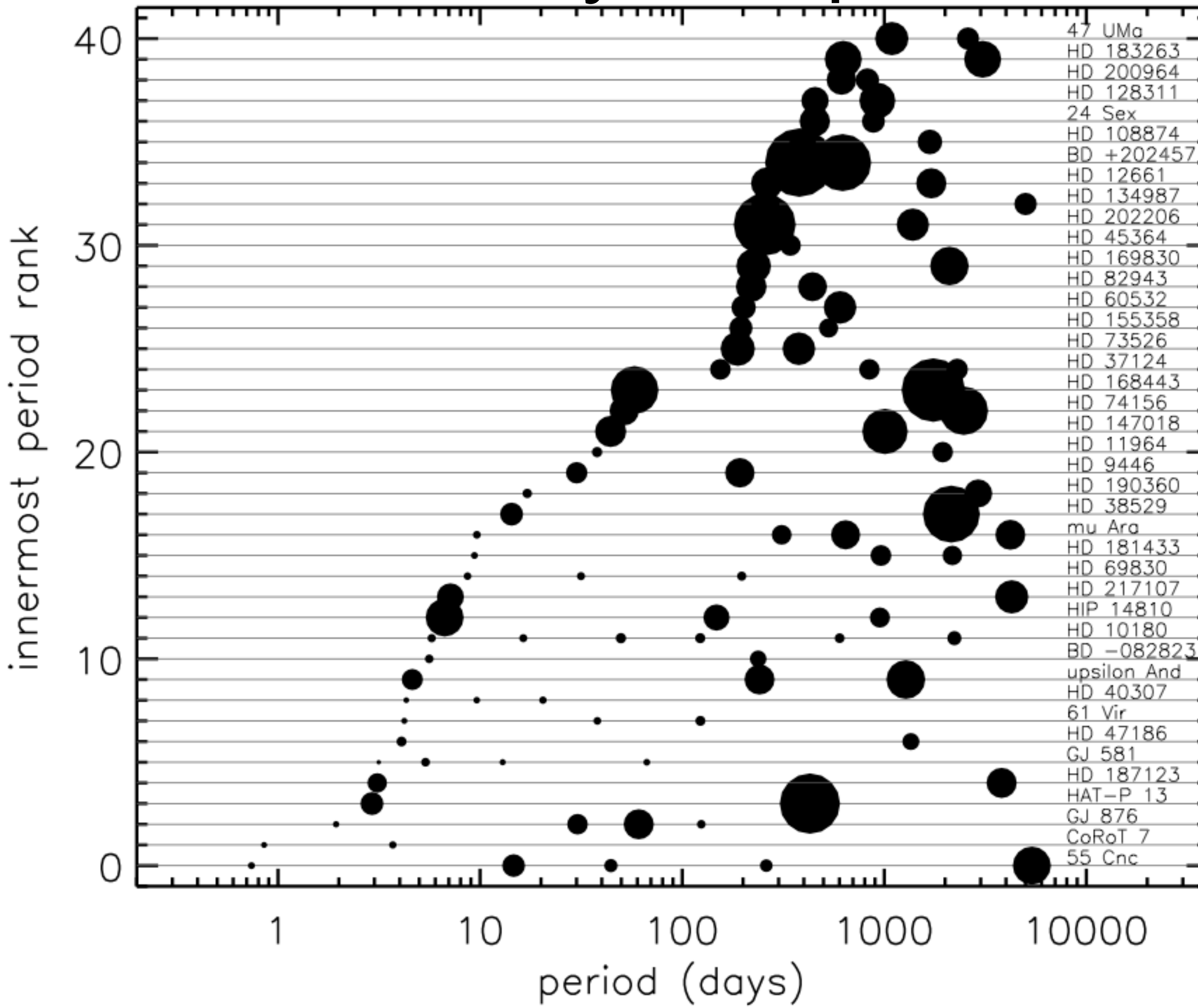
Planetary Systems from *Kepler*

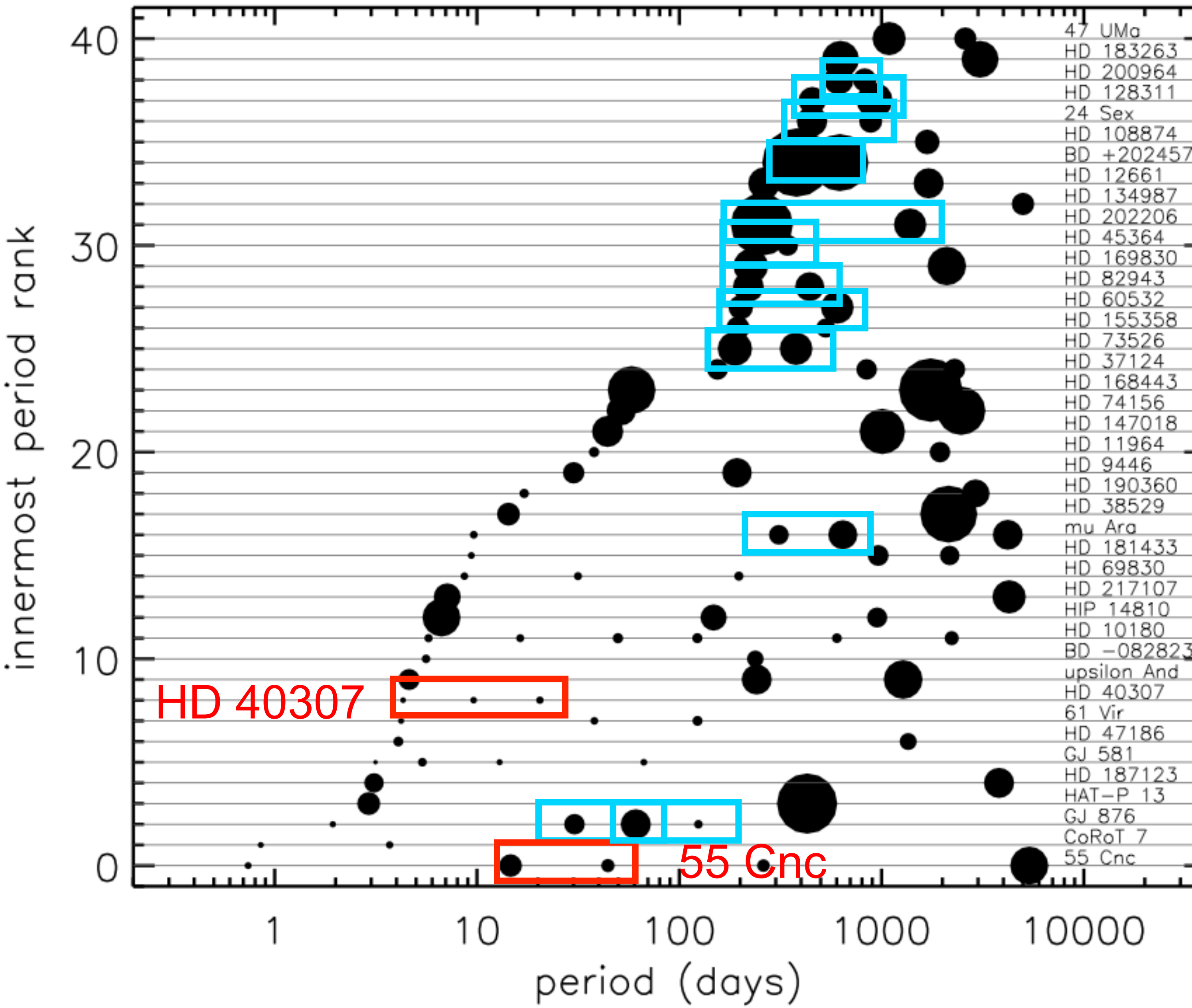
Dan Fabrycky
UC Santa Cruz

… greatly indebted to the Kepler team!

Radial Velocity Multiple Planets



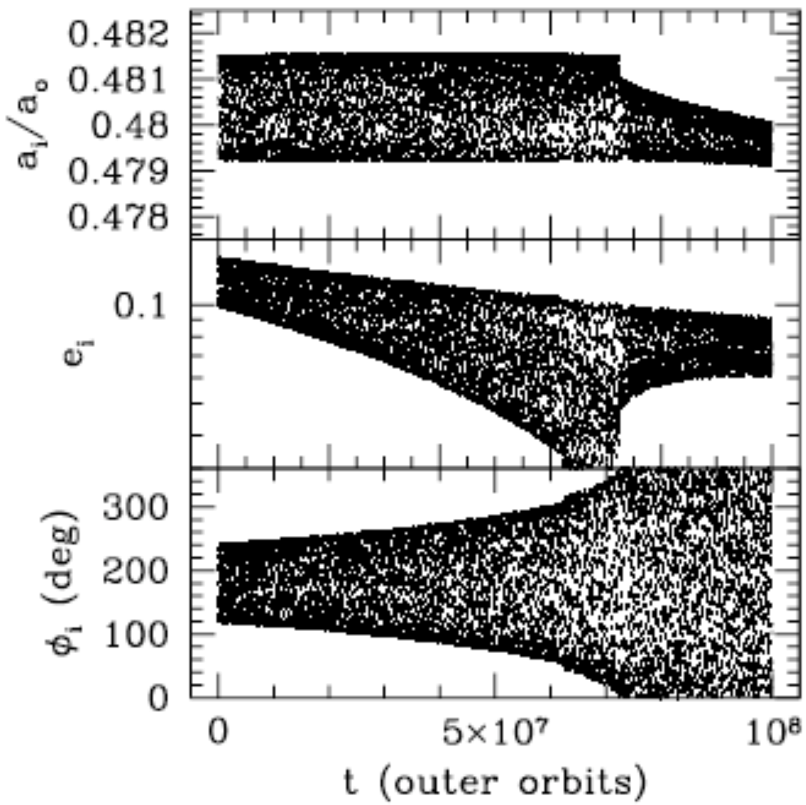
Resonances

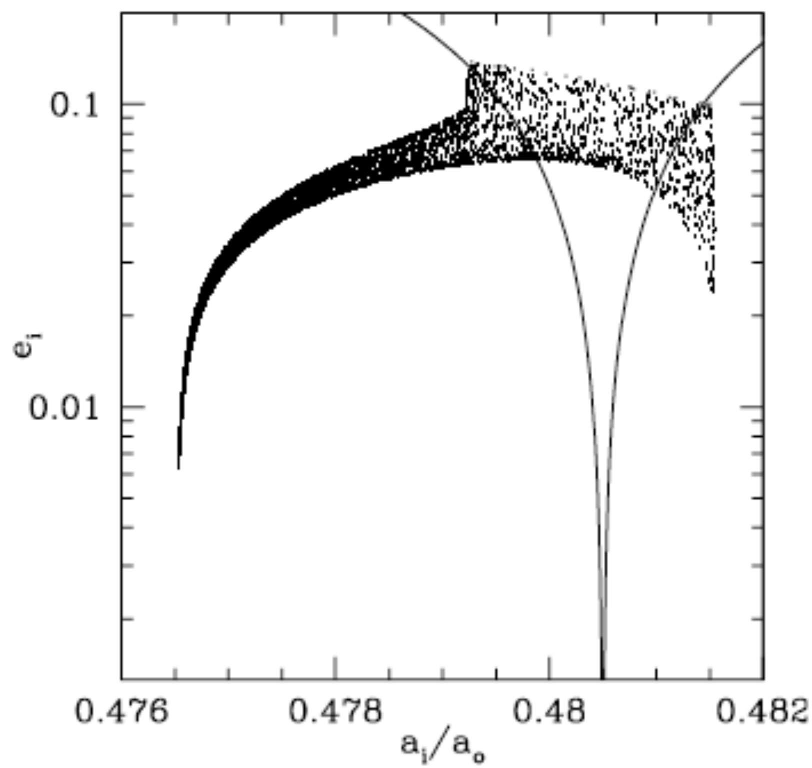


innermost period rank
period (days)
0
10
20
30
40
1
10
100
1000
10000
47 UMa
HD 183263
HD 200964
HD 128311
24 Sex
HD 108874
BD +202457
HD 12661
HD 134987
HD 202206
HD 45364
HD 169830
HD 82943
HD 60532
HD 155358
HD 73526
HD 37124
HD 168443
HD 74156
HD 147018
HD 11964
HD 9446
HD 190360
HD 38529
mu Ara
HD 181433
HD 69830
HD 217107
HIP 14810
HD 10180
BD −082823
upsilon And
HD 40307
61 Vir
HD 47186
GJ 581
HD 187123
HAT−P 13
GJ 876
CoRoT 7
55 Cnc
HD 40307
55 Cnc

55 Cnc b-c

Name	Msin(i) mjupiter ±	Orbital Period days ±	Orbital Eccentricity ±
55 Cnc c	0.168	44.379	0.05
55 Cnc b	0.83	14.6513	0.016



