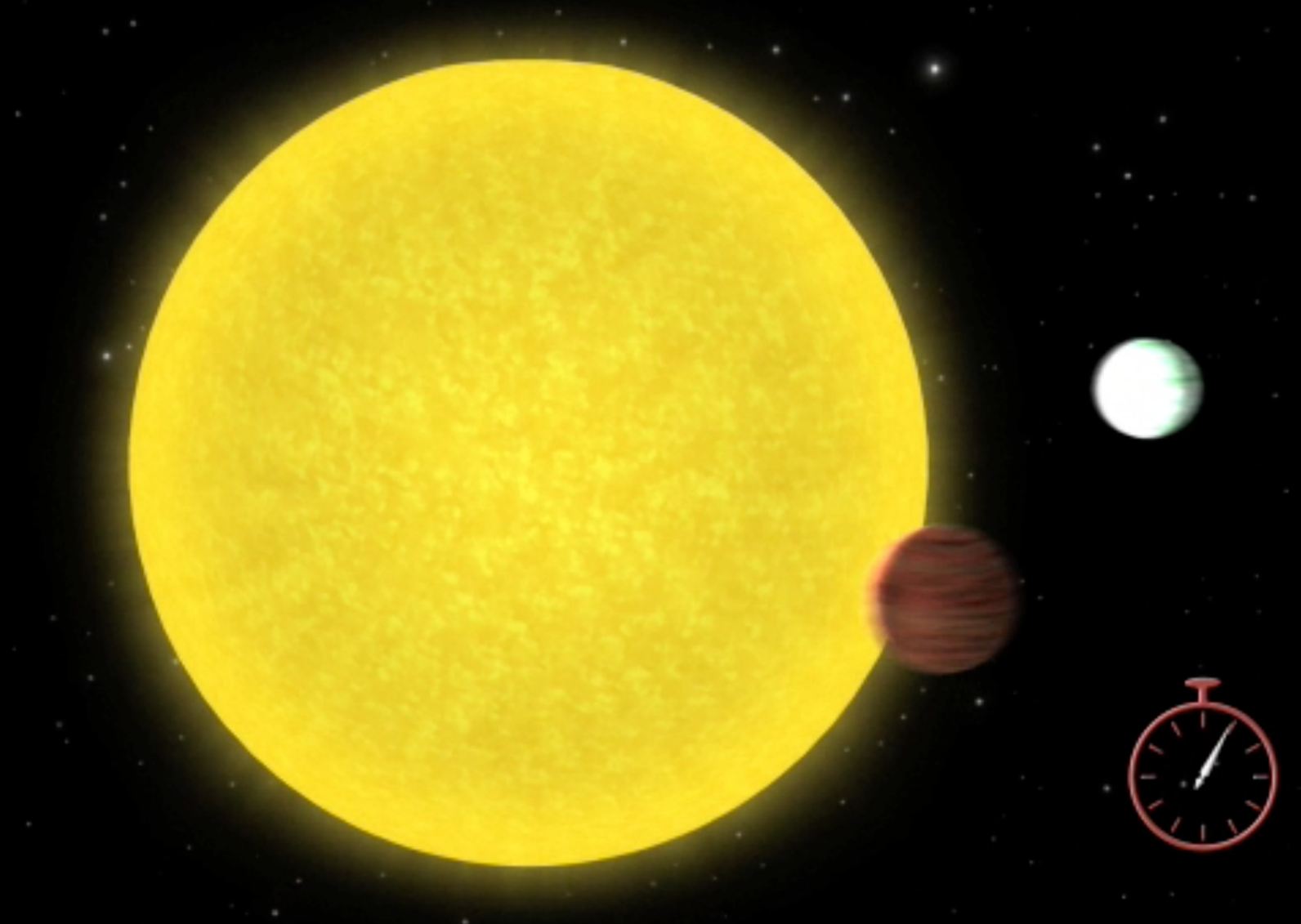
2017 Sagan/Michelson Fellows Symposium
@California Institute of Technology (Nov.10, 2017)

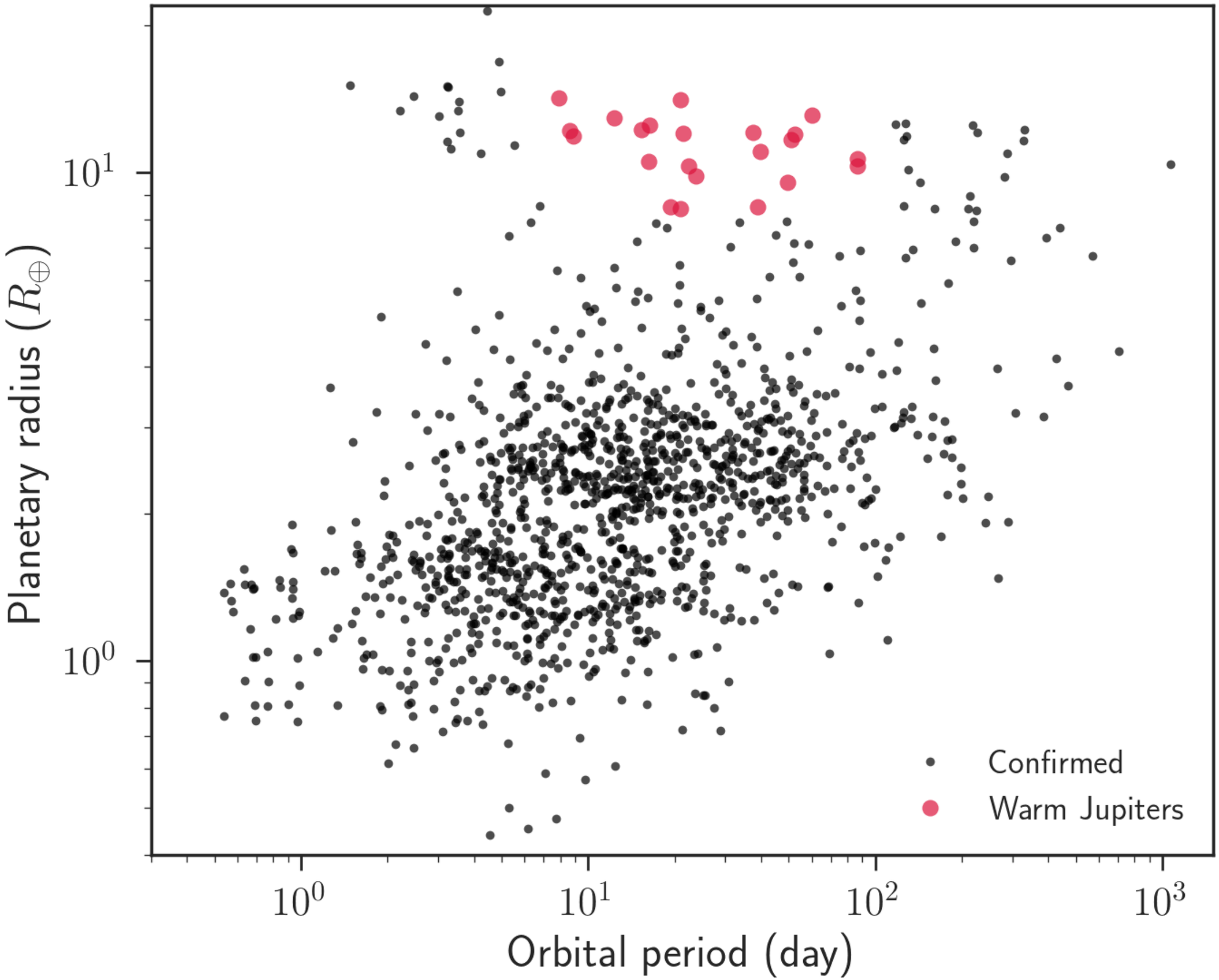
A Search for Non-transiting Companions to Kepler Warm Jupiters: Clues to their Formation



Kento Masuda (Princeton University/Sagan Fellow)

image credit: NASA Ames Research Center/Kepler Mission

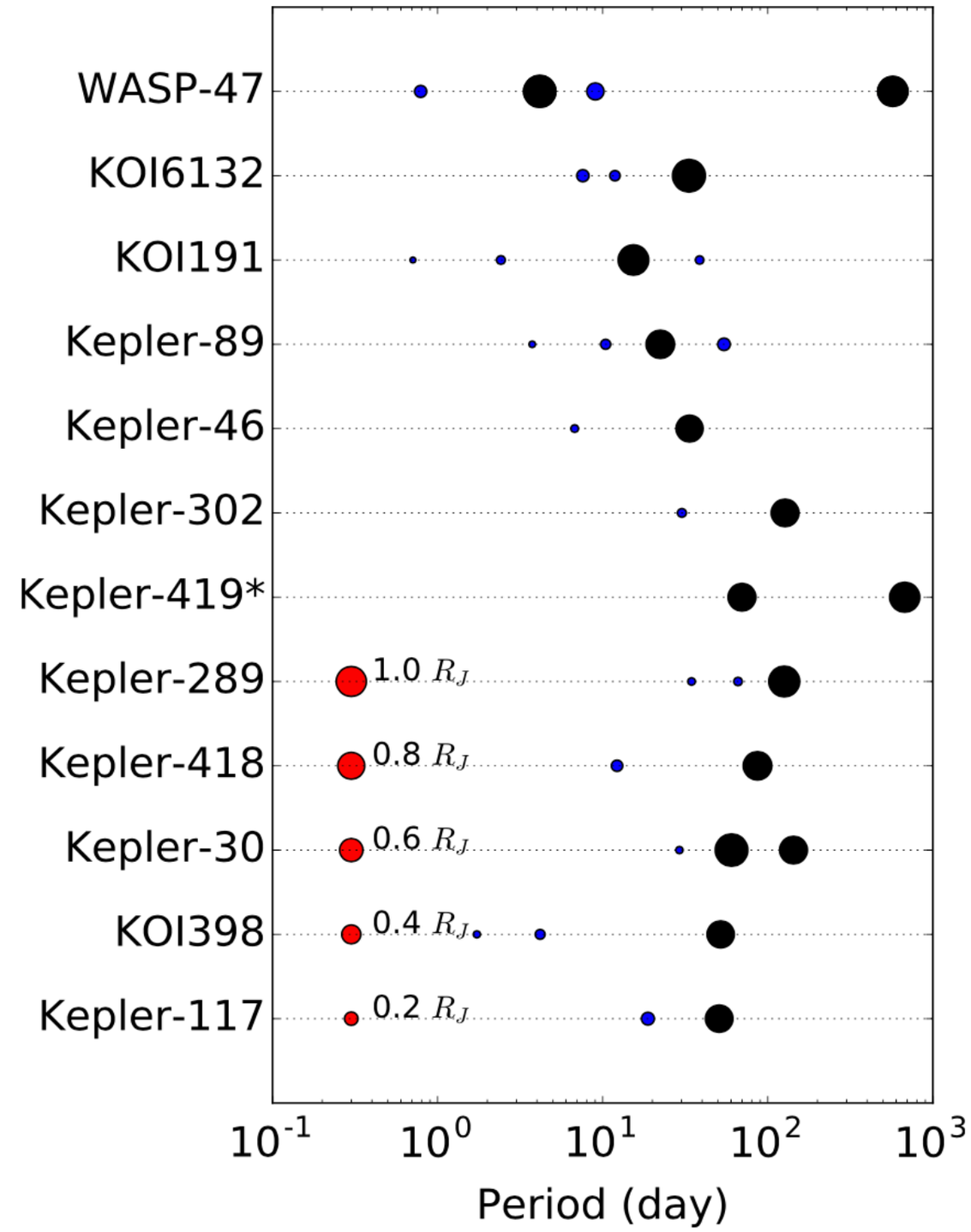
Warm Jupiters: additional clues to the migration



