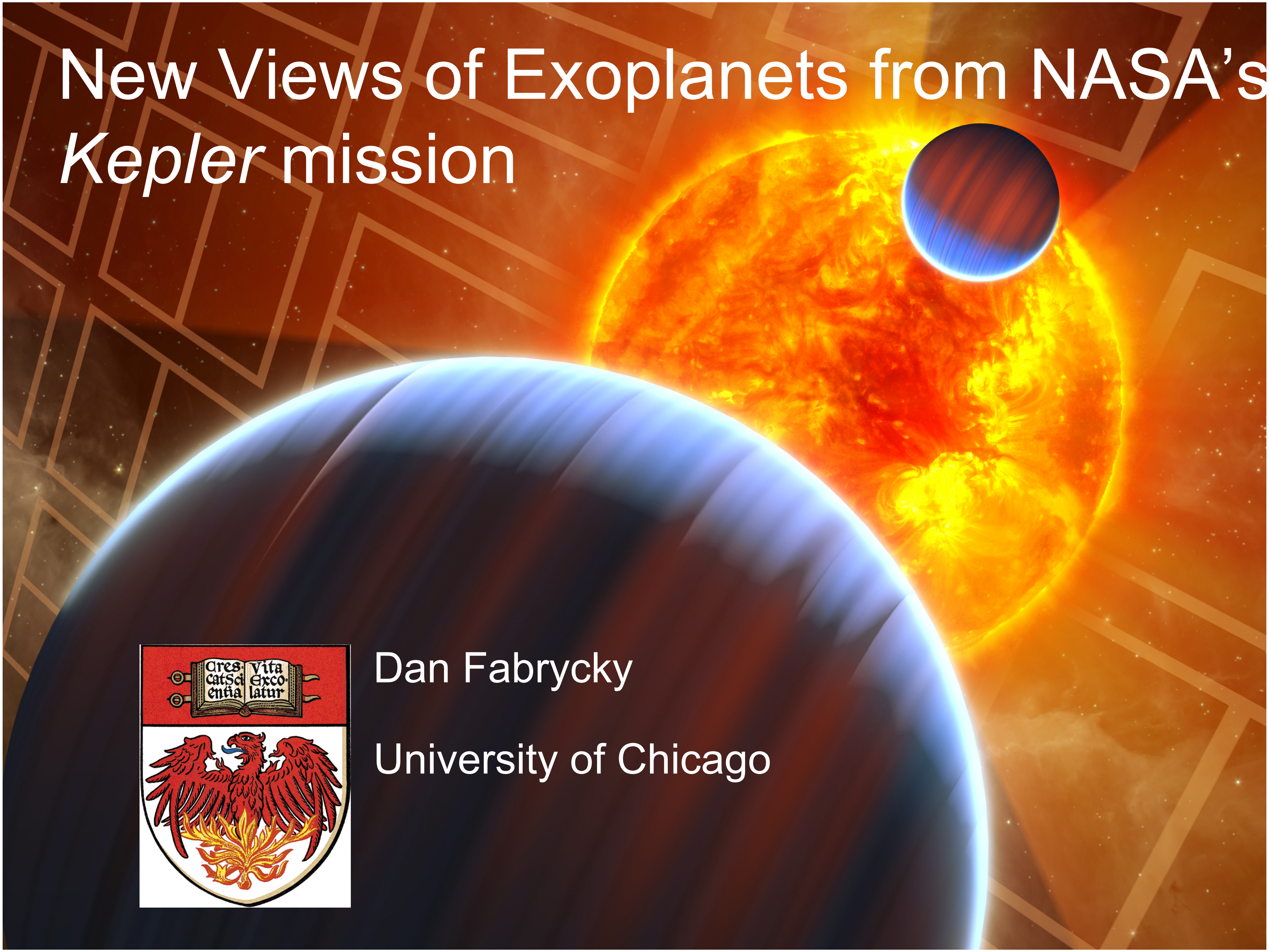
New Views of Exoplanets from NASA's *Kepler* mission

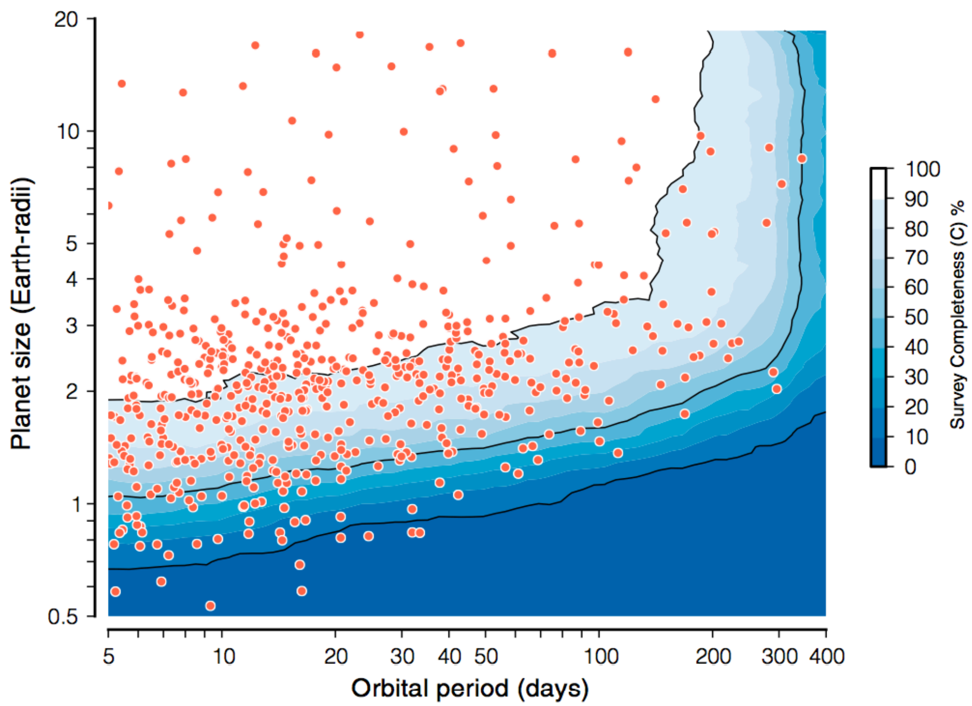


Dan Fabrycky

University of Chicago

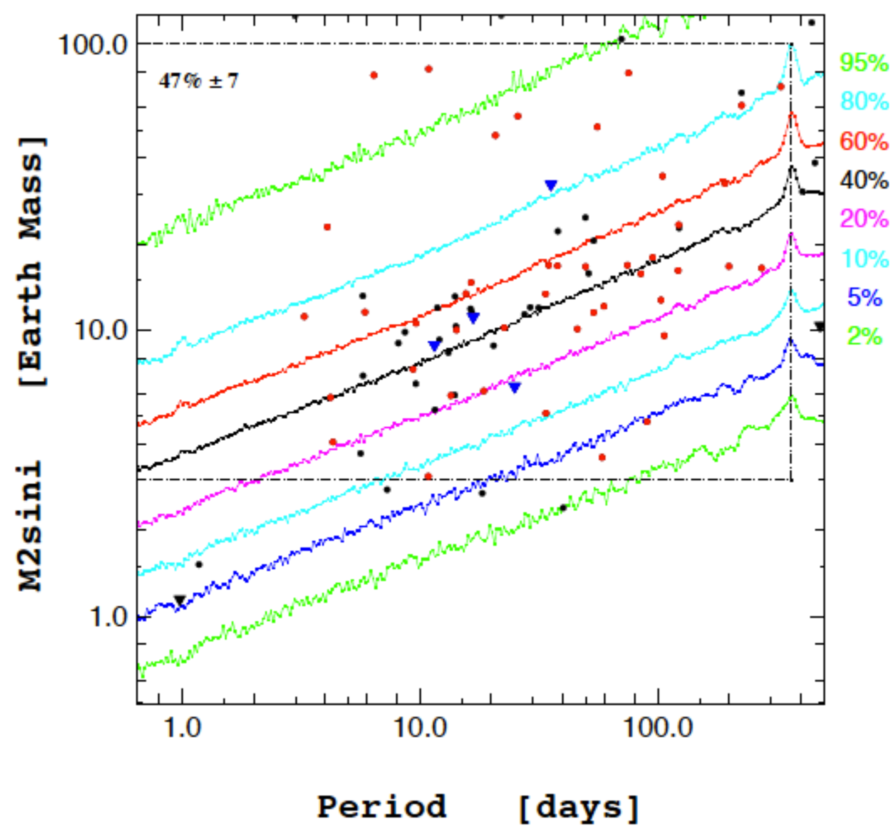
Planets are common

Transits/Kepler



(Petigura, Howard, Marcy 2013)

Doppler/HARPS



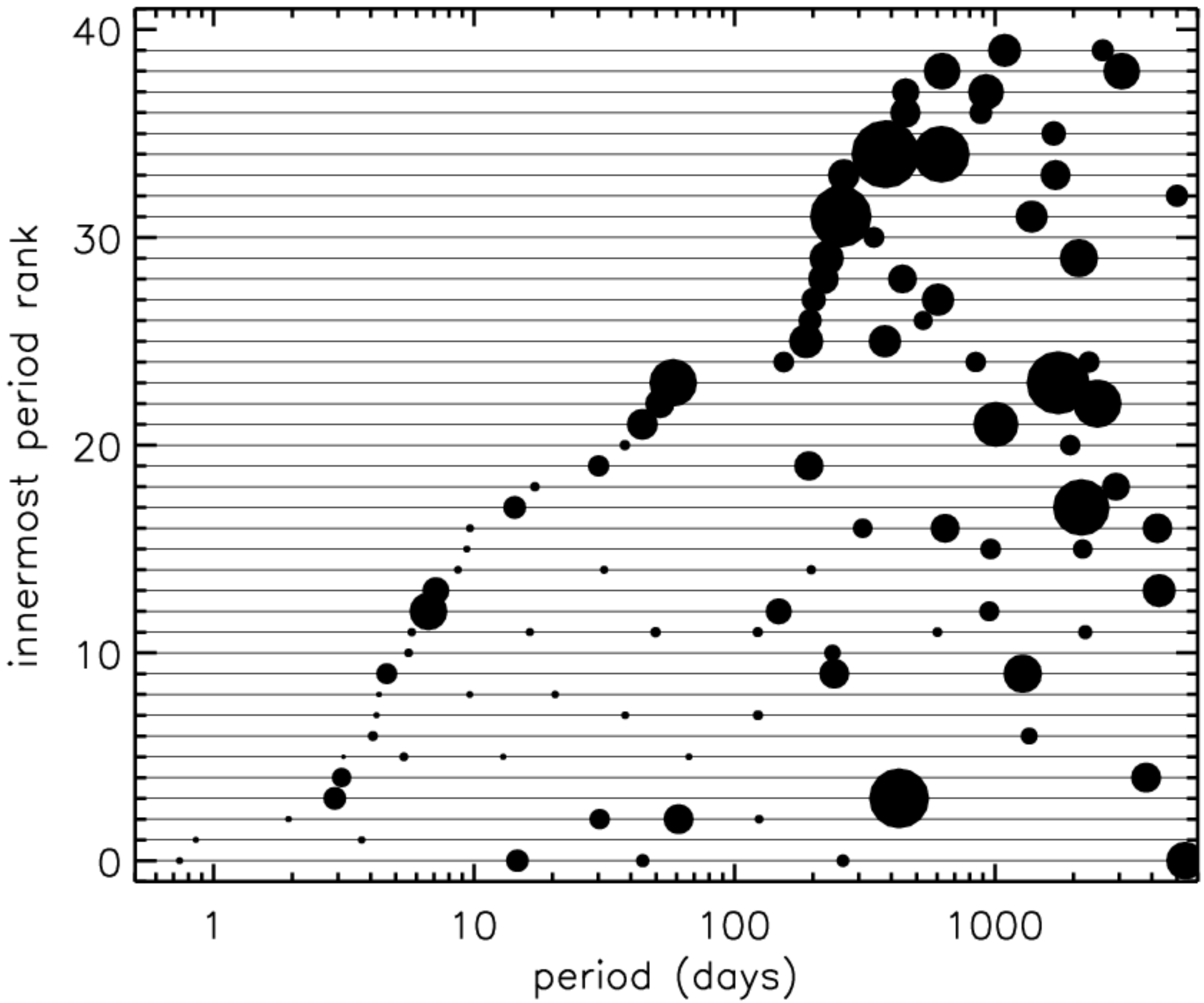
(Mayor et al. 2011)

…and small planets are the most common

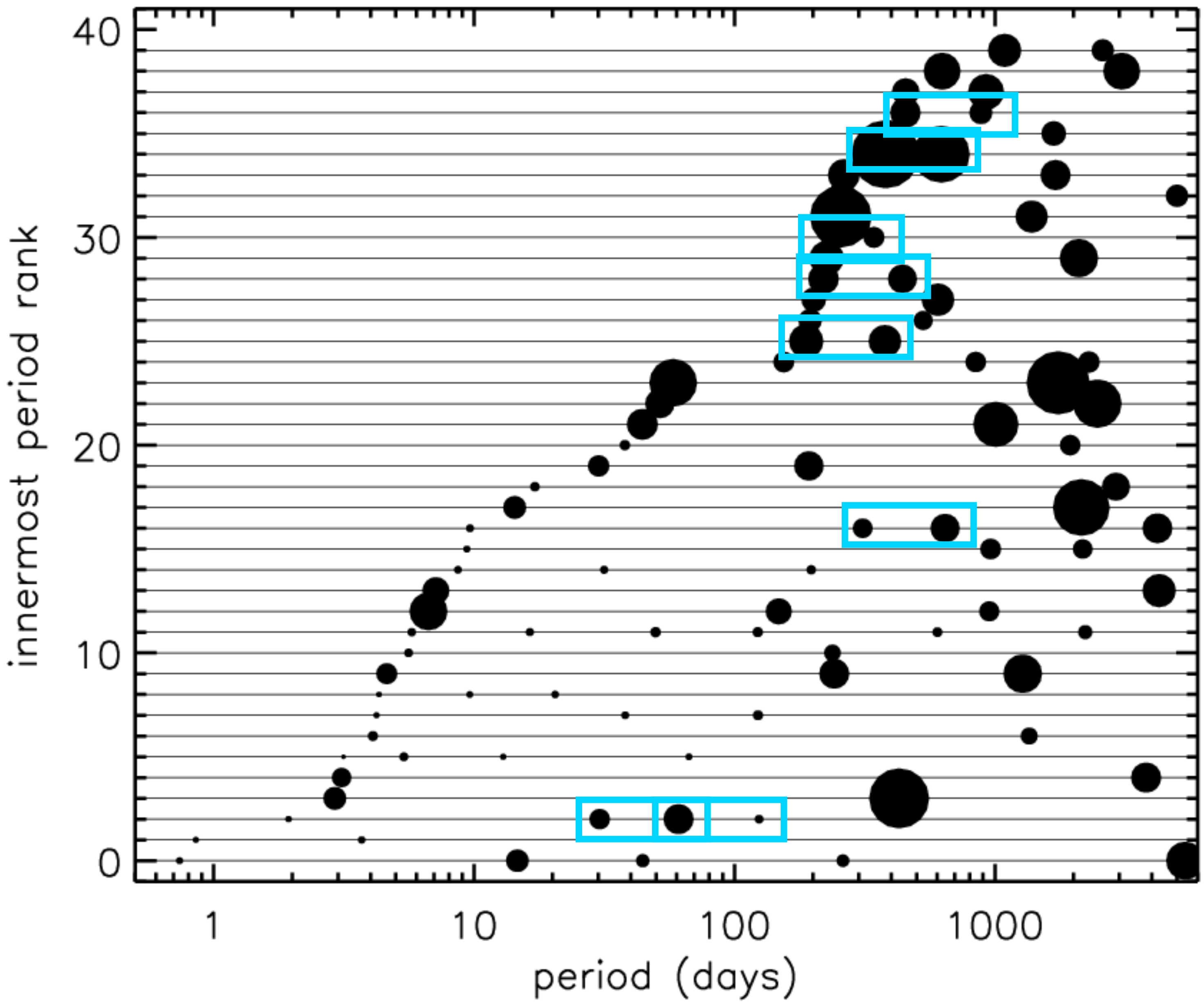
Solar System properties

- Rocky planets in close (<2 AU)
- Gas giant planets where volatile compounds could solidify (5.2,9.5 AU)
- “Ice” giant planets in the outskirts (19,30 AU)
- Low eccentricities (mostly <0.1)
- Flat relative to each other (~2 degrees of tilt)
- No orbital resonances

