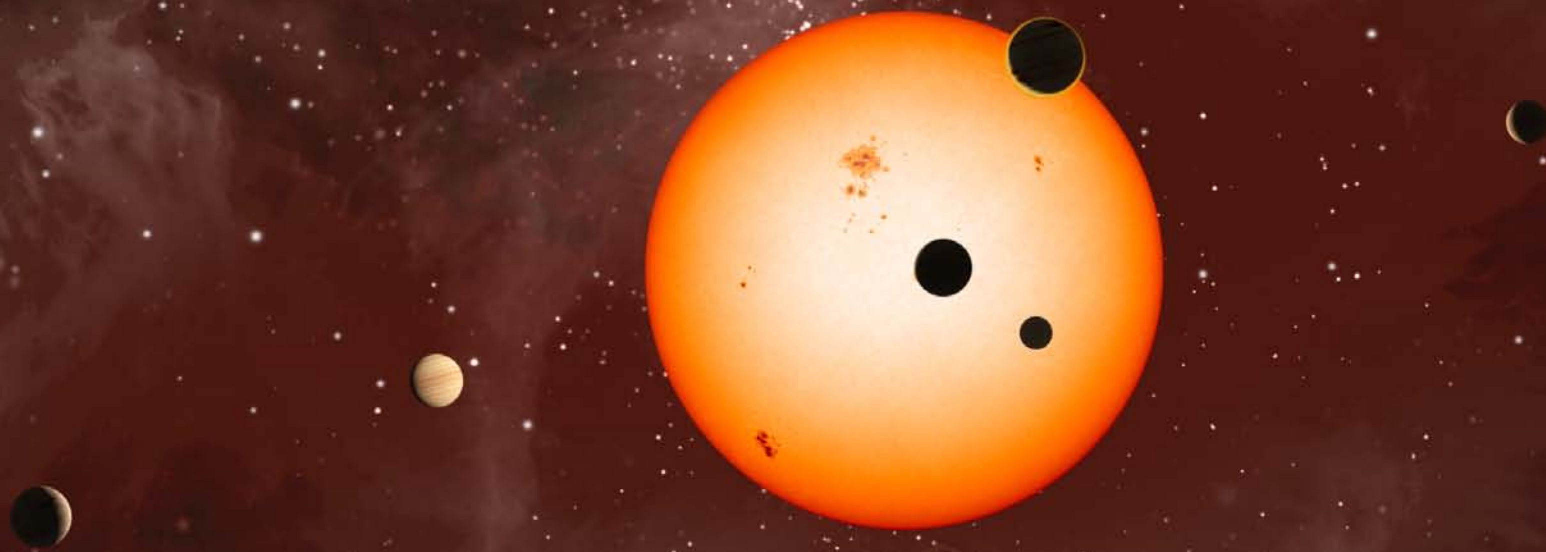
Kepler's Multiple Planet Systems

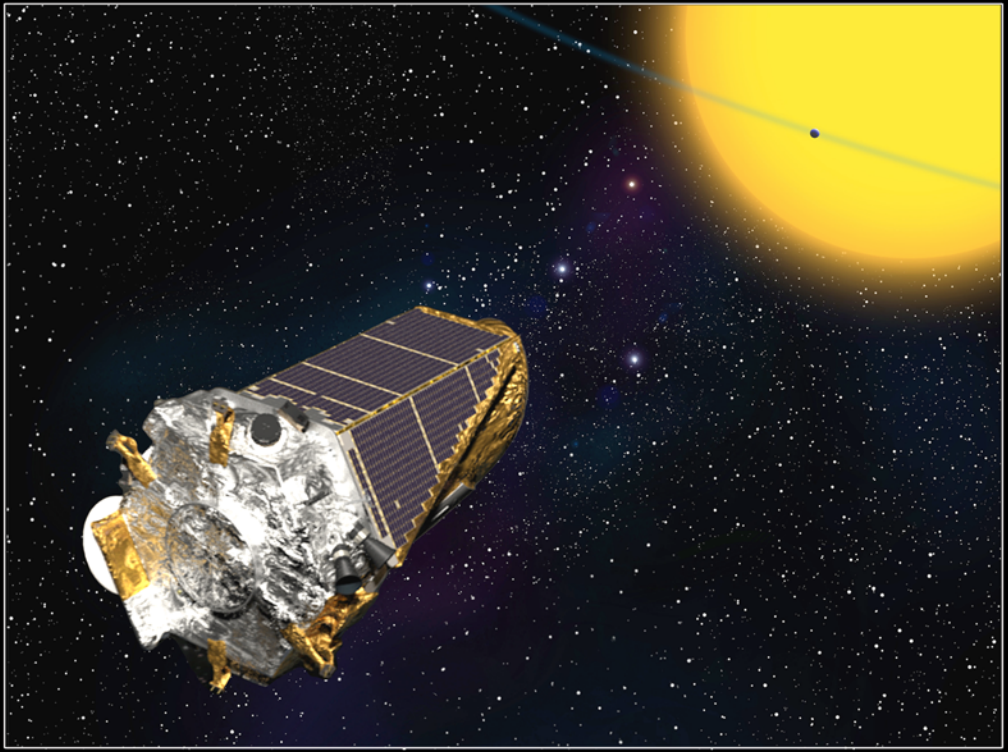


July 2012

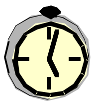
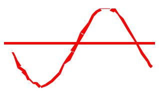
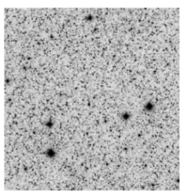
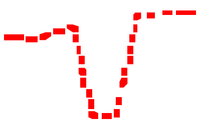
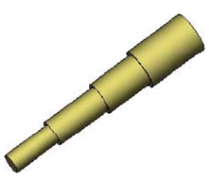
Jack J. Lissauer
NASA Ames

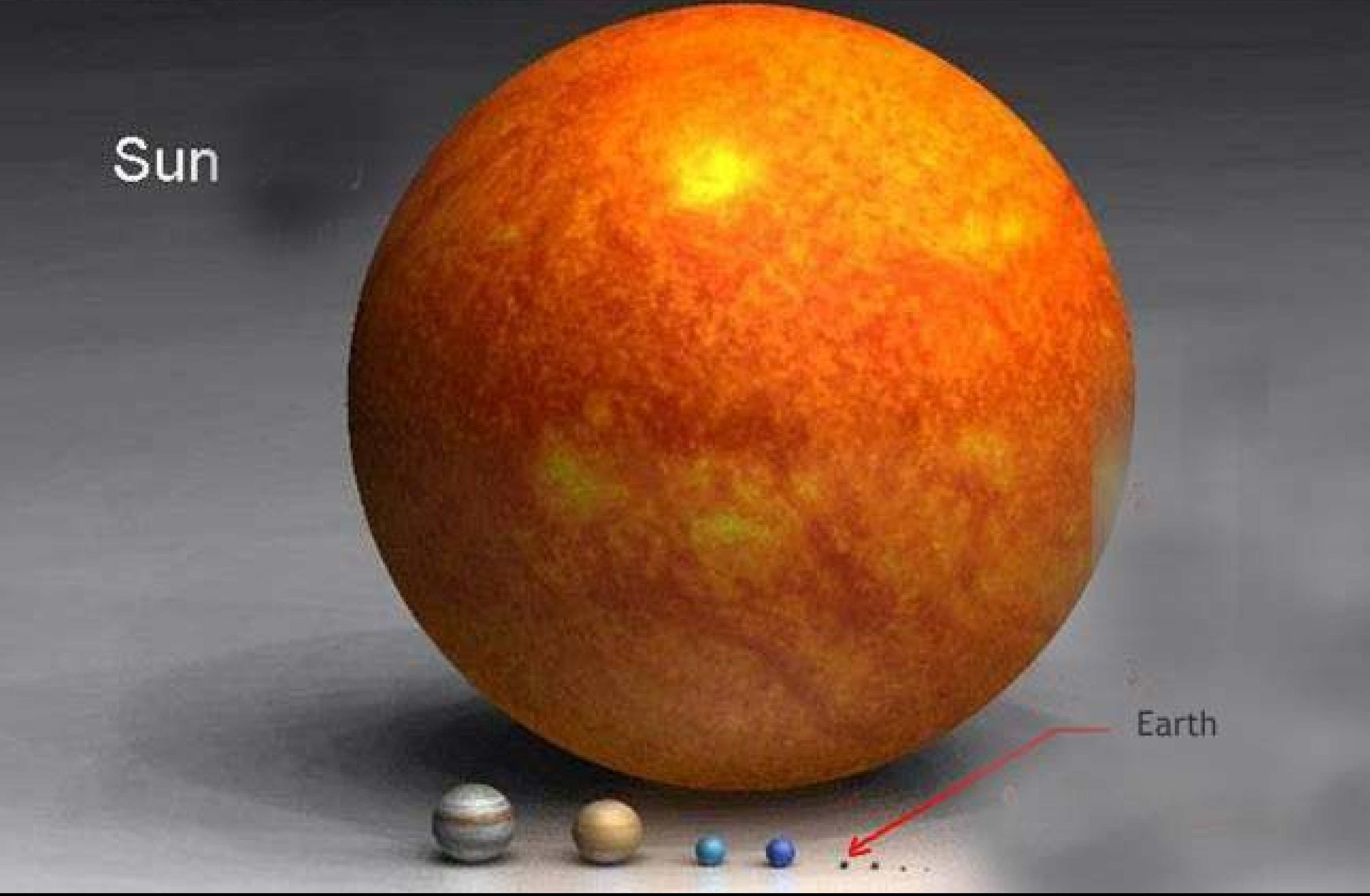
NASA's Kepler Mission

- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets



TECHNIQUES FOR FINDING EXTRASOLAR PLANETS

Method	Yield	Mass Limit	Status
 Pulsar Timing	m/M ; τ	Lunar	Successful (3+~2)
 Radial Velocity	$m \sin i$; τ	super-Earth	Successful (500+)
 Astrometry	m ; τ ; D_s ; a		
Ground: Telescope		Jupiter	
Ongoing			
Ground: Interferometer		sub-Jupiter	In development
Space: Telescope		sub-Jupiter	Ongoing
Space: Interferometer		Uranus	Being studied
 Transit Photometry	A ; τ ; $\sin i=1$		
Ground		sub-Jupiter	Successful (100+)
 Space, 27 cm		sub-Uranus	*CoRoT* (~25)
Space, 1 m		Mars	*Kepler* (~60 + ~2000)
 Microlensing:	$f(m,M,r,D_s,D_L)$		
Ground		super-Earth	Successful (~ 14)
Direct Imaging	$albedo*A$; τ ; D_s ; a ; M		
Ground		Saturn	Successful (10+)
Space		Earth	Being studied


Sun
Earth

Transits Can Reveal Earth-size Planets

From **TRANSIT DATA** obtain:

Duration, depth, orbital period and inclination.

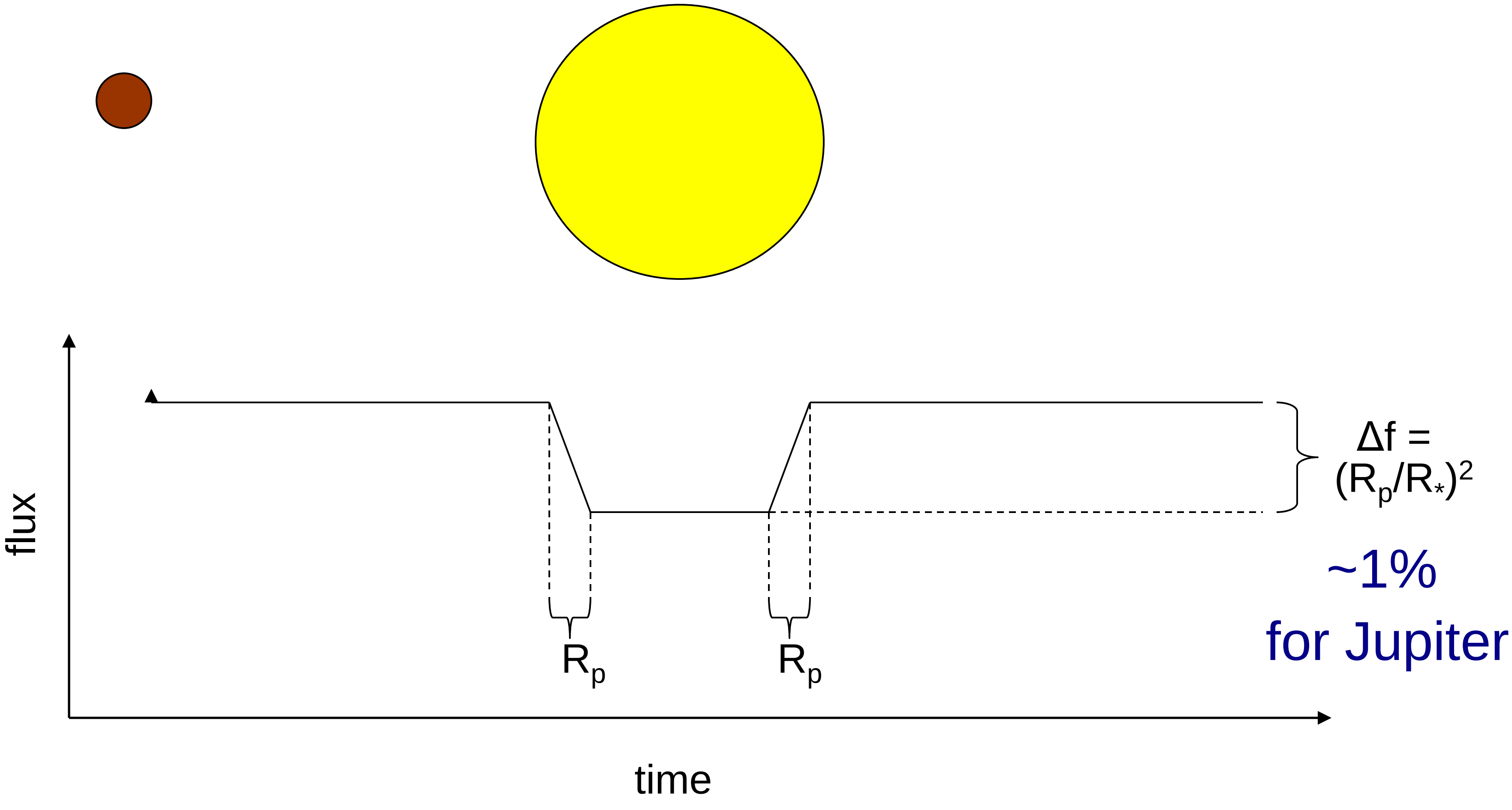
Derive planet sizes and orbital radii (when combined with stellar information)

From **ENSEMBLE of PLANETARY SYSTEMS** obtain:

Estimates frequency of planet formation for inner planets.

Requires thousands of stars because most orbits won’t be aligned properly

Transit Lightcurve

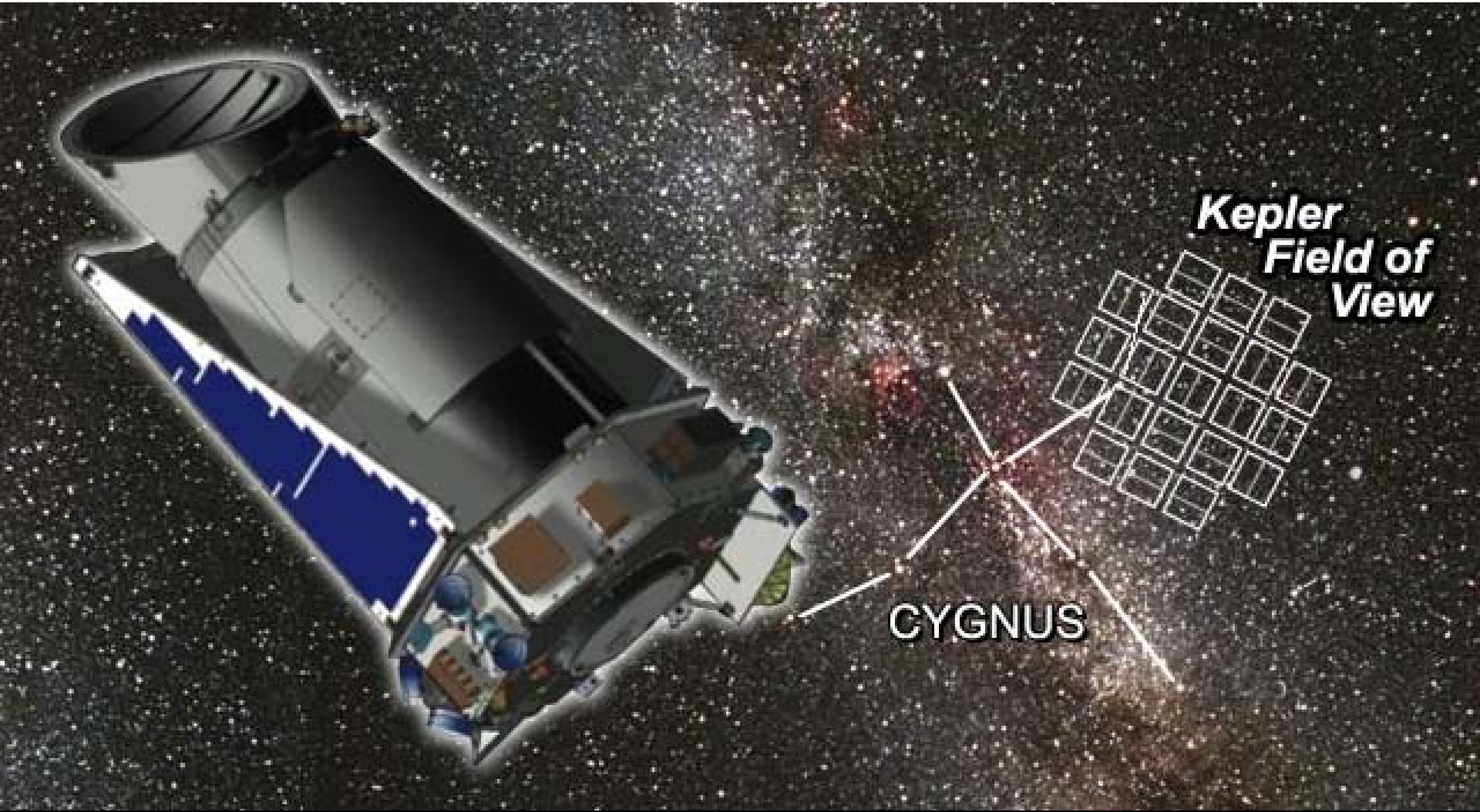


Josh Pepper

2004 Venus Transit at Sunrise

Kepler Mission

- NASA, photometry of > 150,000 stars
- Looking for Earth-like planets in transit
- < 40 ppm in 6 hours; 30 minute cadence



Kepler Mission Goals

Explore the structure and diversity of extrasolar planetary systems

1. Determine the **frequency of terrestrial planets in or near the habitable zone** of a wide variety of spectral types of stars;

2. Determine the distributions of **size** and **semi-major axis** of these planets;

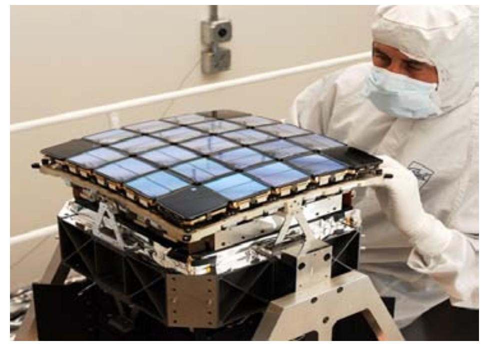
3. Estimate the frequency and orbital distribution of planets in **multiple-star systems**;

4. Determine the distributions of semi-major axis, albedo, size, mass and density of short-period **giant planets**;

5. **Identify additional members** of each photometrically-discovered planetary system using complementary techniques;

6. Determine the **properties of those stars** that harbor planetary systems.

SPACECRAFT & INSTRUMENT

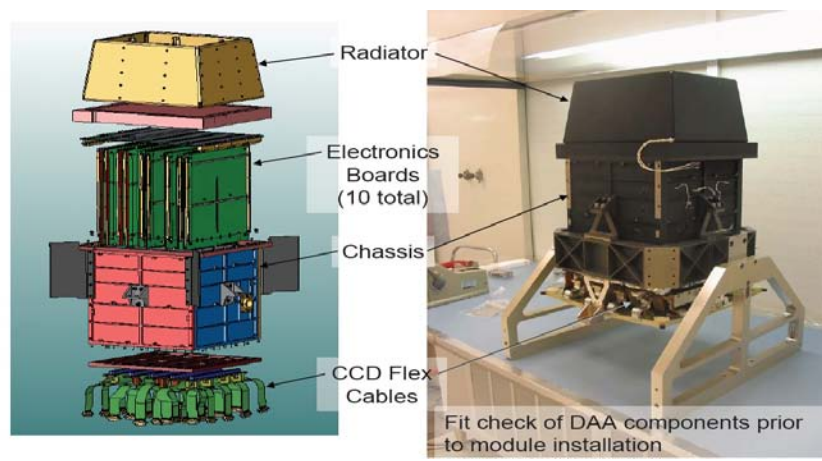


Largest focal plane for a NASA flight mission: 94.6 million science pixels

42 science CCDs, 2 channels each

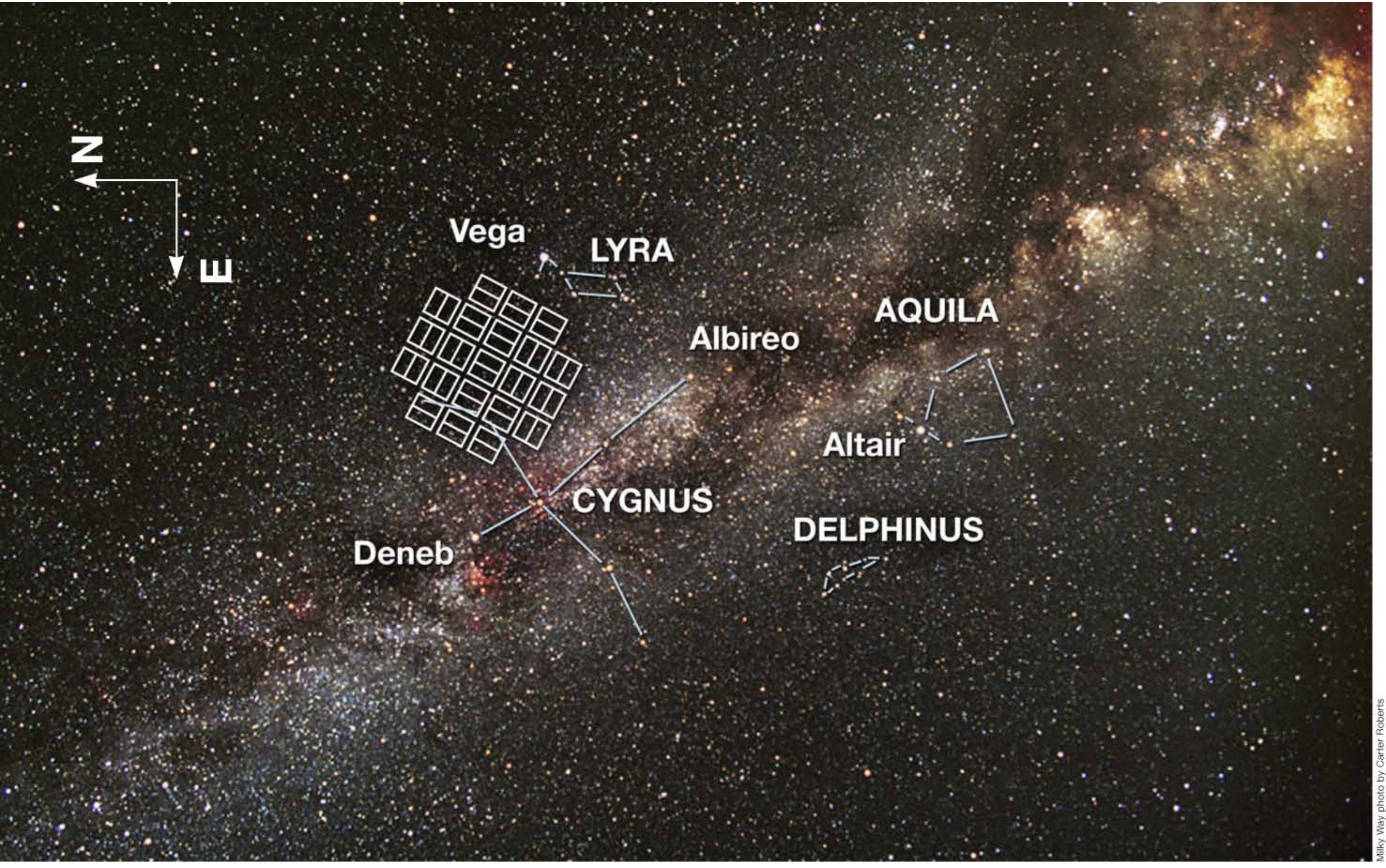
4 fine guidance sensor (FGS) CCDs

CCDs controlled at -85C, Readout electronics at room temperature



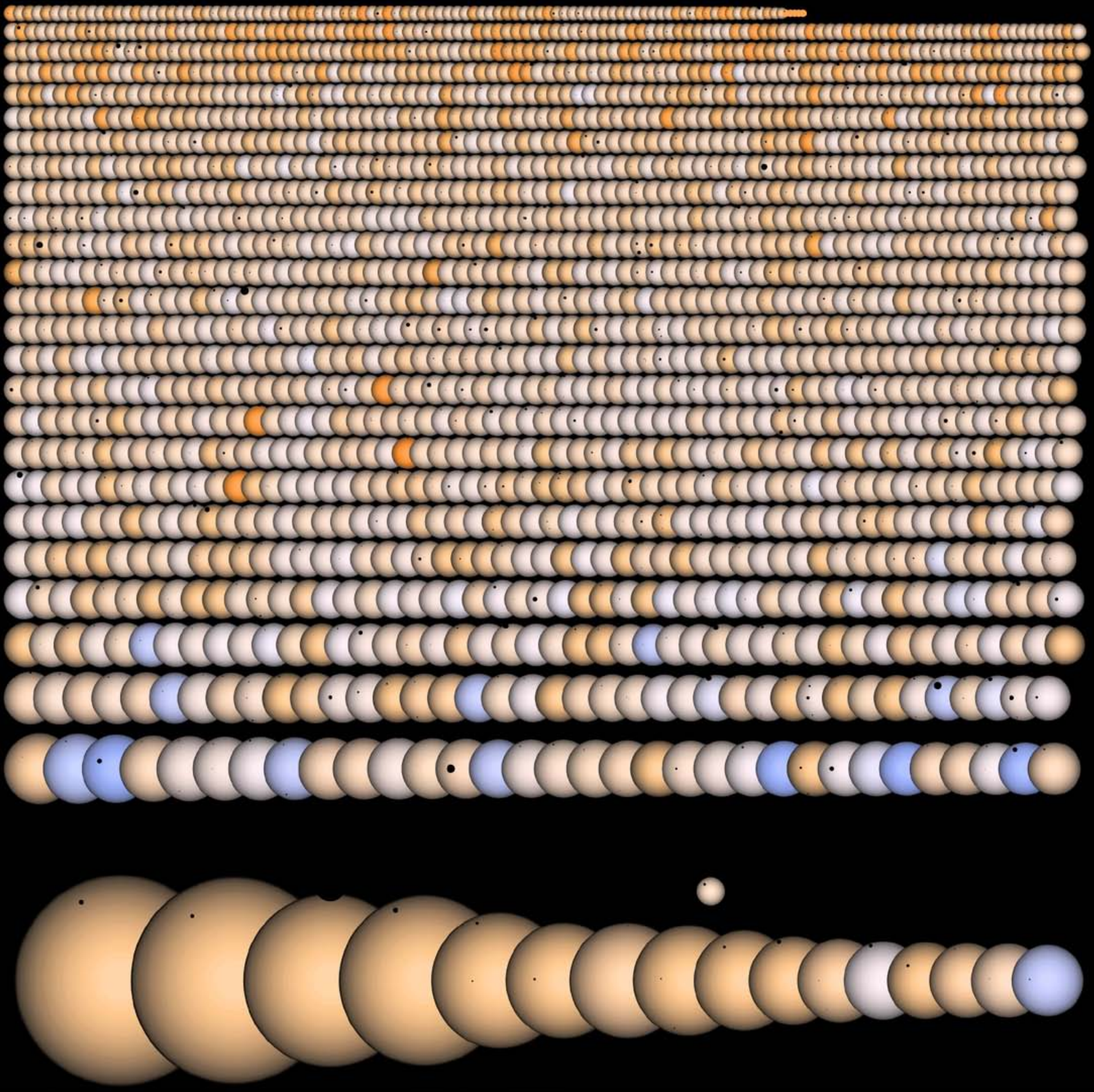
Fit check of DAA components prior to module installation

Star Field: Cygnus-Lyra



2326 *Kepler* Planet Candidates

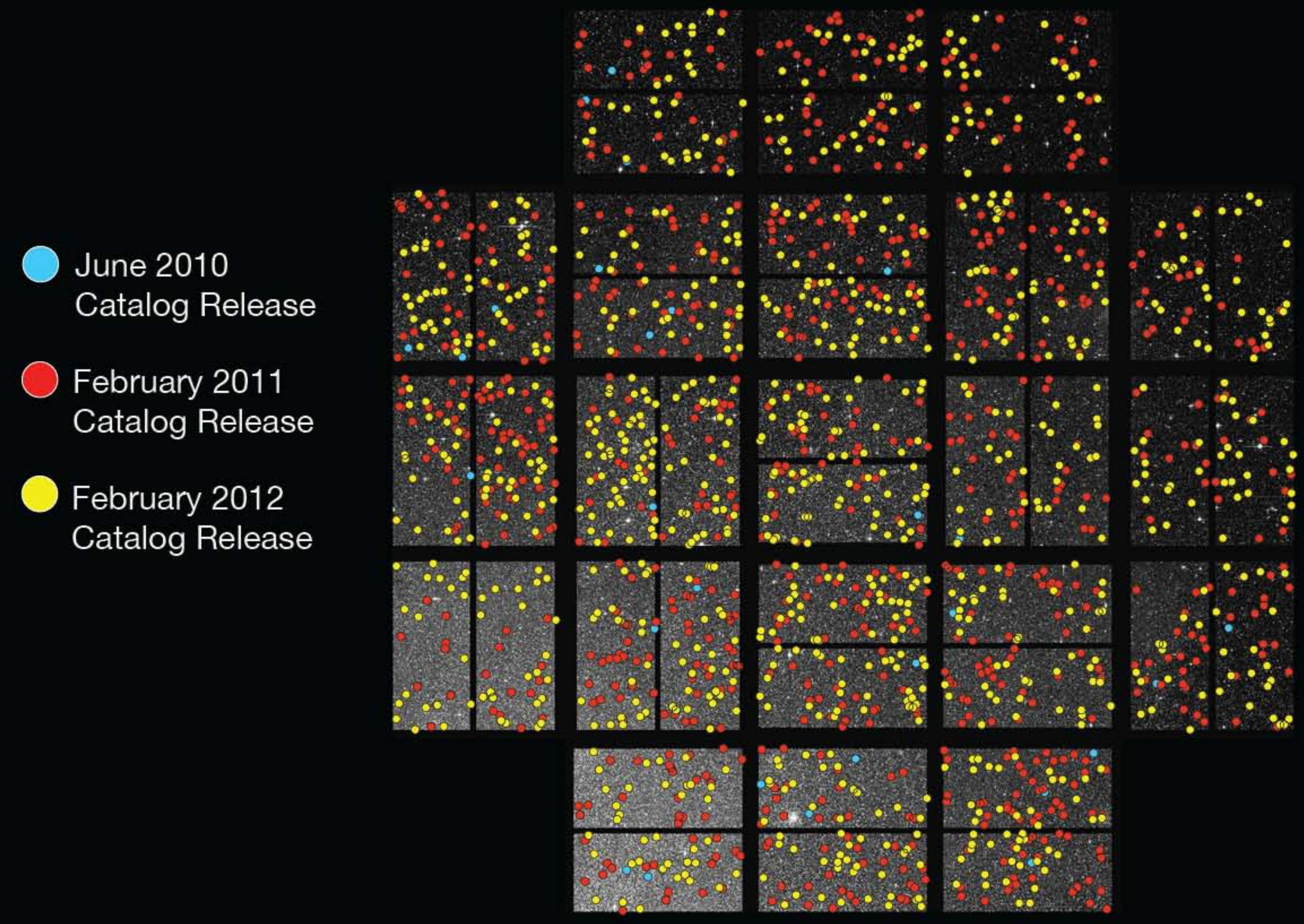
12/2011



(Jason Rowe)

Locations of Kepler Planet Candidates

By Catalog Release Date



PART OF THE SCIENCE TEAM AND A FEW OF THE MANY WHO HAVE MADE *KEPLER* POSSIBLE

William Borucki[1], David Koch[1], Gibor Basri[2], Natalie Batalha[3] , Timothy Brown[4], Derek Buzasi[23], Douglas Caldwell[5], John Caldwell[17], Jørgen Christensen-Dalsgaard[6] , William D. Cochran[7], Edna DeVore[5], Laurance Doyle[5], Edward W. Dunham[8], Andrea K. Dupree[10], Eric B. Ford[13], Jonathan Fortney[25], Thomas N. Gautier III[9], John C. Geary[10], Ronald Gilliland[11], Alan Gould[18], Matthew J. Holman[10], Steve B. Howell[15], Jon M. Jenkins[5], Hans Kjeldsen[6], Yoji Kondo[30], Jack J. Lissauer[1], David W. Latham[10], Geoffrey W. Marcy[2], Søren Meibom[10], David G. Monet[12], David Morrison[1], Dimitar Sasselov[10], Sara Seager[26], Jason H. Steffen[27], Jill Tarter[5], William F. Welsh[28],

