Measuring planet masses with synodic chopping

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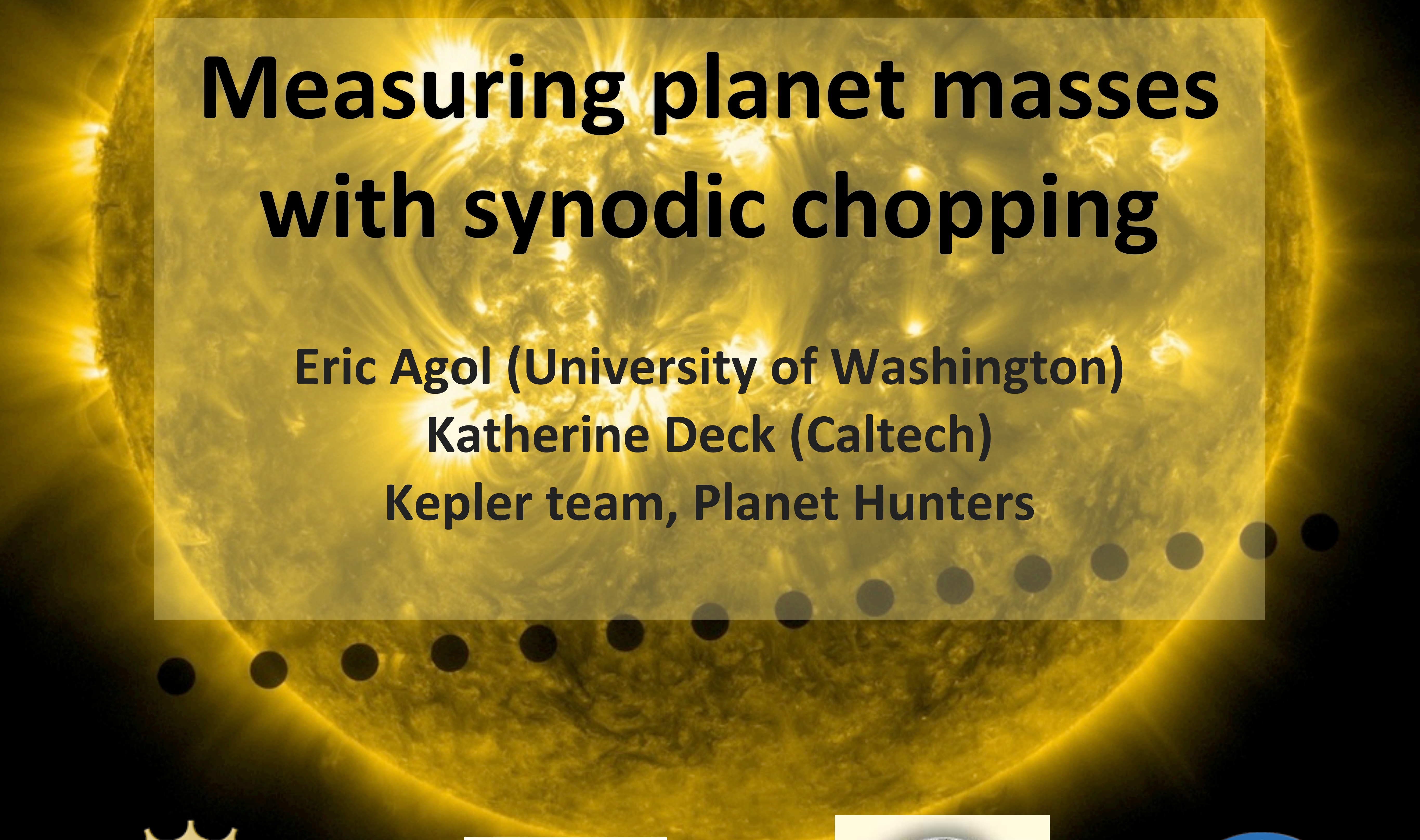

NSF

Kepler

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NASA

Photo: Solar Dynamics Observatory

Masses from TTVs

- How are transit times converted into masses?
- How reliable are TTV masses?

Glossary:

"TTV" = transit timing variation

"conjunction" = closest approach planets

"synodic period" = time between conjunctions

"near resonant" = period ratio close to integer ratio

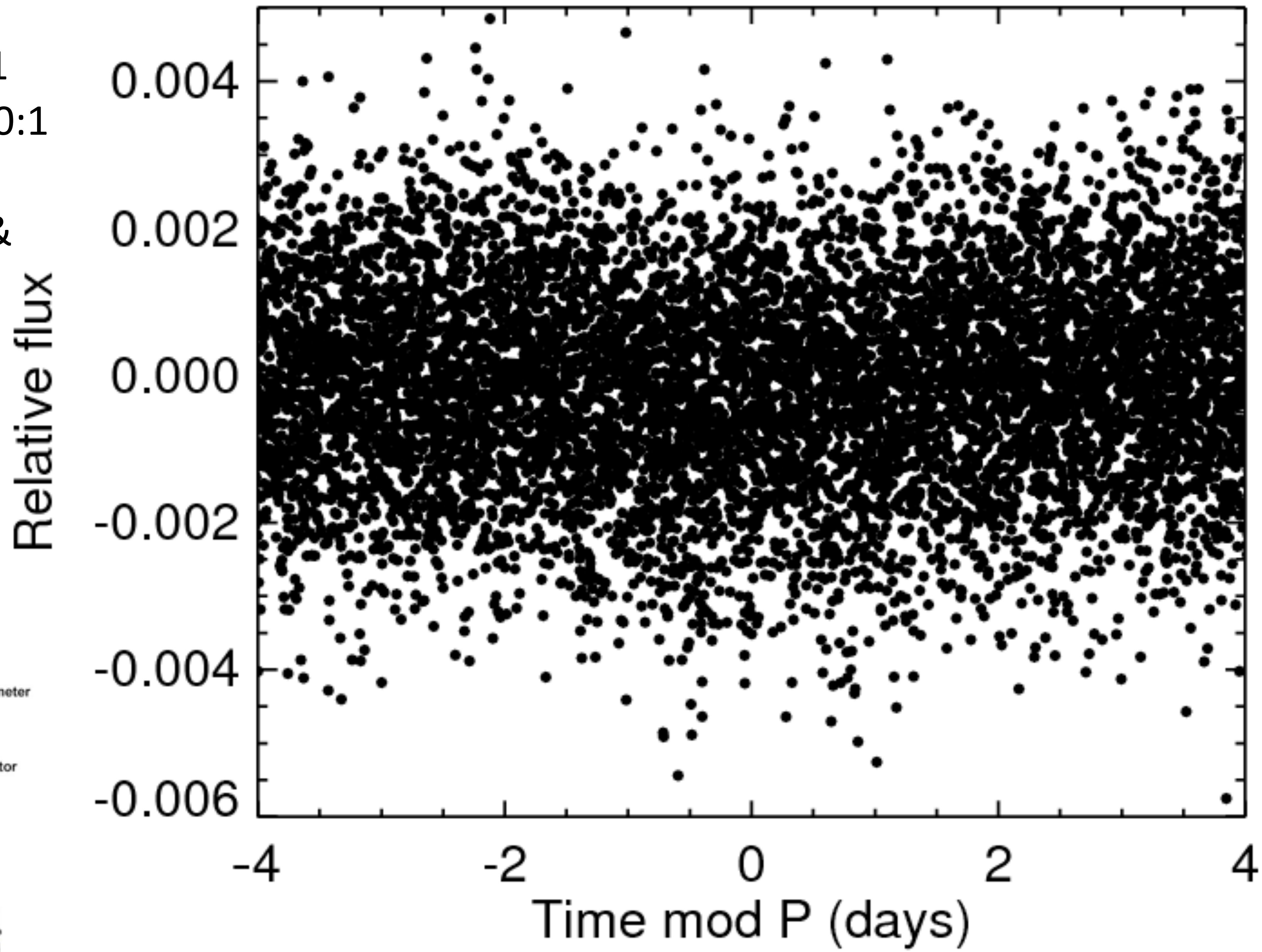
"chopping" = alternating early/late transit times