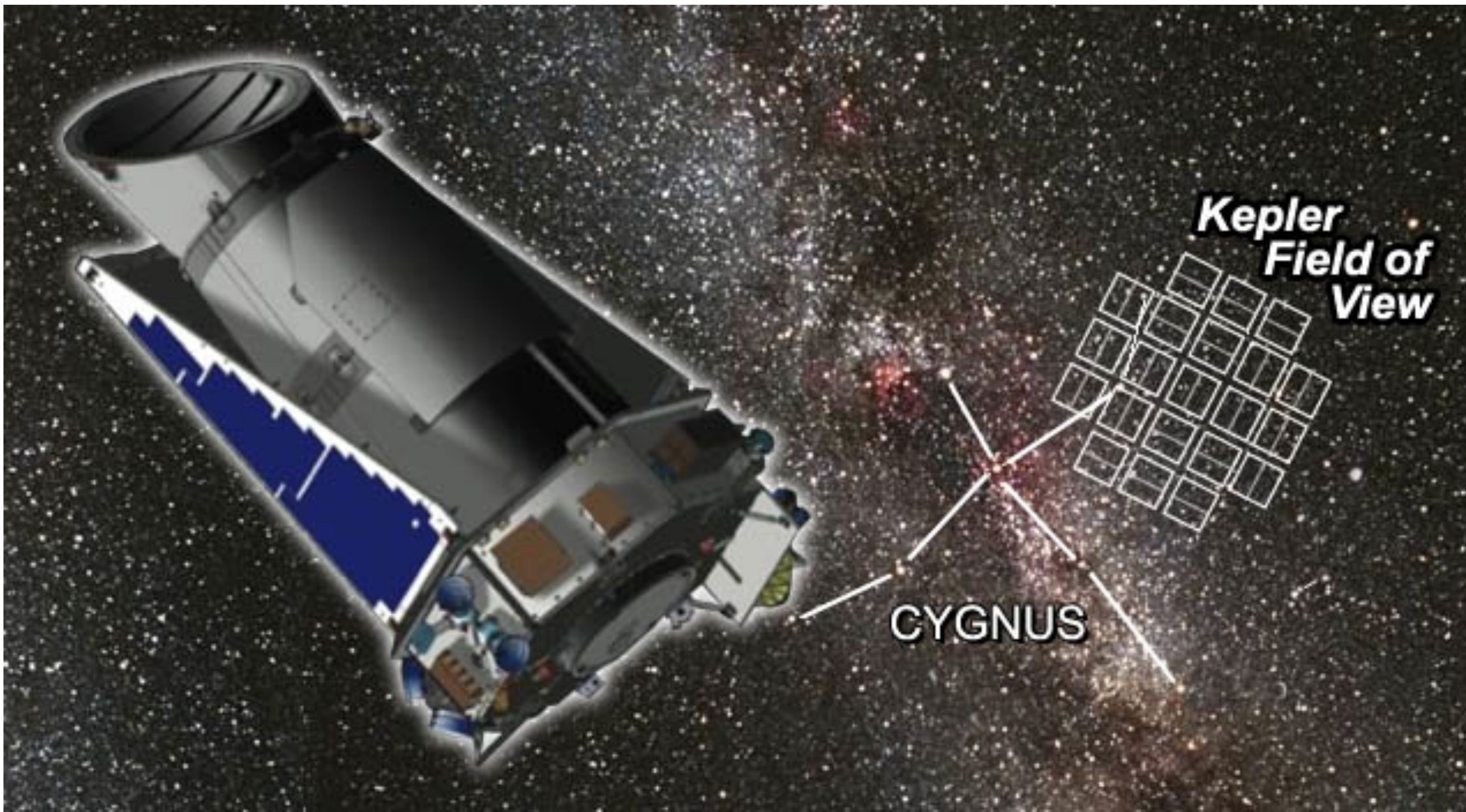


Novak, Lai, Lin 2003

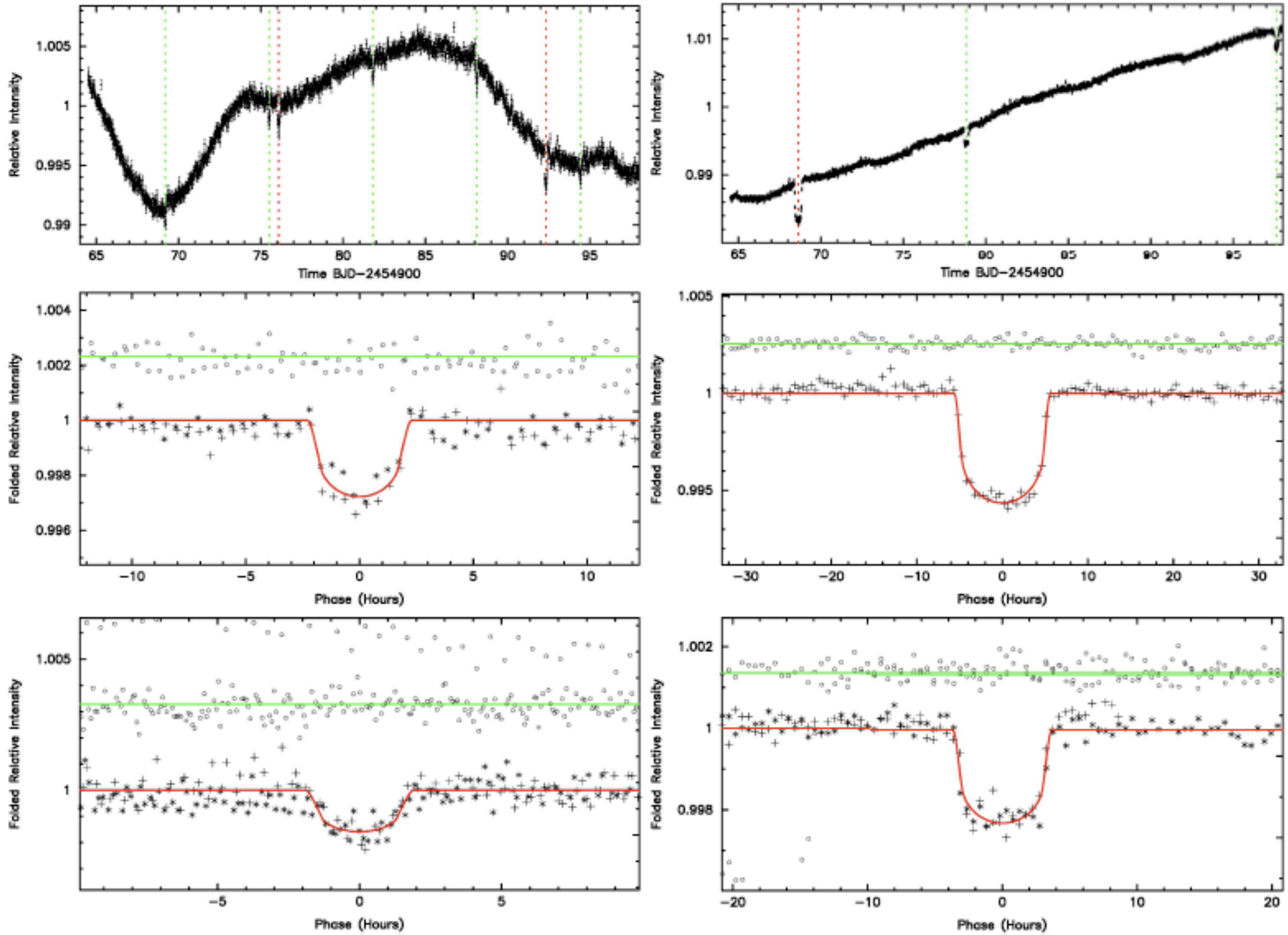
see also: Terquem & Papaloizou 2008

Kepler Mission

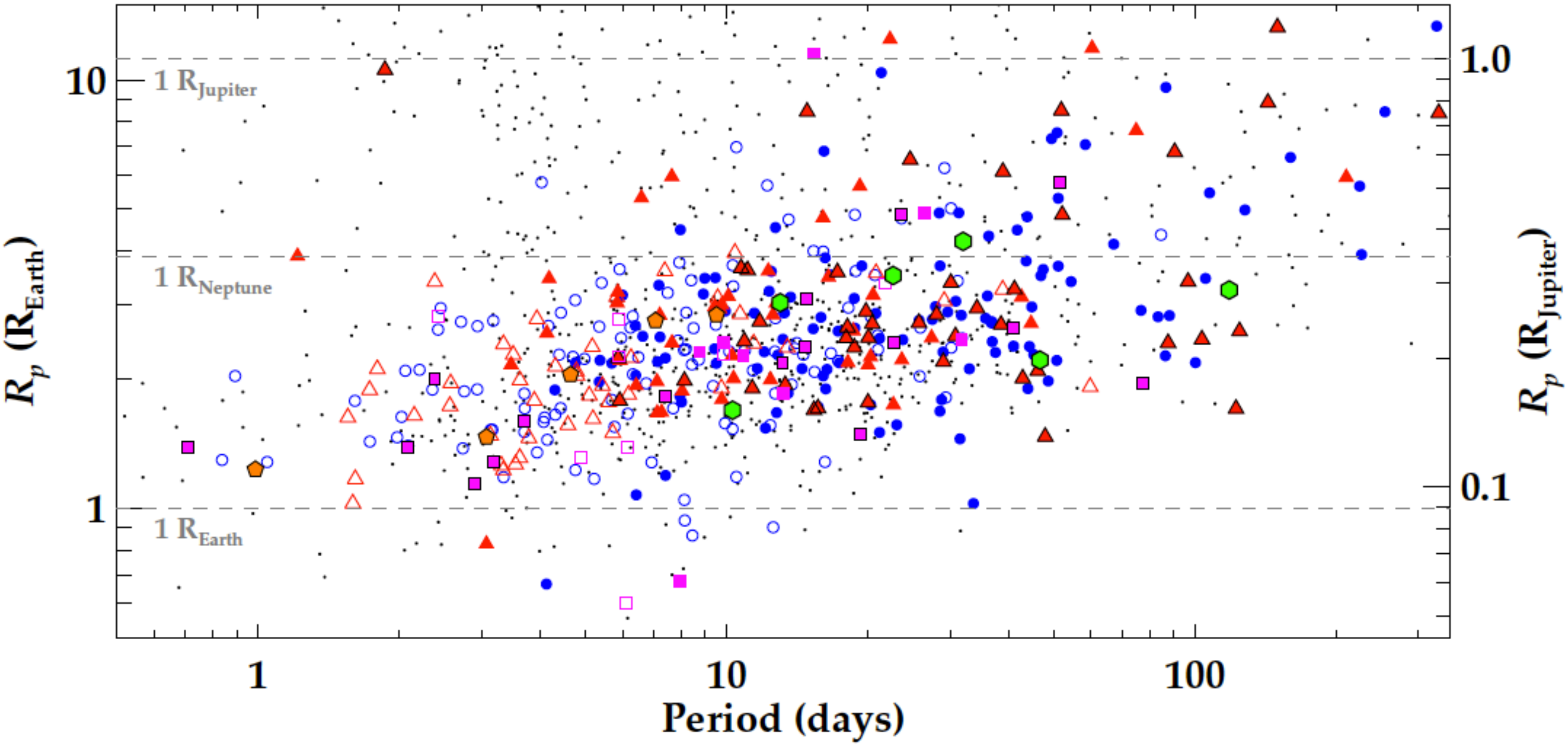
- NASA, photometry of 150,000 stars
- Looking for Earth-like planets in transit
- ~30 ppm in 6 hours; 30 minute cadence
- 120 days are public (+90d this month!)



Kepler finds Multiplanets



(Steffen et al. 2010) Transit search and figures by Jason Rowe



Numbers of multiplanets:

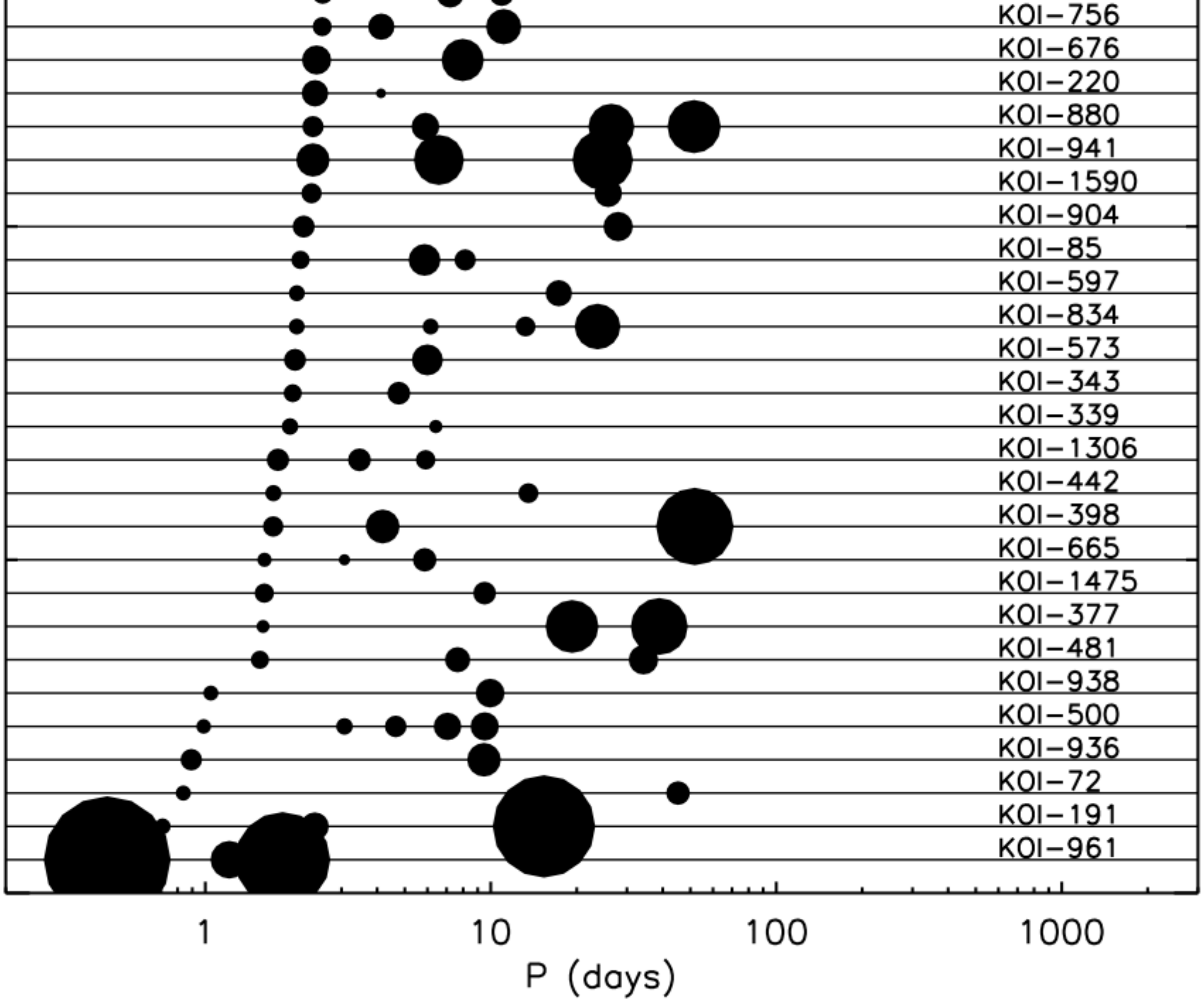
115 doubles, 45 triples, 8 quaduples,

1 quintuple and 1 sextuple

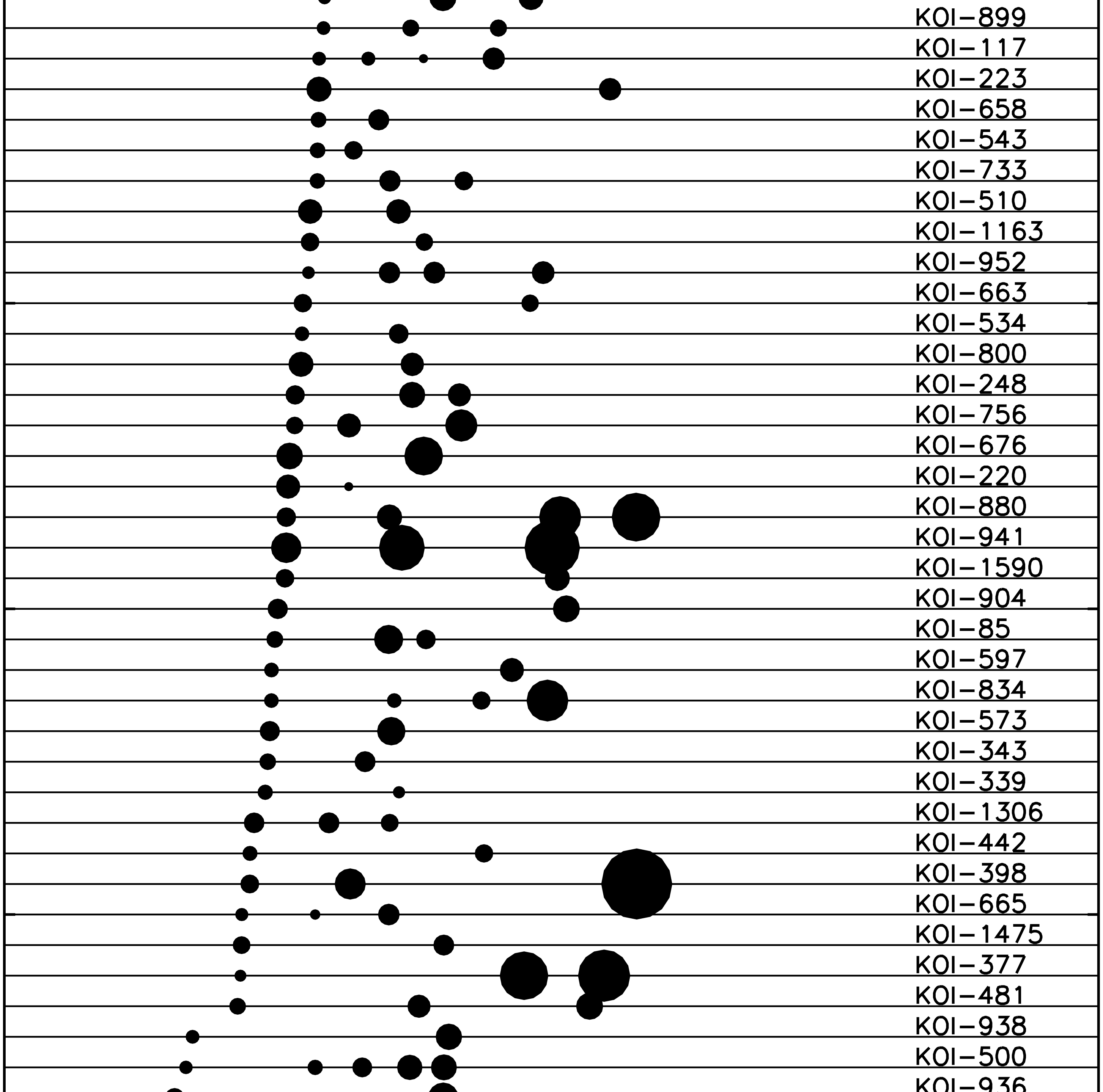
Borucki et al. 2011

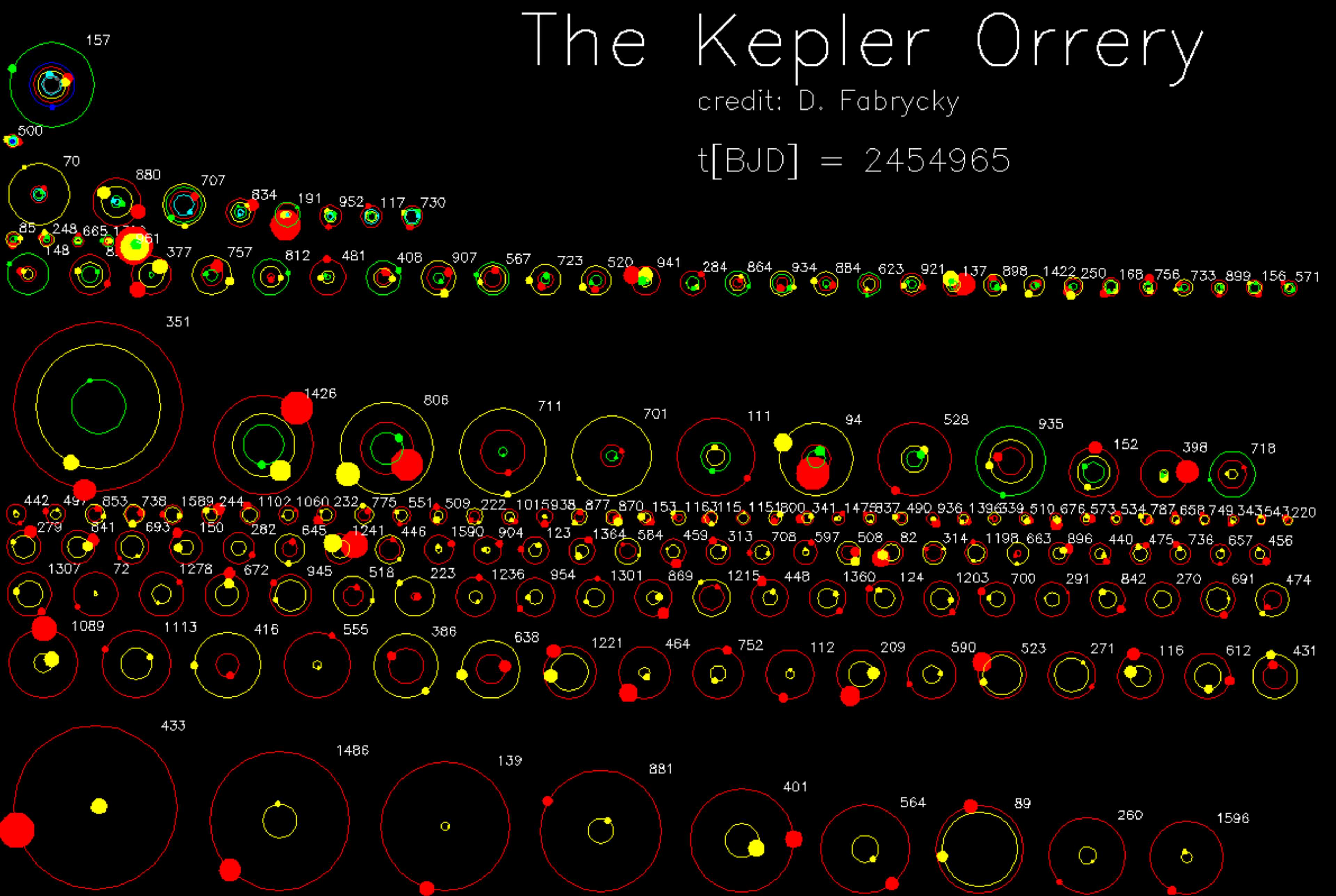
Latham, Rowe, Quinn et al. 2011

Lissauer, Ragozzine, Fabrycky et al. 2011



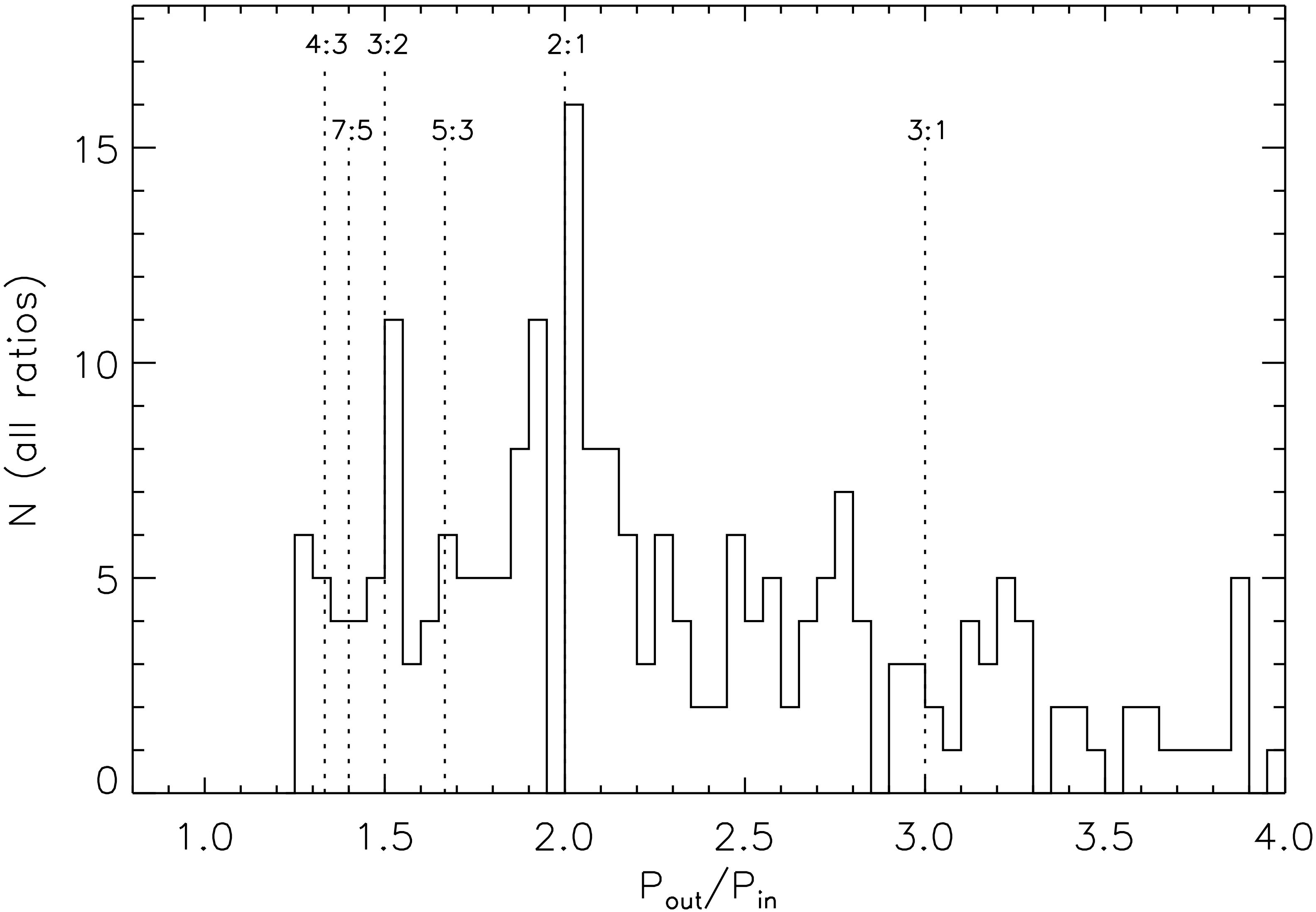
Kepler systems


KOI−899
KOI−117
KOI−223
KOI−658
KOI−543
KOI−733
KOI−510
KOI−1163
KOI−952
KOI−663
KOI−534
KOI−800
KOI−248
KOI−756
KOI−676
KOI−220
KOI−880
KOI−941
KOI−1590
KOI−904
KOI−85
KOI−597
KOI−834
KOI−573
KOI−343
KOI−339
KOI−1306
KOI−442
KOI−398
KOI−665
KOI−1475
KOI−377
KOI−481
KOI−938
KOI−500