---

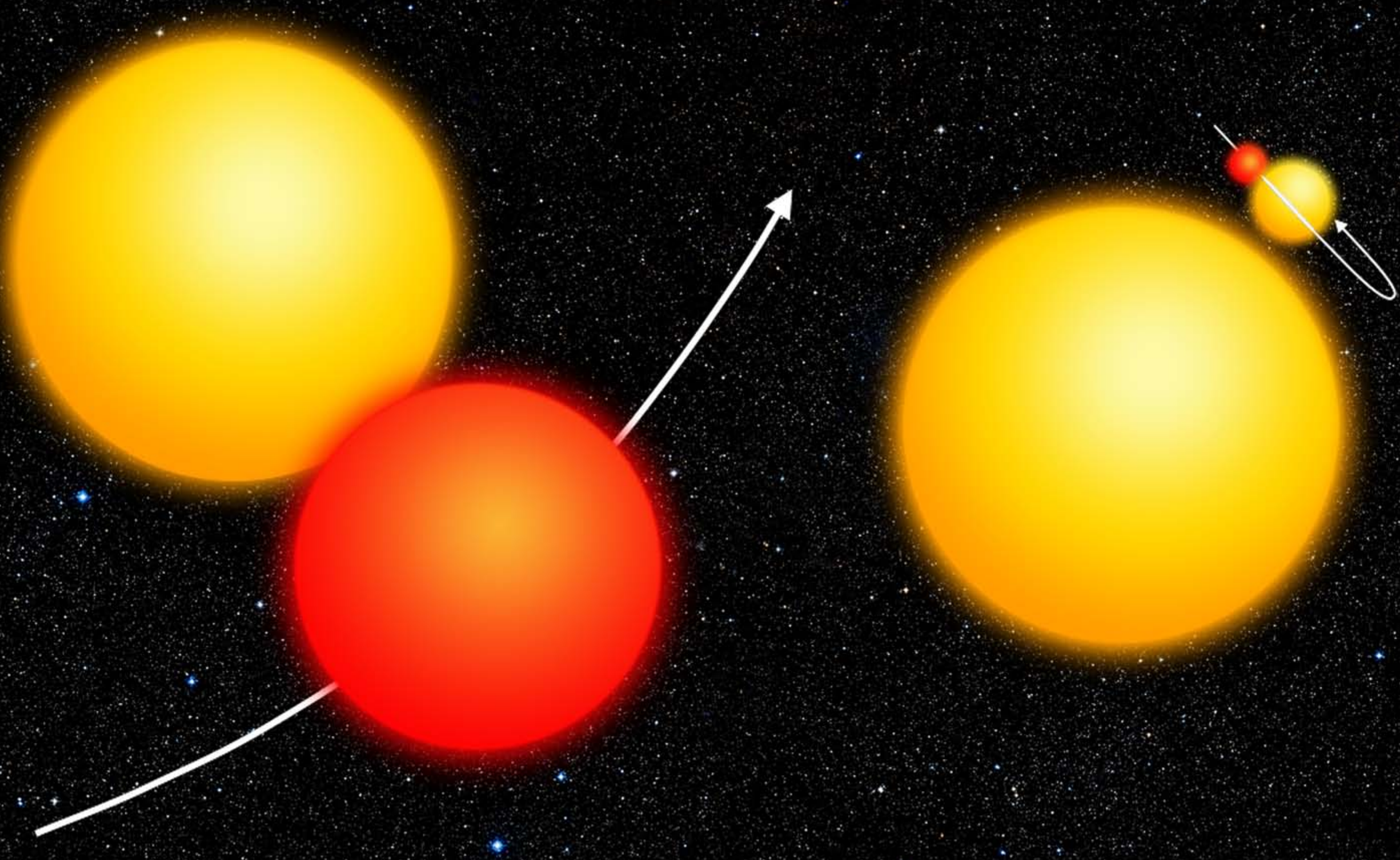
Christopher Allen[32], Howard Anderson[2], Jason Barnes[34], Alan Boss[19], Don Brownlee[22], Frederick Bruhweiler[33], Stephen T. Bryson[1], Lars Buchhave[10], Hema Chandrasekaran[5], David Charbonneau[10], David Ciardi[29], Bruce D. Clarke[5], Jessie Dotson[1], Debra Fischer[16], Michael Haas[1], Elliott Horch[24], Howard Isaacson[2], John Asher Johnson[29], Jie Li[5], Toby Owen[21], Andrej Prsa[35],Elisa V. Quintana[5], Jason Rowe[1], Phillip MacQueen[7], William Sherry[15], Peter Tenenbaum[5], Guillermo Torres[10] , Joseph D. Twicken[5], Jeffrey Van Cleve[5], Ekaterina Verner[33], Lucianne Walkowicz[2], Haley Wu[5] , Jeffrey Kolodziejczak[31],

Affiliations

[1]NASA Ames Research Center, Moffett Field, CA
[2]University of California, Berkeley, CA
[3]San Jose State University, San Jose, CA,
[4]Las Cumbres Observatory Global Telescope, Goleta, CA
[5]SETI Institute, Mountain View, CA,
[6]Aarhus University, Aarhus, Denmark
[7]McDonald Observatory, University of Texas at Austin, Austin, TX,
[8]Lowell Observatory, Flagstaff, AZ,
[9]Jet Propulsion Laboratory, Calif. Institute of Technology, Pasadena, CA,
[10]Harvard-Smithsonian Center for Astrophysics, Cambridge, MA,
[11]Space Telescope Science Institute, Baltimore, MD,
[12]United States Naval Observatory, Flagstaff, AZ,
[13]Univ. of Florida, Gainesville, FL
[14]Planetary Science Institute, Tucson, AZ
[15]NOAO, Tucson, AZ
[16]Yale University, New Haven, CT
[17]York University, North York, ON, Canada
[18] Lawrence Hall of Science, Berkeley, CA
[19]Carnegie Institute of Washington, Washington, DC
[21]Univ. of Hawaii, Hilo, HI
[22]Univ.of Washington, Seattle, WA
[23]Eureka Scientific, Inc., Oakland, CA
[24]Southern Connecticut State University, New Haven, CT
[25]Univ. of Calif., Santa Cruz, CA
[26]MIT, Cambridge, MA
[27]Fermilab, Batavia, IL
[28]San Diego State Univ., San Diego, CA
[29]Exoplanet Science Institute/Caltech, Pasadena, CA
[30]GSFC, Greenbelt, MD
[31]MSFC, Huntsville, AL
[32]Orbital Sciences Corp., Mountain View, CA
[33]Catholic University of America, Washington, DC
[34]Univ. Idaho, Moscow, ID
[35]Villanova University, Villanova, PA

Michael Endl[7], Mark E. Everett[14],

Common False Positives

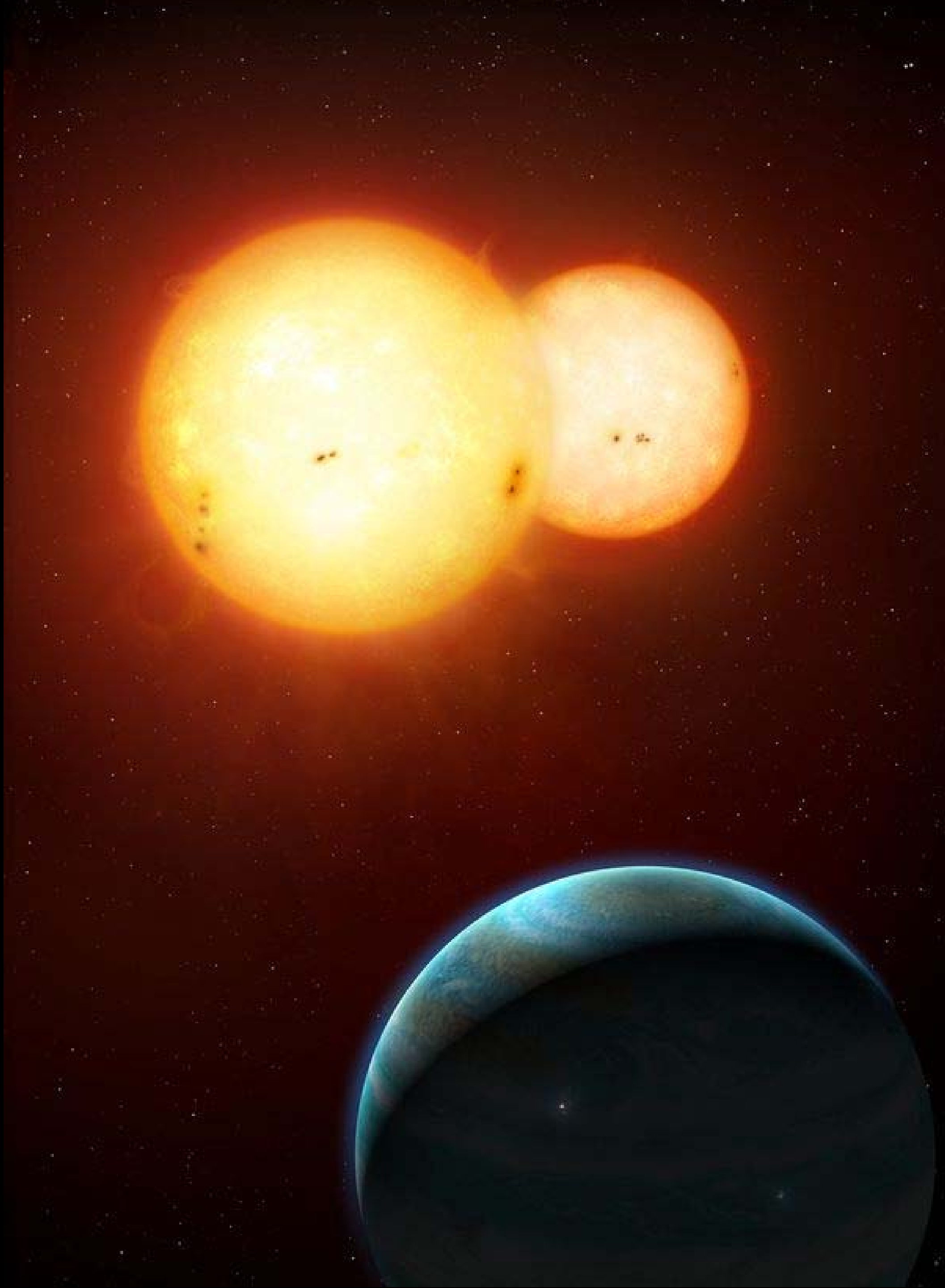


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

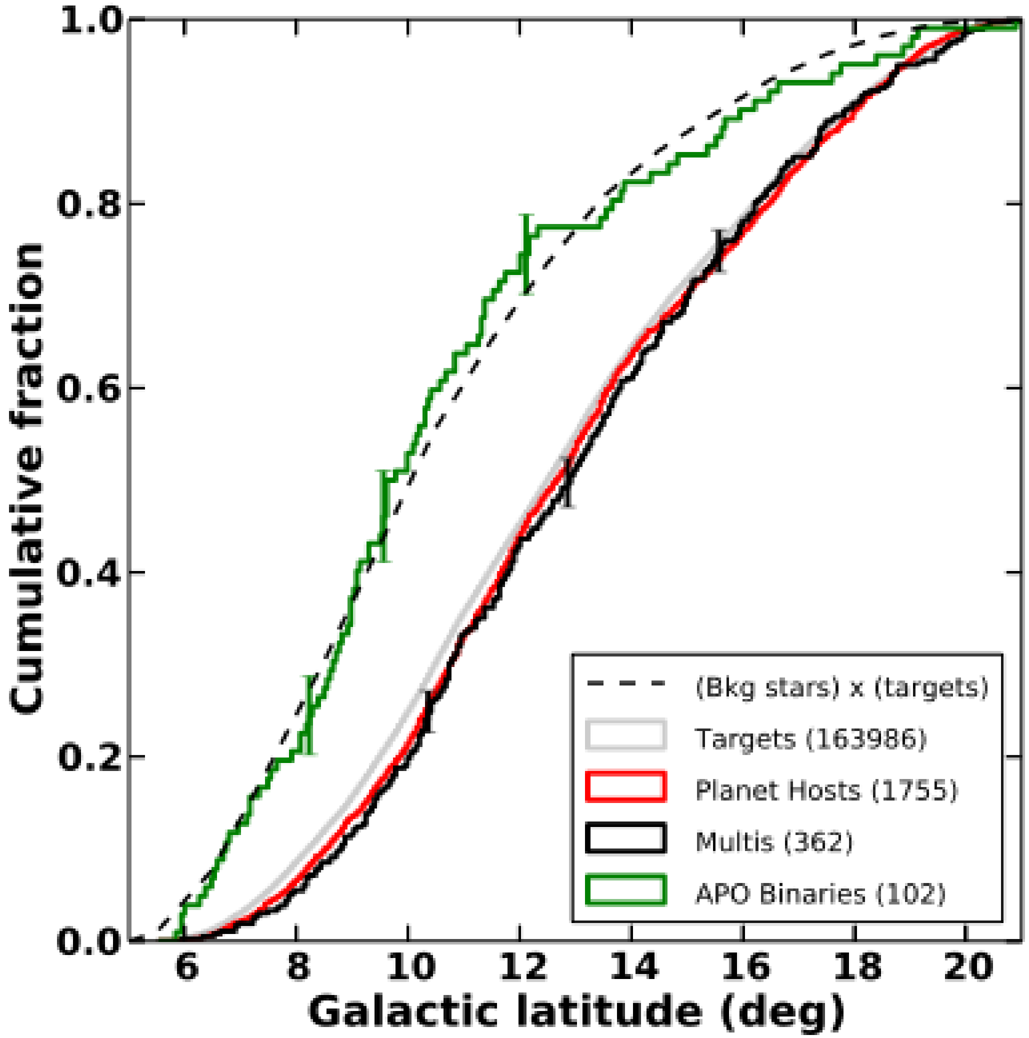
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Kepler-16:
A Saturn-like planet orbiting a close binary

Kepler-35(AB)b



Distributions vs. Galactic Latitude



Planet candidates, including multis, track targets, not BGEB FPs

Few planet candidates are BGEB FPs!

Most Multi-planet Candidates are Planets

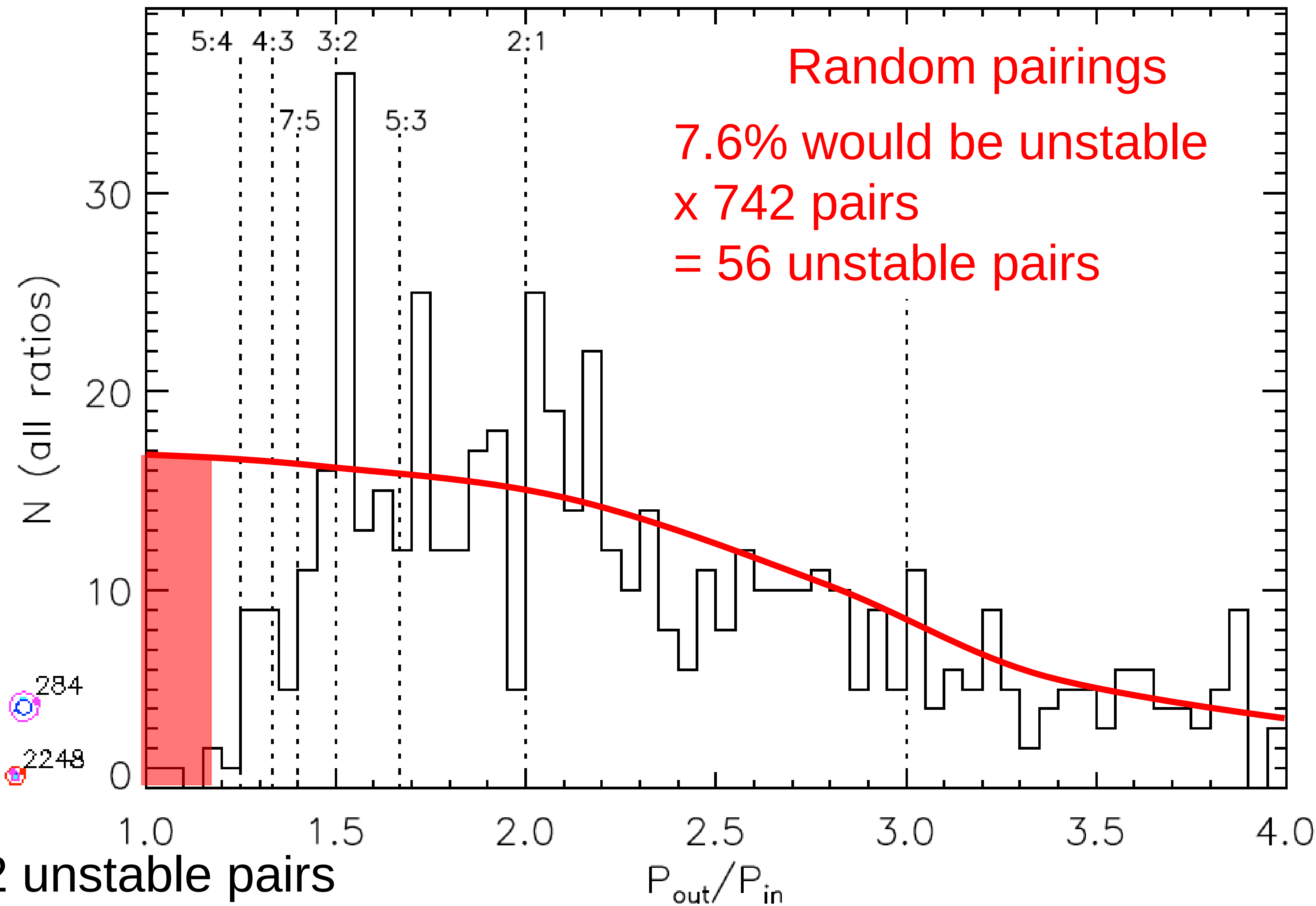
- 175,000 *Kepler* targets
- 2321 KOIs (1.33% of the targets)
- 232 false positives (assume 10% are FPs)
- EBs are distributed randomly among targets
- Fraction of targets near EB = 232/175000 = 0.133%
- Number of KOIs (planet or EB) accompanied by EB:

= 2321 x 0.133% = 3

Then we expect only 1.33% x 232 = 3 multis with a FP

But we observe 365 multis (with 897 planet candidates)!

Period ratios and stability



2 unstable pairs

“False Multi” Scenarios

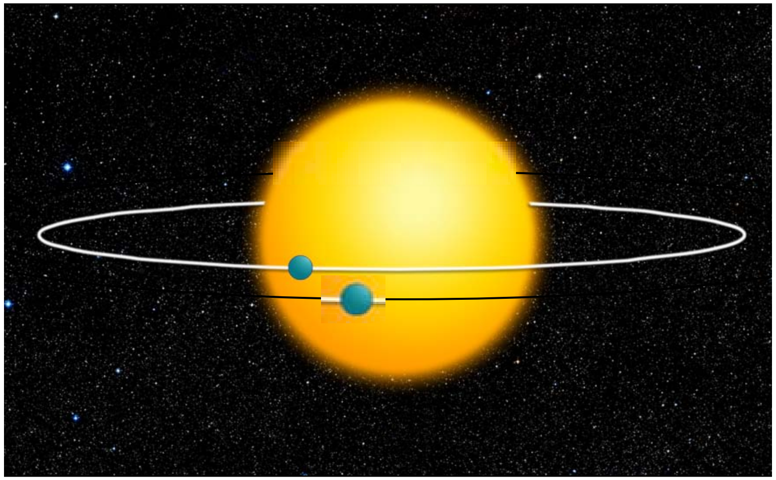
- One of the transit signals is from a background binary star or background star with planets, blended.
- The transits are from planets around different, physically-bound, stars.

- If all pairs were “false multis”, ~ 56 would seem unstable.
- 2 pairs seem unstable => ~ 3 - 4% are “false multis”
- ~ 96% are real => high fidelity for statistical investigations.

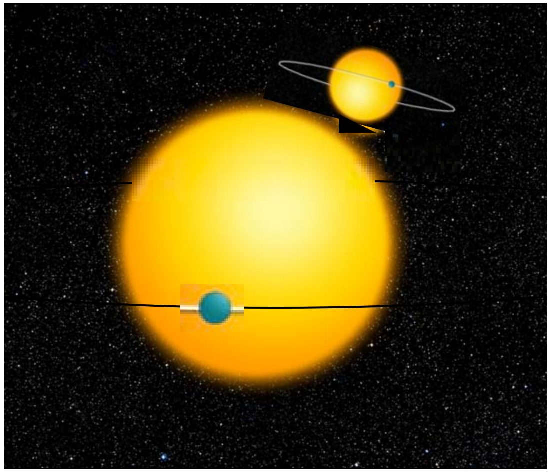
Double Planets:
Orbiting 1 or 2 stars?

Double Transit signal could be due to:

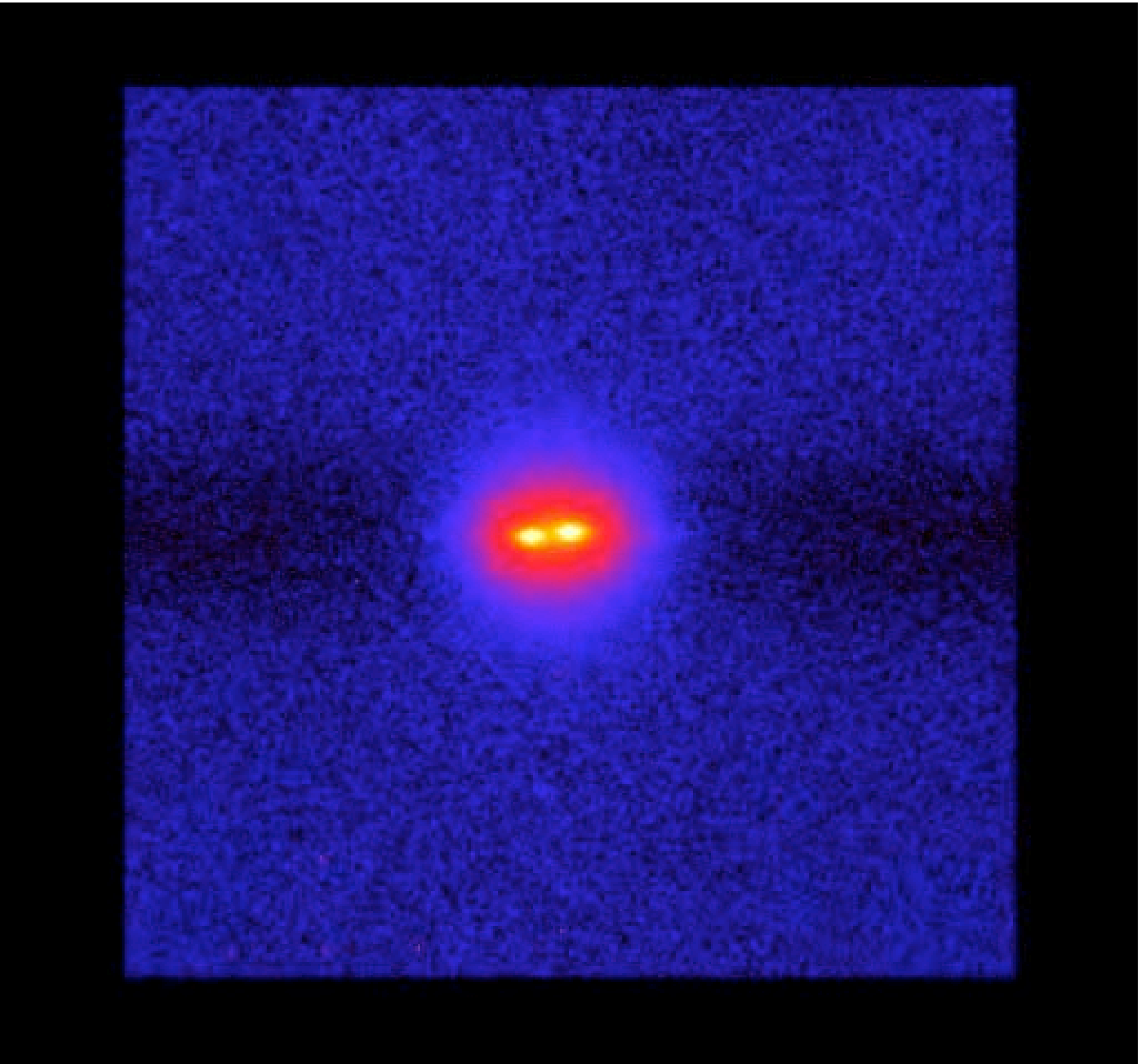
Two Planet System



2 Stars with 1 Planet each



KOI-284, The 1st Unstable Multi



3 candidates

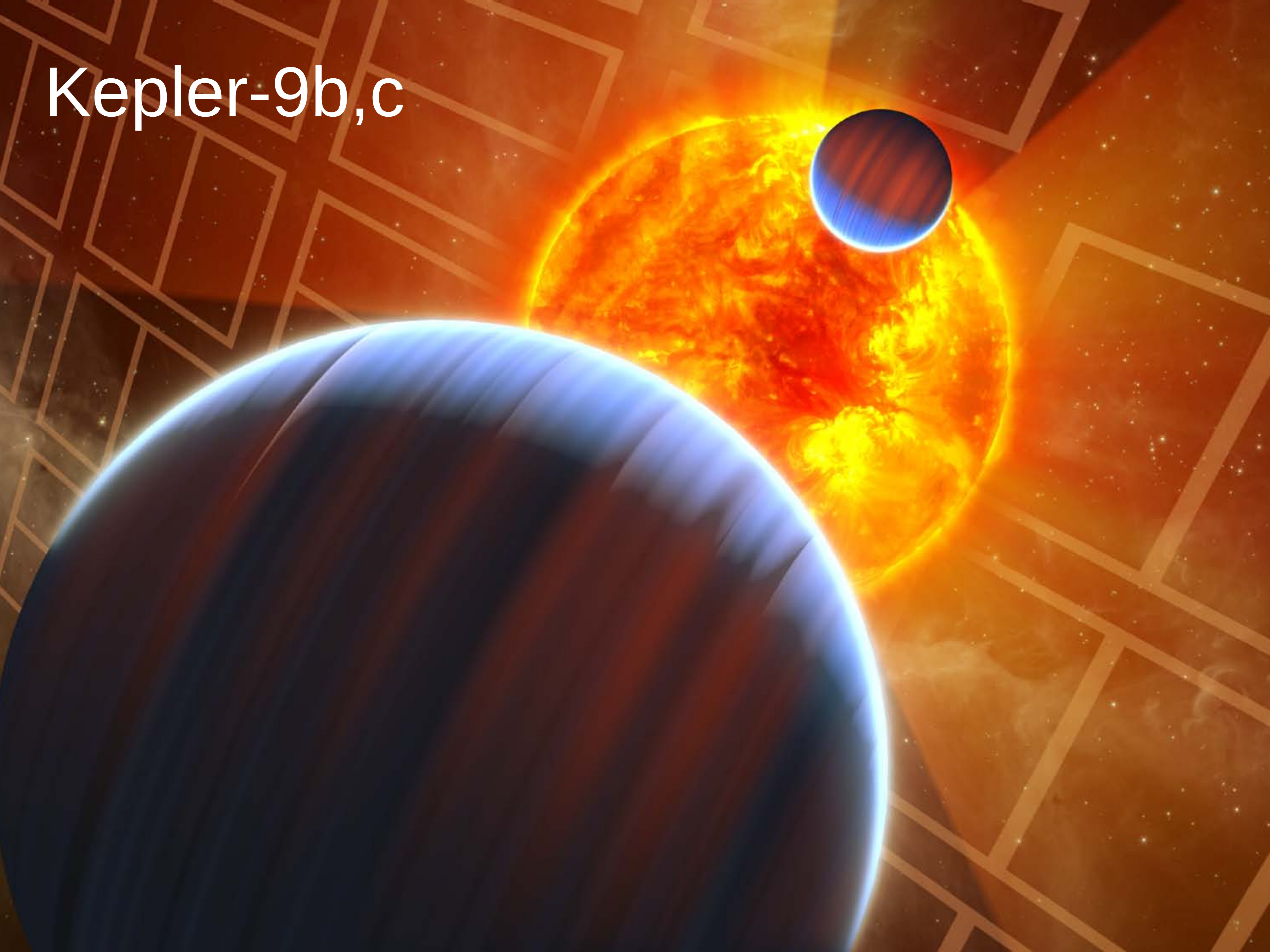
Periods:

6.18, 6.42, 18.0 days

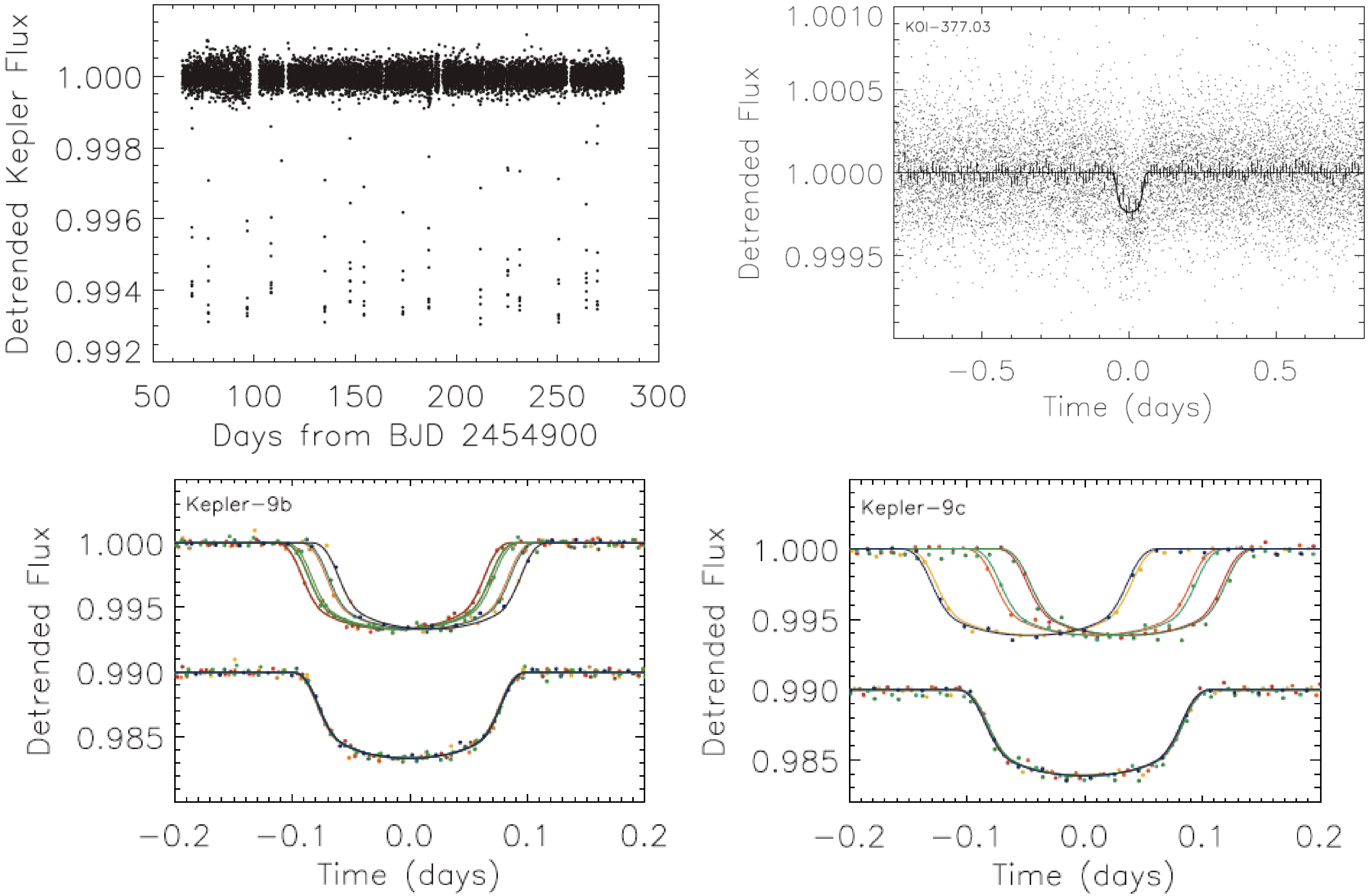
The one multi (of 170 studied) that is clearly unstable

Most likely answer: one star has 2 planets, the other has 1

Kepler-9b,c



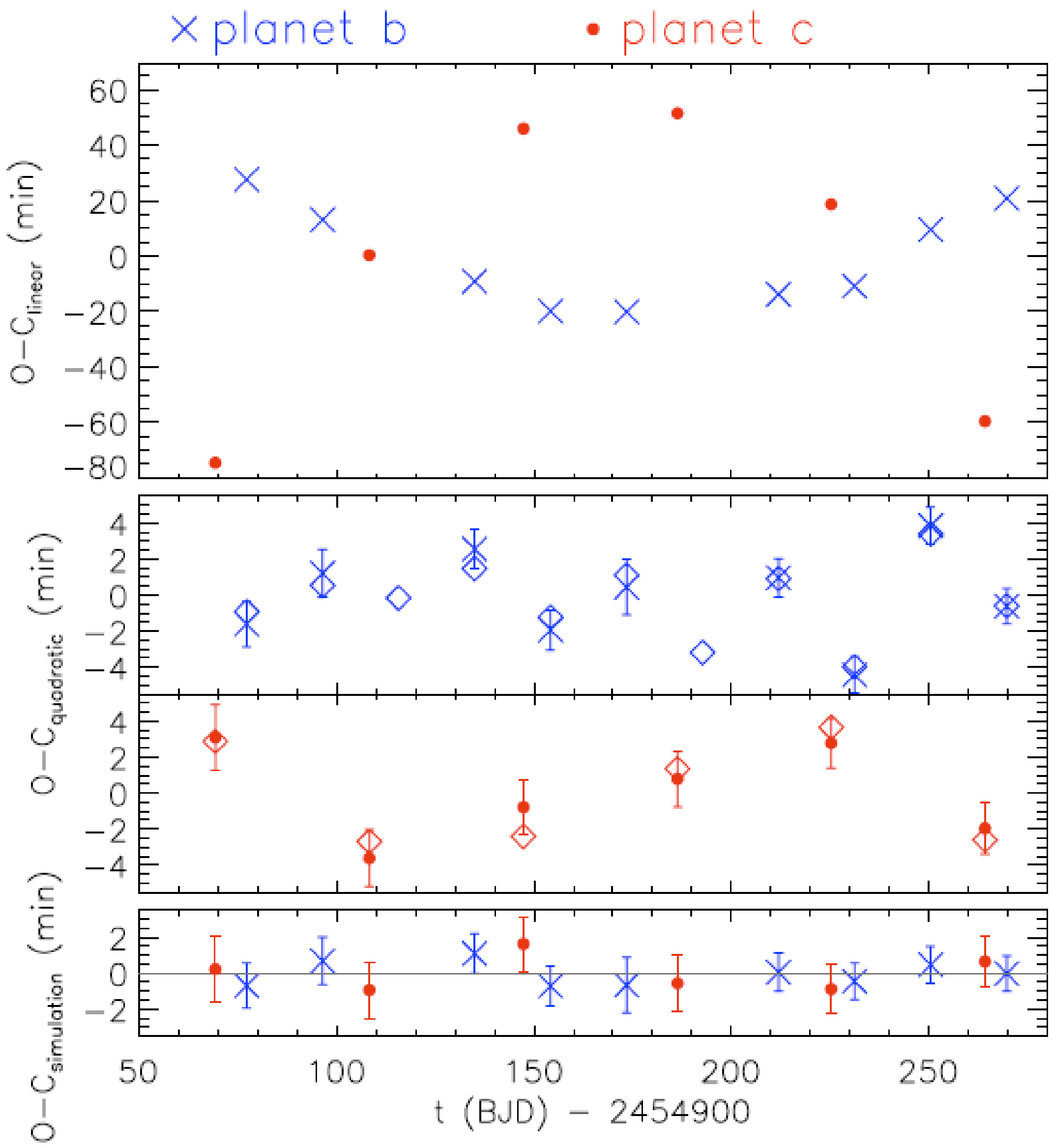
Kepler-9 b,c,d



Detrended Kepler Flux
1.000
0.998
0.996
0.994
0.992
50
100
150
200
250
300
Days from BJD 2454900
KOI-377.03
Detrended Flux
1.0010
1.0005
1.0000
0.9995
−0.5
0.0
0.5
Time (days)
Kepler−9b
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)
Kepler−9c
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)

Transit timing - Planet perturbations

- Models without interactions give poor fits
- Models with planets affecting each other give good fits
- TTVs can be used to confirm planets & measure masses



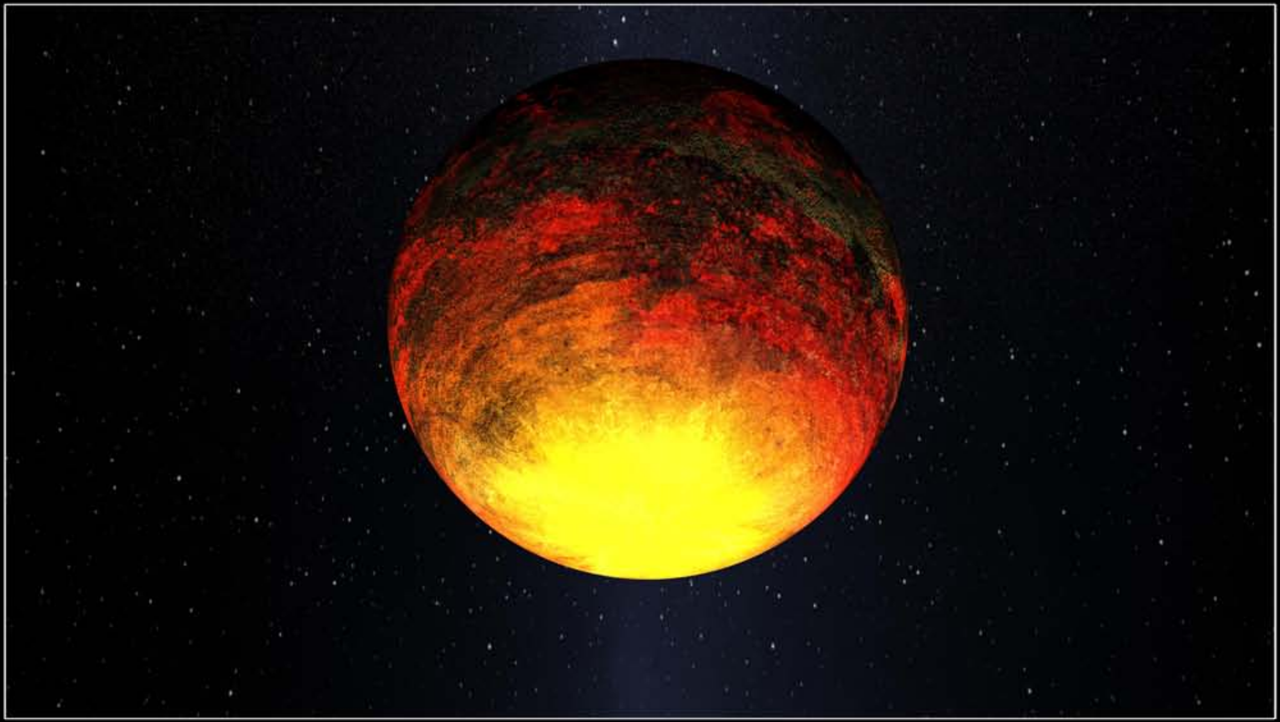
Kepler-10

10b: $R = 1.4\ R_{Earth}$, $M = 4.6\ M_{Earth}$, $P = 0.8$ days

10c: $R = 2.2\ R_{Earth}$, $M < 20\ M_{Earth}$, $P = 45$ days

Kepler's First Rocky Planet: Kepler-10b

Kepler is giving us new knowledge about the frequency of near Earth-size planets.



