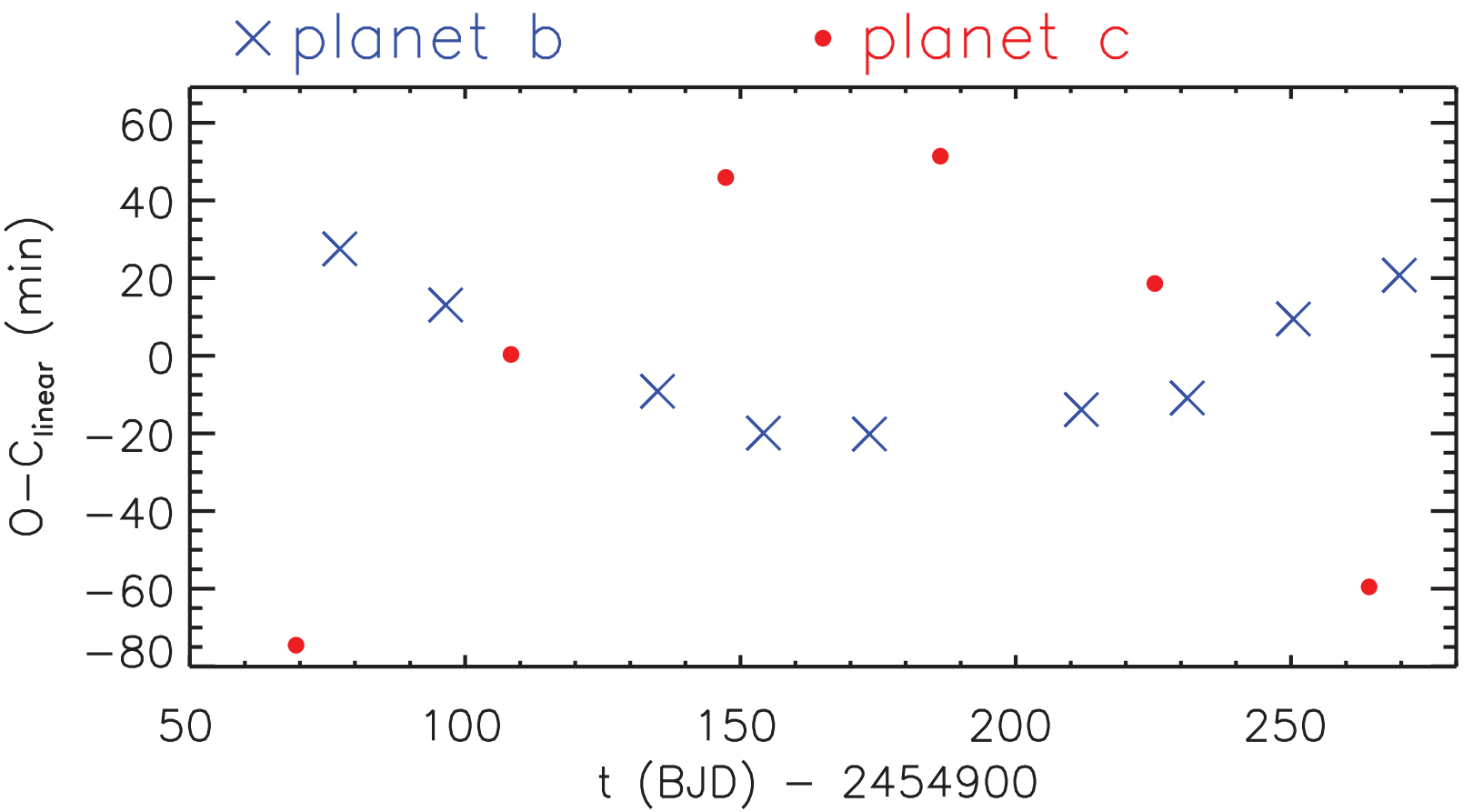








Kepler 9: First definitive TTV signal

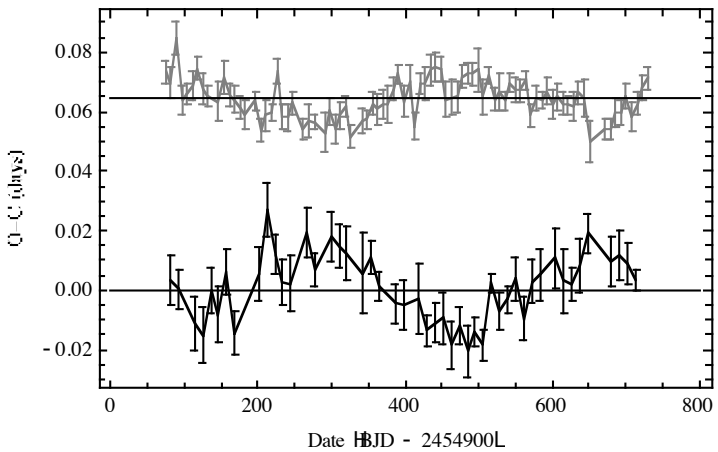


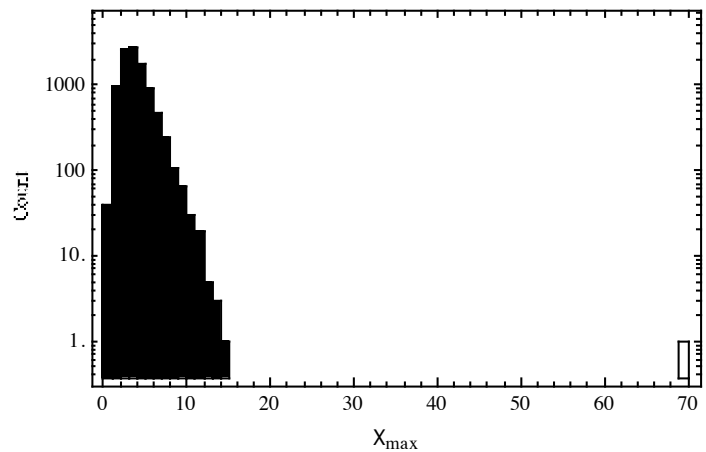
Holman et al. 2010

TTVs for planet confirmation

Candidate ⟶ Planet

Show from TTVs that two planets must be in the same system.





Steffen et al. (2012a), Steffen et al. (2013a)

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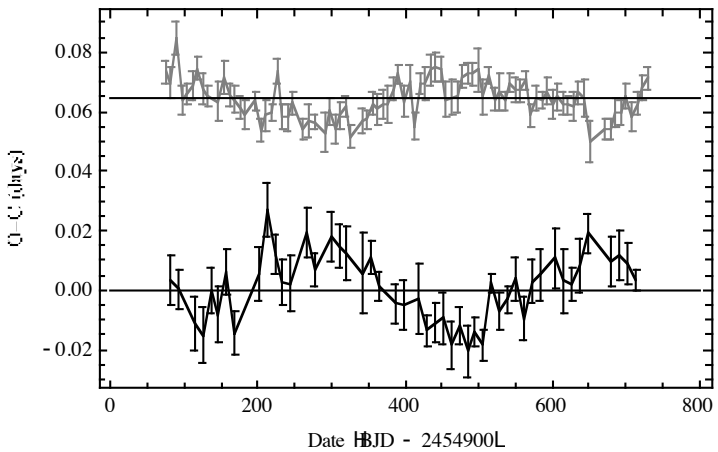
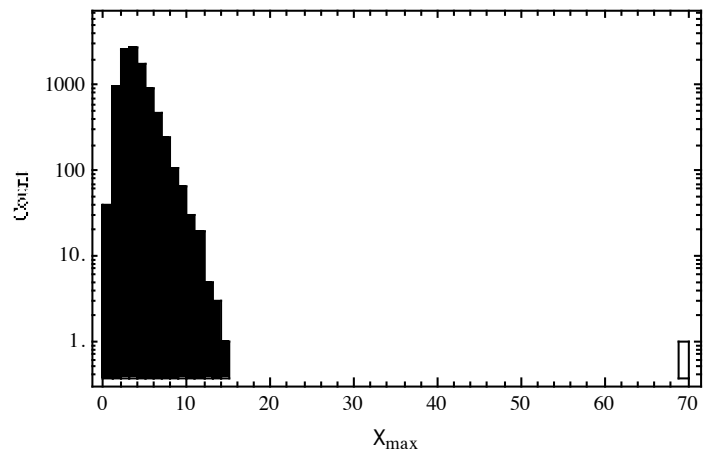
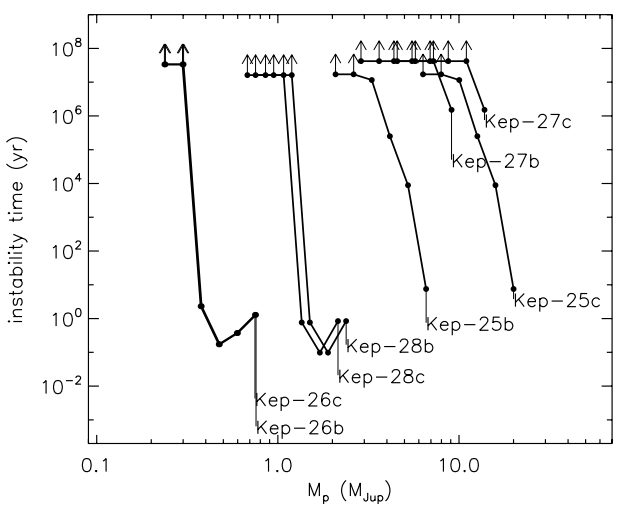
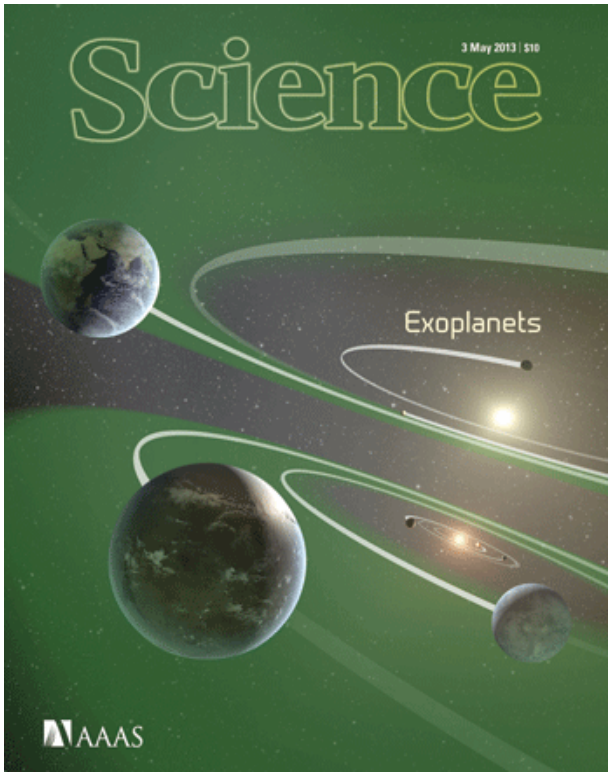


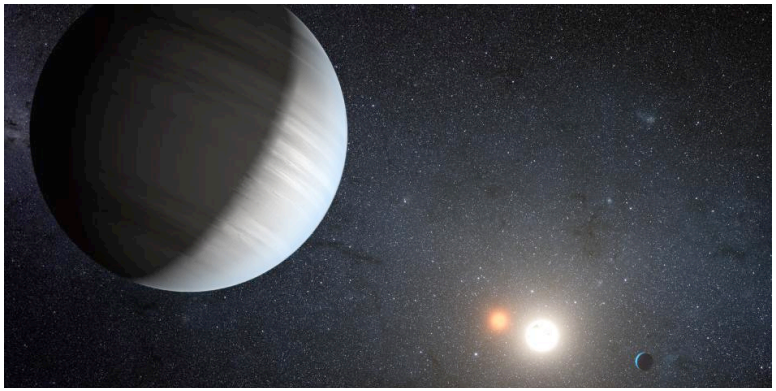




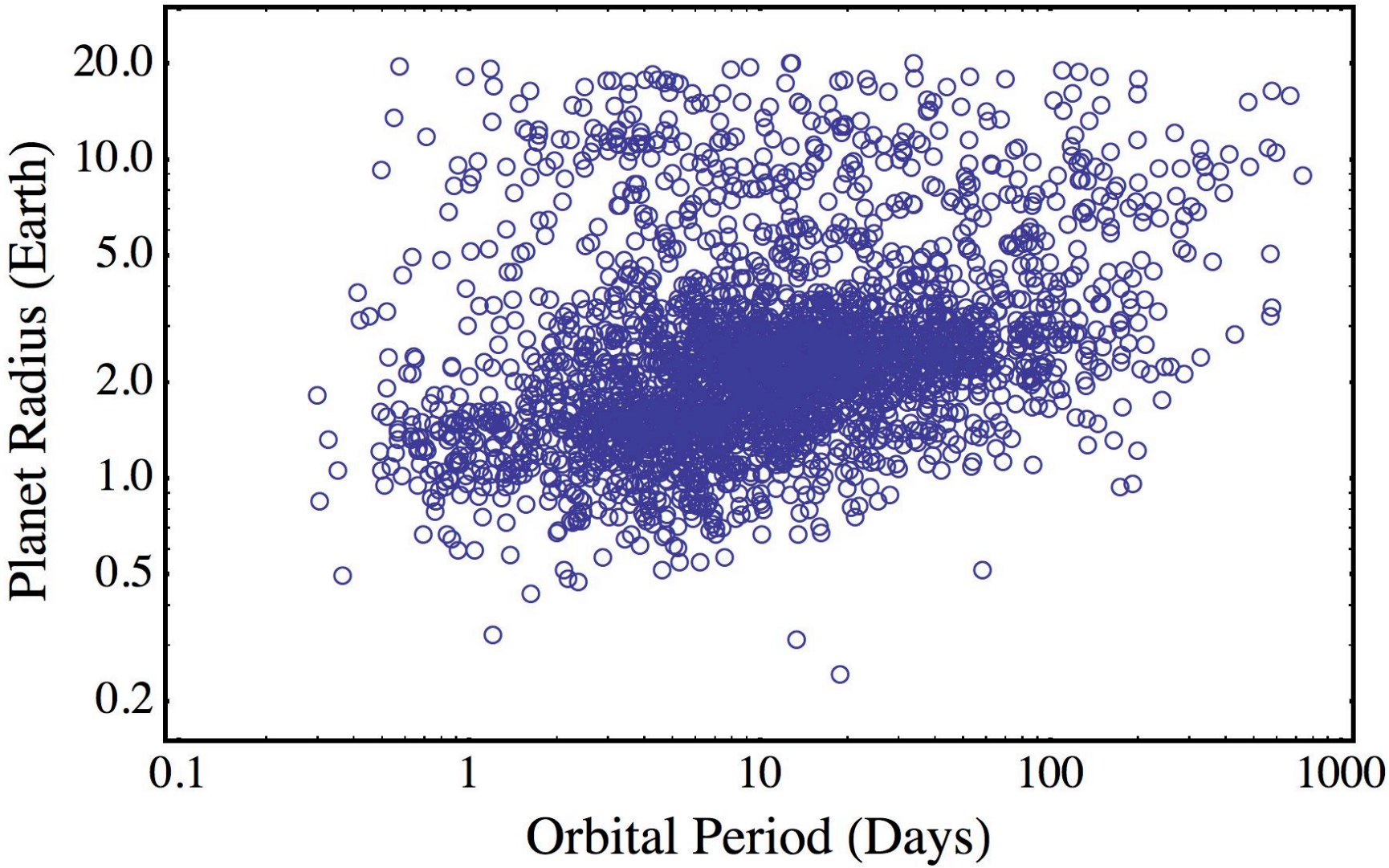
Show that their masses are planetary by requiring orbital stability.

Steffen et al. (2012a), Steffen et al. (2013a)