Radial Velocity Multiple Planets



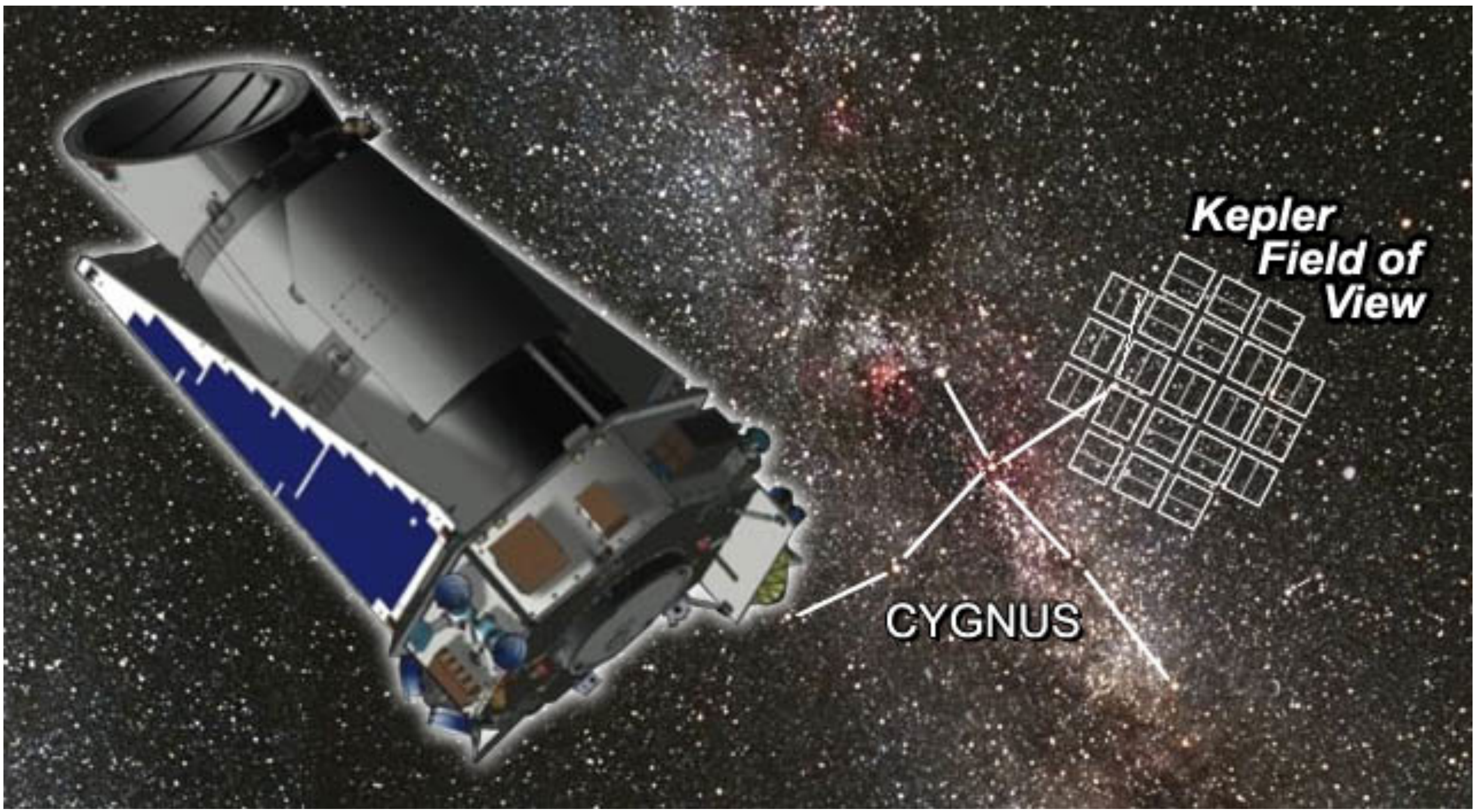
Resonances

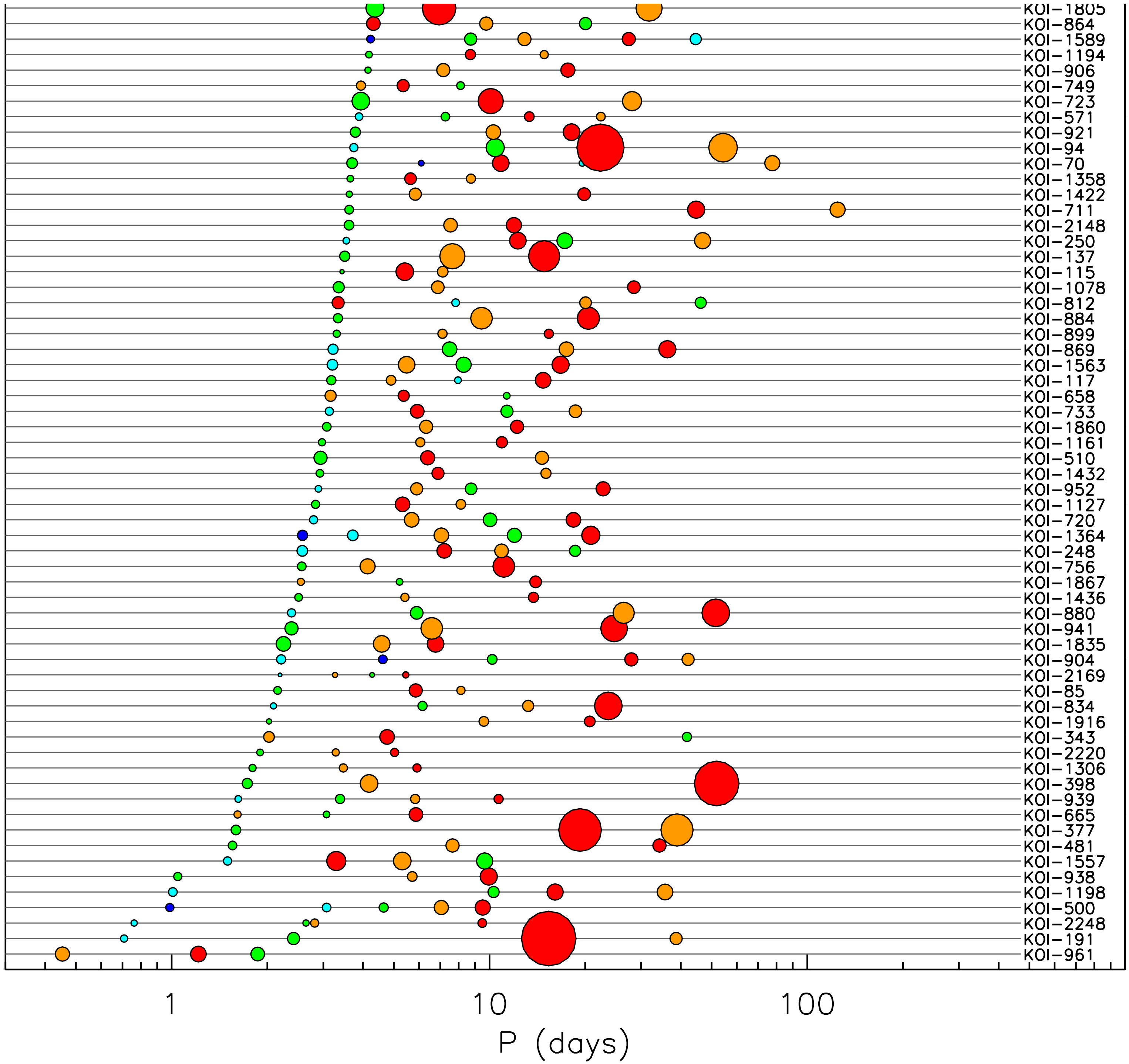


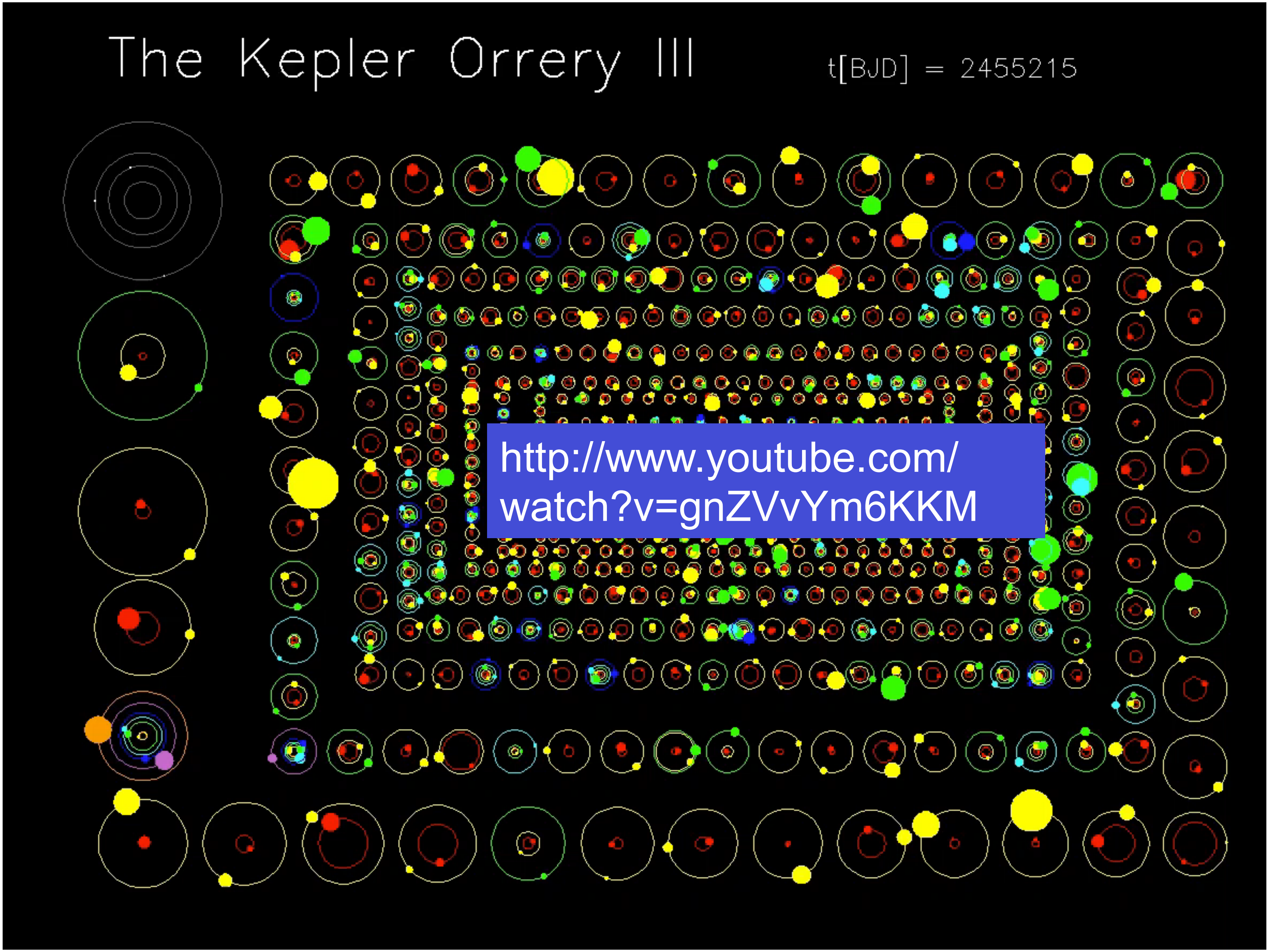
Kepler Mission (*NASA, 2009-2013**)

**resurrection being planned*

- A search for Earth-like planets in transit
- Photometry of 150,000 stars
- ~20 ppm in 6 hours; 30 minute cadence
- In heliocentric orbit