Measuring density with transits

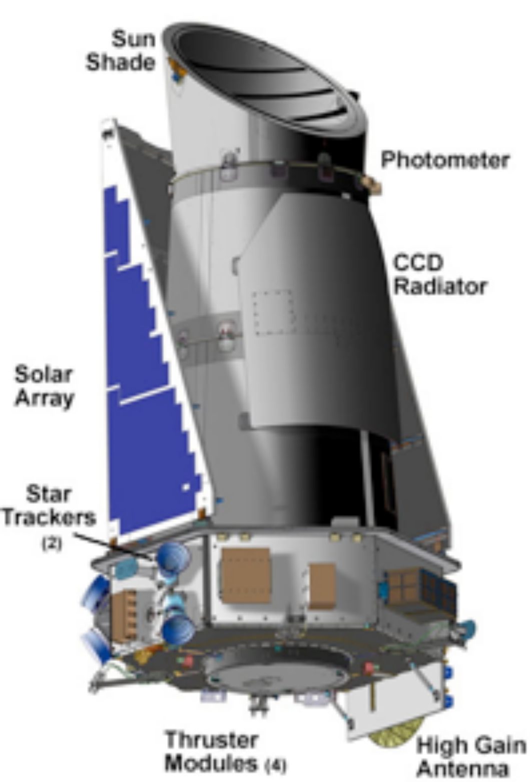
- Amplitude of TTVs scales with:
  - orbital period of planets
  - mass ratio of *perturbing* planet to the star
  - works best when *both* planets are detected
  - independent of frequency of transiting planet
- Depth of transit scales with radius ratio of planet to star squared
- With mass & radius of star, obtain mass & radius of planet(s)