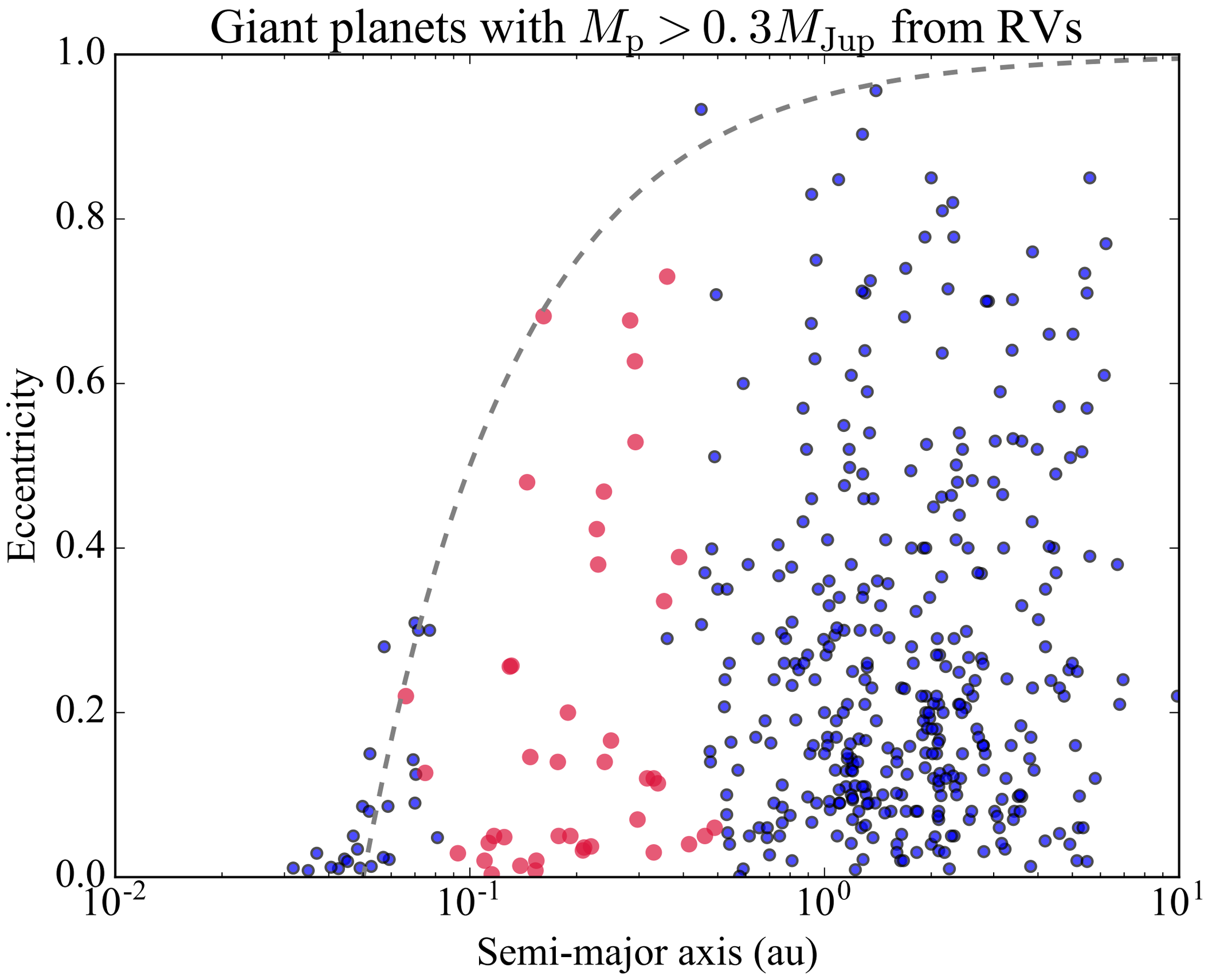
Warm Jupiters in multi-transiting systems: quiet formation

Huang et al. (2016)

- 10/27 in multi-transiting systems
- flat planetary orbits -> disk migration (or in-situ formation)

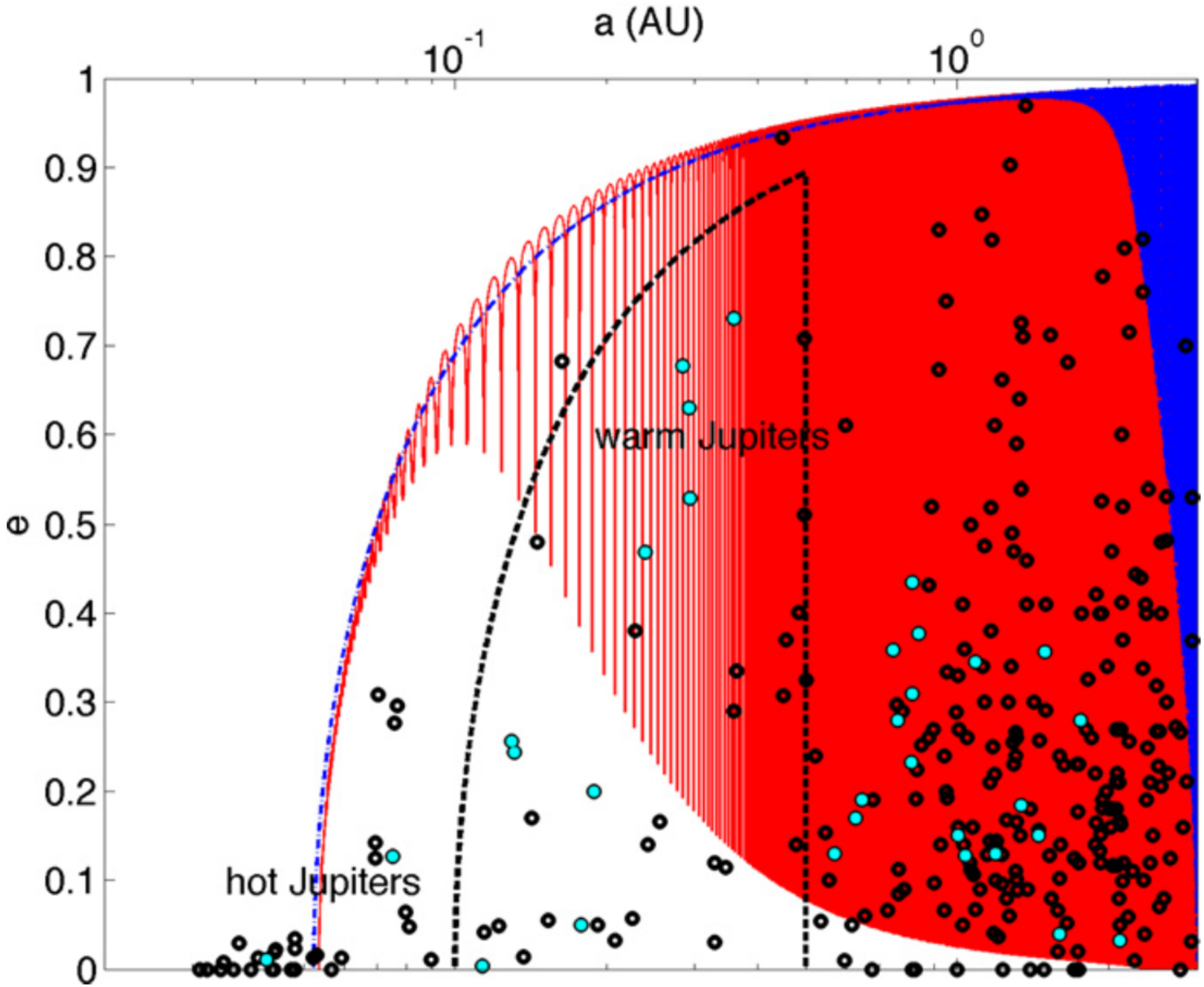


Eccentric warm Jupiters from RVs: dynamical origin?