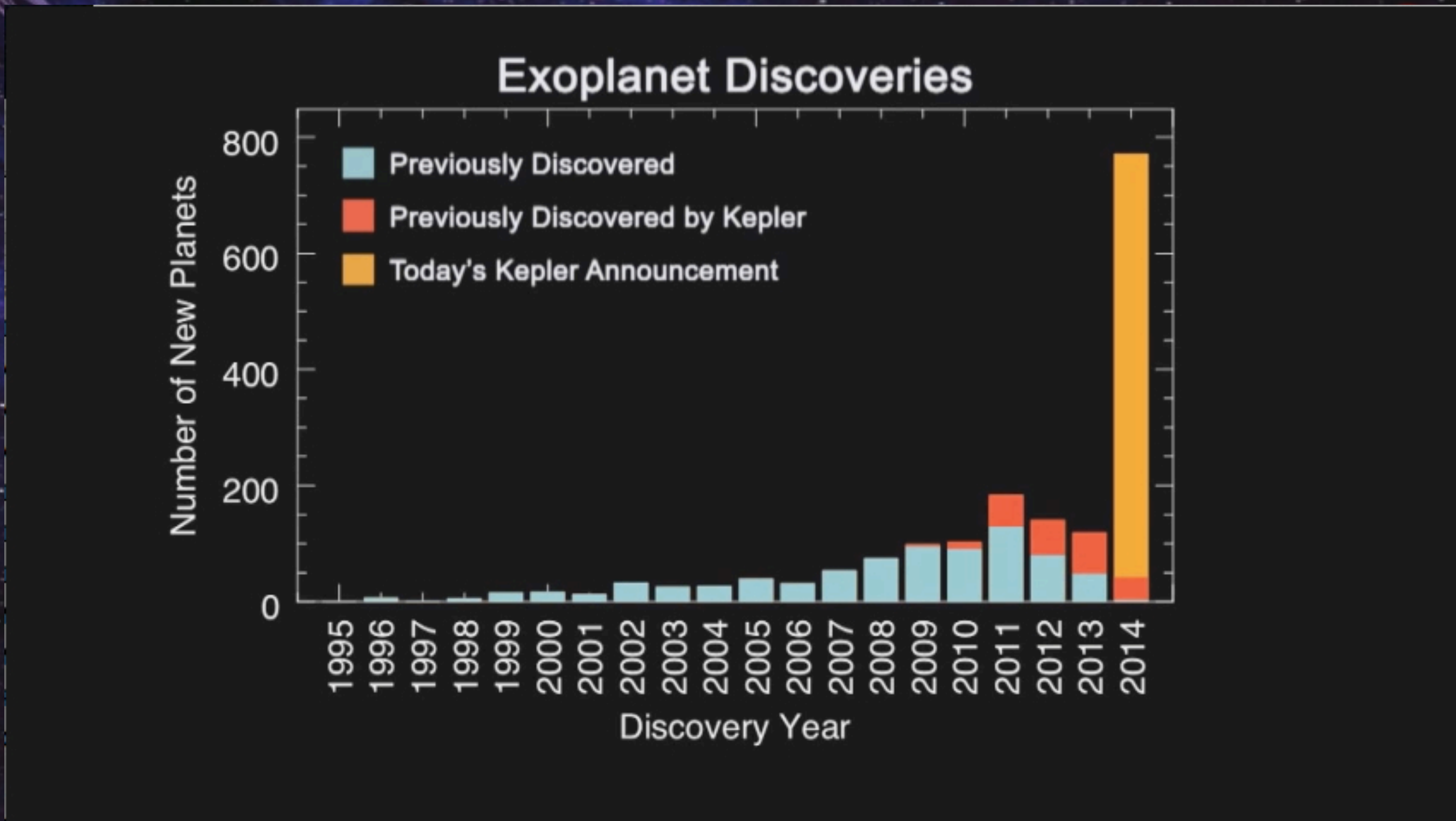


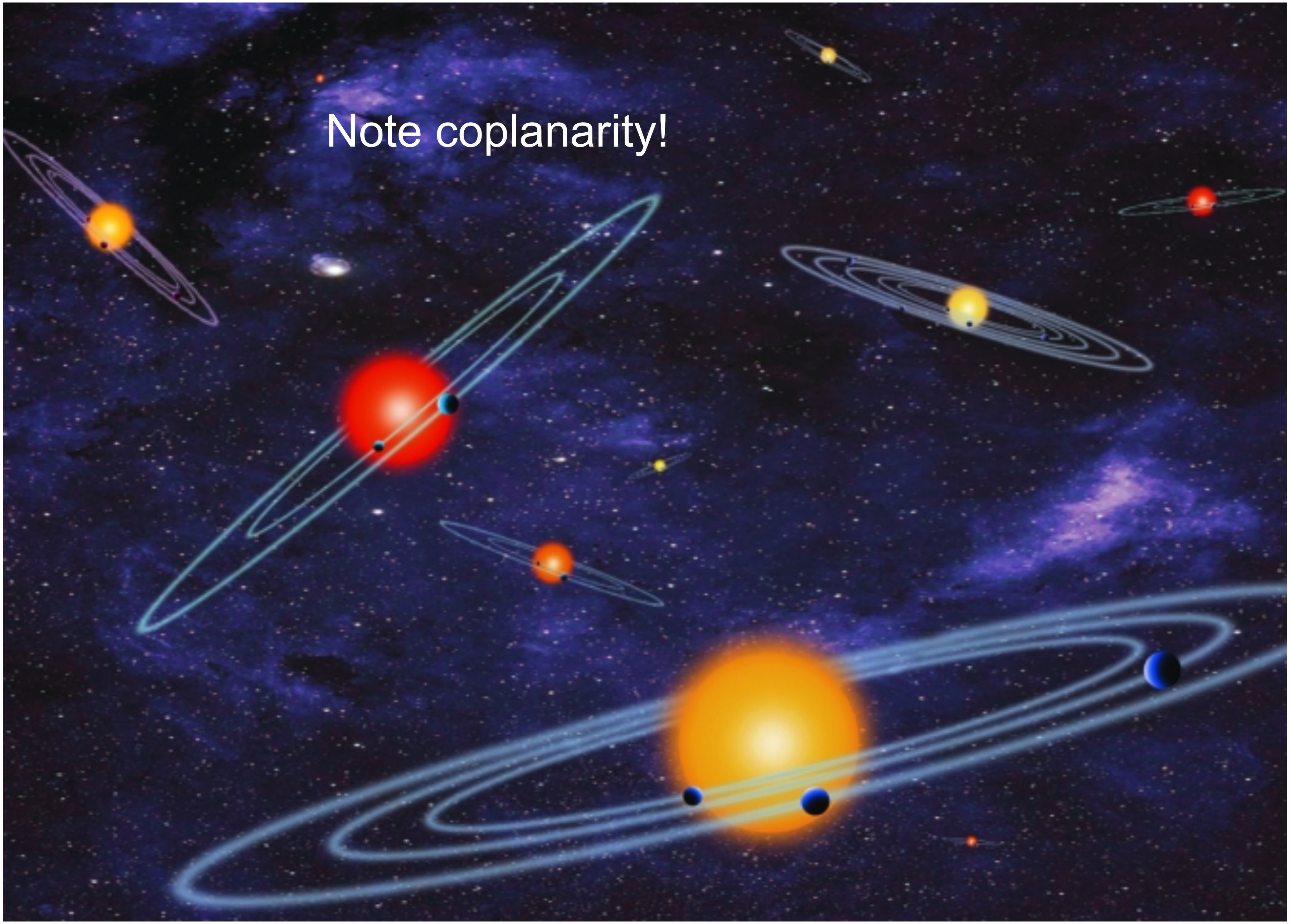

KOI−1805
KOI−864
KOI−1589
KOI−1194
KOI−906
KOI−749
KOI−723
KOI−571
KOI−921
KOI−94
KOI−70
KOI−1358
KOI−1422
KOI−711
KOI−2148
KOI−250
KOI−137
KOI−115
KOI−1078
KOI−812
KOI−884
KOI−899
KOI−869
KOI−1563
KOI−117
KOI−658
KOI−733
KOI−1860
KOI−1161
KOI−510
KOI−1432
KOI−952
KOI−1127
KOI−720
KOI−1364
KOI−248
KOI−756
KOI−1867
KOI−1436
KOI−880
KOI−941
KOI−1835
KOI−904
KOI−2169
KOI−85
KOI−834
KOI−1916
KOI−343
KOI−2220
KOI−1306
KOI−398
KOI−939
KOI−665
KOI−377
KOI−481
KOI−1557
KOI−938
KOI−1198
KOI−500
KOI−2248
KOI−191
KOI−961
1
10
100
P (days)


The Kepler Orrery III
t[BJD] = 2455215
http://www.youtube.com/watch?v=gnZVvYm6KKM


715 Newly Verified Planets More Than Triples the
Number of Confirmed Kepler Planets -- 2/26/14

715 Newly Verified Planets Means *Kepler* has found the majority of Exoplanets (961 of ~1790)




Note coplanarity!

Full architectures of Exoplanetary Systems?

Basic facts:

- Planet number
- Masses
- Radii

Dynamical properties:

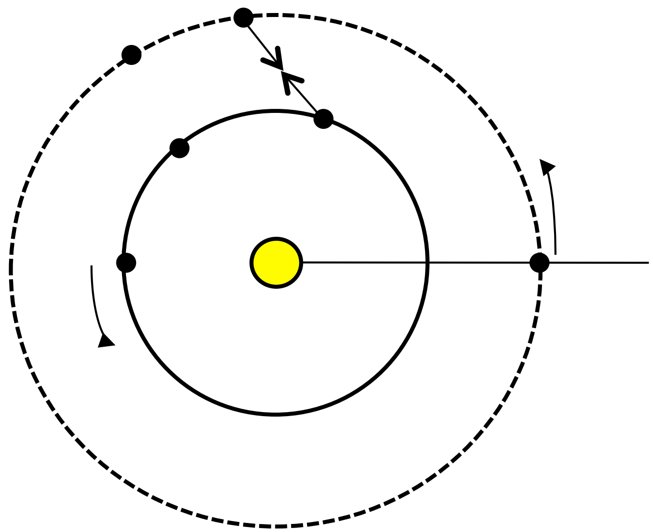
- Periods (n.b.: their ratios)
- Eccentricities
- Mutual Inclinations

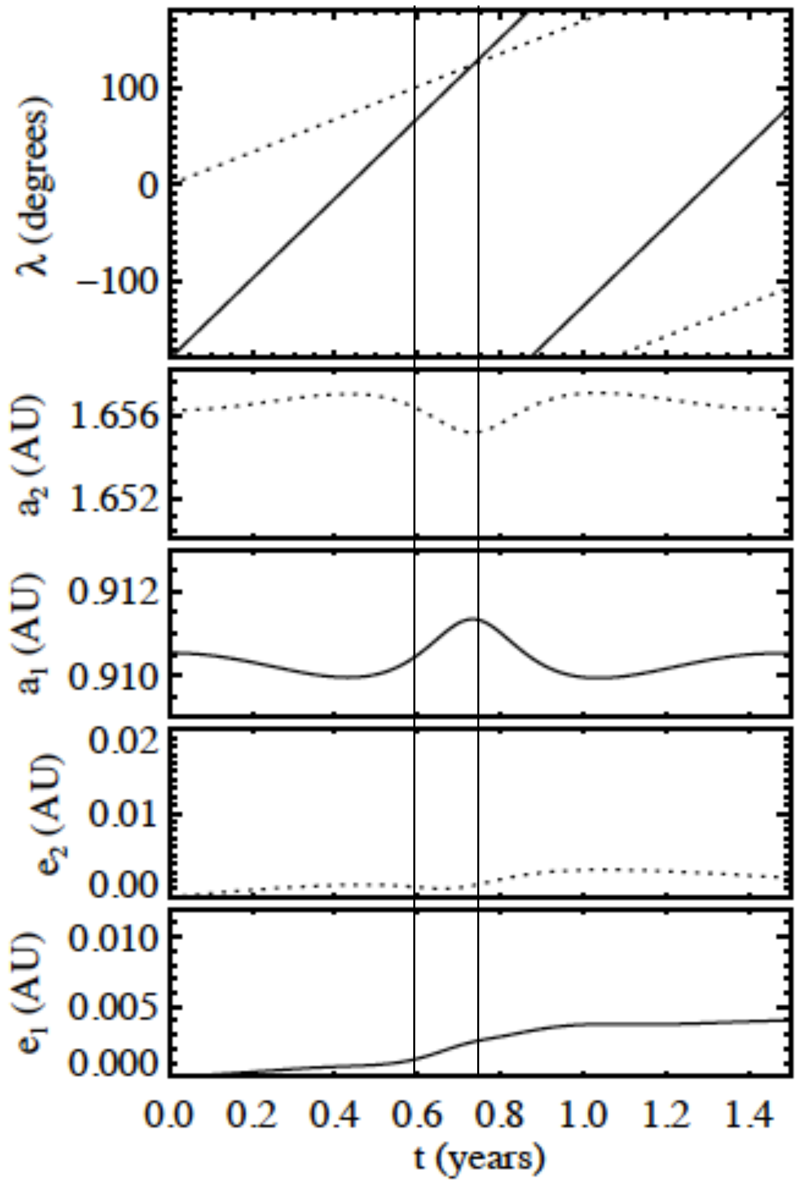
Transits	Radial Velocities
w/ TTV	✔
w/ TTV	✔
✔	
✔✔	✔
w/ TTV	✔
w/ Duration Variations	

TTV = Transit timing Variation

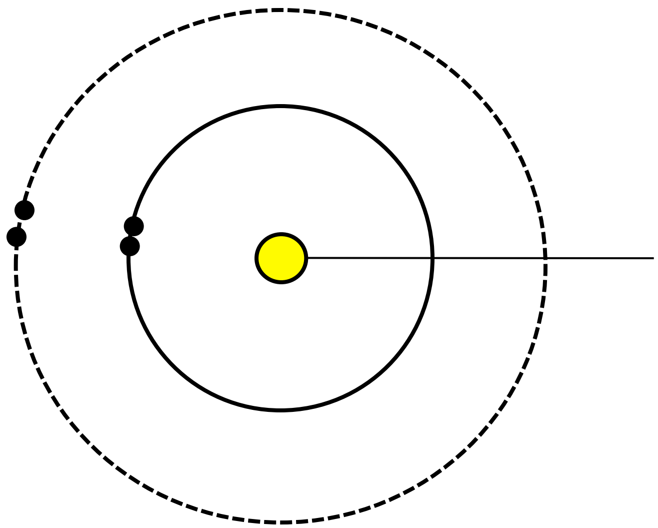
>~100 significant TTV cases: Mazeh et al. 2013)