Quasi-periodic planet problem

Simulated 2:1 resonance; 10:1 mass ratio; super-Earth & gas giant

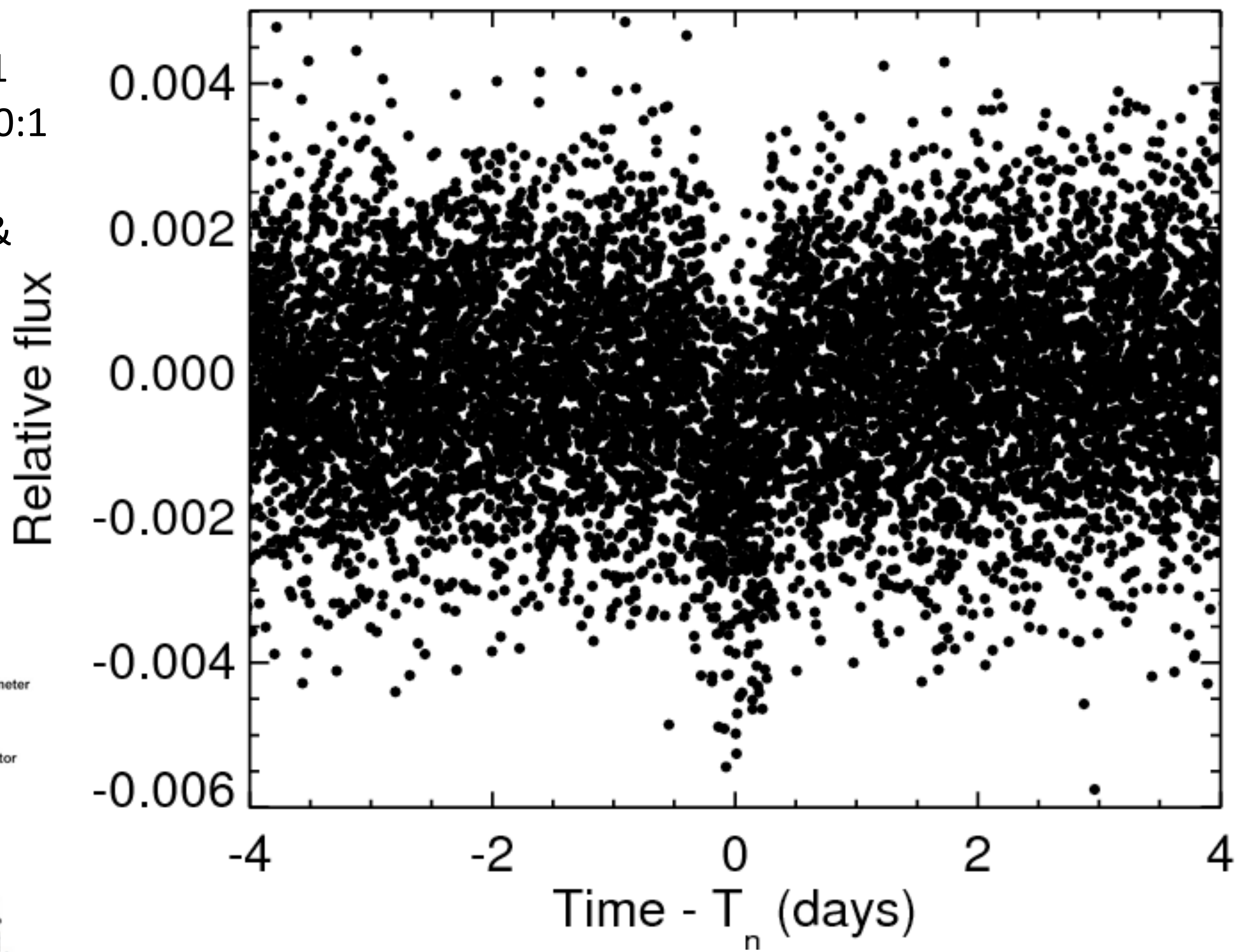


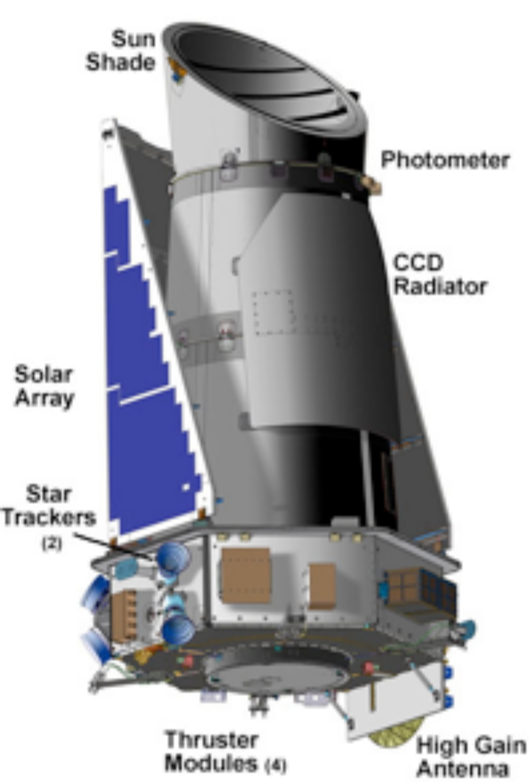
Kepler



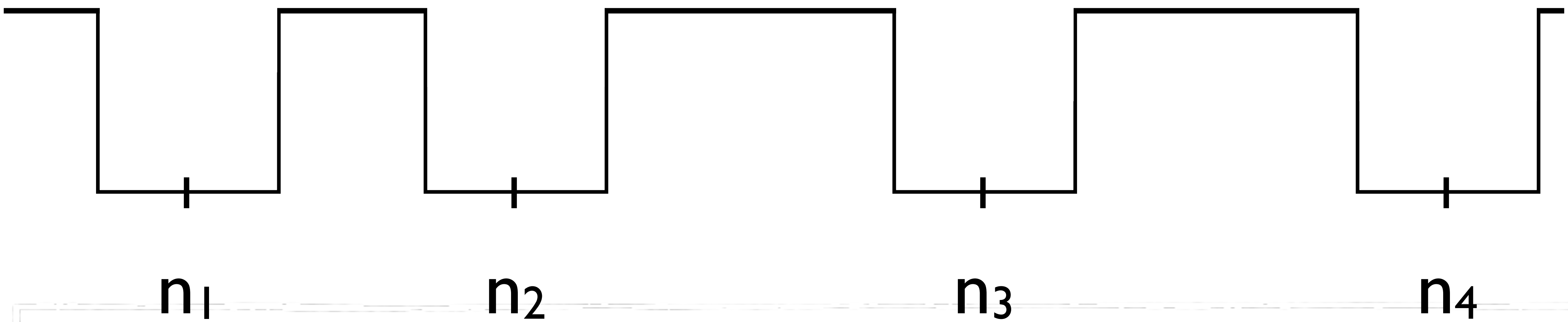
Quasi-periodic planet problem

Simulated 2:1 resonance; 10:1 mass ratio; super-Earth & gas giant





Google: “quasi-periodic pulse detection”



A Posteriori Joint Detection and Discrimination of Pulses in a Quasiperiodic Pulse Train