3 May 2013 | $10
Science
Exoplanets
AAAS

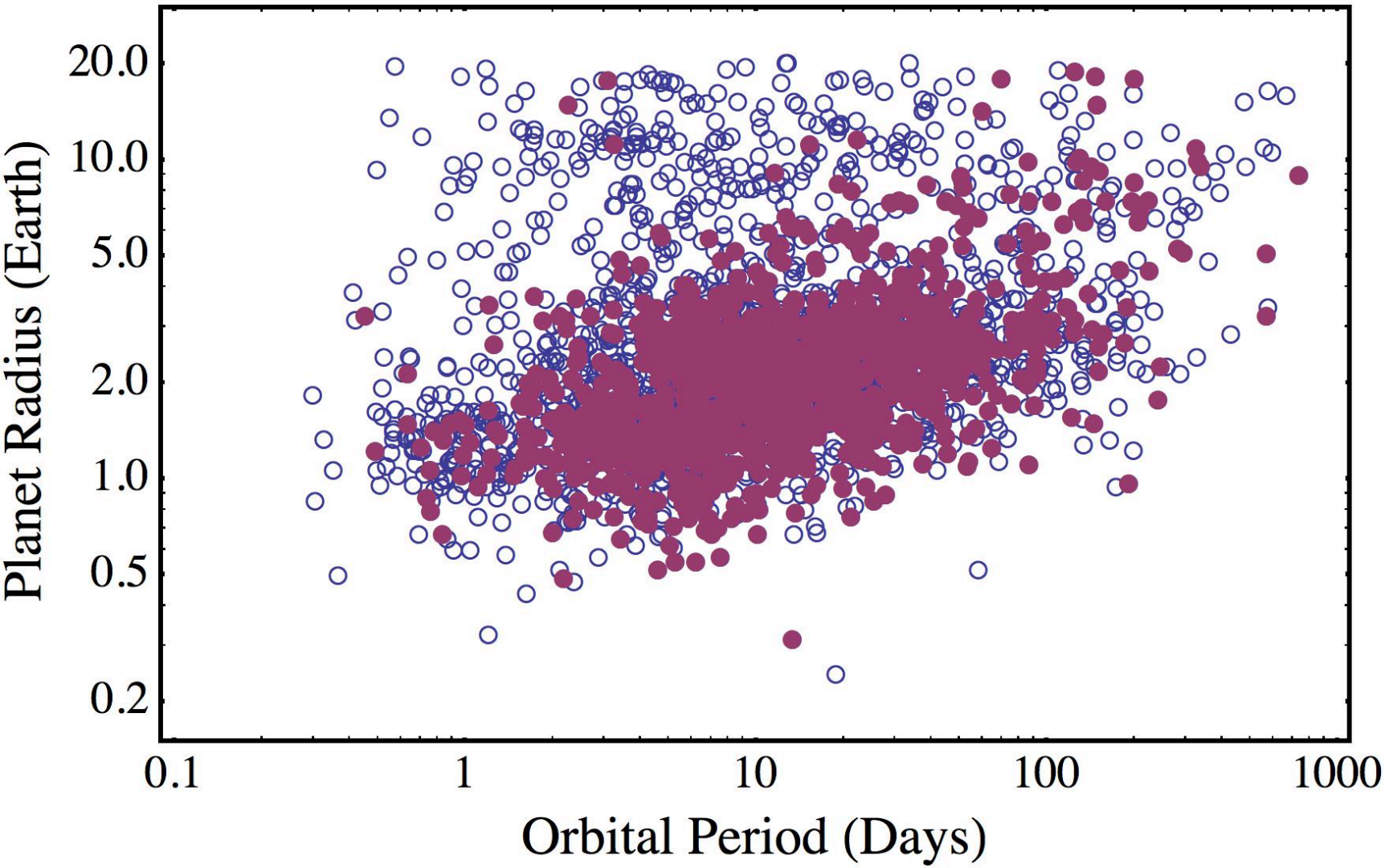


Kepler Planet Candidates through Q8

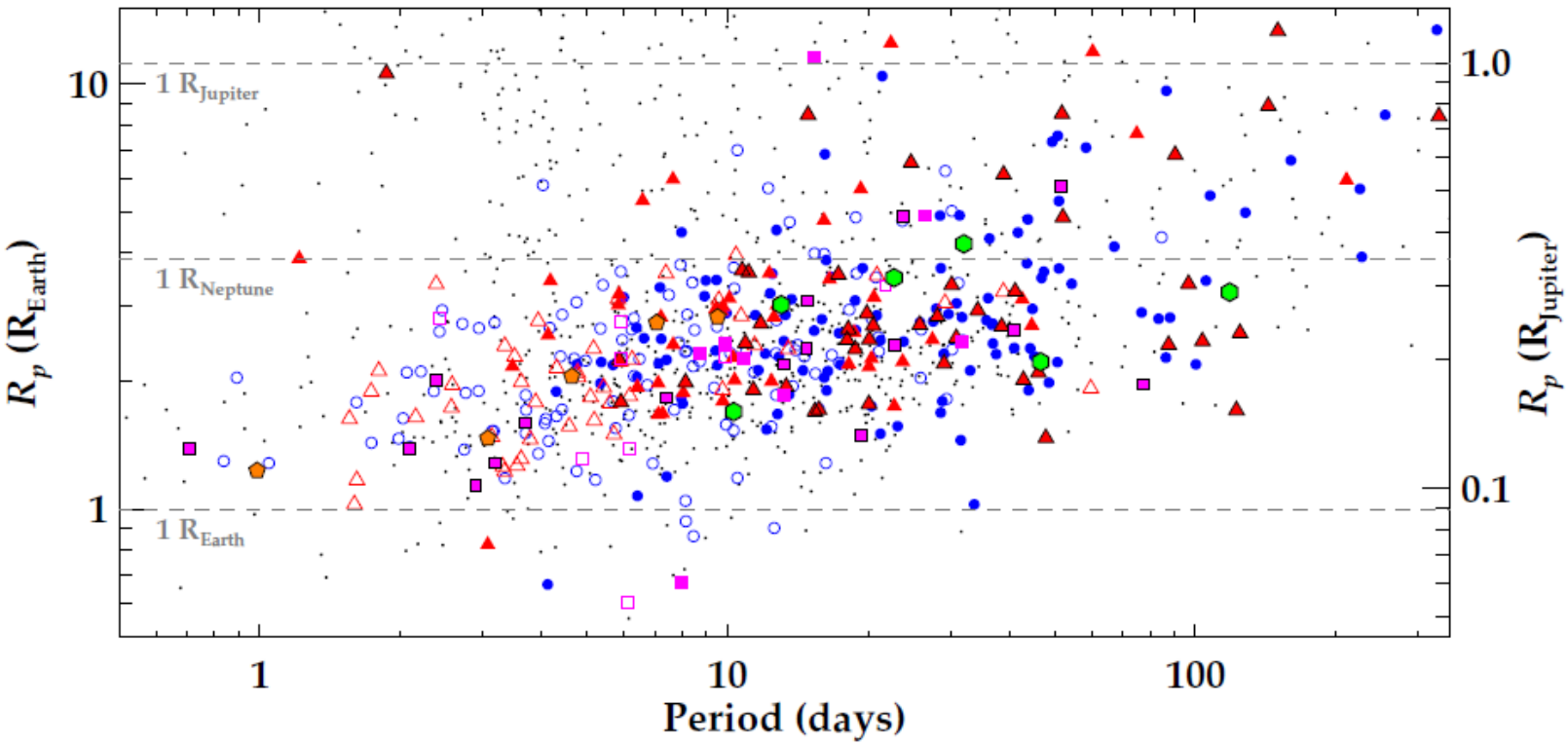


Kepler Planet Candidates through Q8

> 450 multi-planet systems



Different planet populations



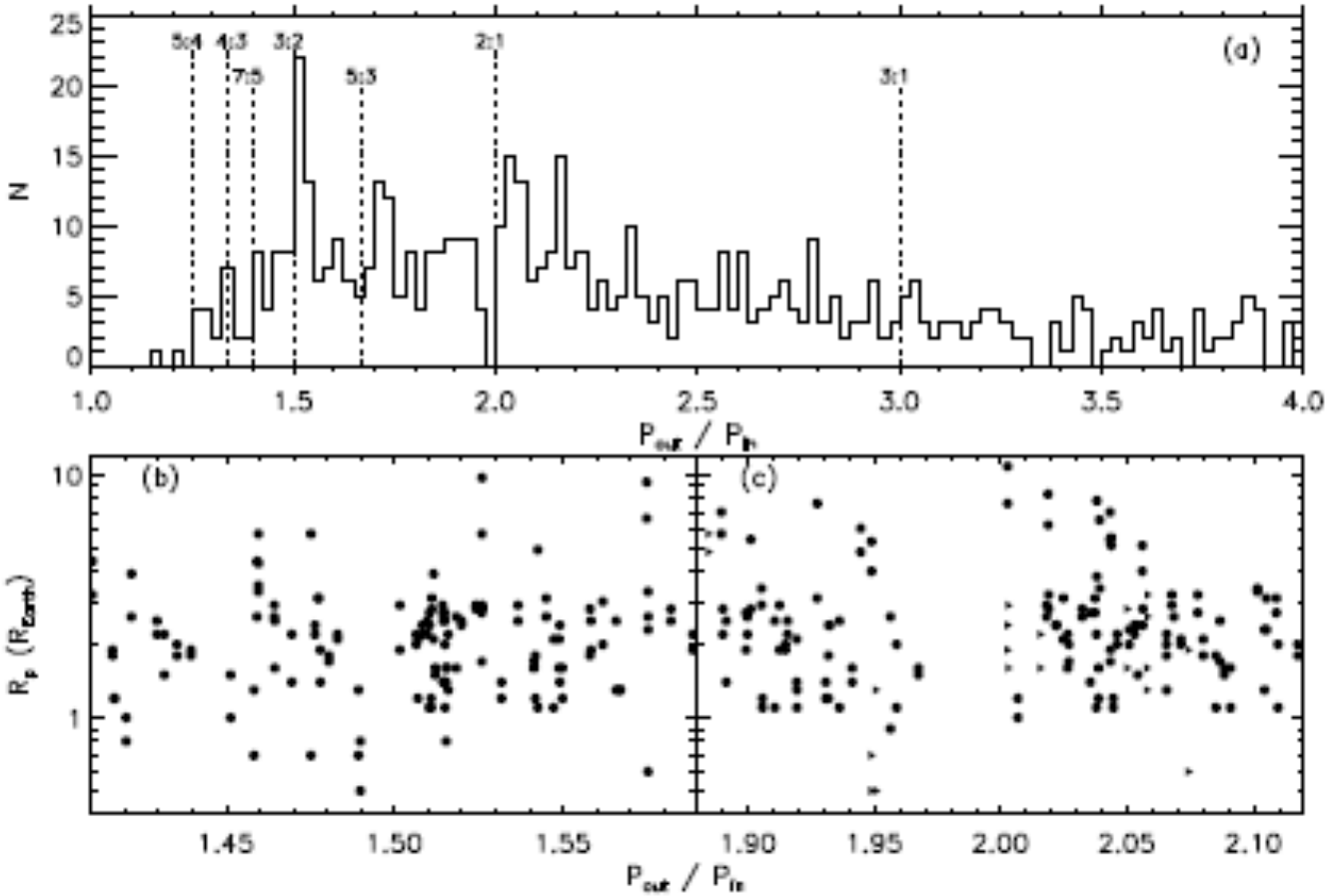
Numbers of multiplanets:

115 doubles, 45 triples, 8 quads,

1 & 1 of five and six

Lissauer et al. 2011

Multiple Candidate Systems

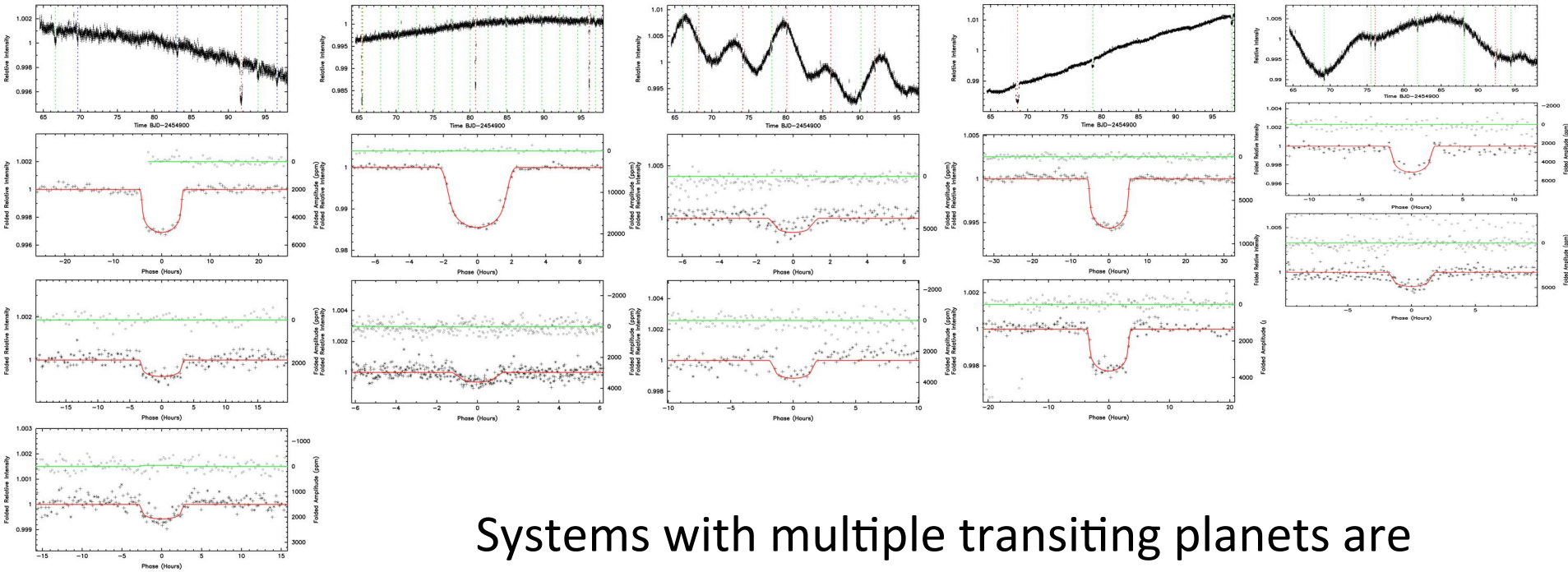


Fabrycky et al. 2012

Multi-transiting Systems

FIVE *KEPLER* TARGET STARS THAT SHOW MULTIPLE TRANSITING EXOPLANET CANDIDATES

Jason H. Steffen[1], Natalie M. Batalha[2], William J. Borucki[3], Lars A. Buchhave[4,5], Douglas A. Caldwell[3,6], William D. Cochran[7], Michael Endl[7], Daniel C. Fabrycky[4], François Fressin[4], Eric B. Ford[8], Jonathan J. Fortney[9], Michael J. Haas[3], Matthew J. Holman[4], Steve B. Howell[10], Howard Isaacson[11], Jon M. Jenkins[3,6], David Koch[3], David W. Latham[4], Jack J. Lissauer[3], Althea V. Moorhead[8], Robert C. Morehead[8], Geoffrey Marcy[11], Phillip J. MacQueen[7], Samuel N. Quinn[4], Darin Ragozzine[4], Jason F. Rowe[3], Dimitar D. Sasselov[4], Sara Seager[12], Guillermo Torres[4], and William F. Welsh[13]



Systems with multiple transiting planets are significantly easier to interpret.

Kepler 36

Large TTVs required the development of a new search algorithm.

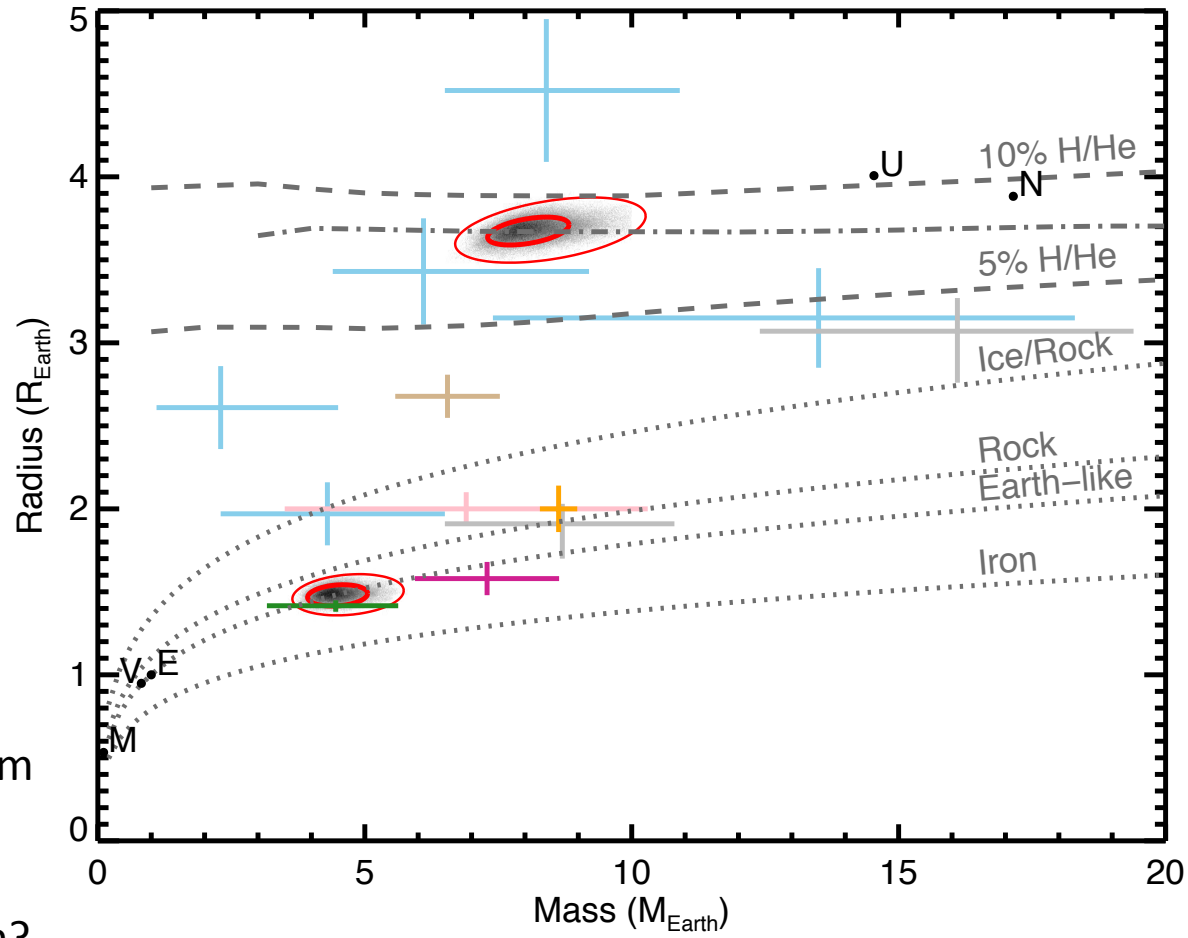
These two planets are very near the 7:6 mean-motion resonance—their orbital distances are 10% different.

Their densities differ by nearly a factor of 10.

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

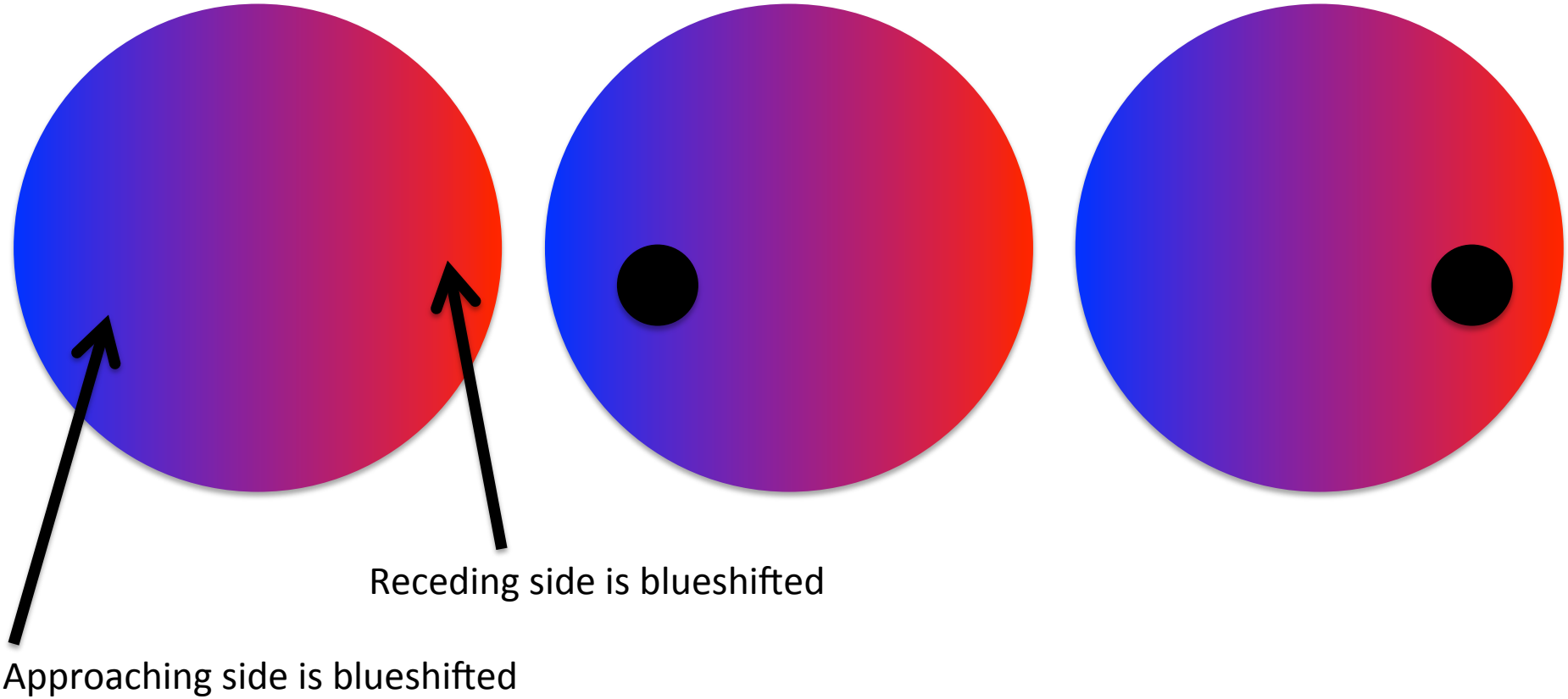
How do you make such a system?

