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Transit timing variations in Kepler's data

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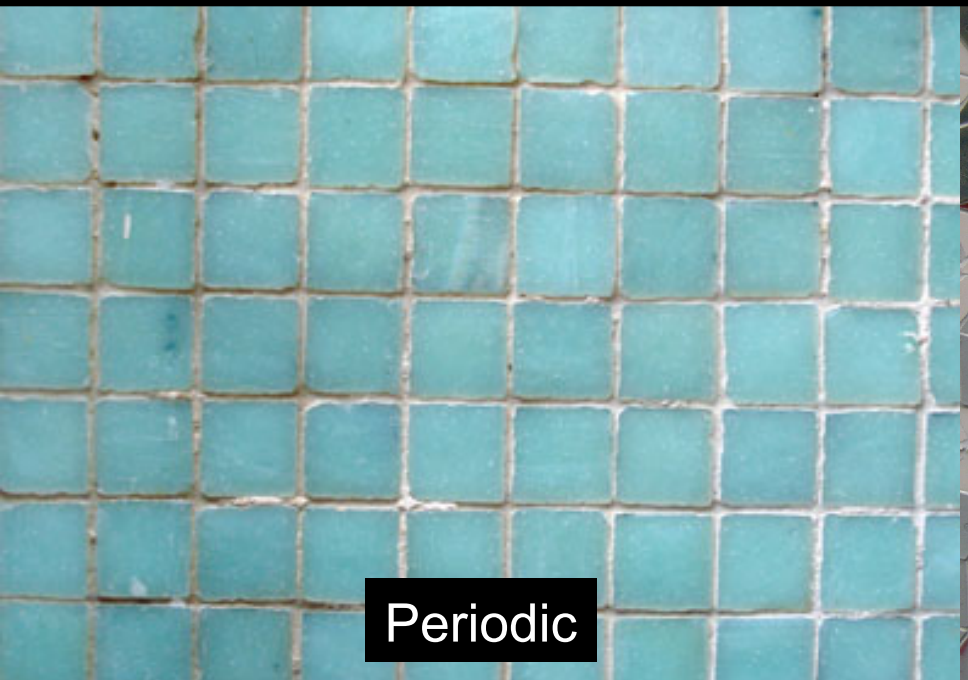
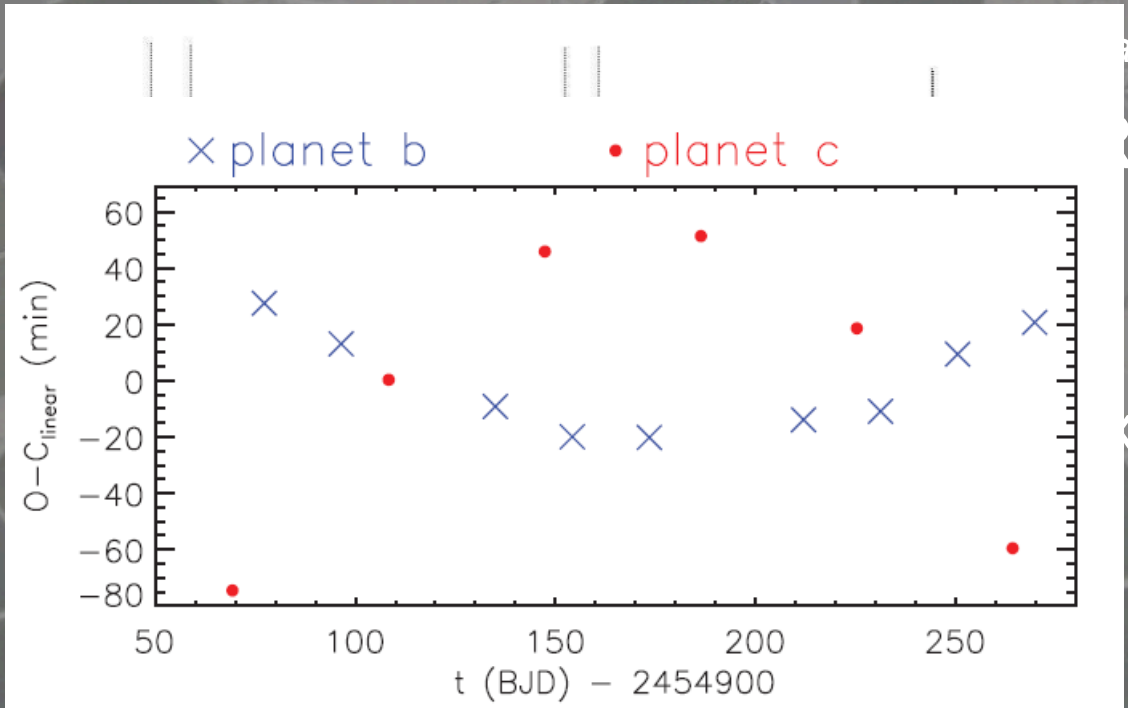