"High-*e*" migration due to an inclined companion

— Eccentric warm Jupiters as **"proto-hot Jupiters"**



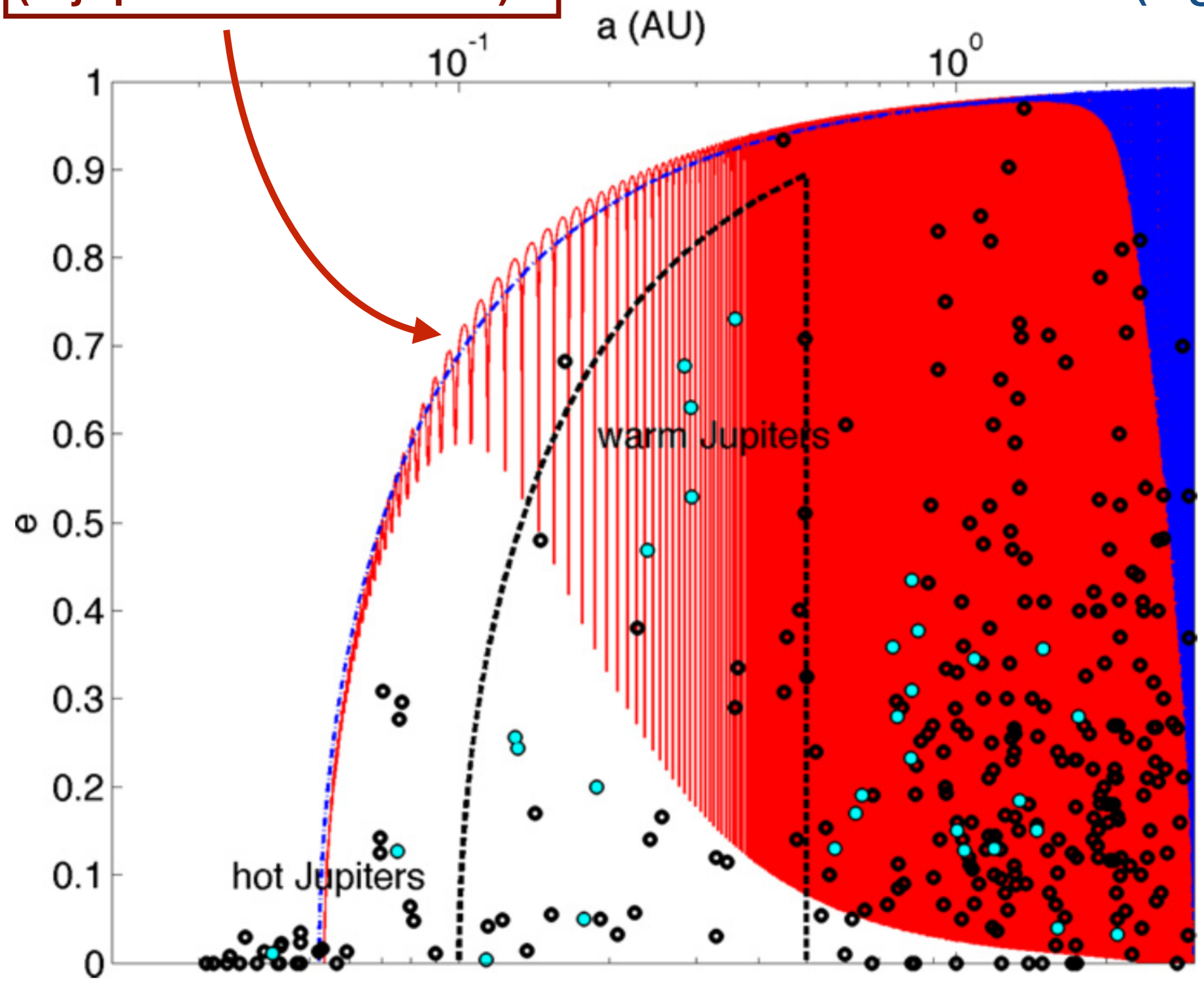
← Dong et al. (2014)

Wu & Lithwick (2011)
Dawson & Chiang (2014)
Petrovich & Tremaine (2017)

“High-e” migration due to an inclined companion

Close companion (Mjup-Msun @3-30au)

Distant companion (e.g. Msun @1000au)



← *Dong et al. (2014)*

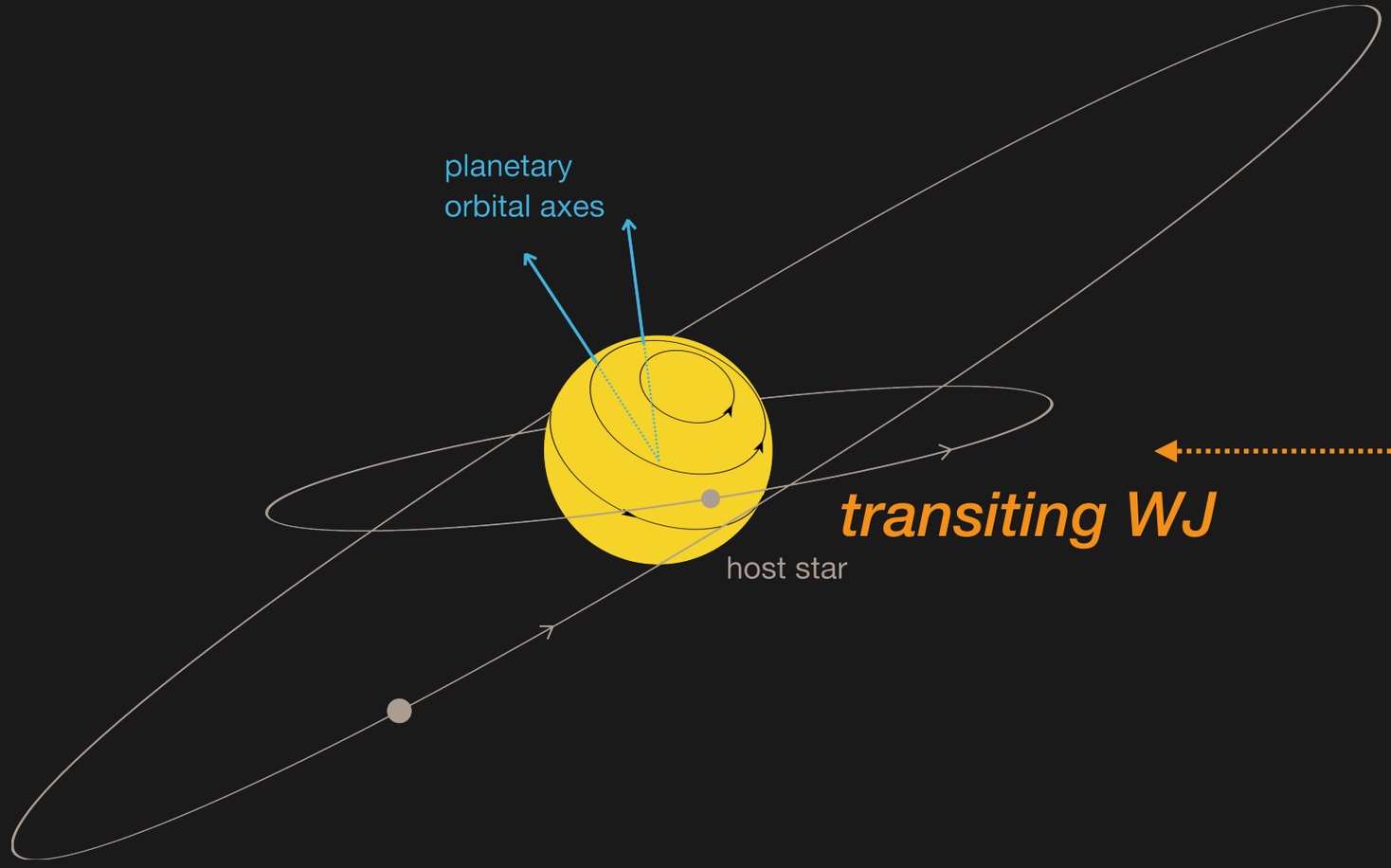
Wu & Lithwick (2011)
Dawson & Chiang (2014)
Petrovich & Tremaine (2017)

Search for mutually-inclined close companions via transit timing variations (TTVs)

- inclined companion -> non-transiting
- 23 confirmed WJs in single-transiting systems analyzed