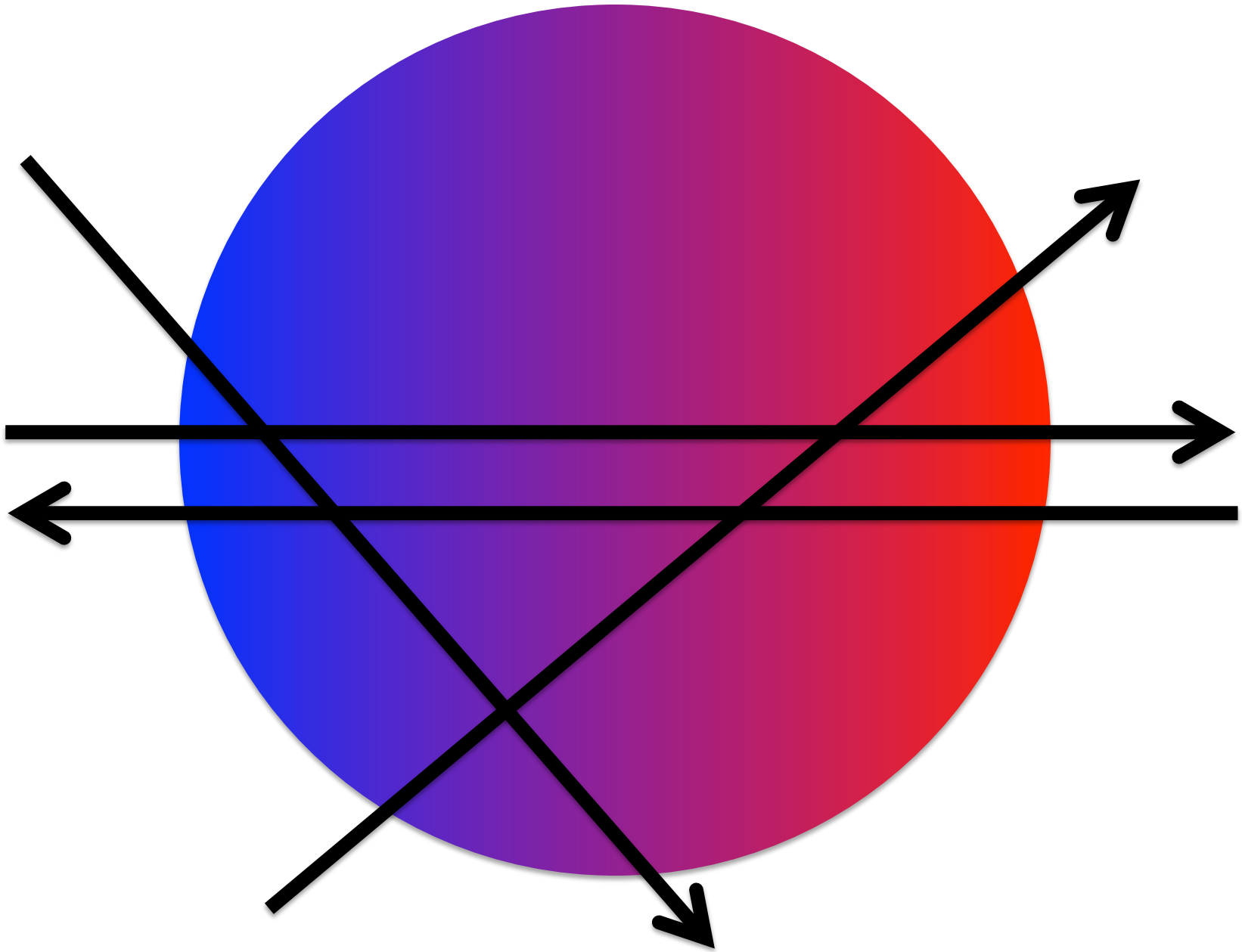
Good question.



Carter, Agol, et al. 2011

Signature of Violence and Mayhem
(Rossiter-McLaughlin Effect)





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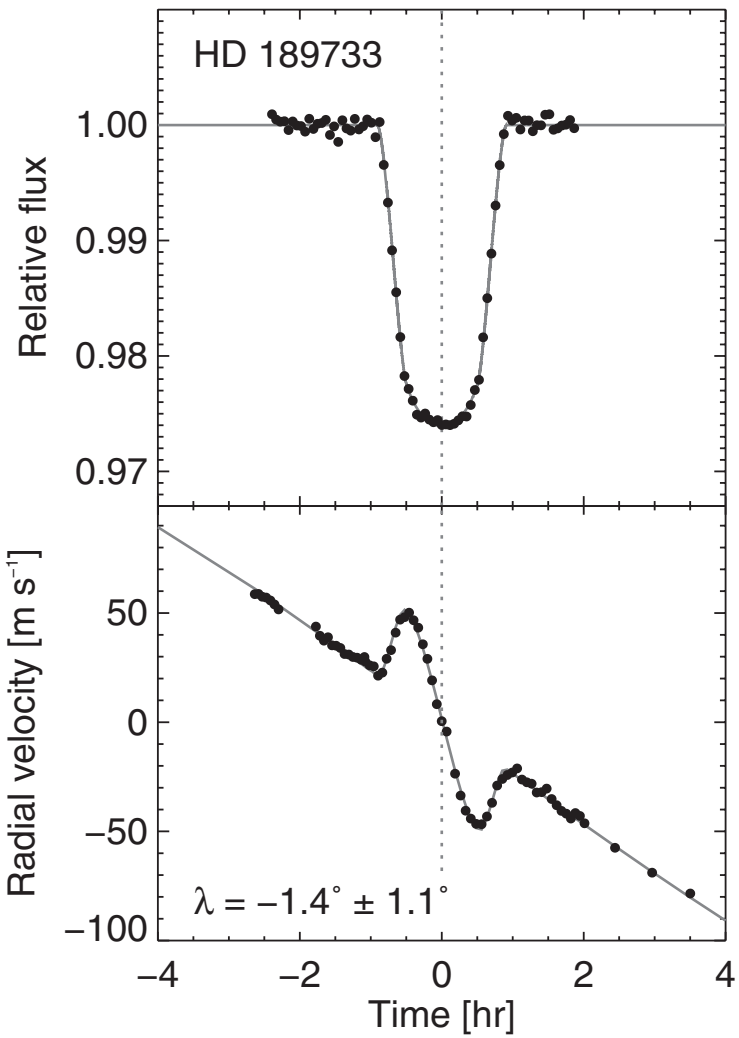
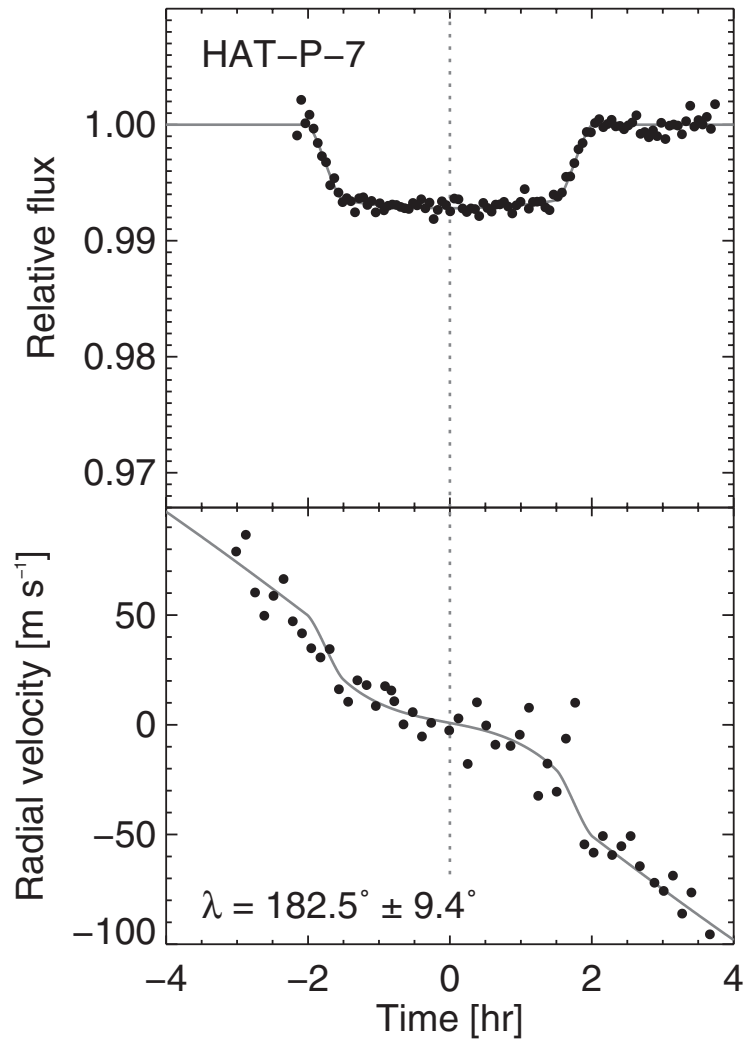
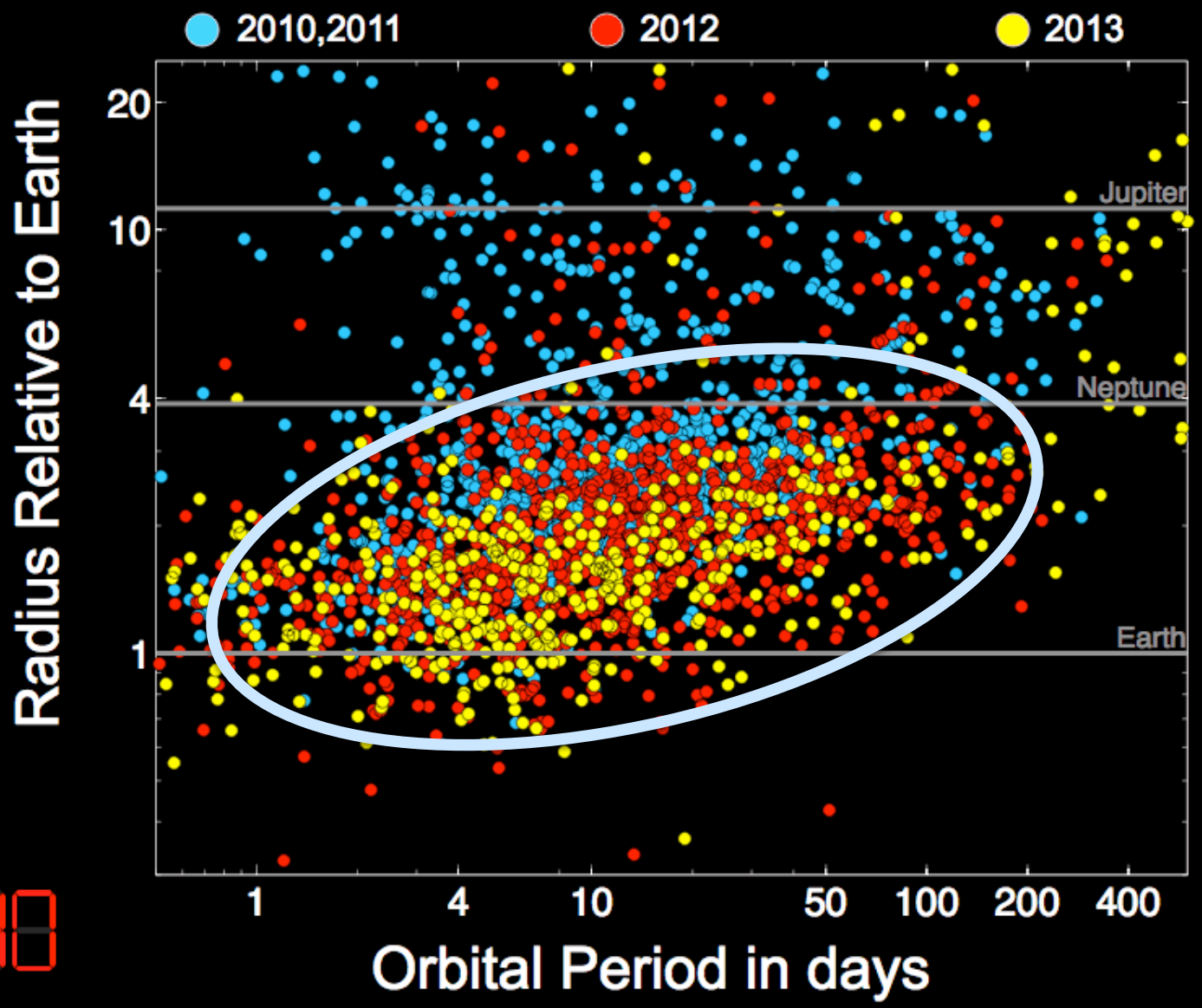




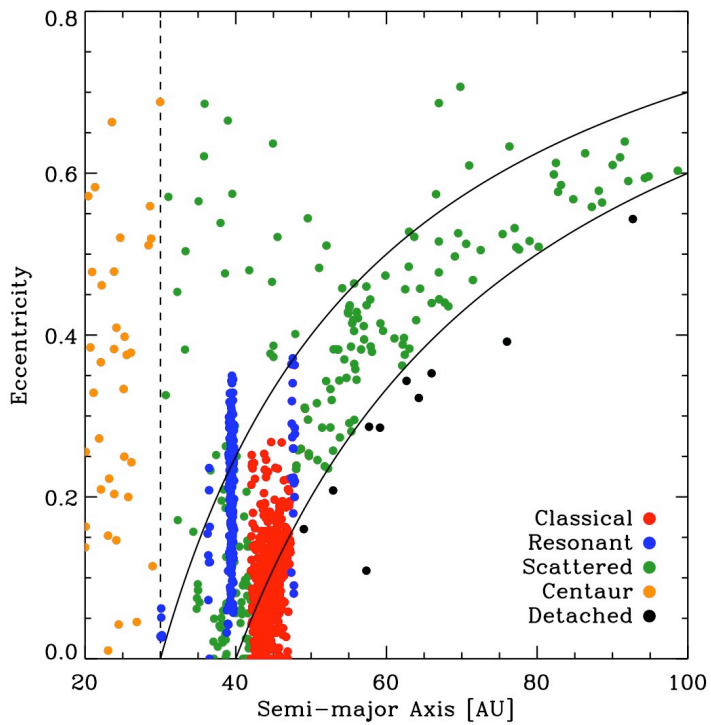
Kepler's Planet Candidates

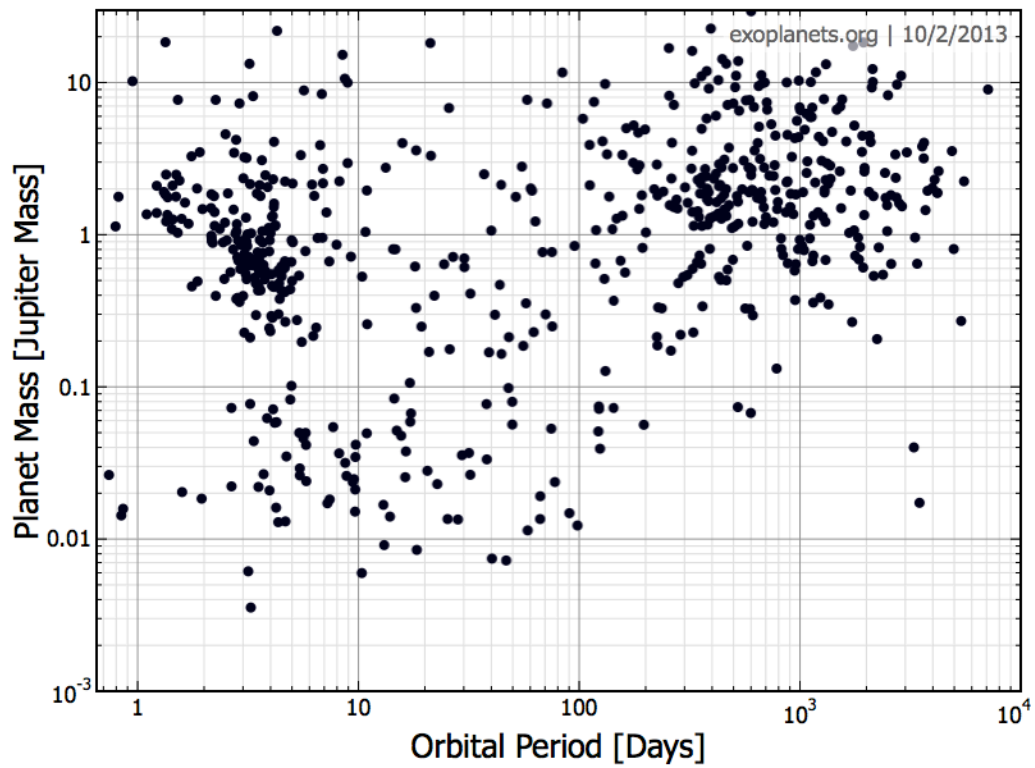
22 Months: May 2009 - Mar 2011



Chris Burke:
216.02

Migration Changes System Architecture



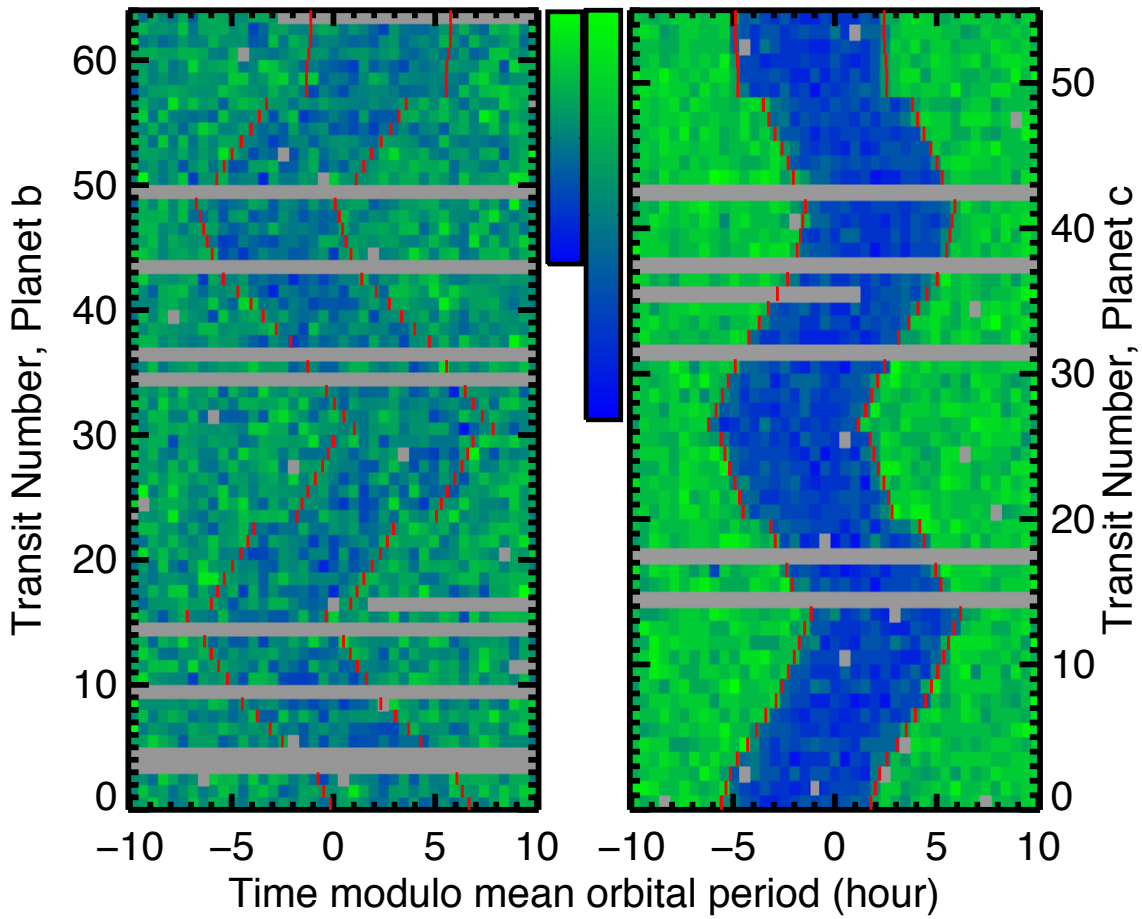


Studying the dynamics of a system today tells us about its history and gives insight into the formation of the system.

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.