Outlook

- Brief history
- Kepler-9
- Kepler-117
- KOINet
- Conclusions

Brief history of TTVs study

- Theoretical predictions:
  - Holman & Murray (2005): planet-planet interactions (angular momentum exchange)
  - Agol *et al* (2005): also indirect interaction
- *al.* (2010)
- Rs):



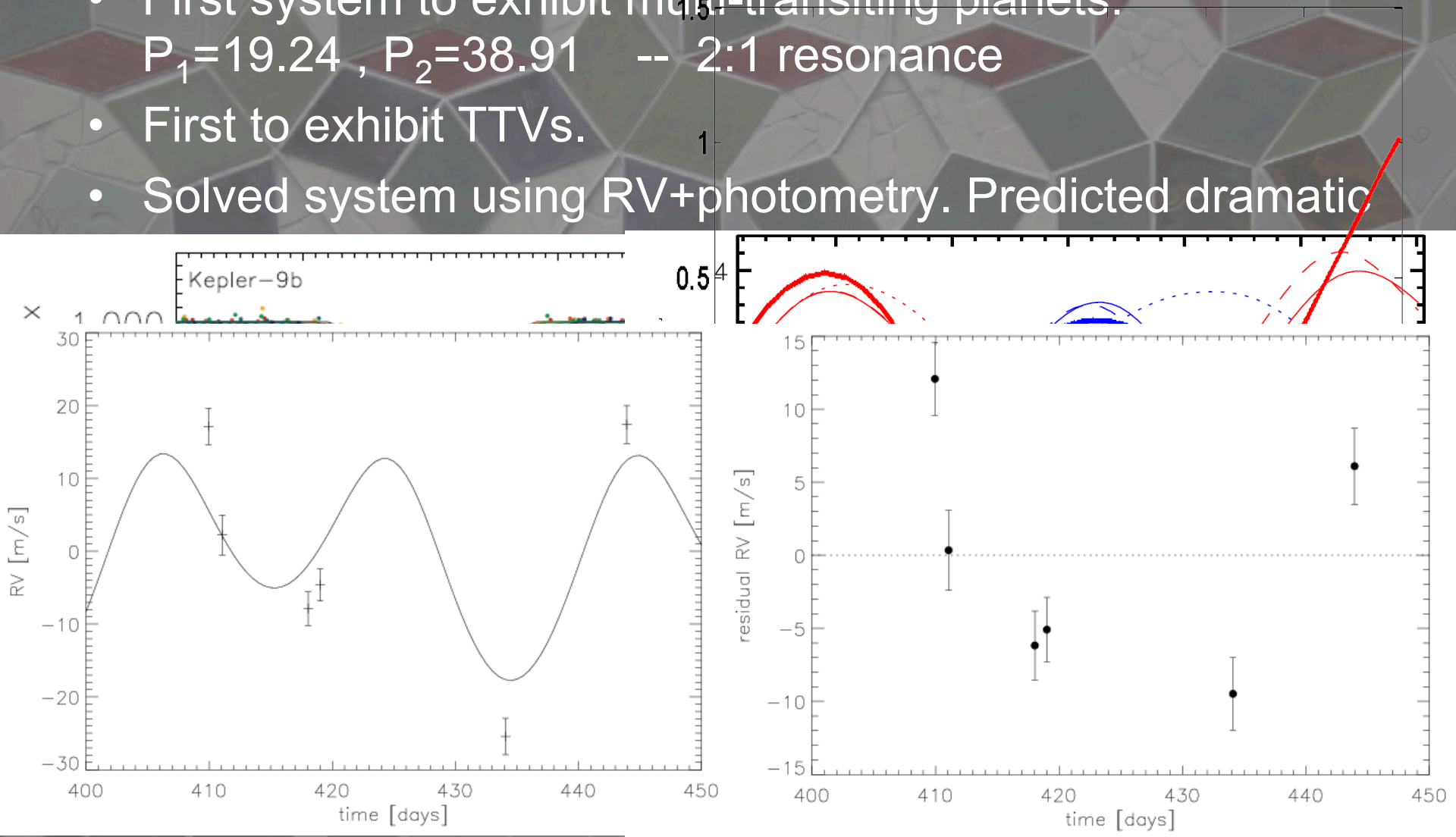
Rs

xact resonances

Revisiting Kepler-9

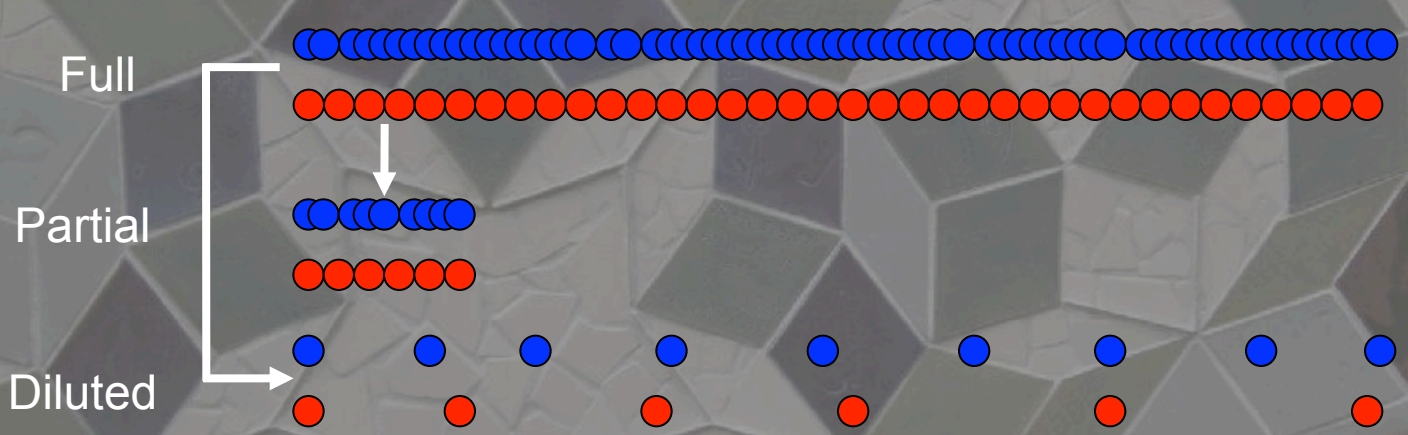
(Holman *et al*. 2010)