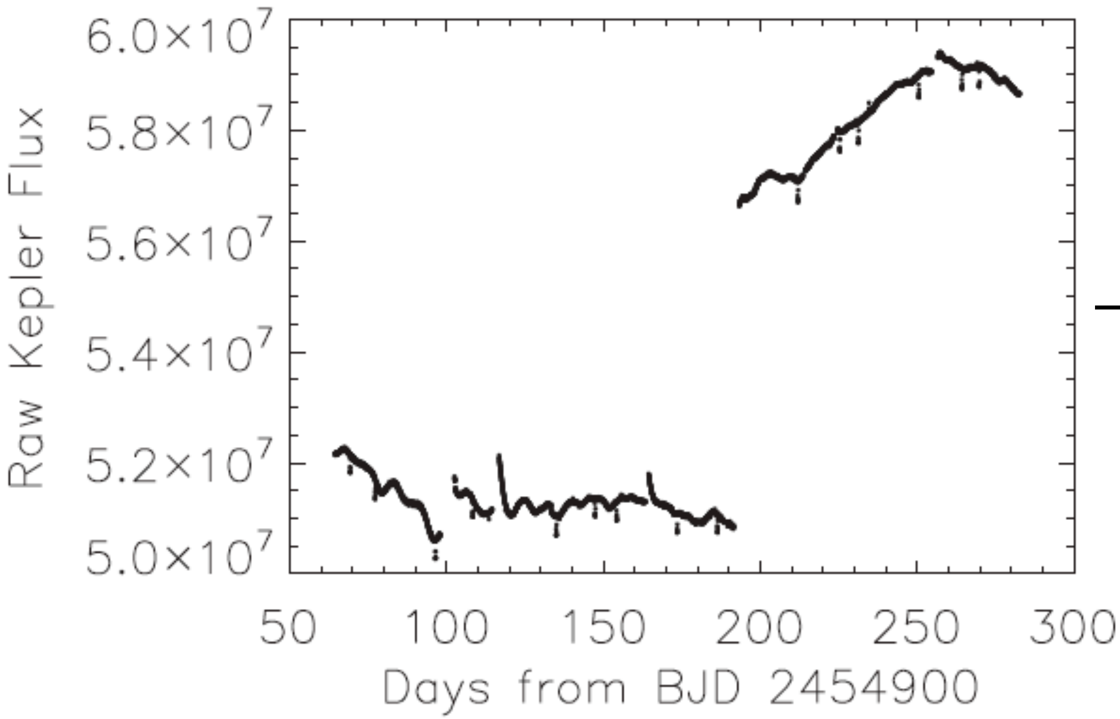


The Kepler Orrery
credit: D. Fabrycky
t[BJD] = 2454965
157 500 70 880 707 834 191 952 117 730
85 248 665 148 377 757 812 481 408 907 567 723 520 941 284 864 934 884 623 921 137 898 1422 250 168 756 733 899 156 571
351 1426 806 711 701 111 94 528 935 152 398 718
442 853 738 1589 244 1102 1060 232 775 551 509 222 1015 938 877 870 153 1163 115 1151 800 341 1475 837 490 936 1396 339 510 676 573 534 787 658 749 343 543 220
279 841 693 150 282 645 1241 446 1590 904 123 1364 584 459 313 708 597 508 82 314 1198 663 896 440 475 736 657 456
1307 72 1278 672 945 518 223 1236 954 1301 869 1215 448 1360 124 1203 700 291 842 270 691 474
1089 1113 416 555 386 638 1221 464 752 112 209 590 523 271 116 612 431
433 1486 139 881 401 564 89 260 1596

Resonance Preference



Confirming a planetary system



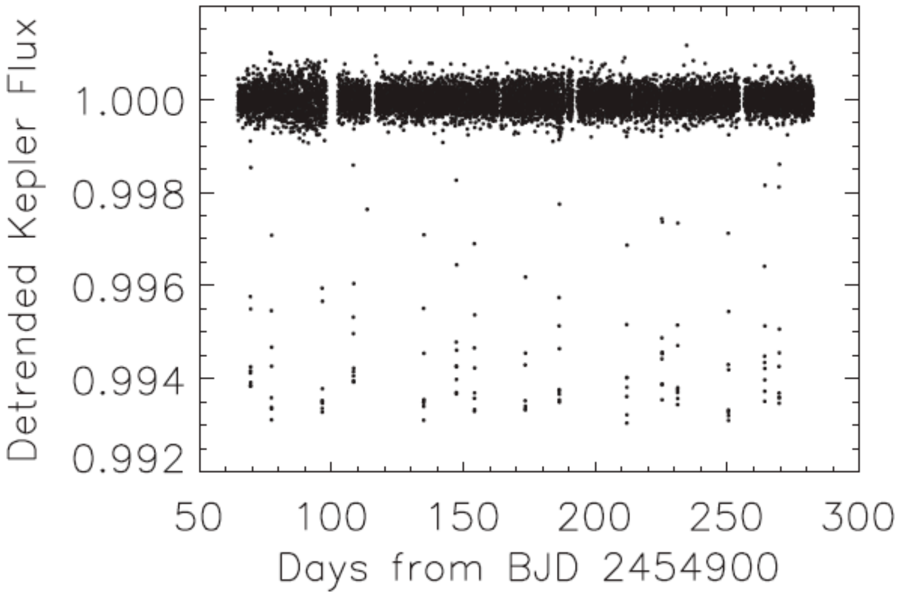
→

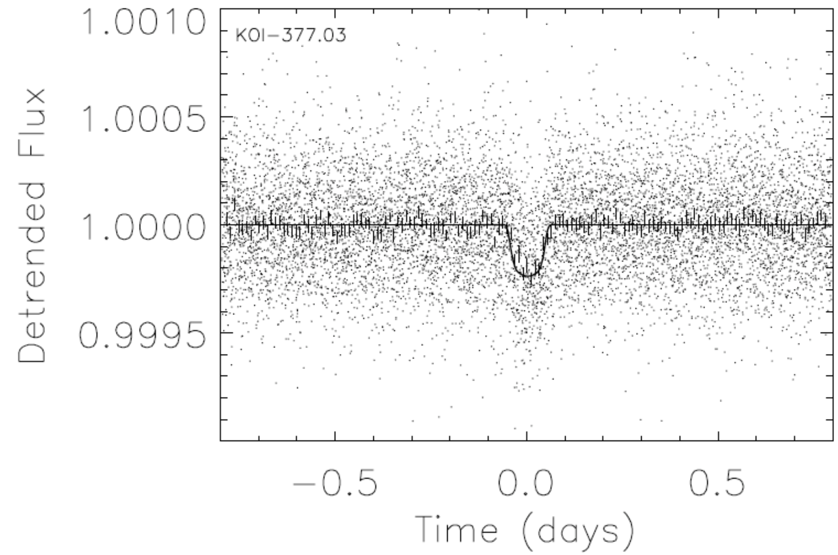
Image: NASA/Pyle

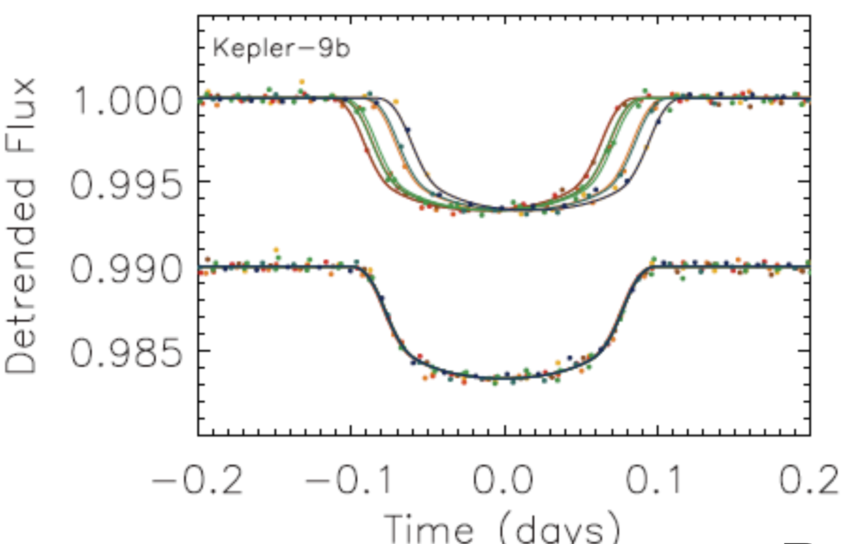
Kepler-9

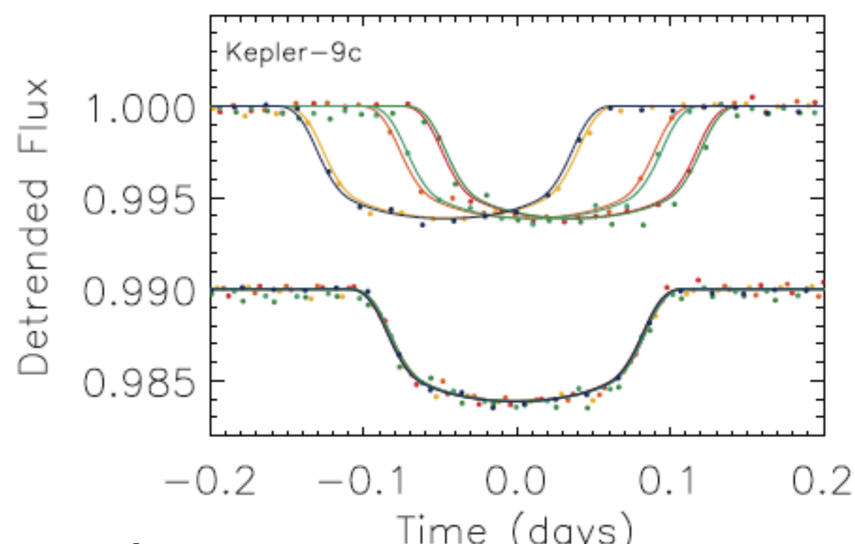
Holman, Fabrycky et al. 2010

Kepler-9 b-c-d



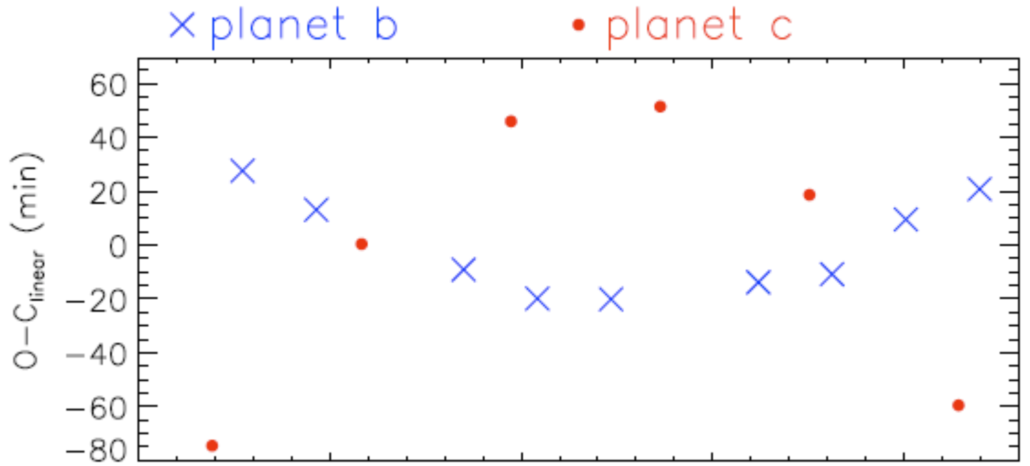


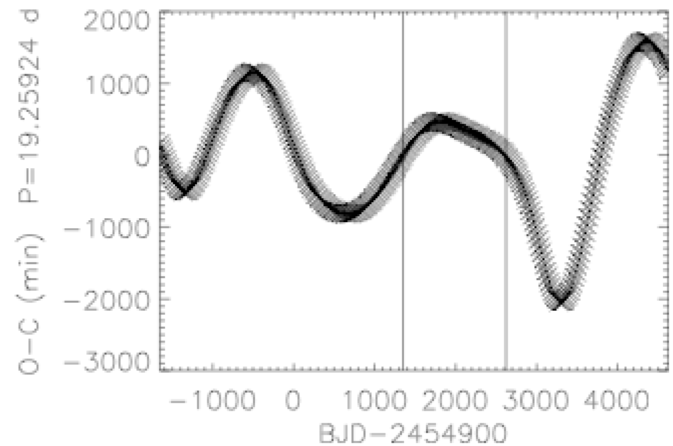


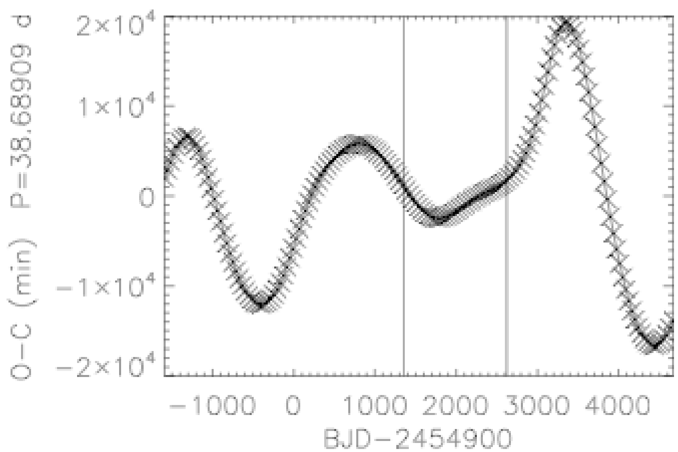


Ragozzine

First Impressions







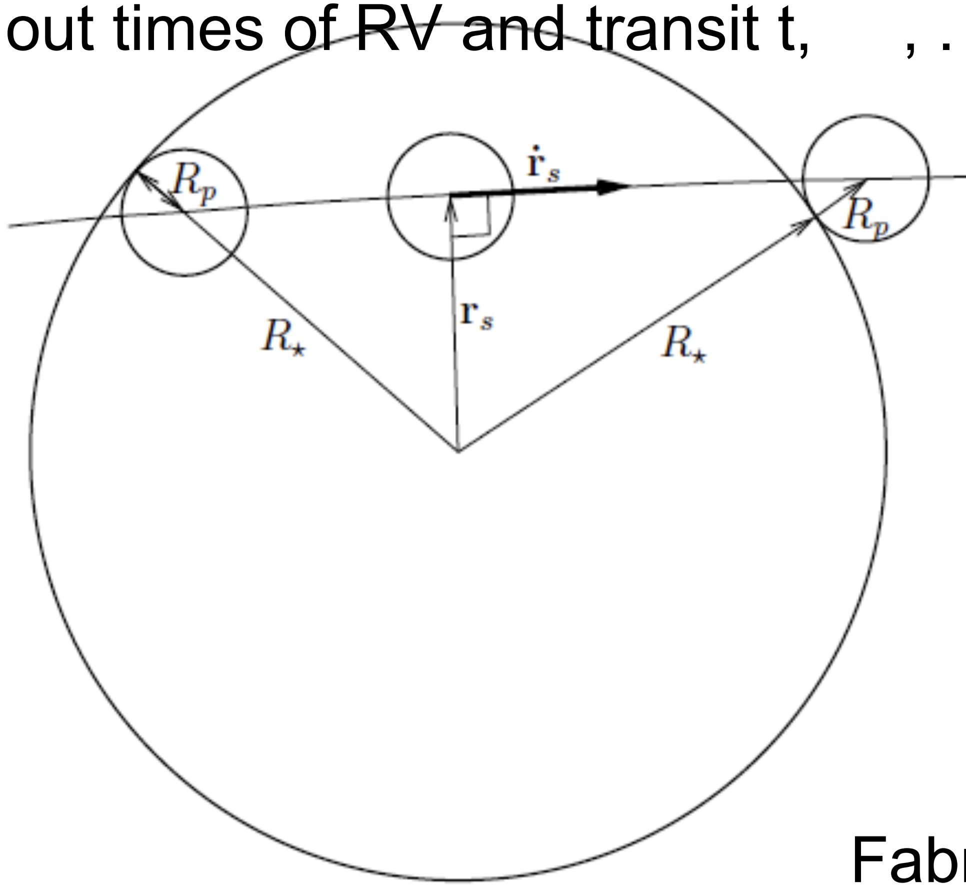
$$-GM_bM_c/2r_{bc}$$

$$\begin{aligned}\mathcal{H} &= \mathcal{H}_b + \mathcal{H}_c + \mathcal{H}_{\rm int} \\ &\approx -\frac{GM_\star M_b}{2a_b} - \frac{GM_\star M_c}{2a_c}\end{aligned}$$

$$\begin{aligned}-\frac{\mathcal{C}_b}{\mathcal{C}_c} &= \frac{M_c/a_c}{M_b/a_b} \\ &\approx (1/2)^{2/3}(M_c/M_b)\end{aligned}$$