Alexander V. Kel’manov and Byeungwoo Jeon, *Senior Member, IEEE*

(2004)

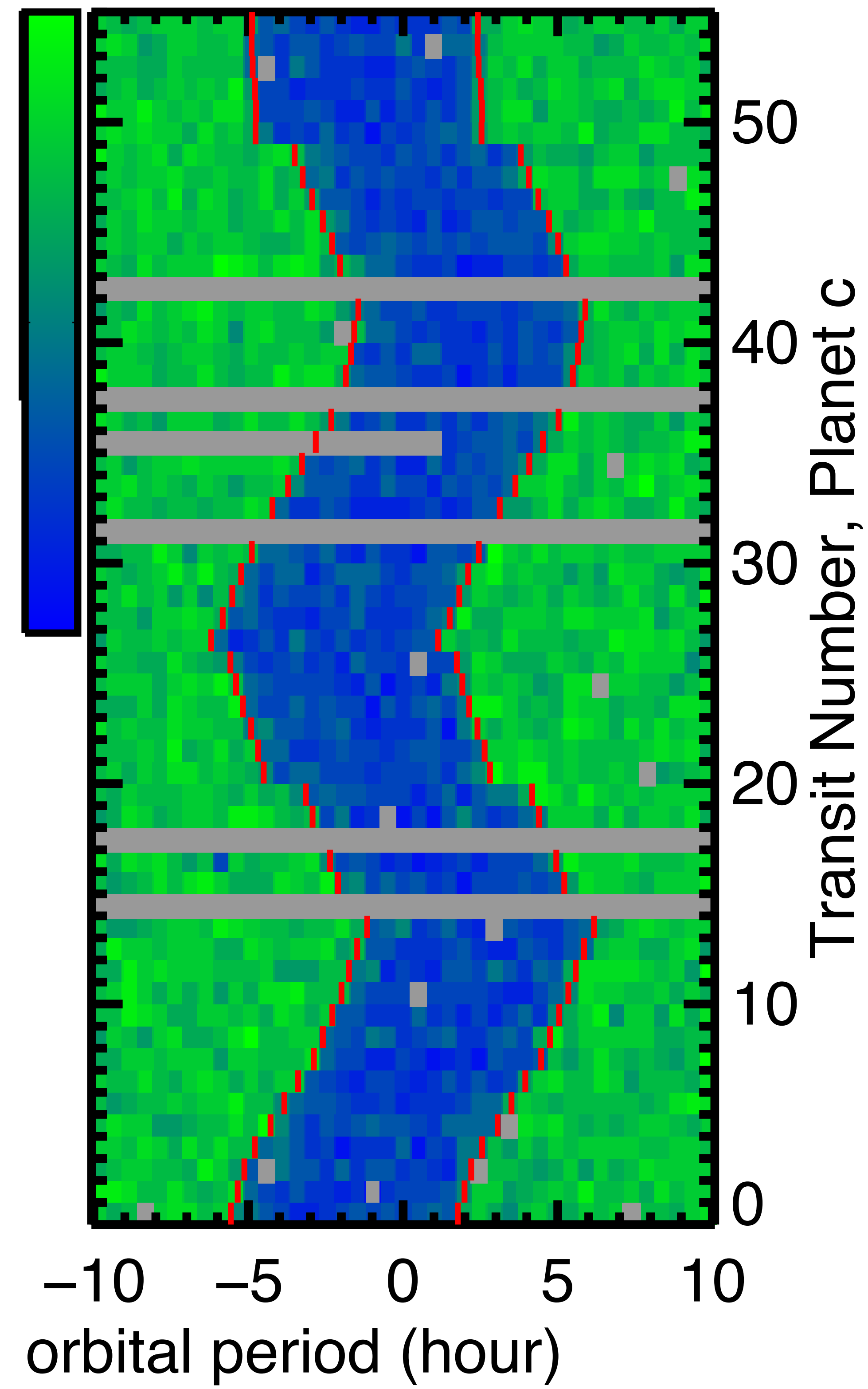
such applications as electronic warfare [1], radar [2], communications [3], geophysics [4], speech processing [5], medical and engineering diagnostics [6], [7], and others. Appropriate pro-

Quasiperiodic = $T_{min} \leq n_m - n_{m-1} \leq T_{max}$

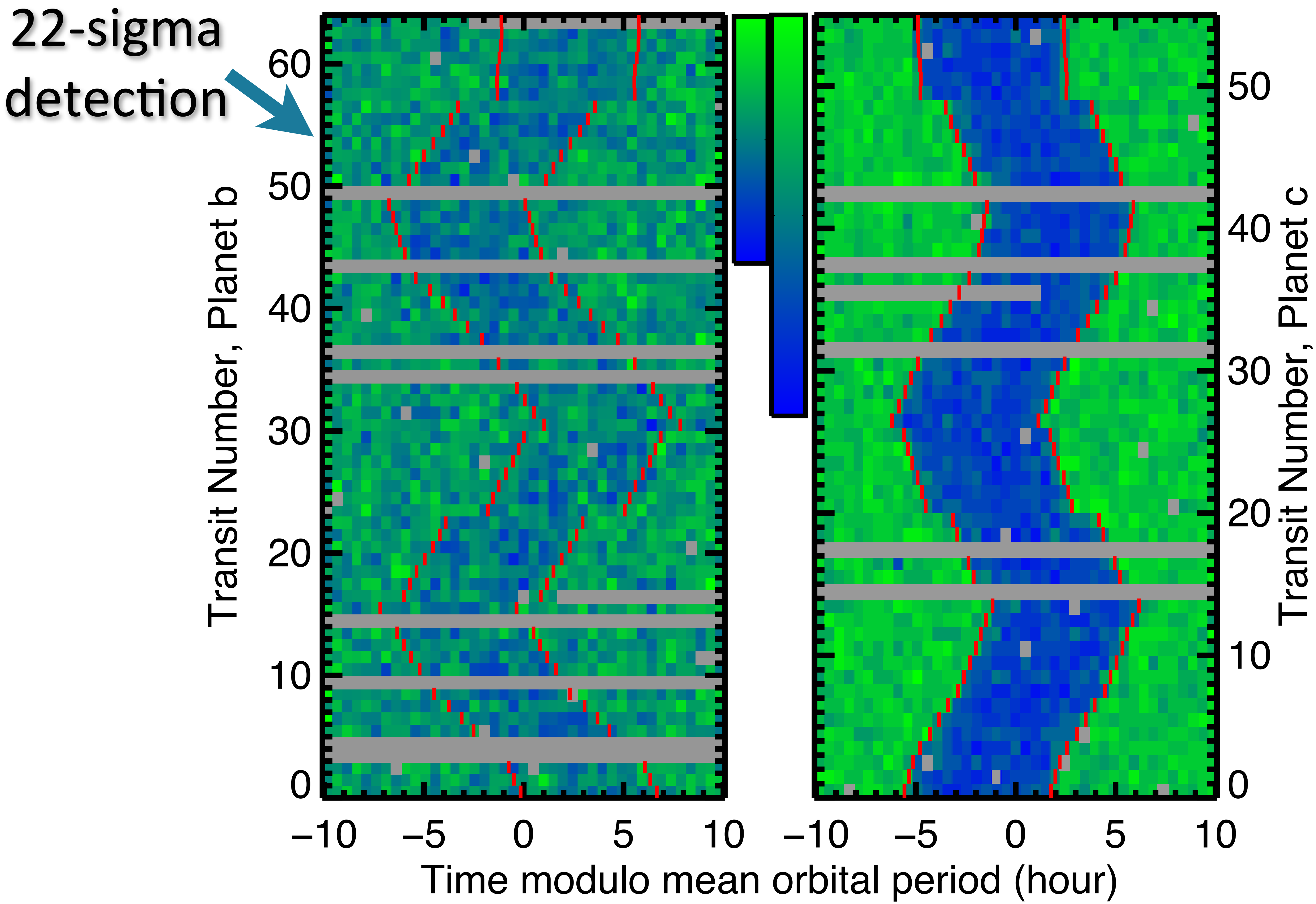
$W = T_{max} - T_{min} = f\,T_{min}$ (simply sets “period” search spacing)