Dynamics: Orbital Timescales

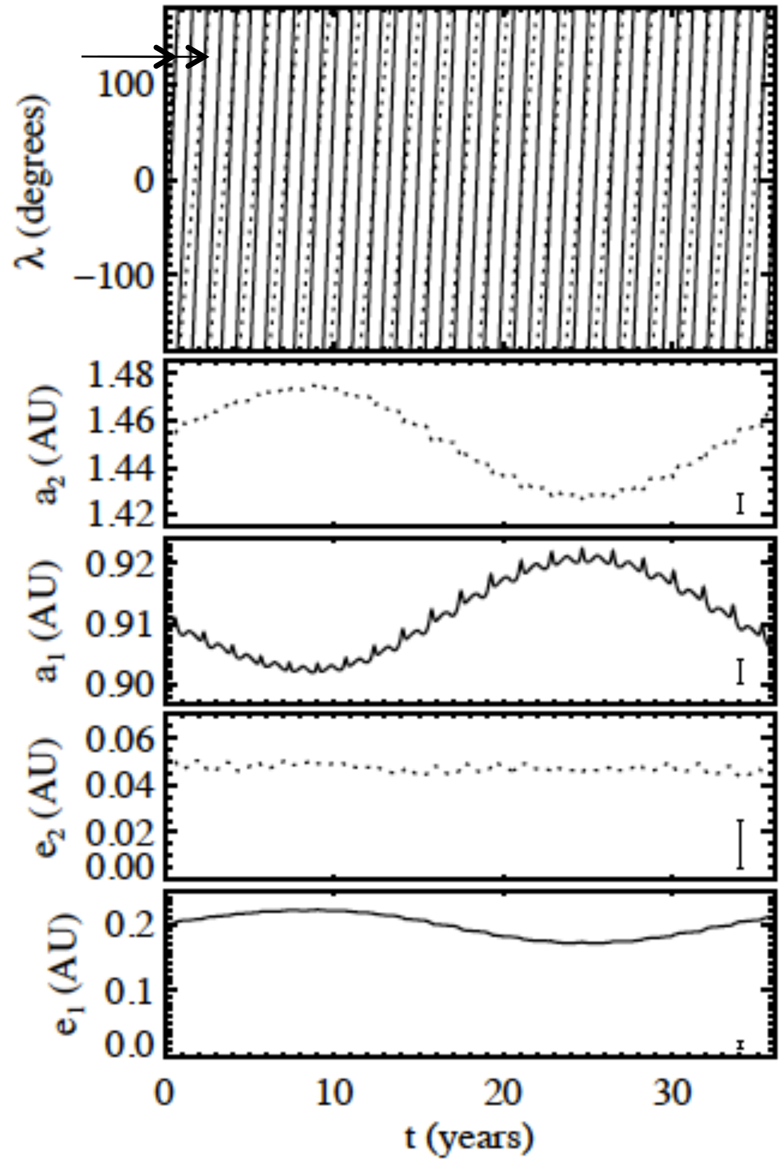




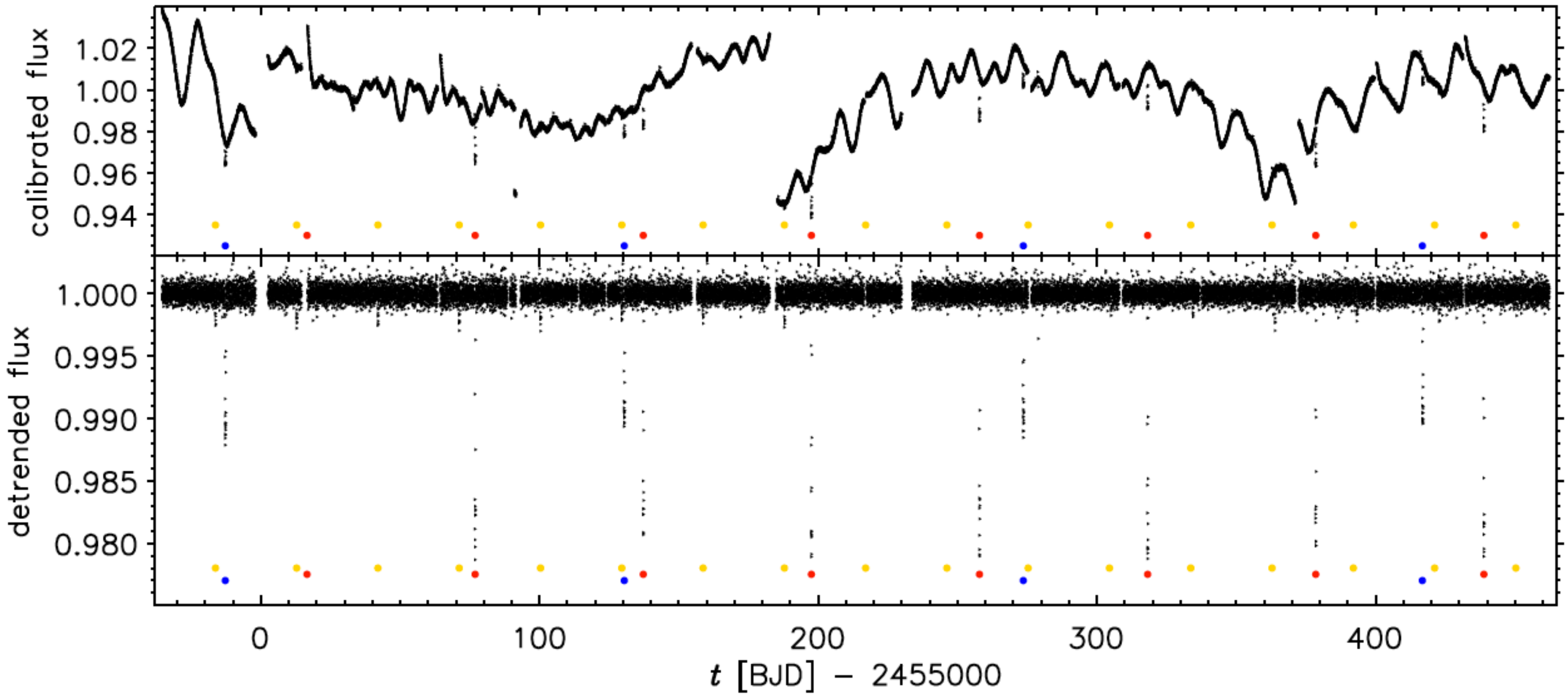
Dynamics: Resonant Orbits



$P_2/P_1 = 2.00$

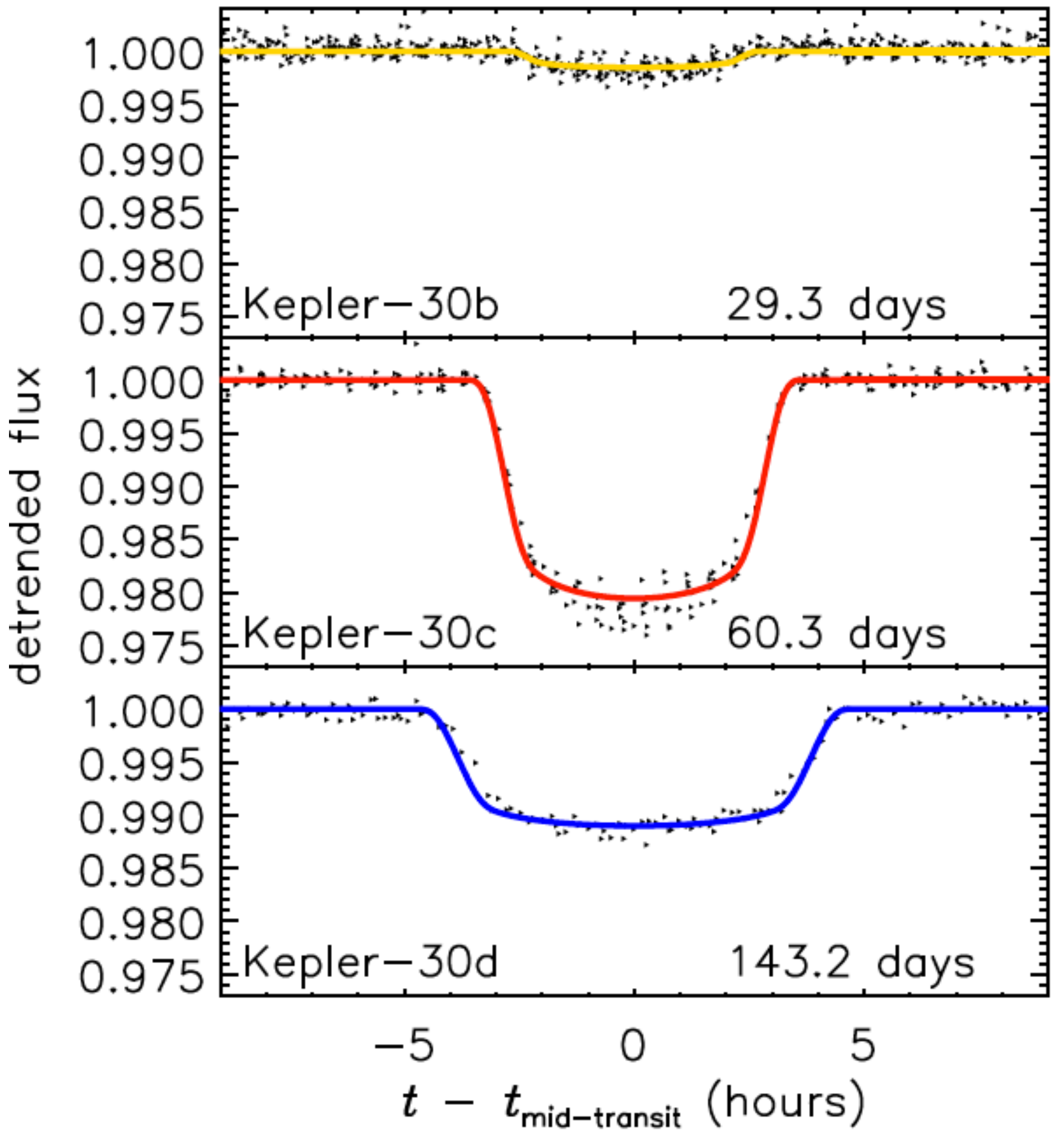


KOI-806 = Kepler-30

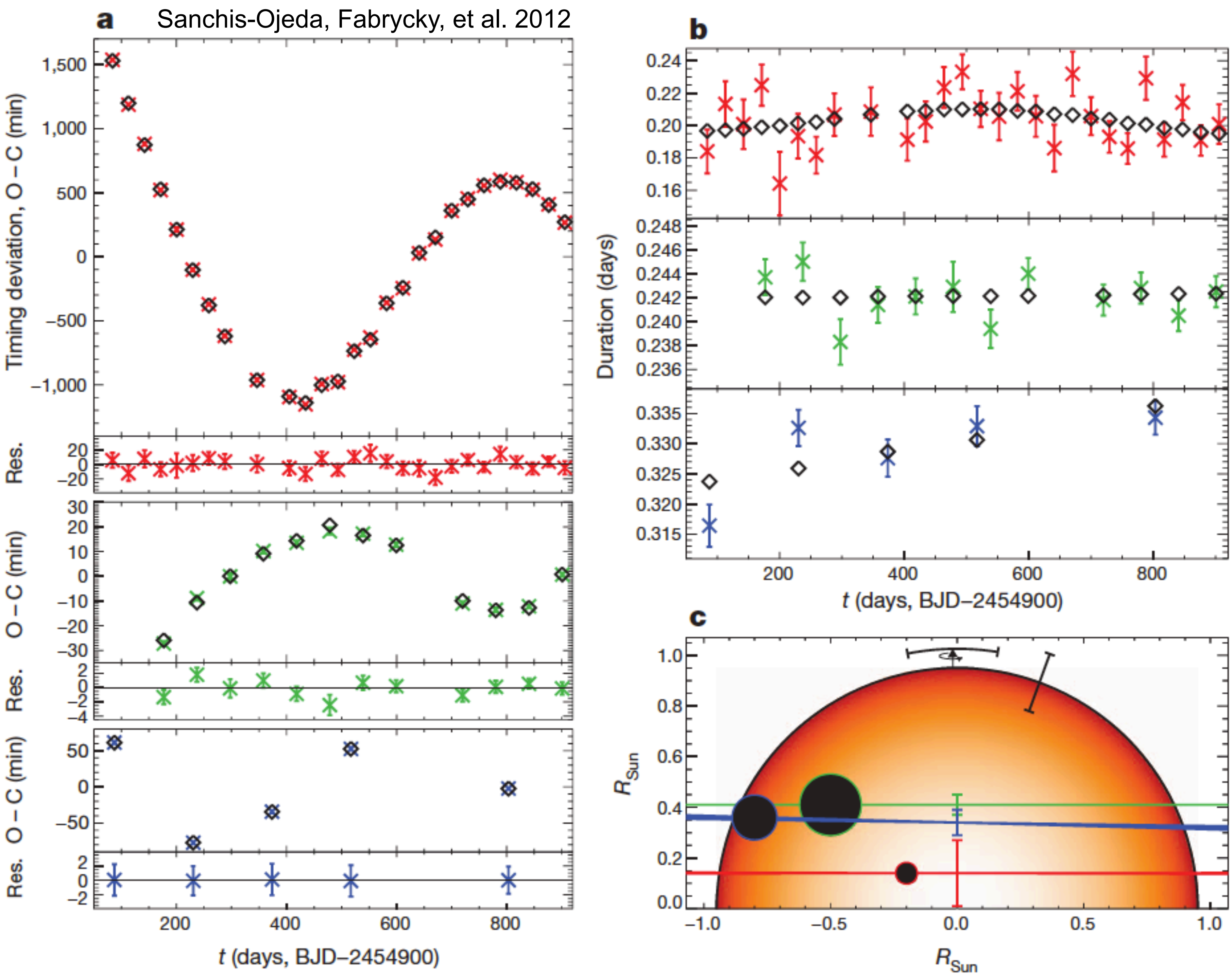


Fabrycky, Ford, Steffen et al. 2012

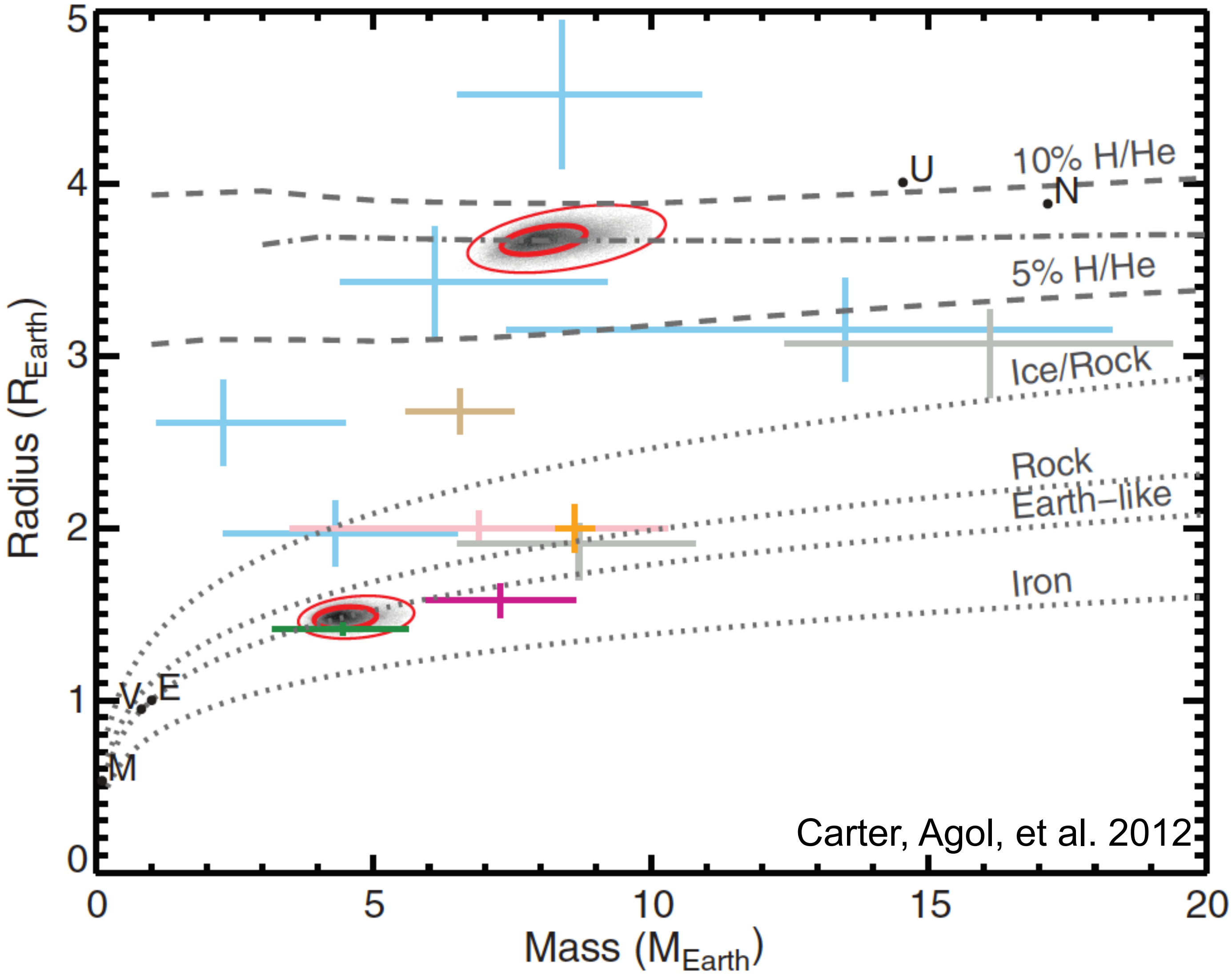
KOI-806 = Kepler-30



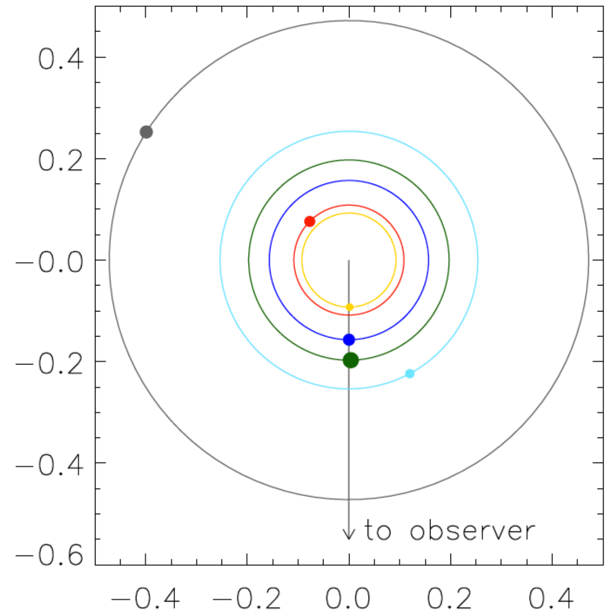
Fabrycky, Ford, Steffen et al. 2012

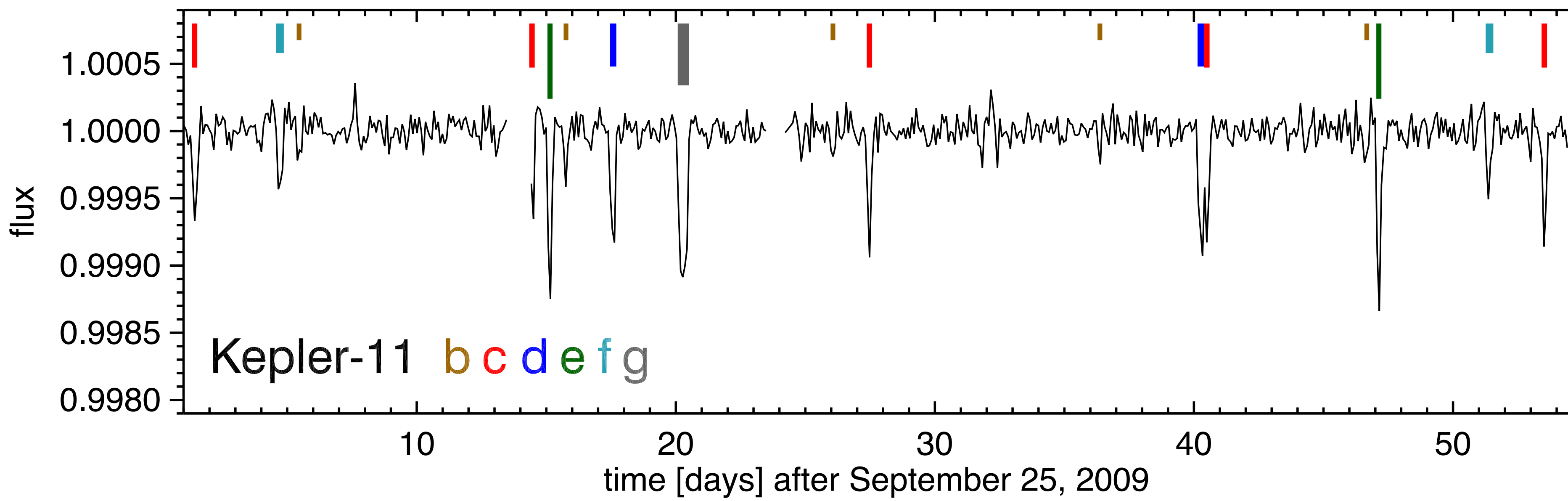

a
Sanchis-Ojeda, Fabrycky, et al. 2012
Timing deviation, O − C (min)
Res.
O − C (min)
Res.
O − C (min)
Res.
t (days, BJD−2454900)
b
Duration (days)
t (days, BJD−2454900)
c
R_{Sun}
R_{Sun}