Kepler-36: A Pair of Planets with Neighboring Orbits and Dissimilar Densities

(Carter et al. 2012)

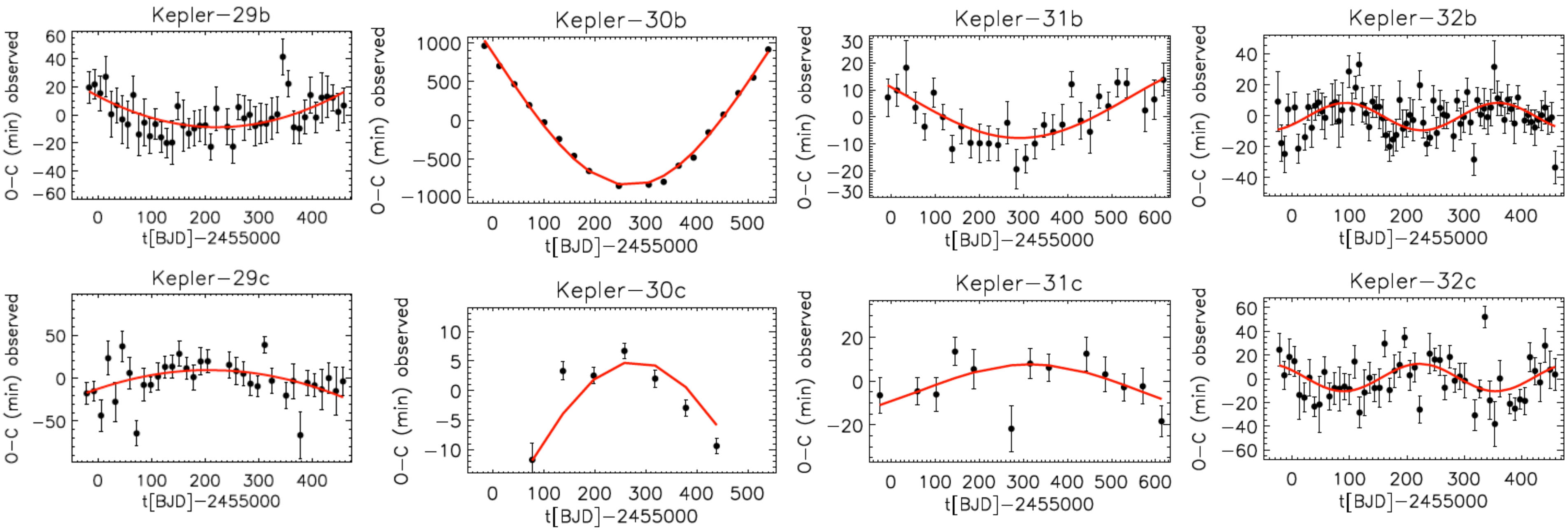
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

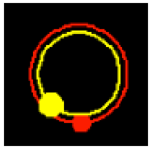
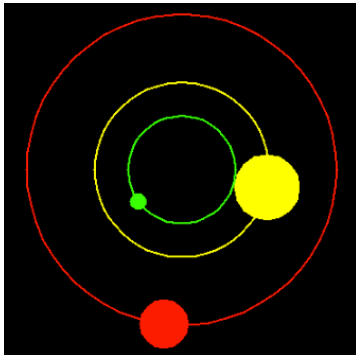
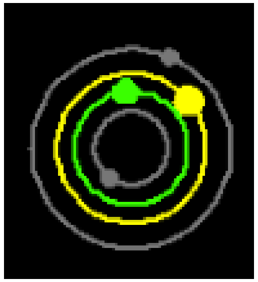
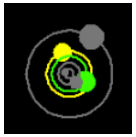
View from Kepler-36b

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Other Systems: A TTV-Confirmation Catalog

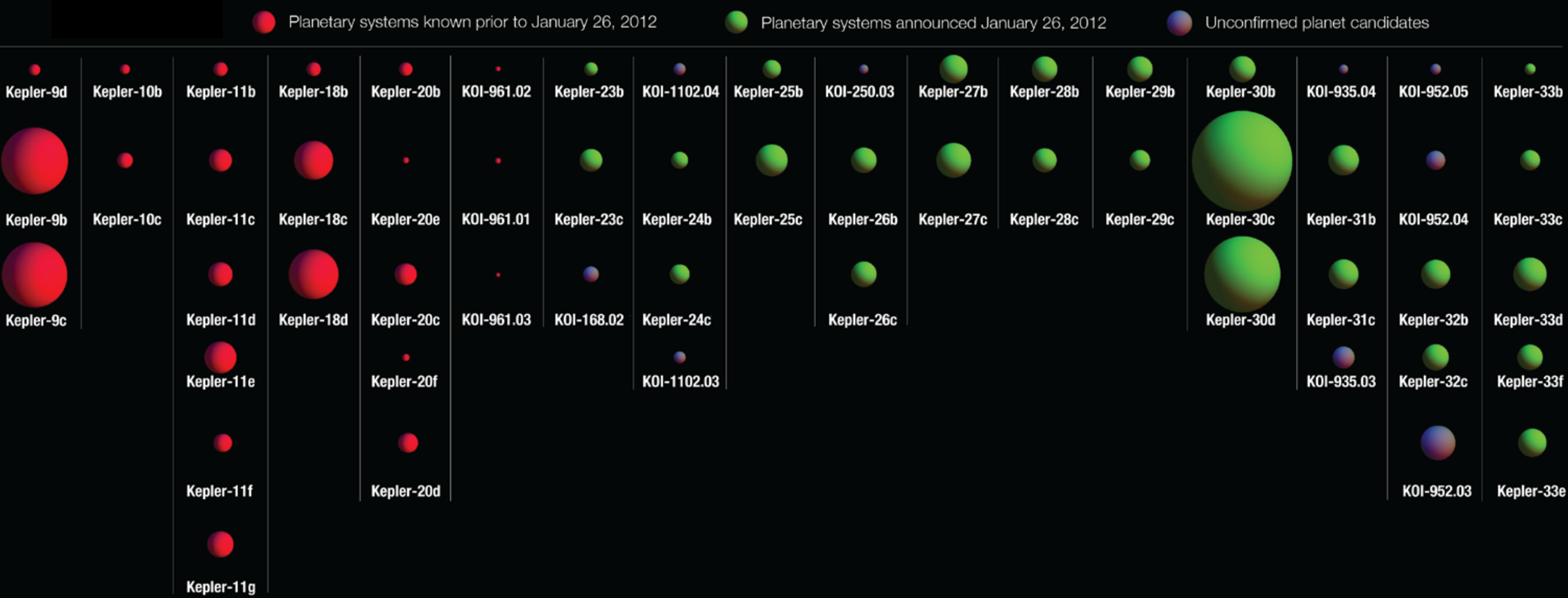


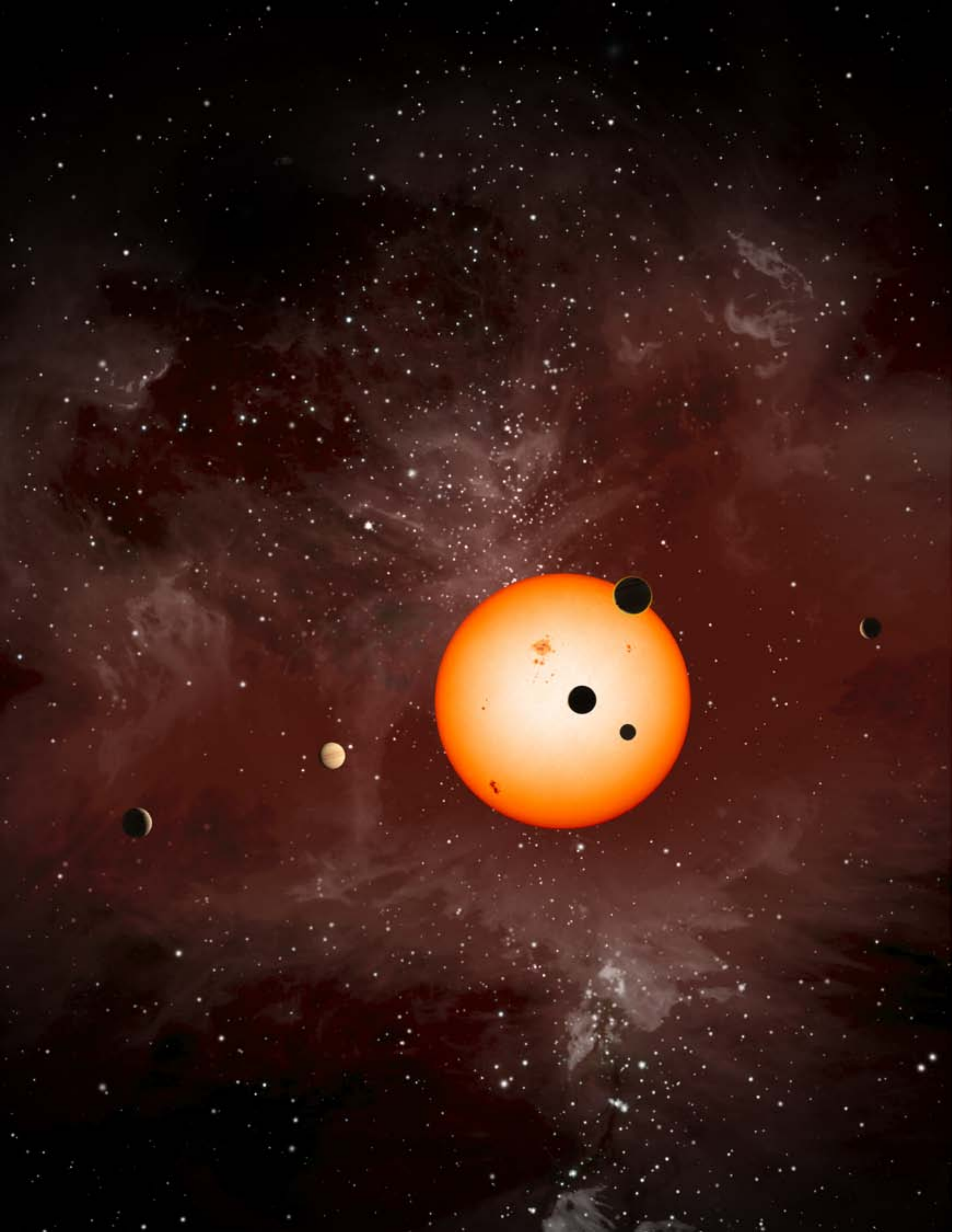
9:7 resonance | near 2:1 | near 2:1 | near 3:2

Ford et al. 2012, Steffen et al. 2012, Fabrycky et al. 2012

Kepler’s Transiting Planet Systems

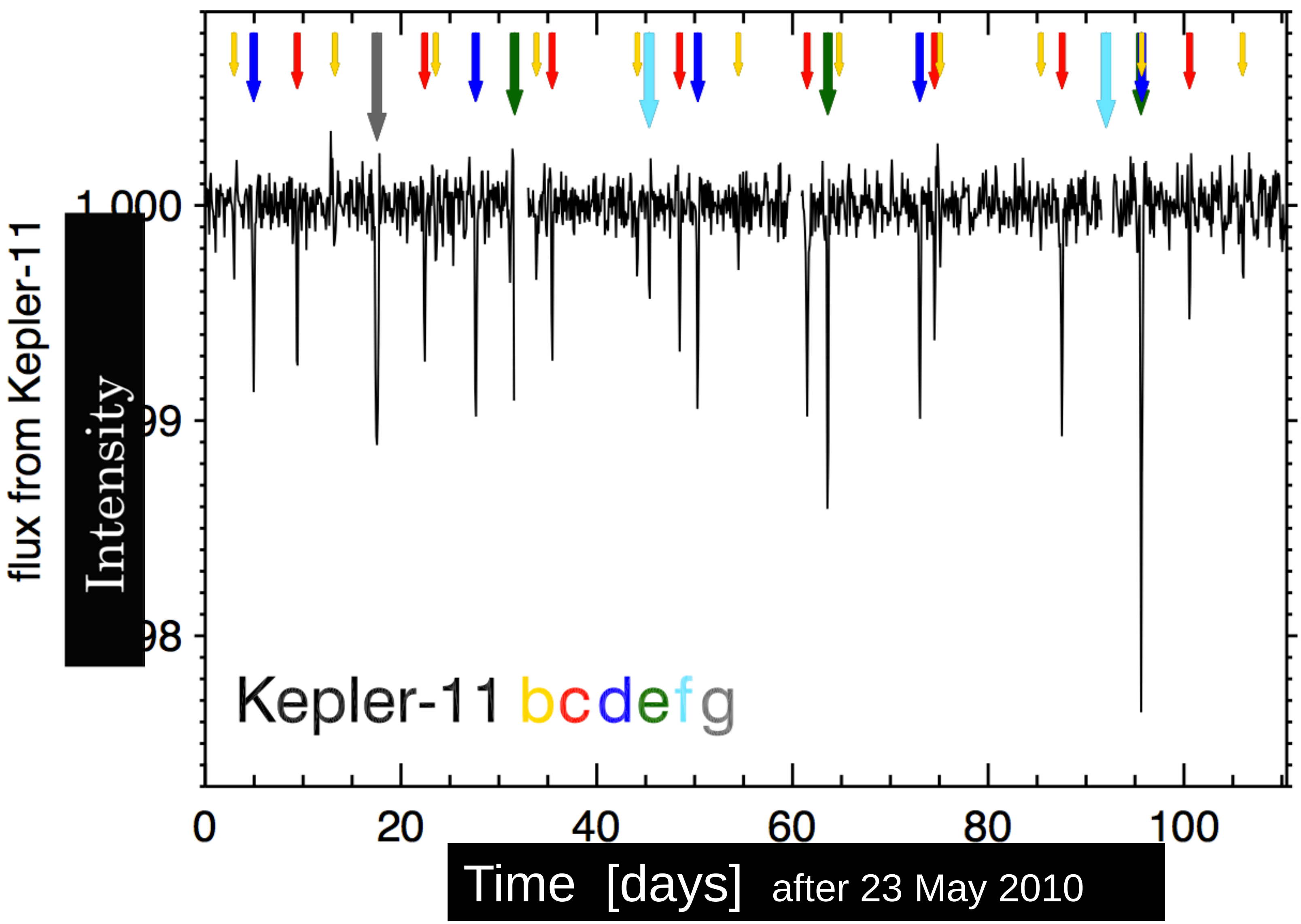




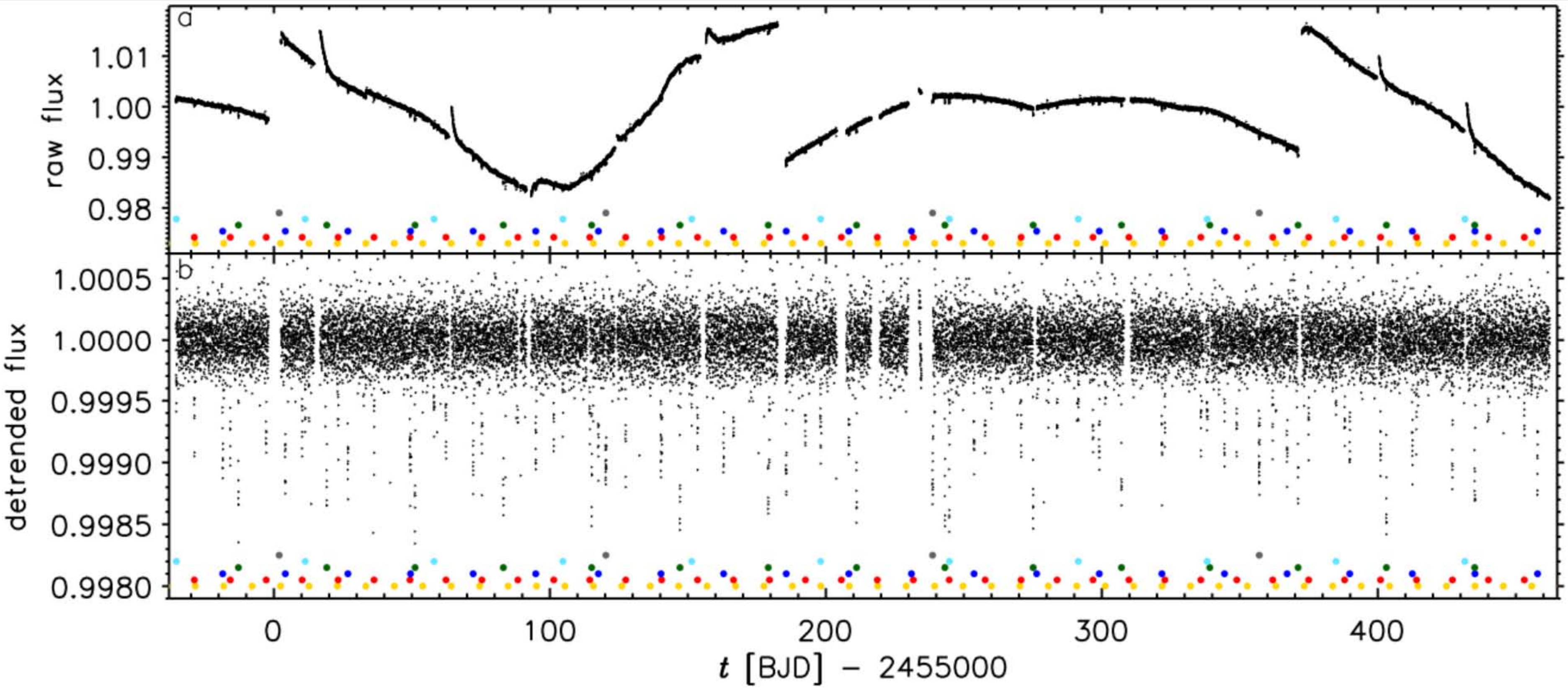
Kepler-11

A really cool system with 6 transiting planets

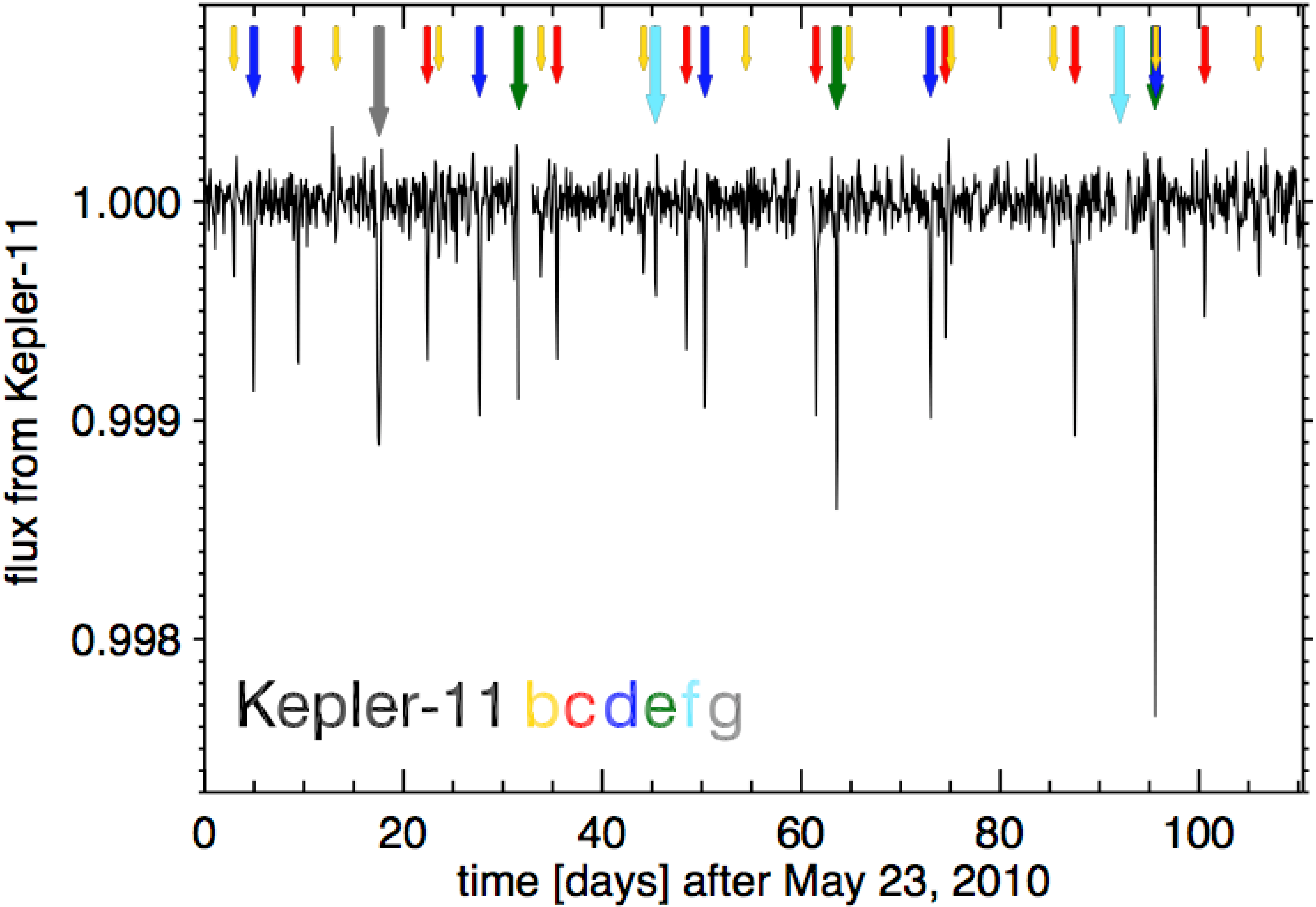
Kepler-11: Six Transiting Planets



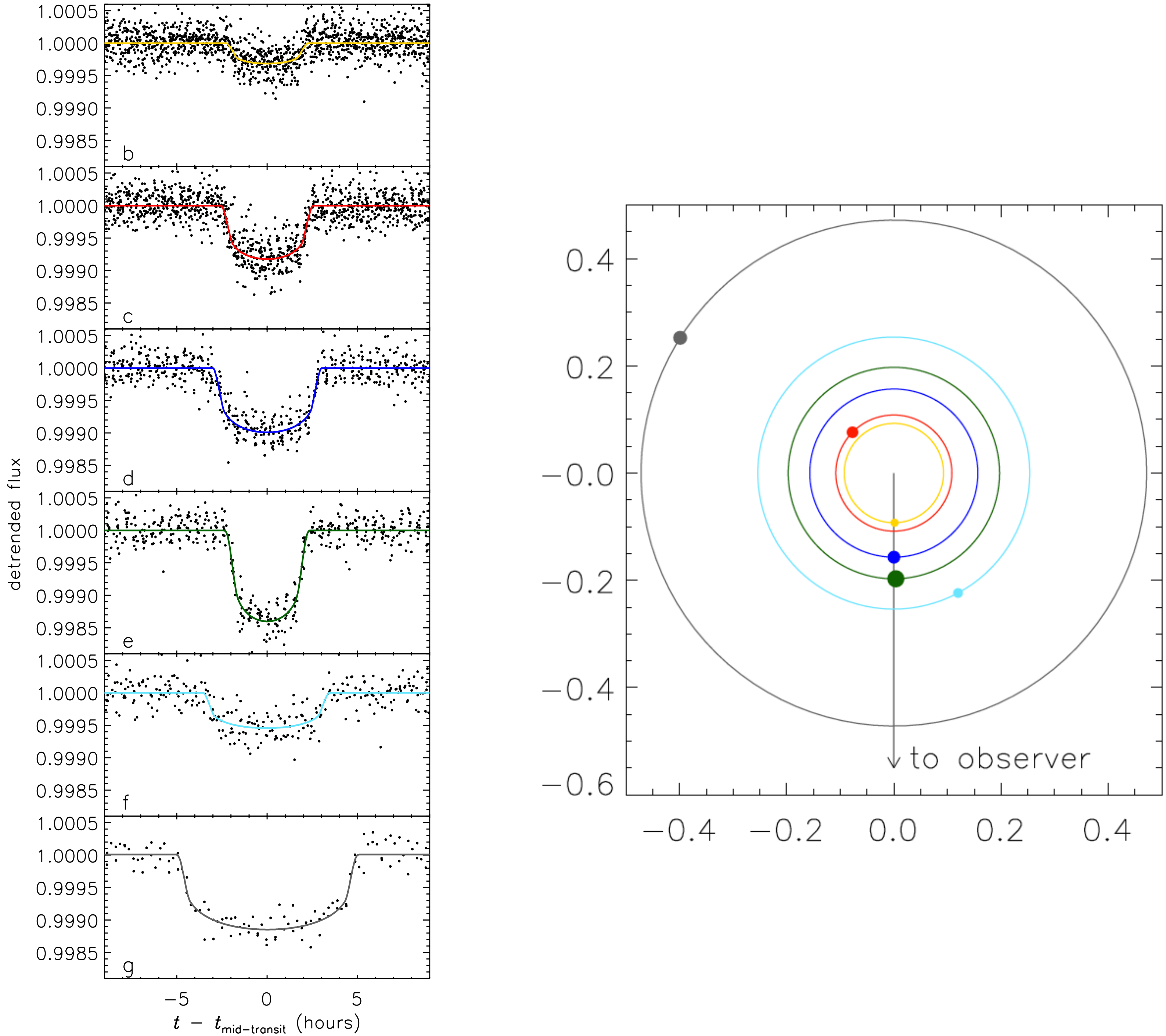
Lightcurve Q1-Q6



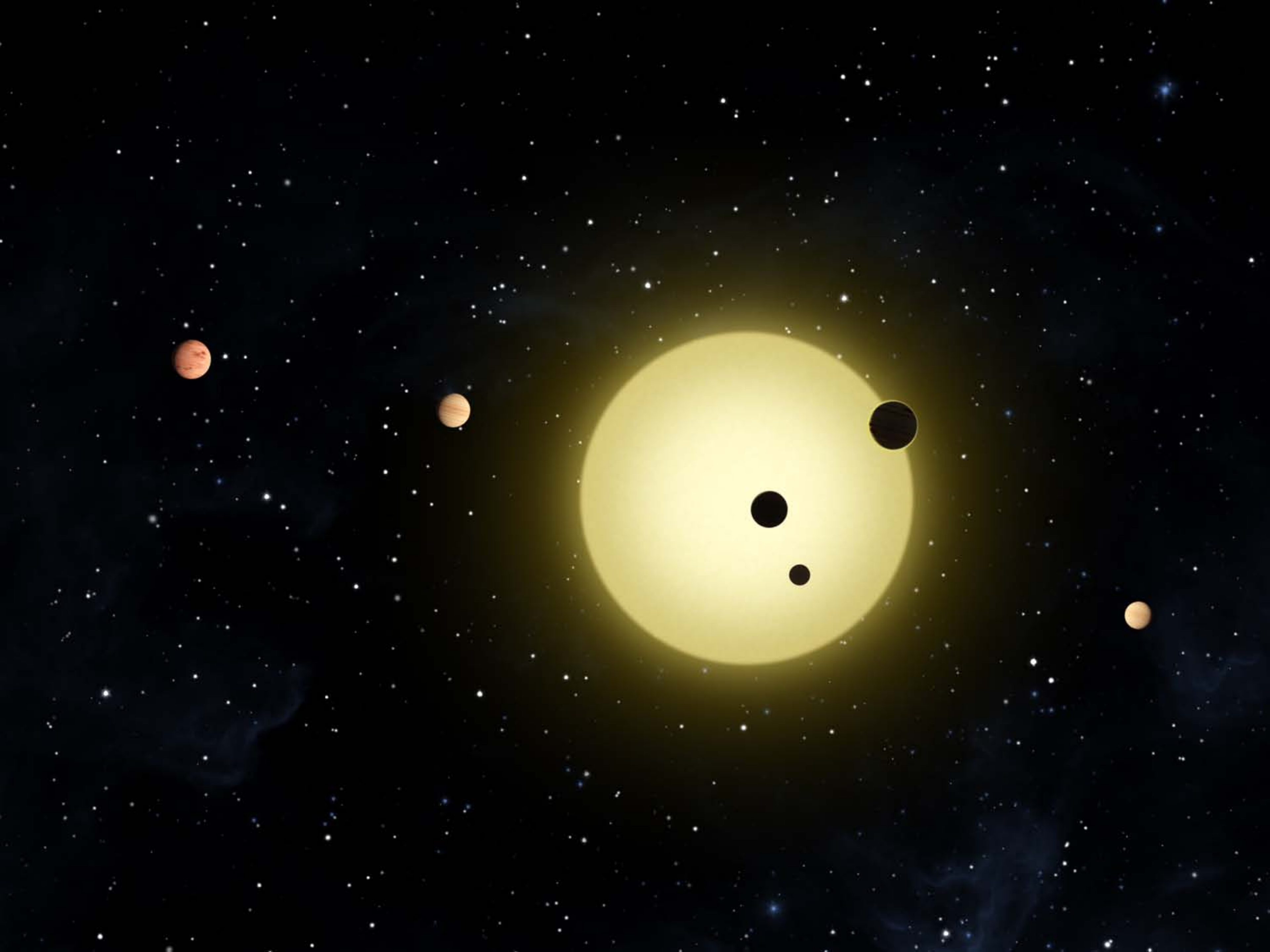
- Colored dots represent transits of six planets

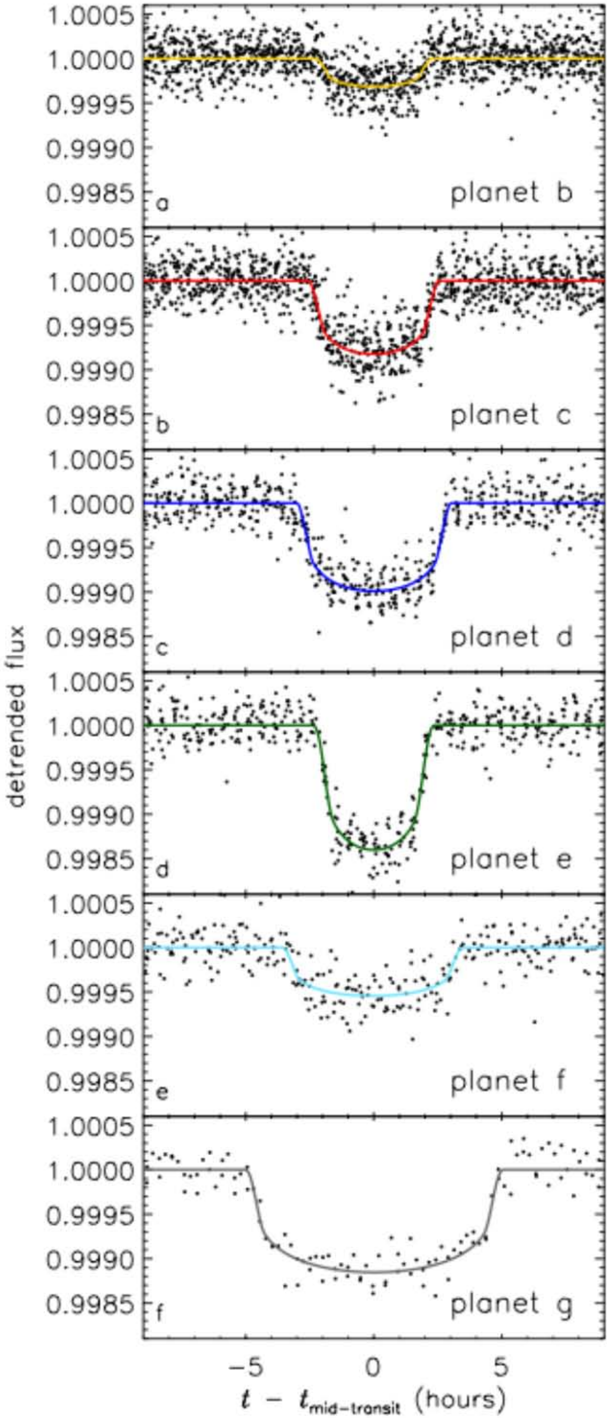


flux from Kepler-11
1.000
0.999
0.998
Kepler-11 bcdefg
0
20
40
60
80
100
time [days] after May 23, 2010



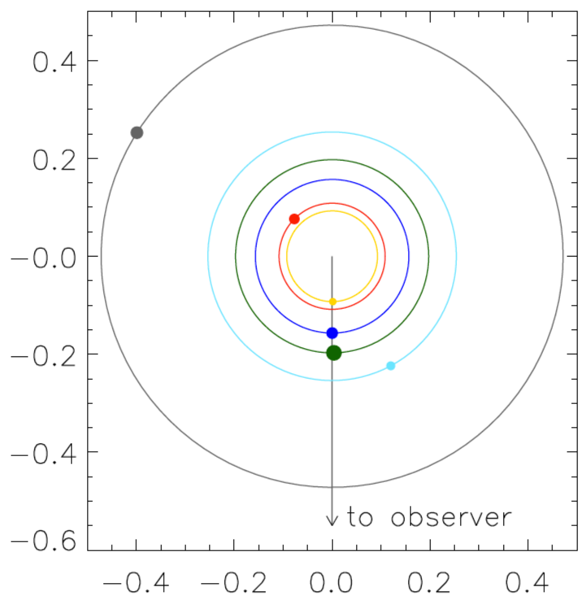
detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
b
c
d
e
f
g
−5
0
5
t − t_mid−transit (hours)
0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer

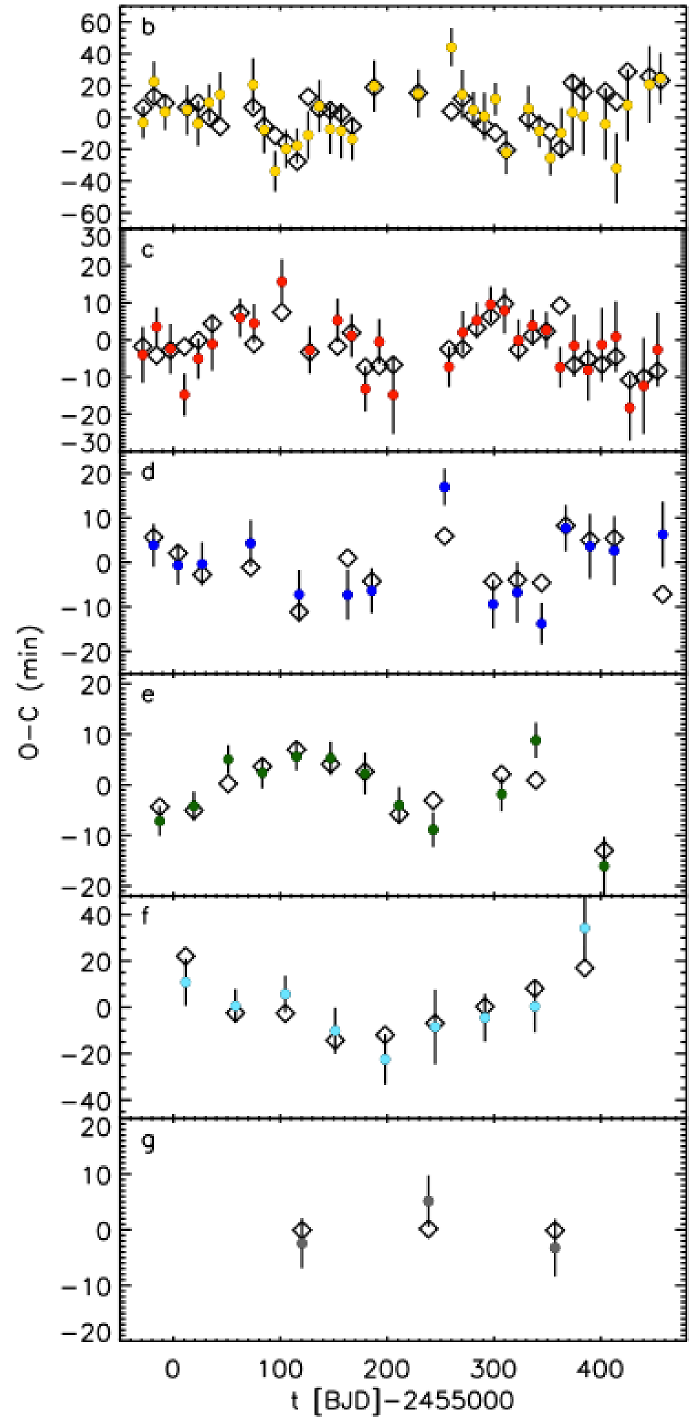


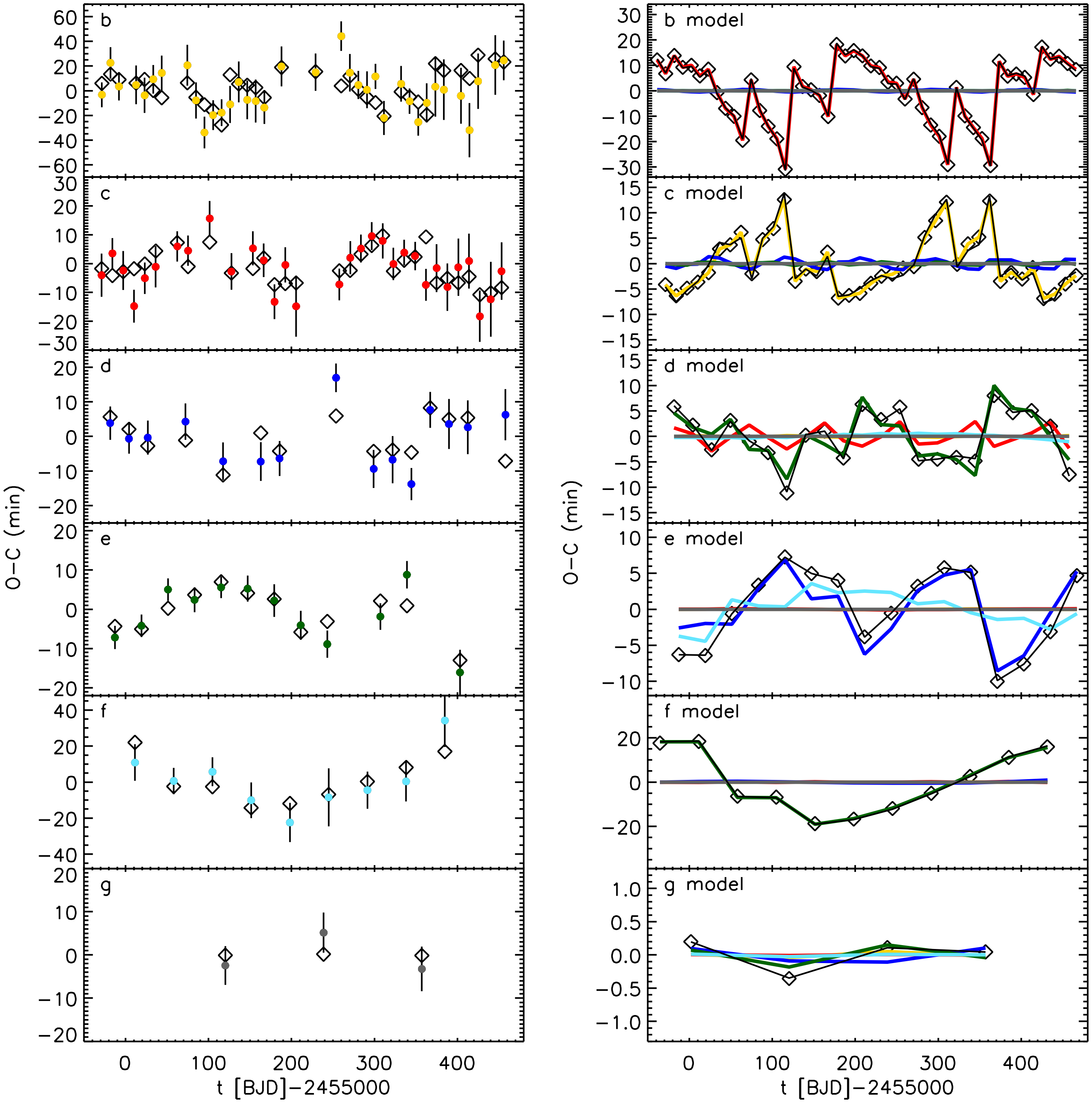


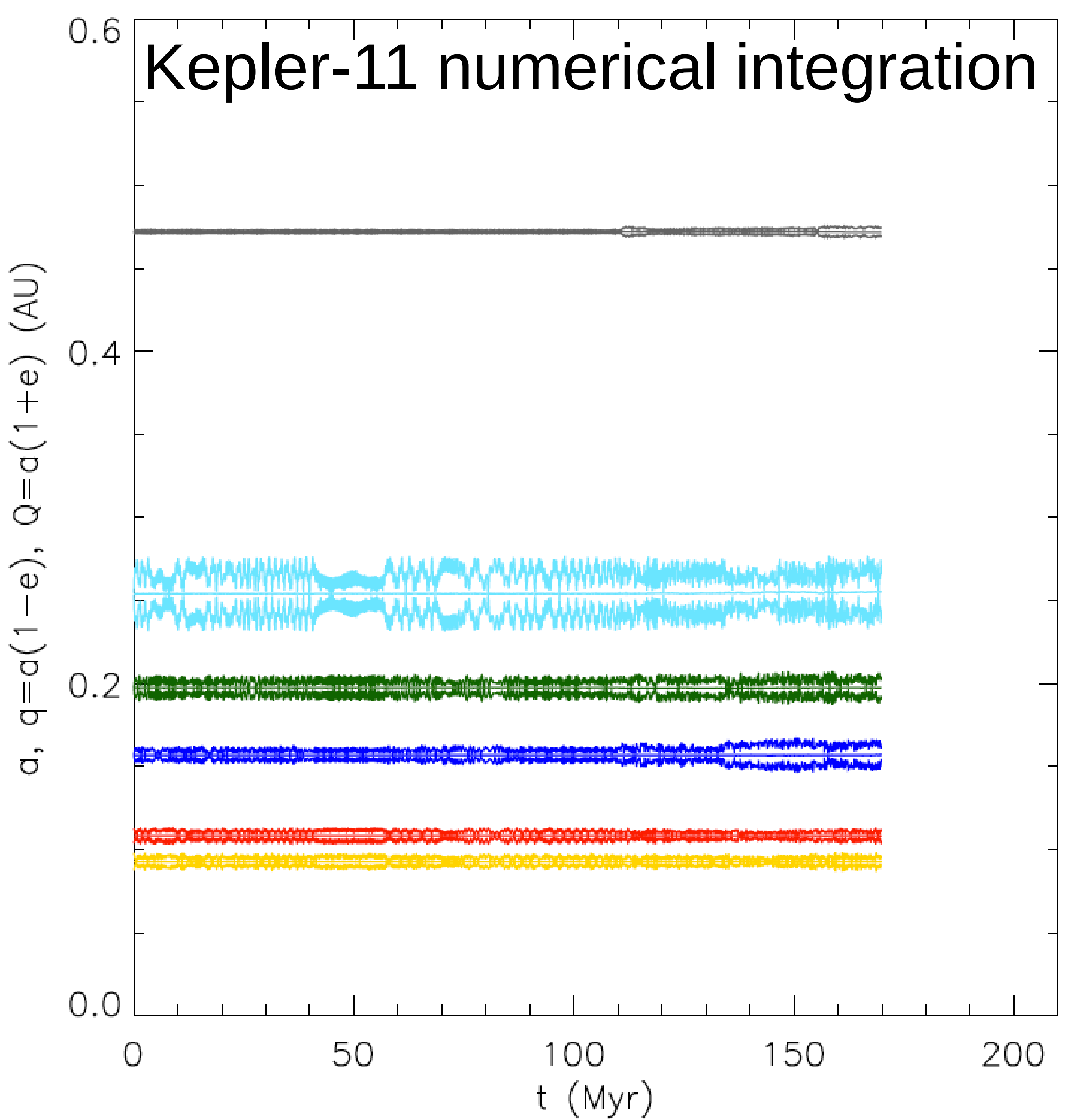
← Transits

TTV's →






b
c
d
e
f
g
b model
c model
d model
e model
f model
g model
O−C (min)
O−C (min)
t [BJD]−2455000
t [BJD]−2455000

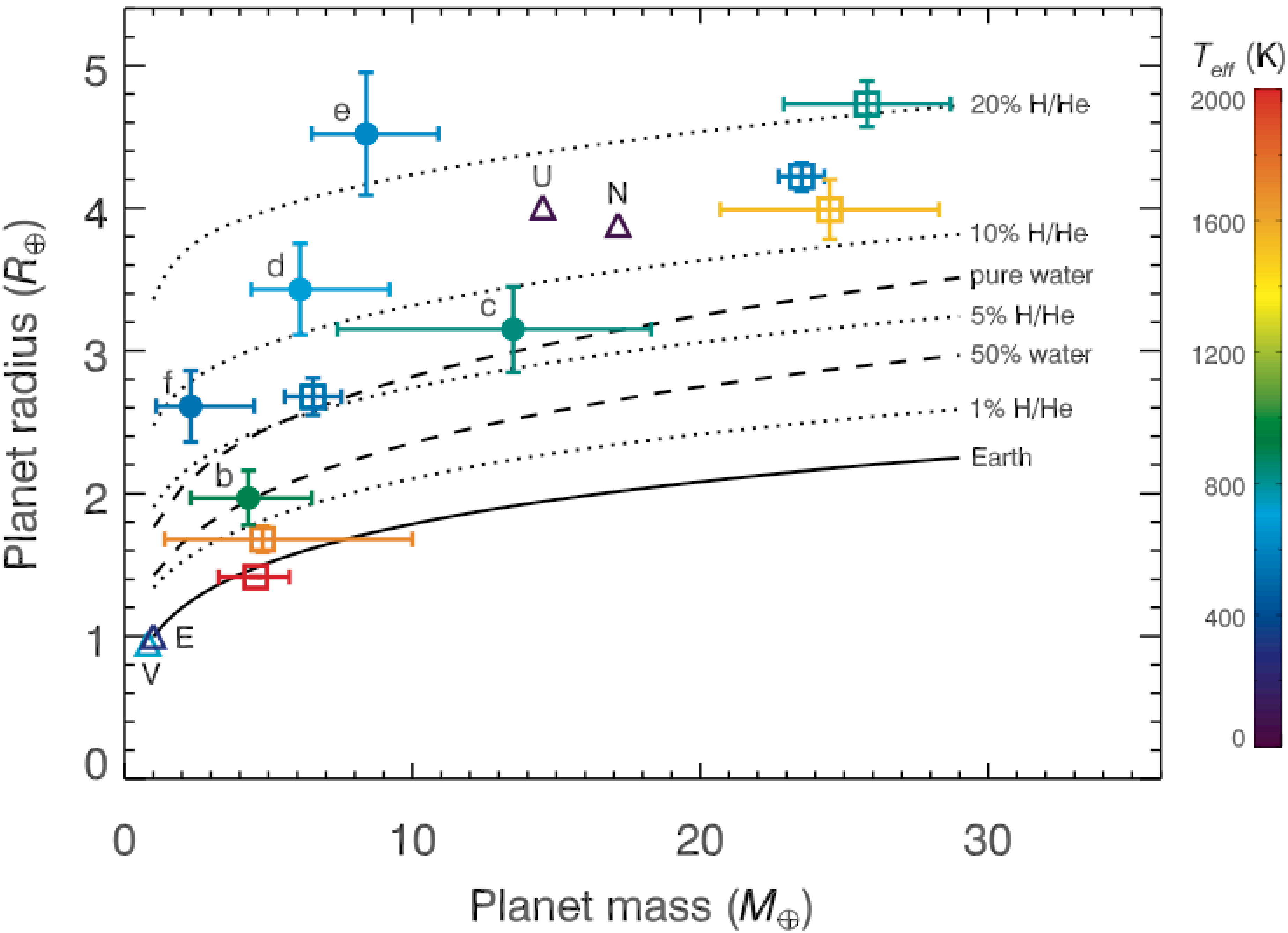


Kepler-11 numerical integration
0.6
0.4
0.2
0.0
a, q=a(1−e), Q=a(1+e) (AU)
0
50
100
150
200
t (Myr)

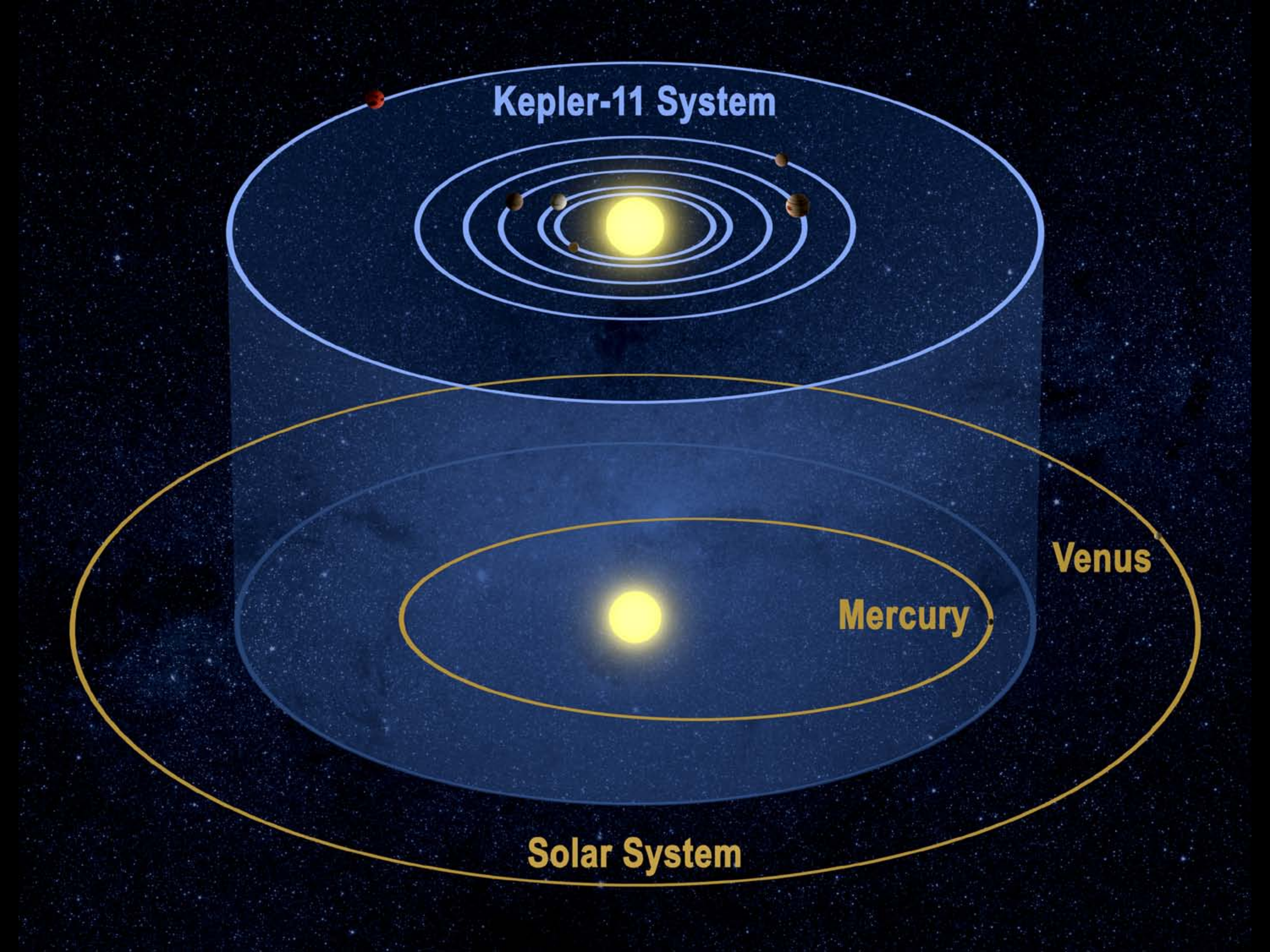
Image: NASA/Pyle

Kepler-11 parameters

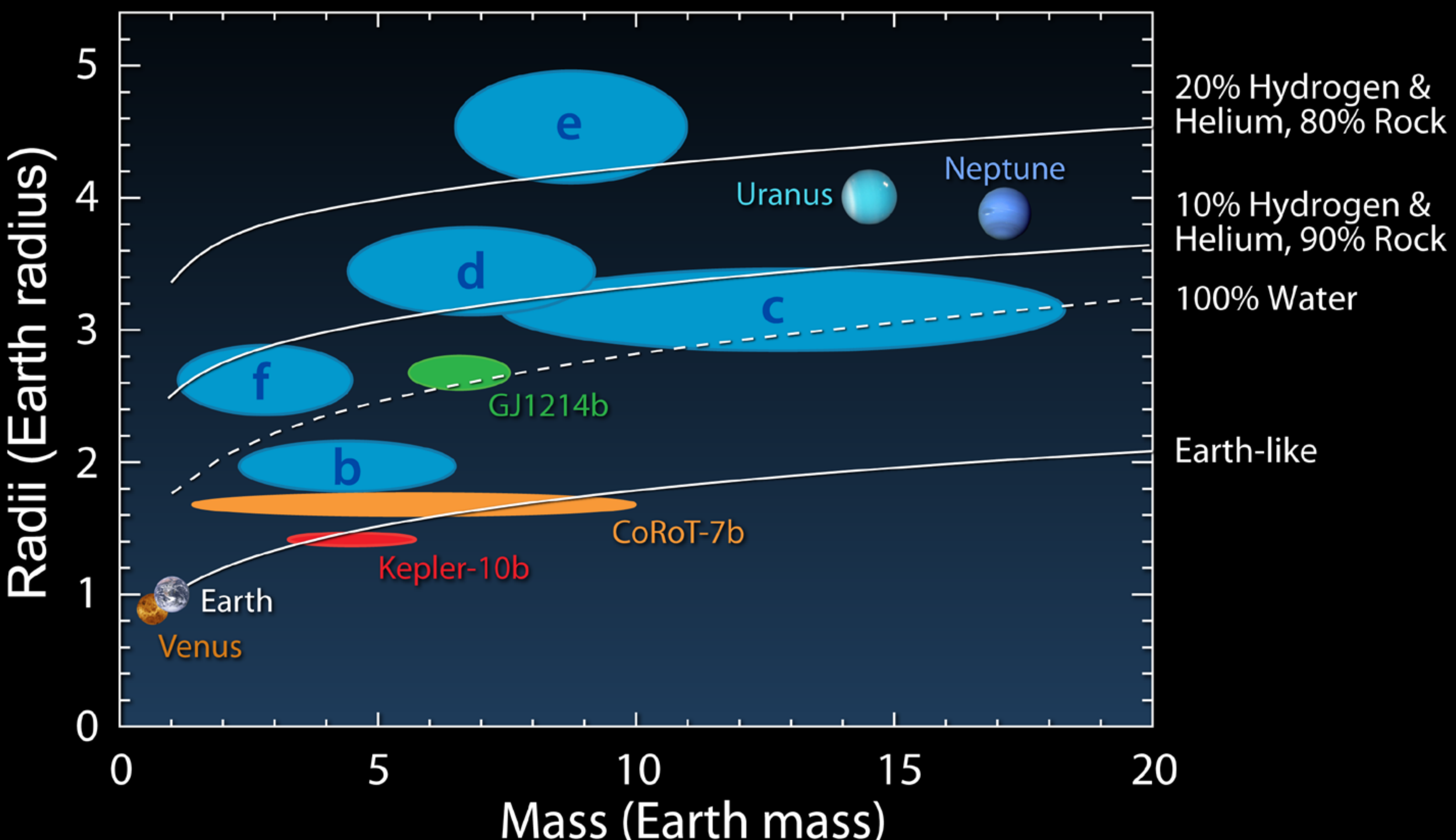
Planet	Period (days)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g/cm³)
b	**10.30375** ± 0.00016	**1.97** ± 0.19	**4.3** +2.2,-2.0	**3.1** +2.1,-1.5
c	**13.02502** ± 0.00008	**3.15** ± 0.30	**13.5** +4.8,-6.1	**2.3** +1.3,-1.1
d	**22.68719** ± 0.00021	**3.43** ± 0.32	**6.1** +3.1,-1.7	**0.9** +0.5,-0.3
e	**31.99590** ± 0.00028	**4.52** ± 0.43	**8.4** +2.5,-1.9	**0.5** +0.2,-0.2
f	**46.68876** ± 0.00074	**2.61** ± 0.25	**2.3** +2.2,-1.2	**0.7** +0.7,-0.4
g	**118.37774** ± 0.00112	**3.66** ± 0.35	< 300	-



Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
T_{eff} (K)
0
1
2
3
4
5
0
10
20
30
2000
1600
1200
800
400
0
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
pure water
5% H/He
50% water
1% H/He
Earth


Kepler-11 System
Venus
Mercury
Solar System

Composition of Kepler-11 Planets

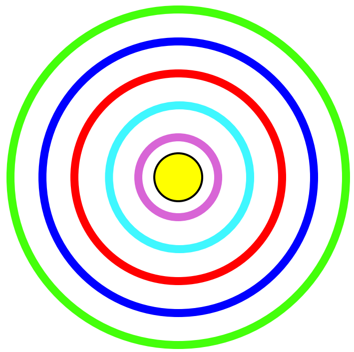


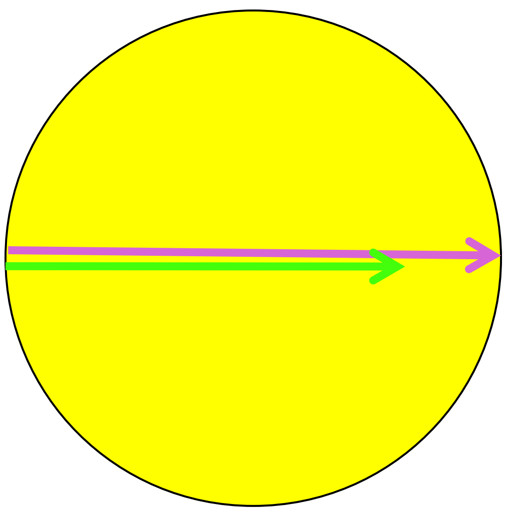
Summary

- Kepler-11 is a surprisingly flat system of six planets.
- The five inner planets comprise the most closely-spaced planetary system known.
- The planets are mid-sized: 2-5 times as large as Earth.
- Most have low densities, implying mixtures of solids and light gases.

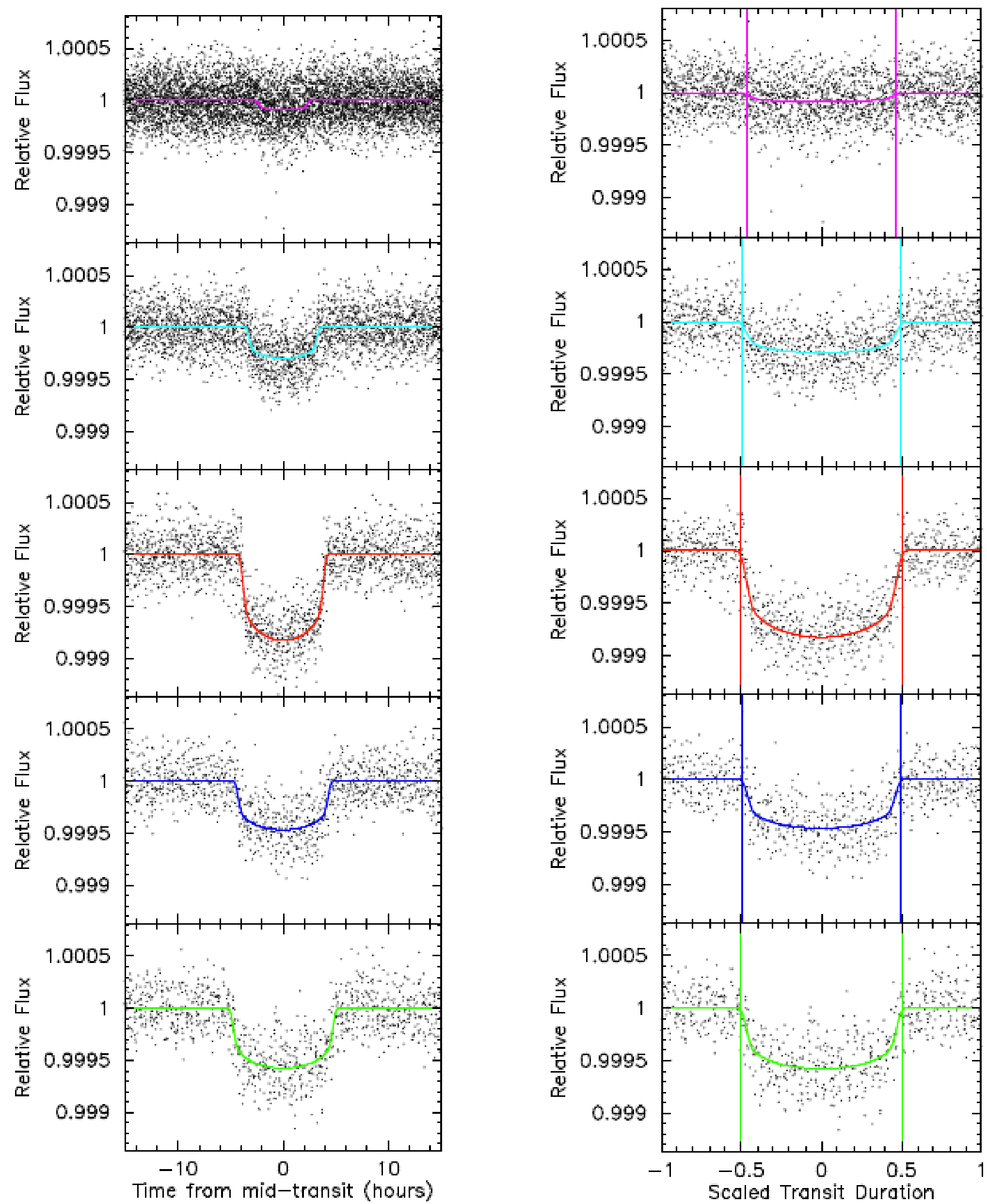

FINDING NEW
PLANETS
Kepler
NASA
Lathrop
DELL'OSSO FAMILY FARM

Durations in the Kepler-33 System

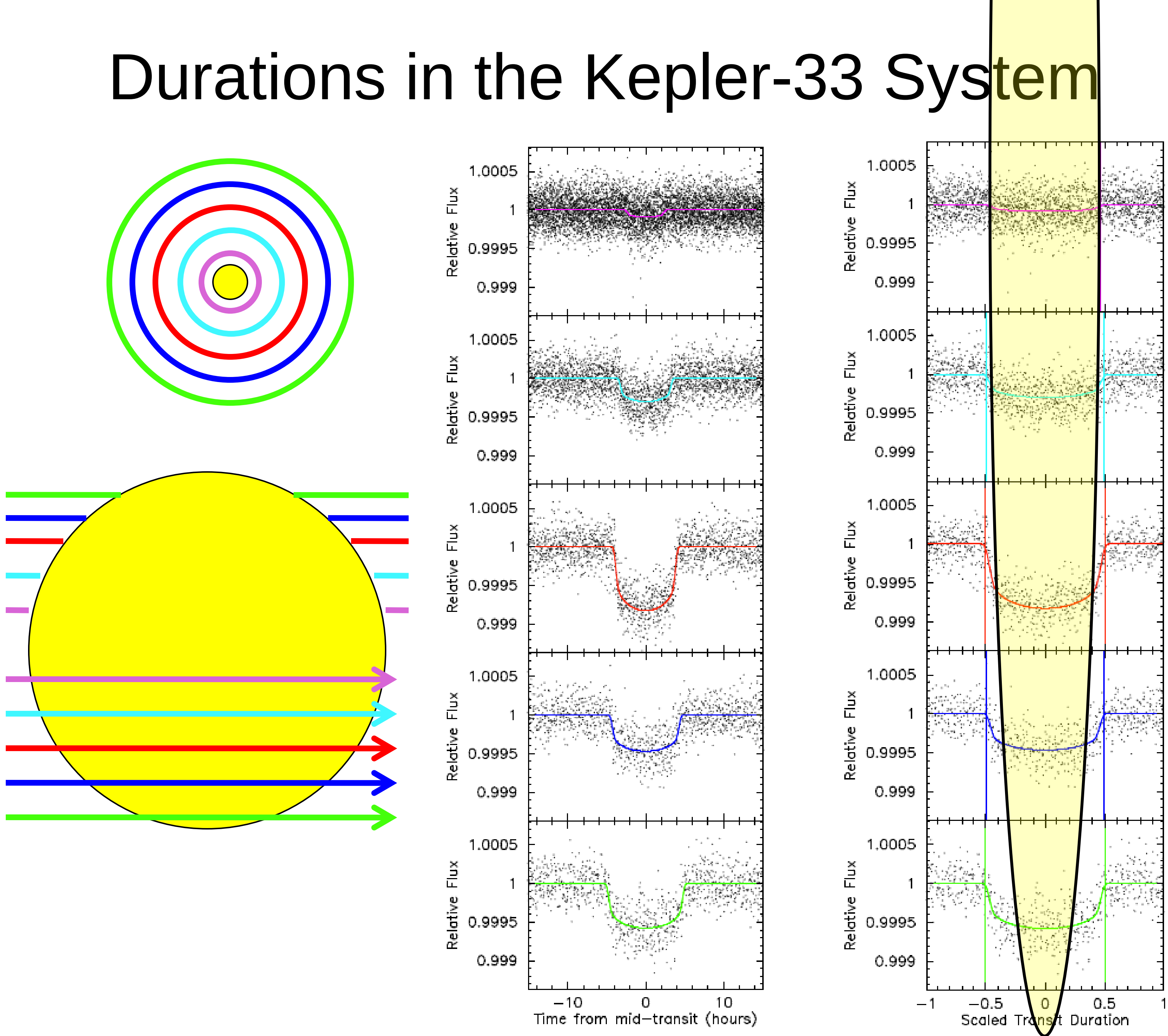




$$T_{\mathrm{dur}} \propto P^{1/3}$$



Durations in the Kepler-33 System

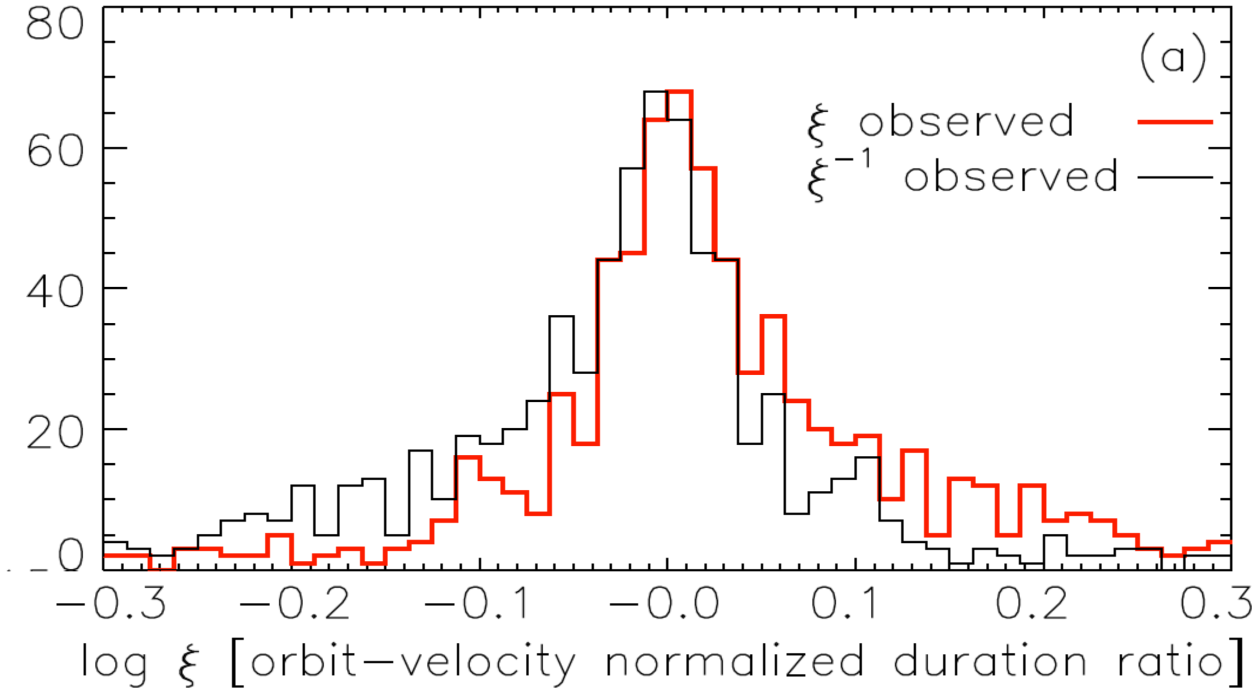


A variable to sense mutual inclinations:

$$\xi \equiv \frac{T_{\mathrm{dur},1}/P_1^{1/3}}{T_{\mathrm{dur},2}/P_2^{1/3}}$$

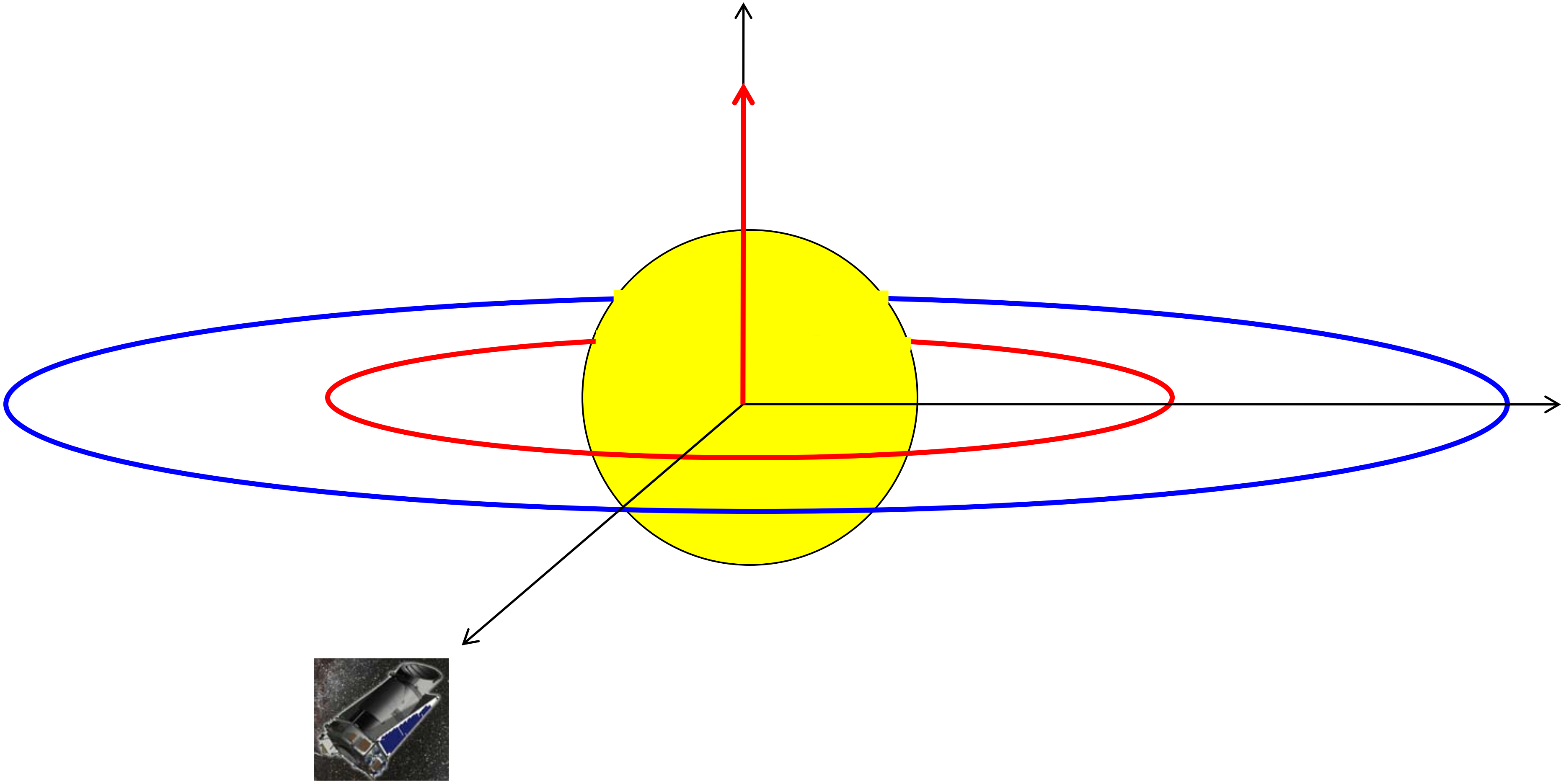
> 1 [circular, coplanar]