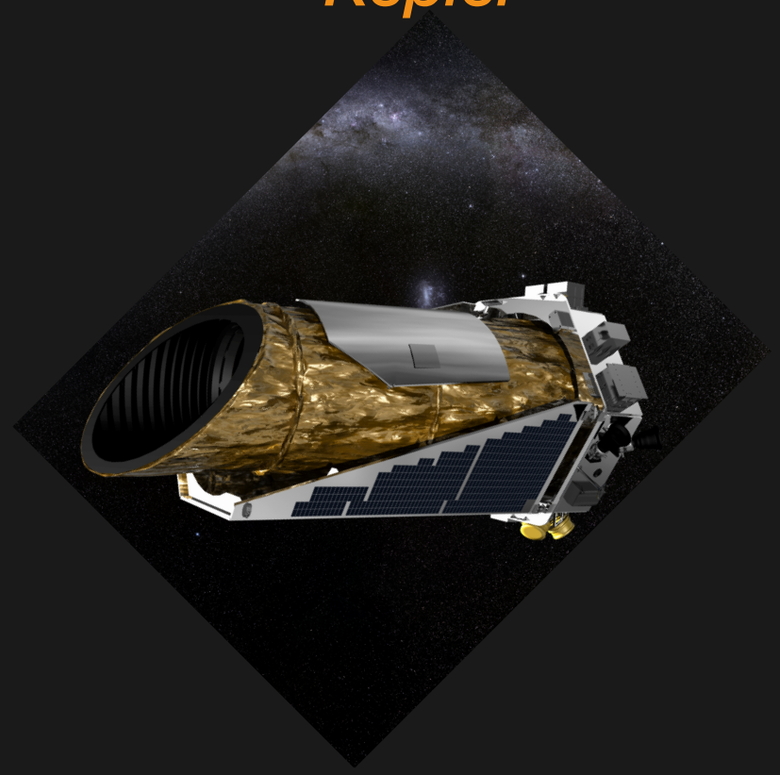
-> detection in two systems

non-transiting companion

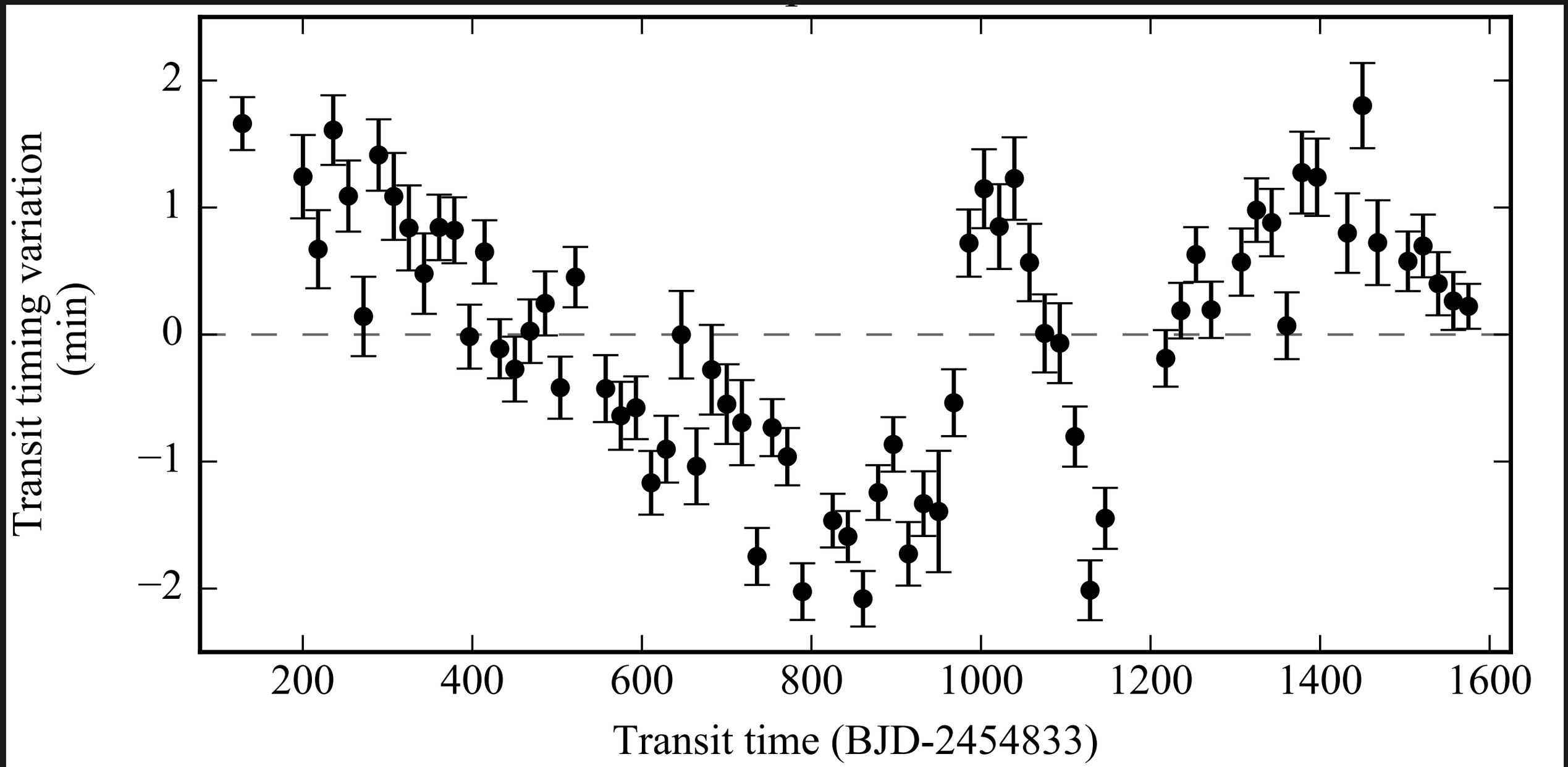


transiting WJ

Kepler

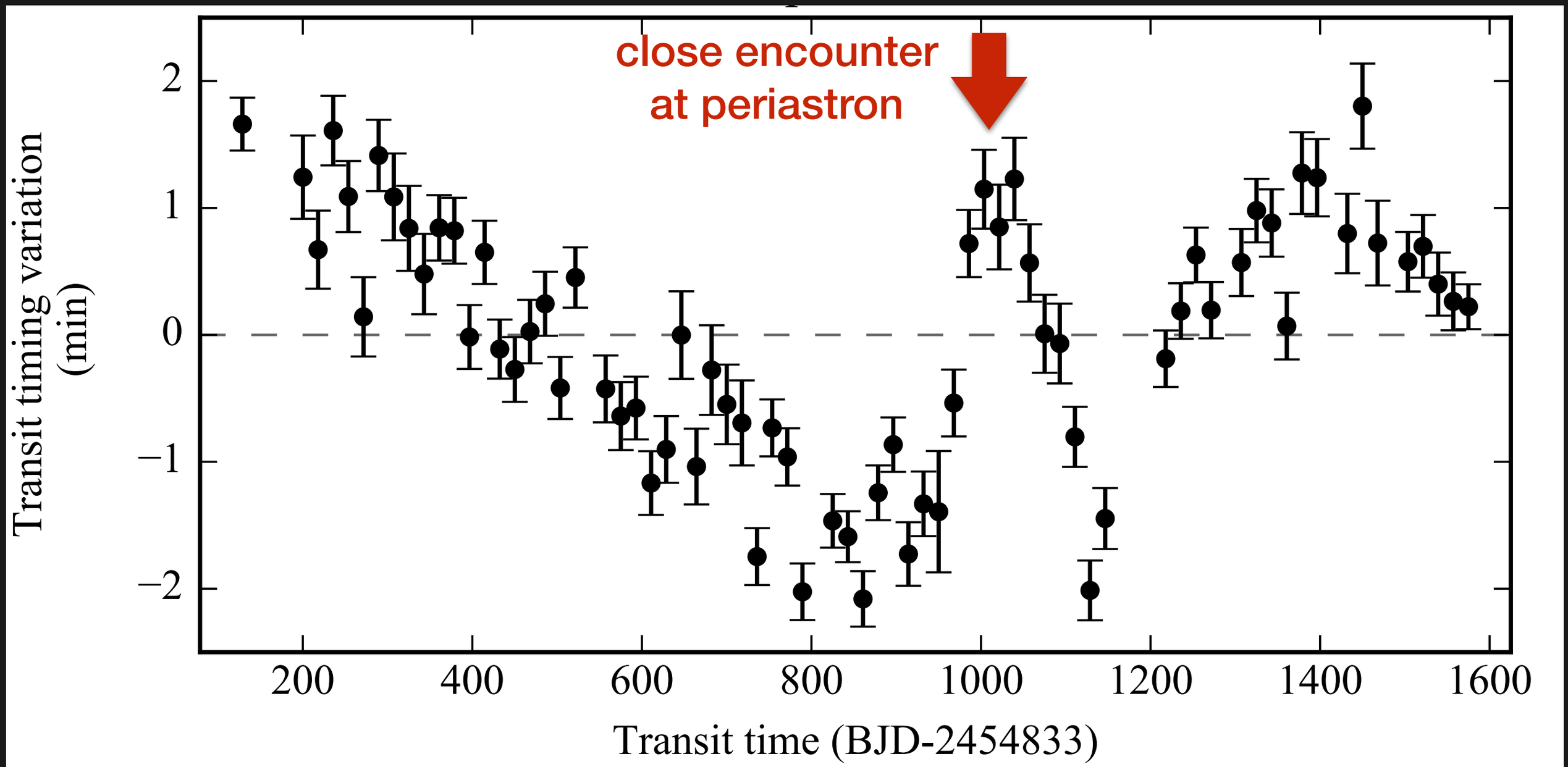


Kepler-448: WJ (18d, 1.2R_J)+F dwarf



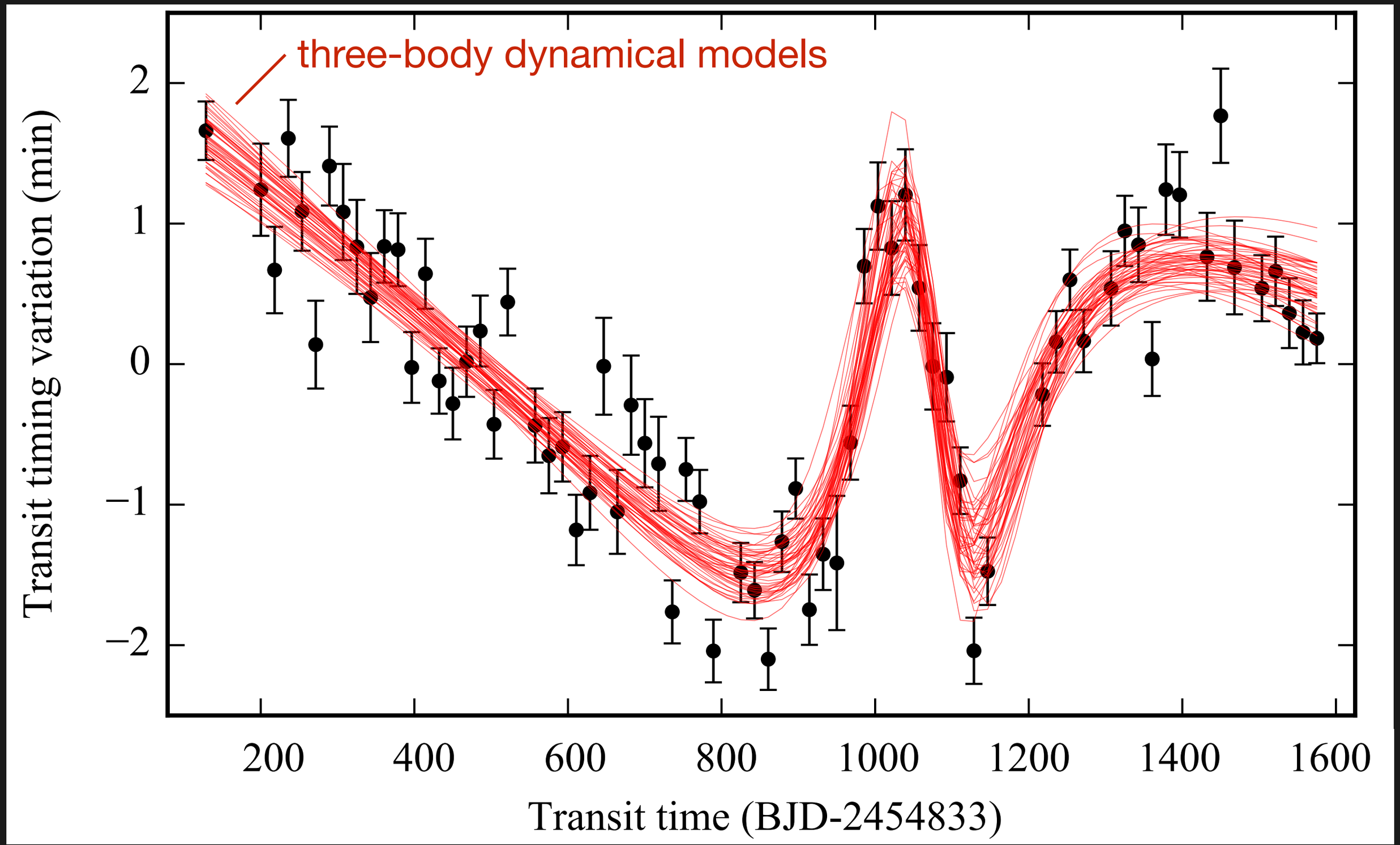
Masuda (2017)