Super-Earths and Mini-Neptunes



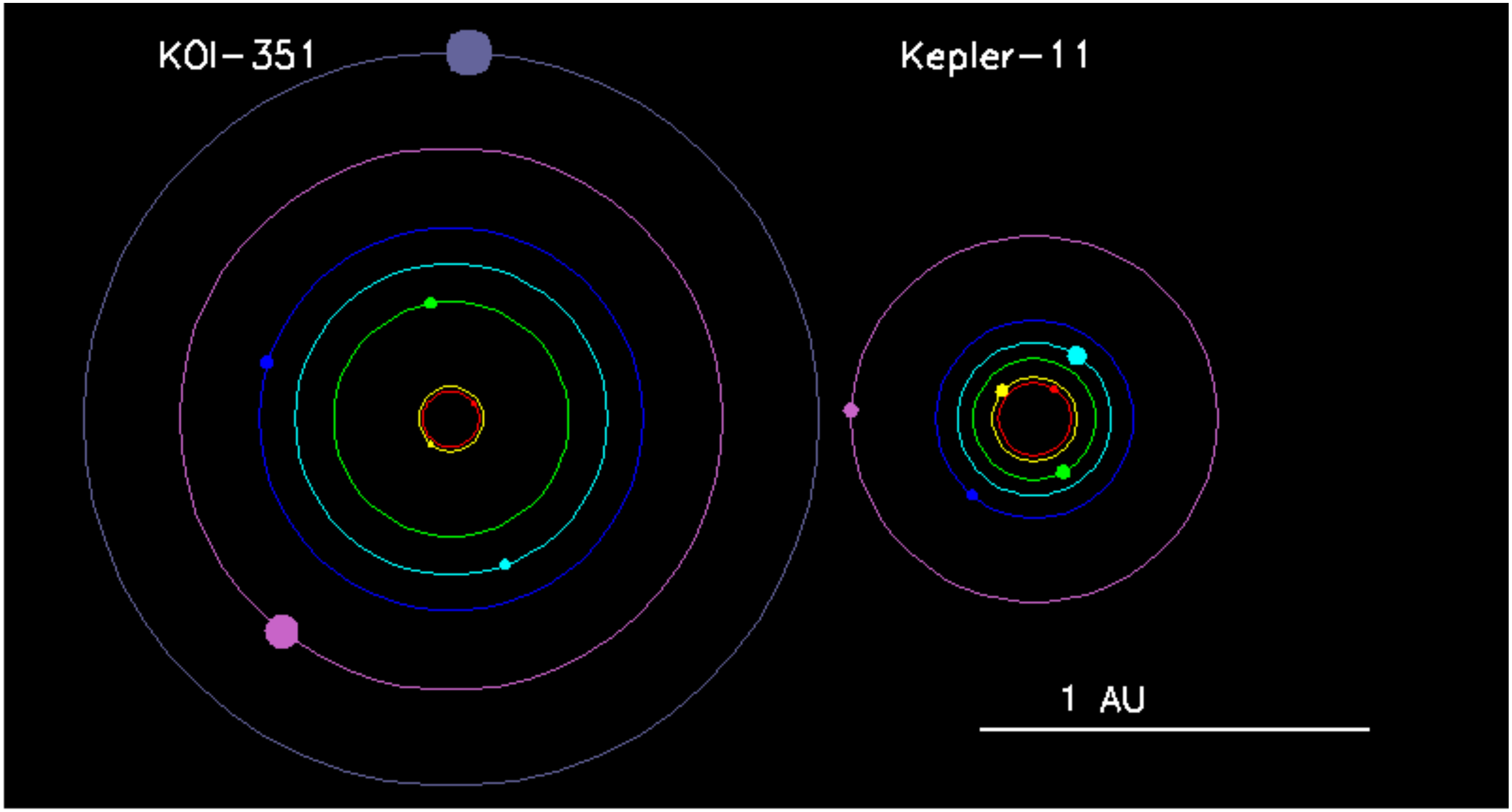
Kepler-11



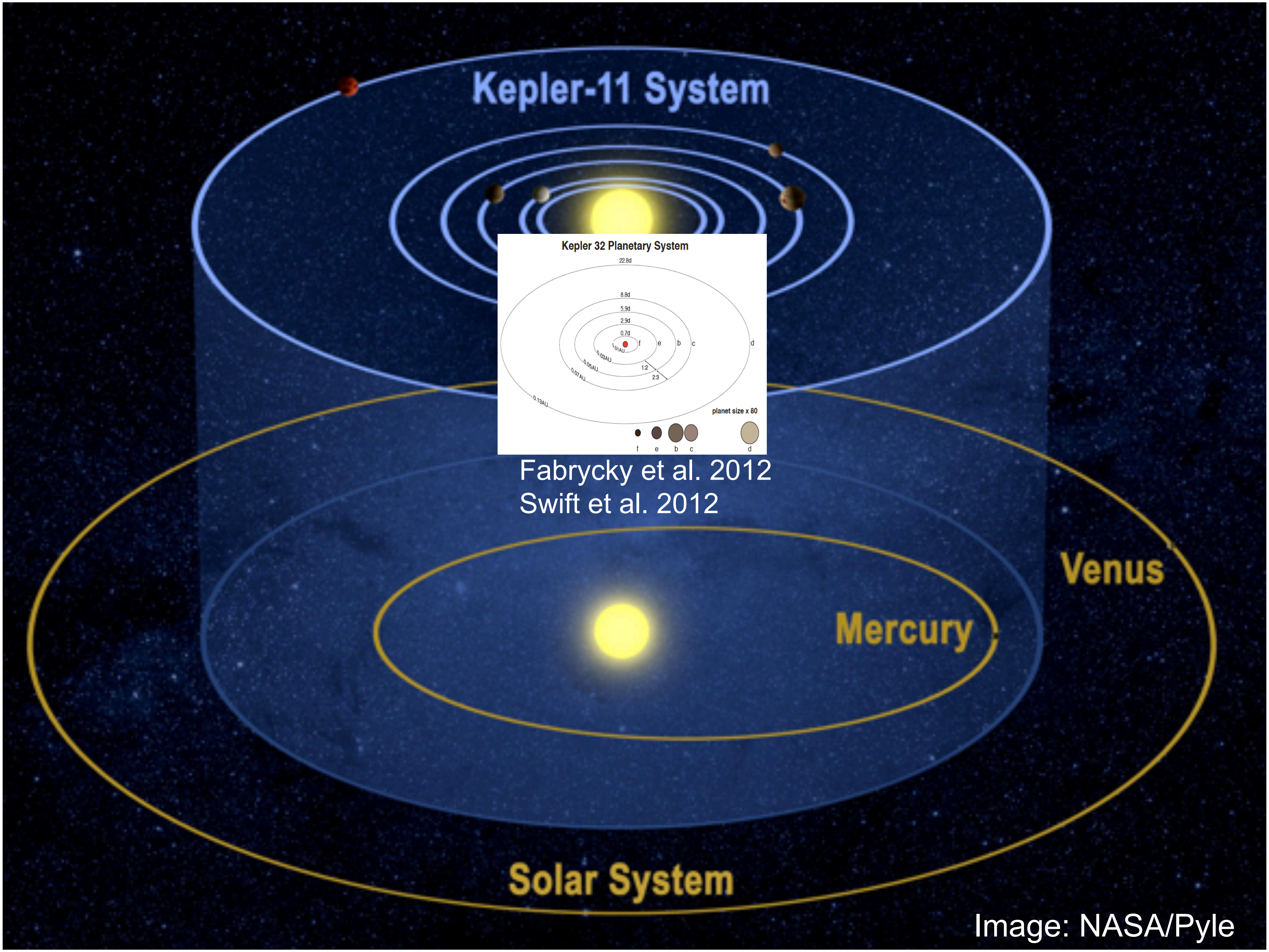


Lissauer, Fabrycky, Ford et al. 2011

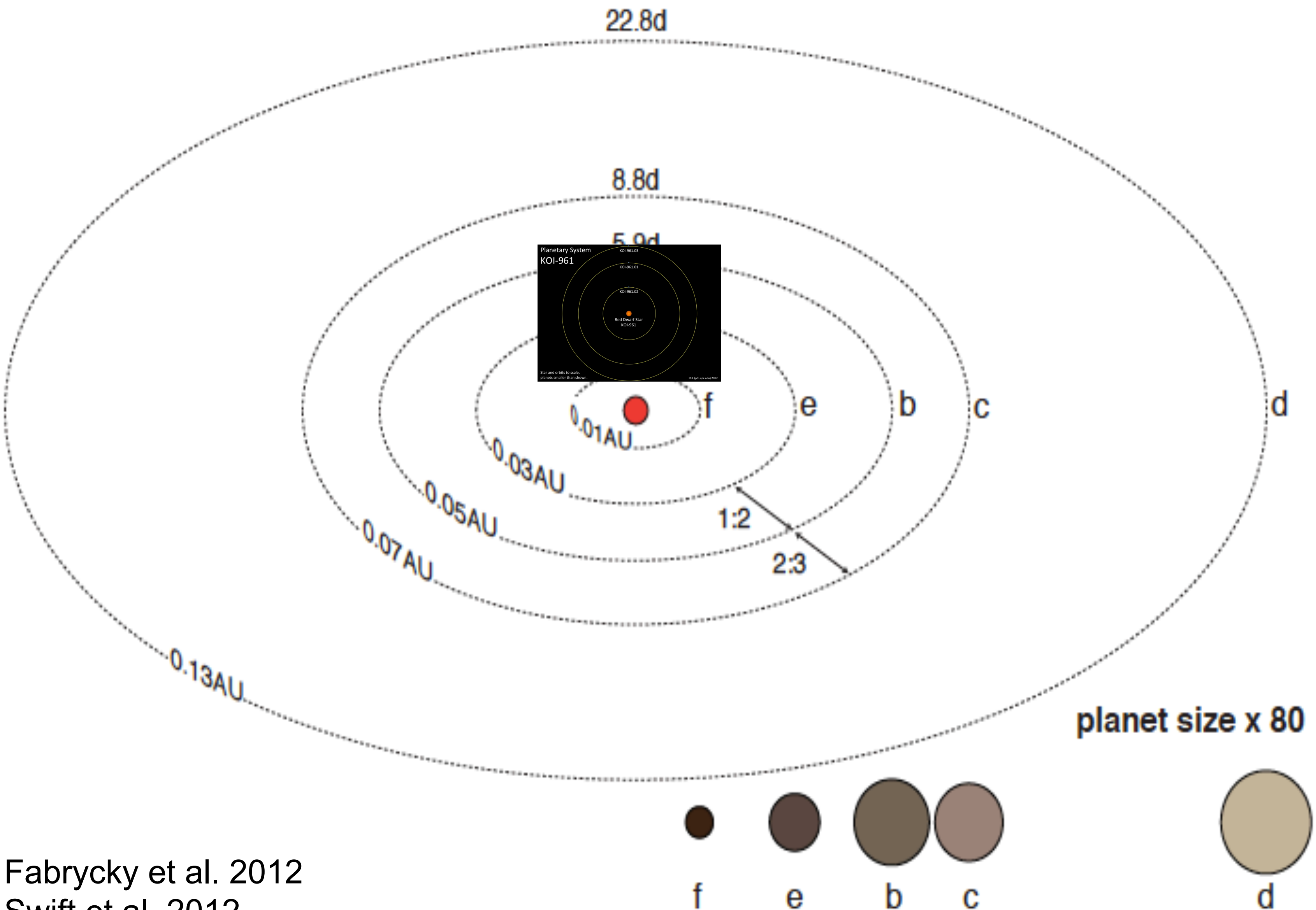
http://kepler.nasa.gov/multimedia/animations/artistsconcepts/?ImageID=119



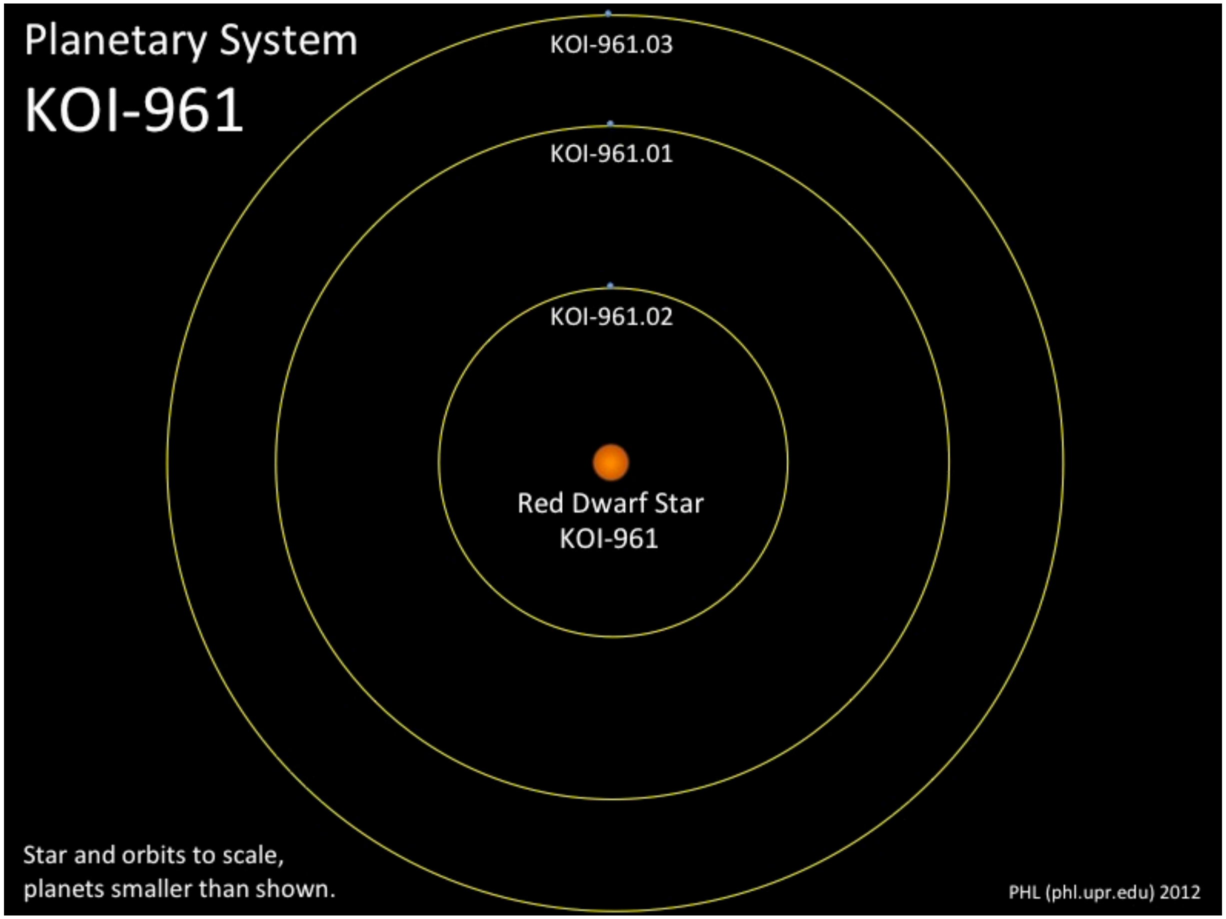
Planet	Kepler-90 b	Kepler-90 c	Kepler-90 d	Kepler-90 e	Kepler-90 f	Kepler-90 g	Kepler-90 h
KOI #	KOI-351.06	KOI-351.05	KOI-351.03	KOI-351.04	KOI-351.07	KOI-351.02	KOI-351.01
T_0 (BJD-2454900)	70.6797± 0.0012	72.5208± 0.0038	91.9622± 0.0035	67.2952± 0.0079	62.791 ± 0.011	79.8448± 0.0015	73.4992± 0.00085
P [days]	7.008214± 0.000102	8.718397± 0.000324	59.73700± 0.00027	91.94080± 0.00078	124.9134 ± 0.0013	210.70287± 0.00037	331.59940± 0.00032
duration [hr]	3.72 ± 0.02	4.02 ± 0.02	7.90 ± 0.06	9.16 ± 0.08	10.03 ± 0.11	11.38 ± 0.06	13.21 ± 0.04
depth [%]	0.0135 ± 0.0009	0.0175 ± 0.0009	0.0580 ± 0.0017	0.0502 ± 0.0019	0.0642 ± 0.0032	0.4225 ± 0.0028	0.8246 ± 0.0055
$R_p/R_\star$	0.0108 ± 0.0004	0.0122 ± 0.0003	0.0223 ± 0.0004	0.0208 ± 0.0004	0.0234 ± 0.0006	0.0605 ± 0.0005	0.0840 ± 0.0005
b	0.02 ± 0.28	-0.00 ± 0.26	0.22 ± 0.13	0.01 ± 0.28	-0.00 ± 0.25	-0.01 ± 0.24	-0.04 ± 0.23
R_p [$R_\oplus$]	1.37 ± 0.08	1.55 ± 0.09	2.83 ± 0.15	2.64 ± 0.14	2.98 ± 0.17	7.65 ± 0.38	10.69 ± 0.53
$S/S_\odot$	292.51 ± 23.27	217.55 ± 17.23	17.18 ± 1.58	9.61 ± 0.82	6.31 ± 0.52	3.17 ± 0.26	1.74 ± 0.15


Kepler-11 System
Kepler 32 Planetary System
planet size x 80
Fabrycky et al. 2012
Swift et al. 2012
Venus
Mercury
Solar System
Image: NASA/Pyle

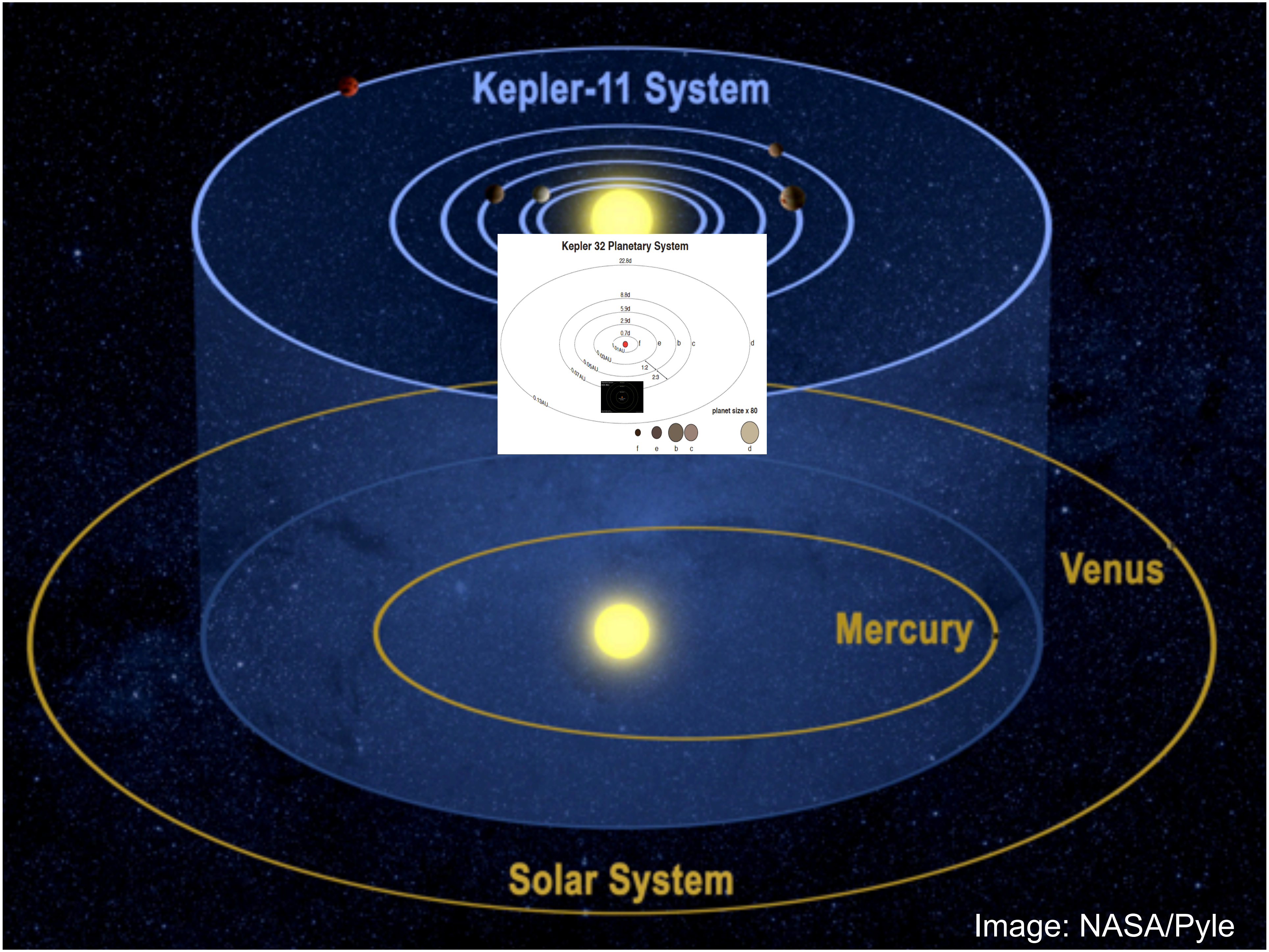
Kepler 32 Planetary System



Fabrycky et al. 2012
Swift et al. 2012



Muirhead, Johnson et al. 2012



Kepler-11 System
Kepler 32 Planetary System
22.8d
8.8d
5.9d
2.9d
0.7d
f
e
b
c
d
0.01AU
0.03AU
0.05AU
0.07AU
0.13AU
1:2
2:3
planet size x 80
f
e
b
c
d
Venus
Mercury
Solar System
Image: NASA/Pyle