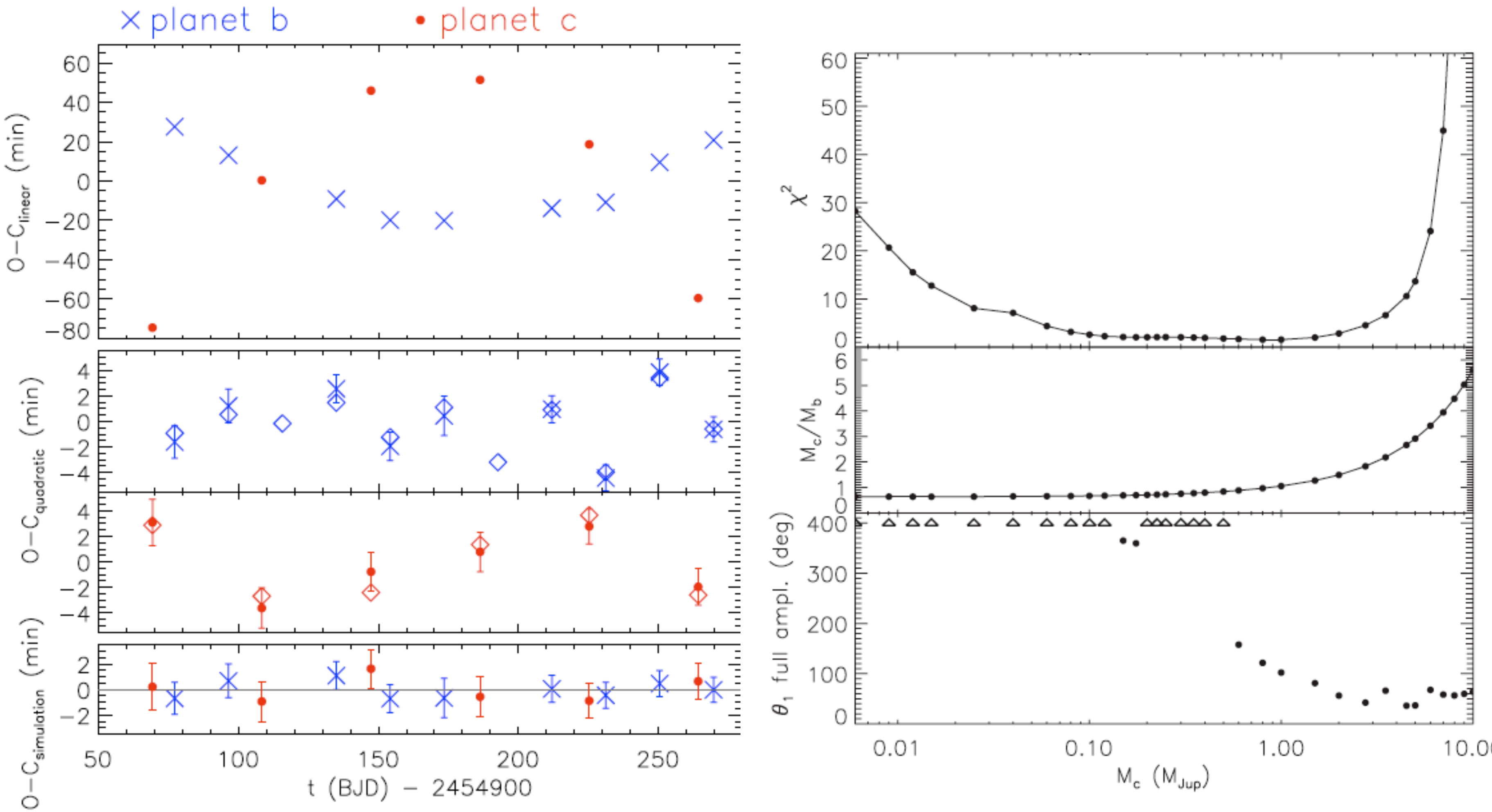
Dynamical Model of Transits

1) Use Newton's equations to integrate a 3-body system. $\mathbf{r}_s$ $\dot{\mathbf{r}}_s$
2) Find transit by Newton's method c$\mathbf{r}_s$ $\dot{\mathbf{r}}_s$
3) Print out times of RV and transit t, , .

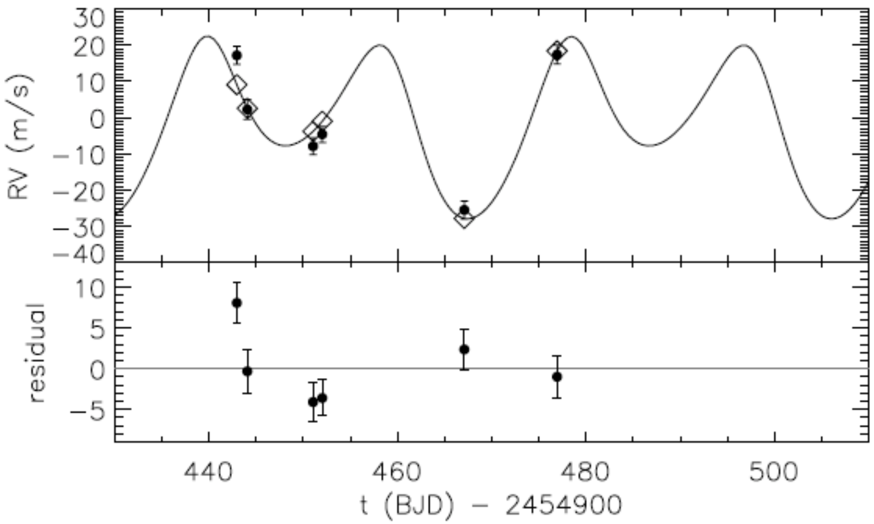


Fabrycky (2010)

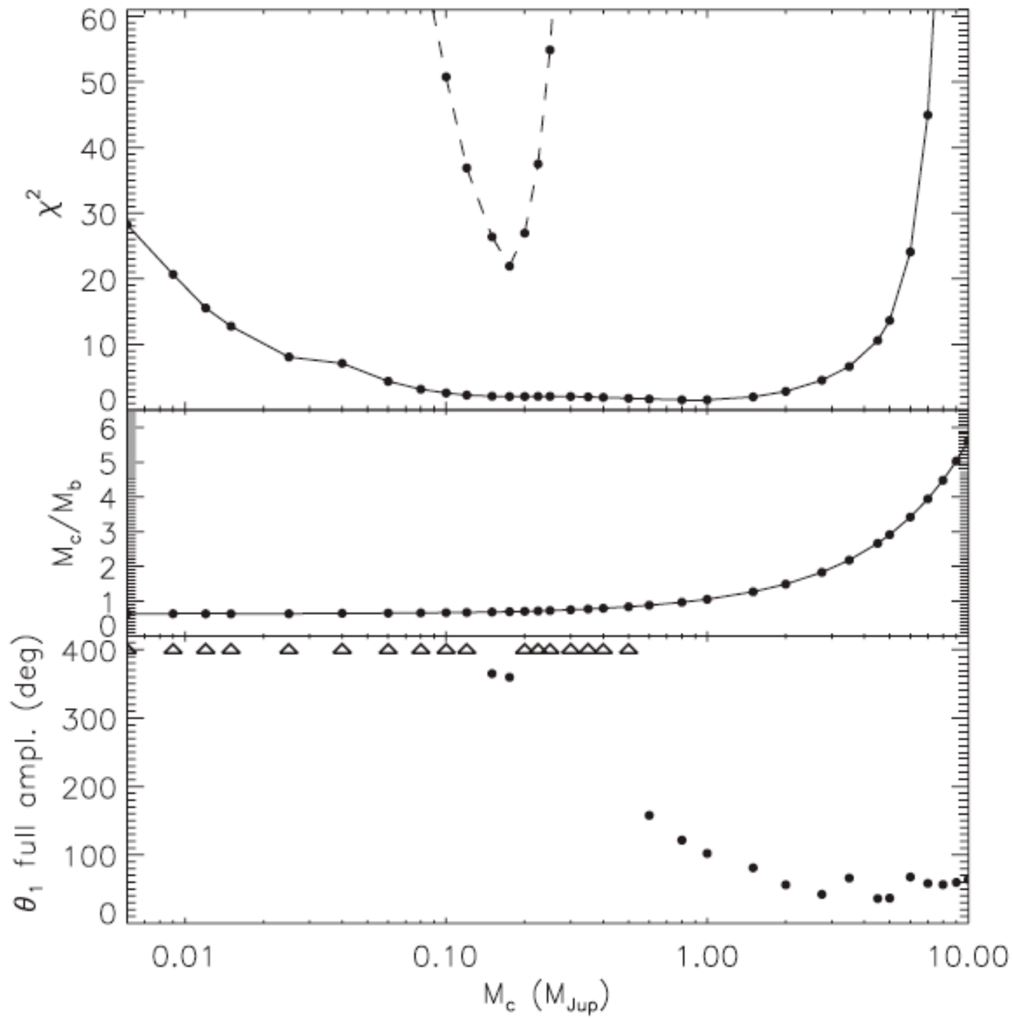
Fits to the data obtained



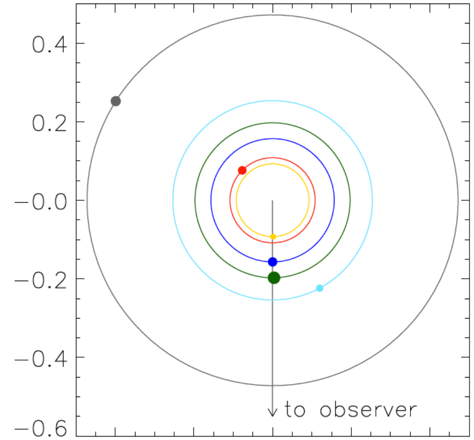
RVs fit, constraining the masses

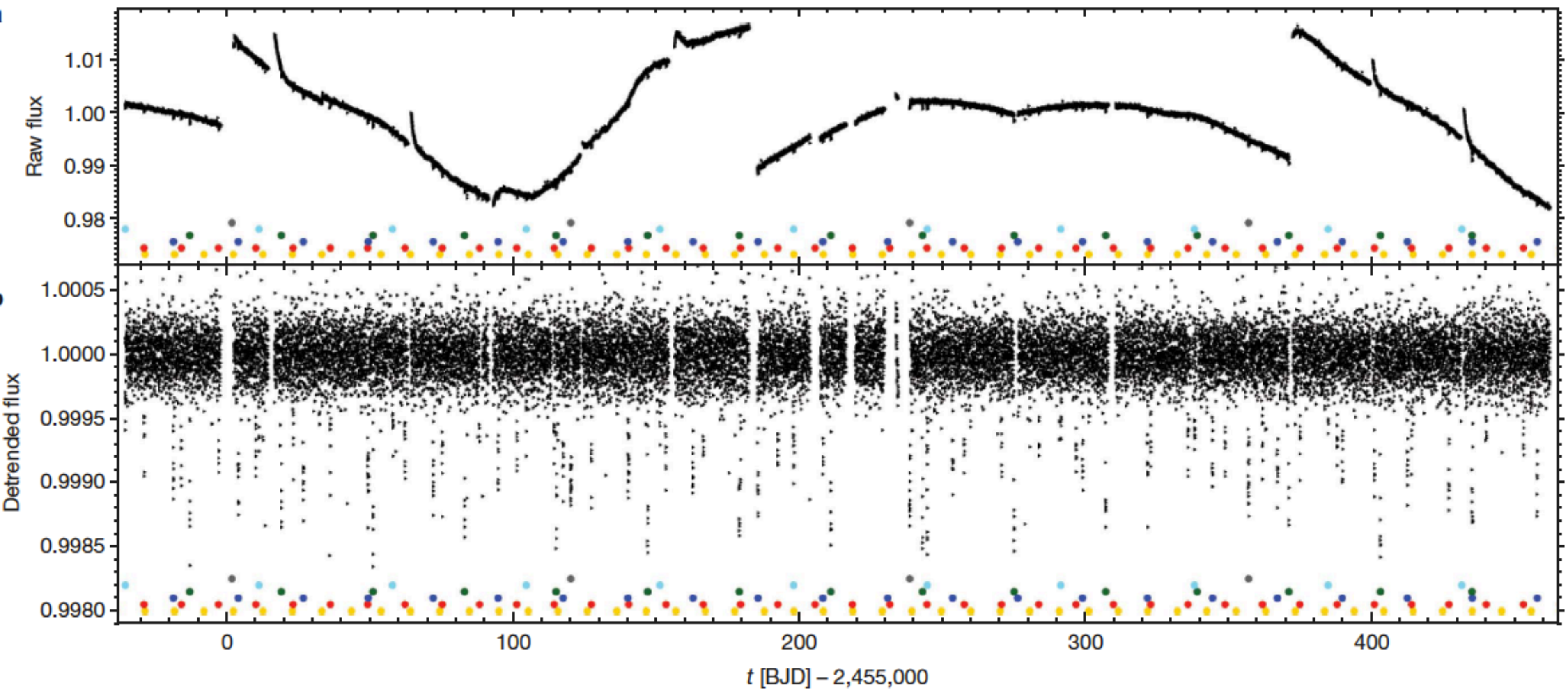


t_{epoch}	BJD 2455088.212
$M_\star$	$1.0 M_\odot$ (assumed)
$R_\star$	$1.10 \pm 0.09\ R_\odot$
M_c	$0.171 \pm 0.013\ M_{Jup}$
M_c/M_b	0.680 ± 0.019
P_b (days)	19.2372 ± 0.0007
$e_b \cos \omega_b$	0.143 ± 0.036
$e_b \sin \omega_b$	0.048 ± 0.008
i_b (degrees)	88.55 ± 0.25
λ_b (degrees)	-9.3 ± 3.2
P_c (days)	38.992 ± 0.005
$e_c \cos \omega_c$	-0.026 ± 0.021
$e_c \sin \omega_c$	0.13 ± 0.04
i_c (degrees)	88.12 ± 0.17
λ_c (degrees)	110.2 ± 2.2