~ 1 [uncorrelated]



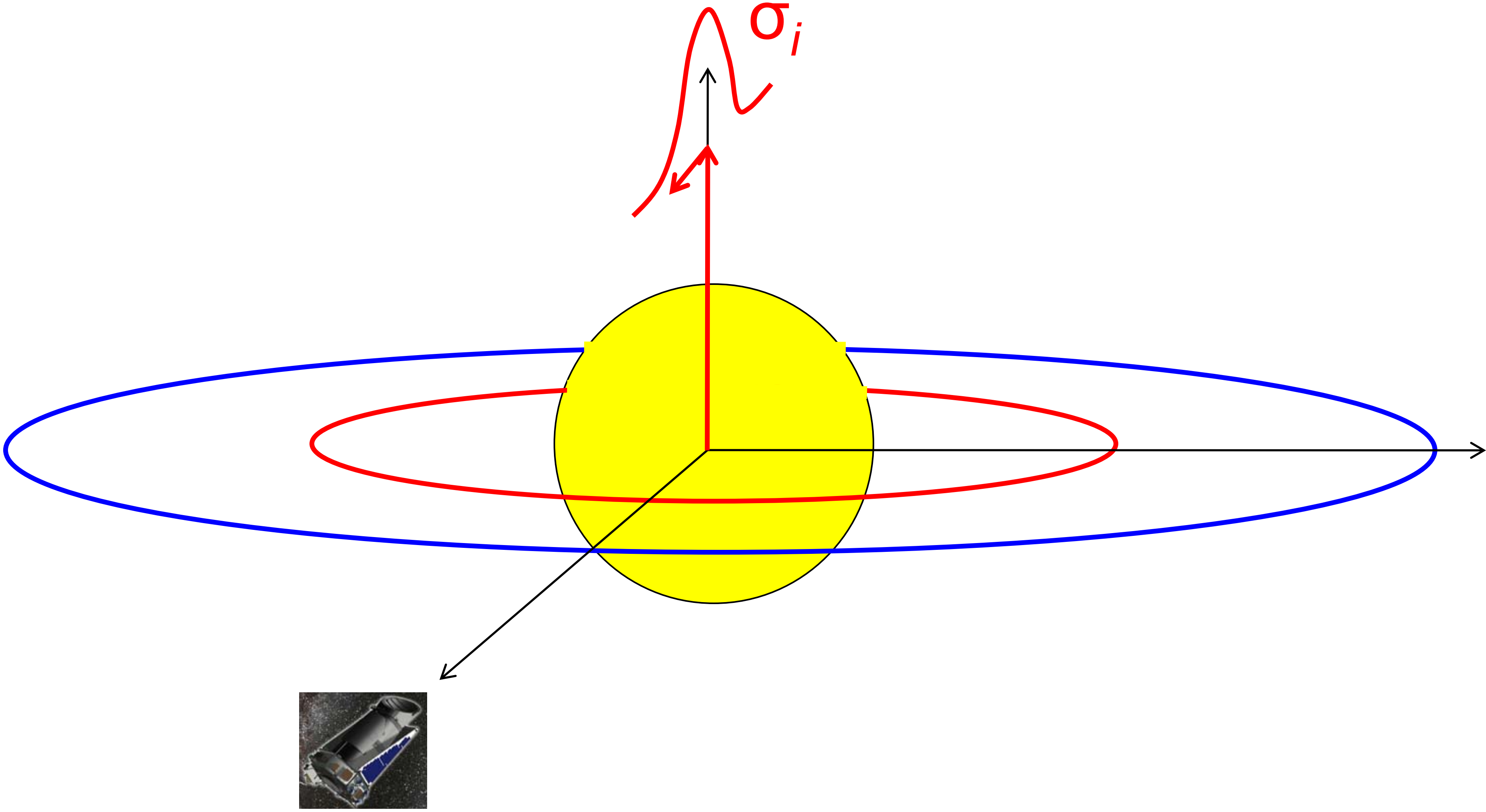
Fabrycky, Lissauer, Ragozzine et al. 2012

Modeling mutual inclinations



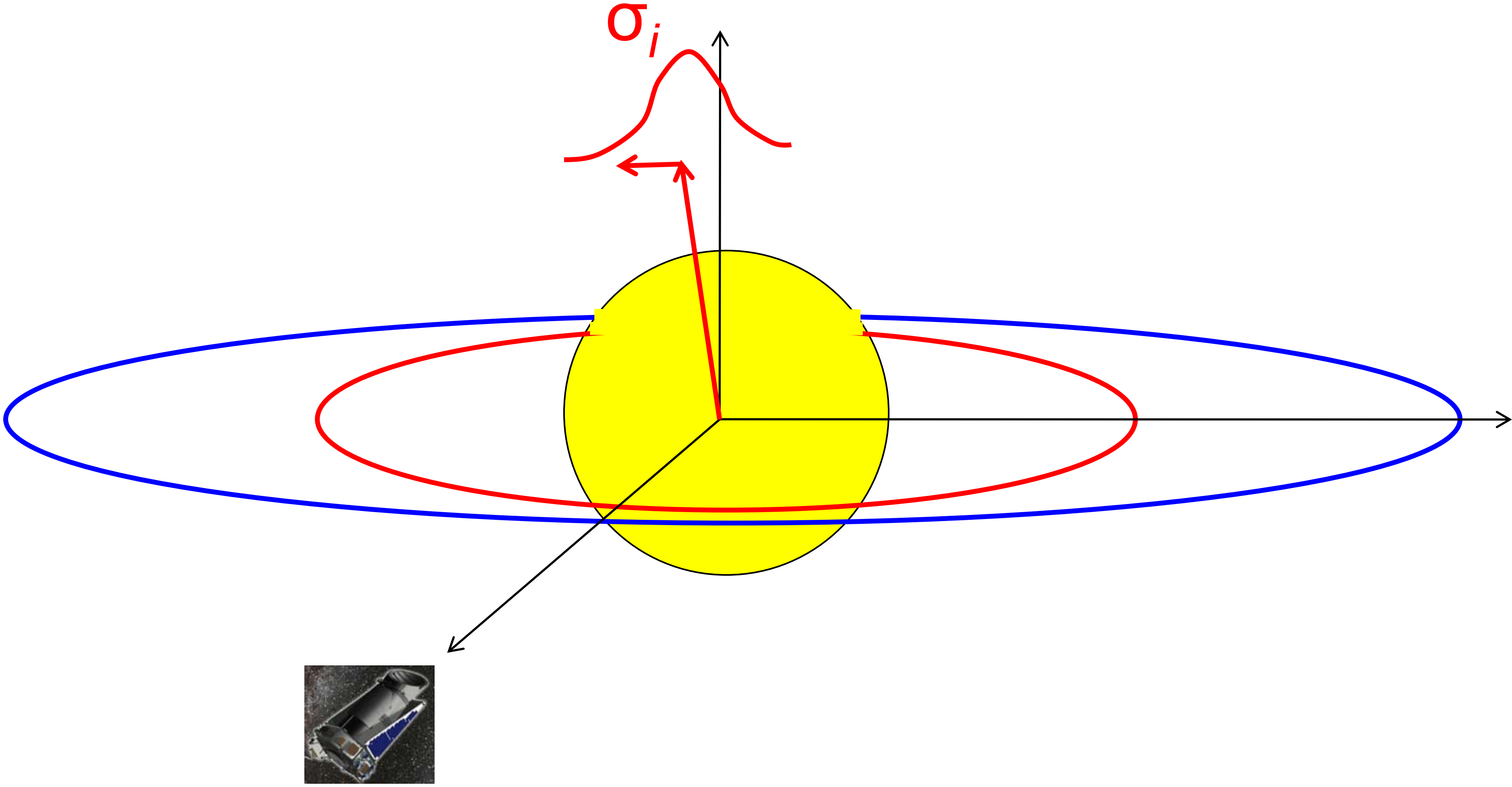
Fabrycky, Lissauer, Ragozzine et al. 2012

Modeling mutual inclinations



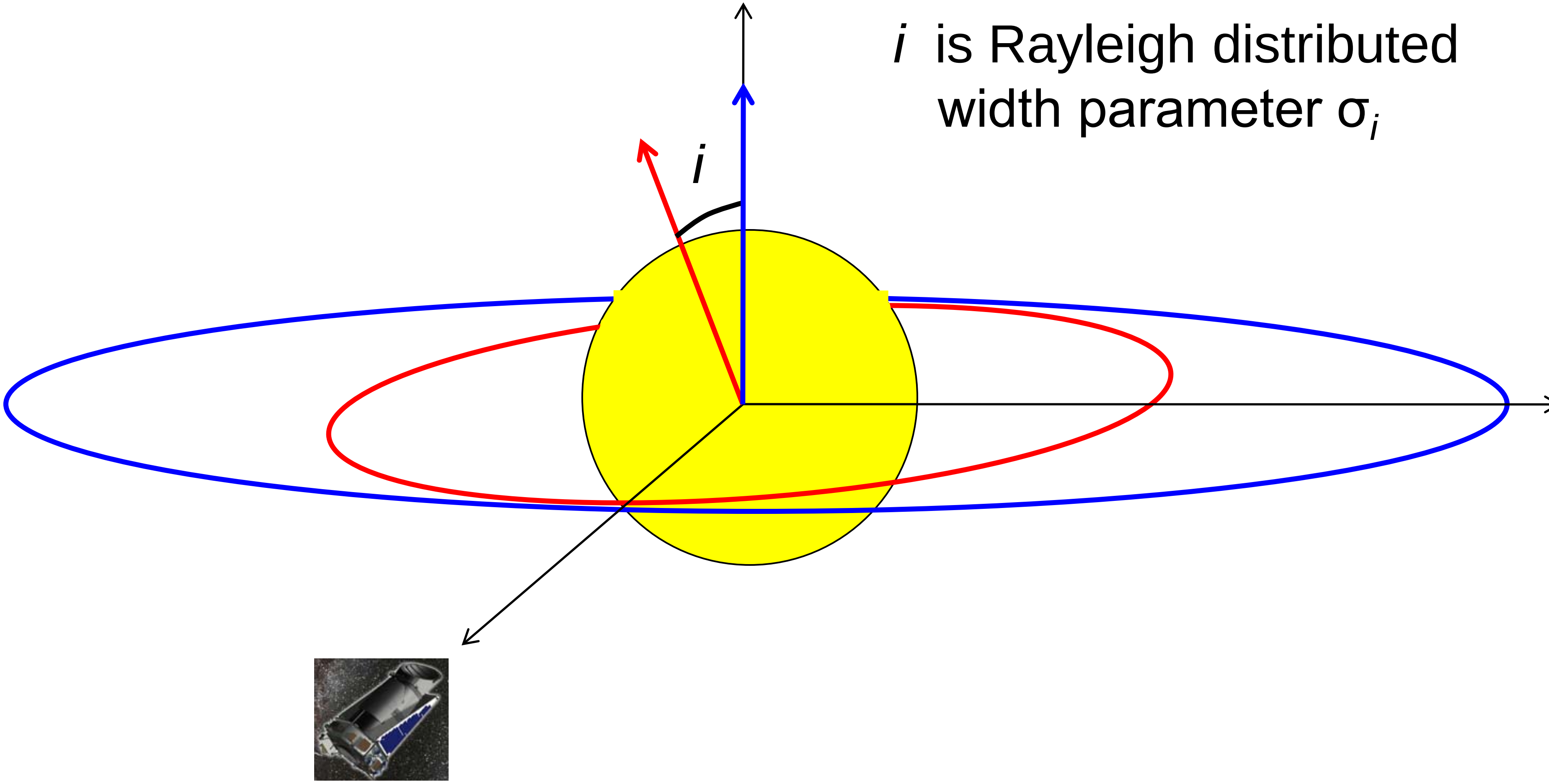
Fabrycky, Lissauer, Ragozzine et al. 2012

Modeling mutual inclinations



Fabrycky, Lissauer, Ragozzine et al. 2012

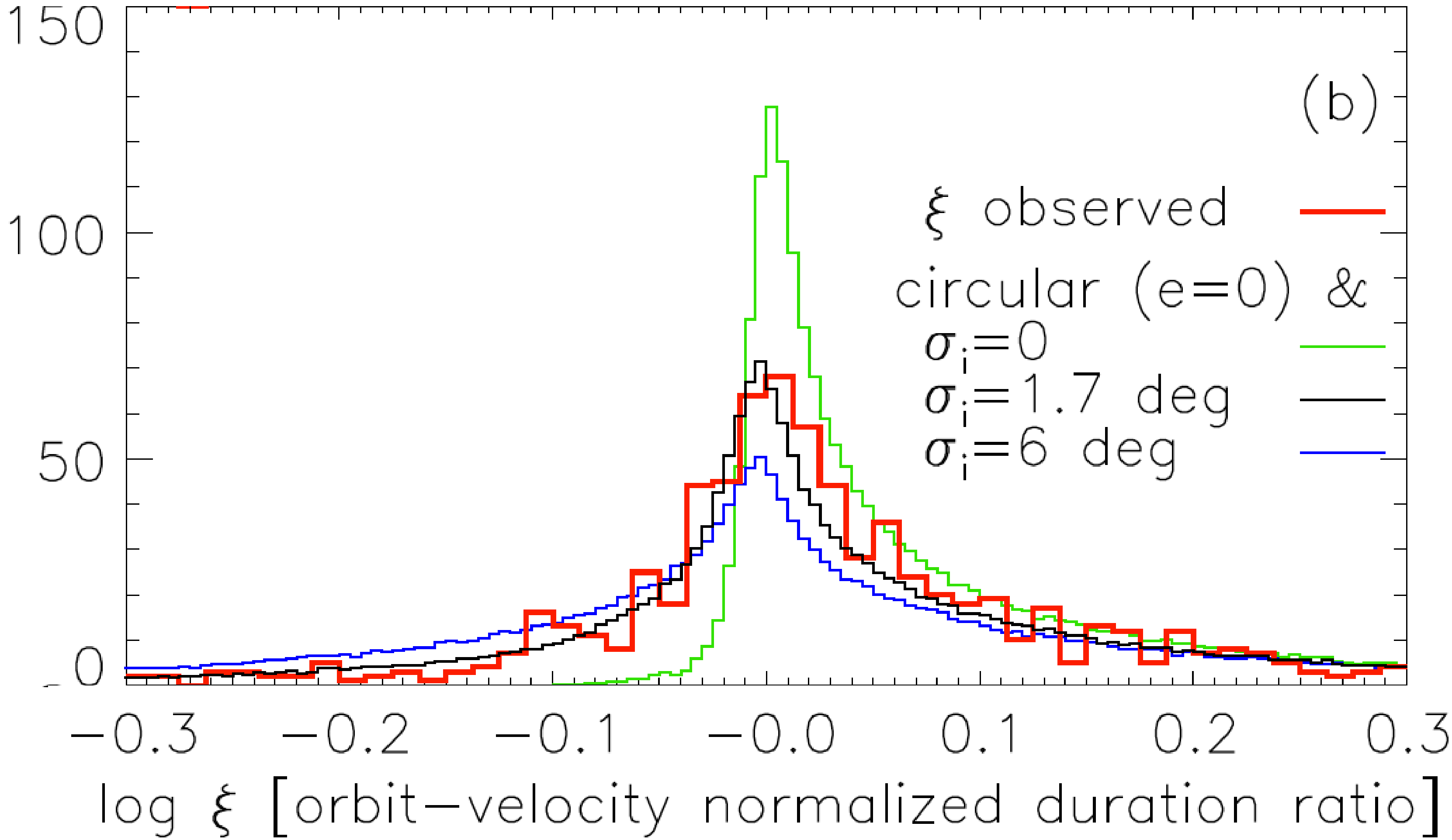
Modeling mutual inclinations



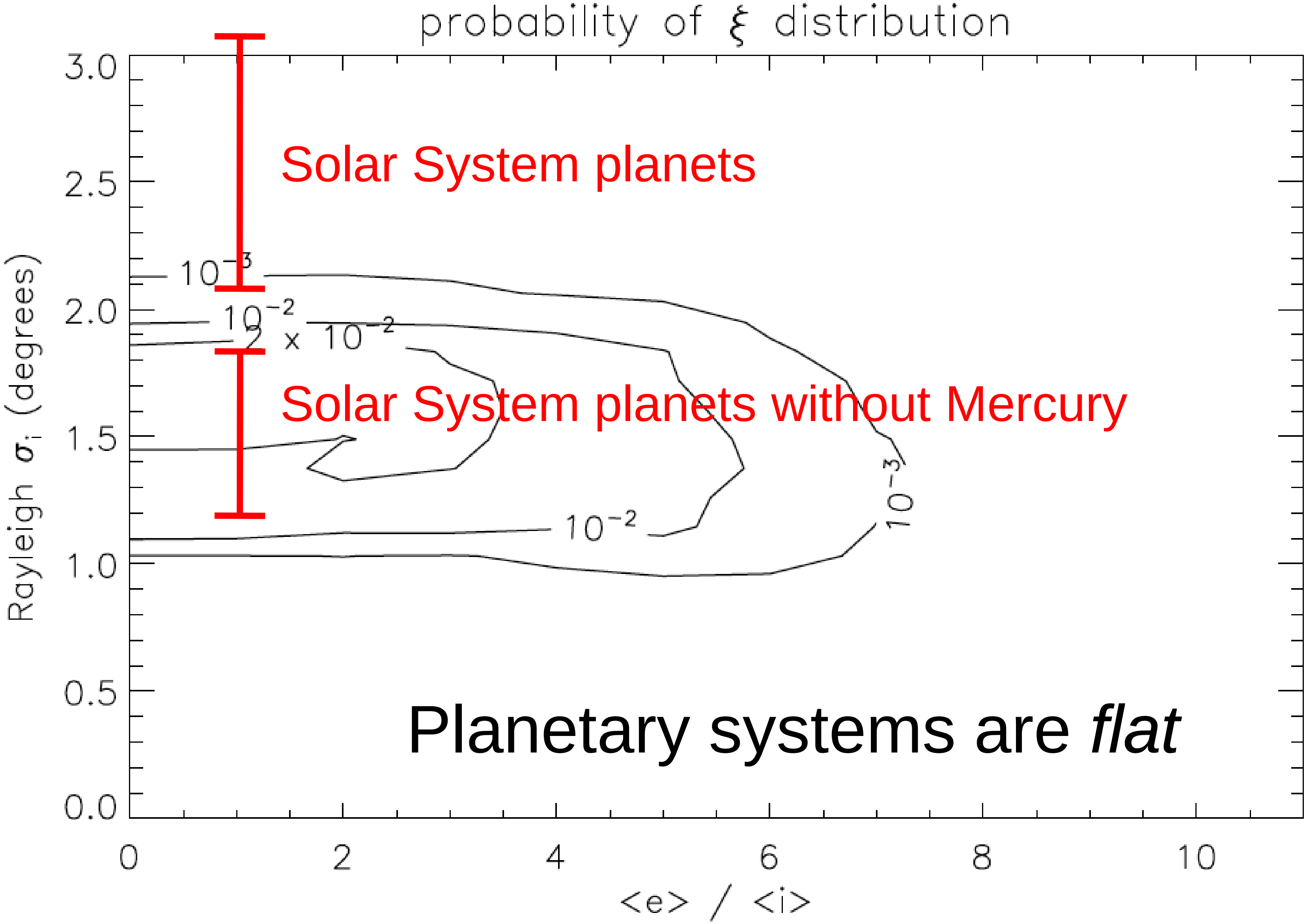
i is Rayleigh distributed width parameter σ_i

Fabrycky, Lissauer, Ragozzine et al. 2012

Fitting Results

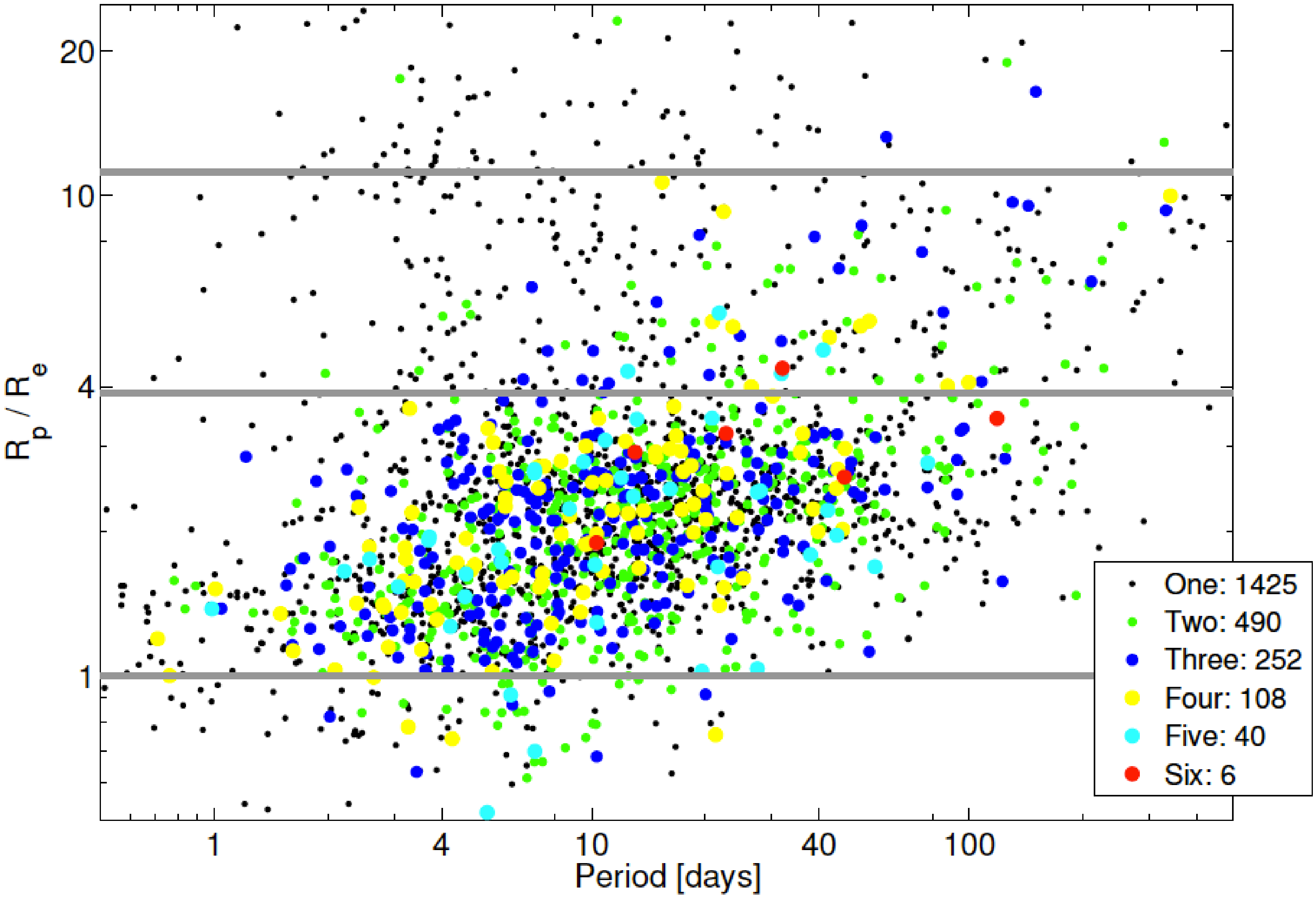


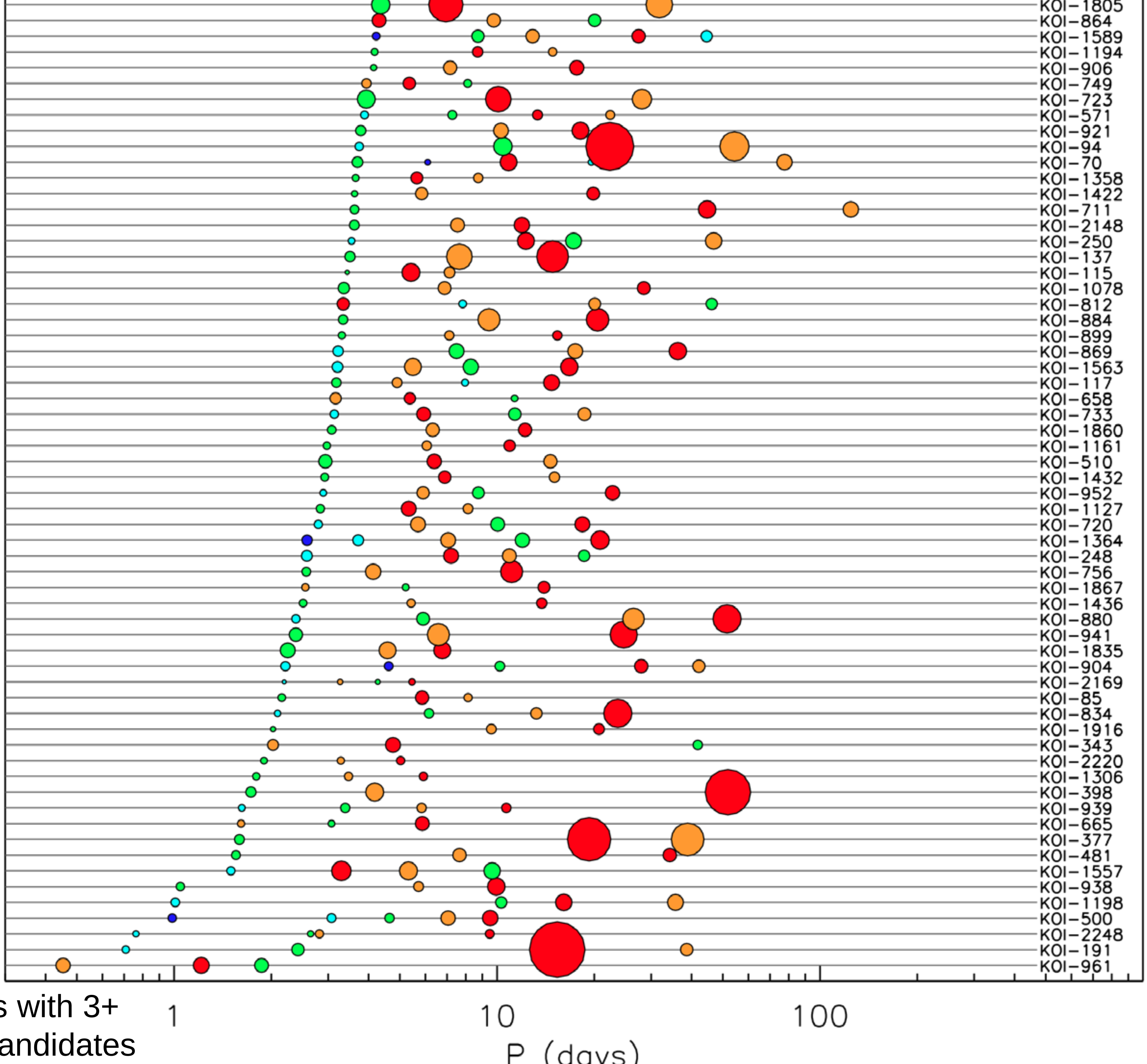
Fabrycky, Lissauer, Ragozzine et al. 2012



Fabrycky, Lissauer, Ragozzine et al. 2012

Planet Candidate Catalog (Batalha et al. 2012)