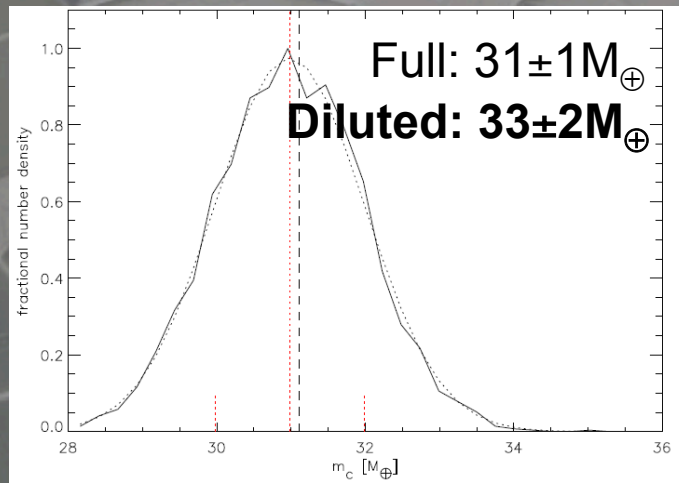
- First system to exhibit multi-transiting planets:
  P_1=19.24 , P_2=38.91 -- 2:1 resonance
- First to exhibit TTVs.
- Solved system using RV+photometry. Predicted dramatic

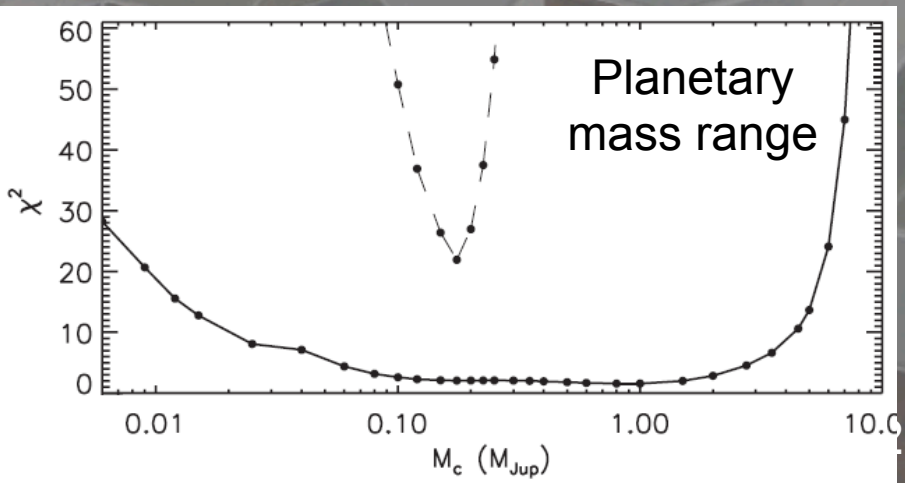


Revisiting Kepler-9: why?

- Interaction time not covered → systematic errors
- Reducing data points - vs. - reducing time span