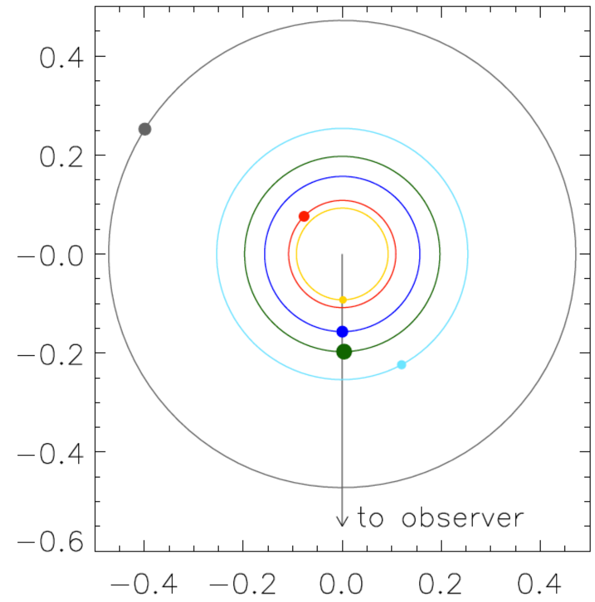
Kepler-11

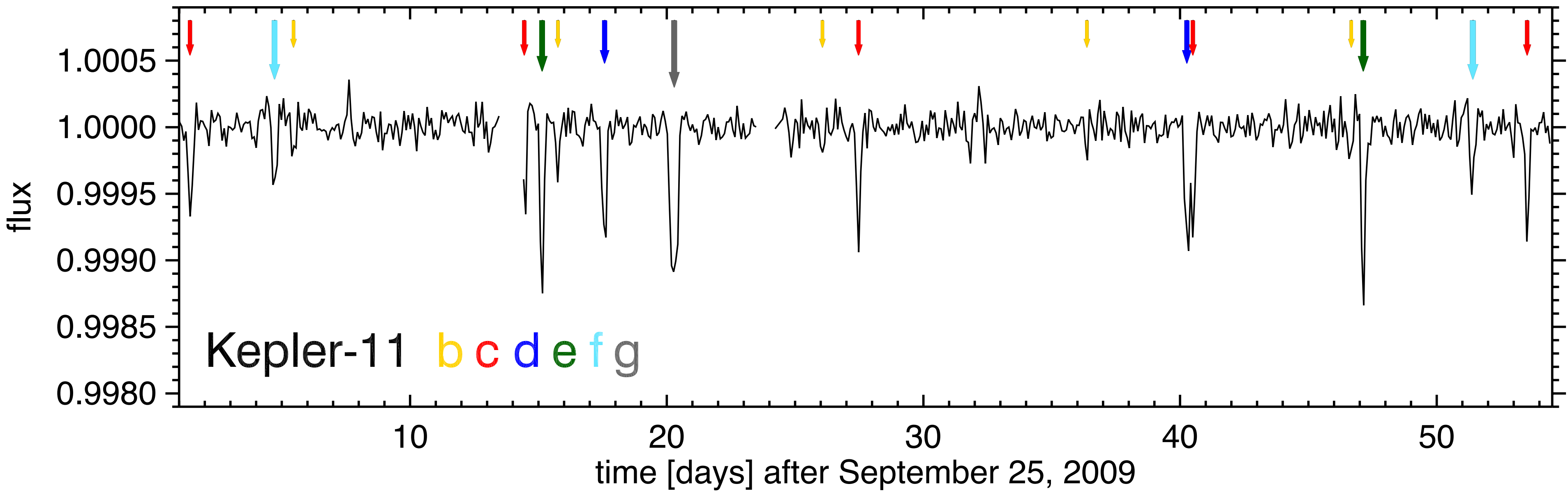




Lissauer, Fabrycky, Ford et al. 2011

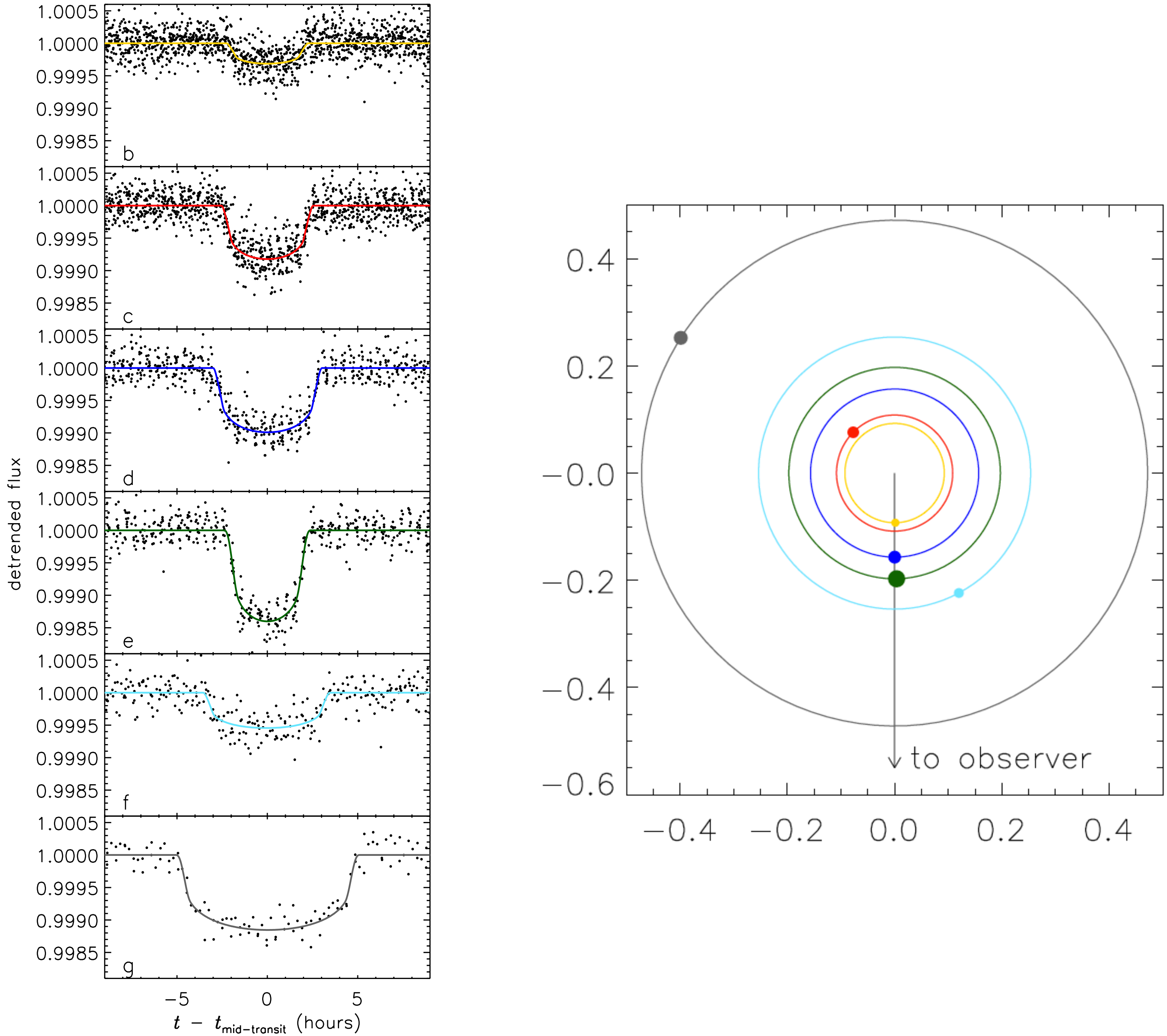
Kepler-11



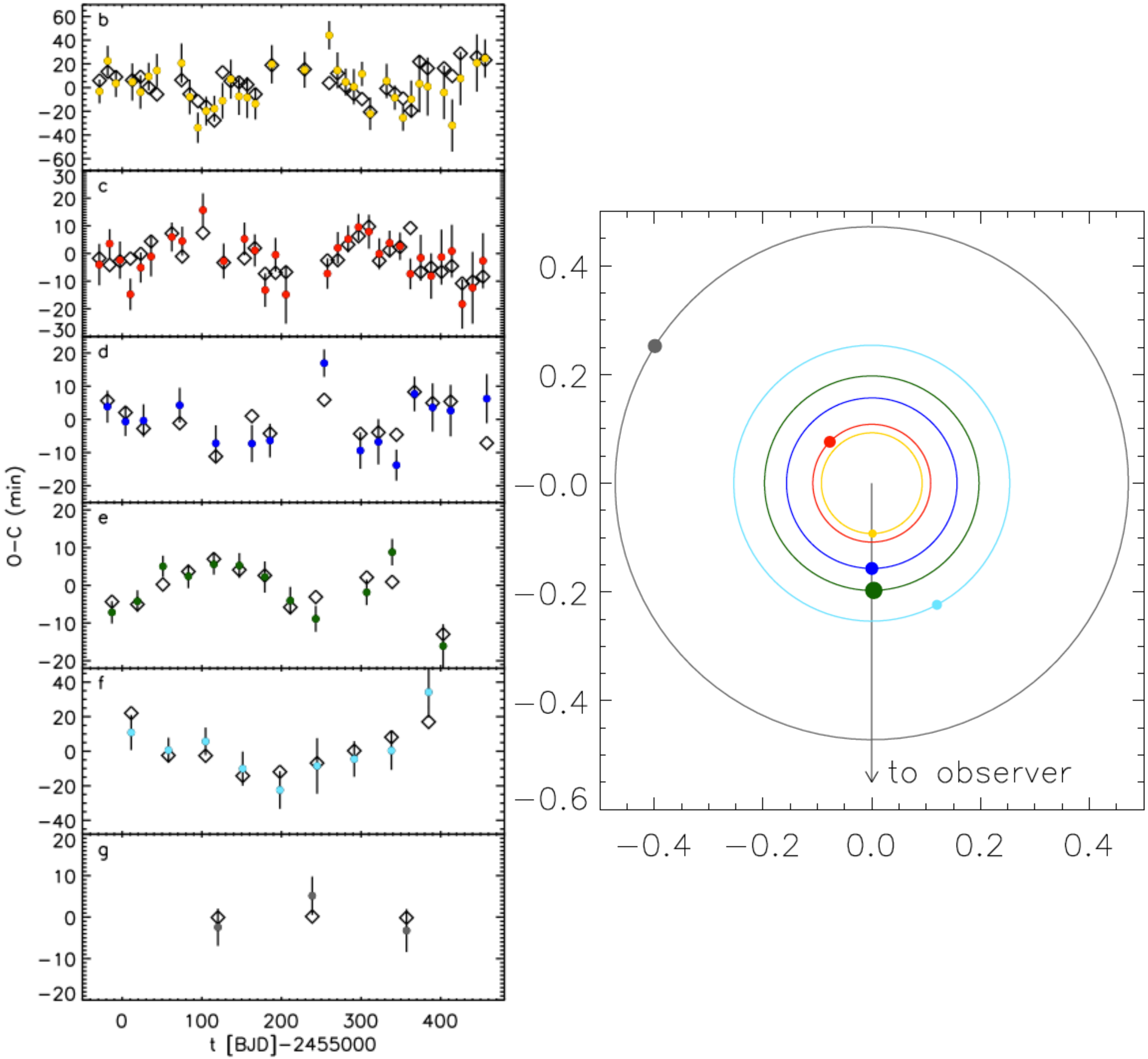


Lissauer, Fabrycky, Ford et al. 2011

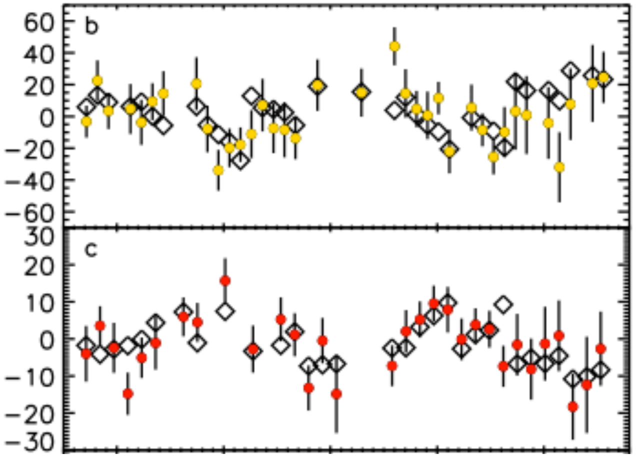
Image: NASA/Pyle



1.0005
1.0000
0.9995
0.9990
0.9985
b
c
d
e
f
g
detrended flux
−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