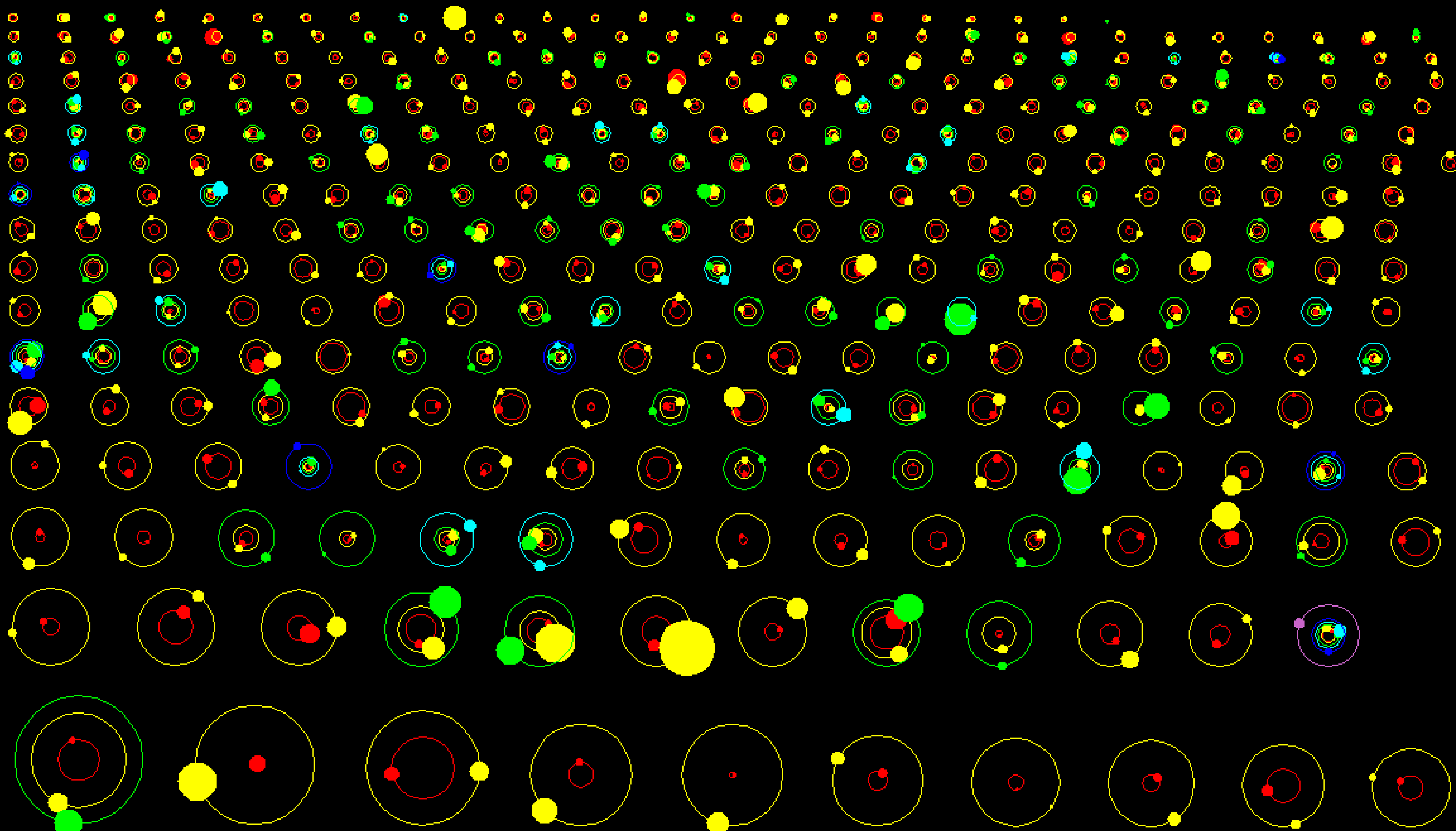


Systems with 3+
planet candidates

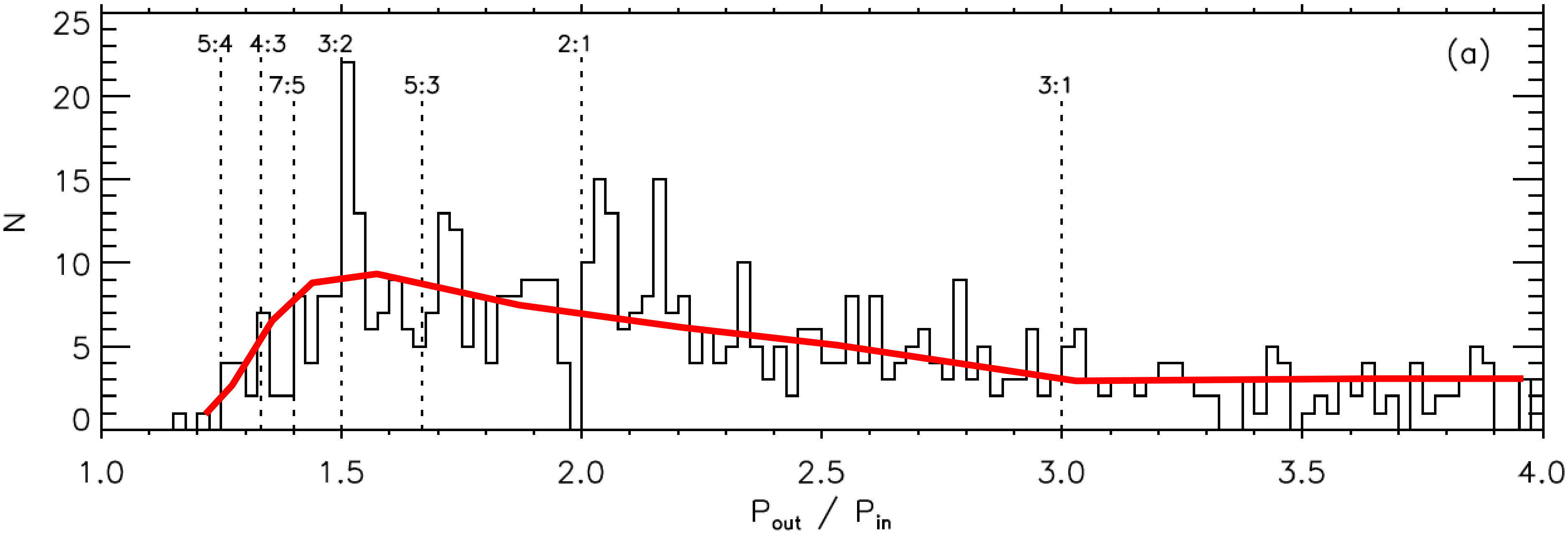
The Kepler Orrery II

t[BJD] = 2454965

D. Fabrycky 2012

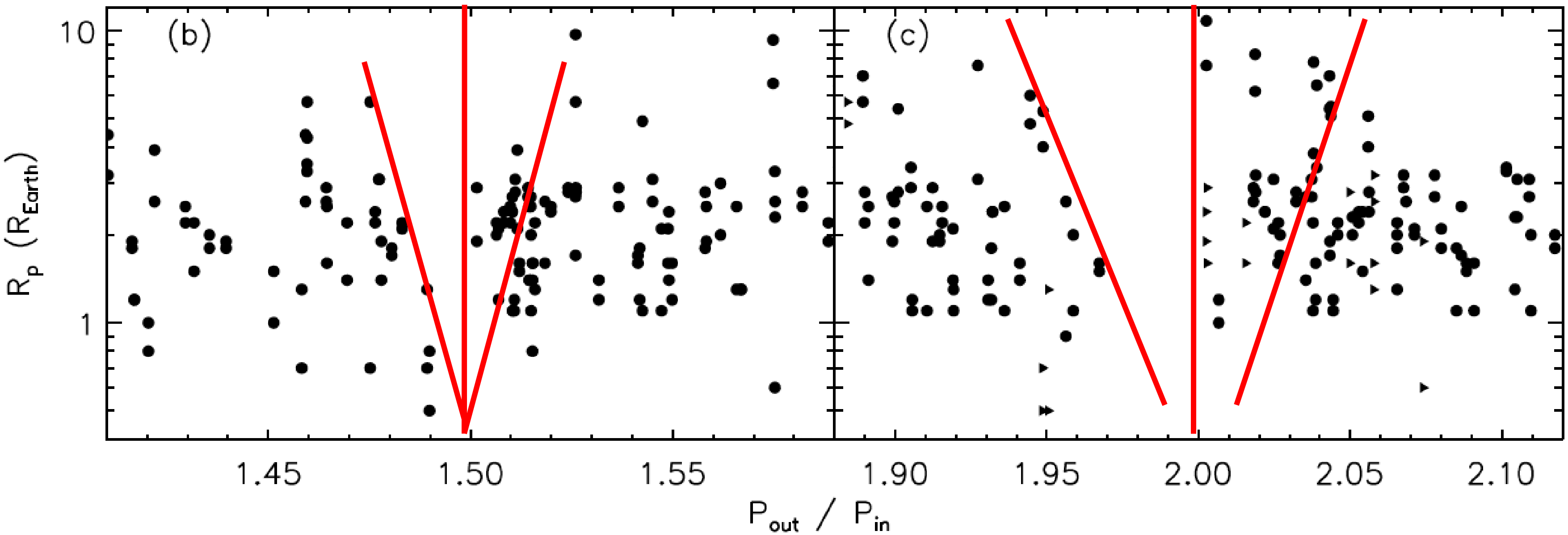


Period ratios



- Broad distribution – most pairs are non-resonant
- Factor-of-2 enhancements near 2:1 and 3:2 resonance
- Enhancement is on the *wide* side of the resonance

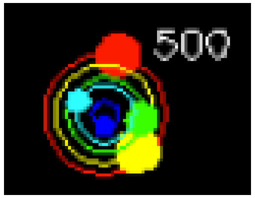
Near-resonance Features

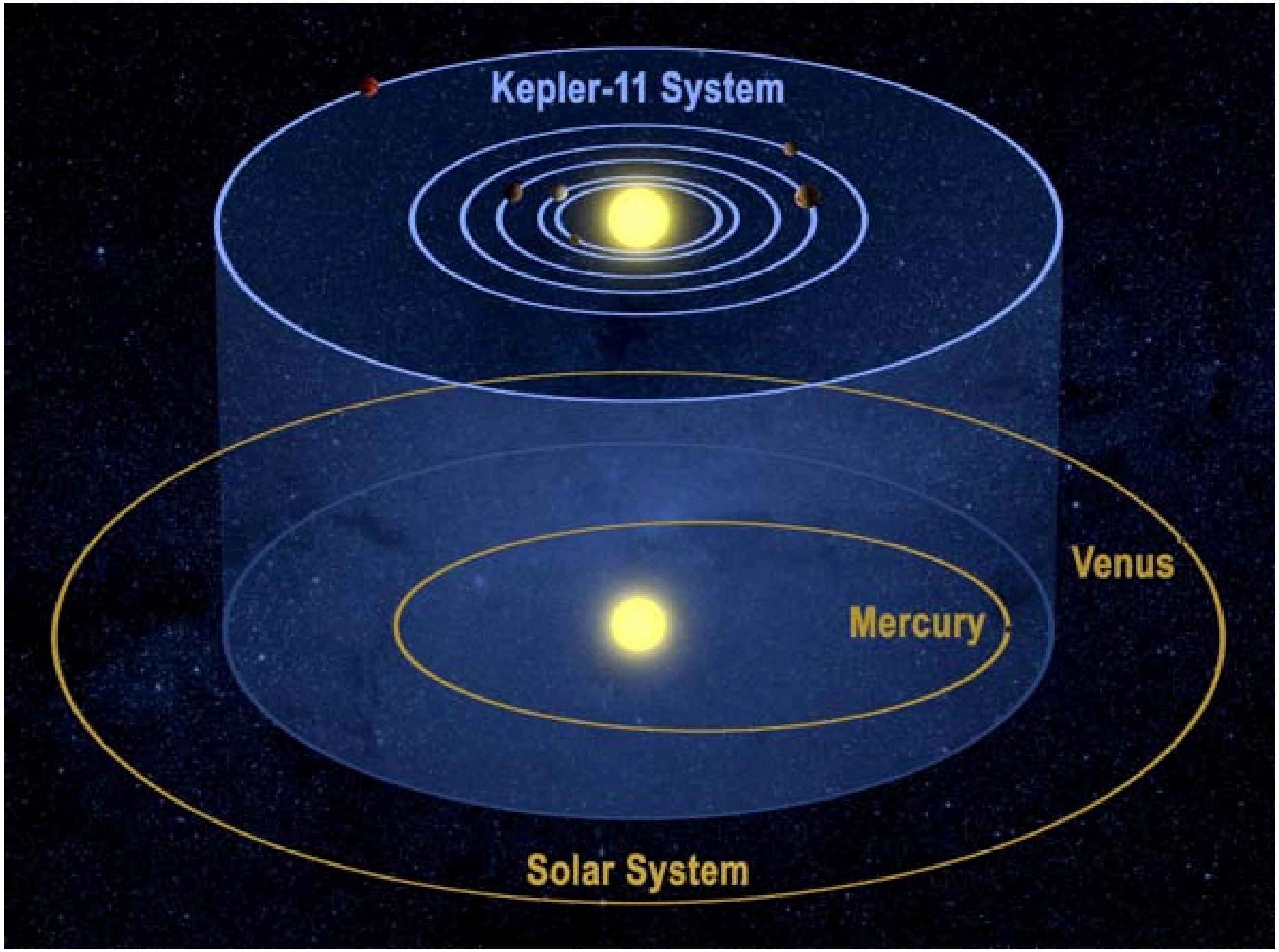


Gravitational effect? (a la Kirkwood gaps)
  pro: Gap seems to scale with planet radius (mass?)
  con: Gap is not symmetric about the resonance
Tidal repulsion?
  pro: Qualitative match to data
  con: Requires substantial tidal damping
  Prediction: Gap shrinks/vanishes farther from star

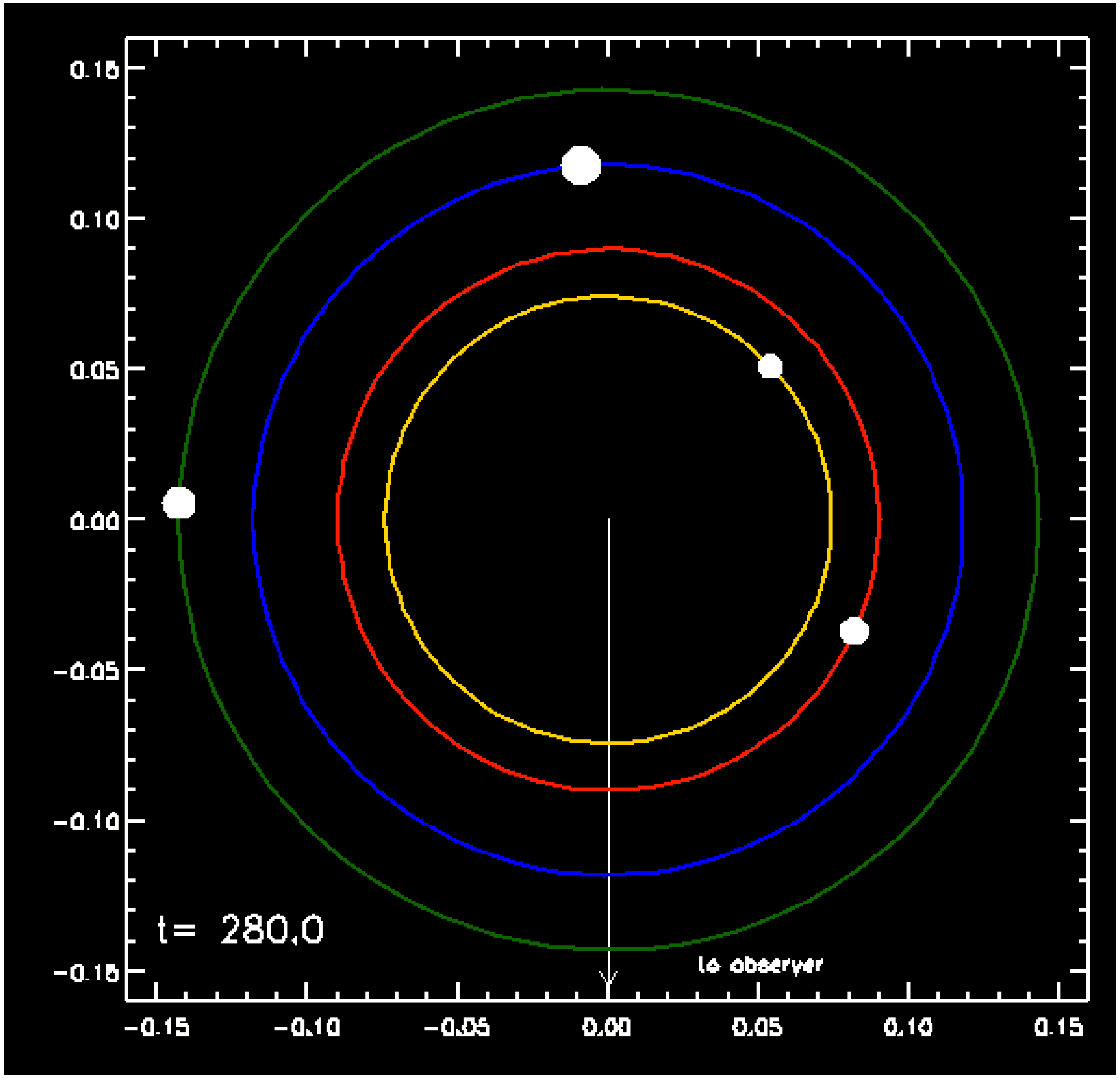
KOI-500

planet	P (days)	Mp(Mearth)
500.05	0.9867790	1.5
500.03	3.0721660	2.2
500.04	4.6453530	4.4
500.01	7.0534780	8.0
500.02	9.5216960	8.5





KOI-730: A Resonant 4-Planet System



P/P=1.33341(3)

P/P=1.50157(5)

P/P=1.33411(8)

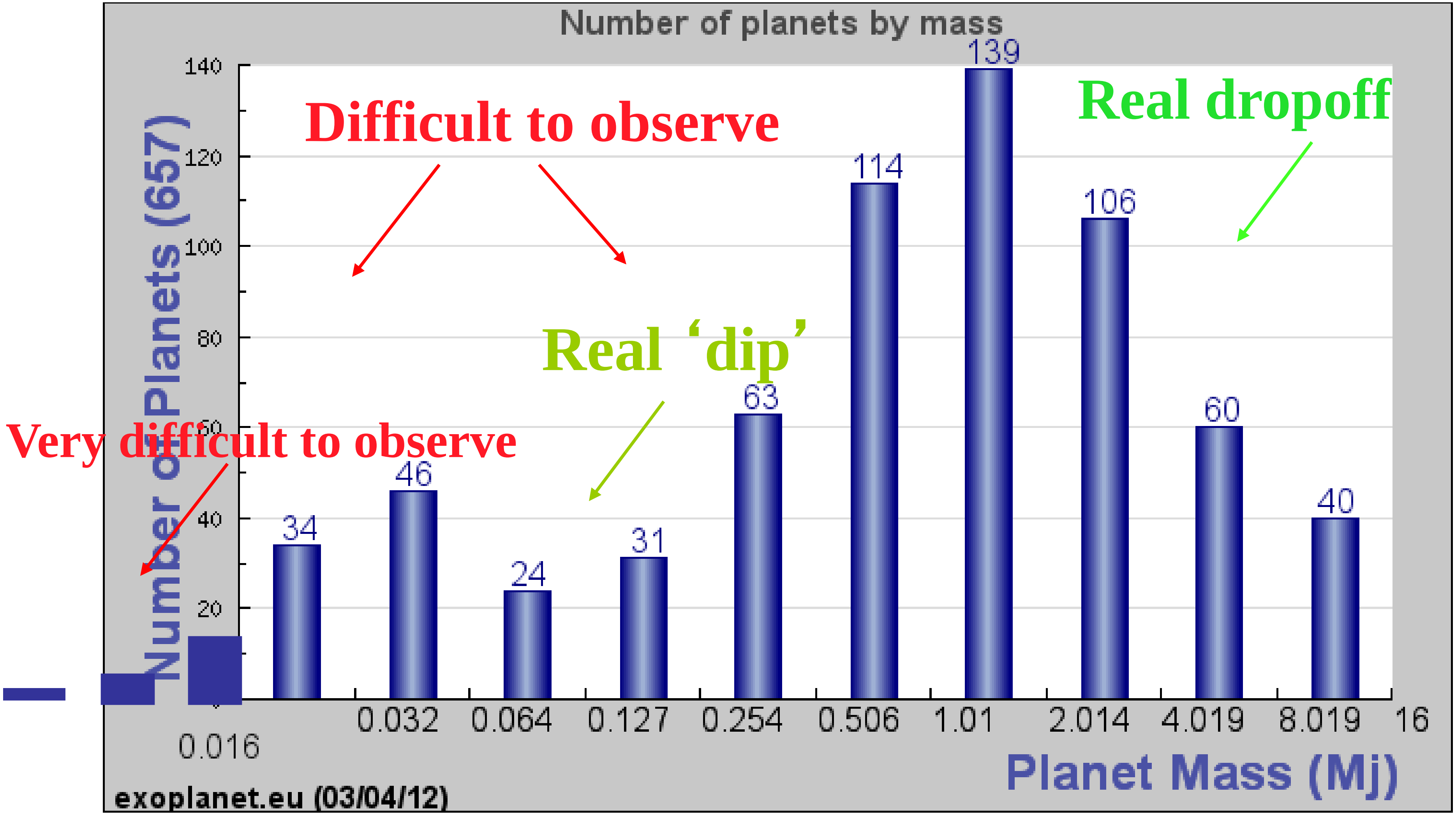
Fabrycky et al., in prep

Kepler, the Multiple-Transiting Planet Machine

- Multiplanets are now on a firm statistical footing
- New types of planetary systems

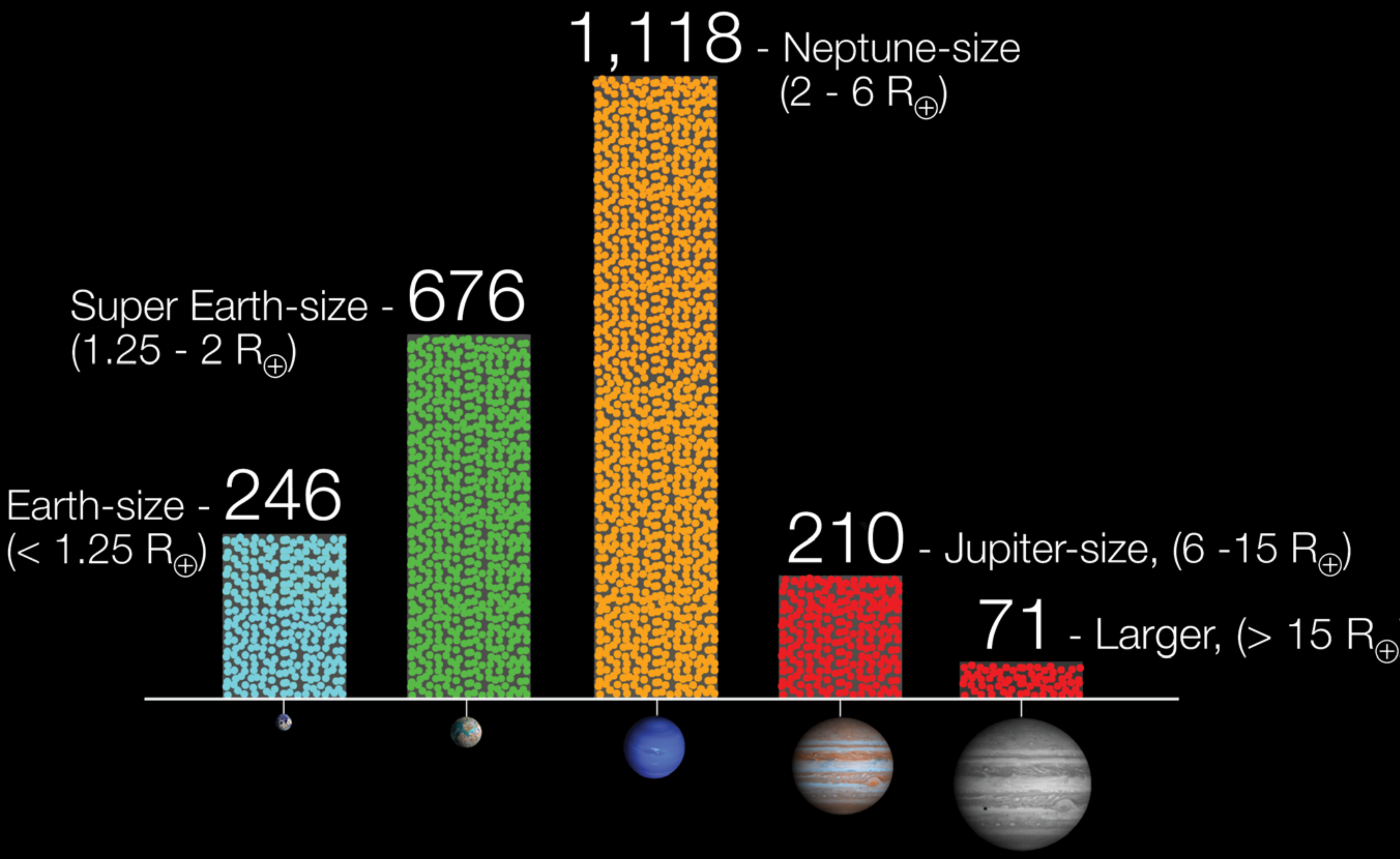
  (extremely compact, multi-resonant)
- Multiple-transits allow for the easy interpretation of transit timing variations (TTV)

Mass Distribution of RV Planets

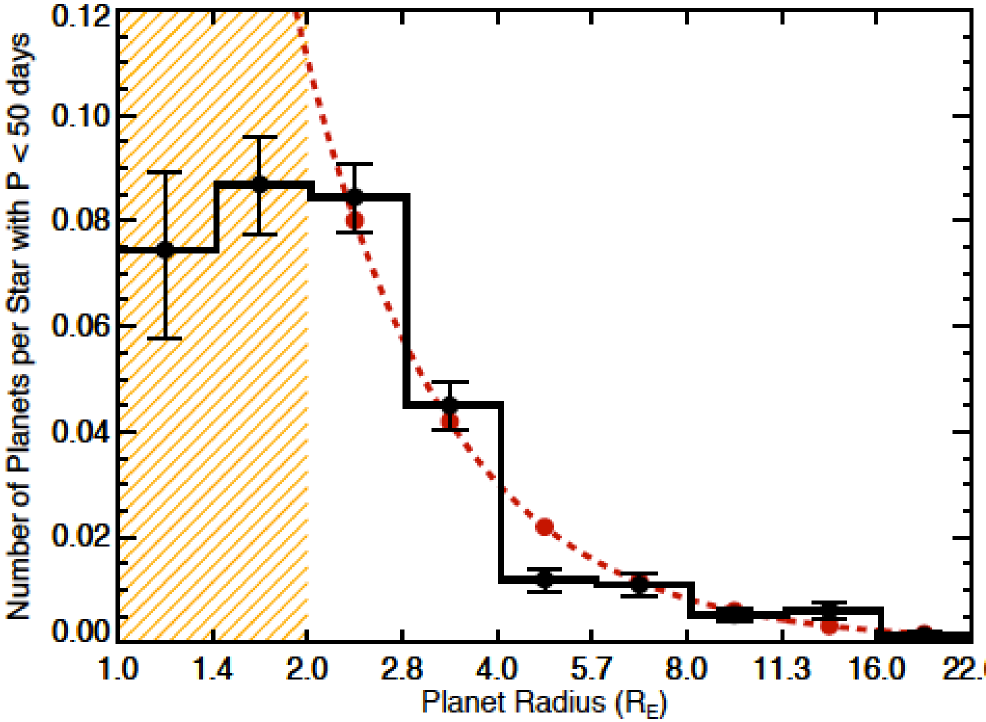


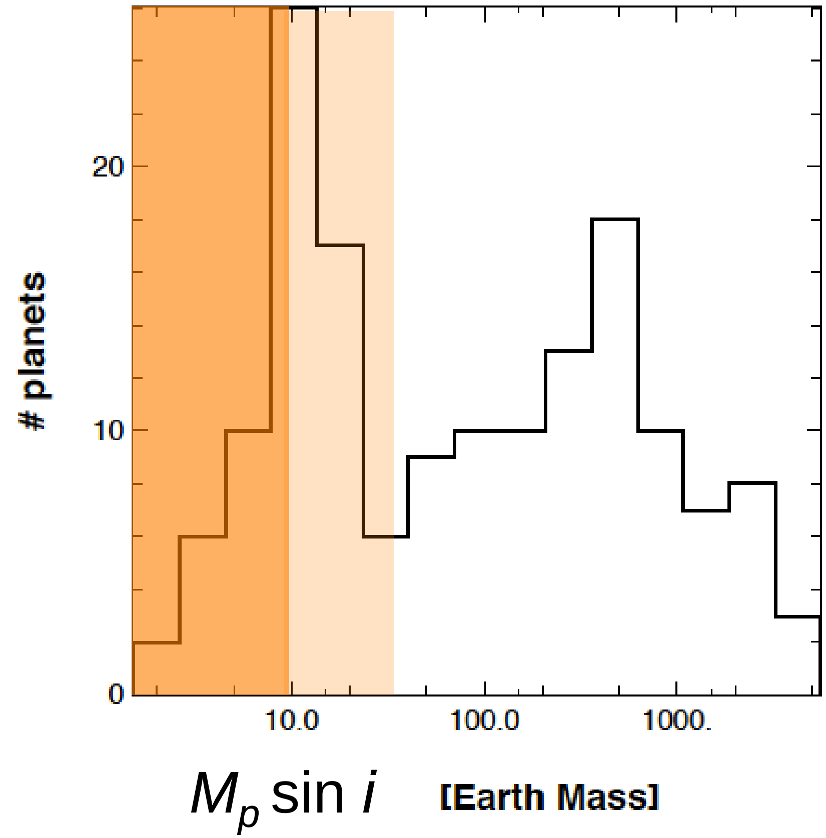
Sizes of Planet Candidates

As of February 27, 2012



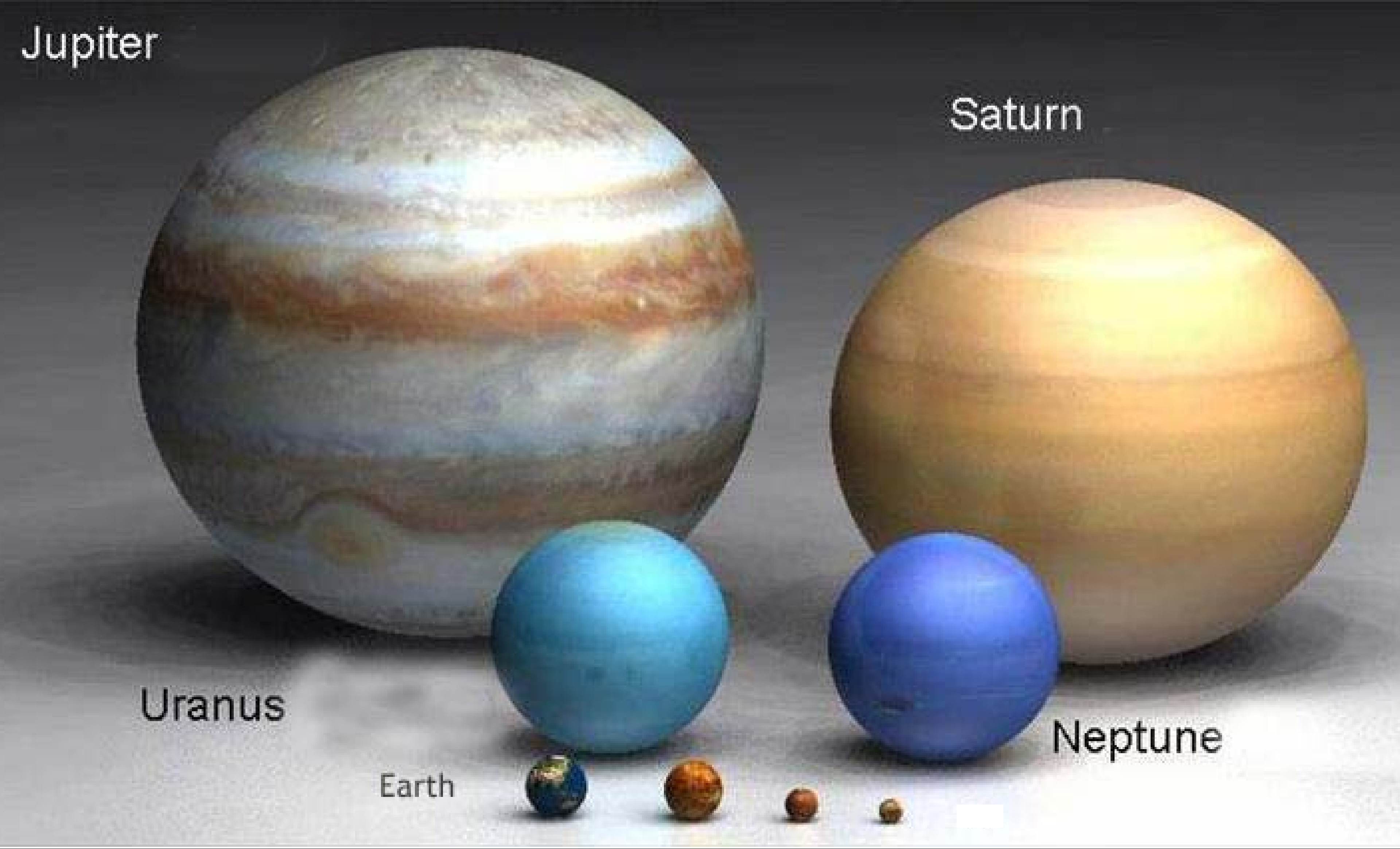
Small planets are numerous





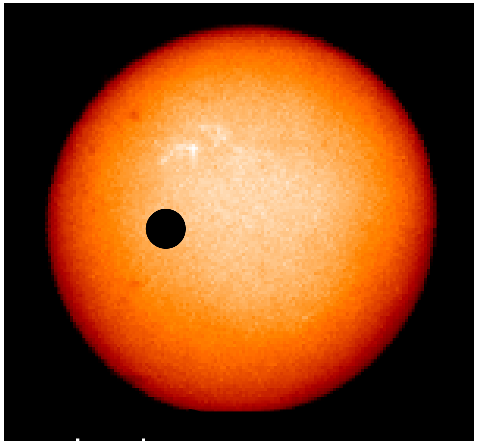
Transits/Kepler
(Howard et al. 2011)

Doppler/HARPS
(Mayor et al. 2011)

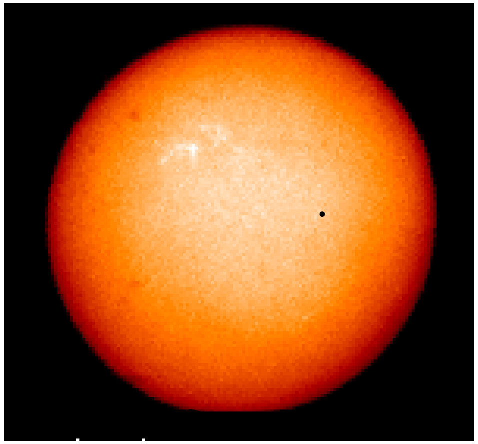

Jupiter
Saturn
Uranus
Neptune
Earth

DETECTING EARTH-SIZE PLANETS

- The relative change in brightness ($\Delta L / L$) is equal to the relative areas (A_{planet}/A_{star})



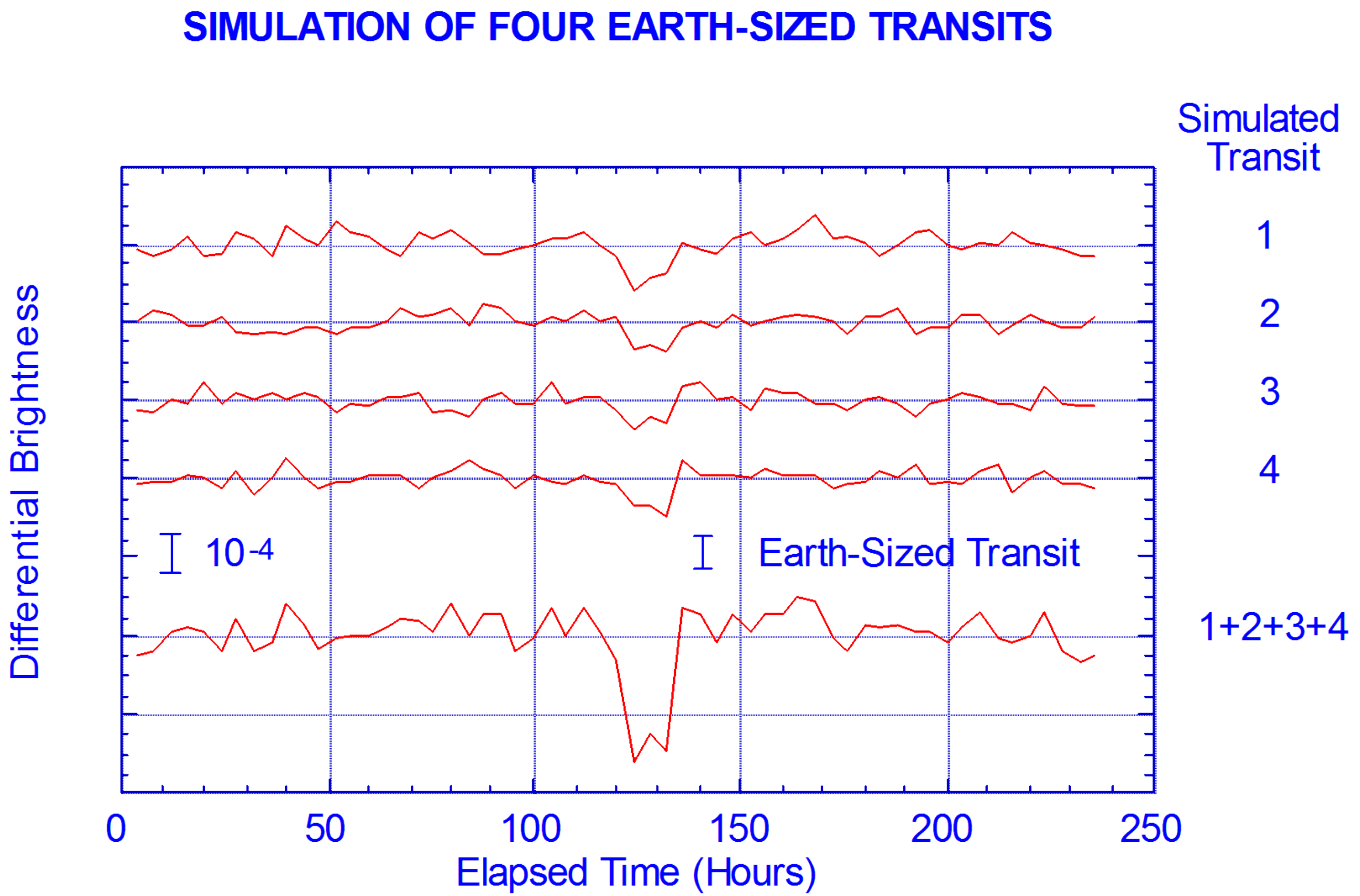
Jupiter:
1% area of the Sun (1/100)