“Period” ~ $(T_{min} + T_{max})/2$

KOI 277.01: a quasi-periodic Neptune

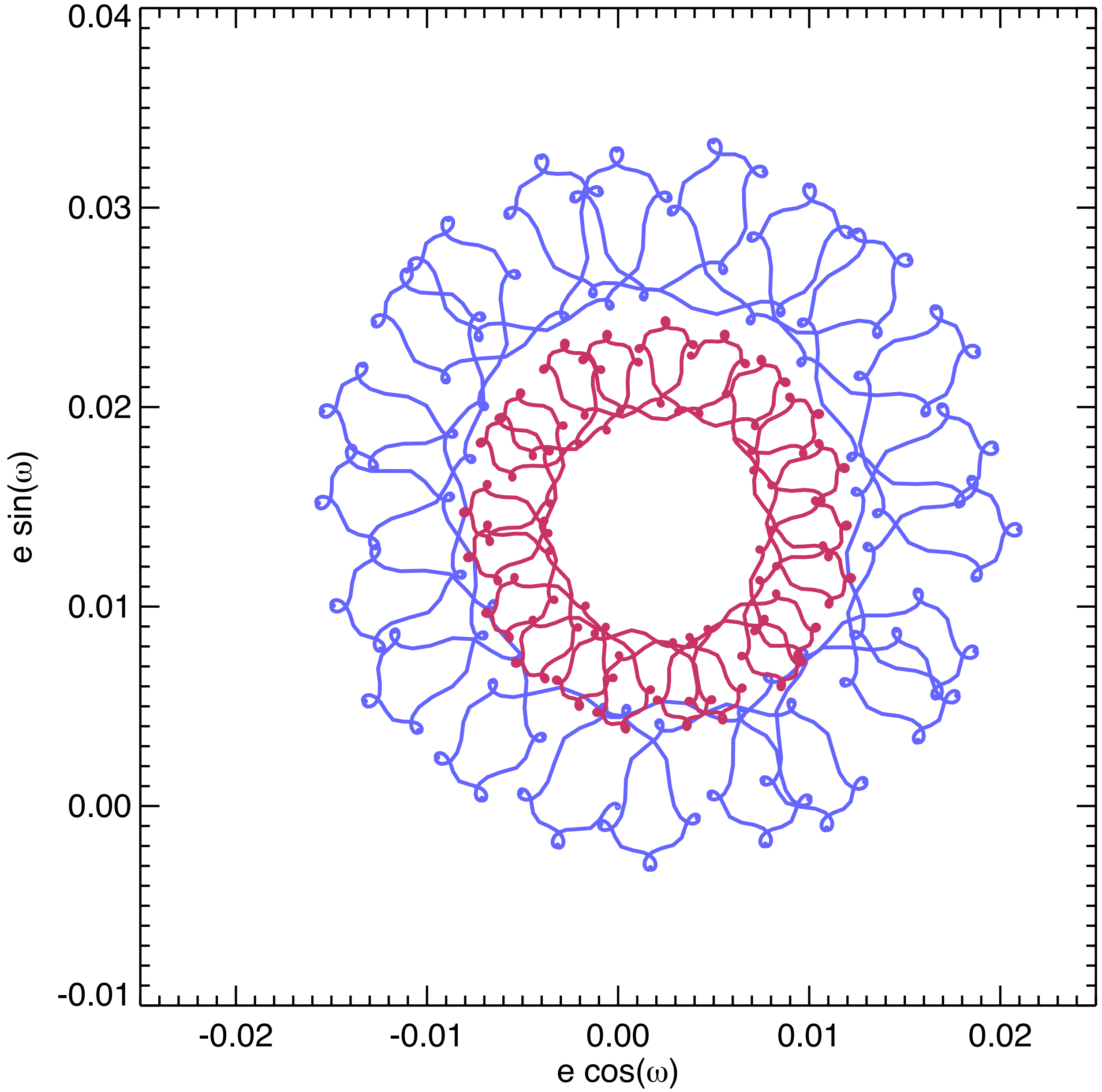


Kepler-36b,c: closest two orbiting planets

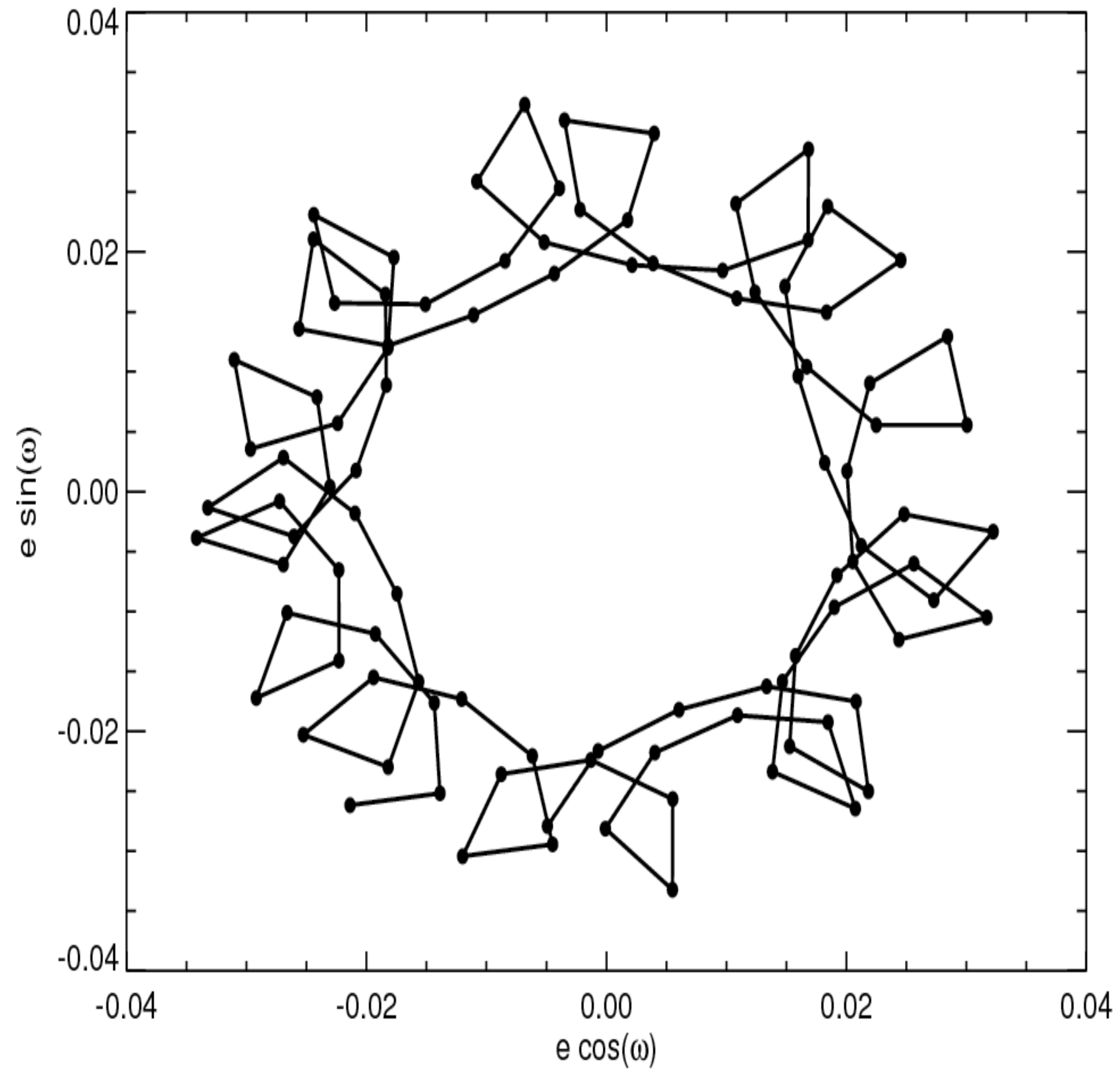


Carter, Agol et al. (2012)