Kepler-448: WJ (18d, 1.2R_J)+F dwarf



Masuda (2017)

Kepler-448: WJ (18d, 1.2R_J)+F dwarf



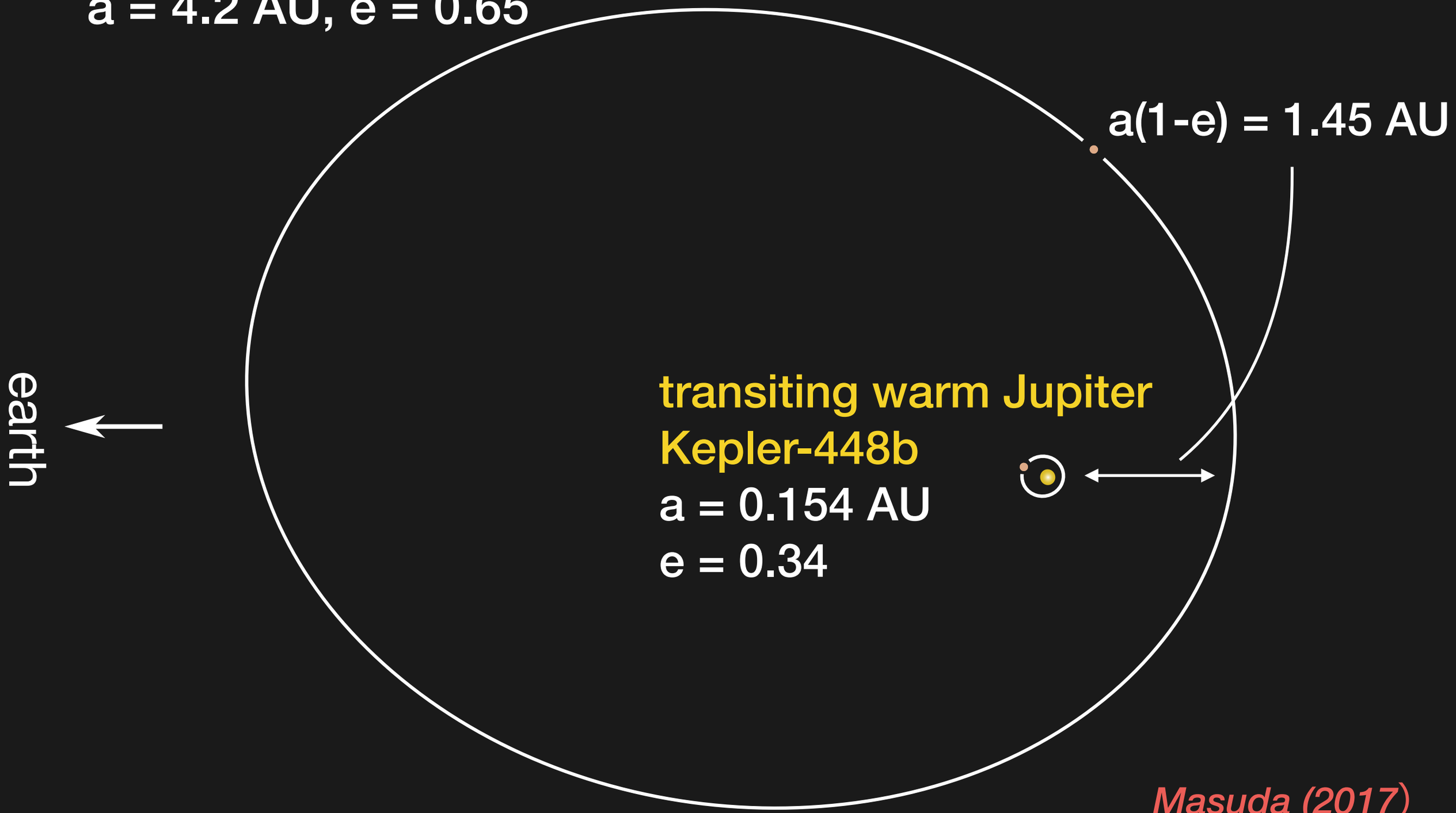
Masuda (2017)