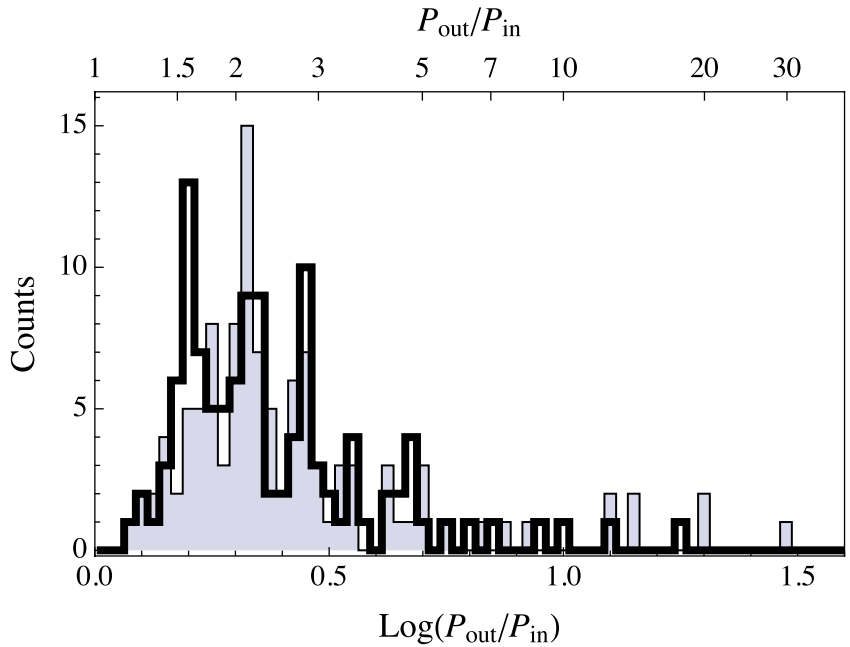


Carter, Agol, et al. 2011

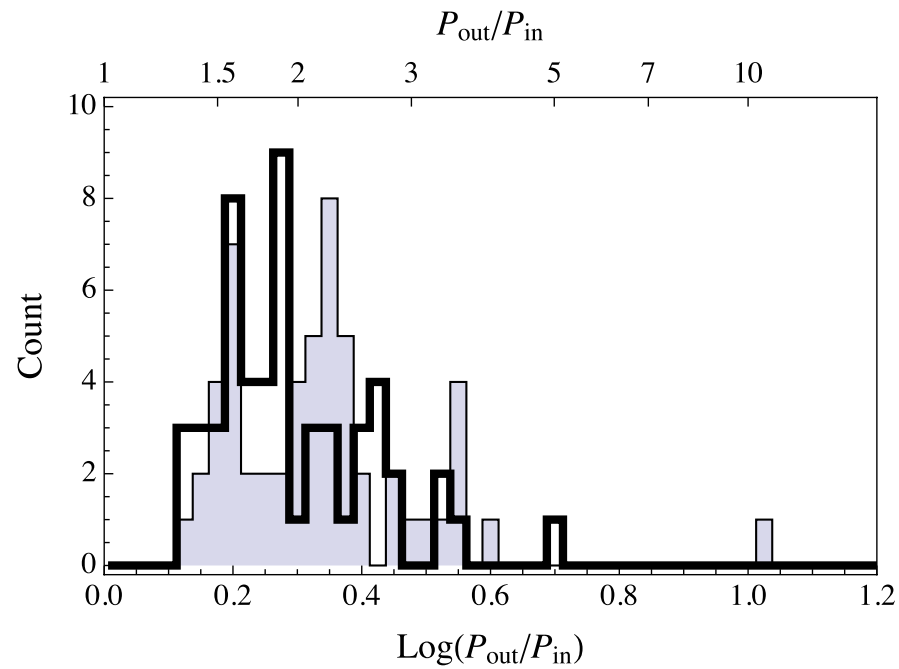
Kepler 36

Self Similarity Test

Three-planet systems



Four-plus planet systems



Outline is the period ratio distribution for the outer two planets.

Solid is the period ratio distribution for the inner two planets.

Kepler 9

Holman et al. 2010

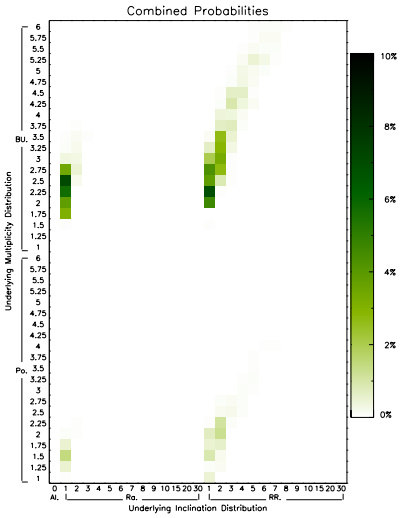
Kepler 11

Lissauer et al. 2011

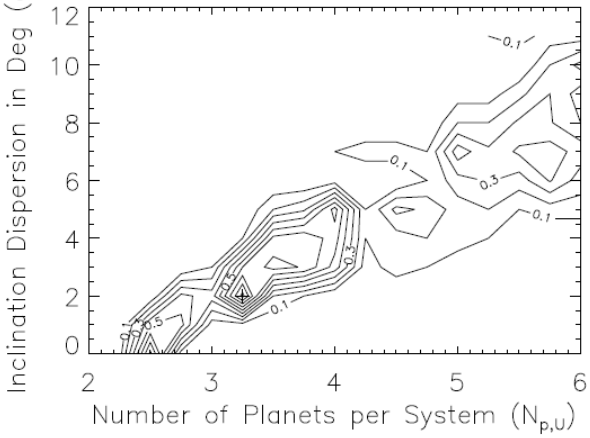
Orbital Architectures with Transiting Planets

Inclination and Multiplicity

Fang and Margot (2012)



Lissauer et al (2011)



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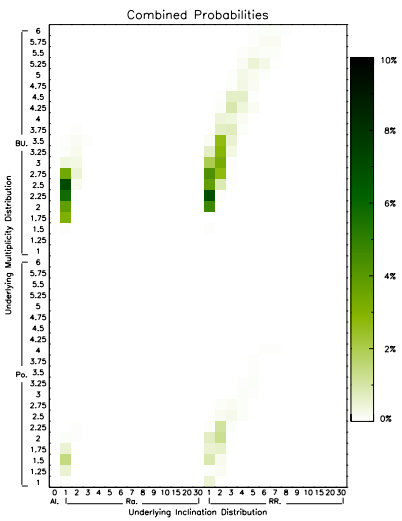
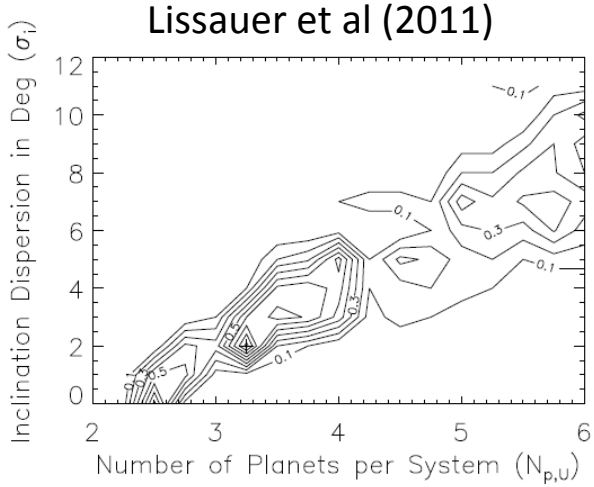
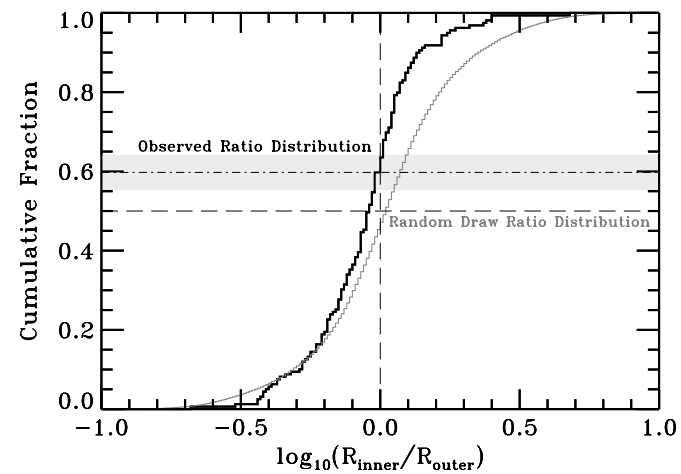


Lissauer et al (2011)



Size Ratios

Ciardi et al. (2013)



Orbital Architectures with Transiting Planets

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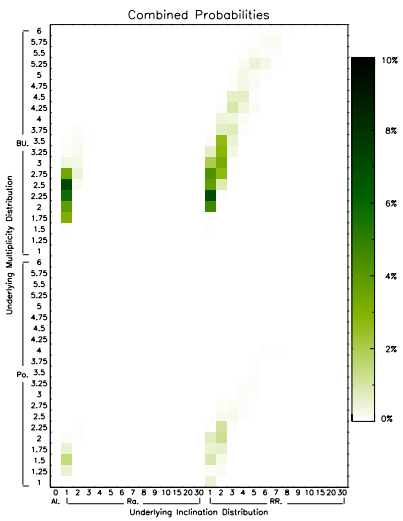
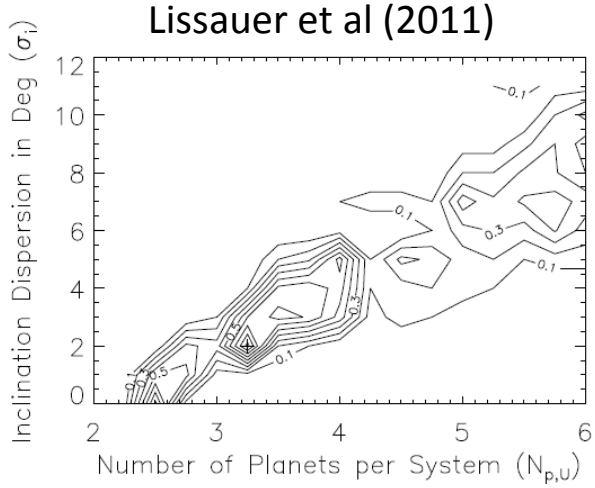
Fang and Margot (2012)

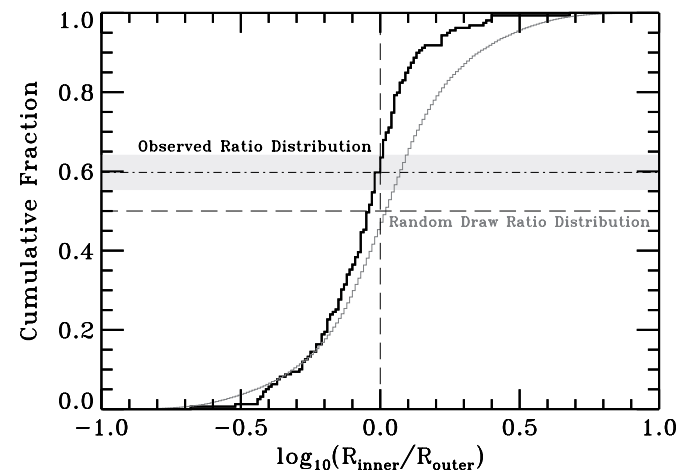


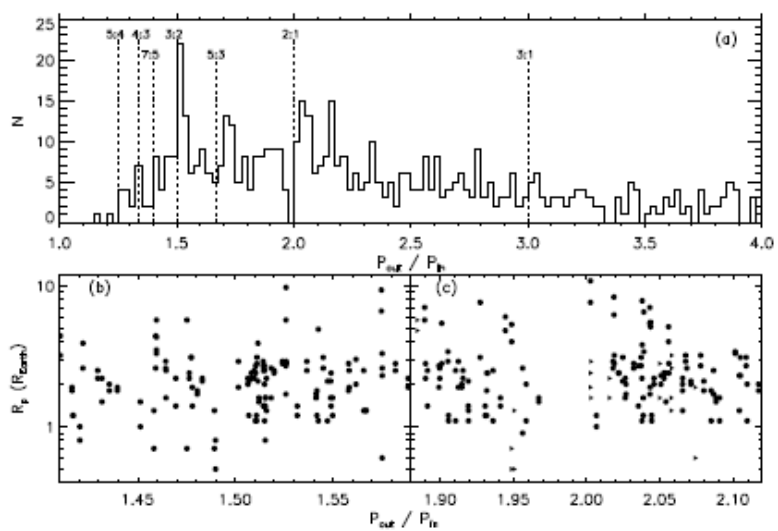
Lissauer et al (2011)



Size Ratios

Ciardi et al. (2013)

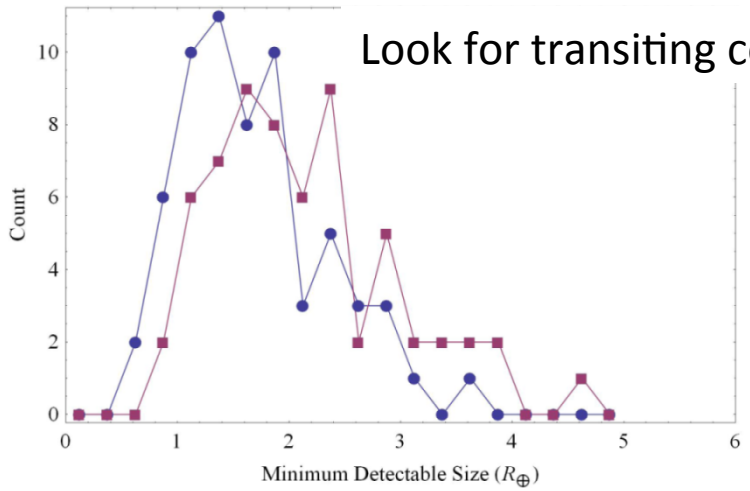




Period Ratios

Fabrycky et al. (2012)

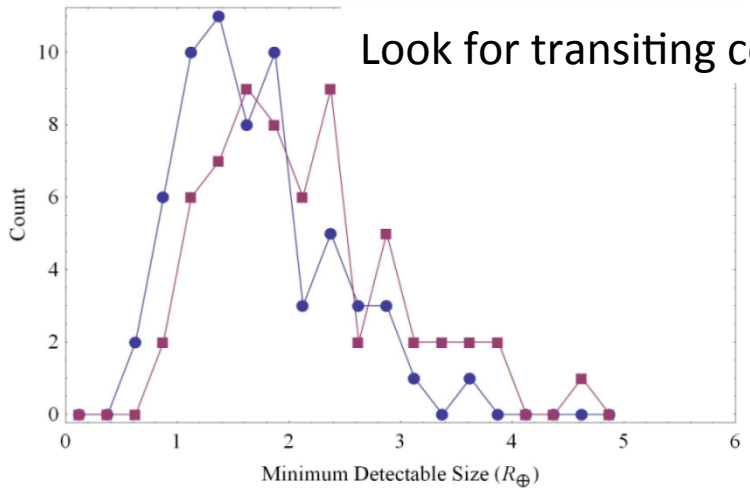
Analysis of Transiting Hot Jupiter Systems



Look for transiting companions…

Steffen et al. PNAS (2013)

Analysis of Transiting Hot Jupiter Systems



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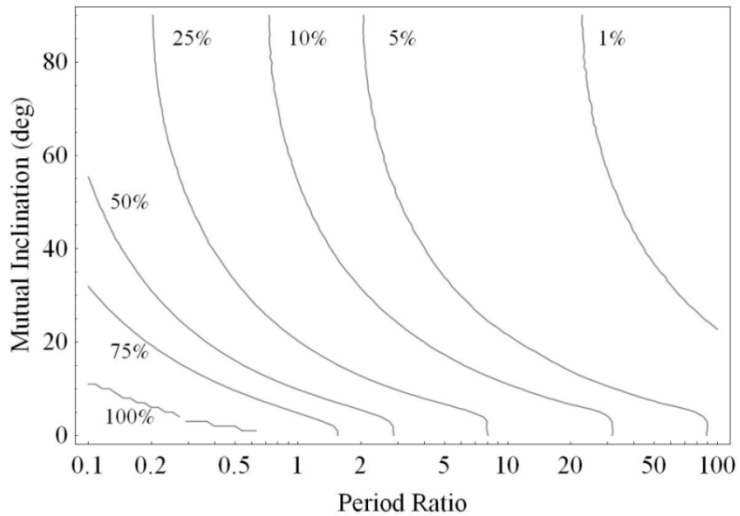
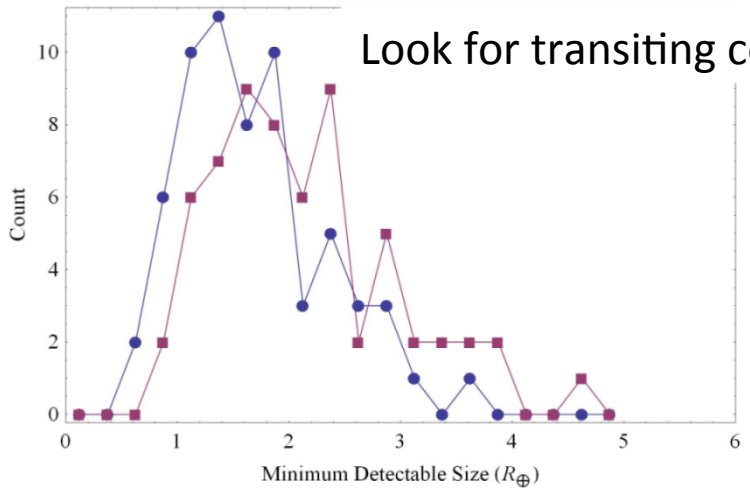


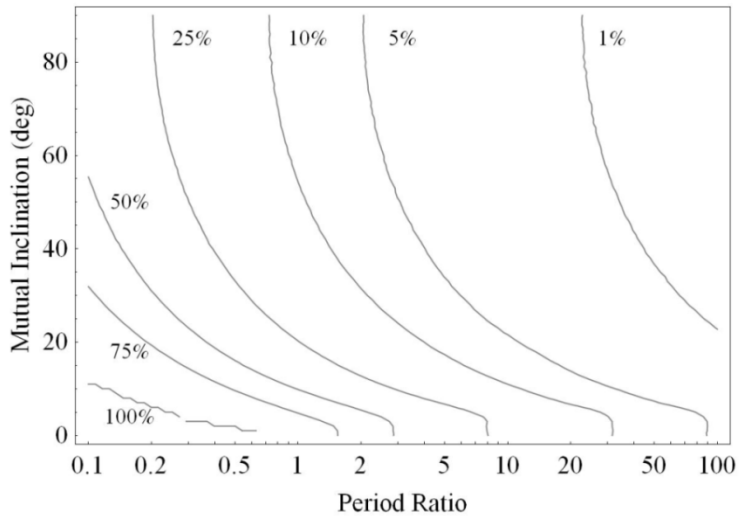
Consider mutual inclinations…

Steffen et al. PNAS (2013)

Analysis of Transiting Hot Jupiter Systems

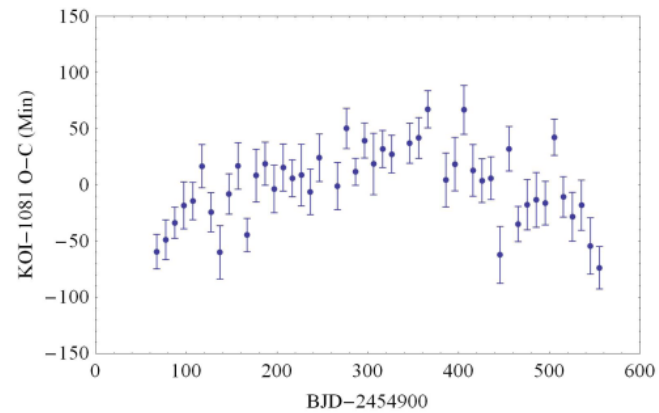
Look for transiting companions…

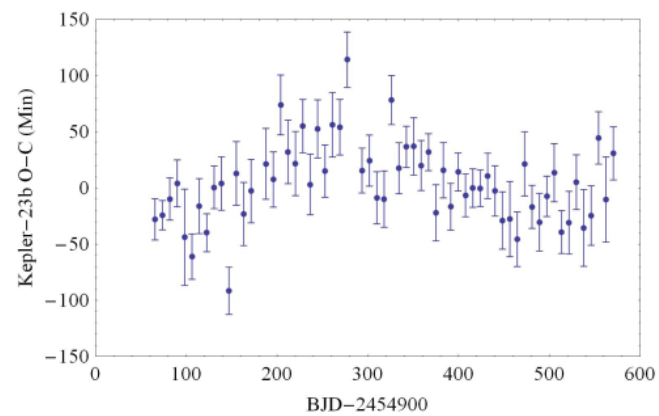




Consider mutual inclinations…

Look for TTVs in both
hot Jupiter and super Earth systems





Steffen et al. PNAS (2013)

Subsets of the Period Ratio Distribution

- Two planet systems vs. inner pair of larger systems ($p \approx 0.0003$)

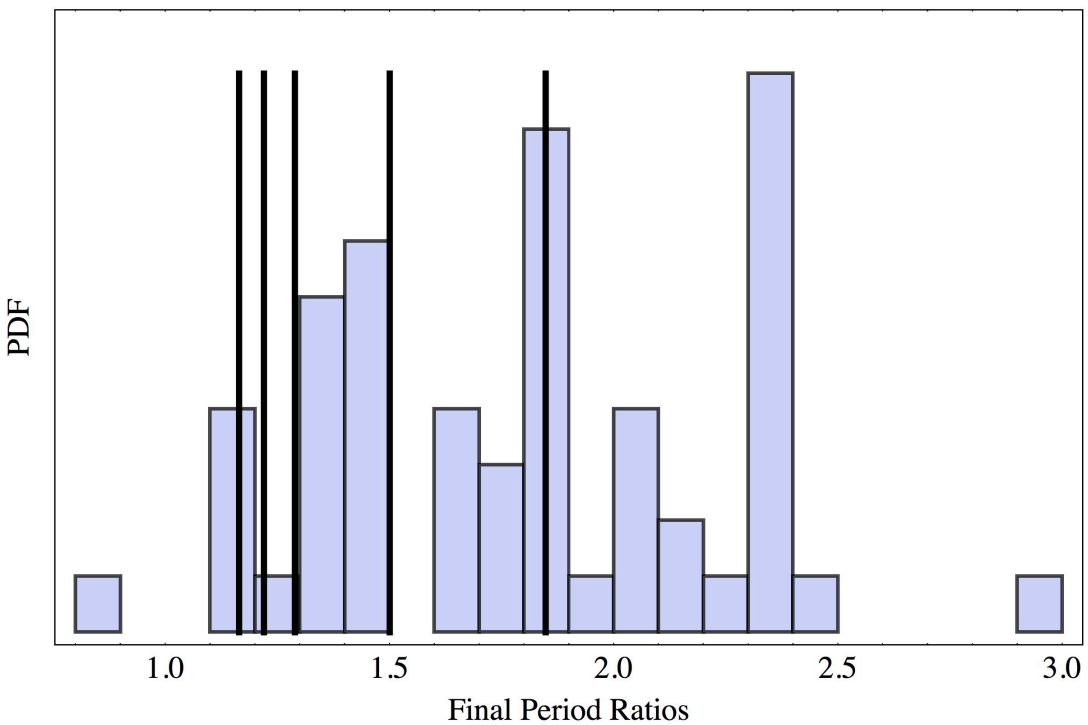
- Self similarity in systems with three or more planets ($p \approx 0.05$)

- Test systems with short and long orbital periods ($p \approx 0.01$ for 3+ planets)

Some possibilities being pursued

Most Kepler multiplanet systems are dynamically packed.
There is not much wiggle room.