KOI-730: Three Pairs of First-Order Resonances

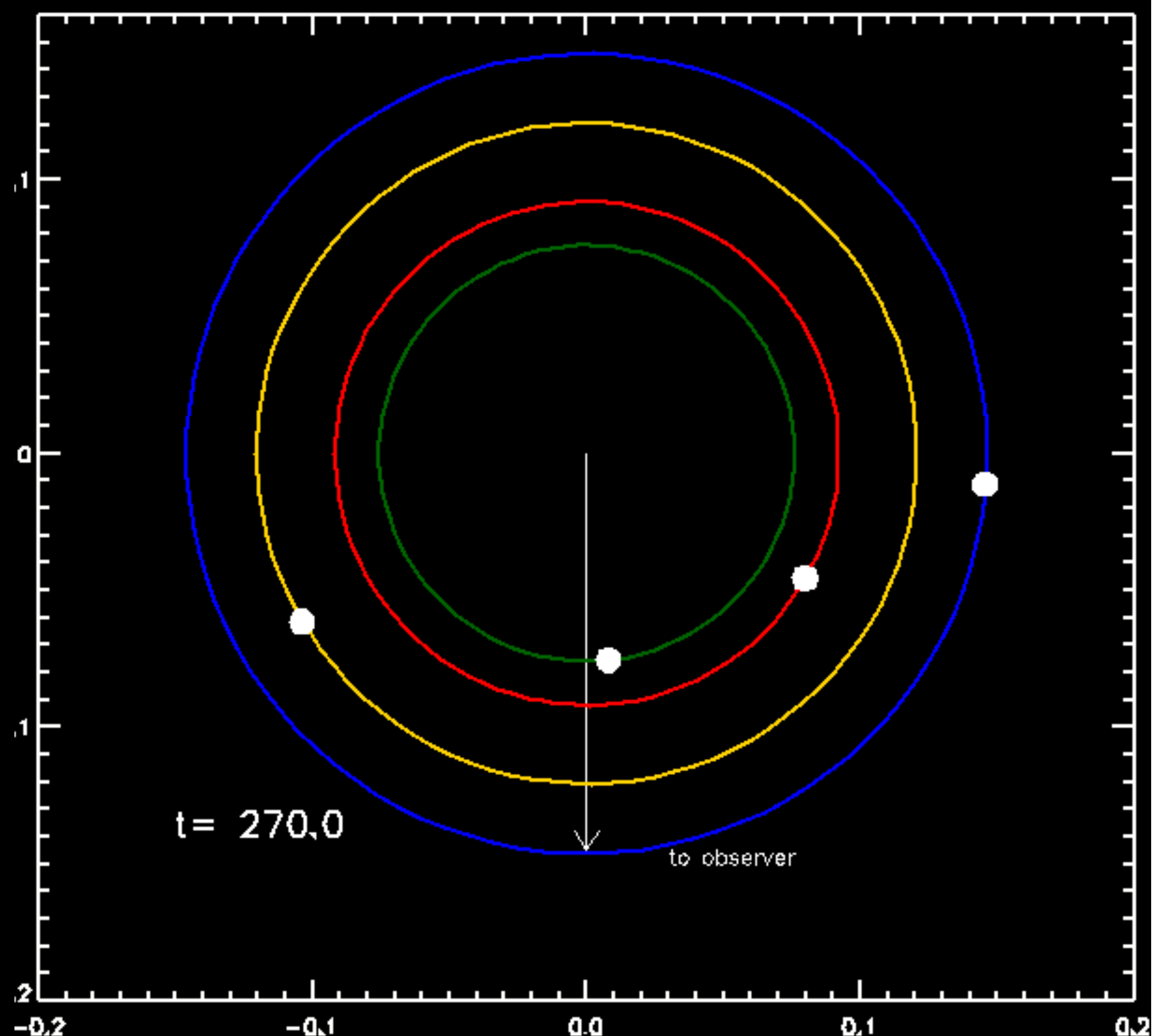
name	period (d)	R_p (R_E)
730.04	7.3831	1.8
730.02	9.8499	2.1
730.01	14.7903	2.8
730.02	19.7216	2.4

P/P=1.33411(8) 4:3

P/P=1.50157(5) 3:2

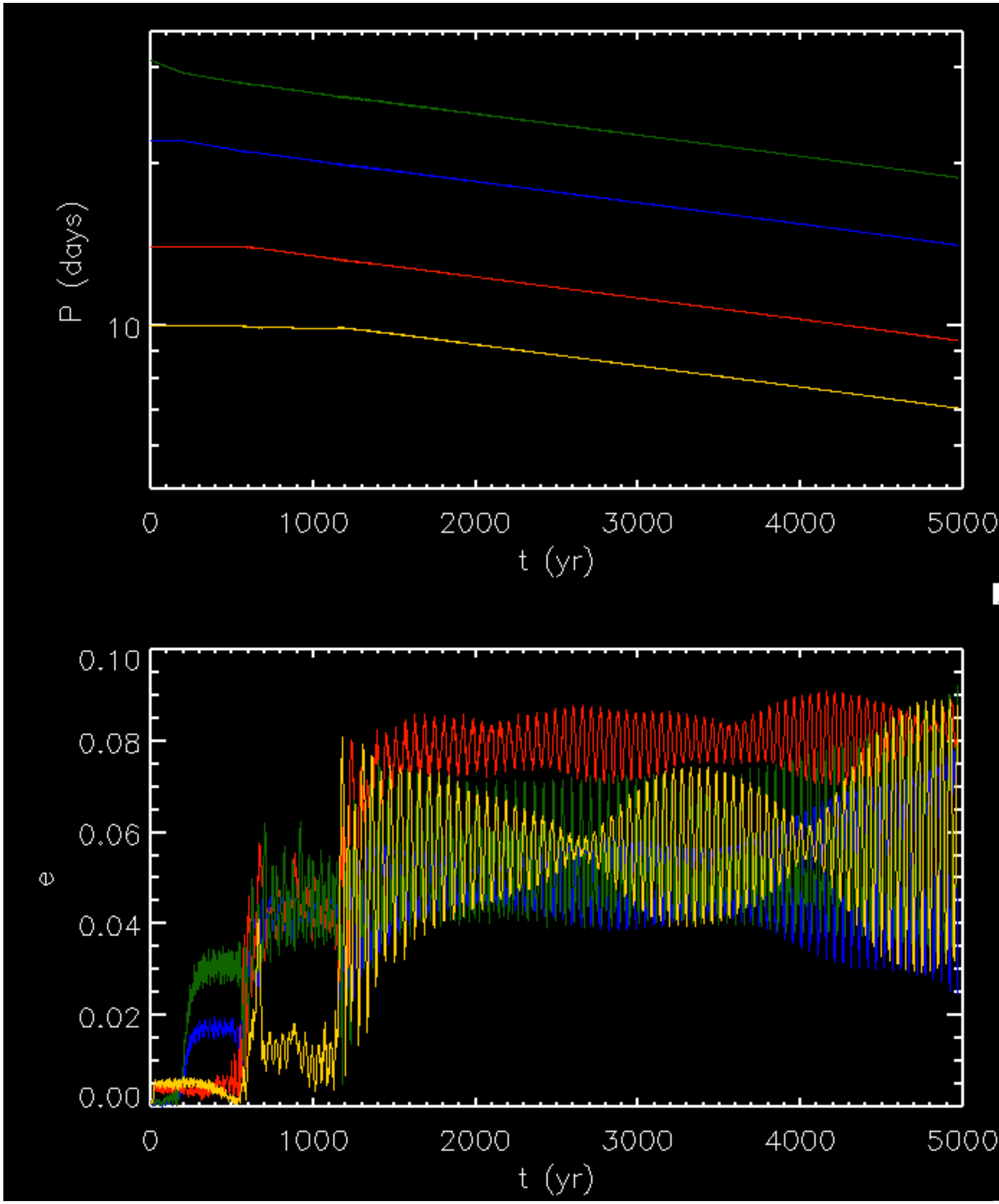
P/P=1.33341(3) 4:3

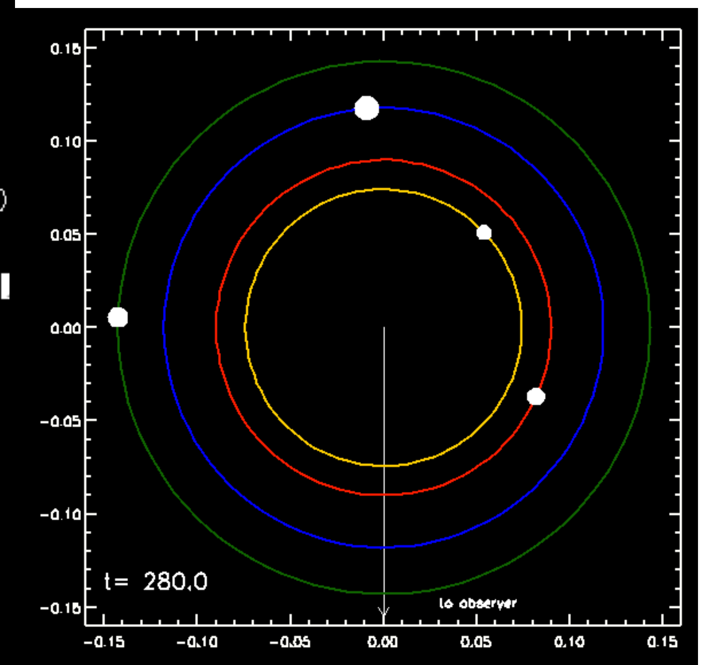
3:4:6:8



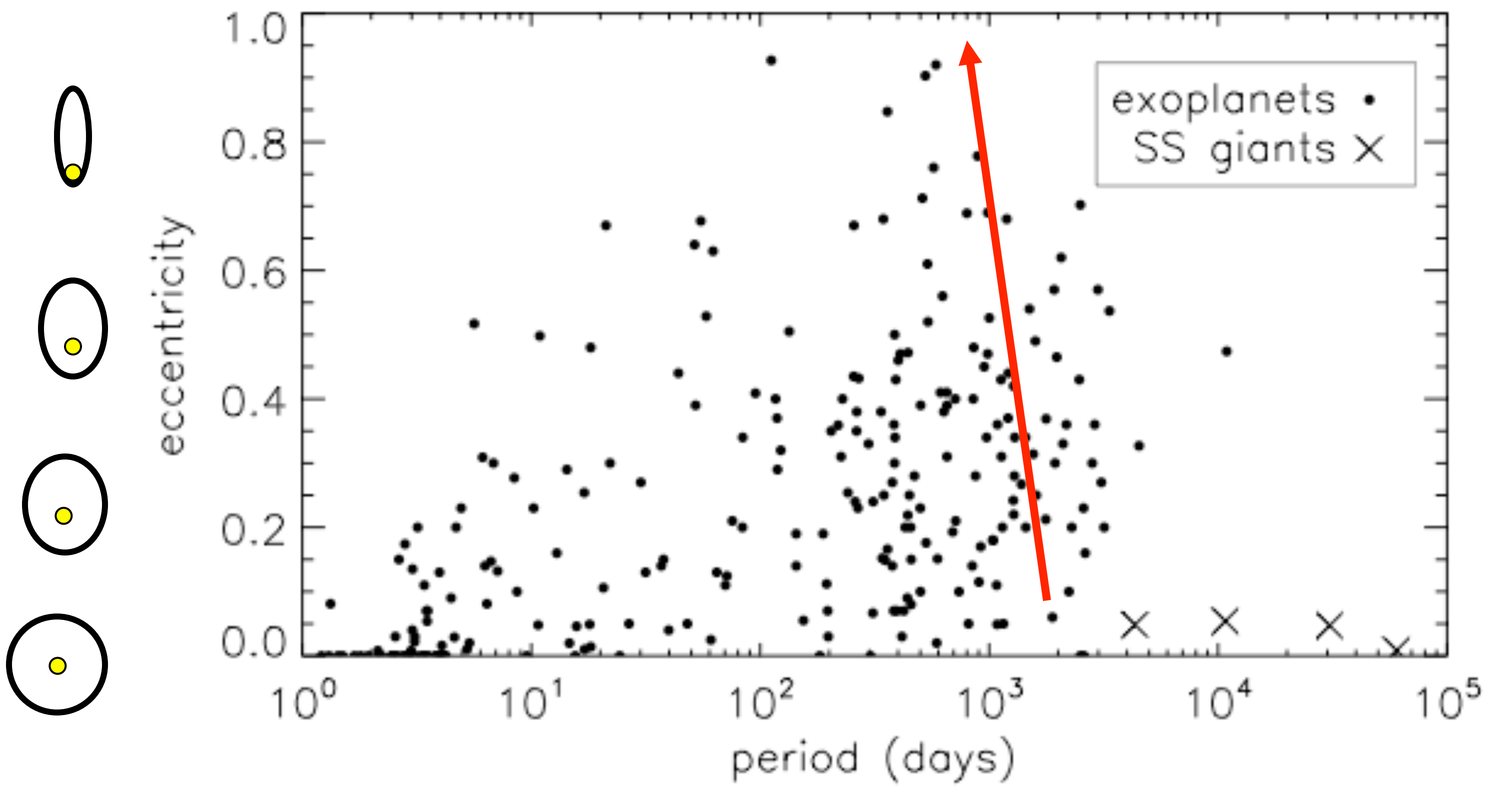
Kepler; Lissauer et al. 2011, Fabrycky et al. 2012