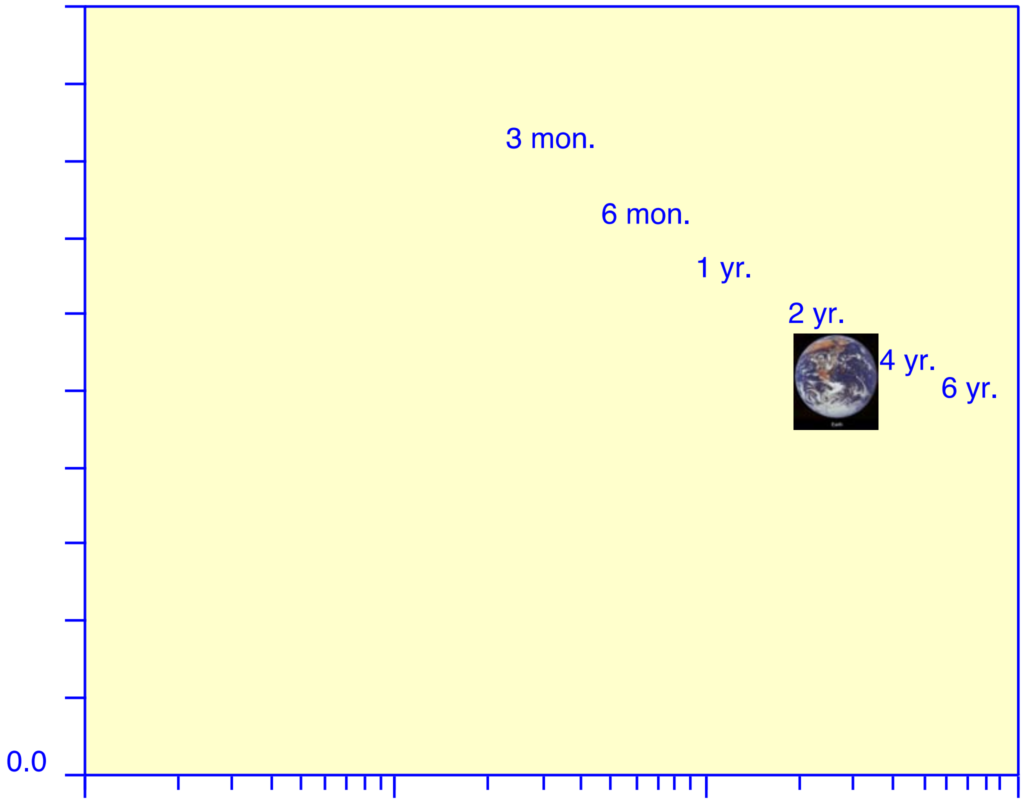
Earth or Venus
0.01% area of the Sun (1/10,000)

- To measure 0.01% must get above the Earth's atmosphere
- Method is robust but you must be patient:

  Require at least 3 transits preferably 4 with same brightness change, duration (how long the star is dimmer) and period (time between dimmings)

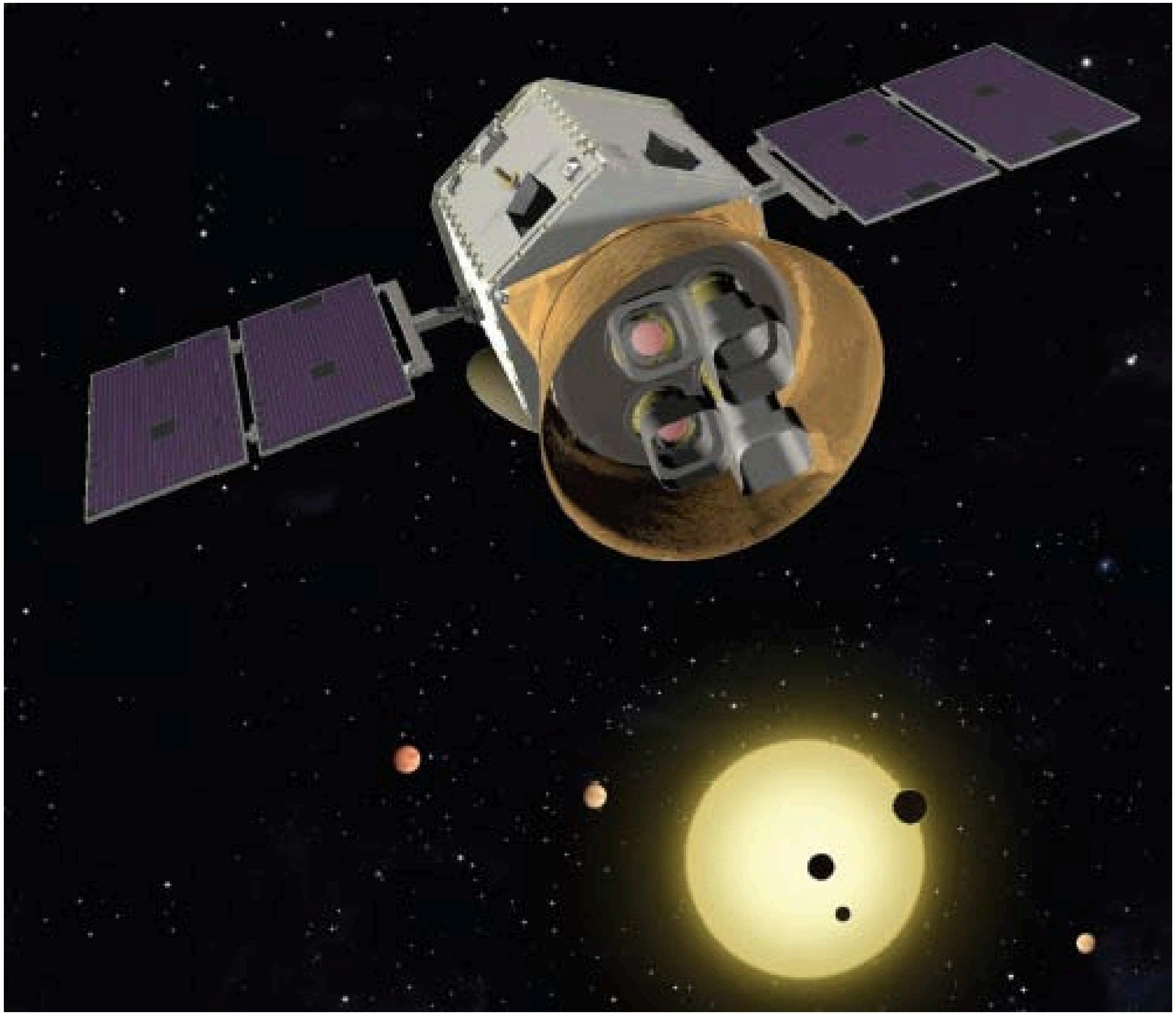

SIMULATION OF FOUR EARTH-SIZED TRANSITS
Simulated Transit
1
2
3
4
1+2+3+4
10-4
Earth-Sized Transit
Differential Brightness
0
50
100
150
200
250
Elapsed Time (Hours)

Kepler Capabilities



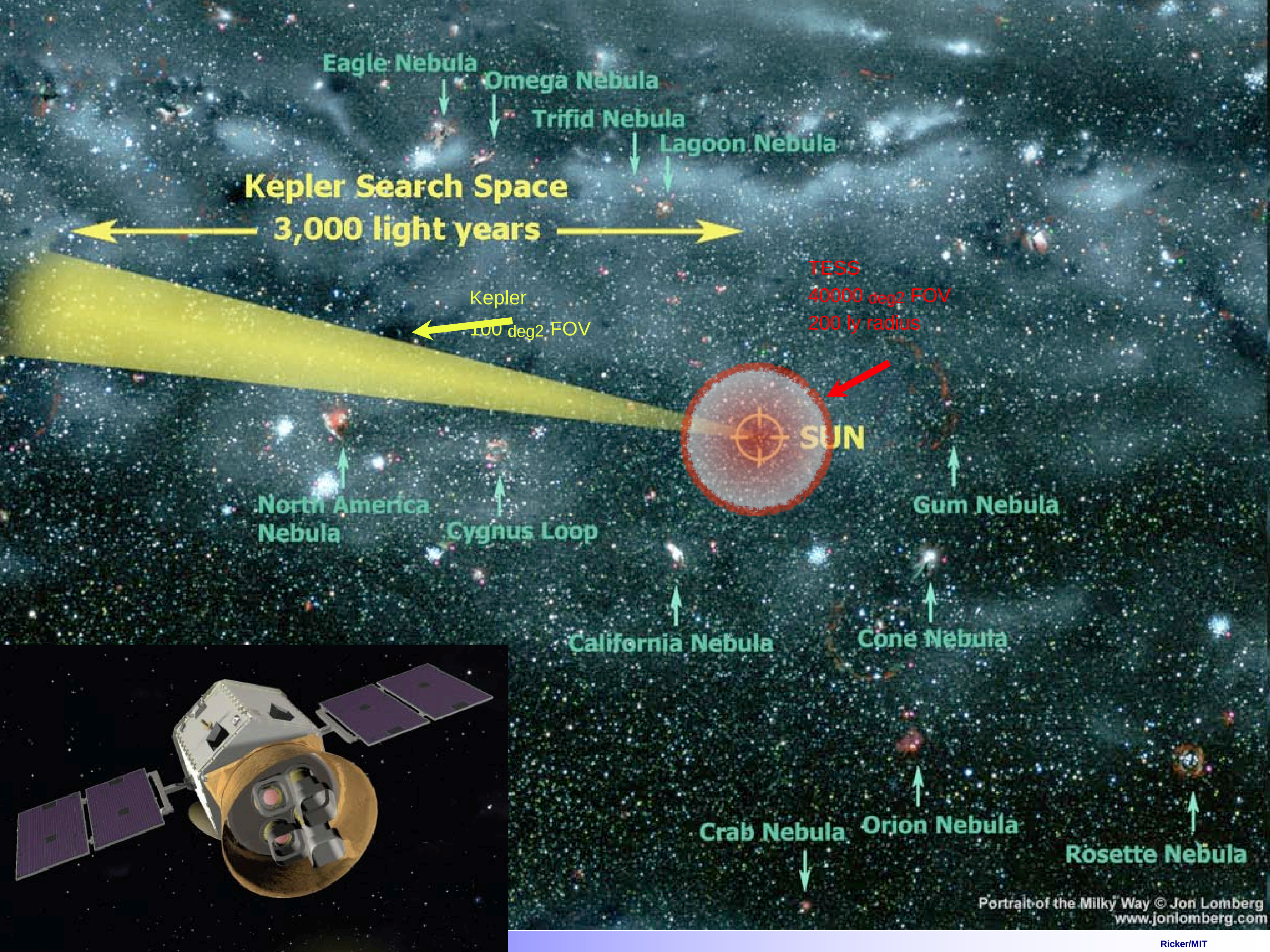
The minimum detectable planet size versus planetary orbital period for a 12th magnitude solar-like star (G2), a CDPP of 20 ppm and ≥4 half-maximum transits.

(Ref: Koch et al, , Overview and Status of the *Kepler Mission,* SPIE Conf **5487**, 1491-1500 *Optical, Infrared, and Millimeter Space Telescopes,* J. Mather ed., Glasgow, Scotland, 2004)



Transiting Exoplanet Survey Satellite (TESS)

- **Adapted from Presentation by**
- George Ricker, on behalf of the TESS Science Team

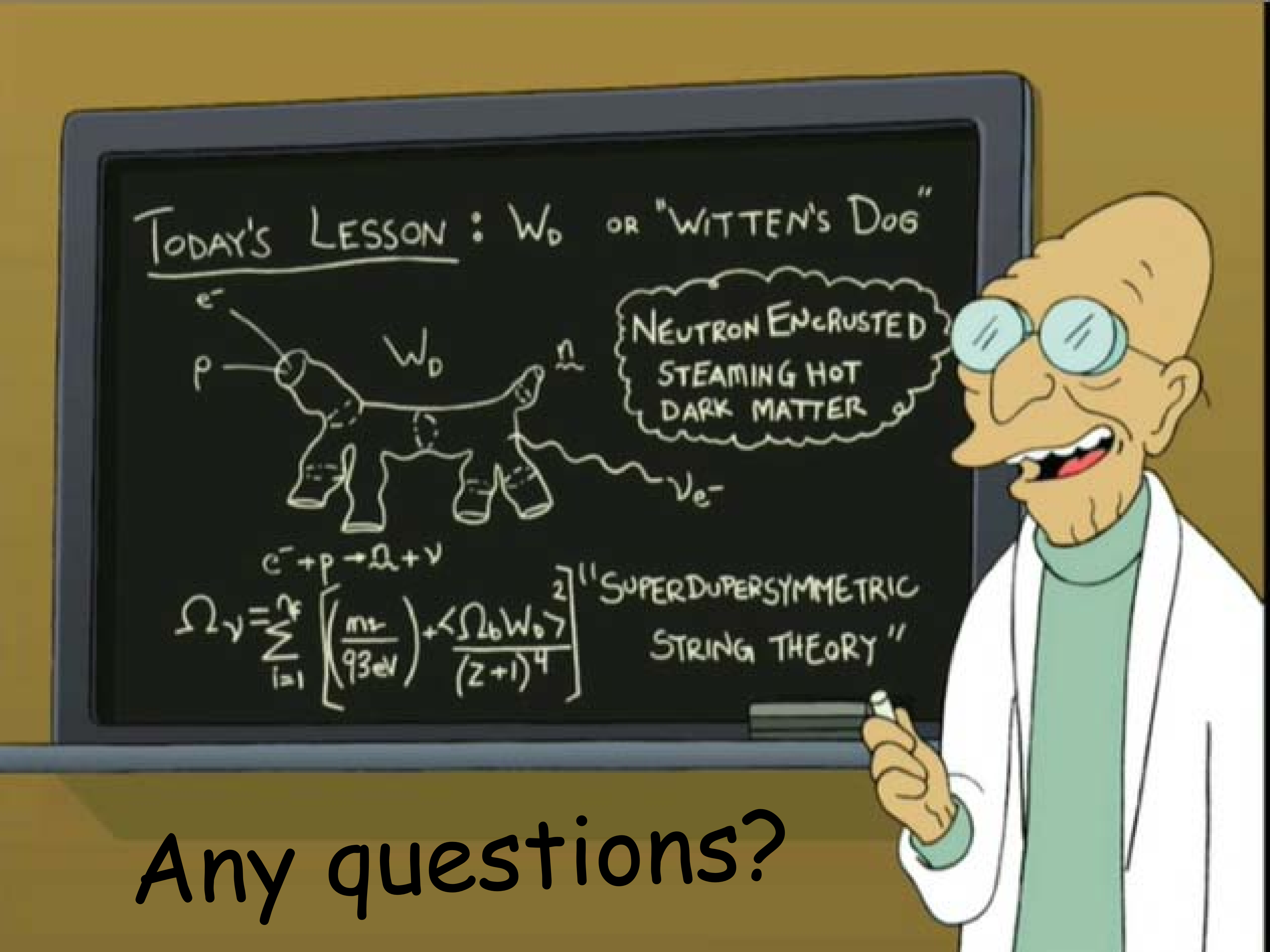

Eagle Nebula
Omega Nebula
Trifid Nebula
Lagoon Nebula
Kepler Search Space
3,000 light years
Kepler
100 deg2 FOV
TESS
40000 deg2 FOV
200 ly radius
SUN
North America Nebula
Cygnus Loop
Gum Nebula
California Nebula
Cone Nebula
Crab Nebula
Orion Nebula
Rosette Nebula
Portrait of the Milky Way © Jon Lomberg
www.jonlomberg.com

Conclusions

365 Kepler targets have 2 or more planet candidates (897 candidates)

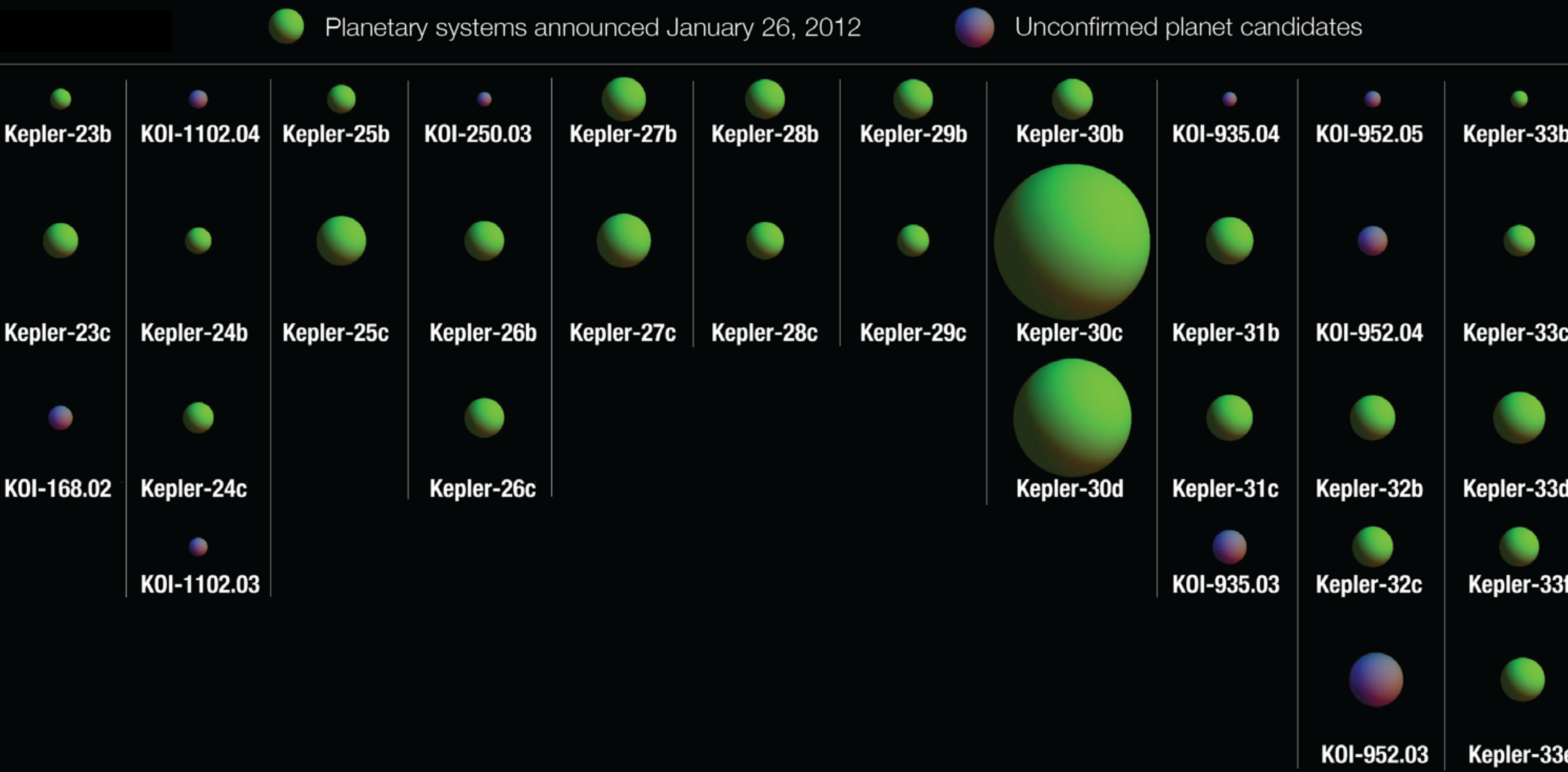
These multi-planet systems tell us a great deal about the architecture of planetary systems

Kepler-11 is supercalifragilisticexpialidocious

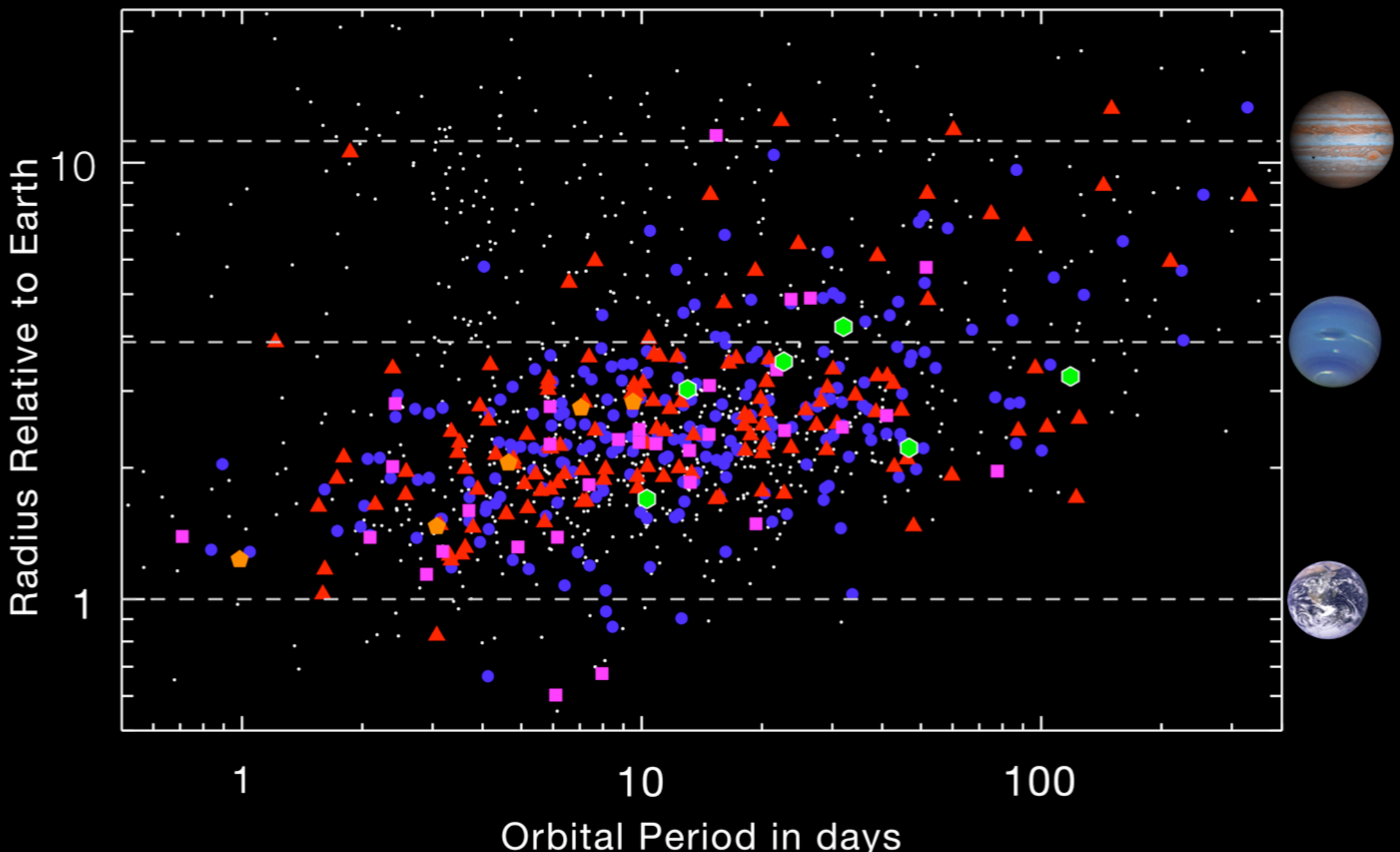


Any questions?

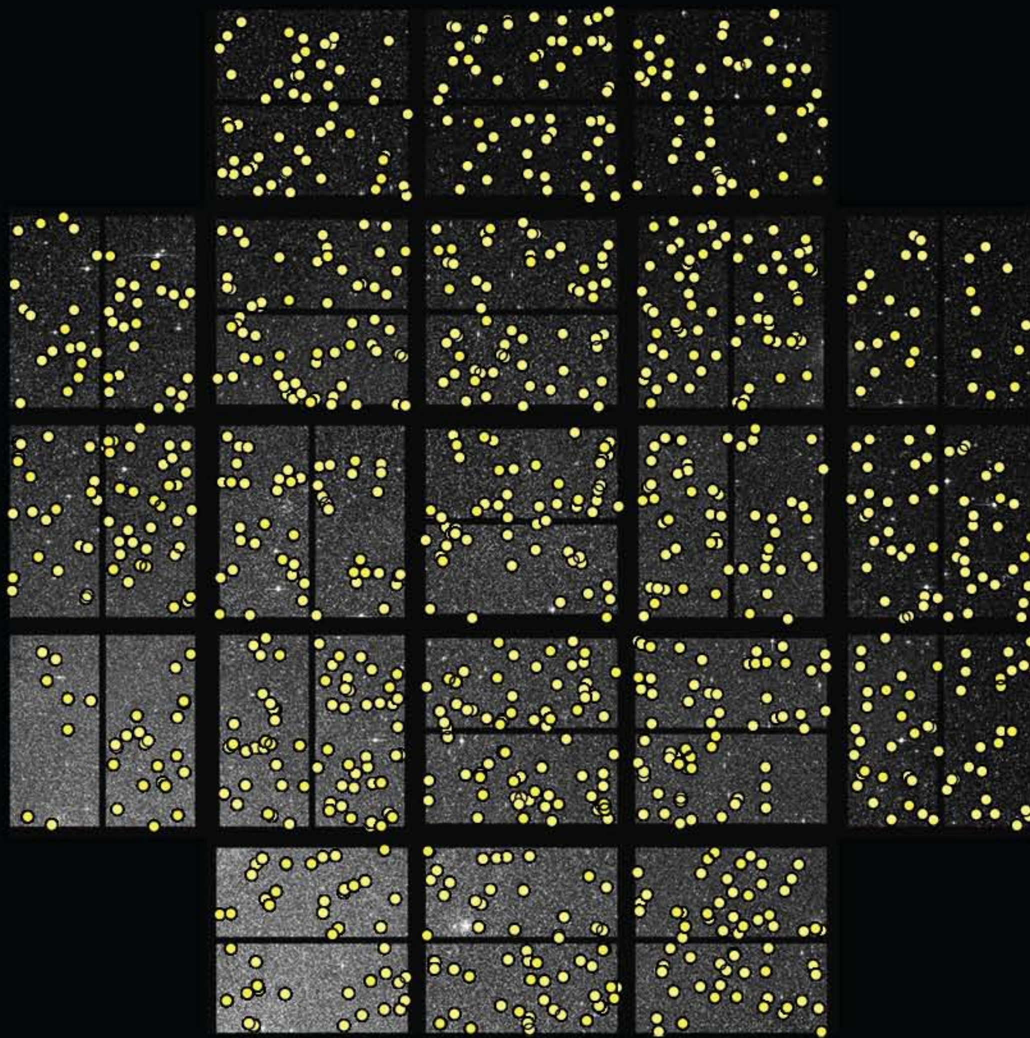
Kepler’s Transiting Planet System


Planetary systems announced January 26, 2012
Unconfirmed planet candidates
Kepler-23b
Kepler-23c
KOI-168.02
KOI-1102.04
Kepler-24b
Kepler-24c
KOI-1102.03
Kepler-25b
Kepler-25c
KOI-250.03
Kepler-26b
Kepler-26c
Kepler-27b
Kepler-27c
Kepler-28b
Kepler-28c
Kepler-29b
Kepler-29c
Kepler-30b
Kepler-30c
Kepler-30d
KOI-935.04
Kepler-31b
Kepler-31c
KOI-935.03
KOI-952.05
KOI-952.04
Kepler-32b
Kepler-32c
KOI-952.03
Kepler-33b
Kepler-33c
Kepler-33d
Kepler-33f
Kepler-33e