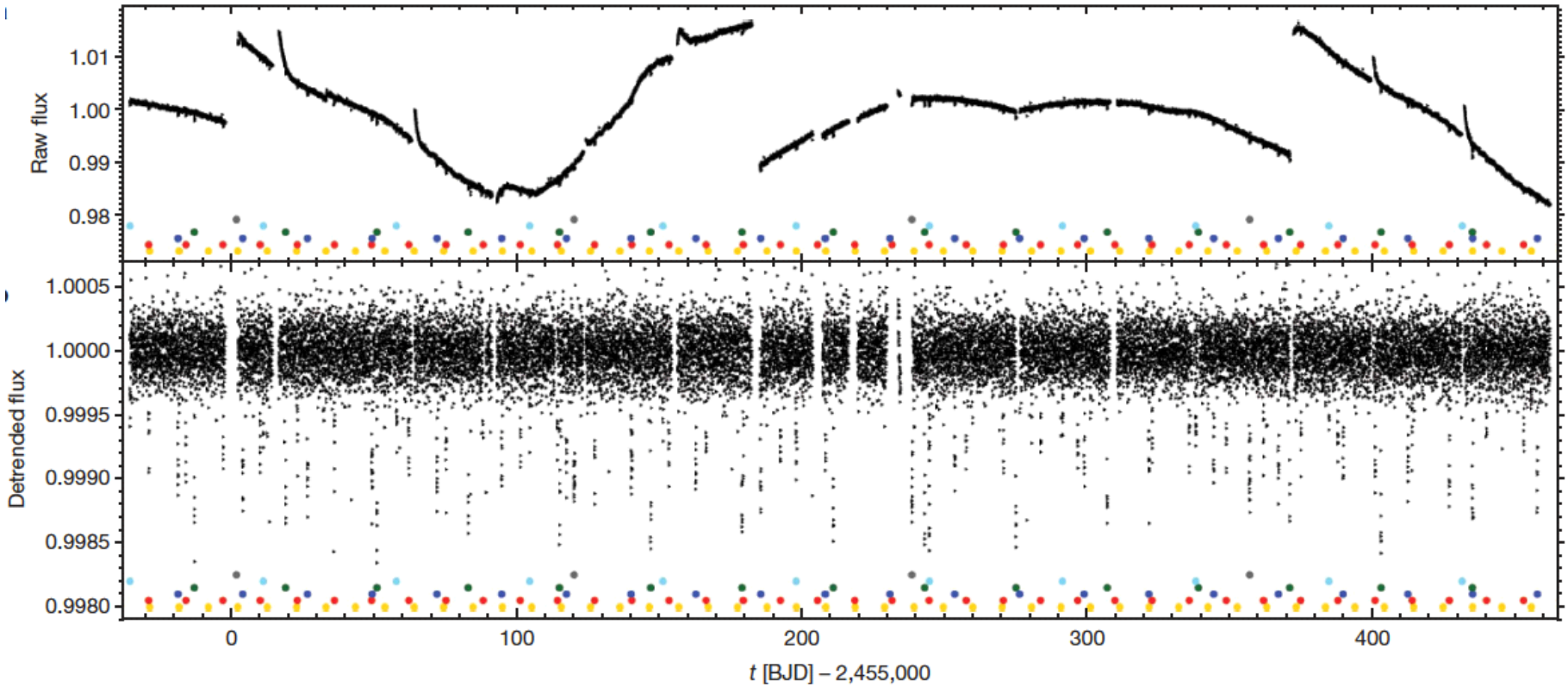
Perhaps some have gone unstable and had subsequent collisions.



(preliminary) Period ratio distribution for unstable Kepler-11 systems.

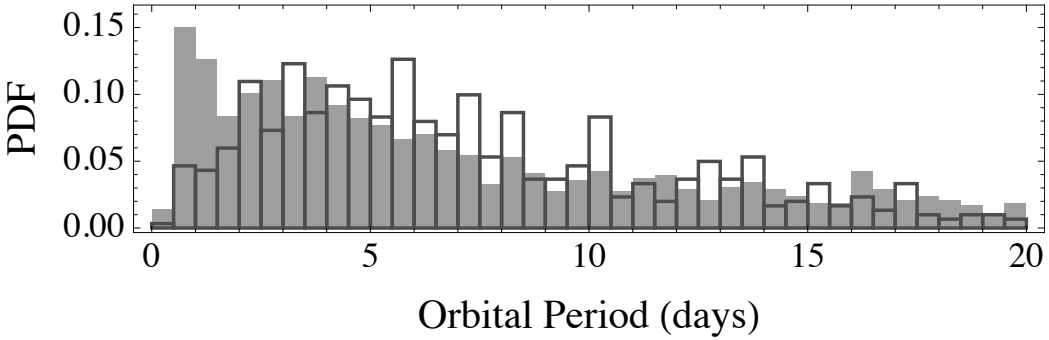
TTVs for Planet Characterization

Kepler 11

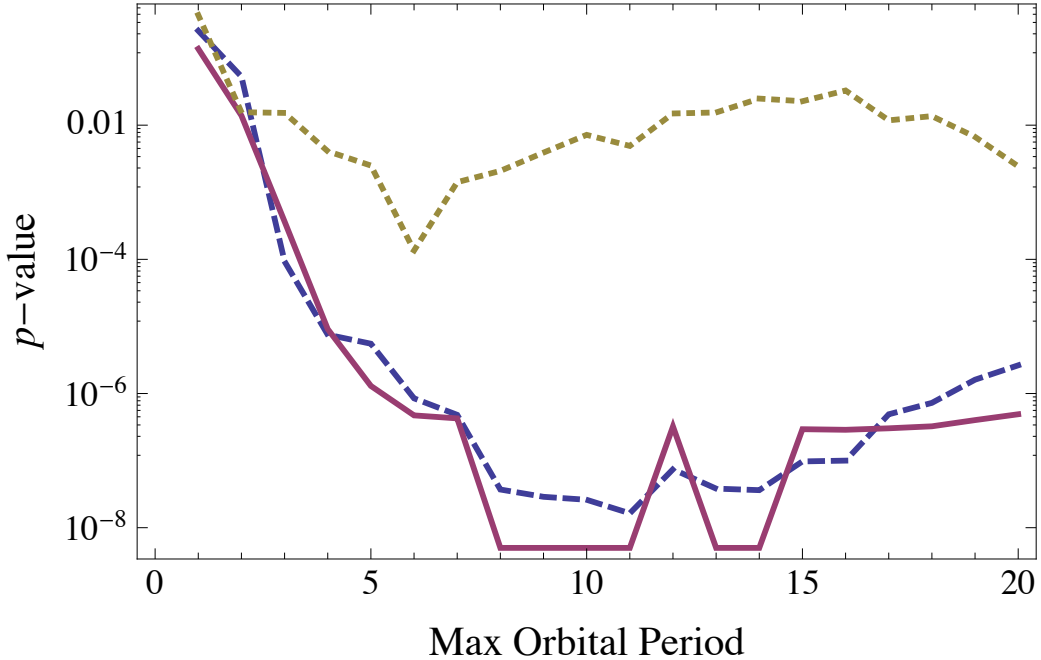


Lissauer et al. 2011

Not from a lack of planets



Orbital period distribution of singles (shaded) and multis (outline).

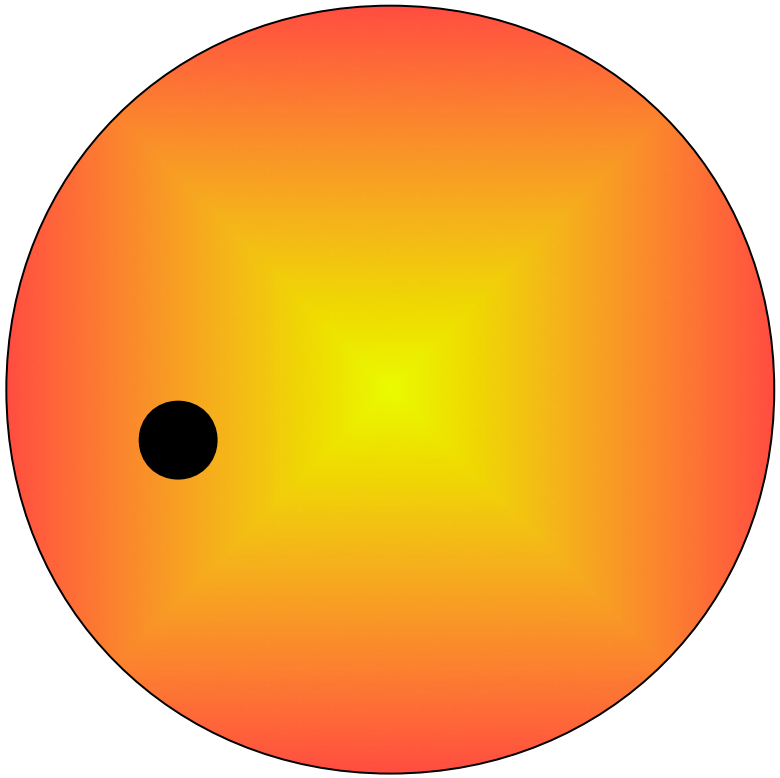


Statistical significance of the difference between the two distributions.

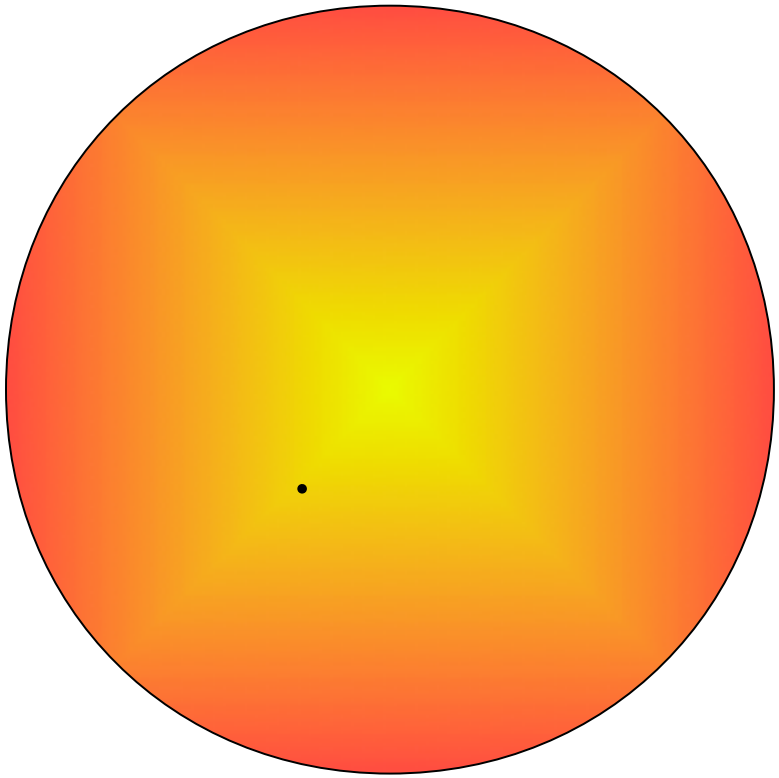
The excess of short-period planets in single-planet systems may be analogous to the hot Jupiters.

Planet Finding Methods

Planetary Transits

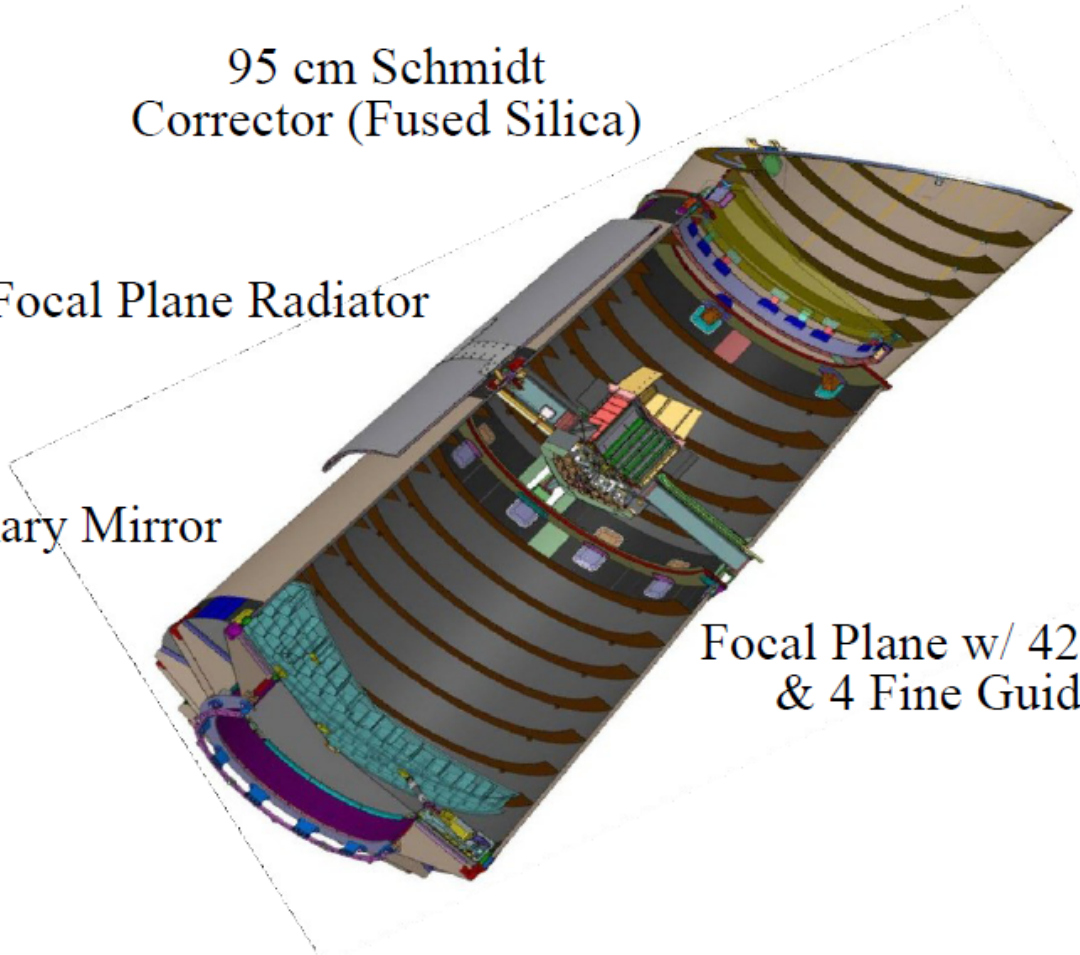


Jupiter: 1 part per 1000



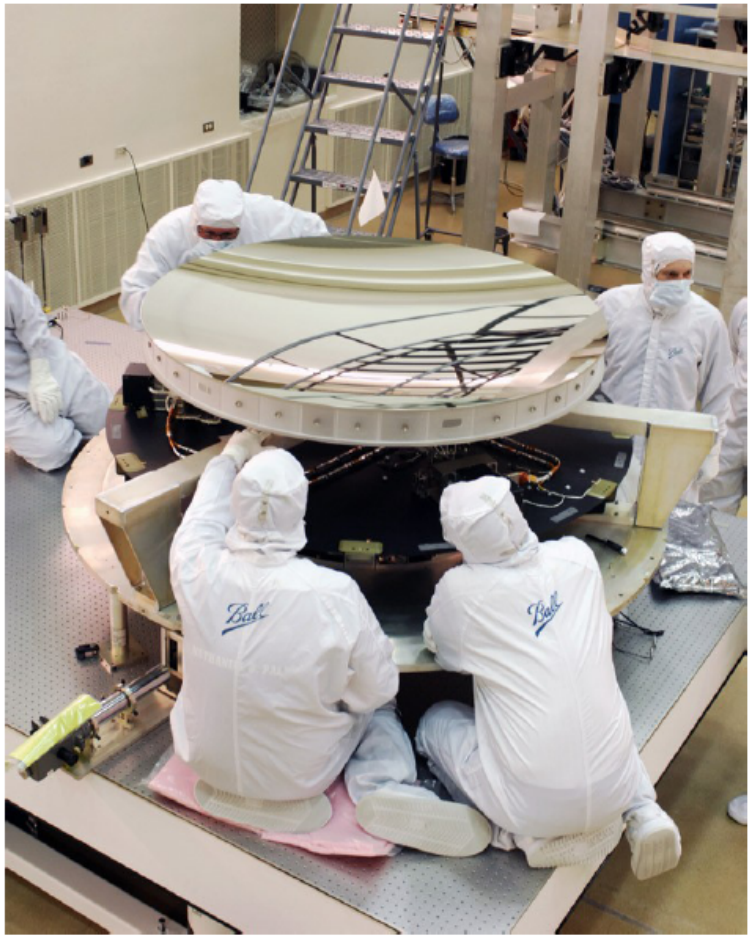
Earth: 1 part per 100,000

Kepler Spacecraft



Kepler Photometer

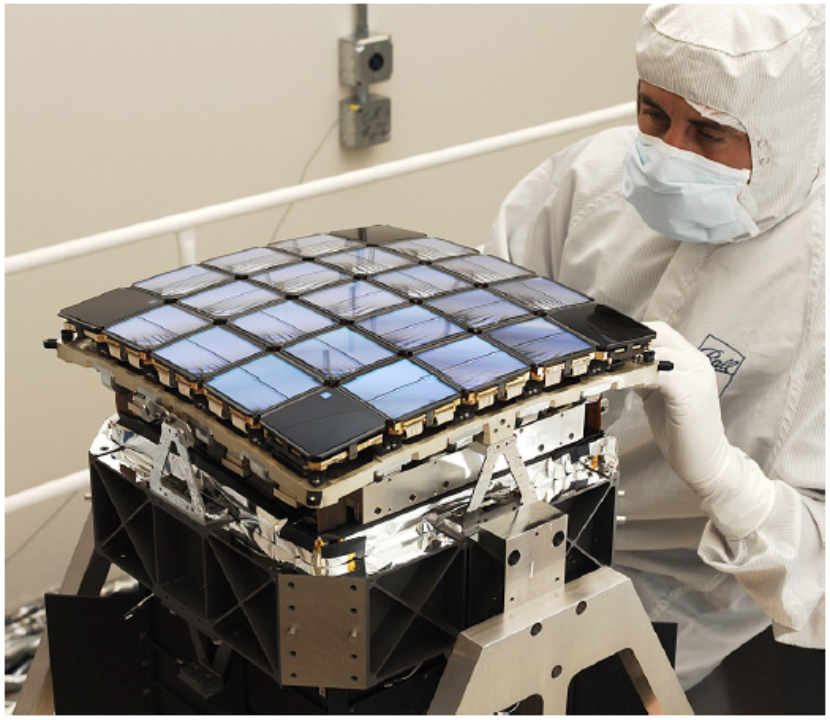
50 micromagnitudes in 6 hours
30 minute cadence