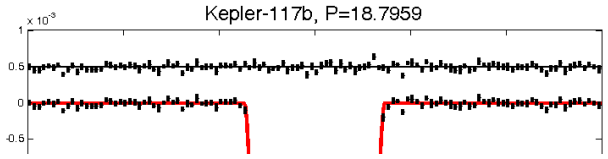


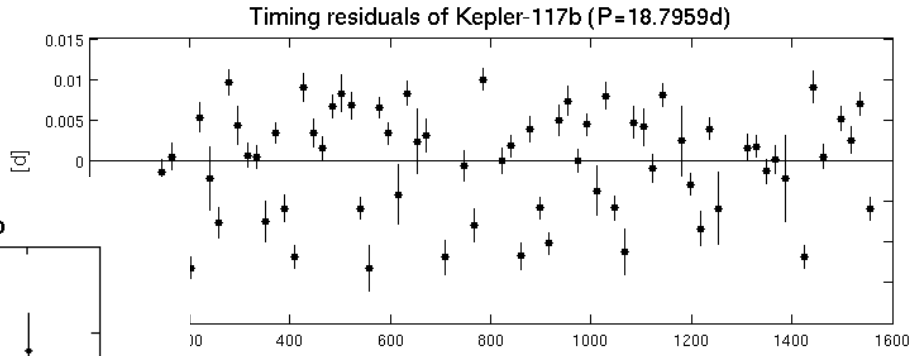


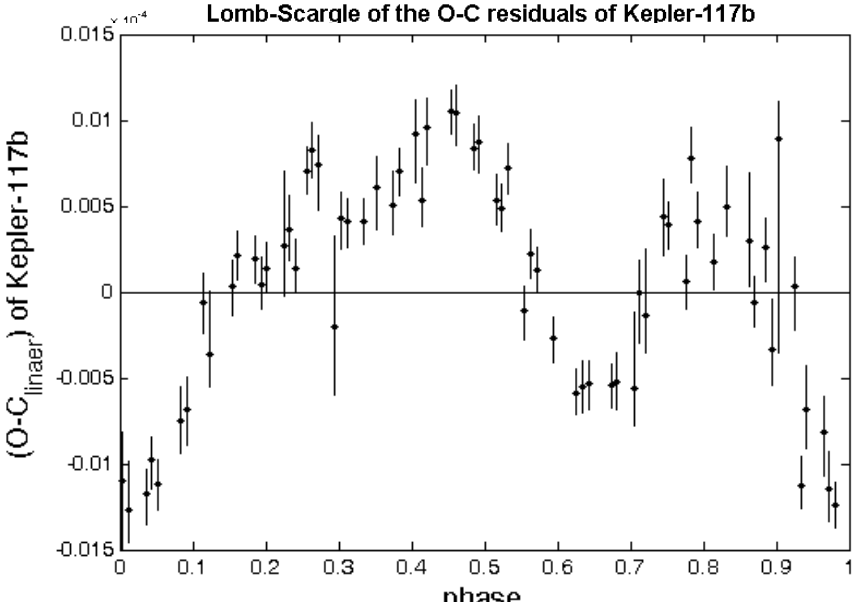
Kepler-117: what

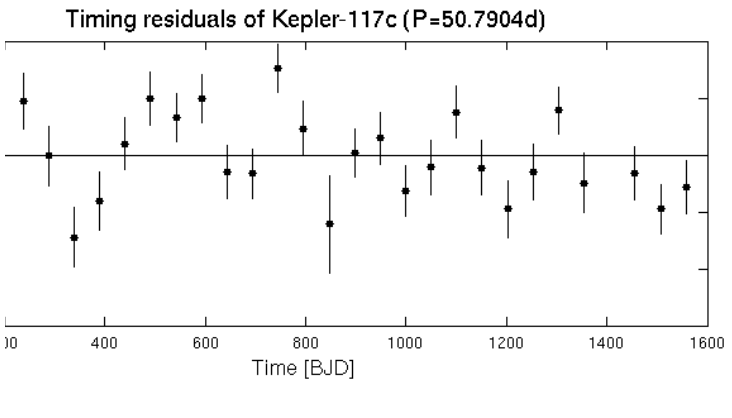
Ofir, Dreizler & Borkovits (A&A submitted)

- Of the very first Multi-transiting systems, recently validated (Rowe et al 2014)
- No long-term TTVs, no low-order MMR.
- BUT: only 2 frequencies in O-C of Kepler-117b