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

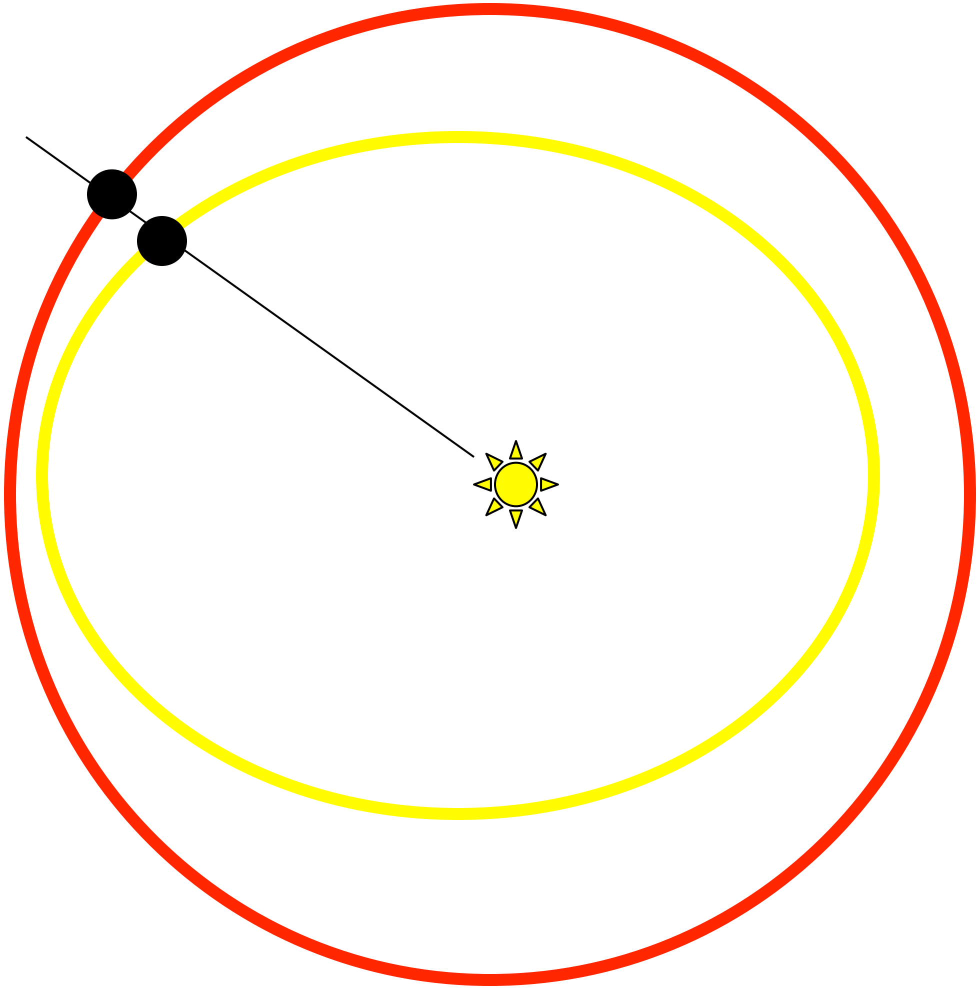


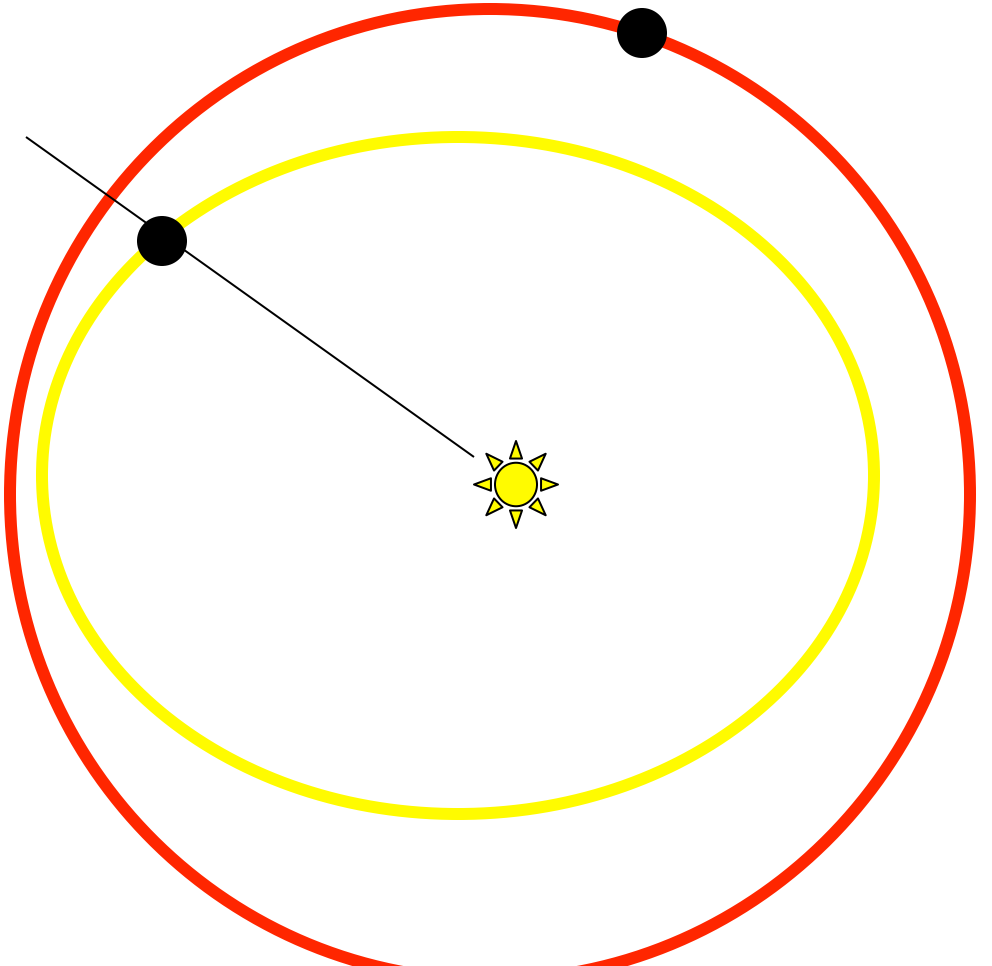
P = 10.3038 days

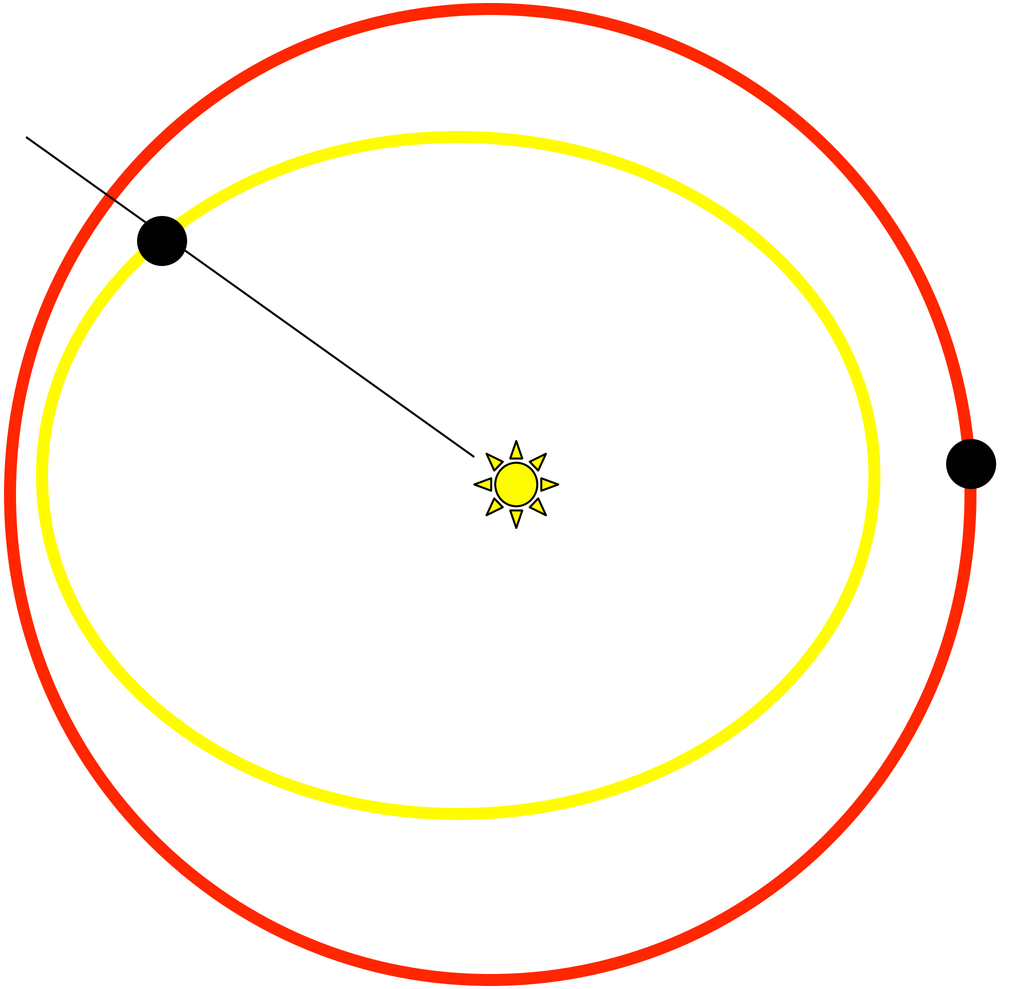
P = 13.02502 days

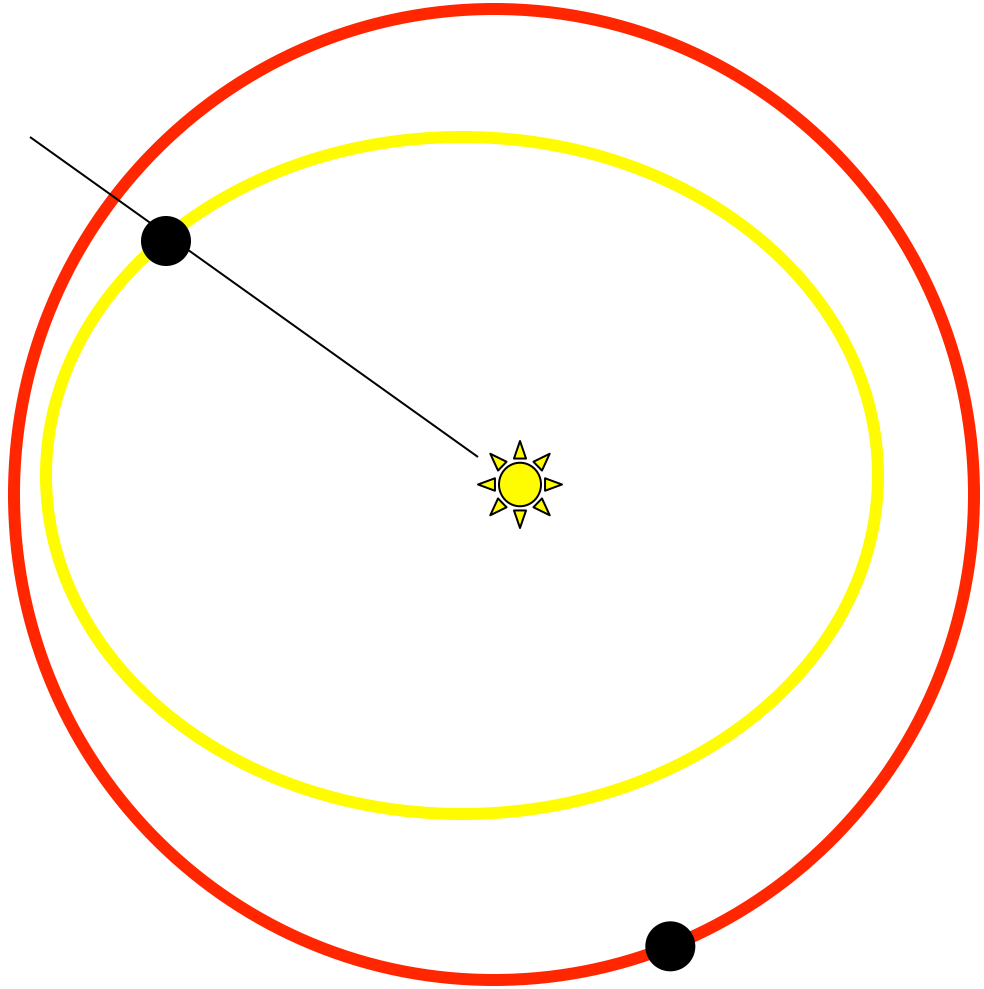
P/P=1.264 ~ 5/4

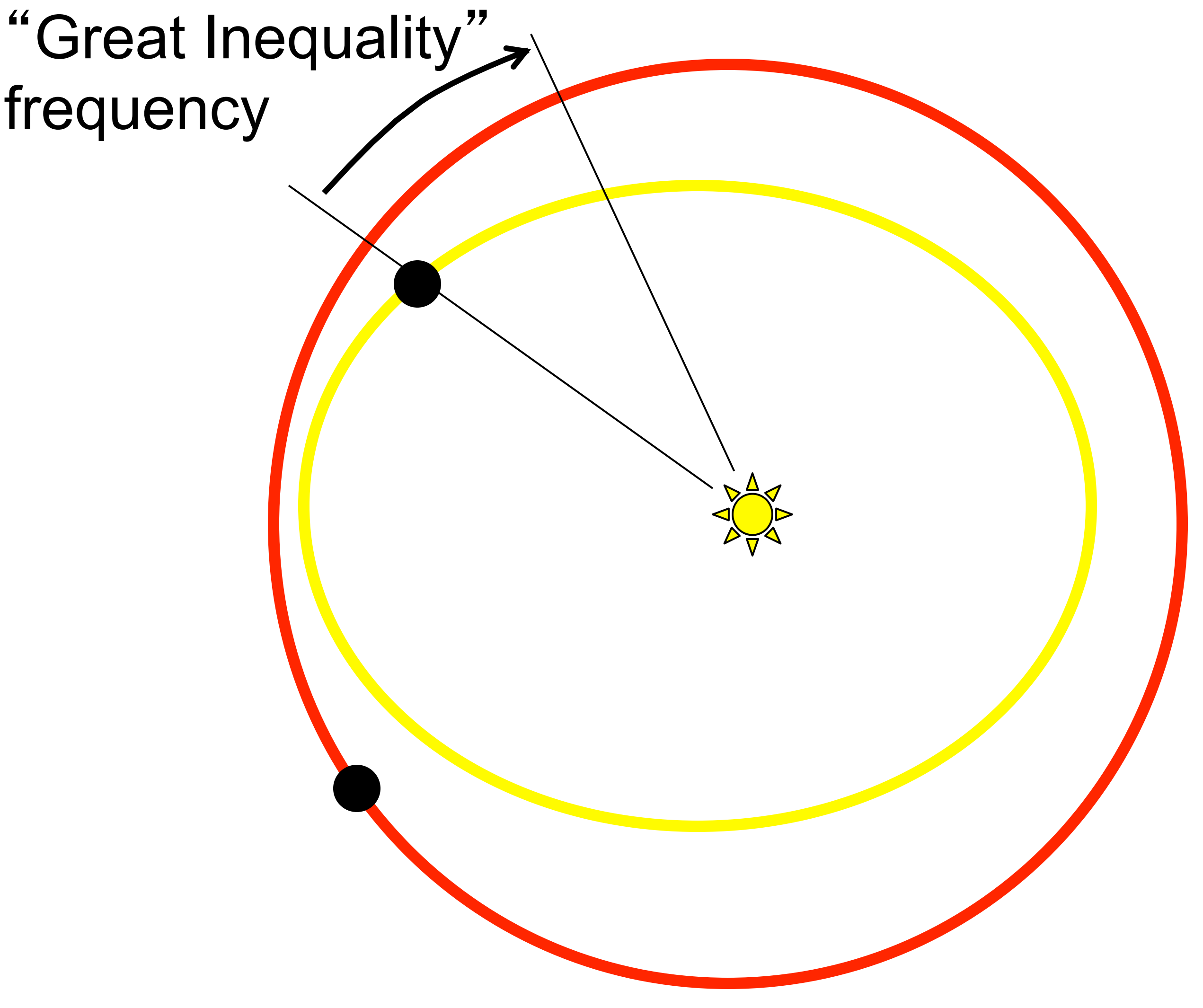
"Great Inequality" timescale:
1/(4/P-5/P) = 231 days



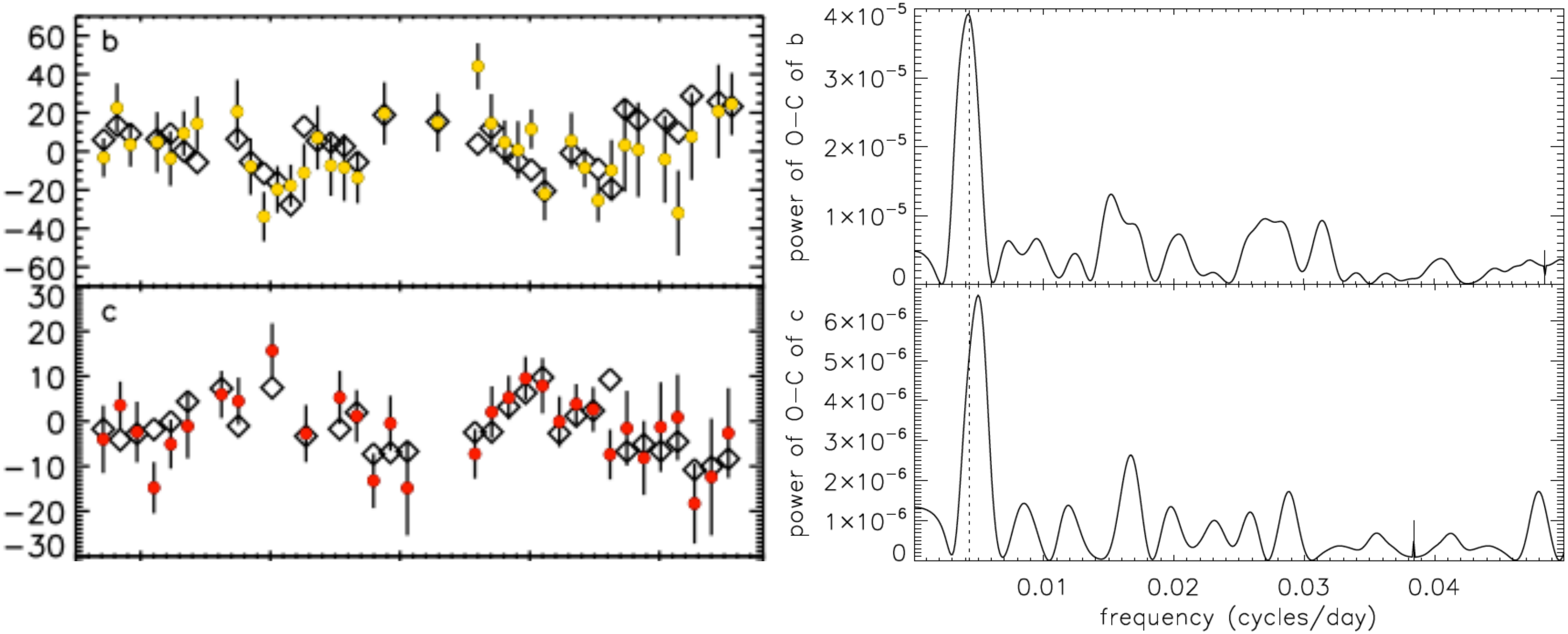




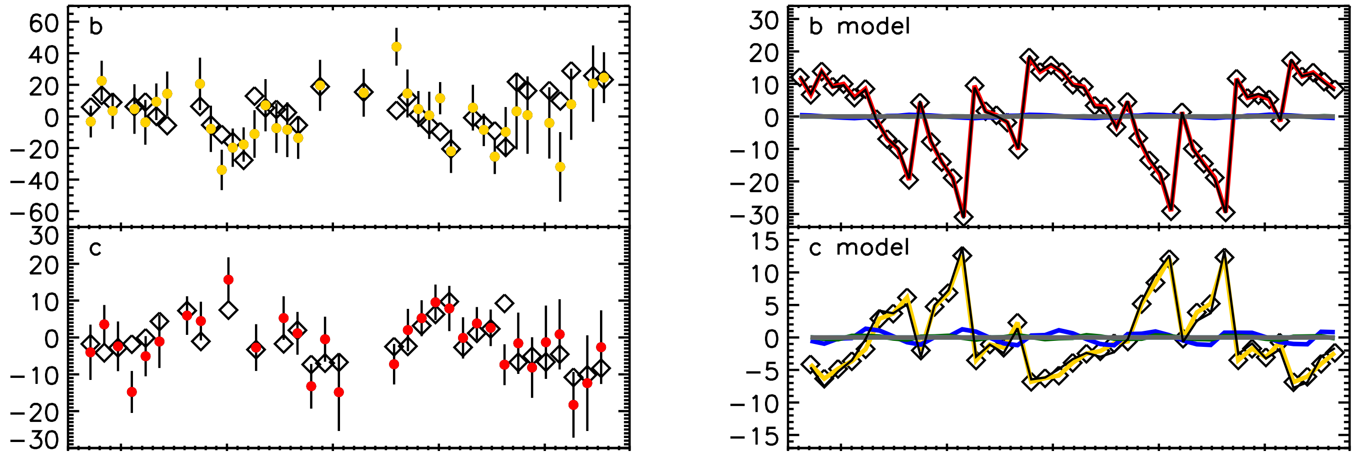




The orbits are torqued up and down (the periods fluctuate) as the line of conjunctions sweeps passed the lines of apsides.



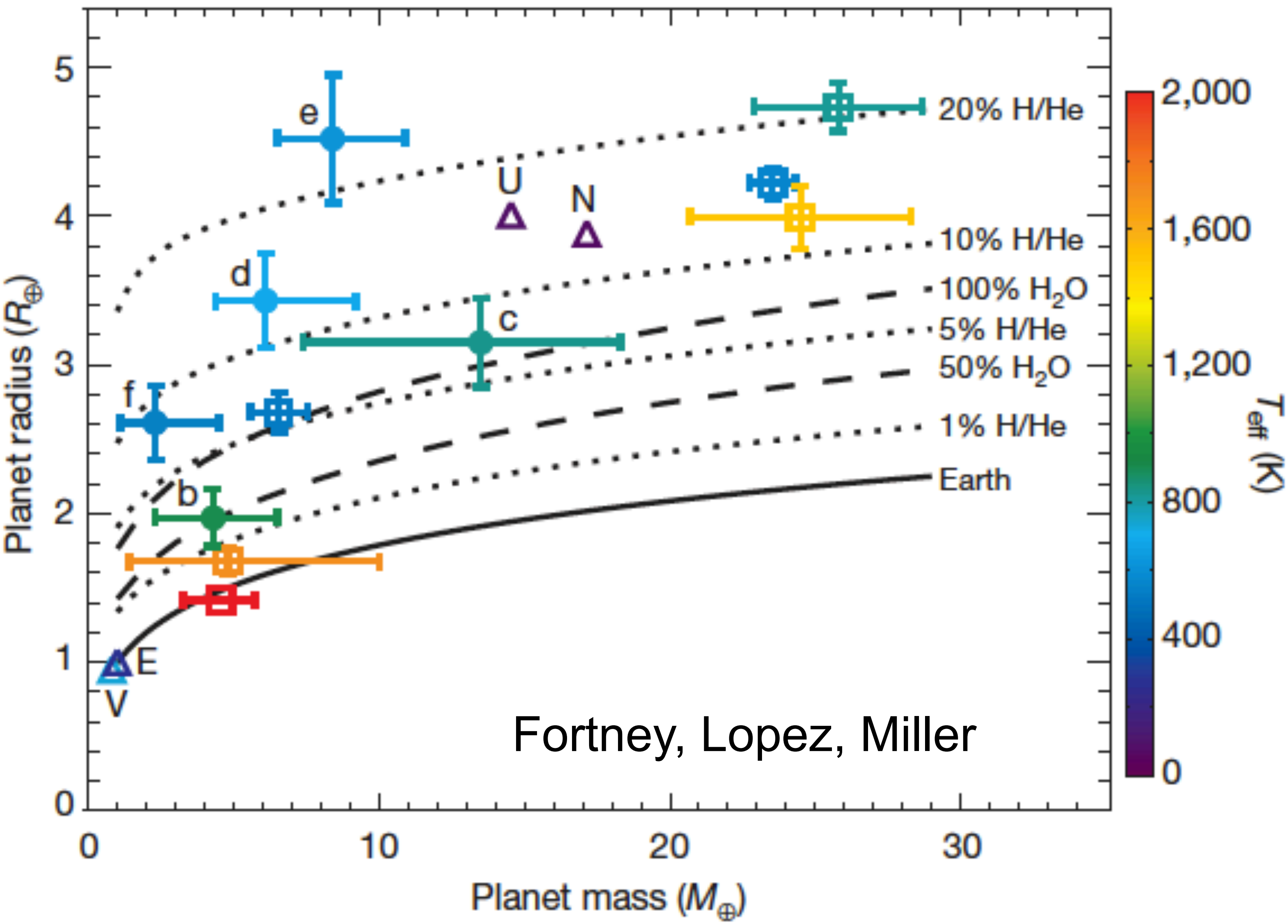
The Great Inequality is observed!



b
c
b model
c model
60
40
20
0
−20
−40
−60
30
20
10
0
−10
−20
−30
15
10
5
0
−5
−10
−15

Kepler-11 parameters

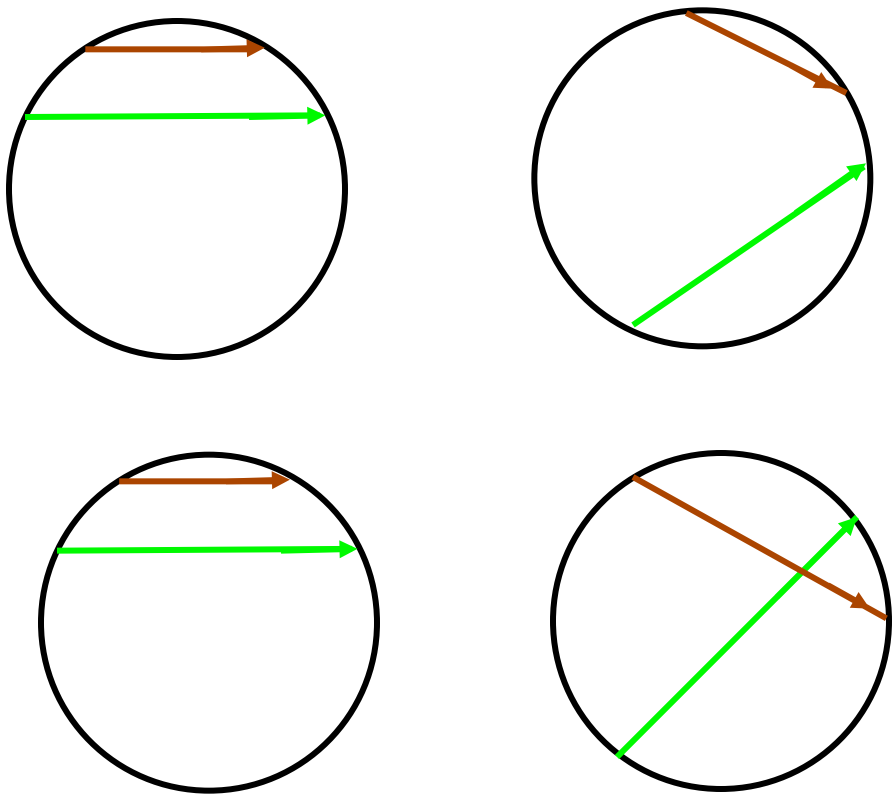
Planet	Period (days)	Radius ($R_{\oplus}$)	Mass ($M_{\oplus}$)	Density (g/cm^3)
b	**10.30375** ± 0.00016	**1.97** ± 0.19	**4.3** +2.2,-2.0	**3.1** +2.1,-1.5
c	**13.02502** ± 0.00008	**3.15** ± 0.30	**13.5** +4.8,-6.1	**2.3** +1.3,-1.1
d	**22.68719** ± 0.00021	**3.43** ± 0.32	**6.1** +3.1,-1.7	**0.9** +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 ($M_\oplus$)
0
1
2
3
4
5
0
10
20
30
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
100% H_2O
5% H/He
50% H_2O
1% H/He
Earth
2,000
1,600
1,200
800
400
0
T_{eff} (K)
Fortney, Lopez, Miller

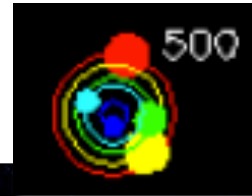
Duration changes probe Mutual Inclination