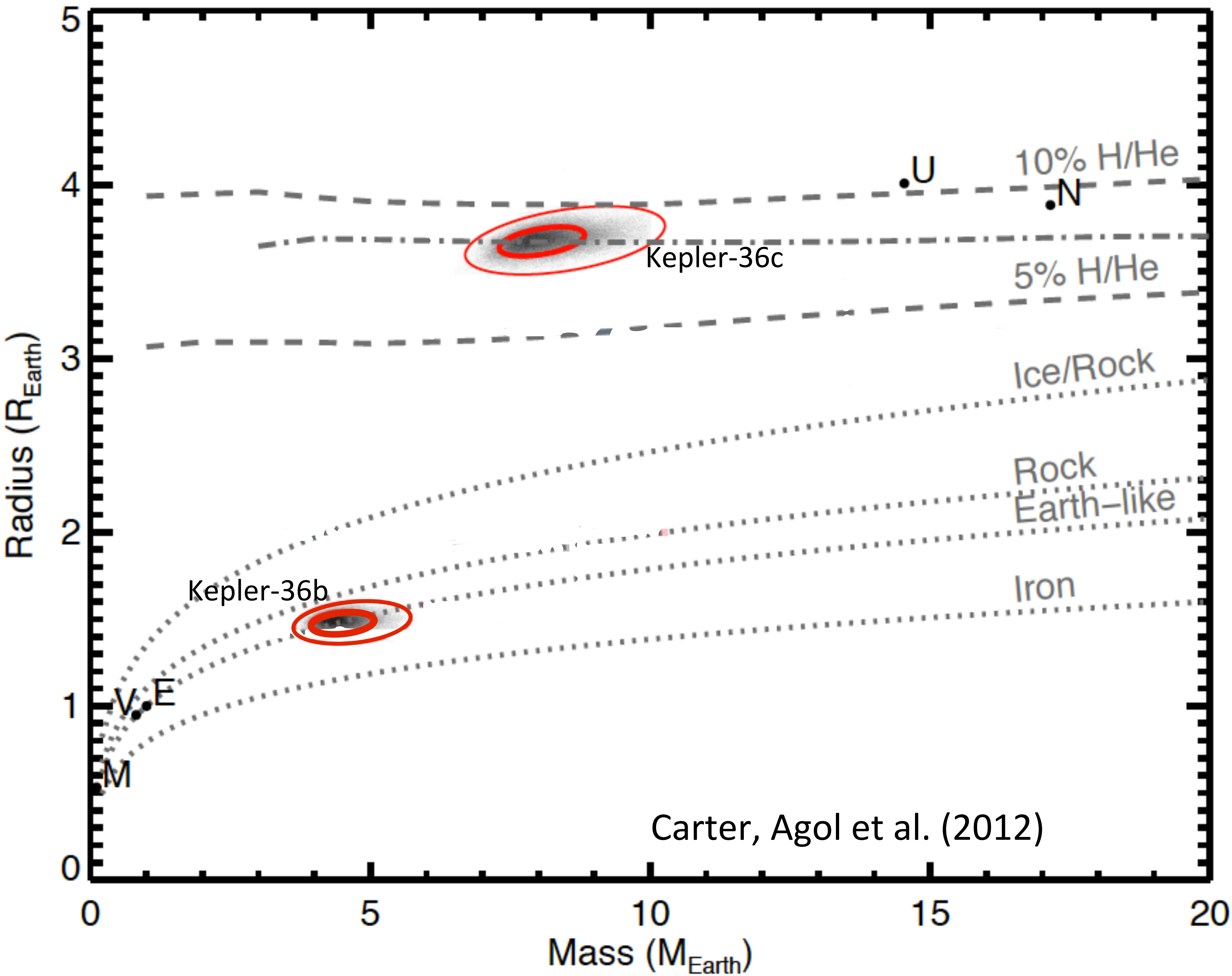
Eccentricity jumps at conjunction



Dynamical integration



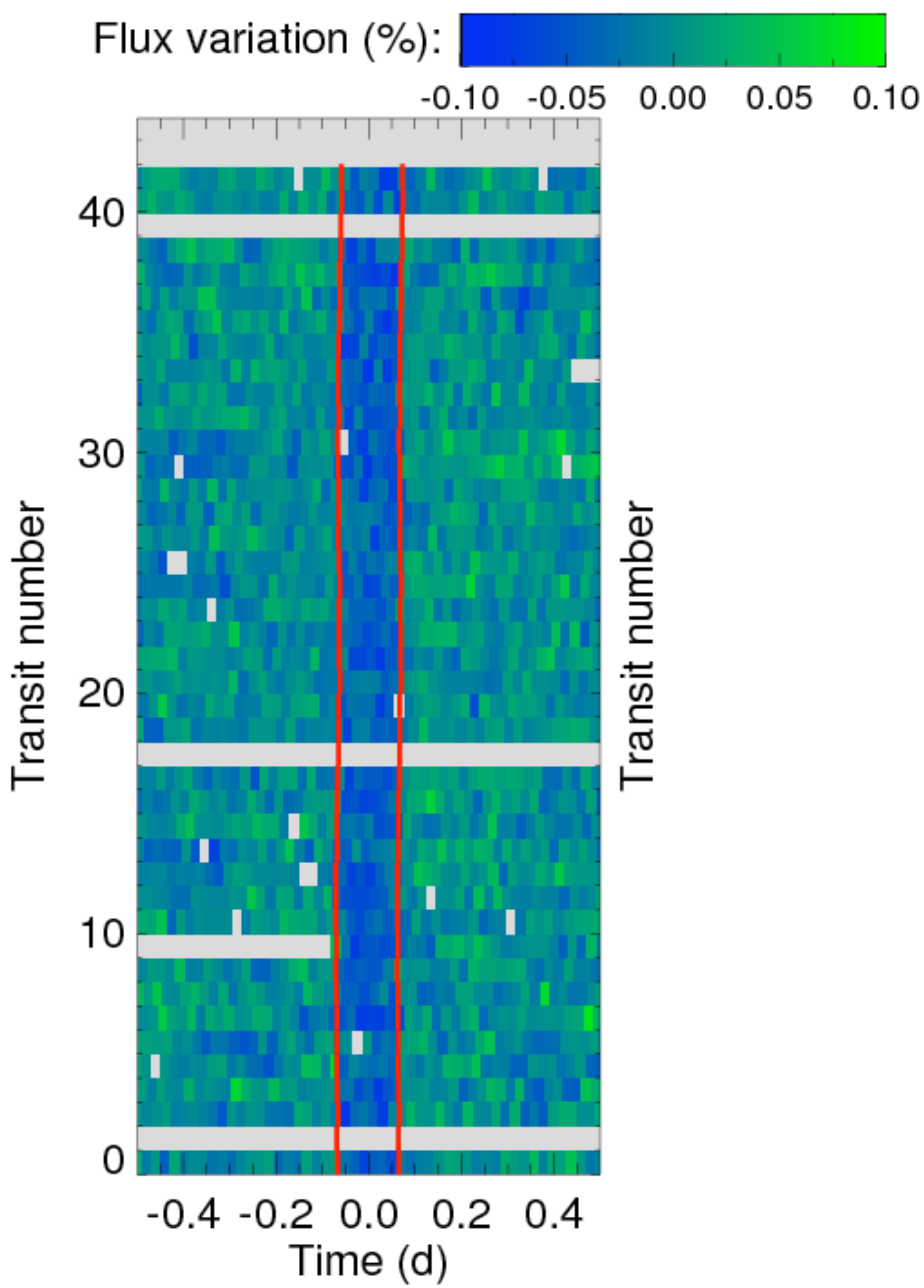
Analytic drift + impulse

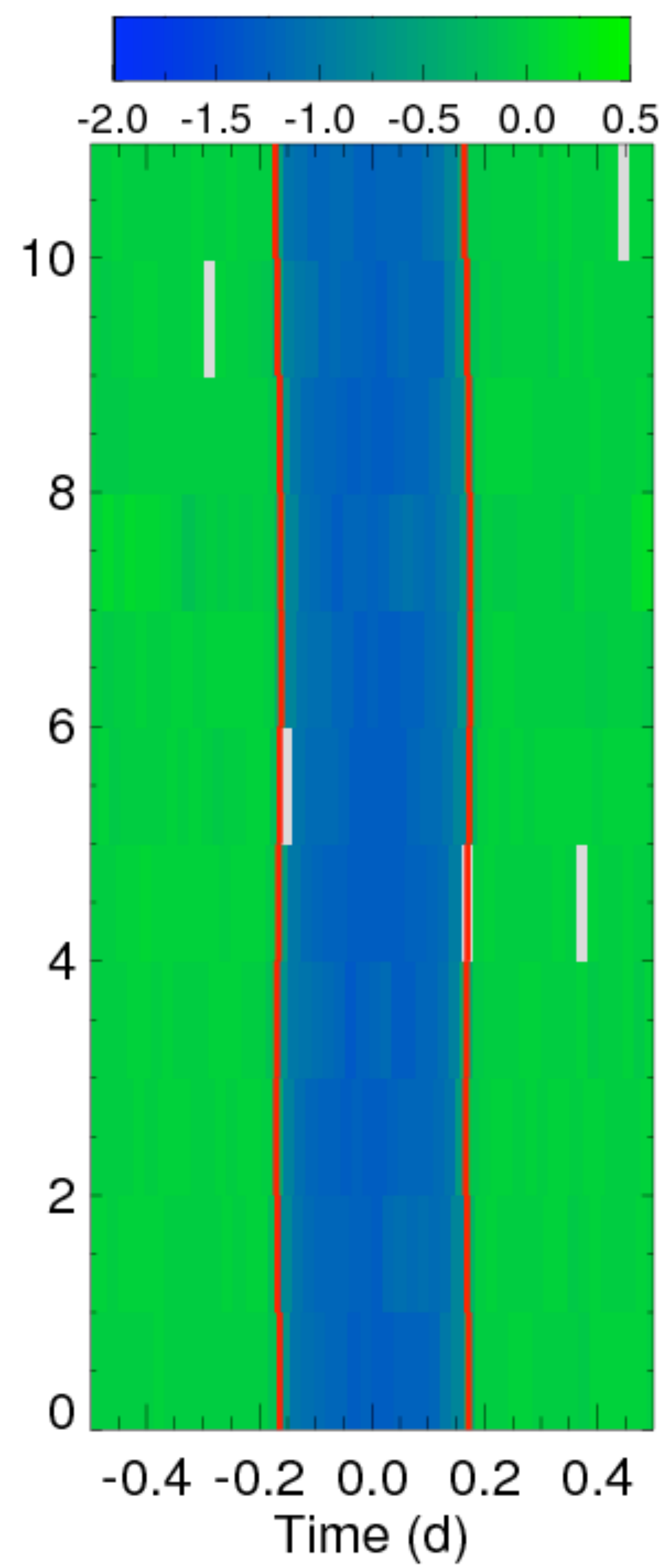


Radius (R_{Earth})
Mass (M_{Earth})
10% H/He
5% H/He
Ice/Rock
Rock
Earth–like
Iron
U
N
V
E
M
Kepler-36c
Kepler-36b
Carter, Agol et al. (2012)
0
1
2
3
4
5
0
5
10
15
20