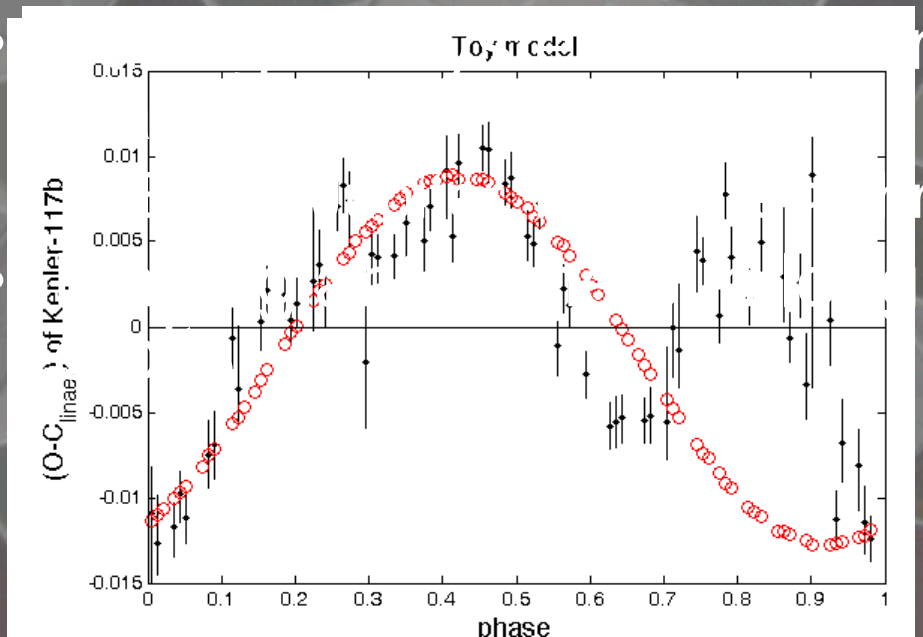




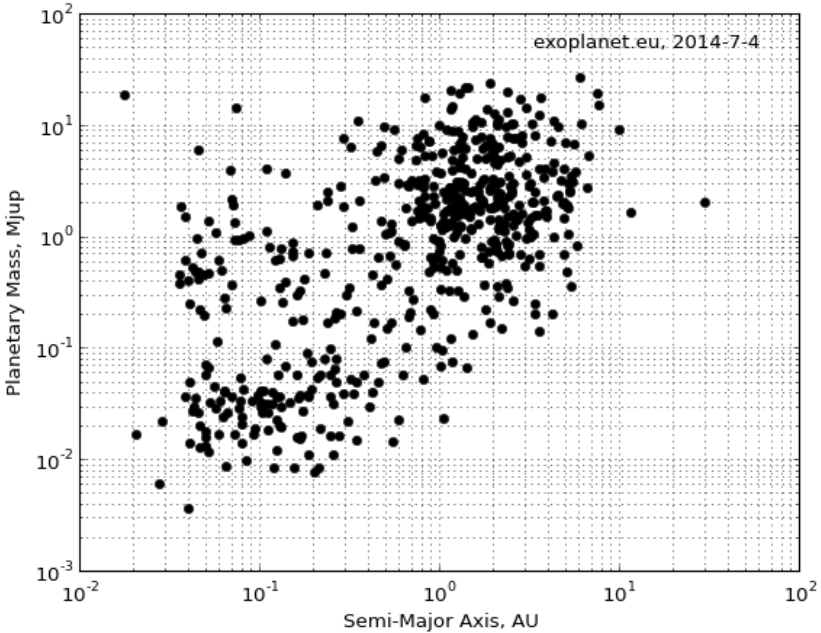
Kepler-117: why

Ofir, Dreizler & Borkovits (A&A submitted)

- N-body fit: Masses of $m_b \sim 2M_{Nep}$ and $m_c \sim 2M_{Jup}$
- It can be harmonically decomposed efficiently.
- Circular toy model of barycenter motion
  - Inner planet a test particle: $TTV = \frac{x_*}{V_b} \approx \frac{-a_c \mu_c \sin\left(2\pi(t - t_{mid,c})/P_c\right)}{2\pi a_b / P_b}$
- Possibly first observation of TTV dominated by indirect interaction (Agol et al. 2005).
- ng-
- rs(!)