Kepler-448: brown dwarf on a close/eccentric orbit

non-transiting companion

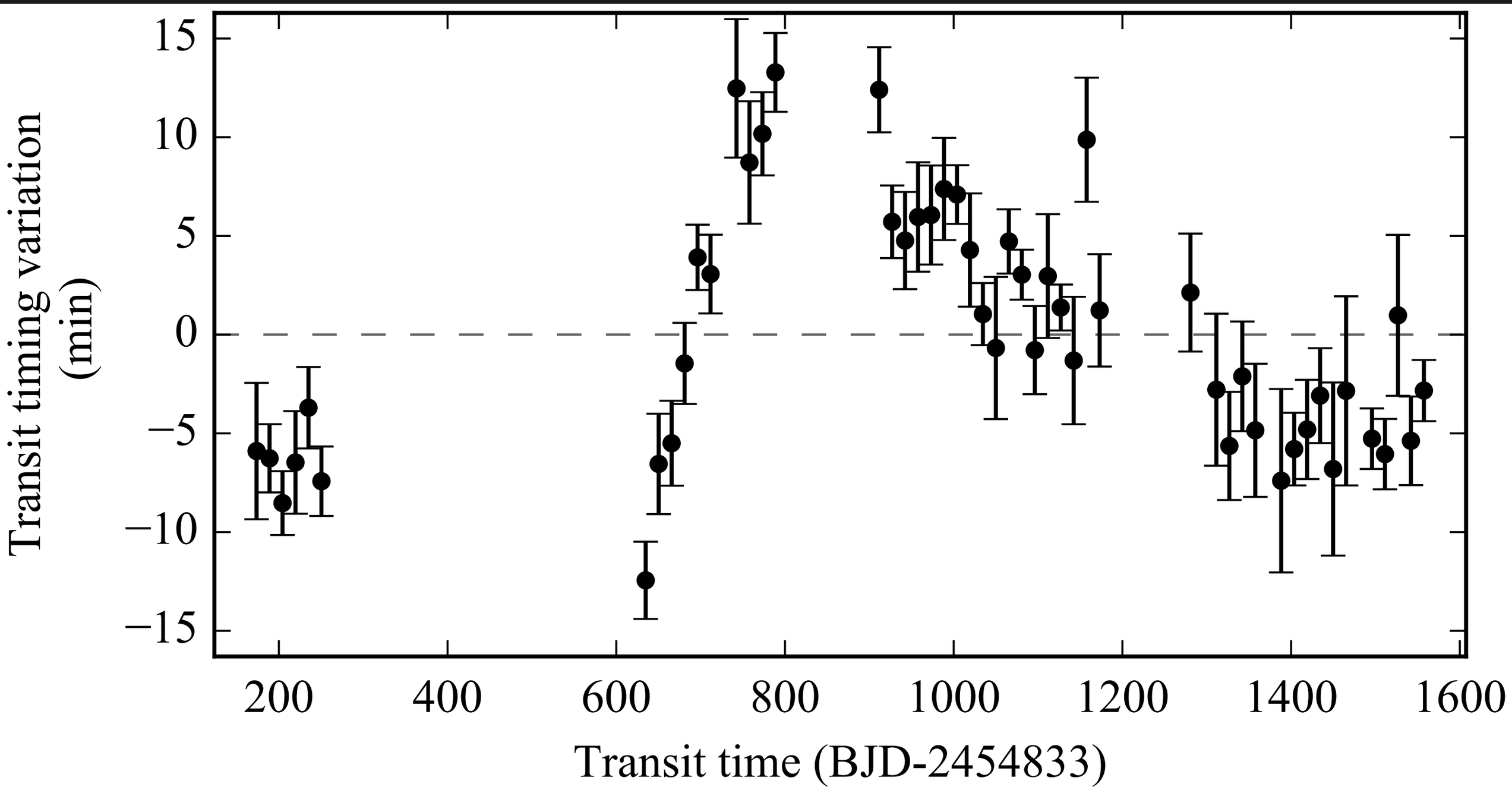
M = 22(+7, -5) M_J

a = 4.2 AU, e = 0.65



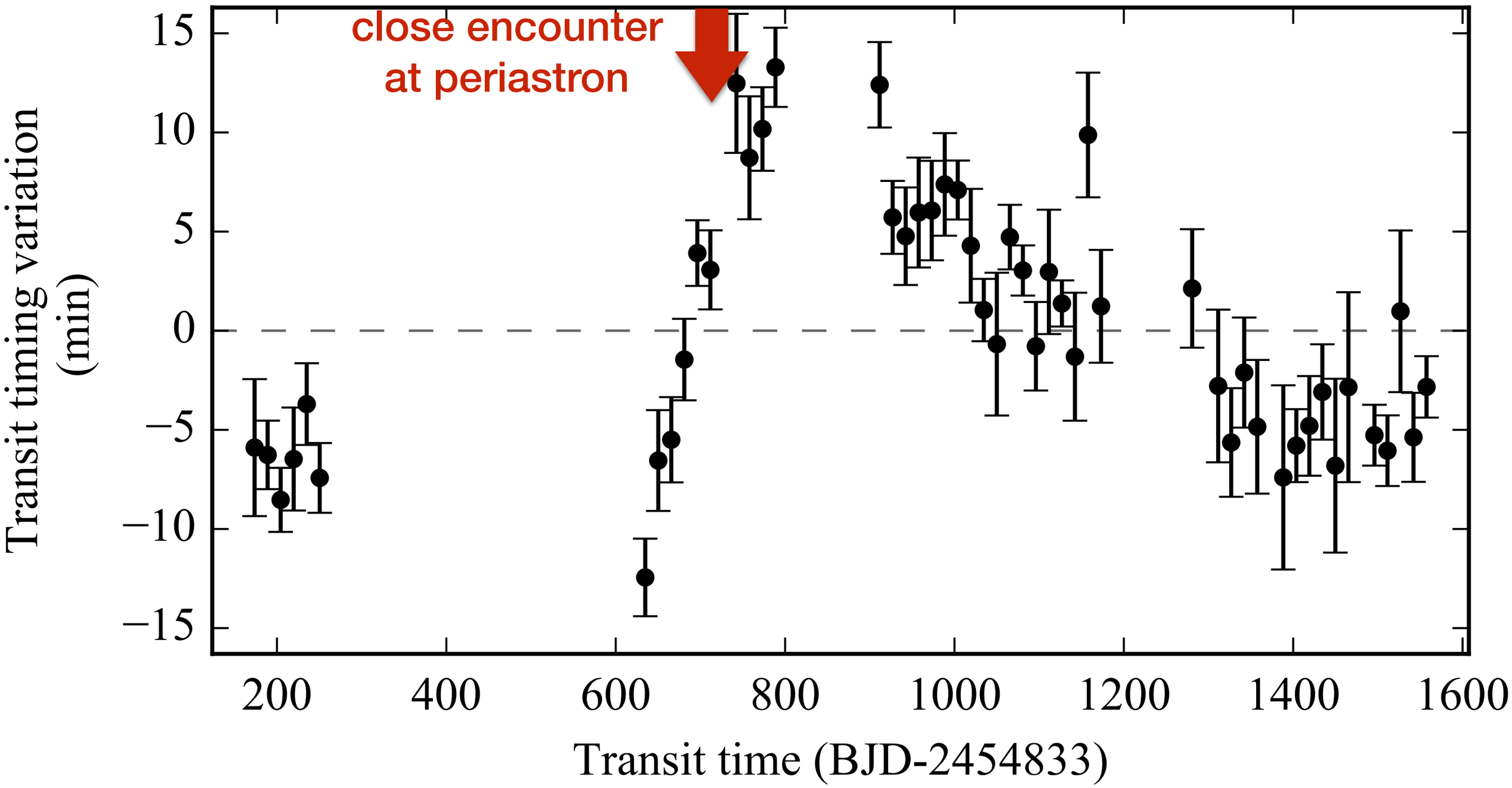
Masuda (2017)

Kepler-693: WJ (15d, 0.9R_J)+K dwarf



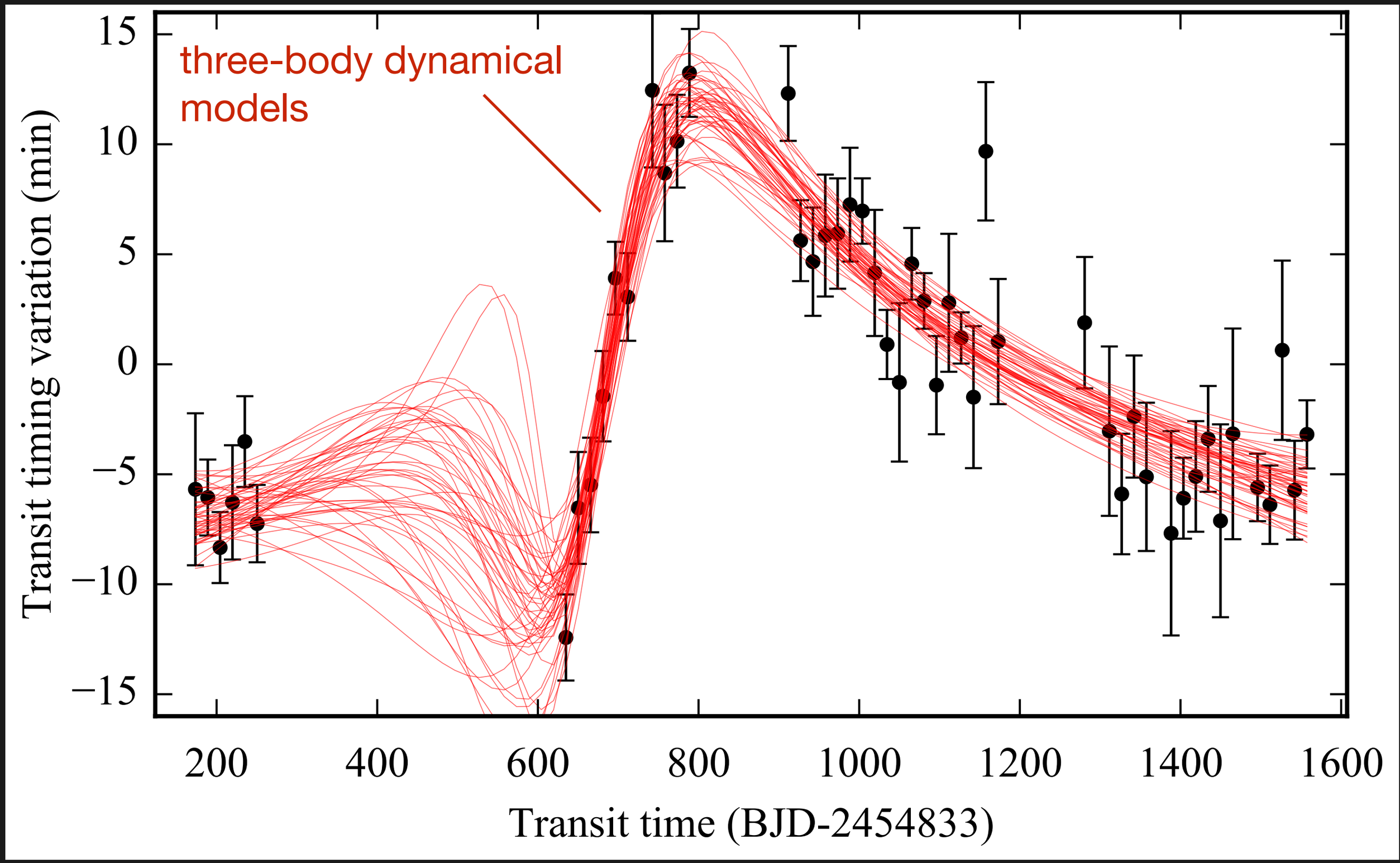
Masuda (2017)

Kepler-693: WJ (15d, 0.9R_J)+K dwarf



Masuda (2017)

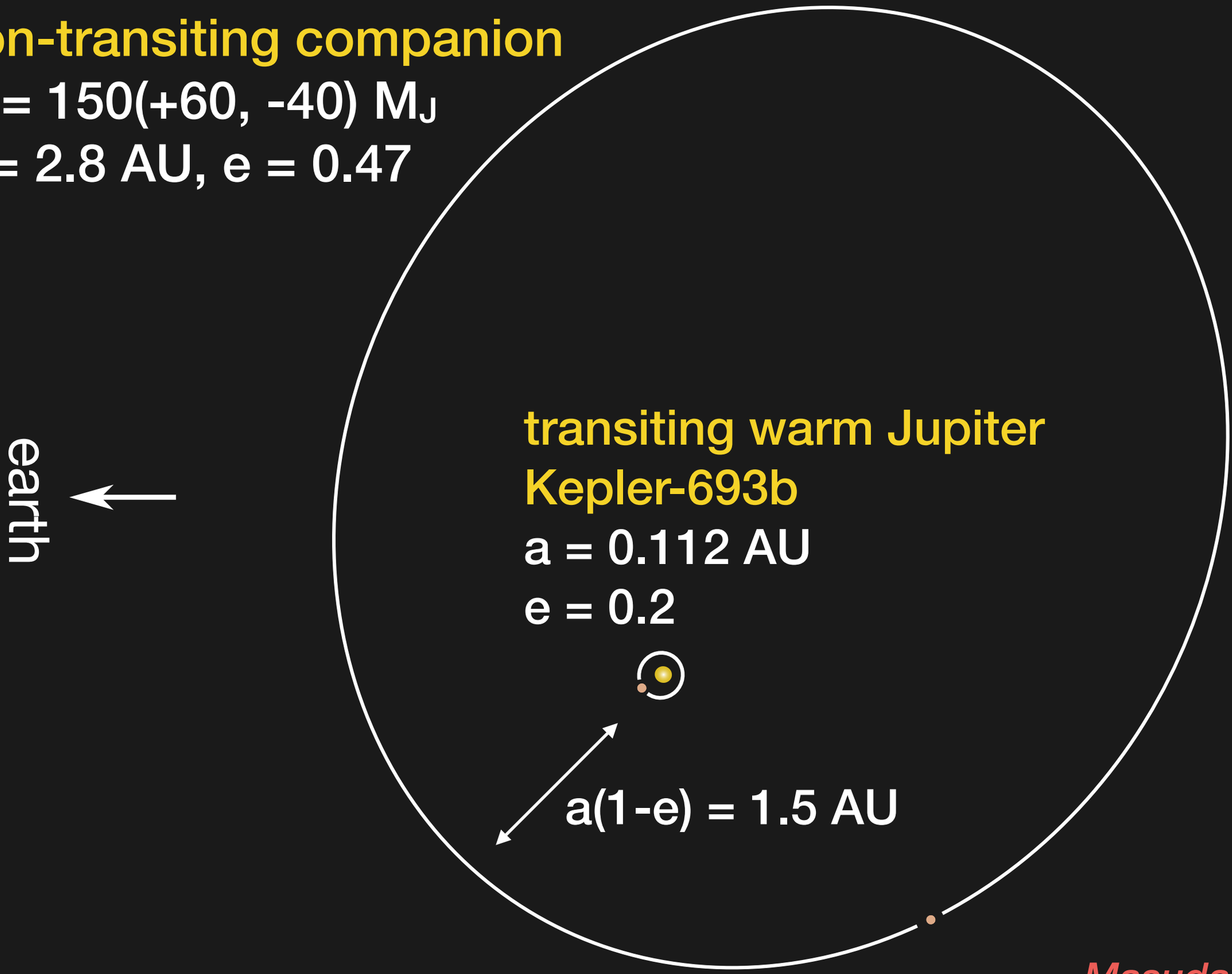
Kepler-693: WJ (15d, 0.9R_J)+K dwarf



Masuda (2017)