Credit: NASA; Frank Melchior, frankacaba.com; Eric Agol

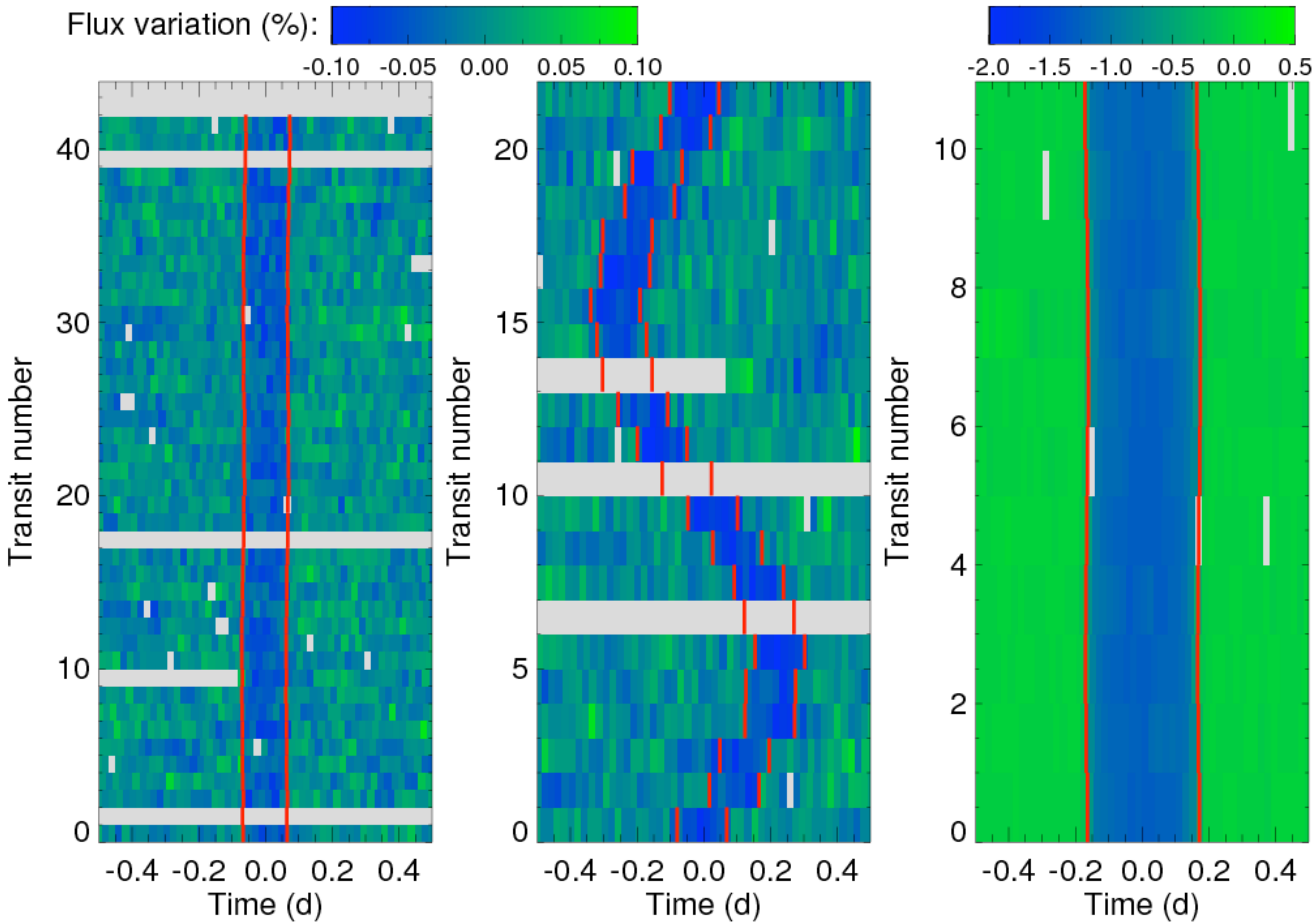
Another one that got away...





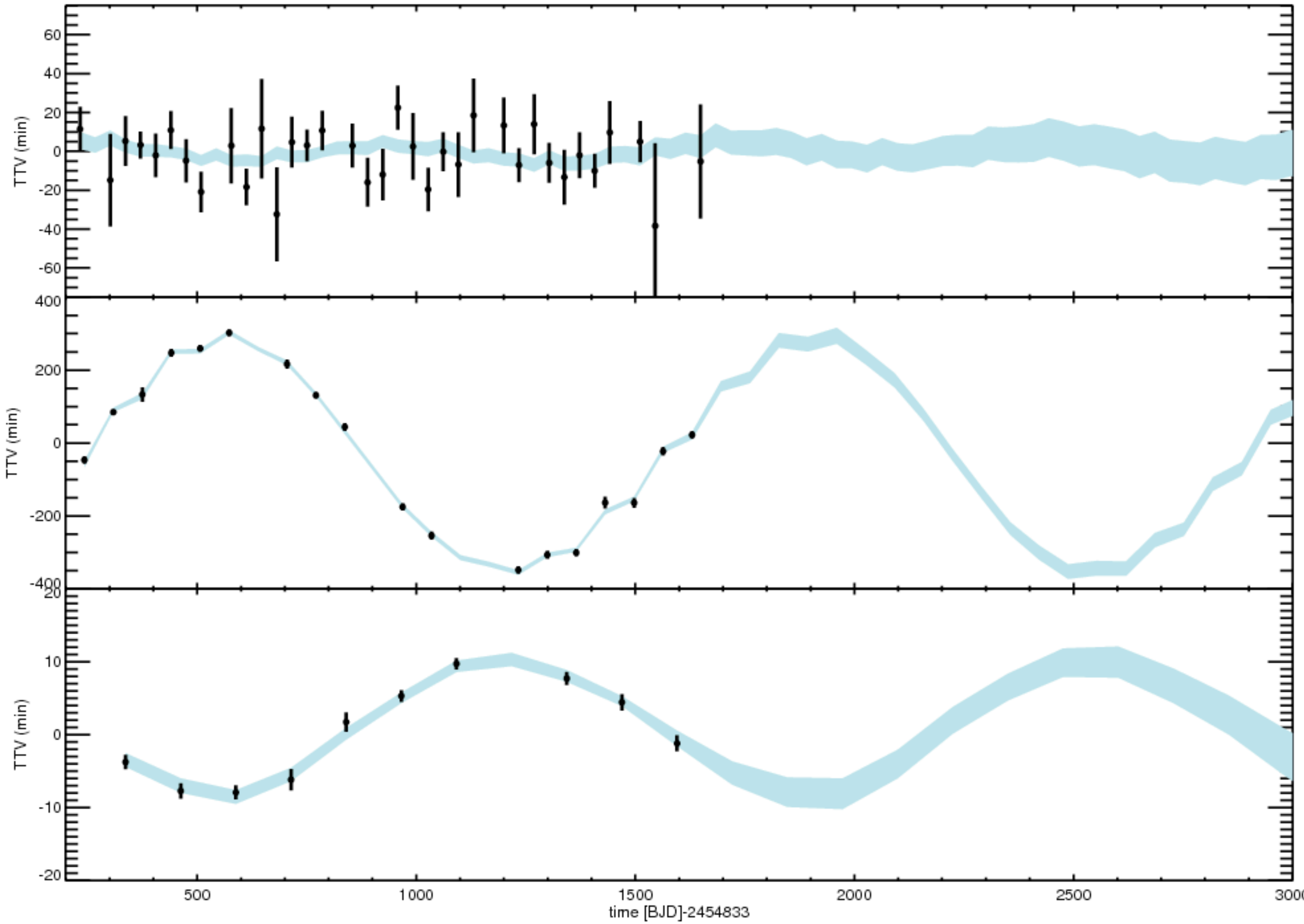
Schmitt, Agol, Deck, Rogers, et al., ApJ (2014)

Planet Hunters 3



Schmitt, Agol, Deck, Rogers, et al., ApJ (2014)

TTV of Planet Hunters 3



Schmitt, Agol, Deck, Rogers, et al., ApJ (2014)

Mass measurement

- Amplitude of resonant terms constrain a combination of mass & eccentricity (Lithwick et al. 2012):