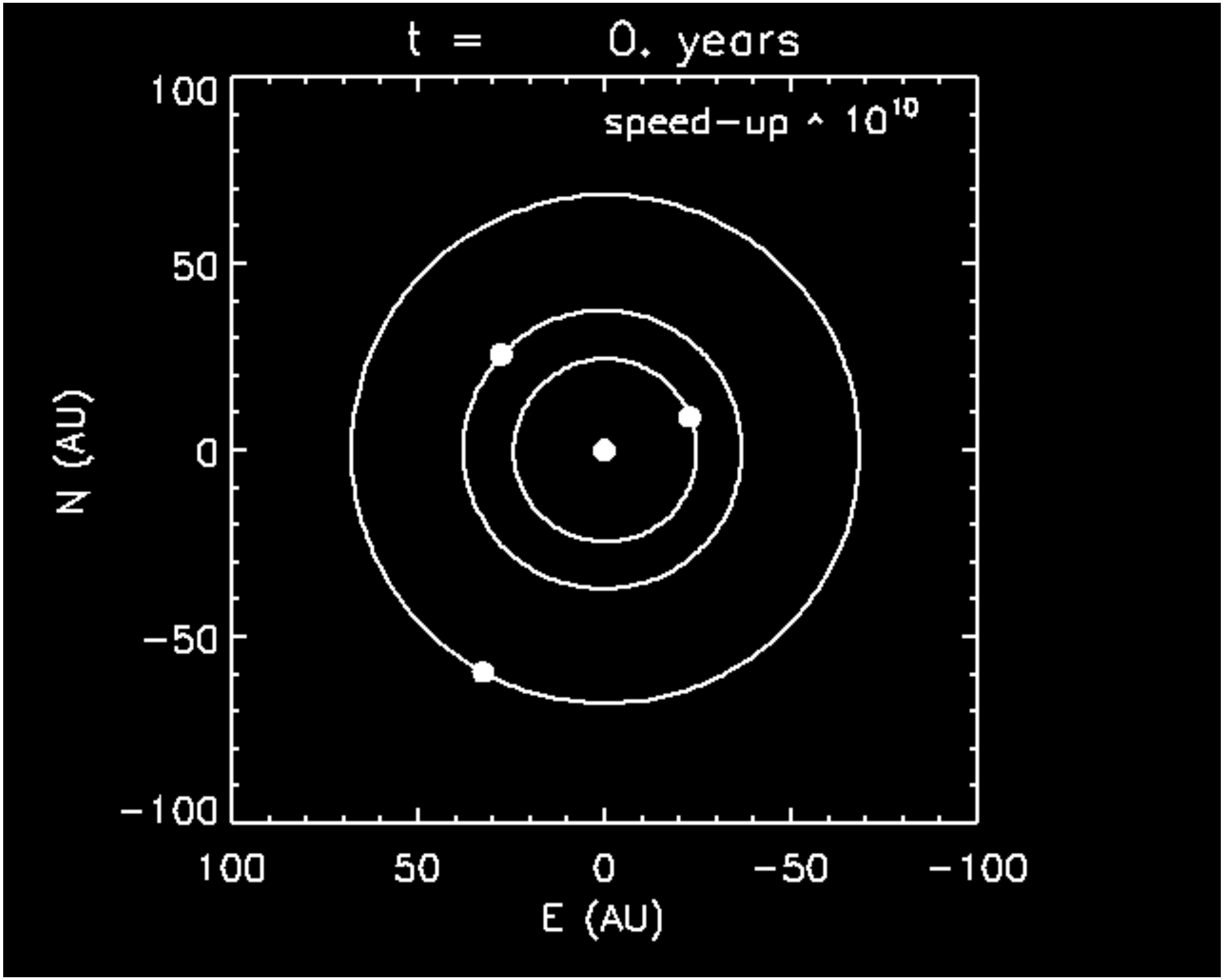
Disk Migration into Resonance





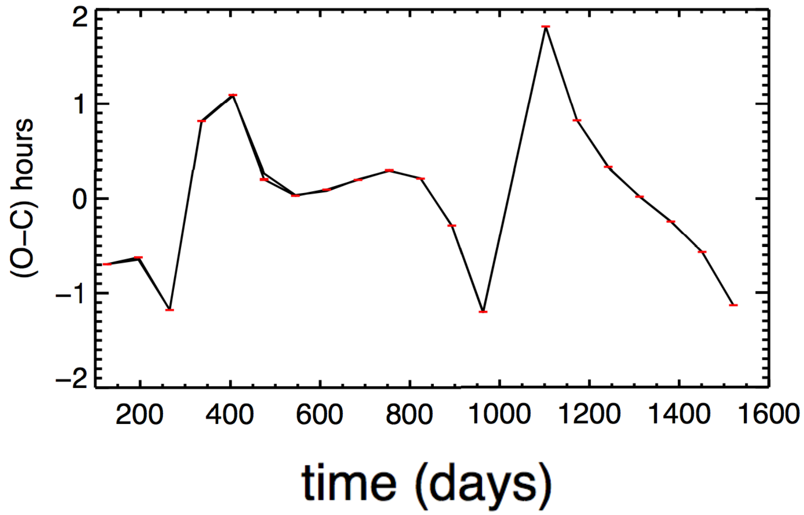
Gas giants can have giant eccentricities

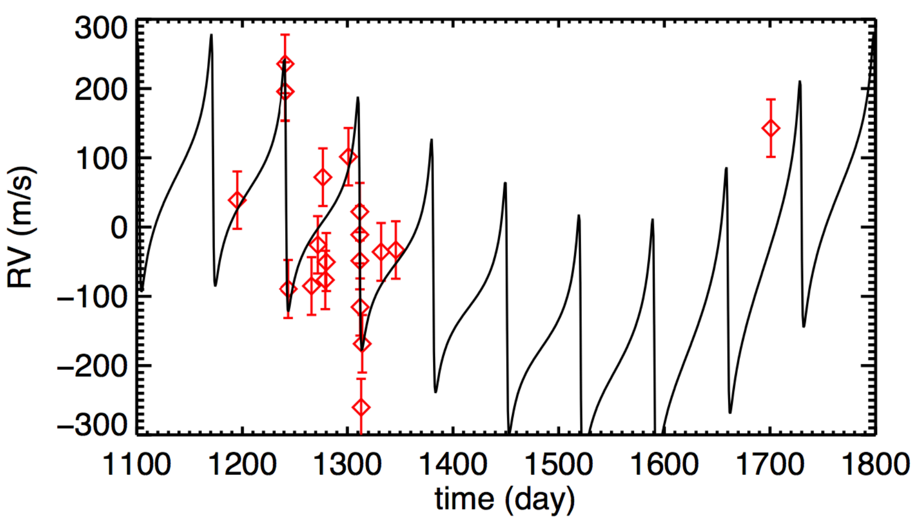




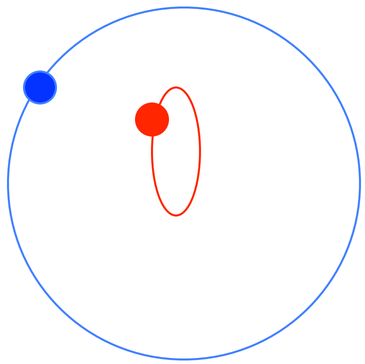
t = 0. years
speed-up ~ 10^10
100
50
0
−50
−100
N (AU)
100
50
0
−50
−100
E (AU)

Planet with Eccentricity, Being Kicked Still!



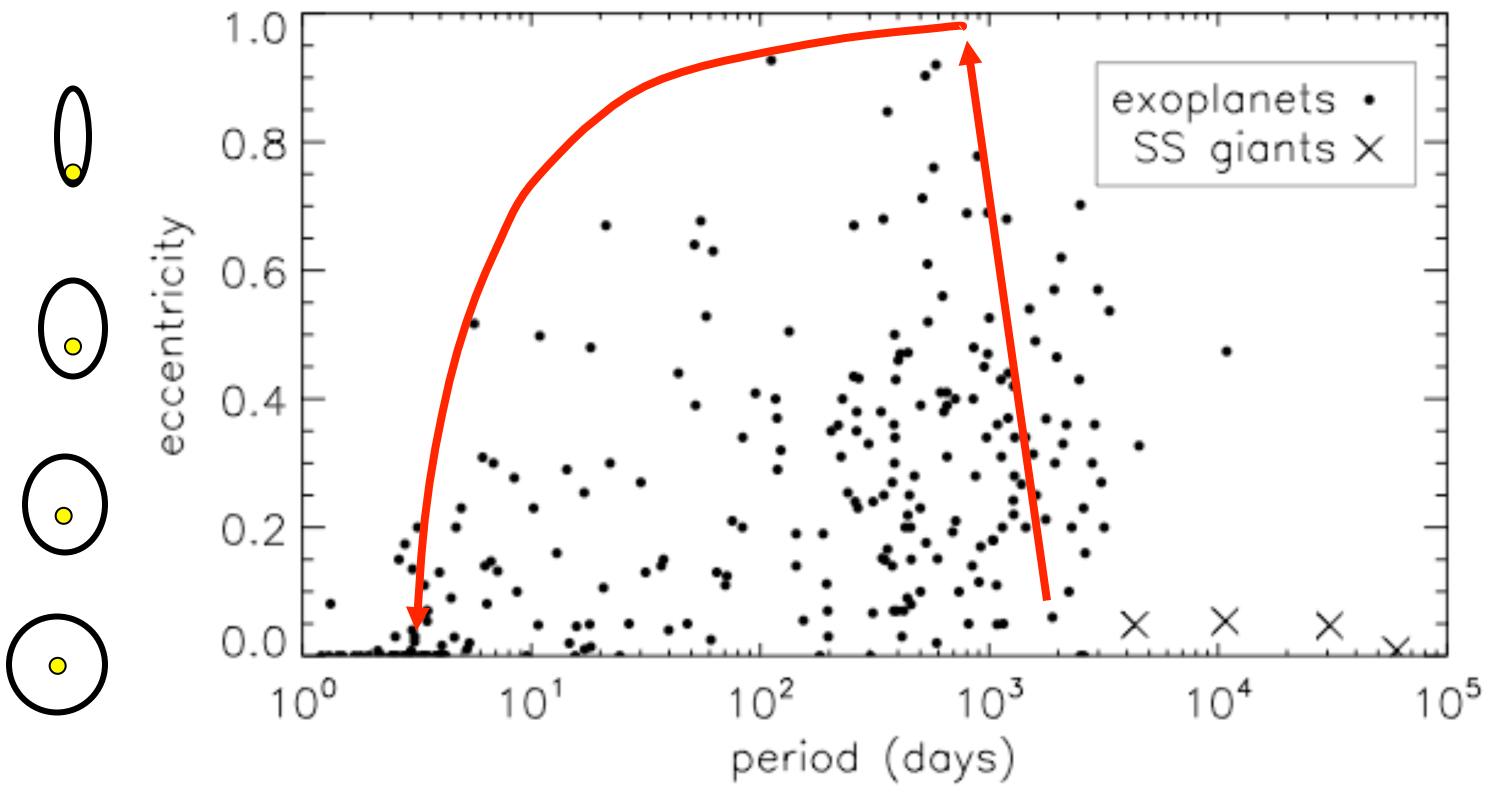


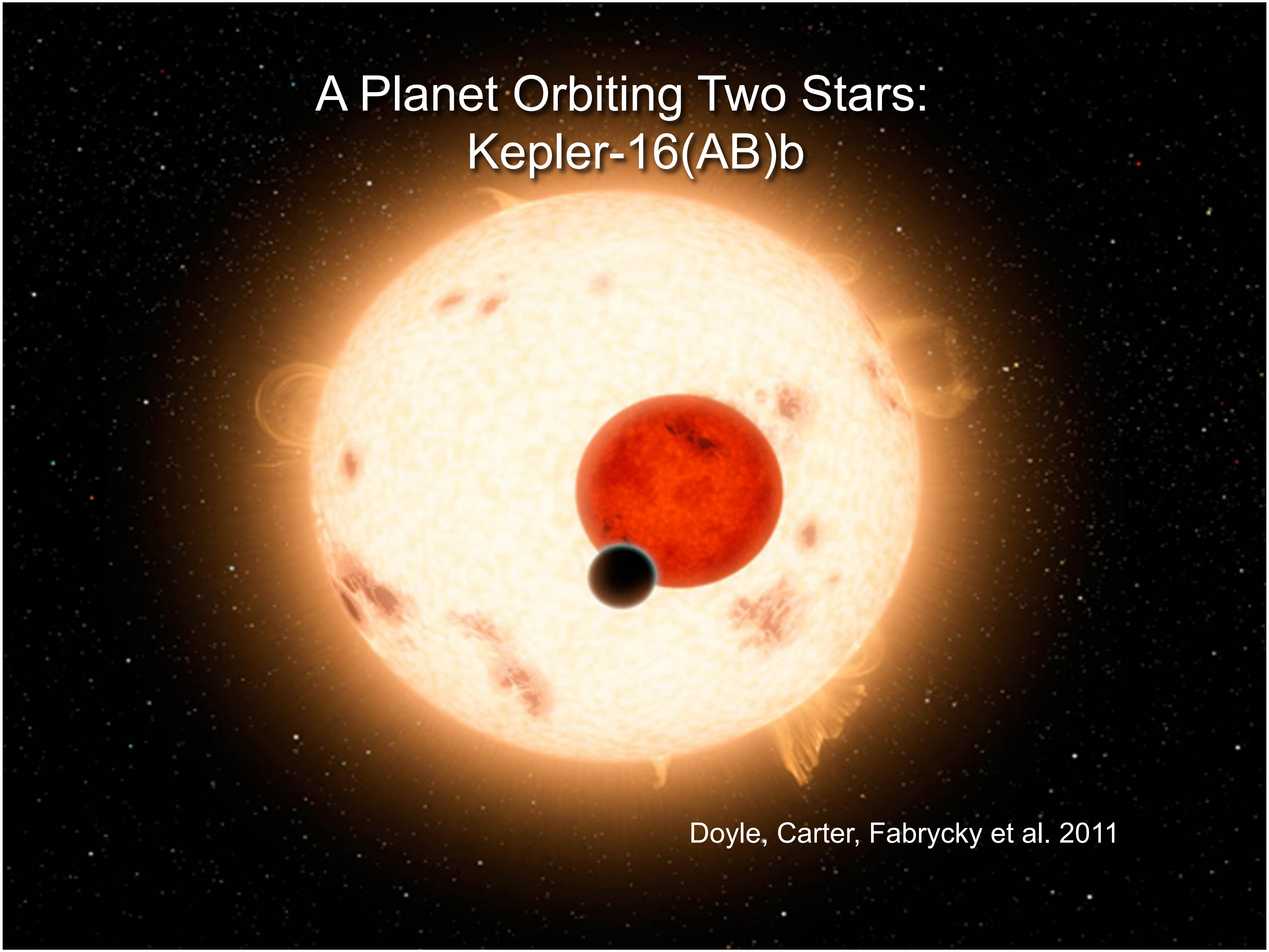
- KOI-1474 (Dawson et al. 2012, 2014)



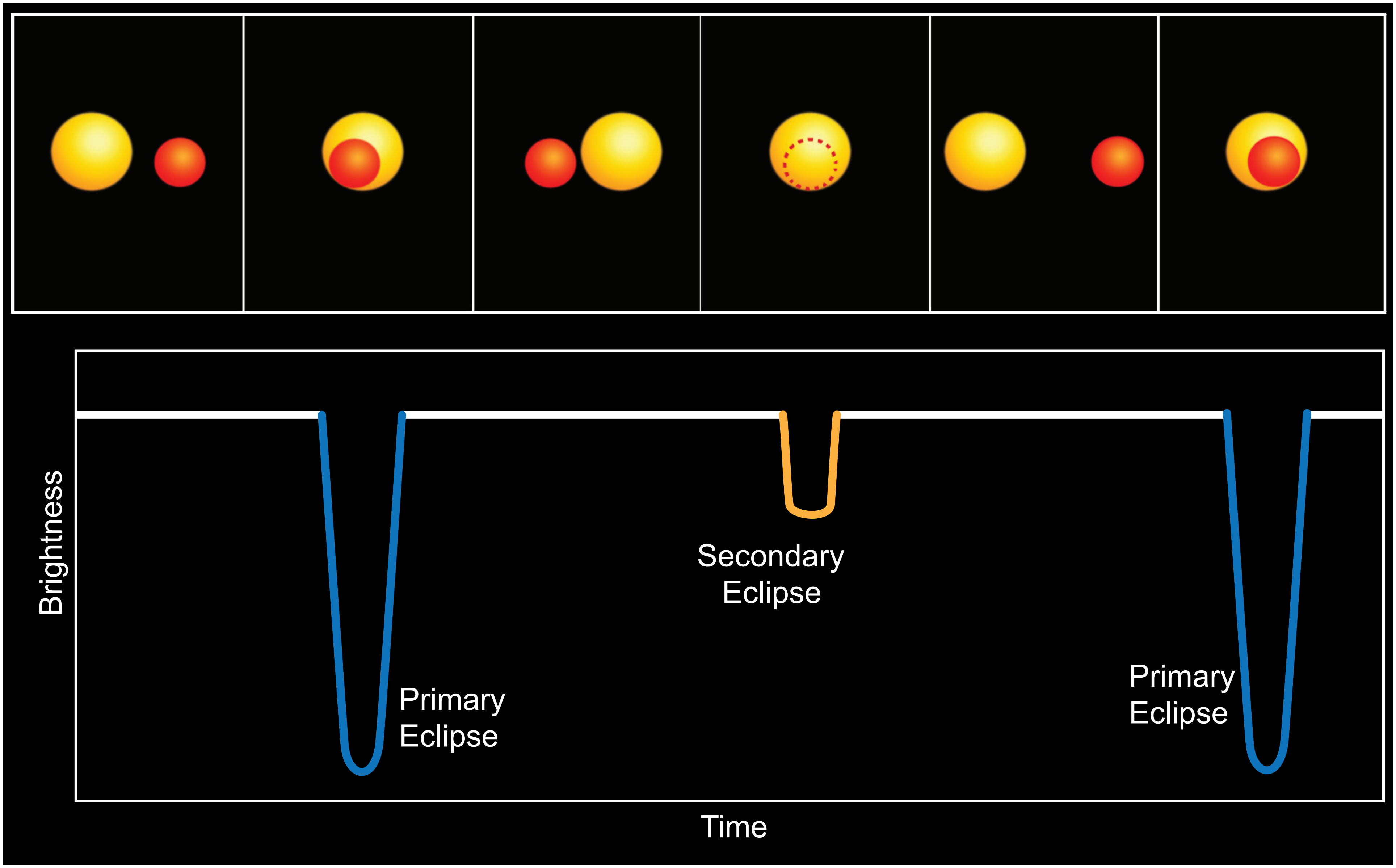
Doppler confirmation of a TTV planet discovery.