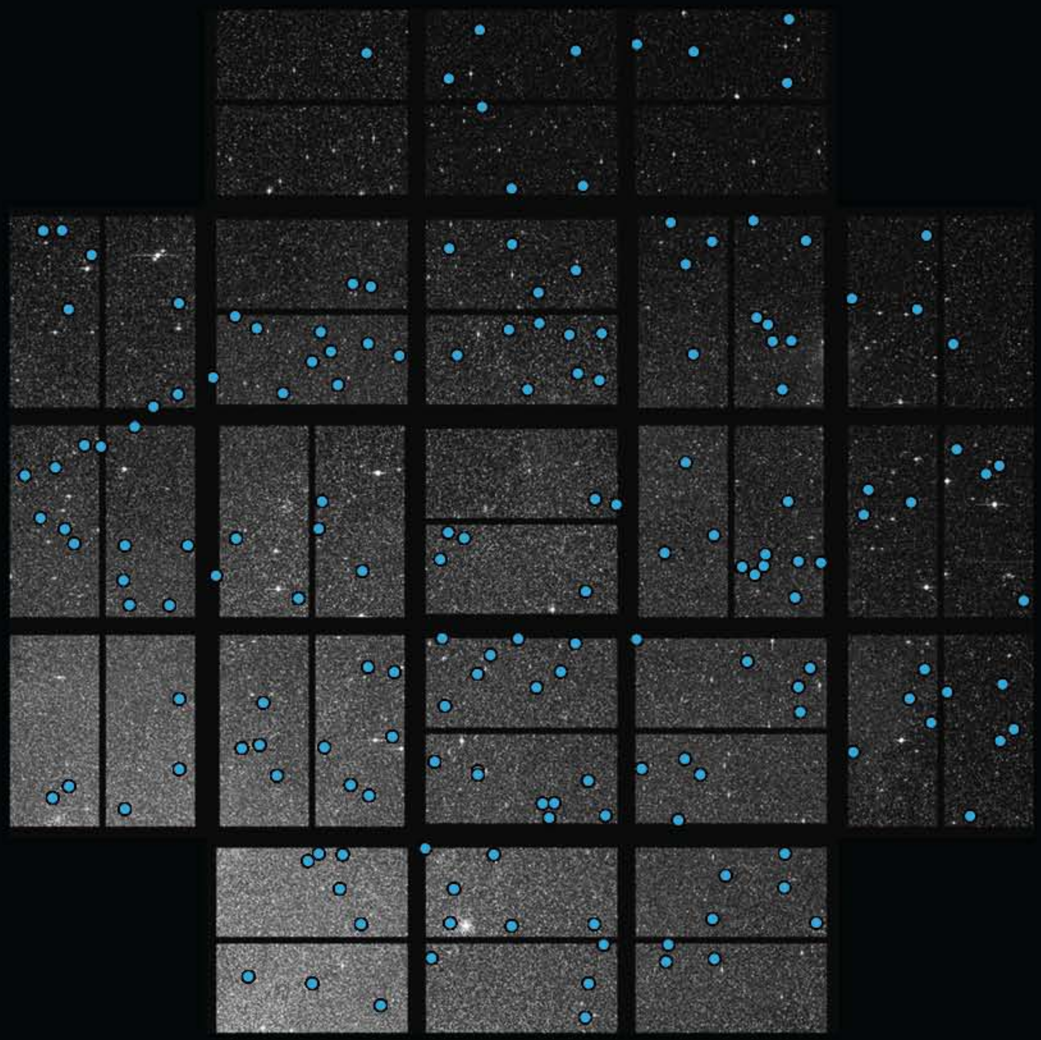
Candidate Multi-Planet Systems



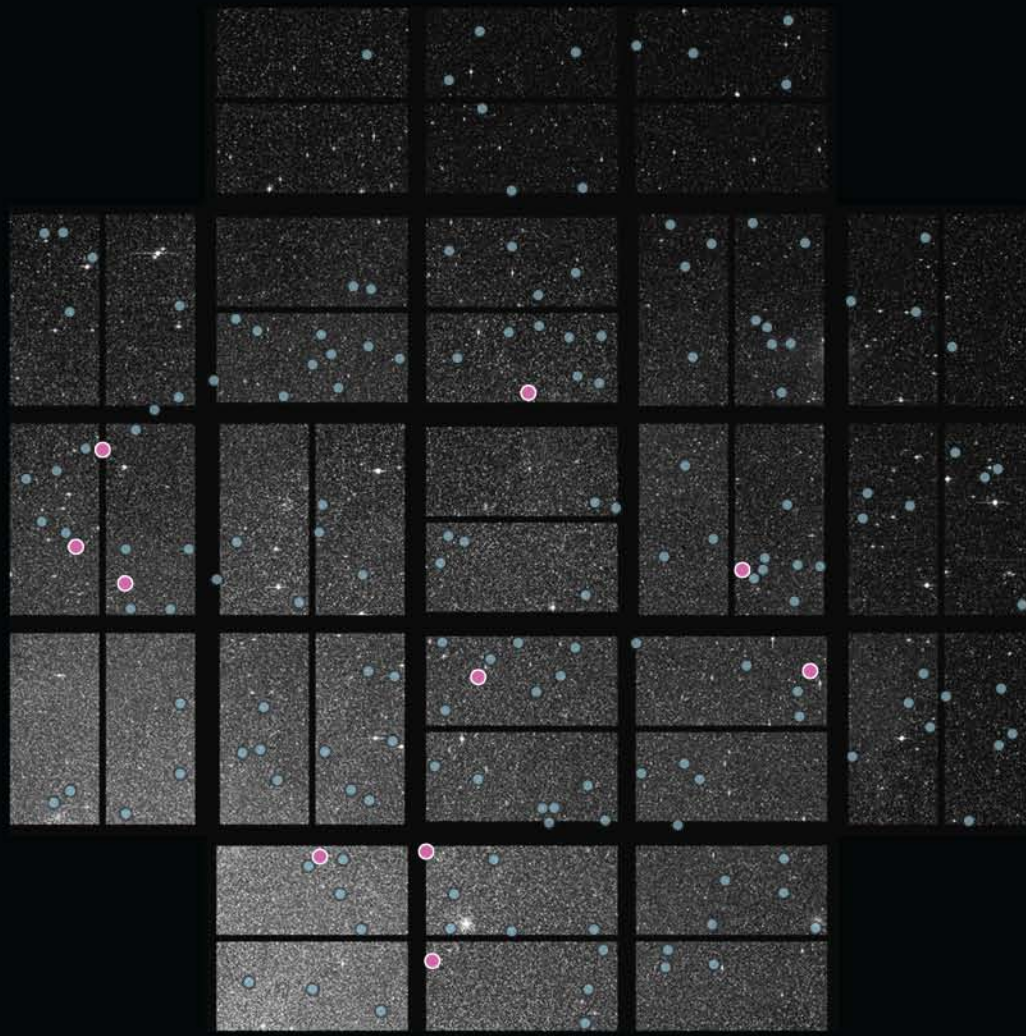
Kepler's 1,000+ Planet Candidates



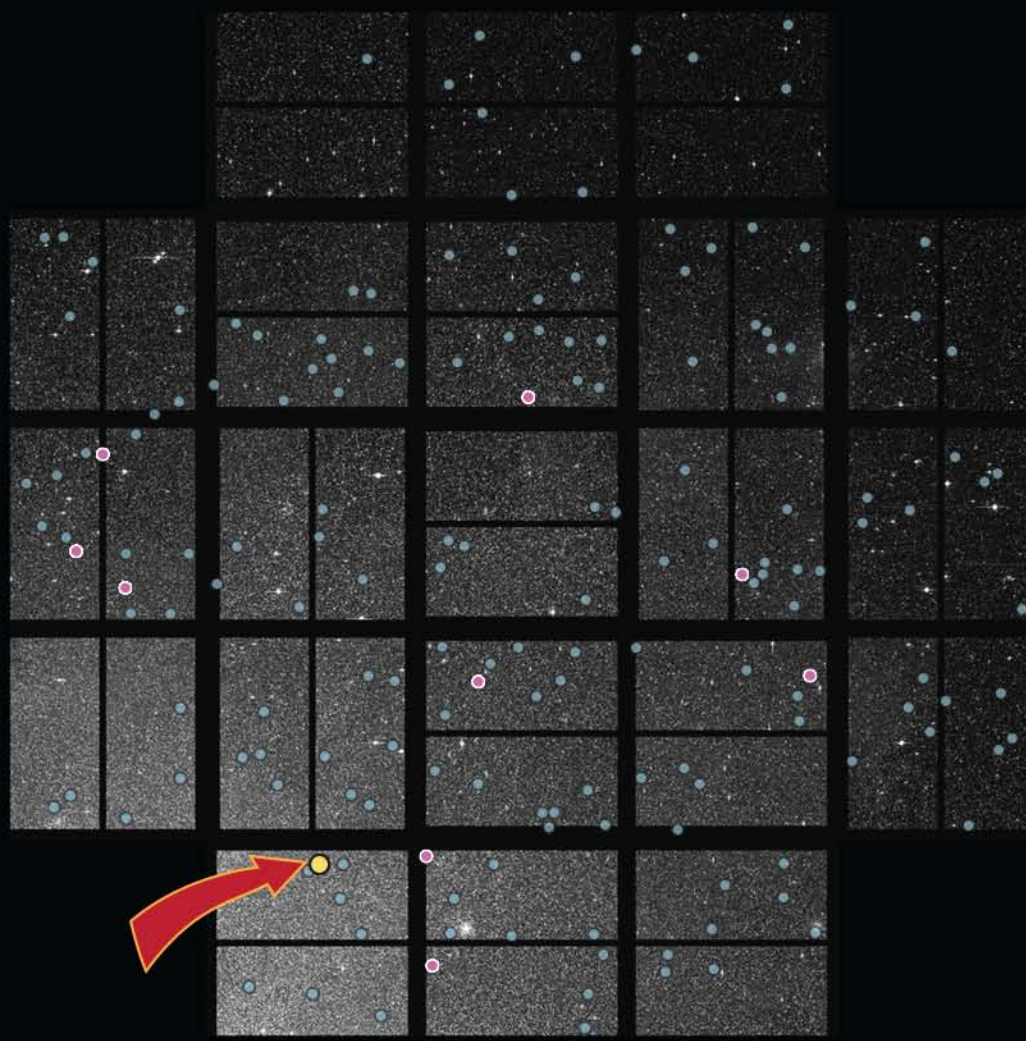
170 Targets With Multiple Candidates



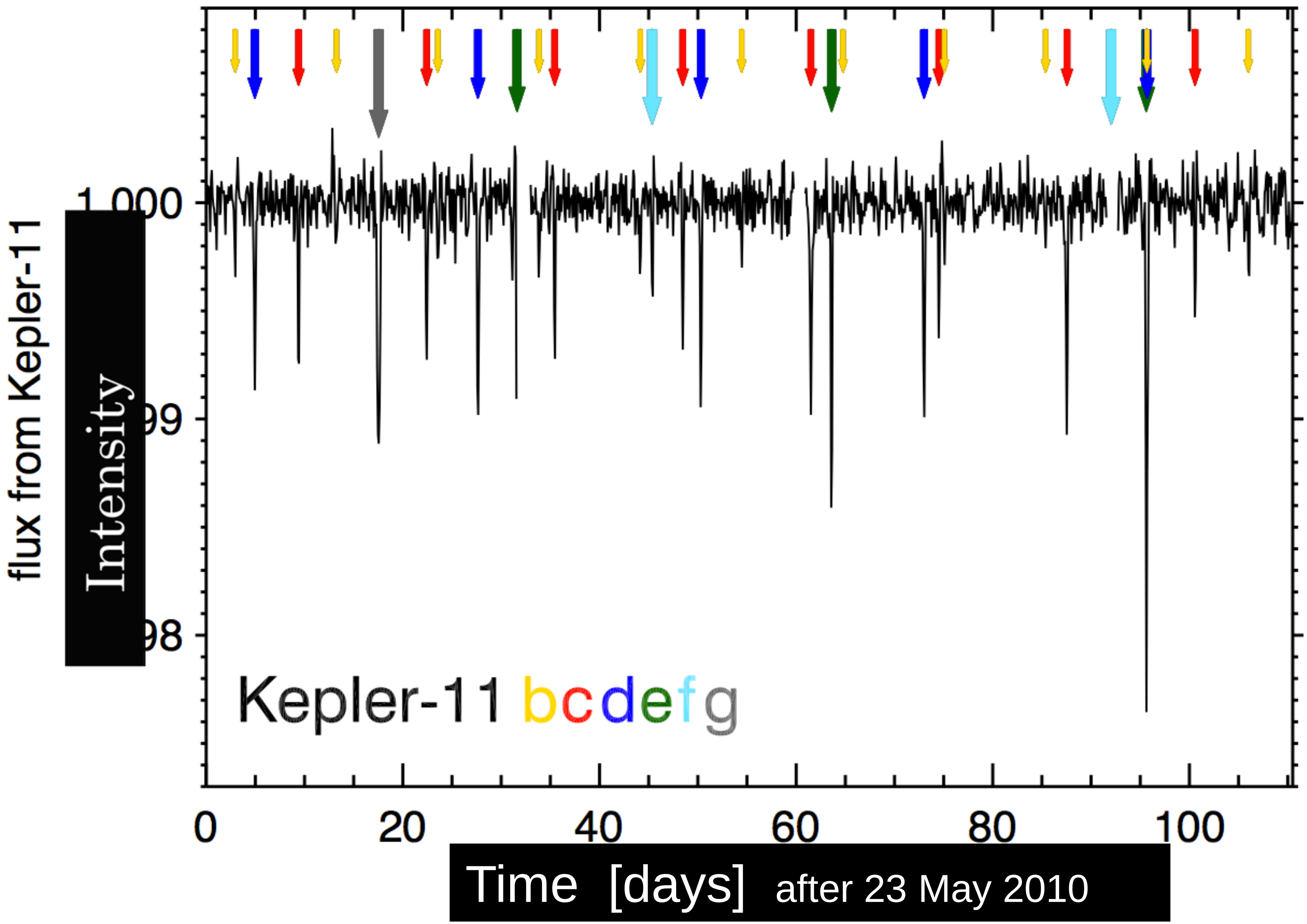
Targets With Four or More Candidates



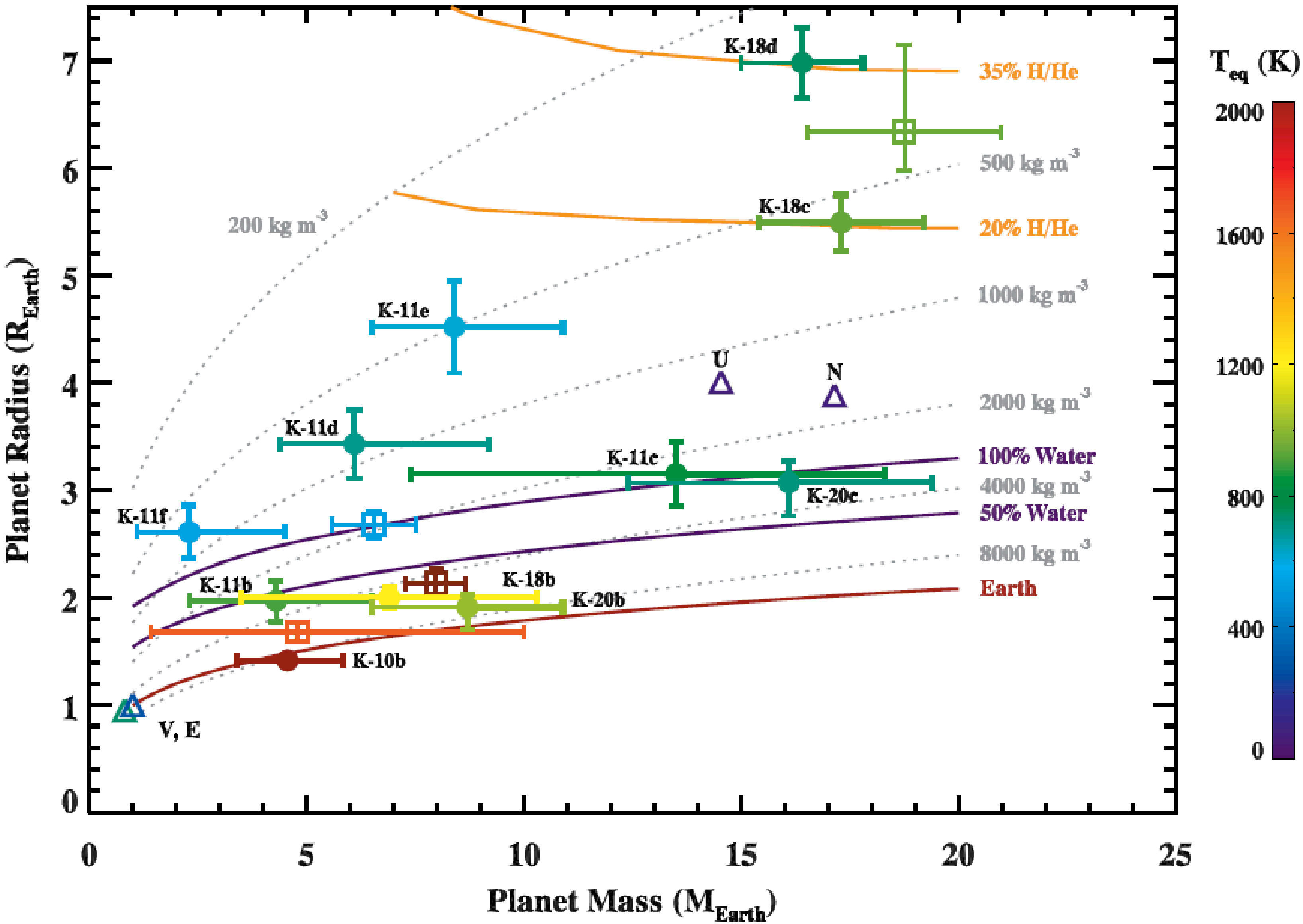
Kepler-11: Six Planets



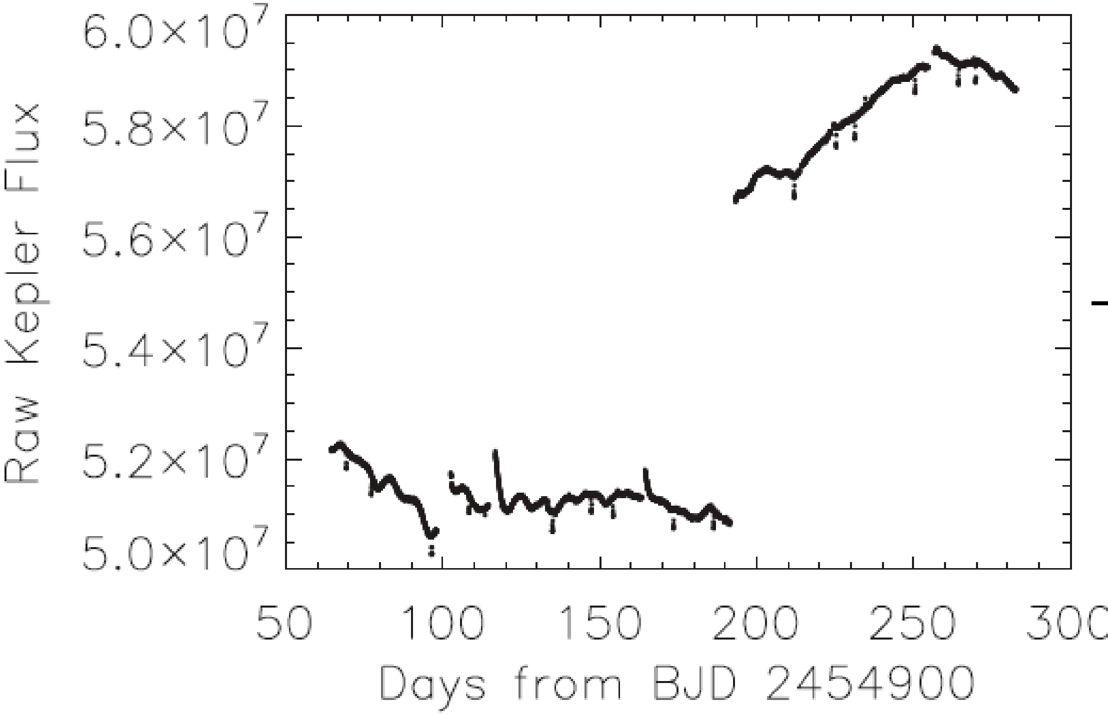
Kepler-11: Six Transiting Planets



Planet Mass-Radius Relationship



Confirming a planetary system

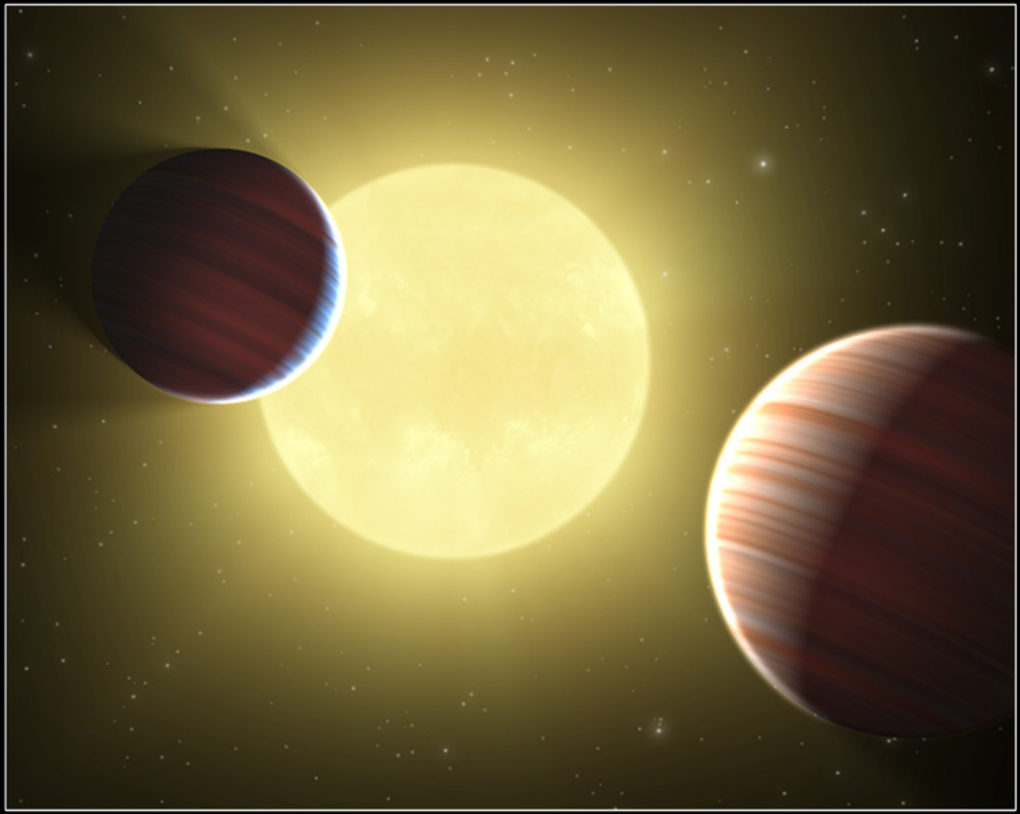


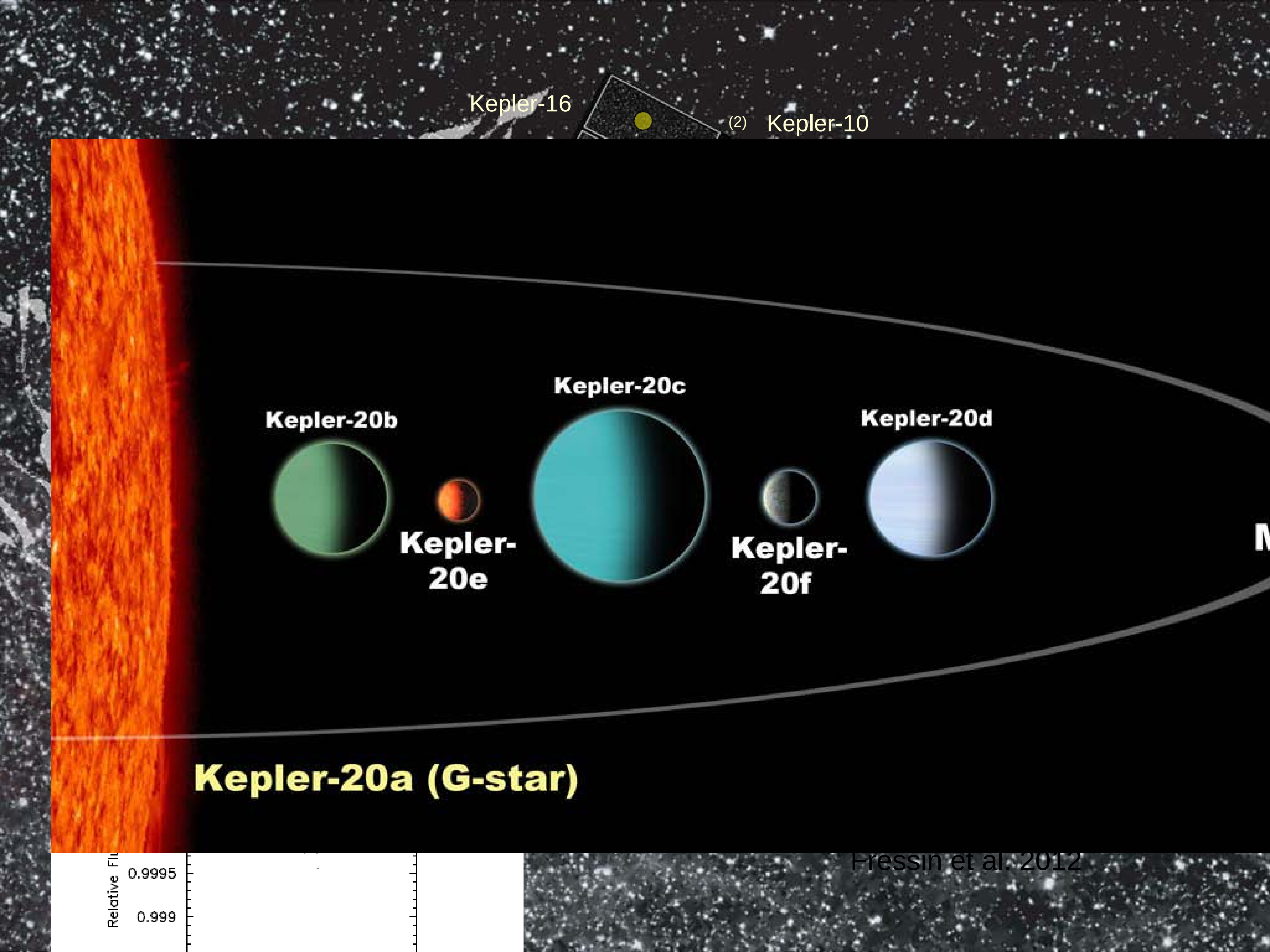
Kepler-9b,c

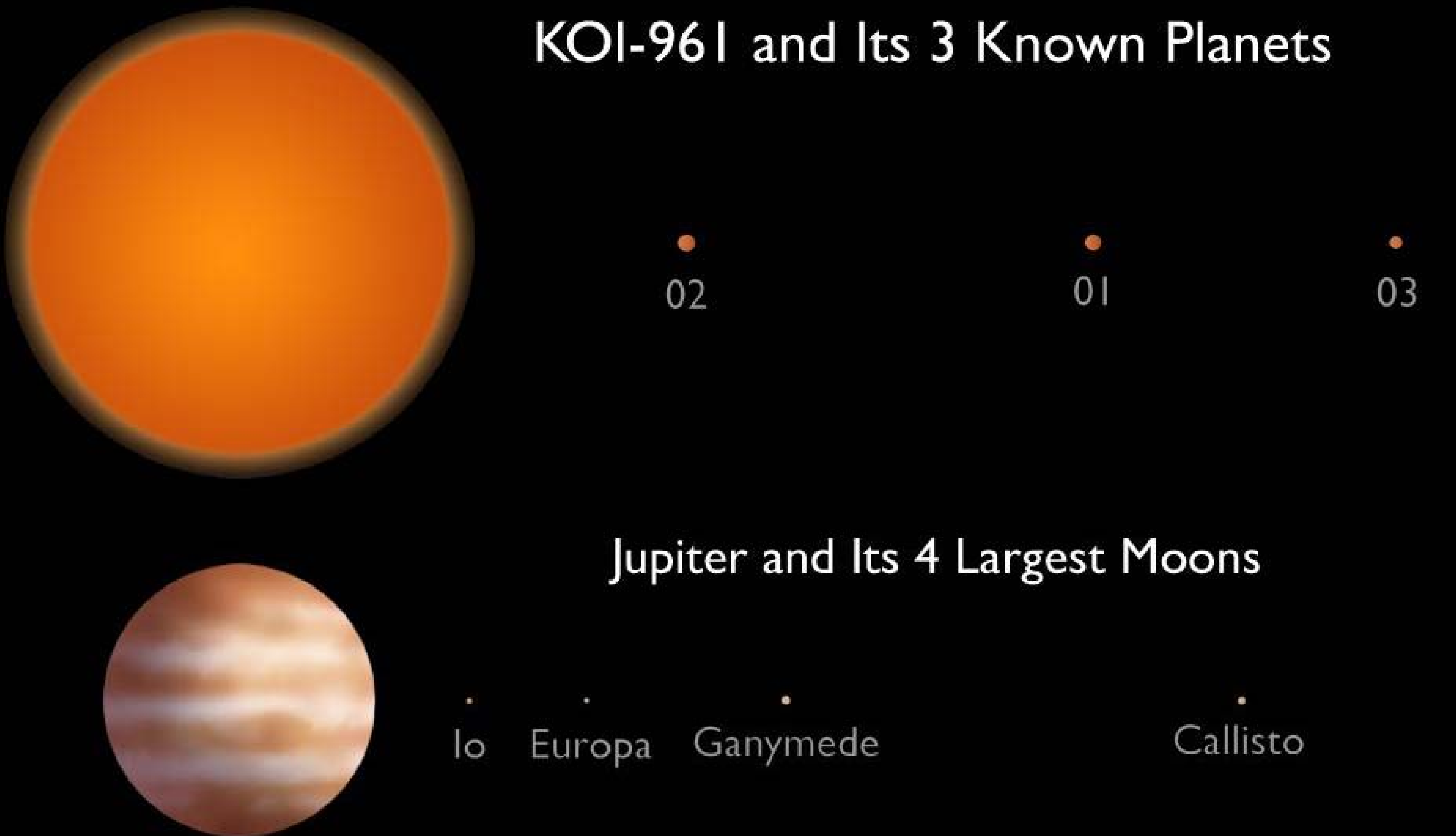
Holman et al. 2010

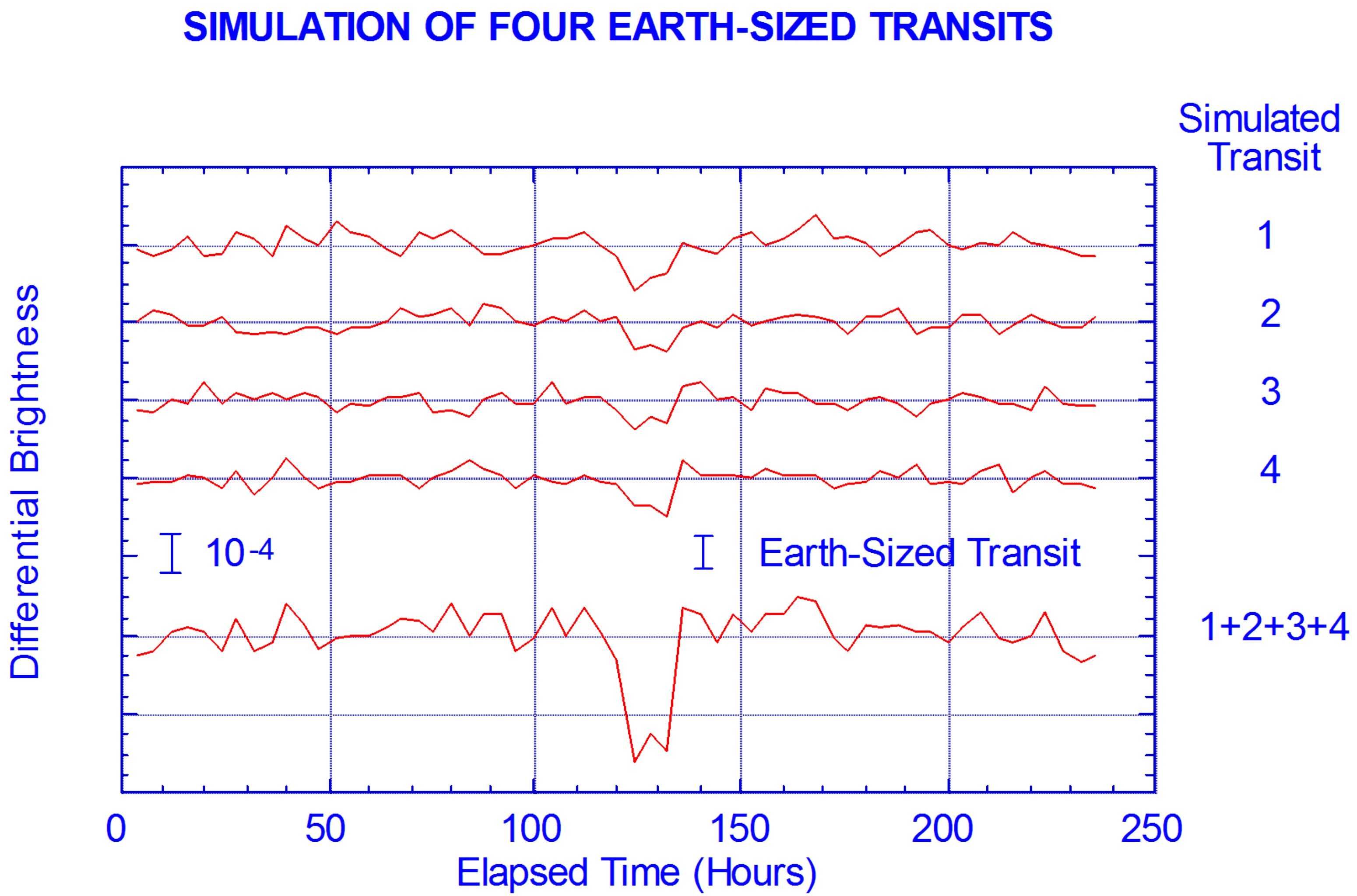
The Kepler-9 Discovery Provided a New Technique for Planet Mass Determination

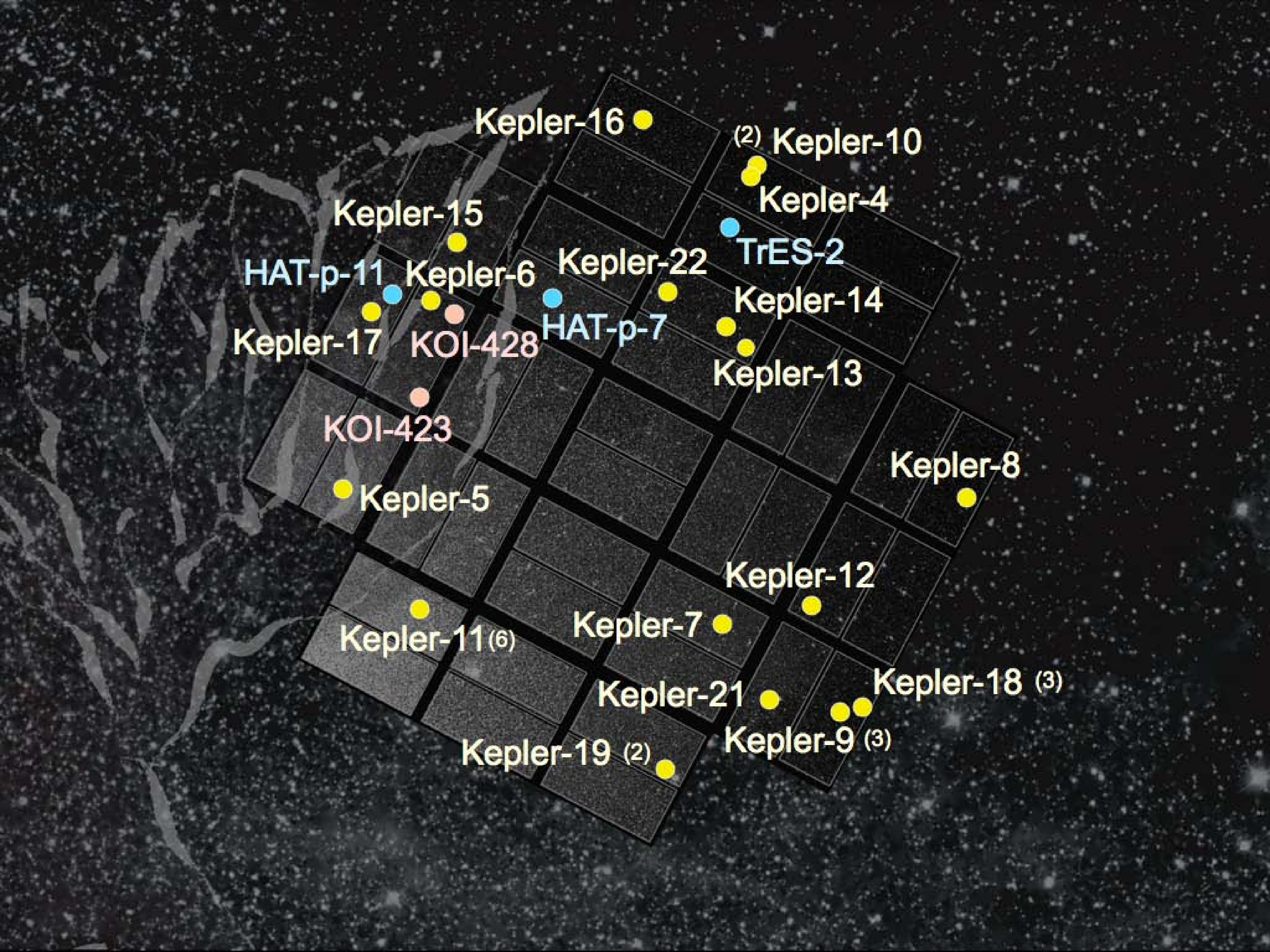
The determination of mass and size provides an estimate of the composition of the planets.

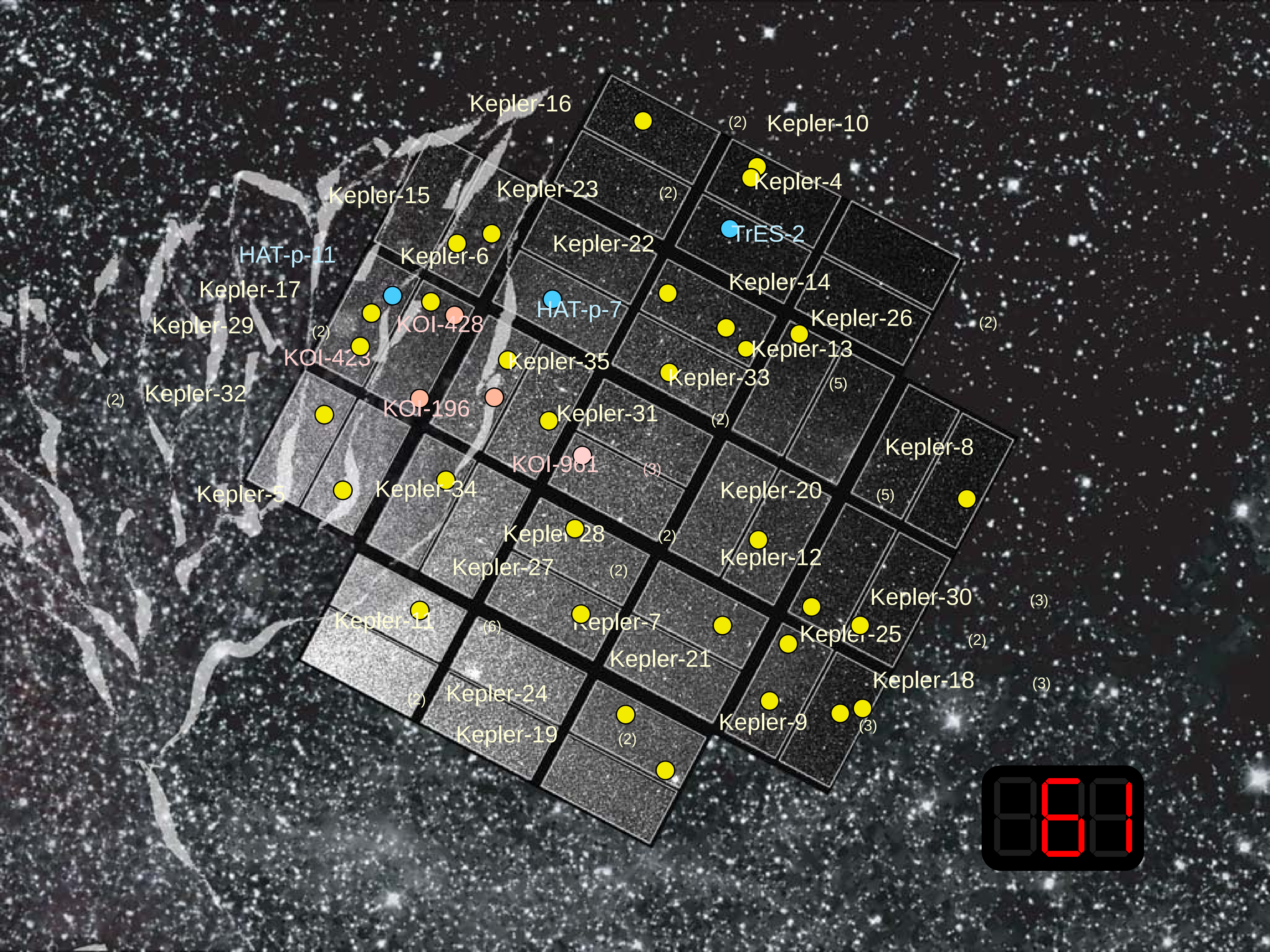



Kepler-16
(2)
Kepler-10
Kepler-20c
Kepler-20b
Kepler-20d
Kepler-
20e
Kepler-
20f
Kepler-20a (G-star)
Relative Fl
0.9995
0.999
Fressin et al. 2012


KOI-961 and Its 3 Known Planets
02
01
03
Jupiter and Its 4 Largest Moons
Io
Europa
Ganymede
Callisto


SIMULATION OF FOUR EARTH-SIZED TRANSITS
Simulated Transit
1
2
3
4
1+2+3+4
10-4
Earth-Sized Transit
Differential Brightness
0
50
100
150
200
250
Elapsed Time (Hours)


Kepler-16
(2) Kepler-10
Kepler-4
Kepler-15
TrES-2
Kepler-22
HAT-p-11
Kepler-6
Kepler-14
HAT-p-7
Kepler-17
KOI-428
Kepler-13
KOI-423
Kepler-8
Kepler-5
Kepler-12
Kepler-7
Kepler-11 (6)
Kepler-18 (3)
Kepler-21
Kepler-9 (3)
Kepler-19 (2)


Kepler-16
(2)
Kepler-10
Kepler-4
Kepler-15
Kepler-23
(2)
TrES-2
HAT-p-11
Kepler-6
Kepler-22
Kepler-17
Kepler-14
HAT-p-7
Kepler-29
(2)
KOI-428
Kepler-26
(2)
KOI-423
Kepler-35
Kepler-13
Kepler-33
(5)
(2)
Kepler-32
KOI-196
Kepler-31
(2)
Kepler-8
KOI-961
(3)
Kepler-5
Kepler-34
Kepler-20
(5)
Kepler-28
(2)
Kepler-12
Kepler-27
(2)
Kepler-30
(3)
Kepler-11
(6)
Kepler-7
Kepler-25
(2)
Kepler-21
Kepler-18
(3)
(2)
Kepler-24
Kepler-9
(3)
Kepler-19
(2)
61