Kepler-693: close & eccentric low-mass star

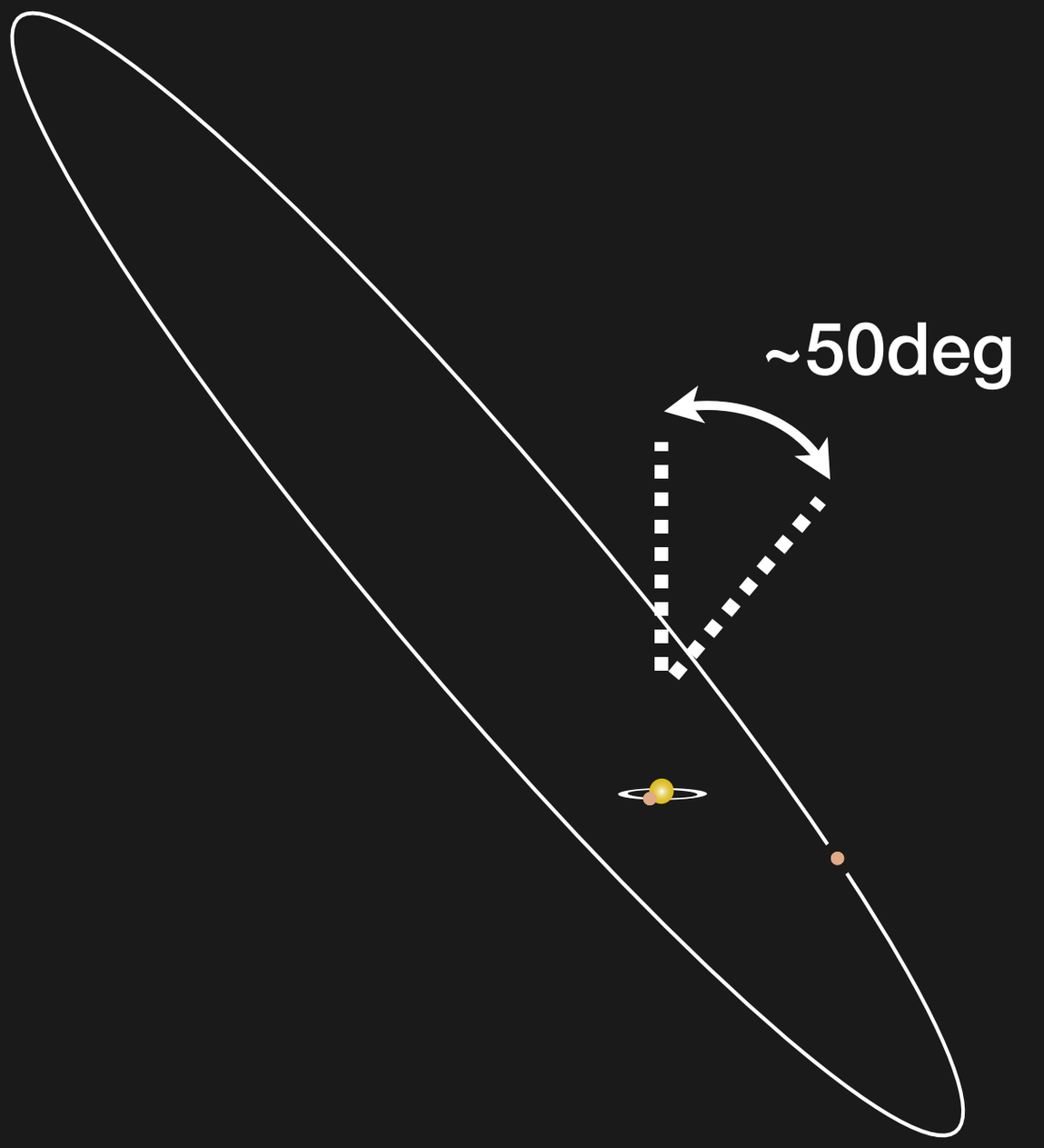
non-transiting companion
M = 150(+60, -40) M_J
a = 2.8 AU, e = 0.47

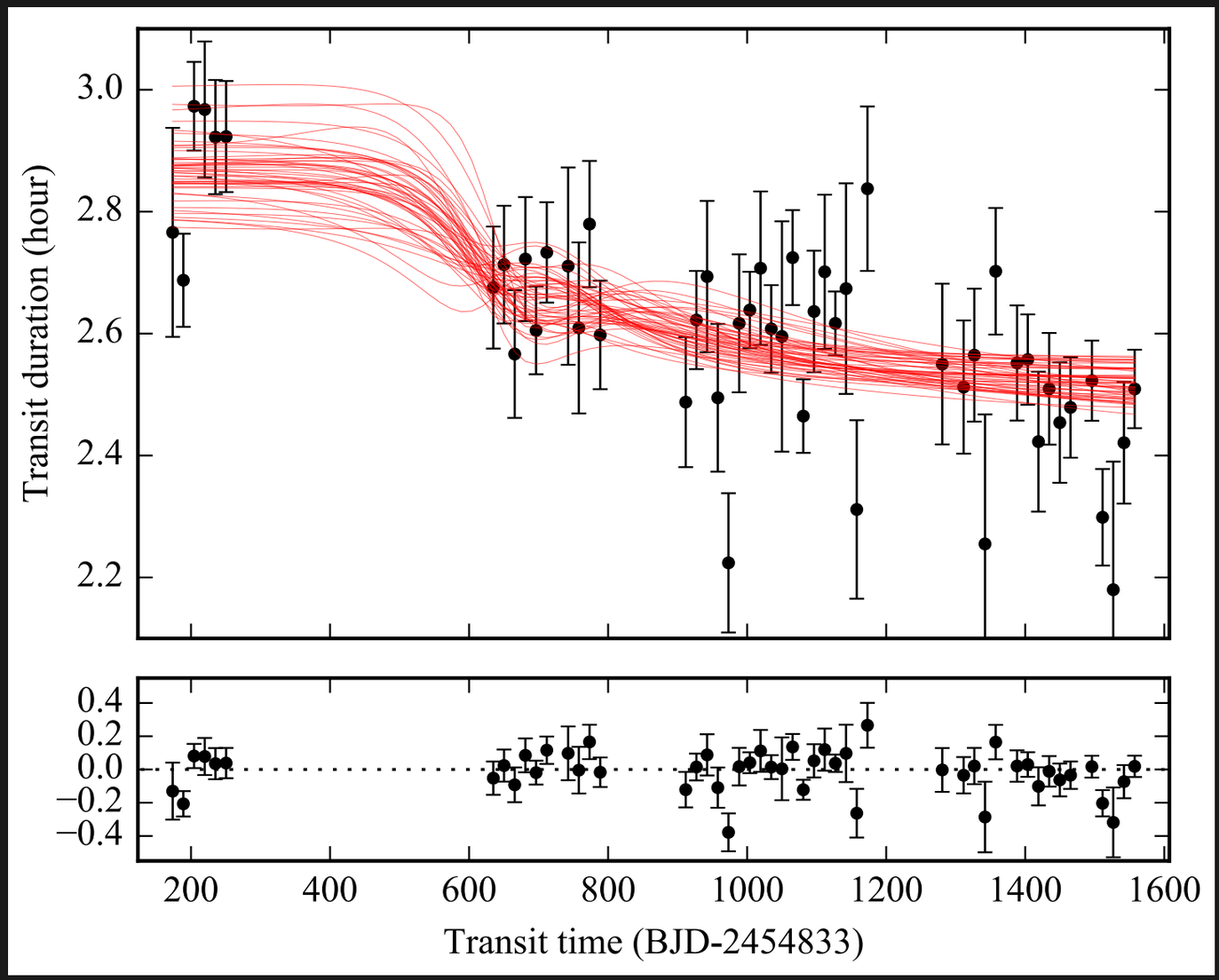


Masuda (2017)

Transit durations indicate a large mutual inclination

- **Misalignment of the companion's orbit relative to that of the transiting WJ: 53(+7, -9)deg**