Continuously monitor
~150,000 target stars

Images are de-focused

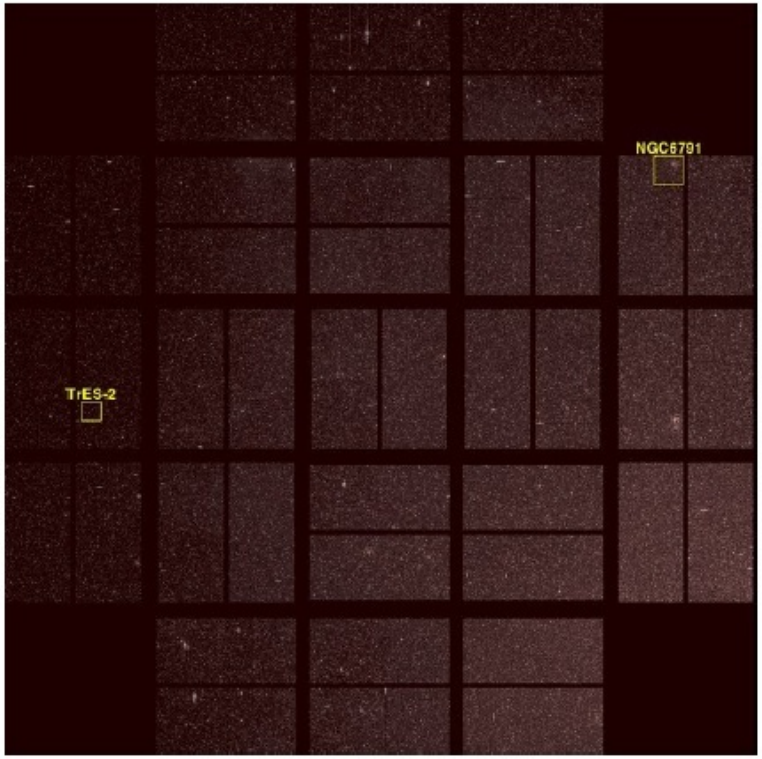
Only target pixels are
sent back to Earth



Kepler Field of View

~100 square degrees

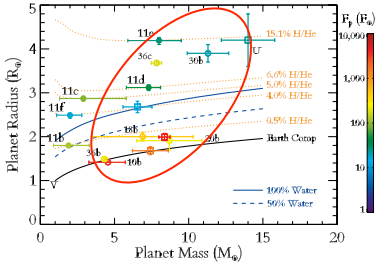
First light image



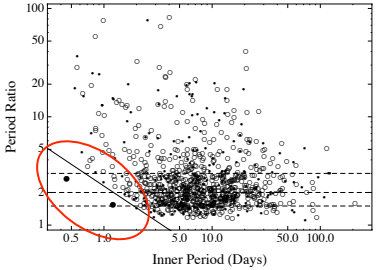
What now?

- Much Kepler data remains to be studied
  - Only ½ of the data were analyzed in the most recent catalog
  - Only ε of the science has been done on those data

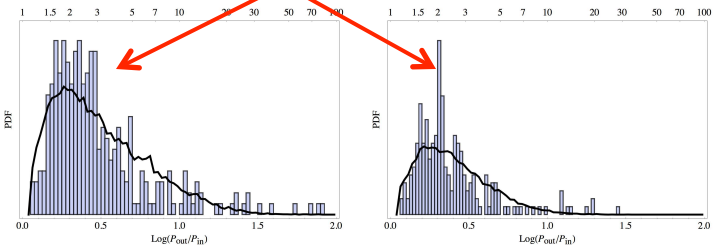
- Flesh out the mass radius relationship at the transition from sub-Neptunes to super-Earths



- Understand the cause of the missing planet pairs at short orbital periods



- Understand the cause of the architectures for 2 planet, 3 planet, and 4+ planet systems
  - Why does mean-motion resonance depend on multiplicity?



Subsets of the Period Ratio Distribution

Do the inner pair of 4+ systems match 2 planet systems?

Steffen (2013b)

Subsets of the Period Ratio Distribution

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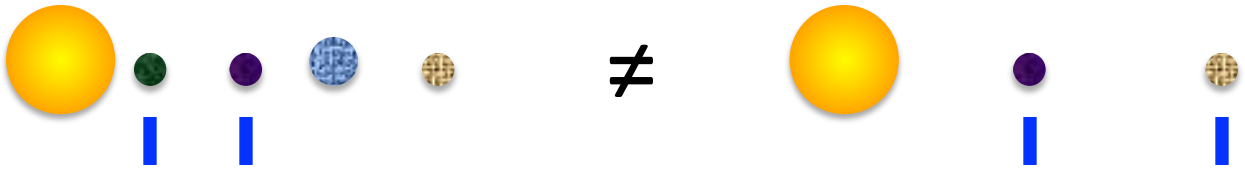

Steffen (2013b)

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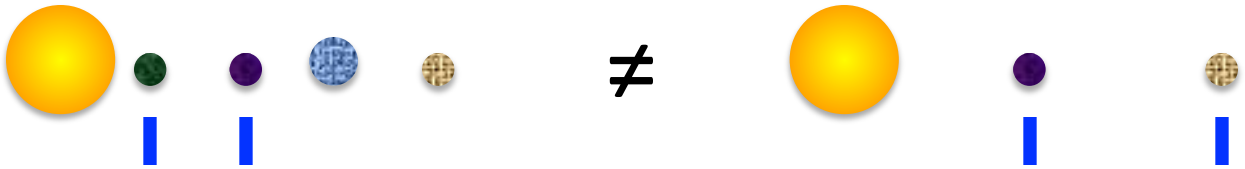
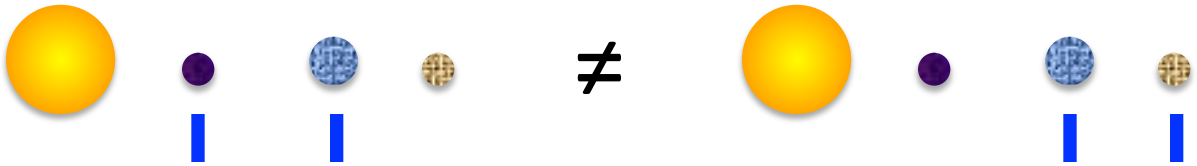


Are systems self-similar?



Steffen (2013b)

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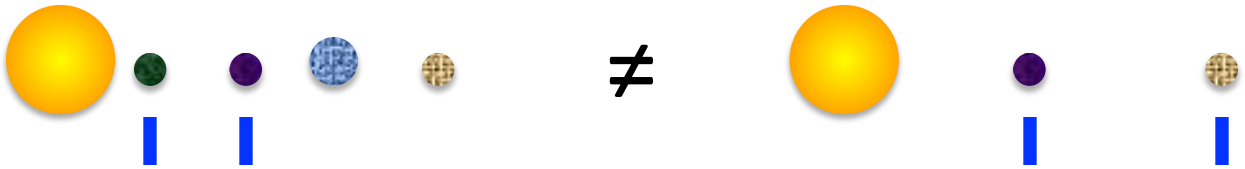

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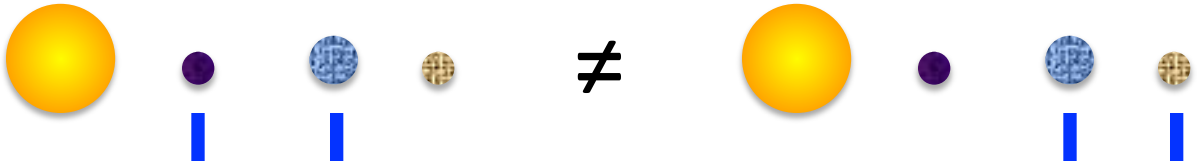
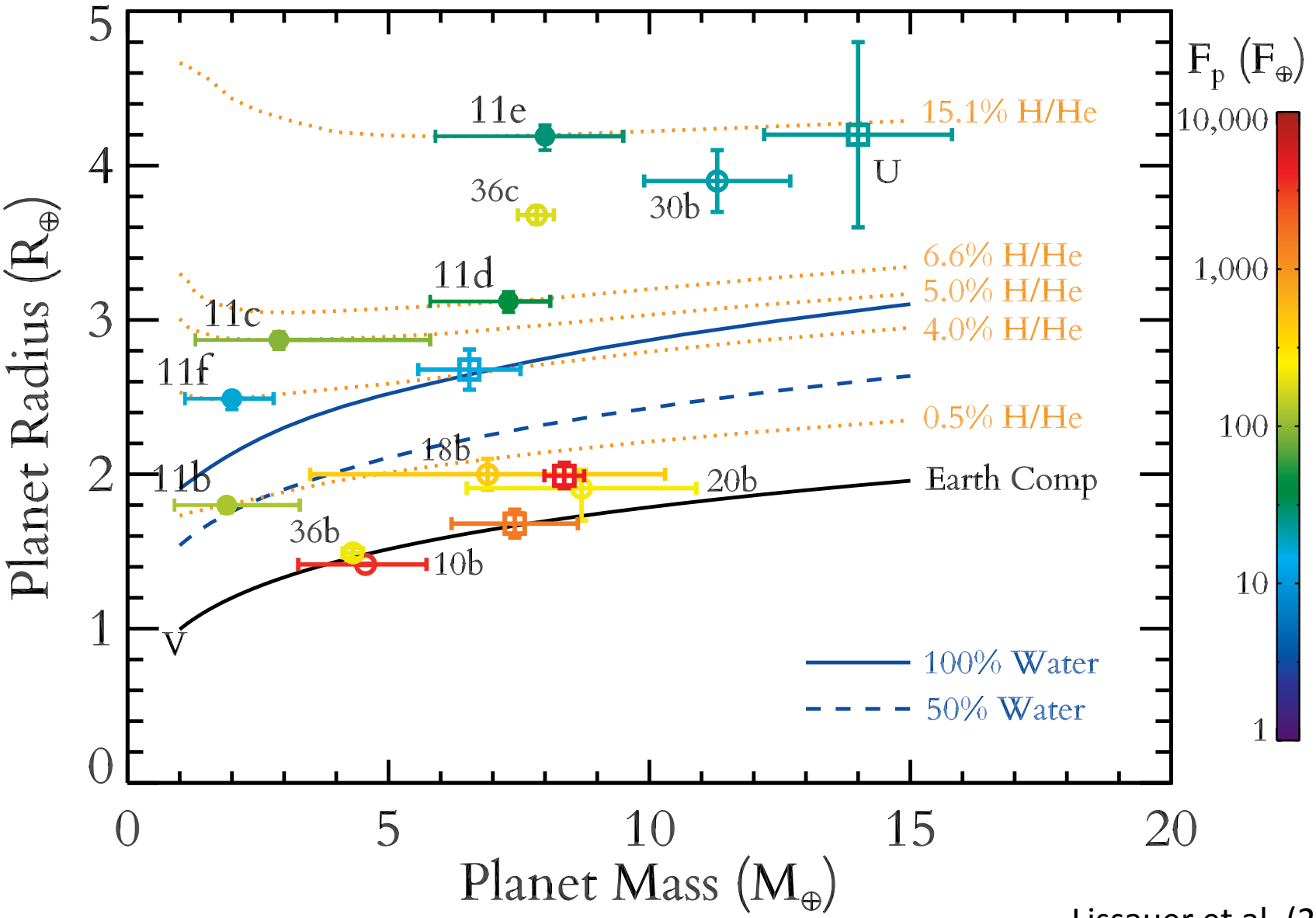


Are small systems the same as large systems?

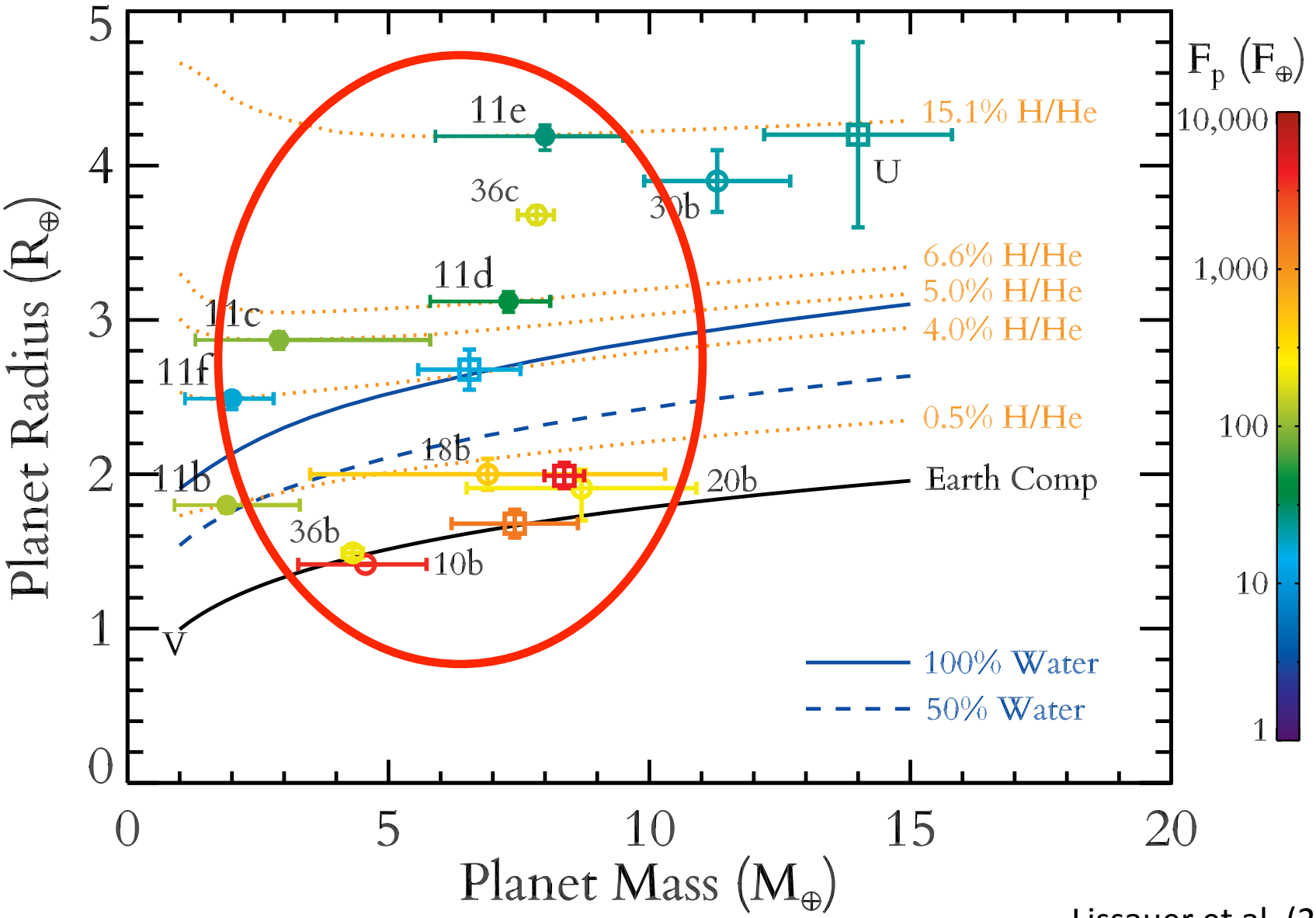
Steffen (2013b)

Planet Properties with Kepler



Lissauer et al. (2013)

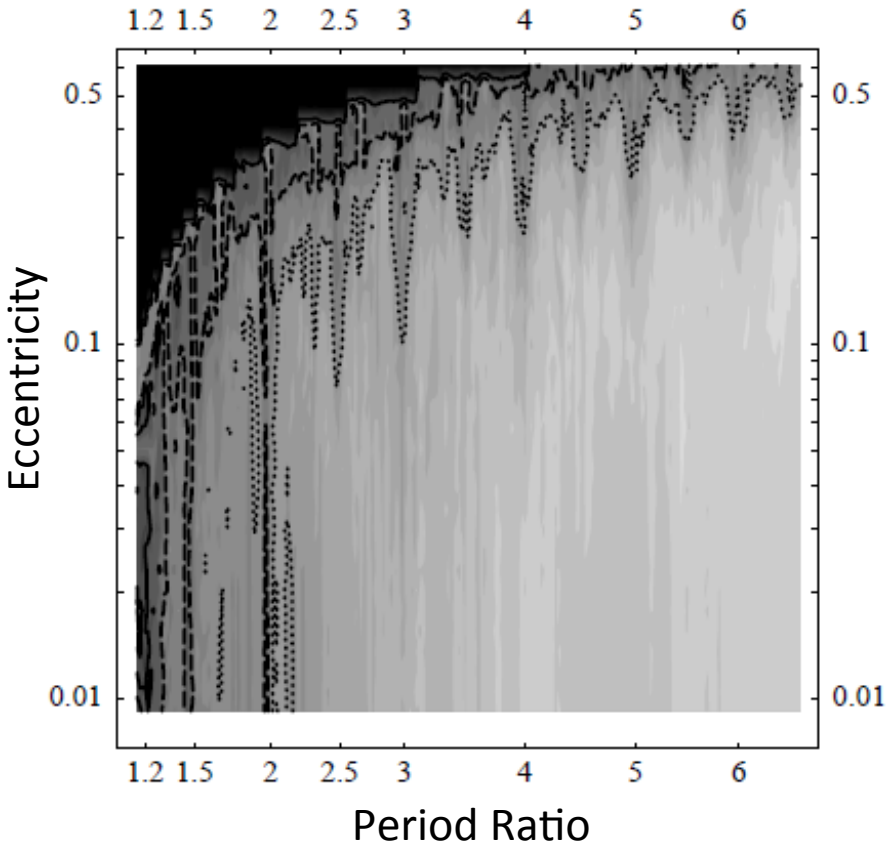
Planet Properties with Kepler



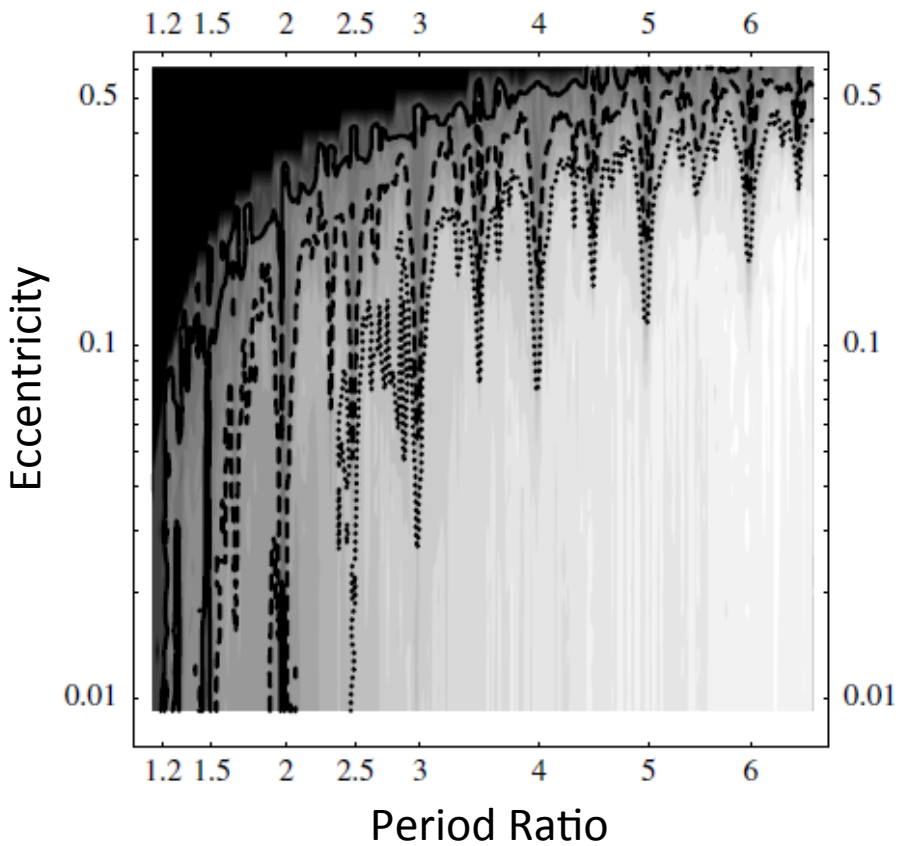
Lissauer et al. (2013)