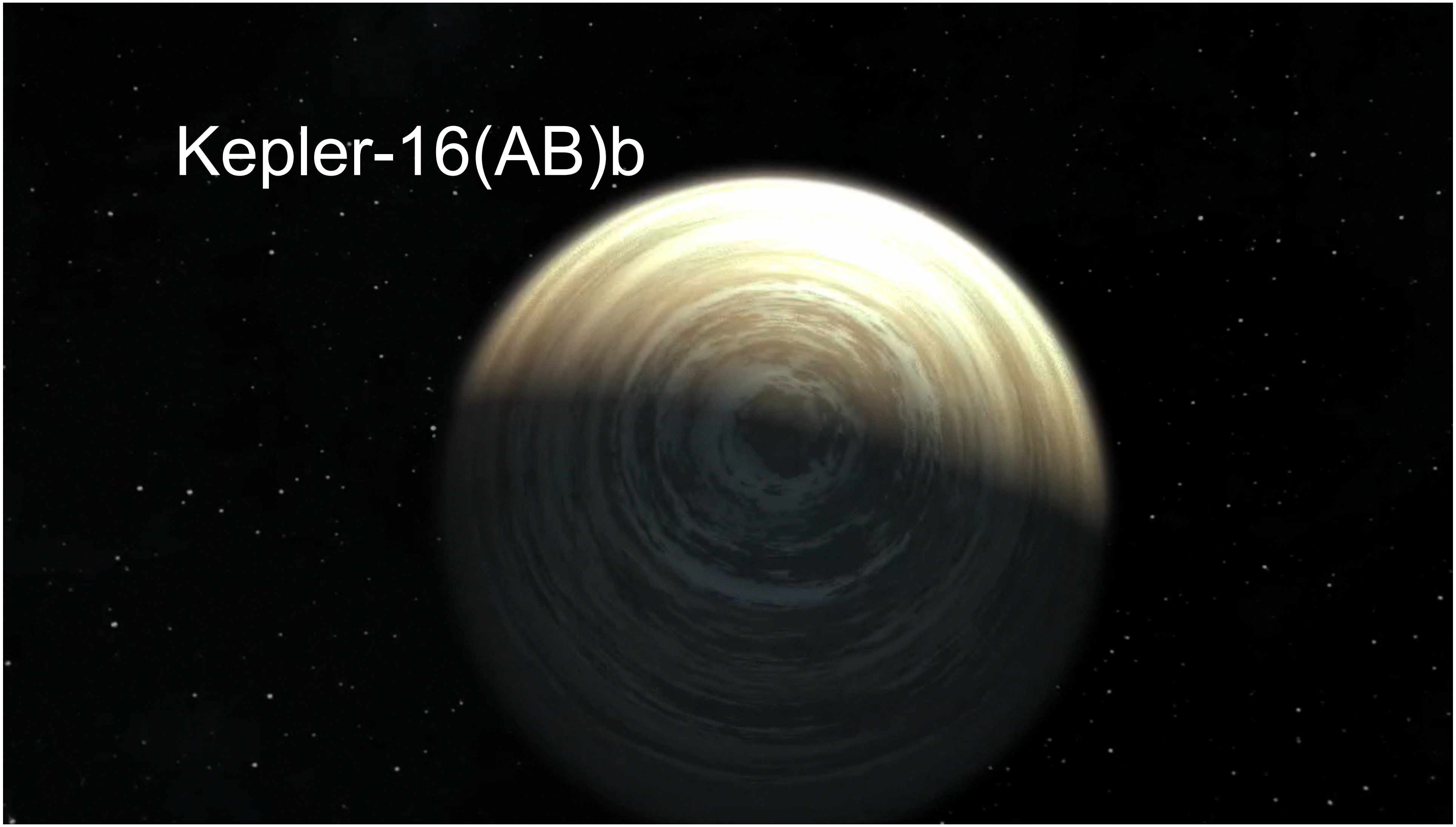
Gas giants can have giant eccentricities…or hug their stars




A Planet Orbiting Two Stars:
Kepler-16(AB)b
Doyle, Carter, Fabrycky et al. 2011

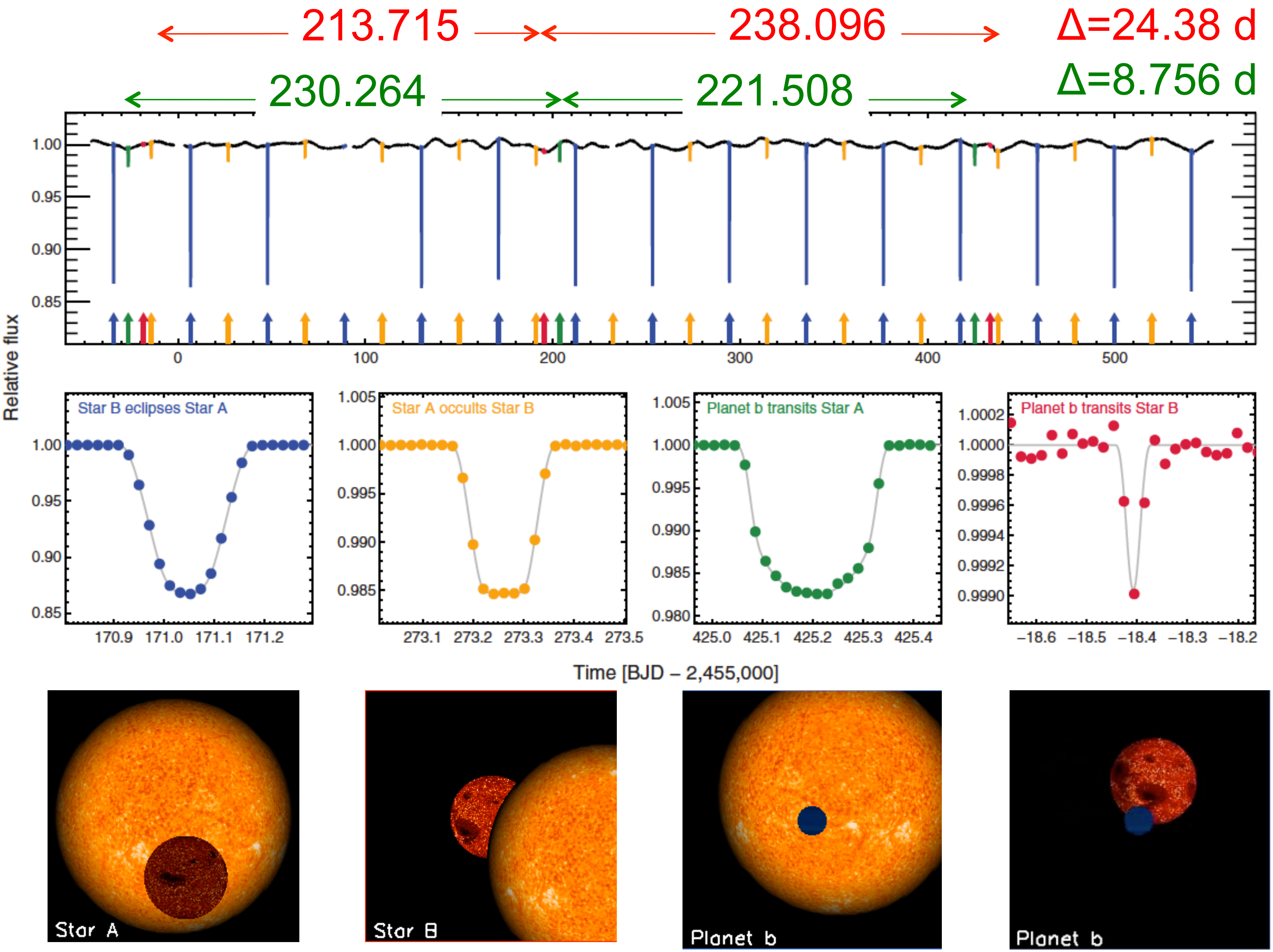
Eclipsing Binary Stars





credit: Tim Pyle (NASA)

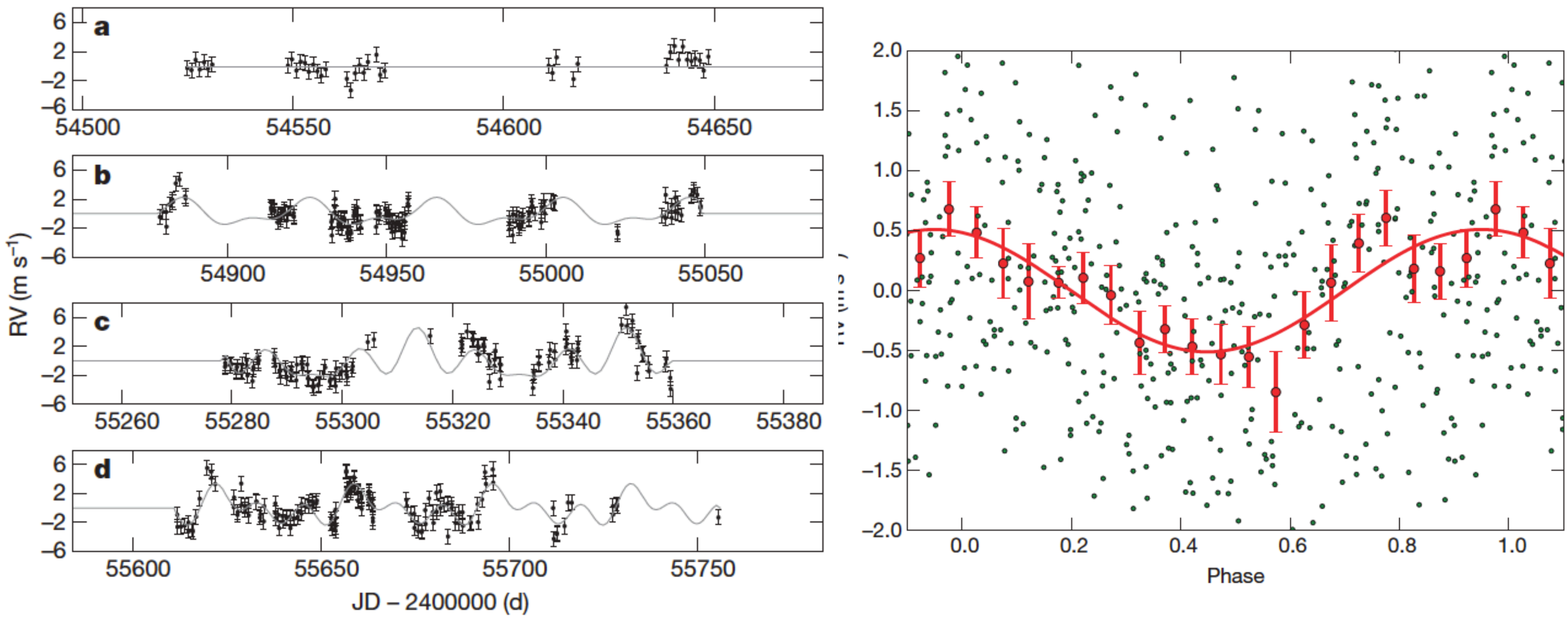
http://kepler.nasa.gov/multimedia/animations/artistsconcepts/?ImageID=166



213.715
238.096
Δ=24.38 d
230.264
221.508
Δ=8.756 d
Relative flux
1.00
0.95
0.90
0.85
0
100
200
300
400
500
Star B eclipses Star A
170.9 171.0 171.1 171.2
Star A occults Star B
1.005
1.000
0.995
0.990
0.985
273.1 273.2 273.3 273.4 273.5
Planet b transits Star A
0.980
425.0 425.1 425.2 425.3 425.4
Planet b transits Star B
1.0002
1.0000
0.9998
0.9996
0.9994
0.9992
0.9990
–18.6 –18.5 –18.4 –18.3 –18.2
Time [BJD – 2,455,000]
Star A
Star B
Planet b
Planet b

Alpha Centauri Bb

Dumusque, Pepe et al. 2012

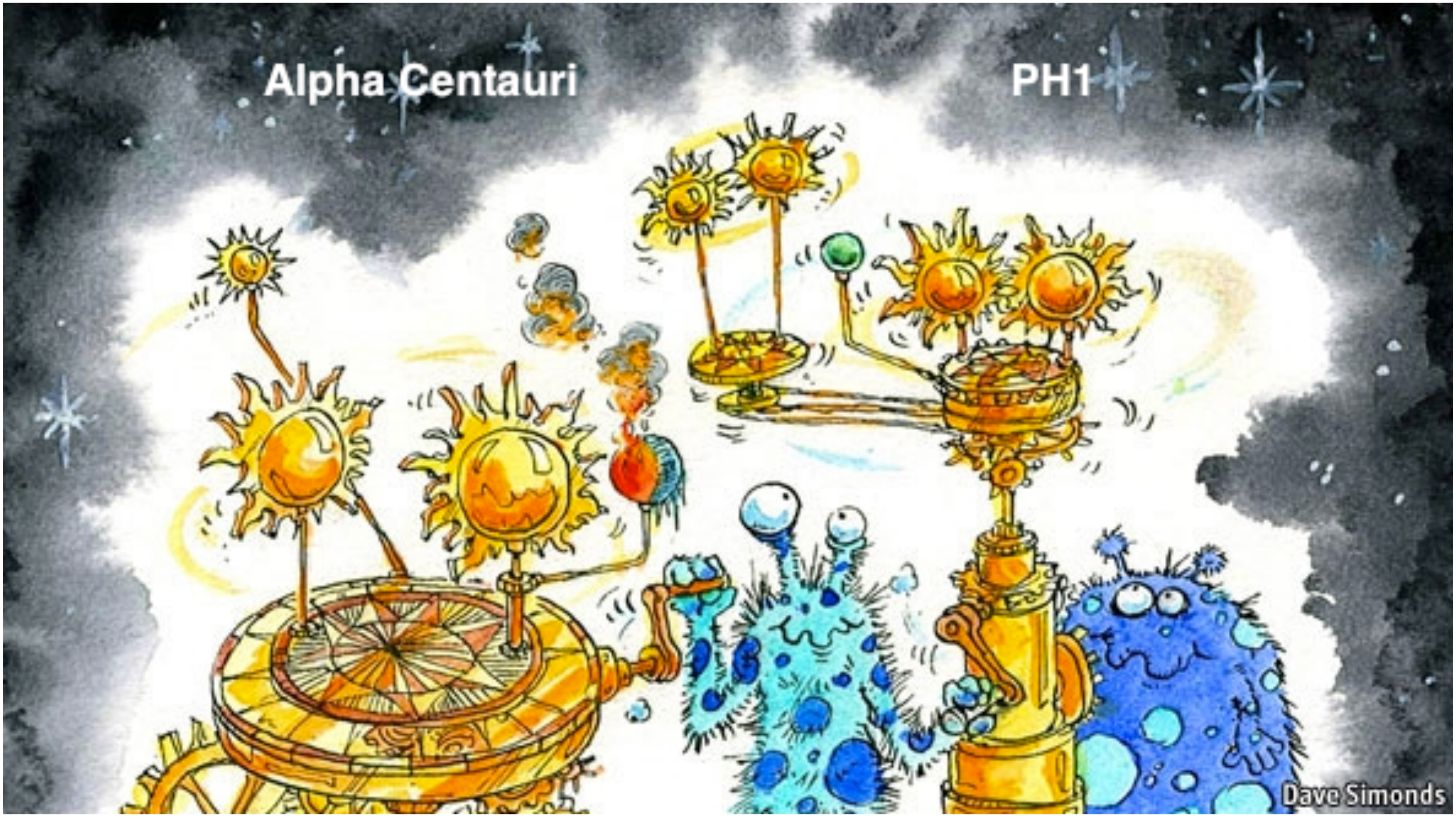


⇒ 3.23 days, $M\sin i$ = 1.13±0.09 M_{earth}

⇒ 4 light years away!

⇒ In a triple stellar system

Filtered out binary motion, magnetic cycles, starspots; to be confirmed….



The Economist

Diversity of Planetary Systems:

Yes, planets are also common *outside* the Solar System… but they are often…

a) Super-Massive Terrestrials
b) Mini-Neptunes with packed orbits
c) Orbits in resonant chains
d) Hot Jupiters (Close-in)
e) Eccentric (and/or flipped over)
f) In binary star systems

Processes forming these systems have worked in the Solar System too, but in subtler ways.

How to get the Data!

http://nexsci.caltech.edu

-- lists of candidates and properties

http://archive.stsci.edu/kepler/

-- download of lightcurves

A cutting-edge dataset for student research projects!