Miralda-Escude 2002



Lack of precession of Kepler-11e

➔ $i_{e\text{-}d}$, $i_{e\text{-}f} < 2°$ at 1-σ



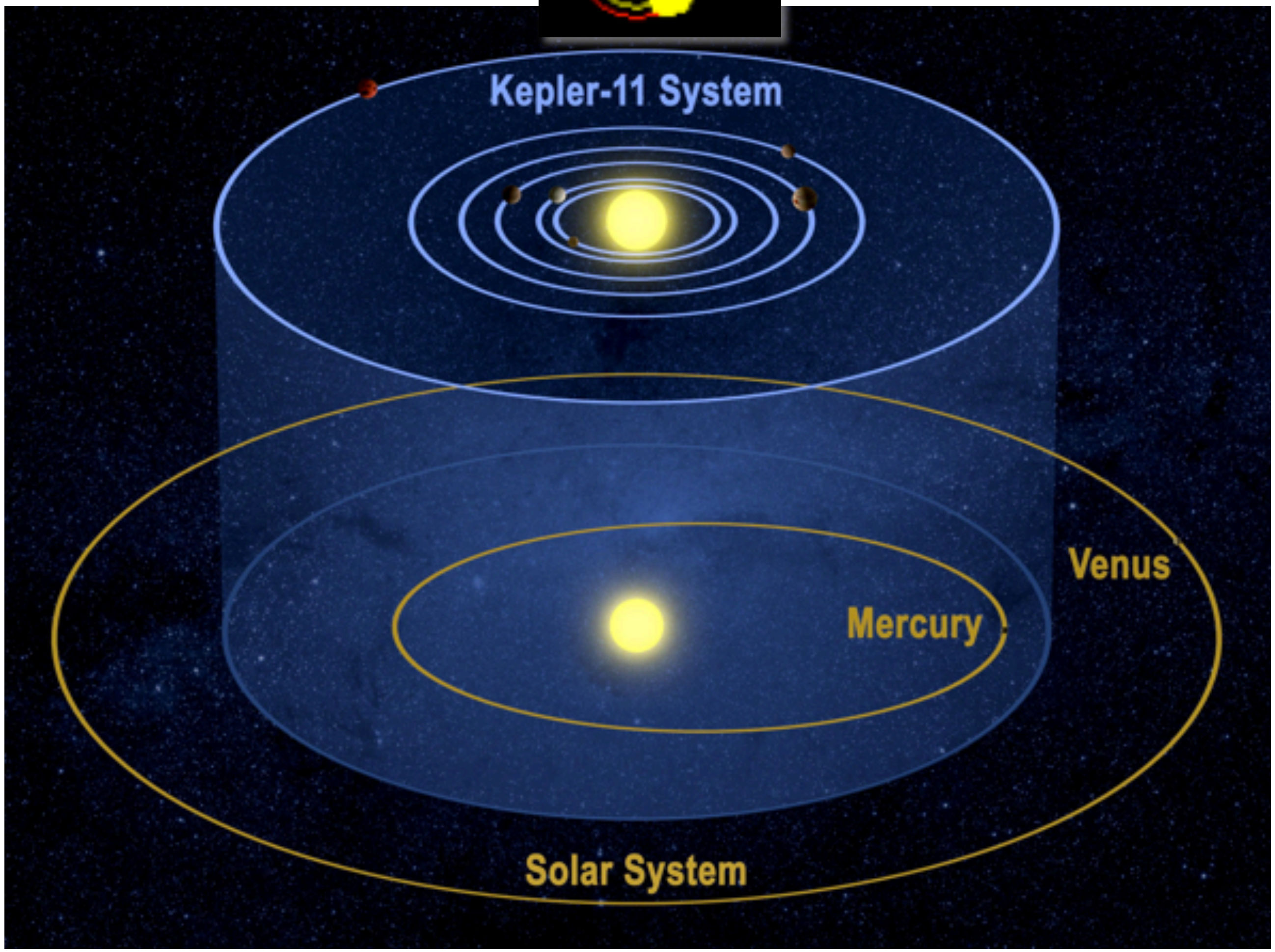
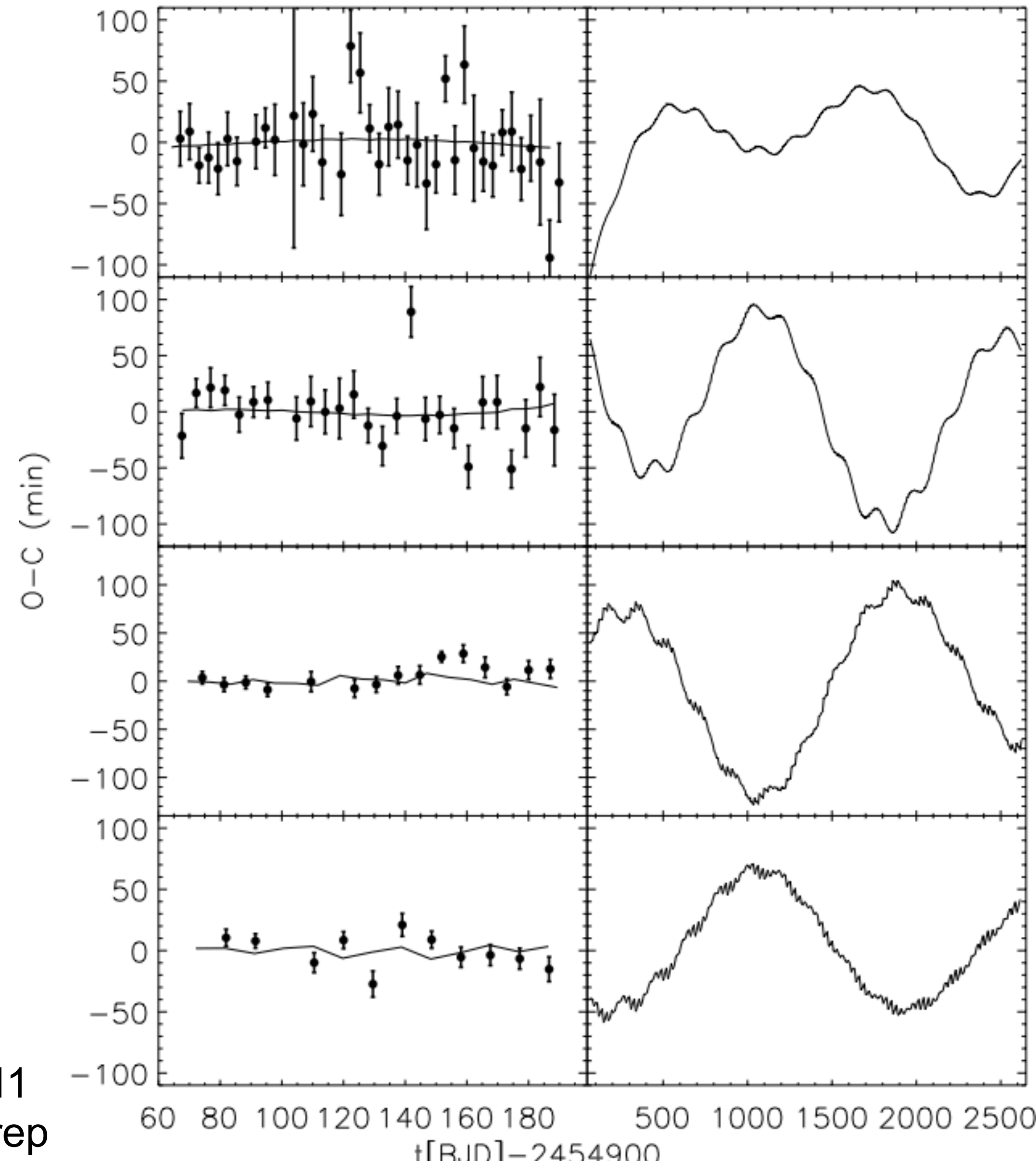


Image: NASA/Pyle

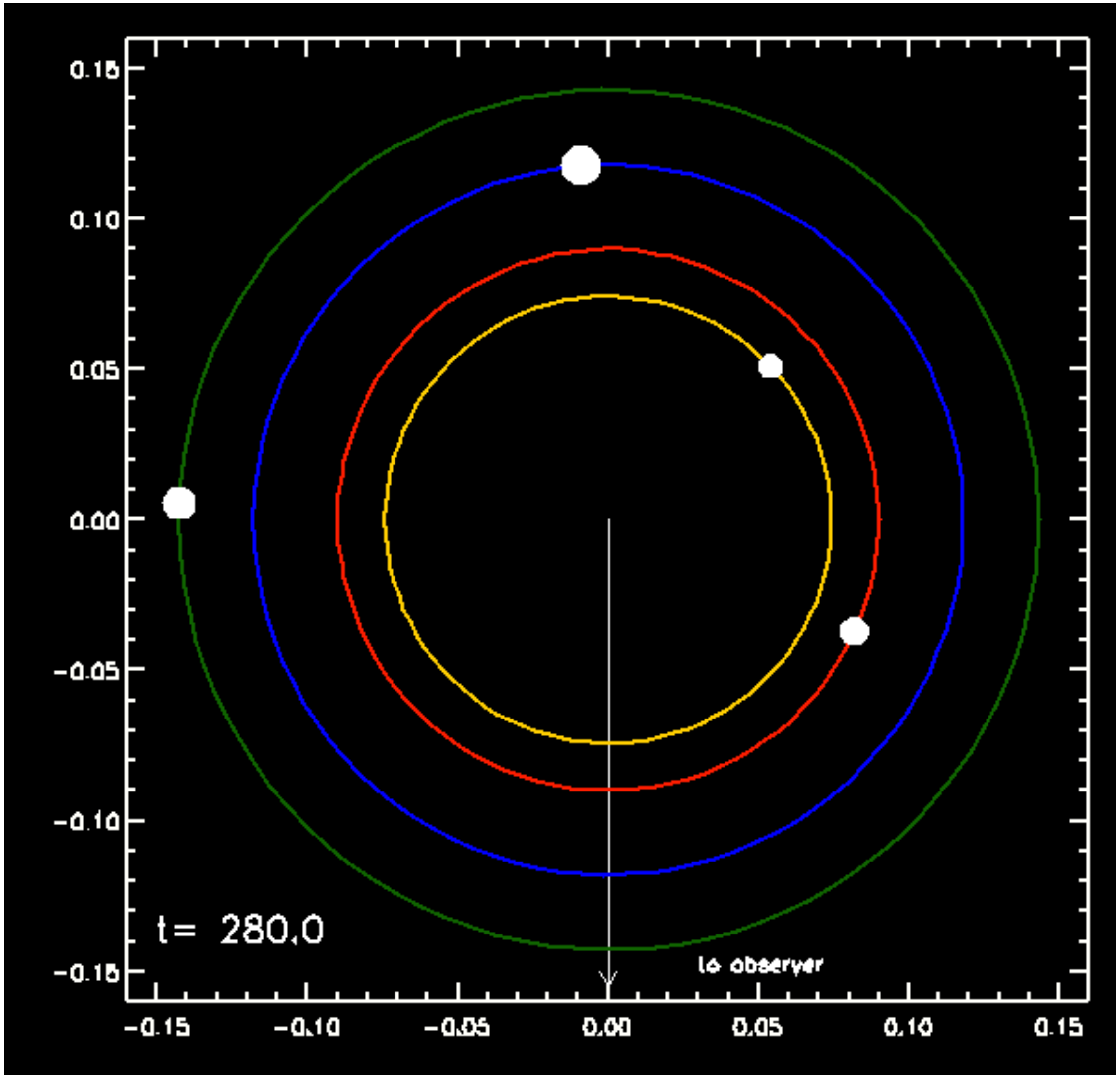
KOI-500

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



Ford, Rowe, Fabrycky et al. 2011
Ragozzine, Fabrycky et al. in prep

KOI-730: A Resonant 4-Planet System



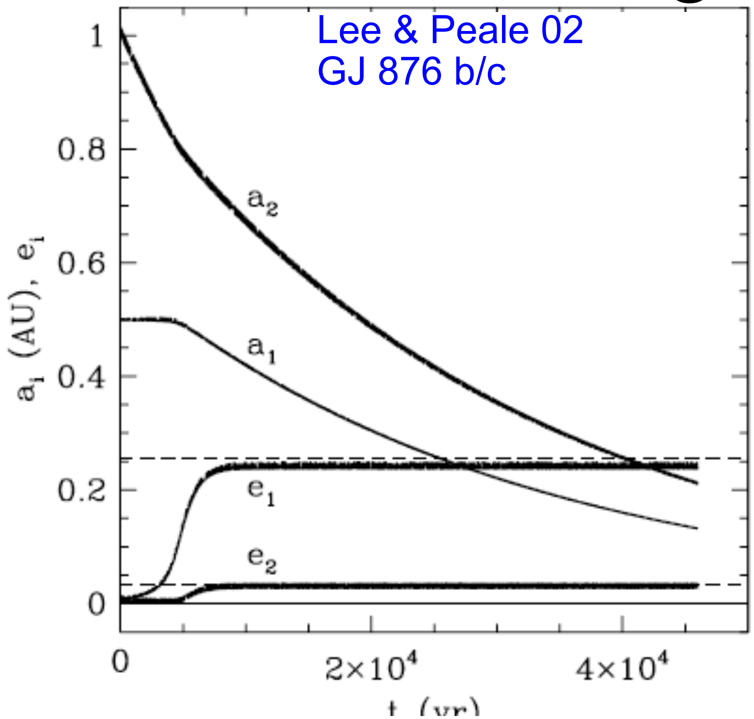
P/P=1.33341(3)

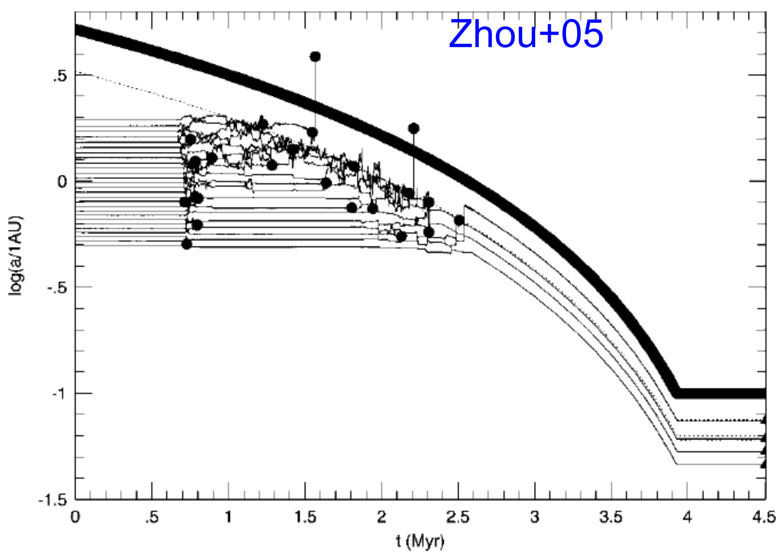
P/P=1.50157(5)

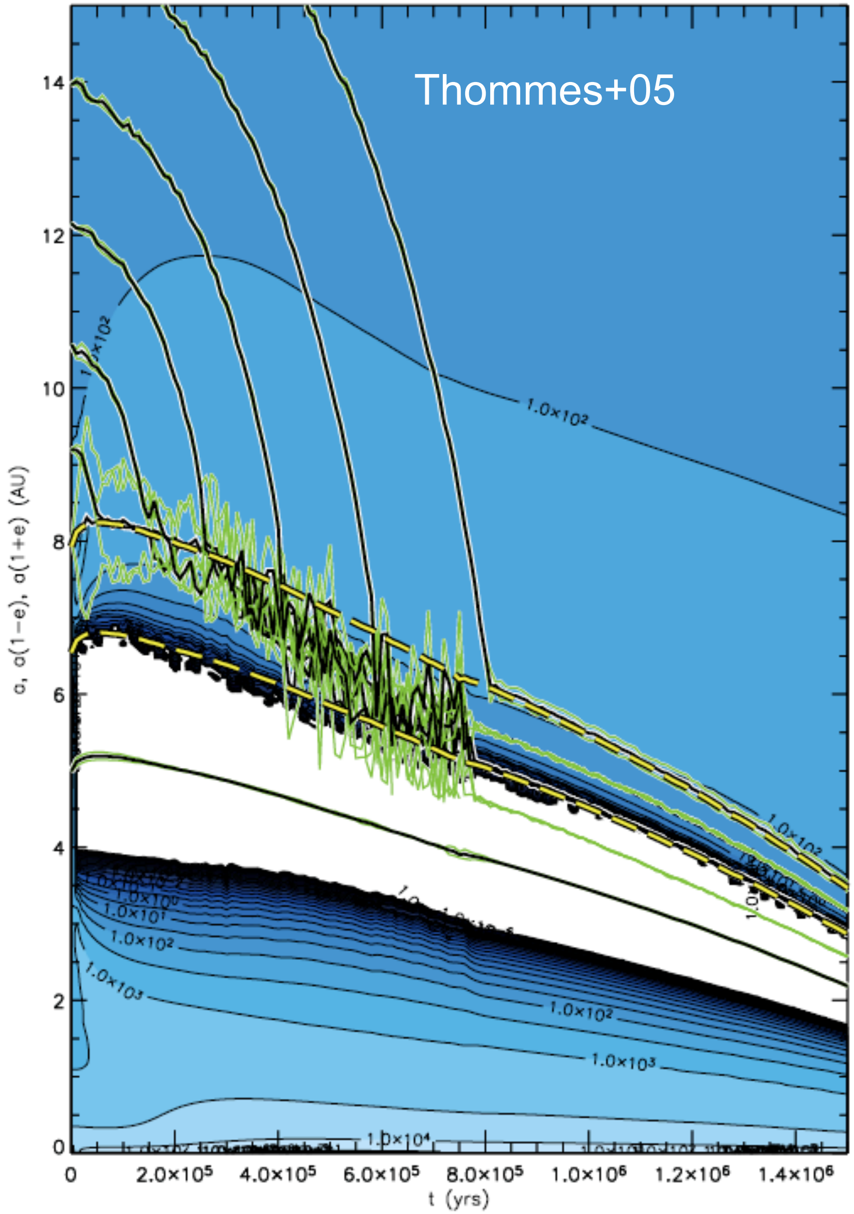
P/P=1.33411(8)