Early searches for a TTV signal

TrES-1



HD 209458

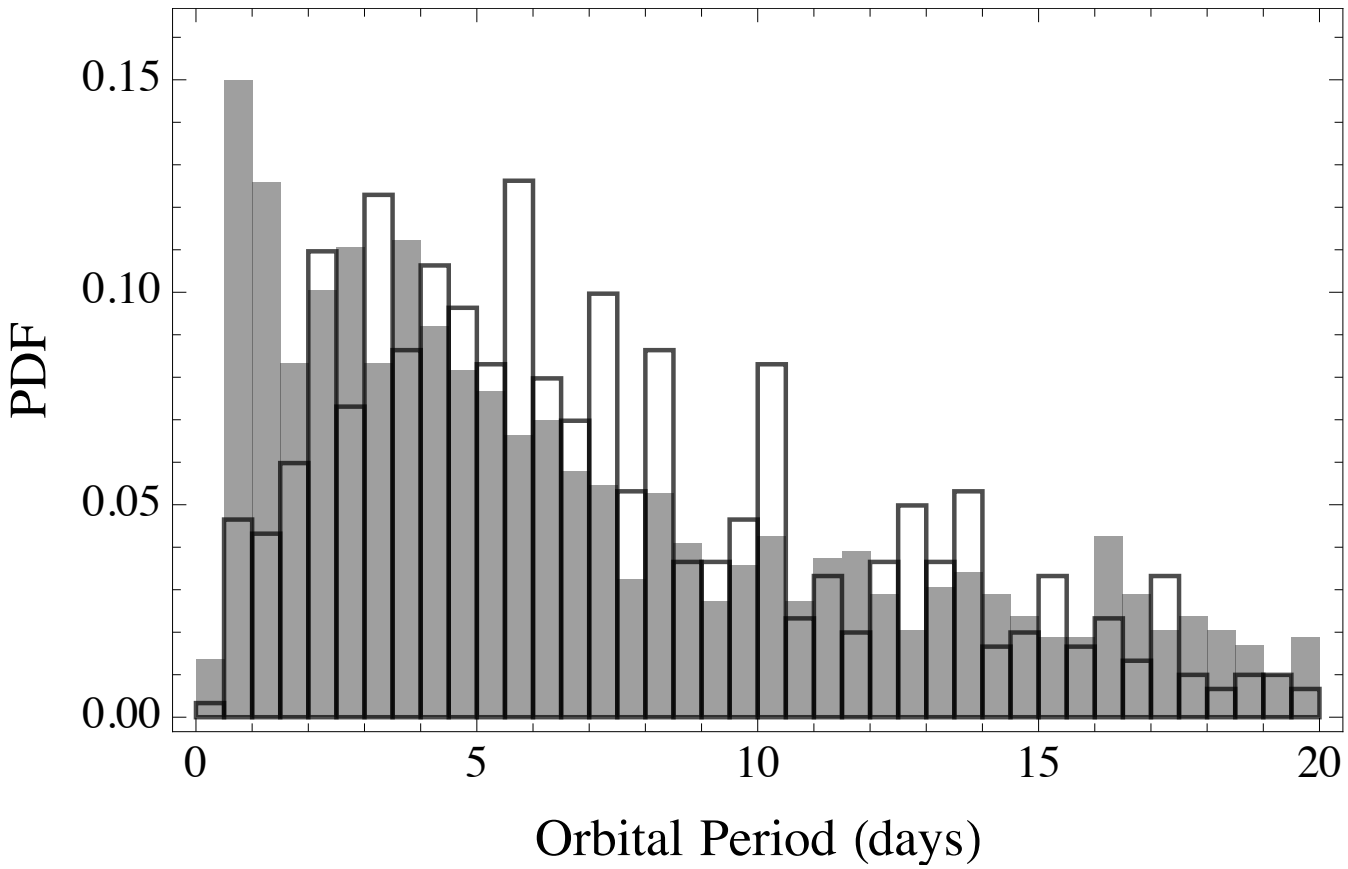


Steffen & Agol (2005)

Agol & Steffen (2007)

Not from a lack of planets

Period distribution of singles (shaded) and multis (outline)

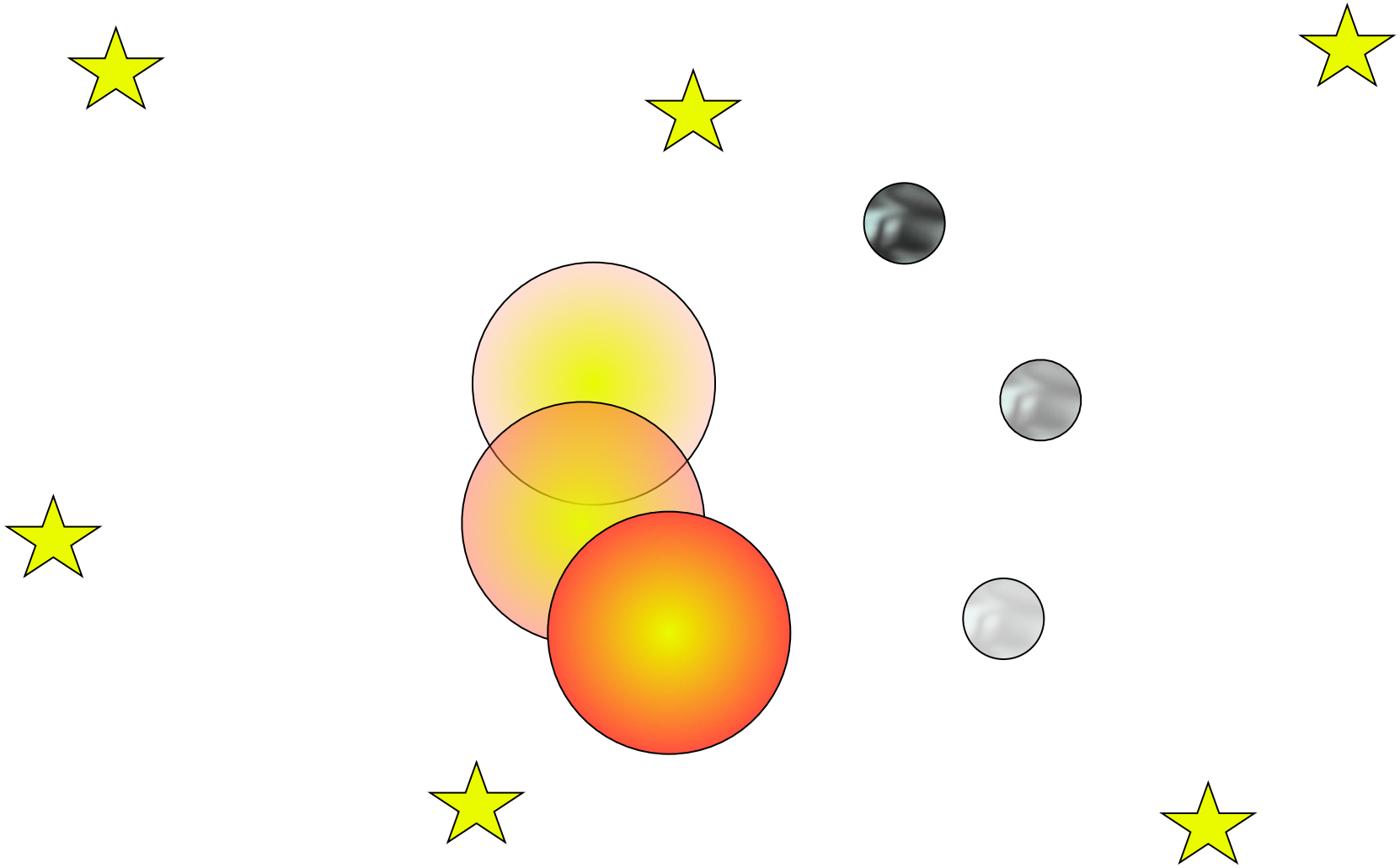


The excess of short-period planets in single-planet systems may be analogous to the hot Jupiters.

Steffen & Farr (2013c)

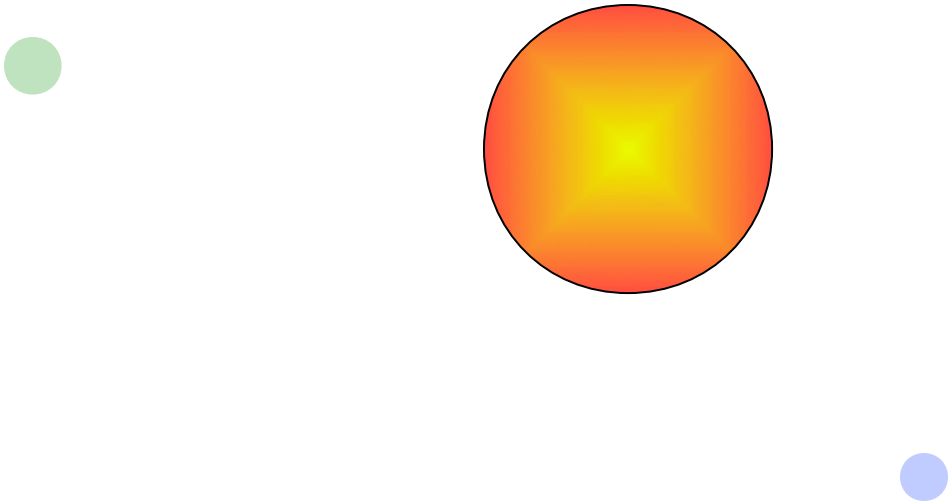
Planet Finding Methods

Astrometry



Planet Finding Methods

Direct Imaging



Planet Finding Methods

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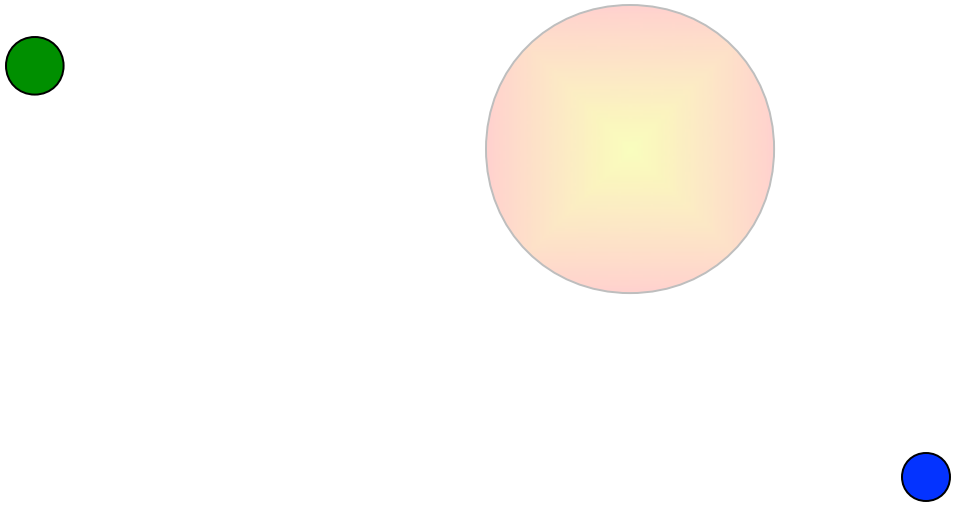
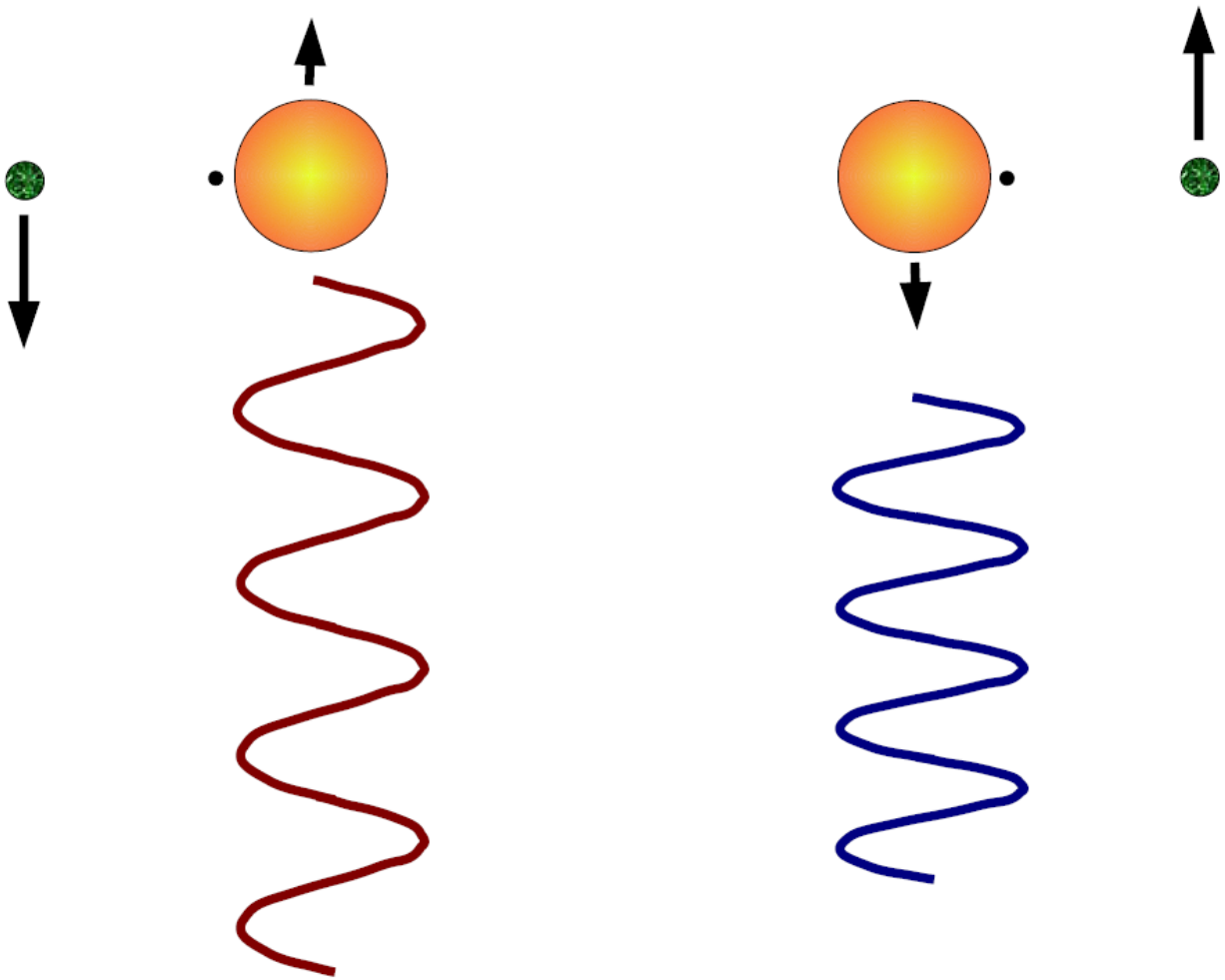
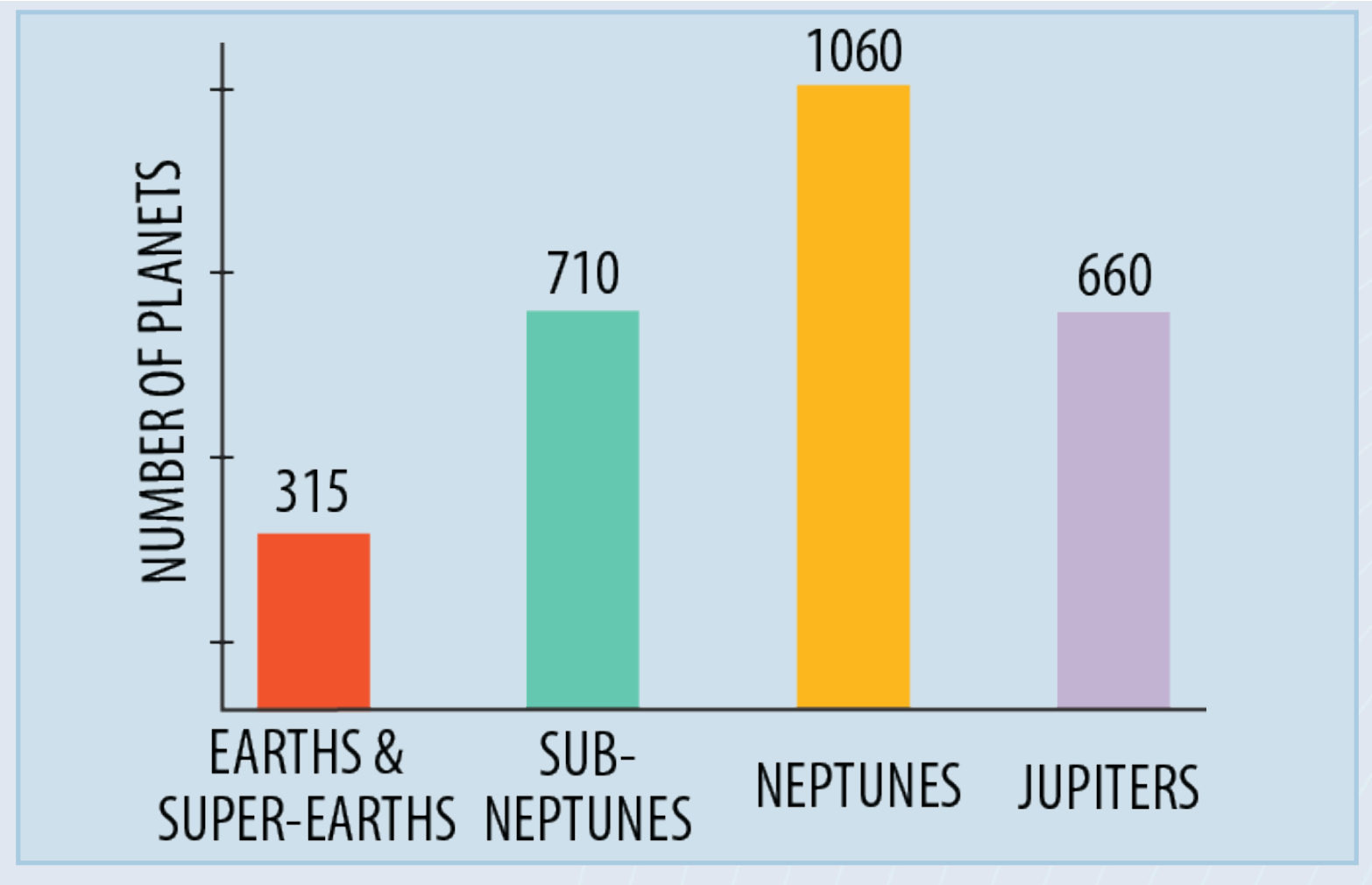