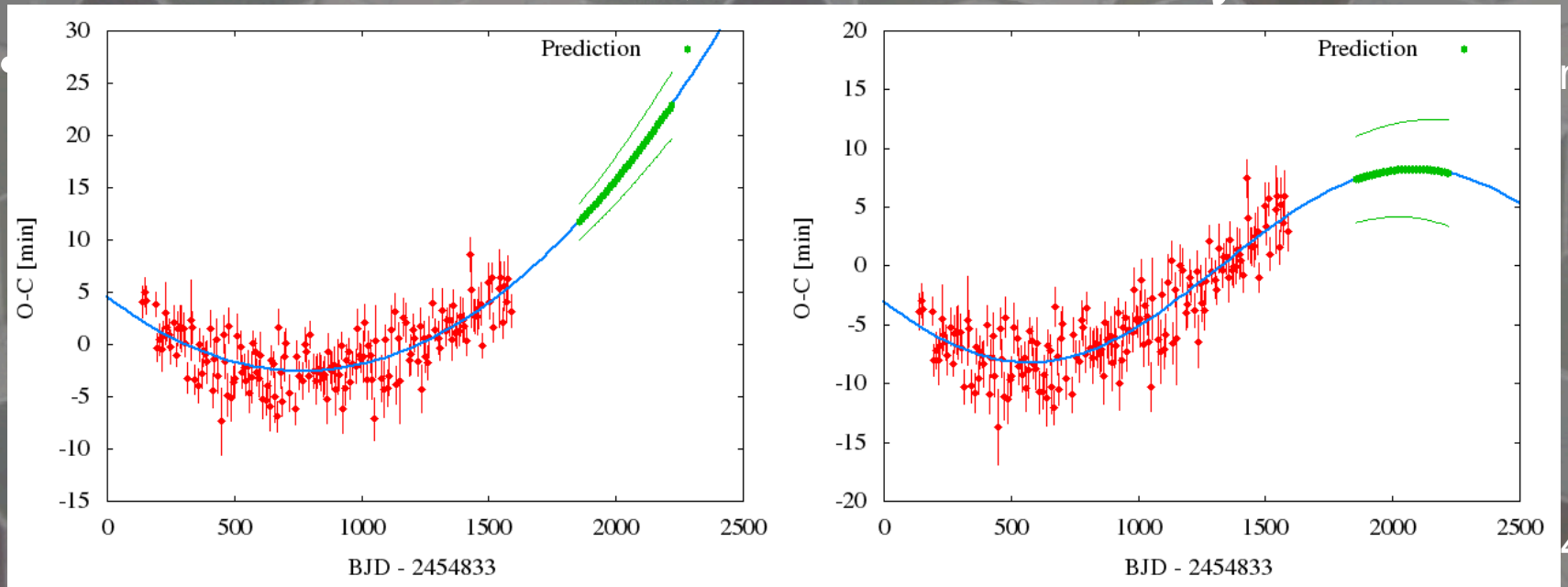


RV planets on Exoplanet Encyclopedia



KOINet (1)

- Kepler-9: increased baseline has non-linear benefits.
- Kepler-87 (Ofir *et al*. 2014), Kepler-90 (Cabrera *et al*. 2014), others: TTVs are sparse on long-period planets.
- KOI-410: TTVs exist, but what are they?



Conclusions

- Kepler-9: observations need to cover interaction time -- rewards are better than linear in time.
- Kepler-117: Barycenter-motion TTVs are important when long baselines are available.
- KOINet tries to extend the baseline where needed.
  - Have a ≥1m telescope? join KOINet!
- Large TTVs exist out of MMRs.
- With long baselines data, TTVs are the rule, not the exception, since multiplicity is the rule.

Thank you.