Fabrycky et al., in prep

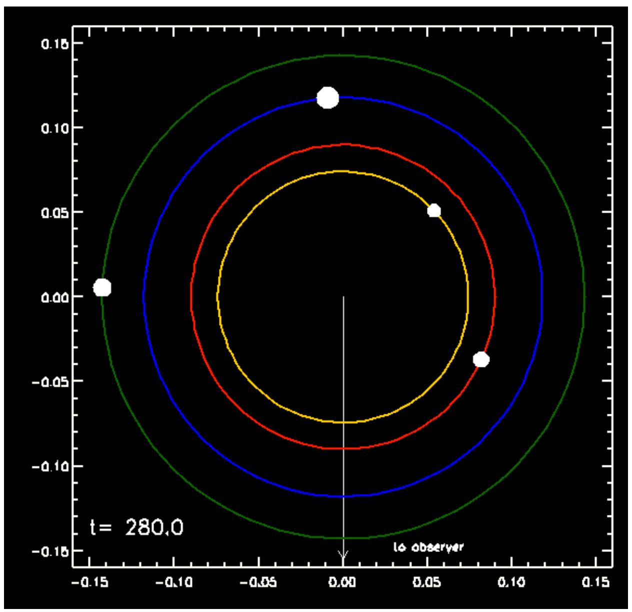
Disk Migration Theory

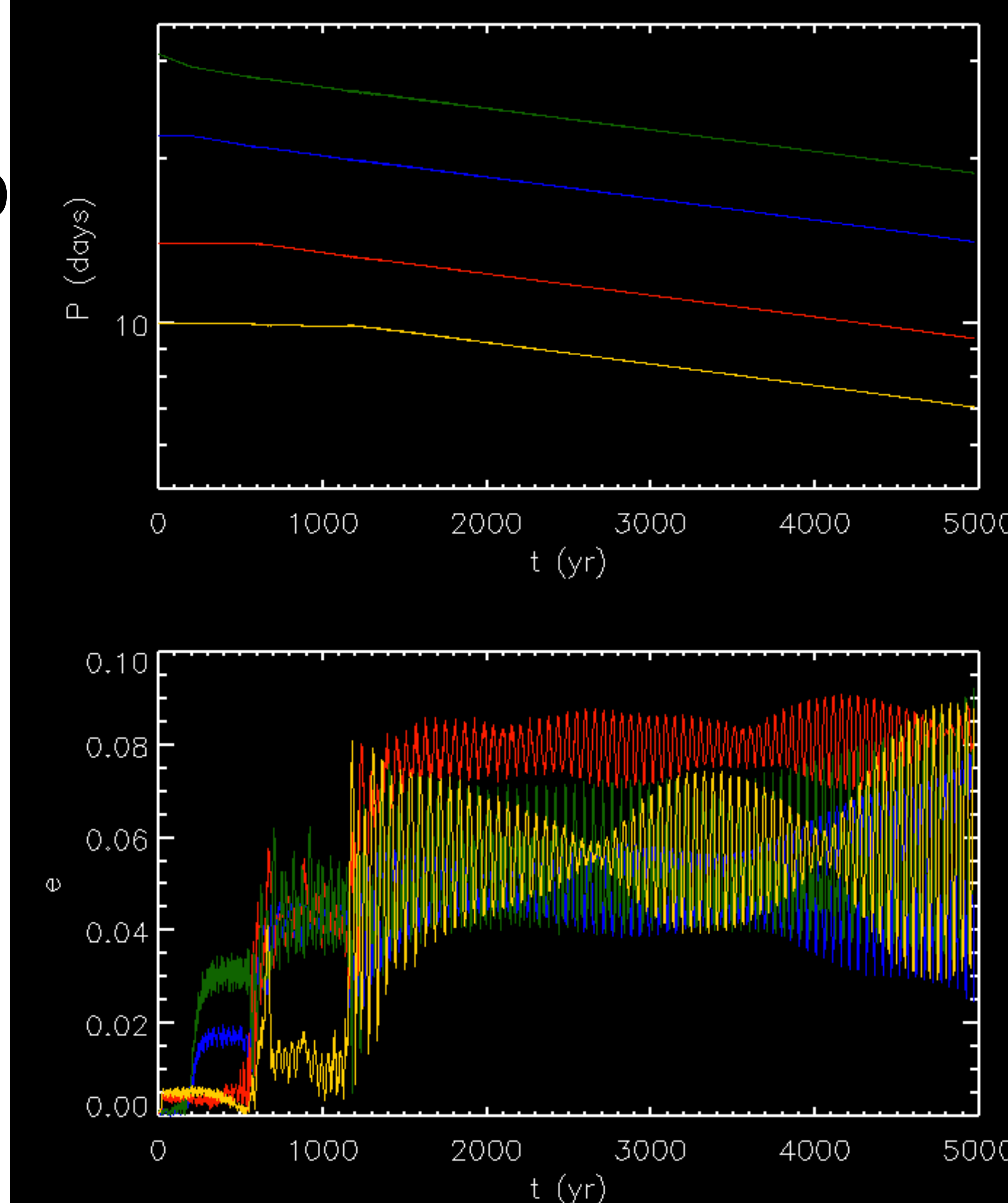






Capture into Resonance

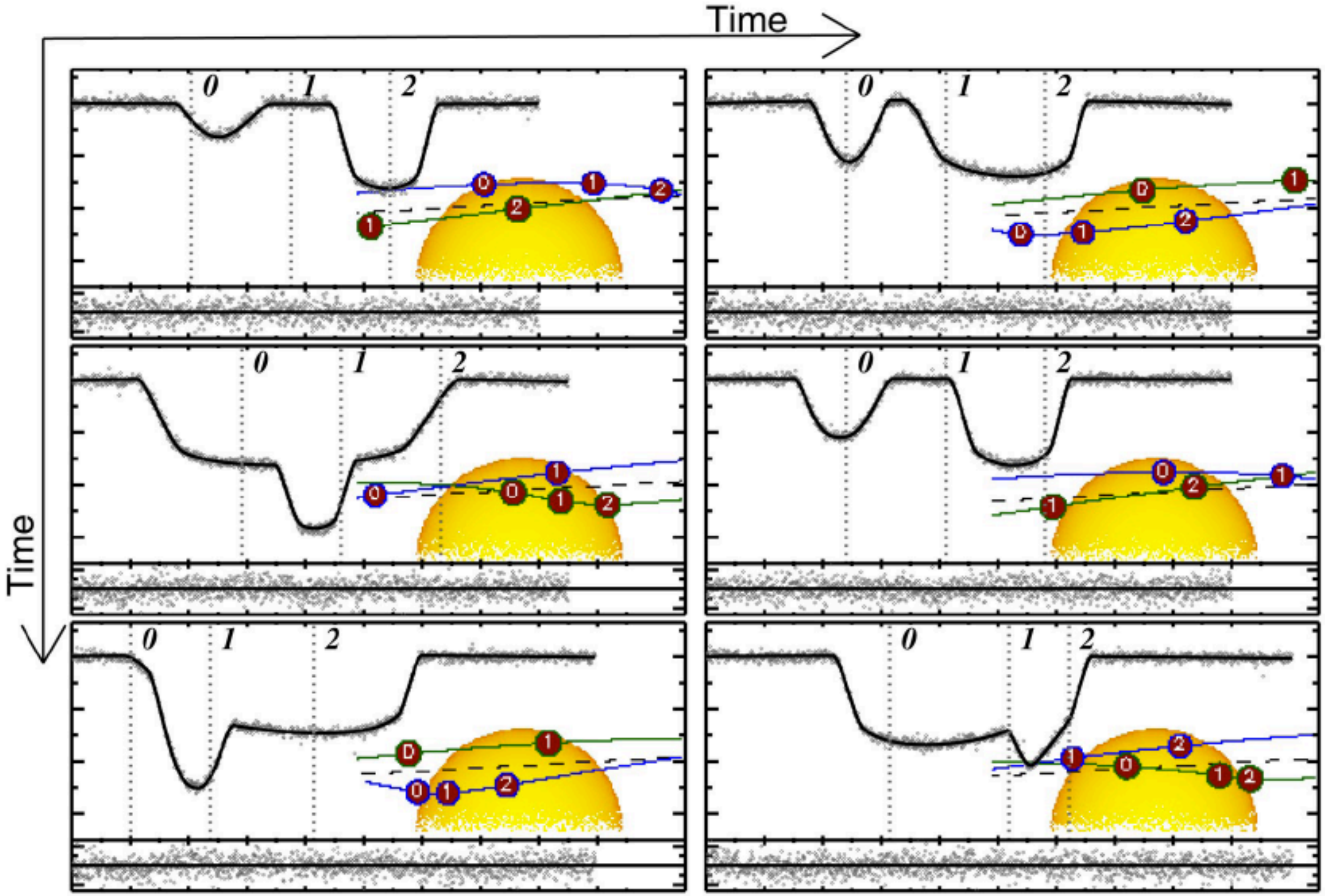




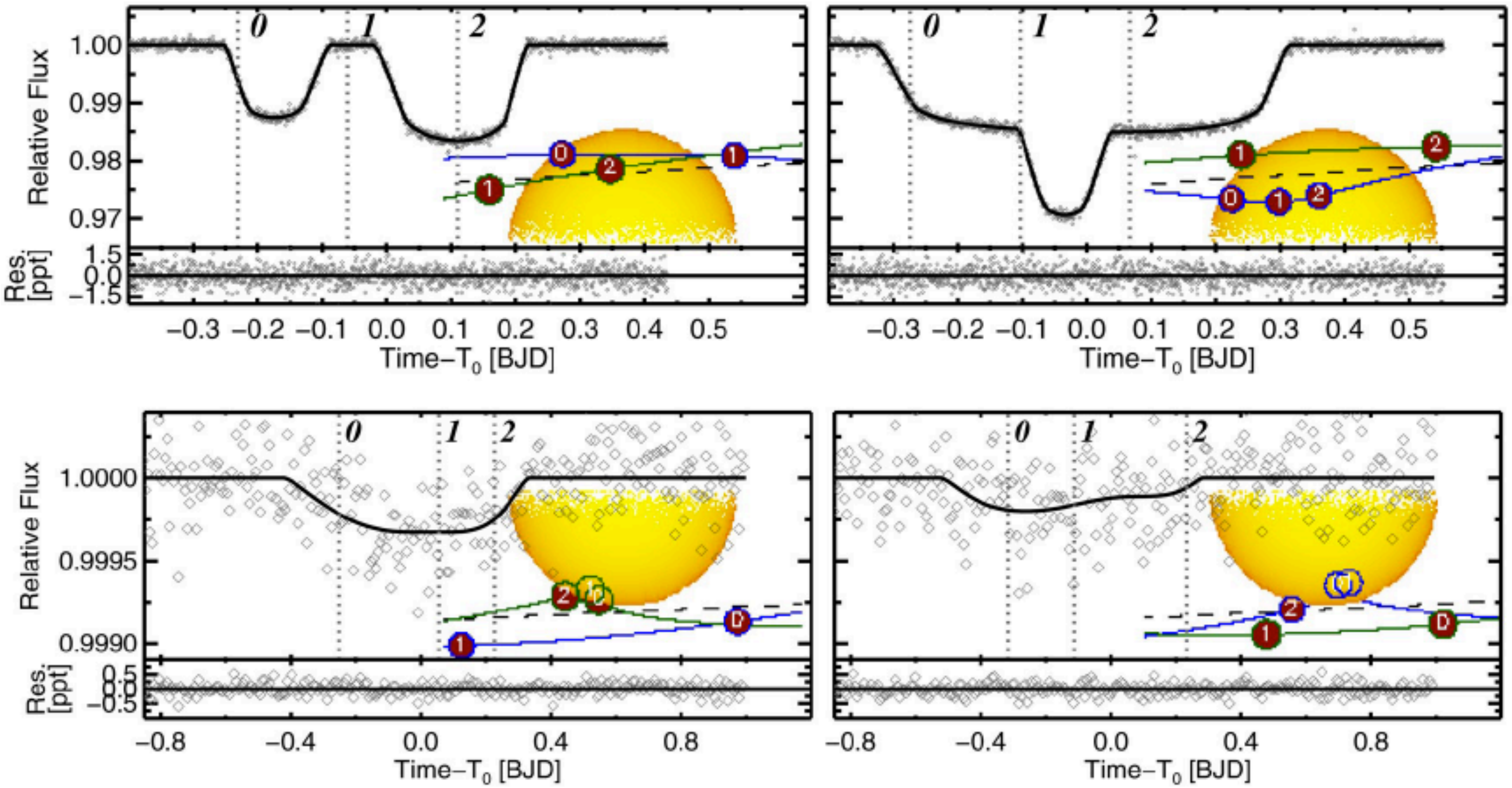
Kepler, the Multiple-Transiting Planet Machine

- 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)

KOI-126: A Triply Eclipsing Hierarchical Triple with Two Low-Mass Stars

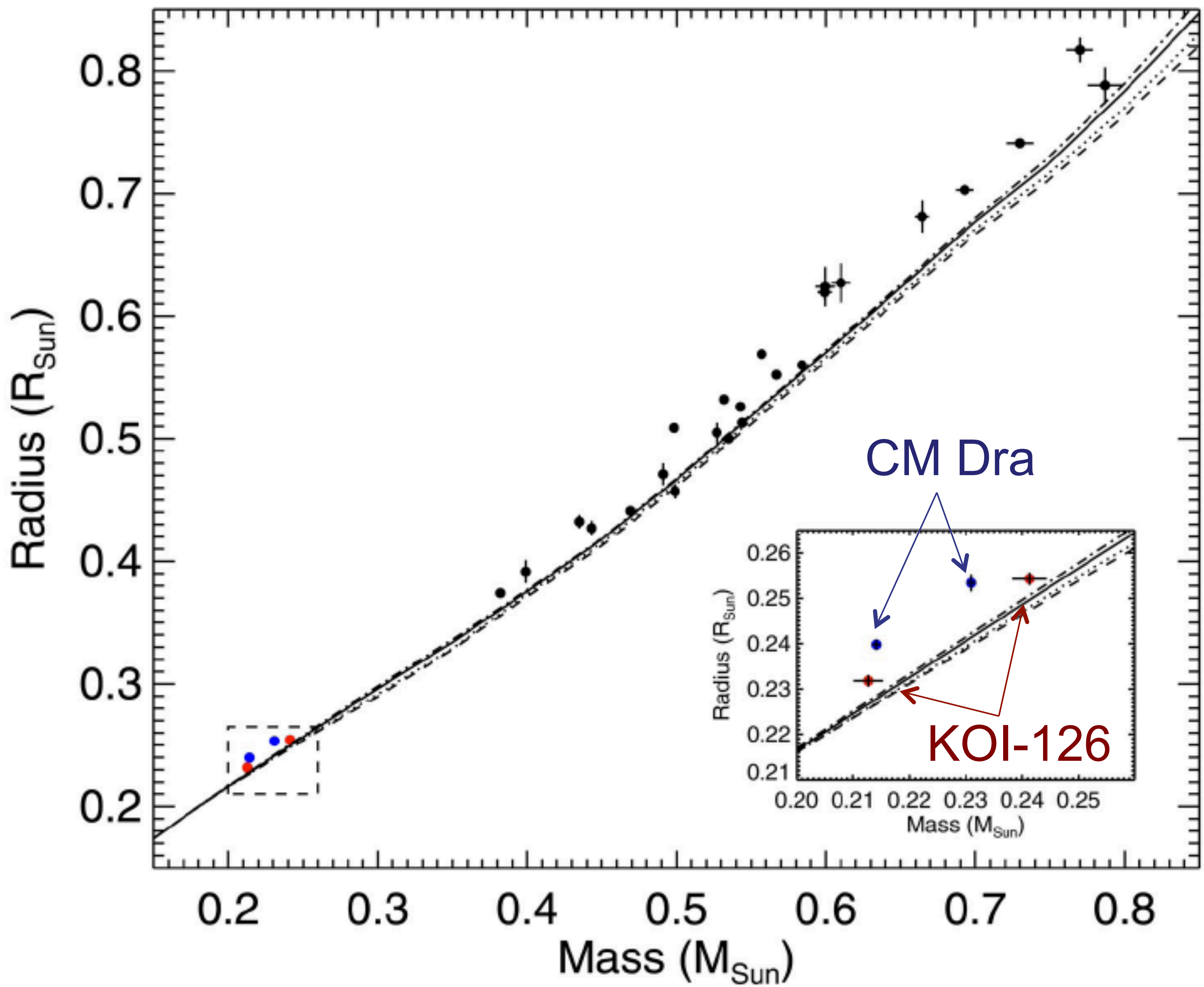


Carter, Fabrycky, Ragozzine et al. 2011, Science

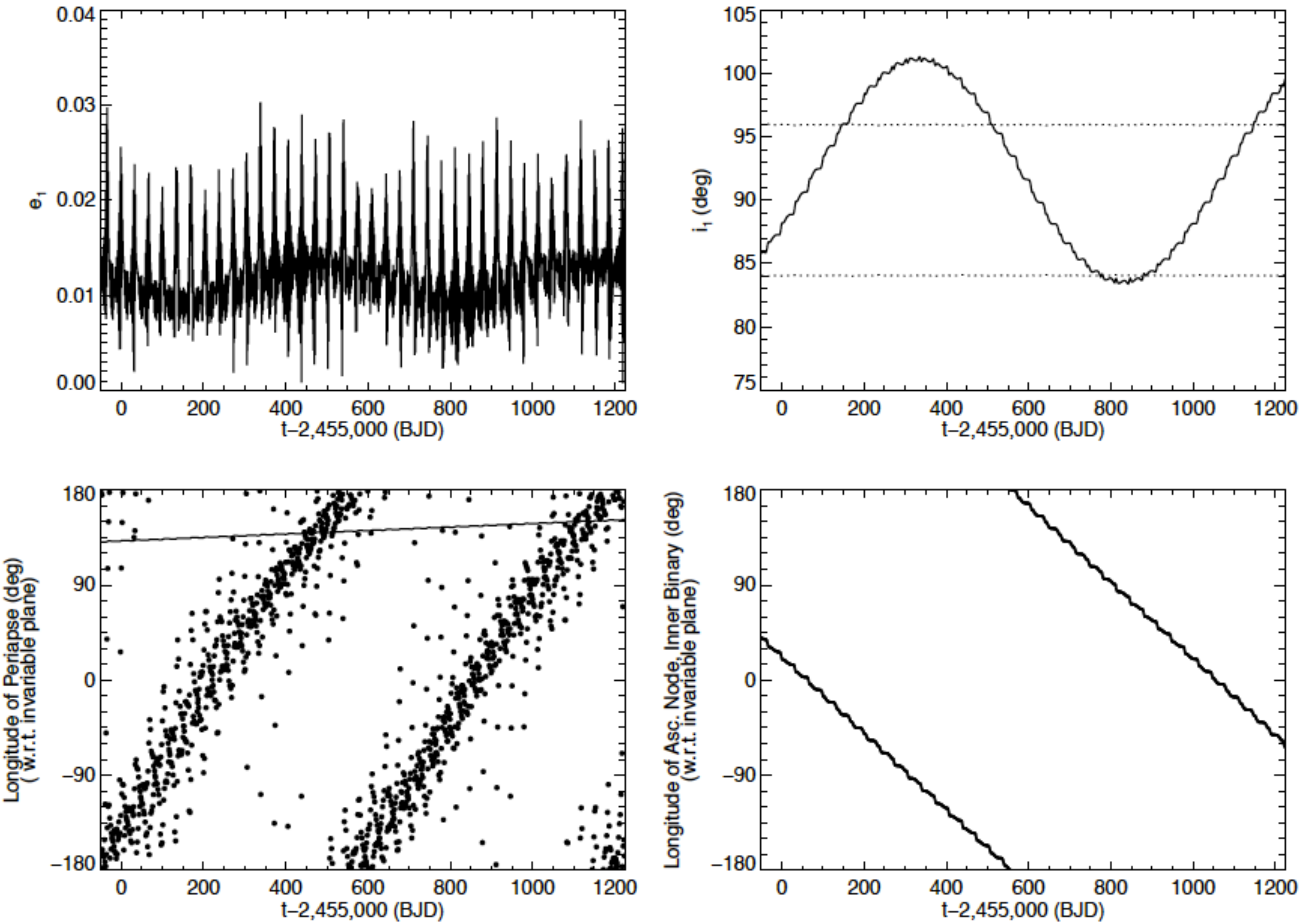


P_1 = 1.77 d, P_2 = 33.9 d

i_{mutual} =9.2^o, oscillating by 0.4^o



Radius (R_Sun)
Mass (M_Sun)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
CM Dra
KOI-126
Radius (R_Sun)
Mass (M_Sun)
0.21
0.22
0.23
0.24
0.25
0.26
0.20
0.21
0.22
0.23
0.24
0.25



e_1
t−2,455,000 (BJD)
i_1 (deg)
t−2,455,000 (BJD)
Longitude of Periapse (deg)
(w.r.t. invariable plane)
t−2,455,000 (BJD)
Longitude of Asc. Node, Inner Binary (deg)
(w.r.t. invariable plane)
t−2,455,000 (BJD)