Planet Finding Methods

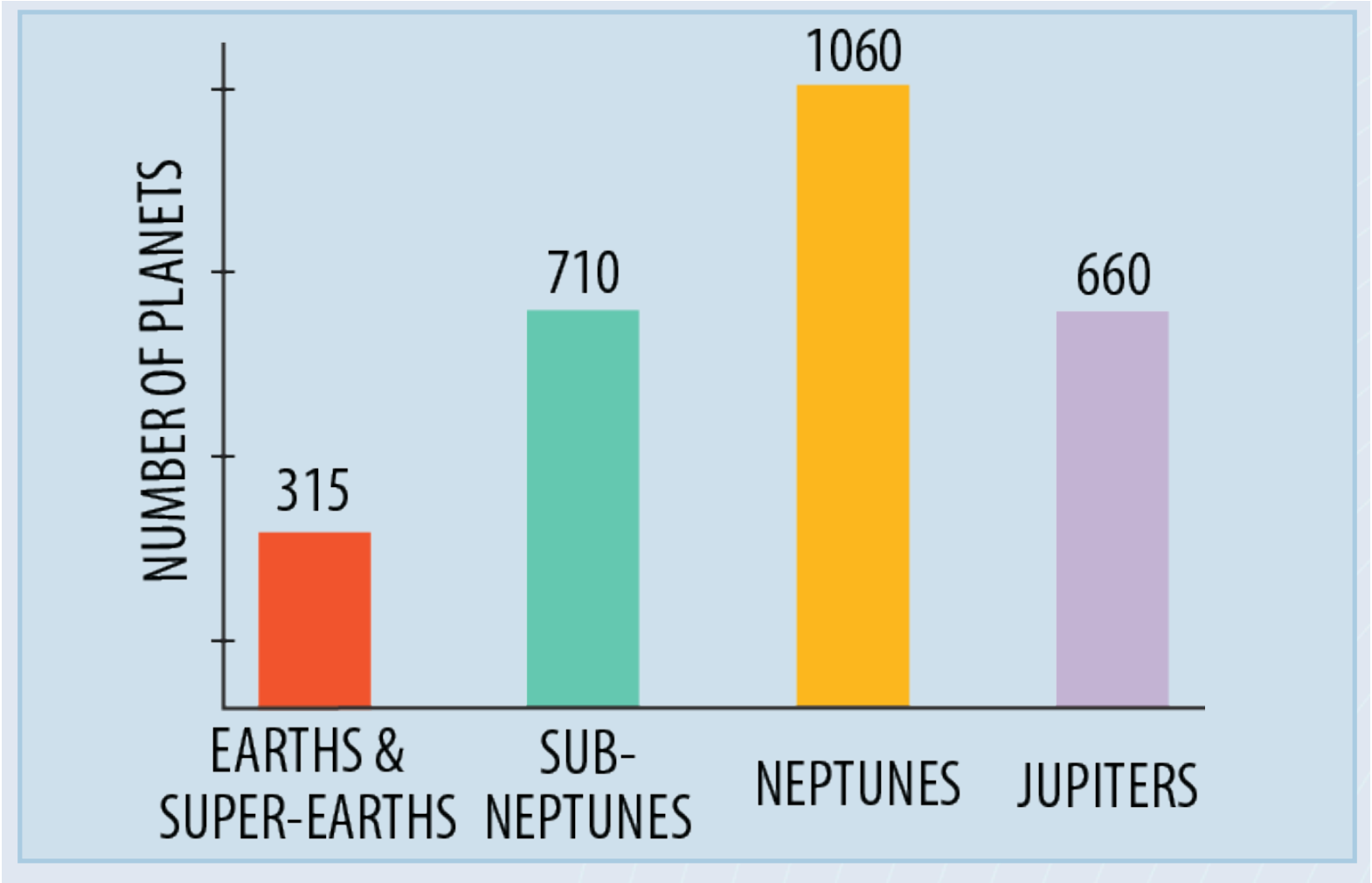
Radial Velocity (Doppler)



Expected TESS exoplanet yield



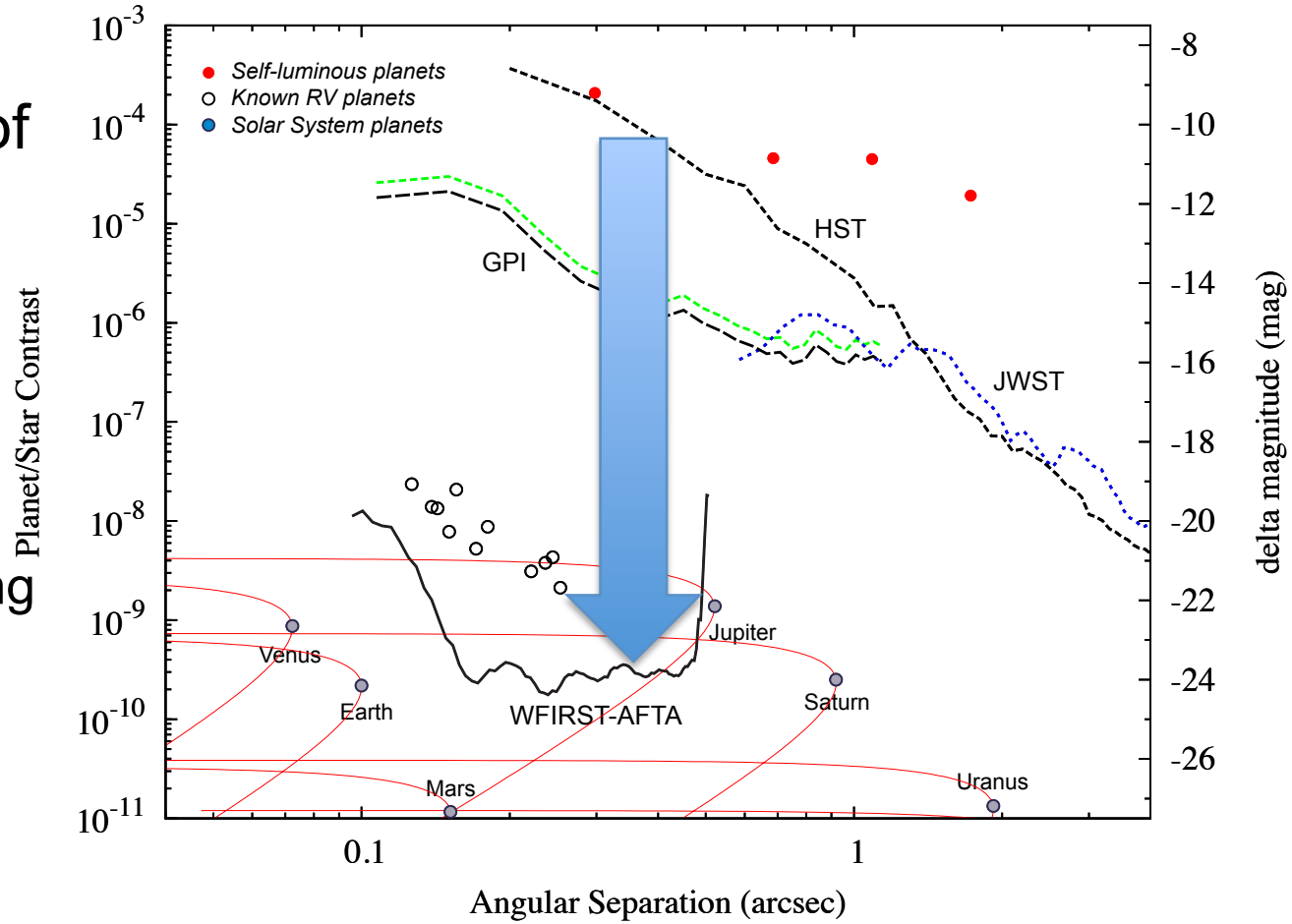
Expected TESS exoplanet yield



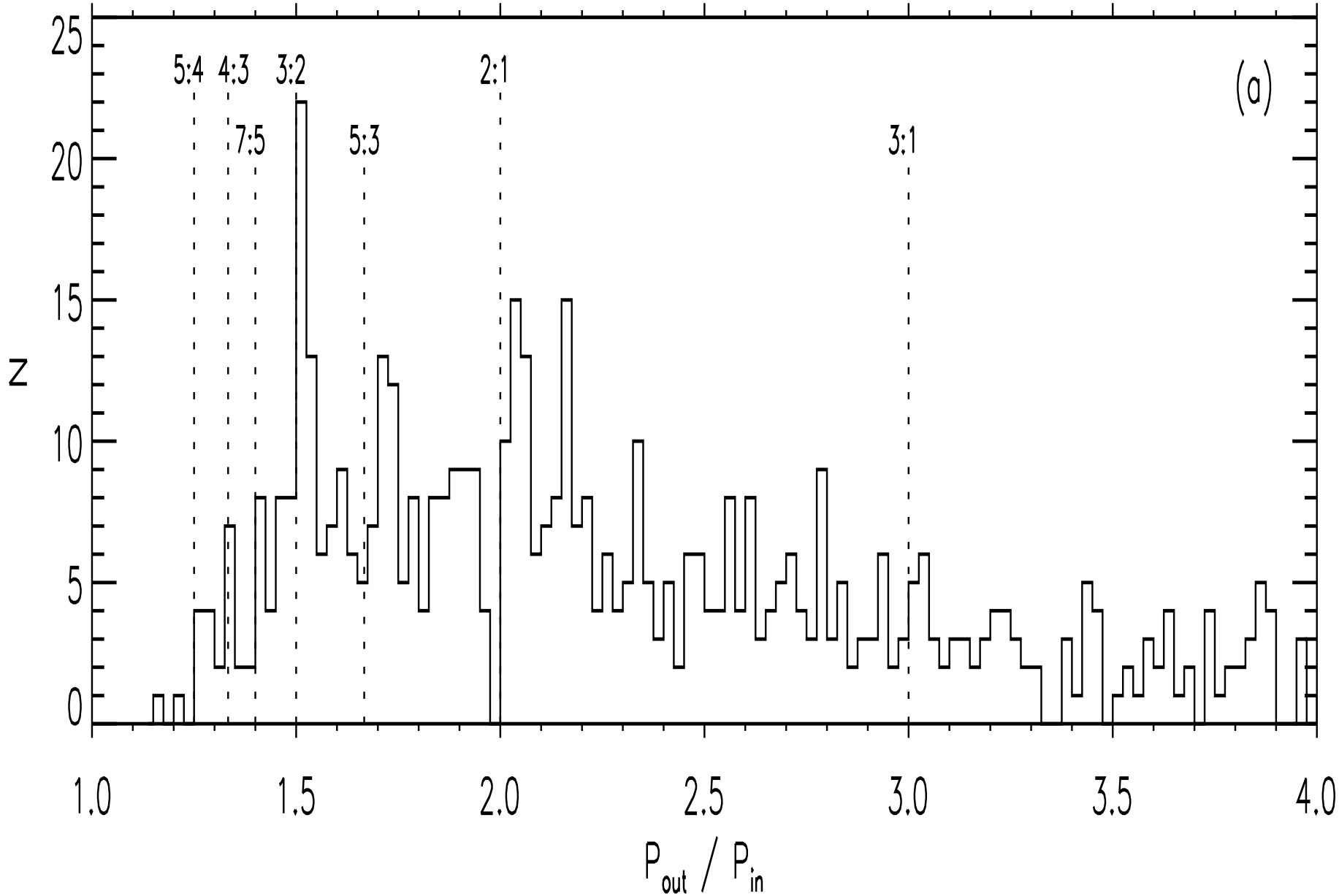
RV follow-up is dedicated to measuring small planet masses.

WFIRST-AFTA Brings Humanity Closer to Characterizing Earths

- WFIRST-AFTA advances many of the key elements needed for a coronagraph to image Earth
  - ✓ Coronagraph
  - ✓ Wavefront sensing & control
  - ✓ Detectors
  - ✓ Algorithms



Raw Distribution of Period Ratios



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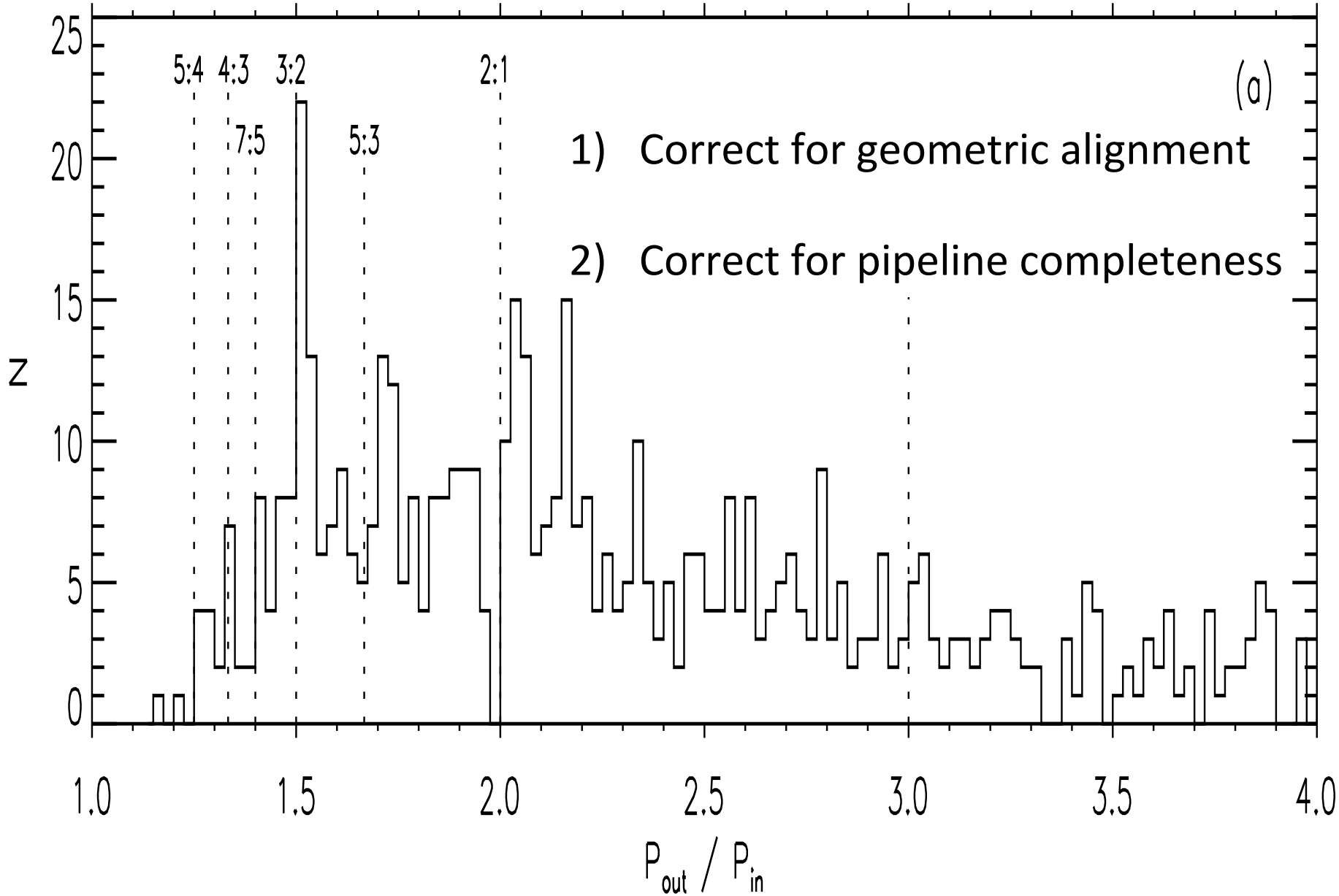
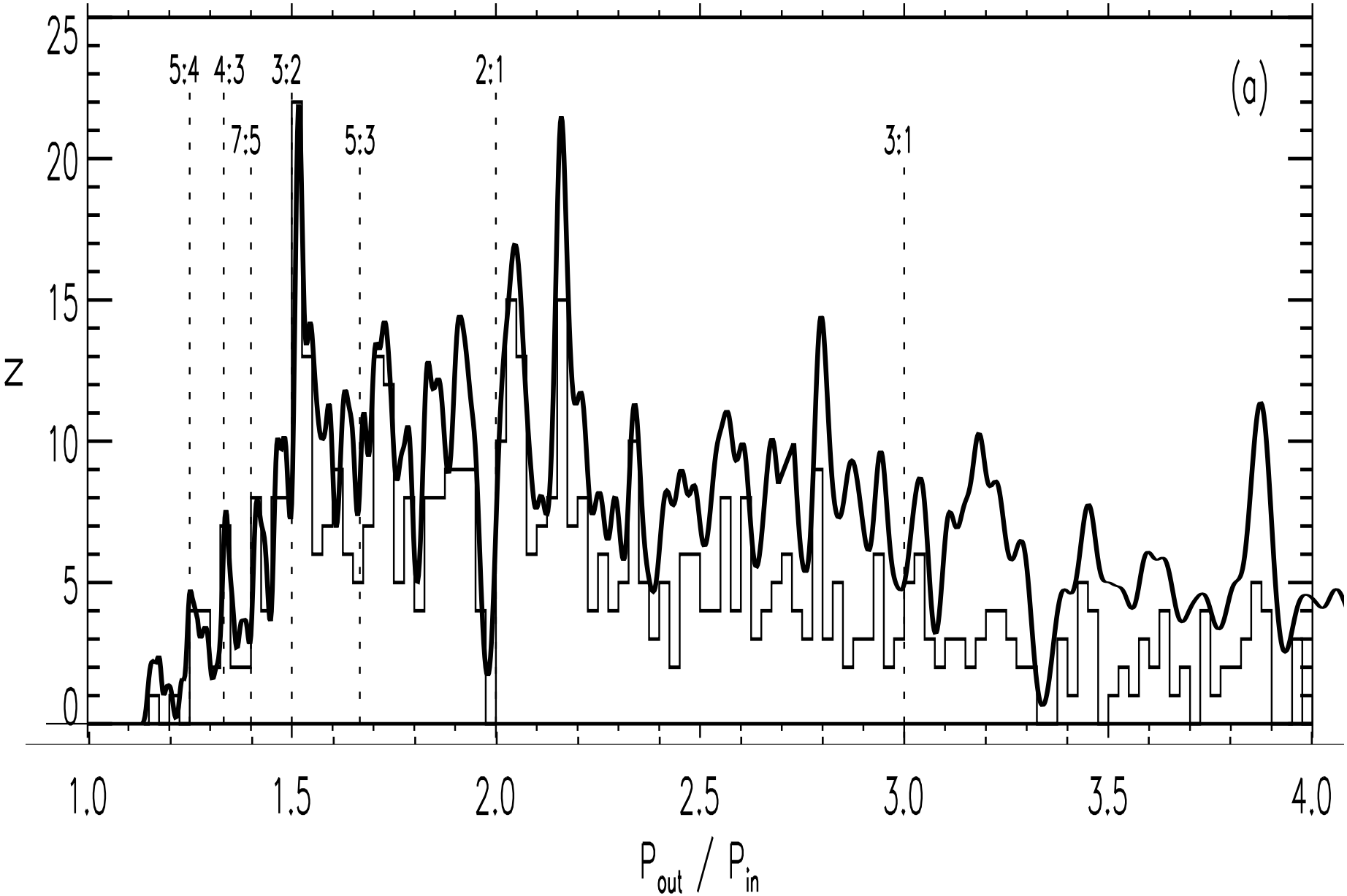


Corrected Distribution of Period Ratios



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- Significant excess of planet pairs near a period ratio of 2.2 (Not a ratio one would naturally predict.)