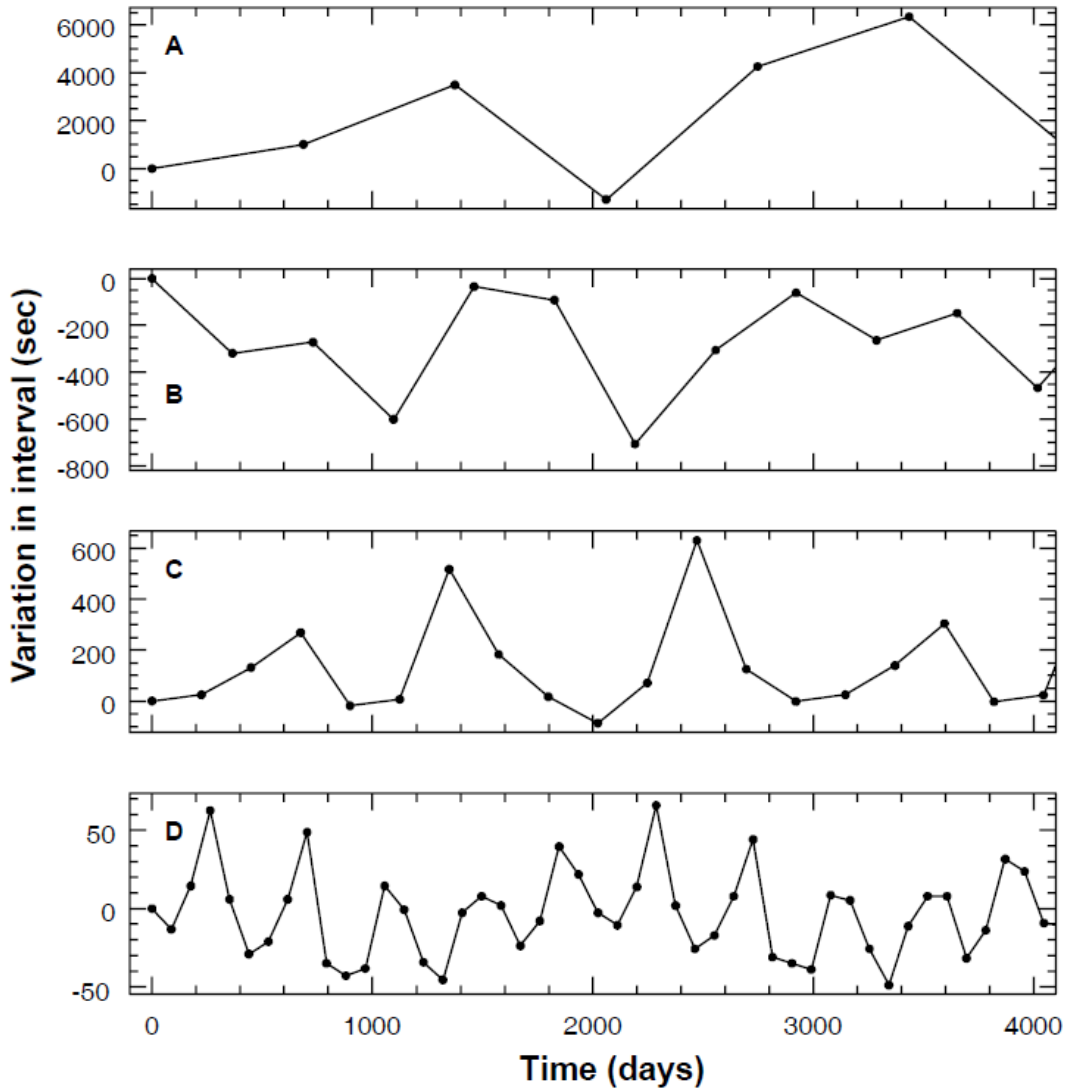


Fig. 1. The variations of the interval between successive transits of terrestrial planets, induced by the other planets in the solar system. (**A** to **D**) The variations for Mars, Earth, Venus, and Mercury, respectively. To guide the eye, the solid line connects the times of each transit. The transit intervals result from numerically integrating the equations of motion of the planets in our solar system and calculating the transit times as seen by distant observers located in the present-day orbital planes of the various planets.