$$\Delta = \frac{P_2}{P_1}\frac{j-1}{j} - 1$$

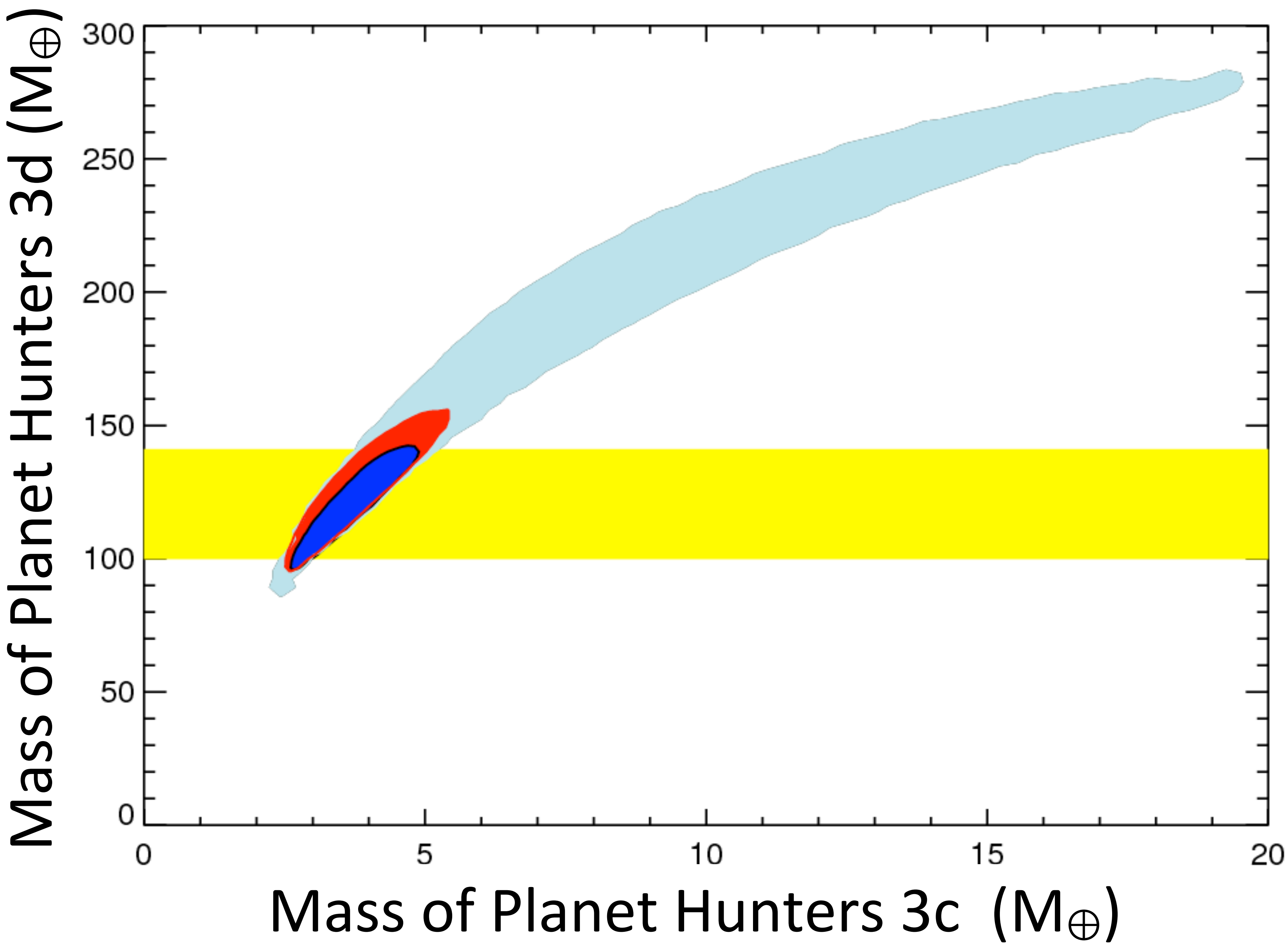
$$\delta t_1 \propto \frac{P_1}{\Delta}\frac{m_2}{m_*}(1 + (\mathcal{O}(e_1) + \mathcal{O}(e_2))/\Delta)e^{i2\pi t[(j-1)/P_1 - j/P_2]}$$

- Amplitude of synodic "chopping" component scales with mass ratio (& weakly with eccentricity):

$$\delta t_1 \propto P_1 f(a_1/a_2)\frac{m_2}{m_*}(1 + \mathcal{O}(e_1) + \mathcal{O}(e_2))e^{i2\pi t[1/P_1 - 1/P_2]}$$

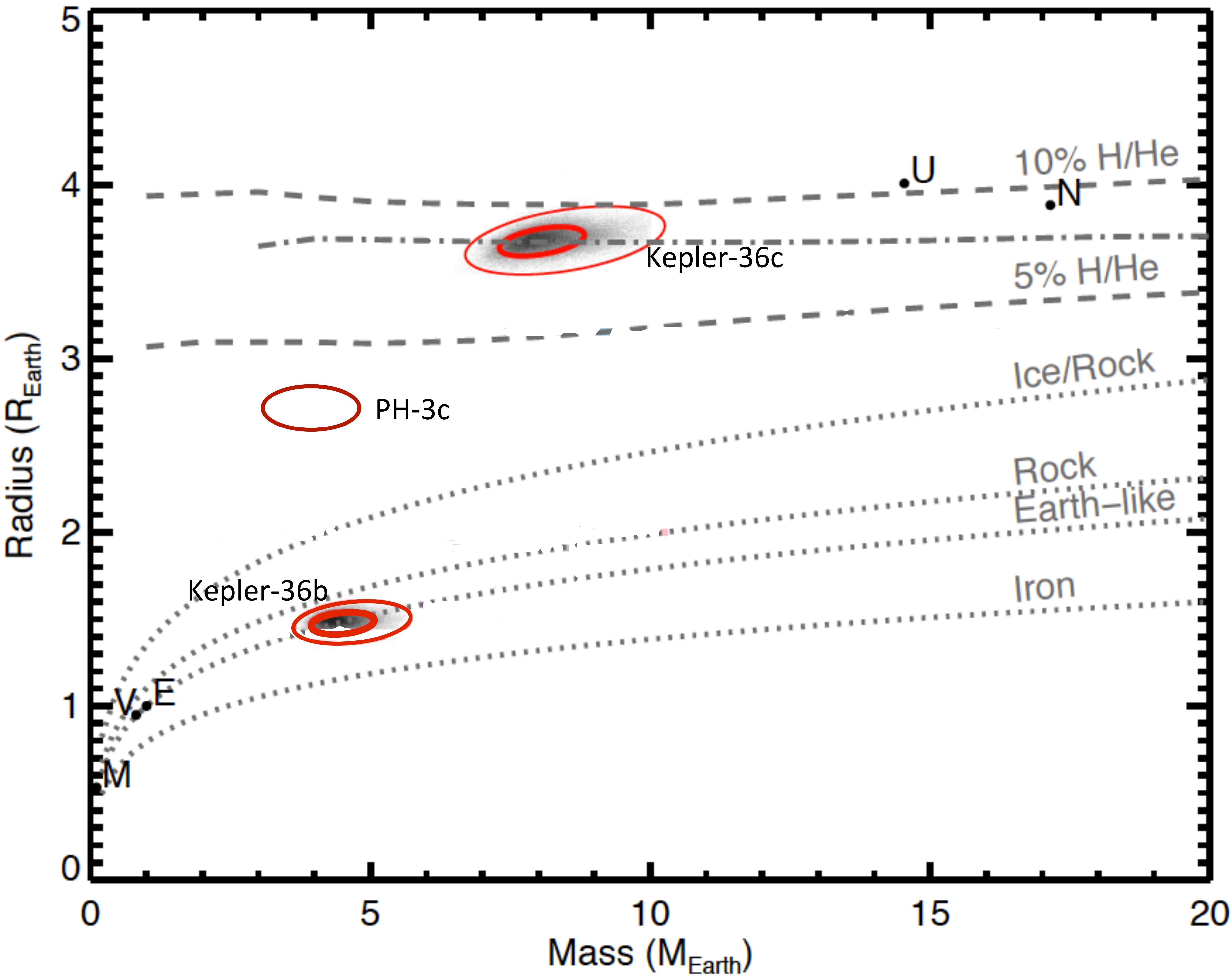
Agol & Deck (2014)

Breaking mass-eccentricity degeneracy



PH 3c:
2.1% H/He
by mass

Agol & Deck (2014)



10% H/He
U
N
Kepler-36c
5% H/He
Ice/Rock
PH-3c
Rock
Earth–like
Iron
Kepler-36b
V
E
M
Radius (R_Earth)
Mass (M_Earth)
0
1
2
3
4
5
0
5
10
15
20

Conclusions

- Close planets show sharp jumps at conjunction which constrain masses & radii of planets
- Near-resonant planets (j:j+1, j integer) show resonant terms; in some cases this causes a mass-eccentricity degeneracy
- High signal-to-noise allows measurement of chopping amplitude or resolving resonant degeneracy; in some cases provides an extra constraint on planet mass
- TESS may measure chopping: constrain masses with few transits