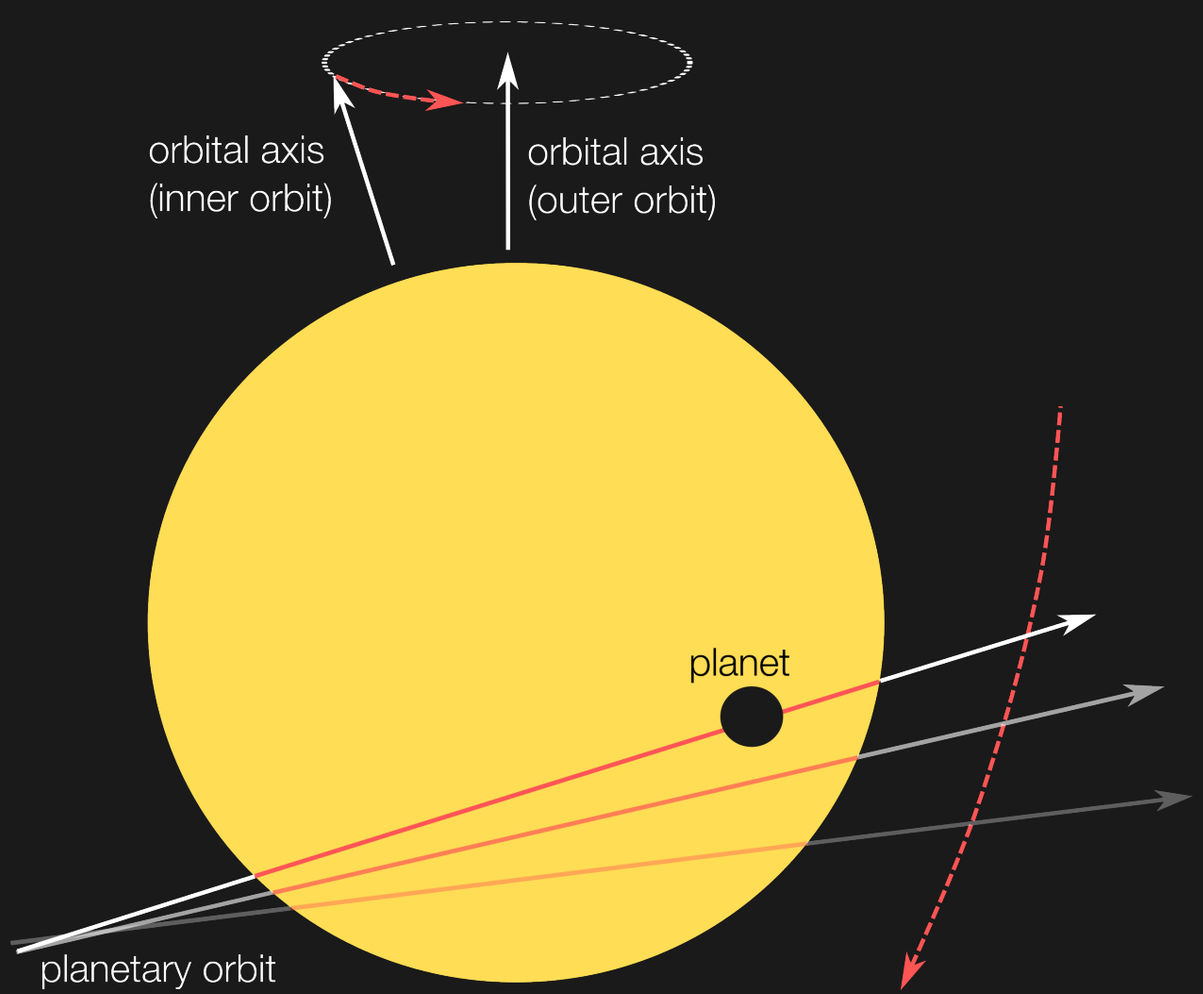


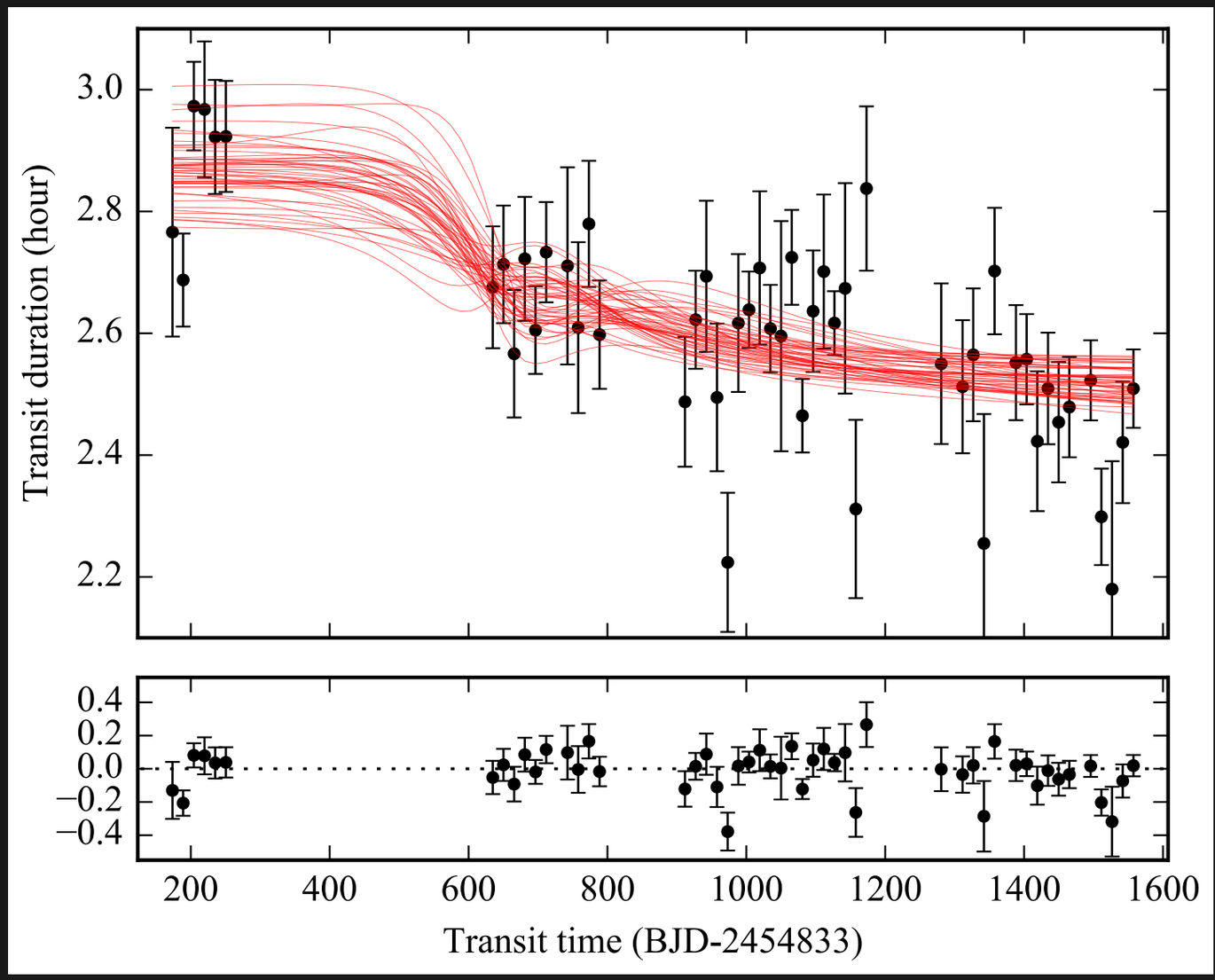


Masuda (2017)

Transit durations indicate a large mutual inclination

- **Misalignment of the companion's orbit relative to that of the transiting WJ: 53(+7, -9)deg**

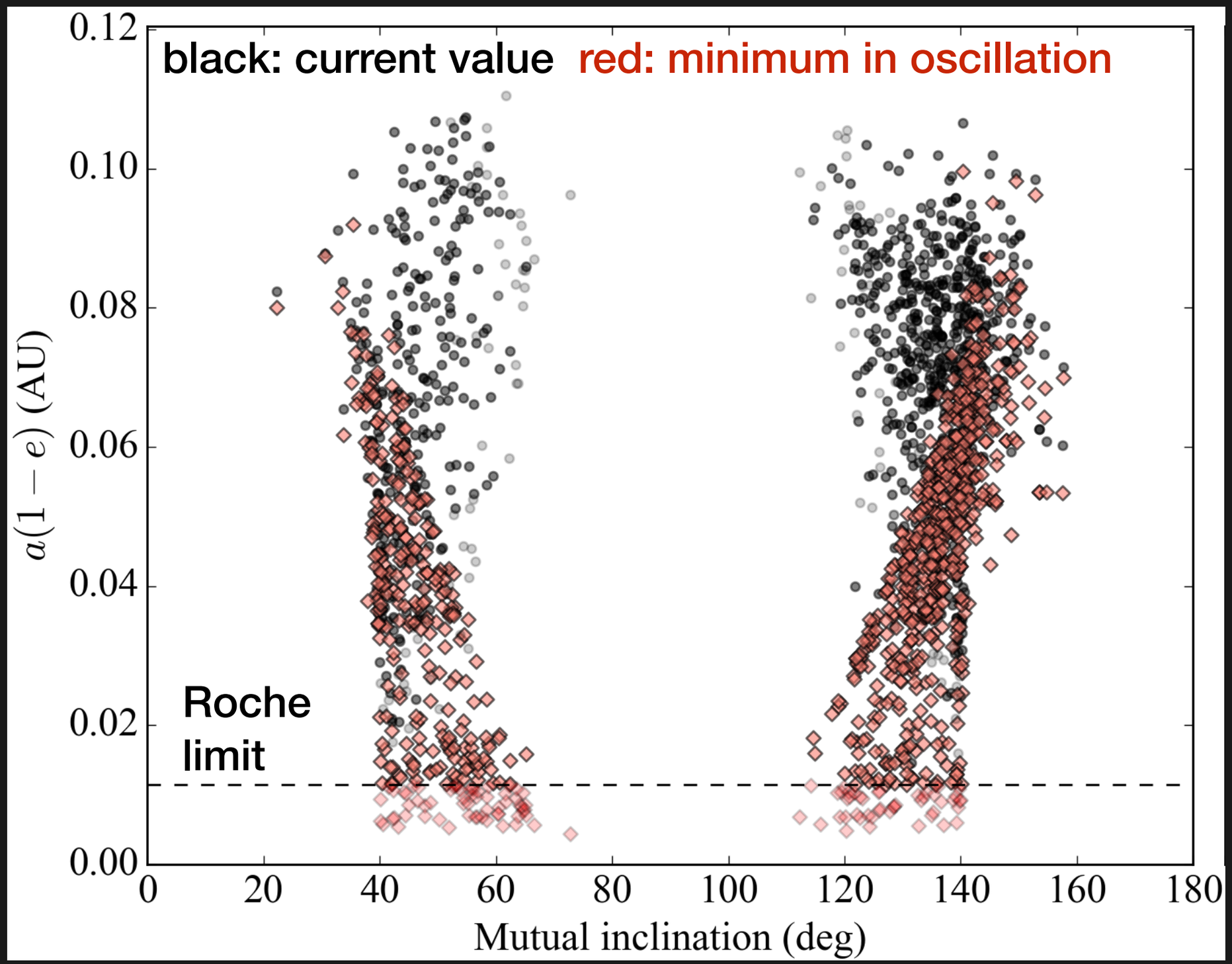




Masuda (2017)

Kepler-693b as a proto-hot Jupiter

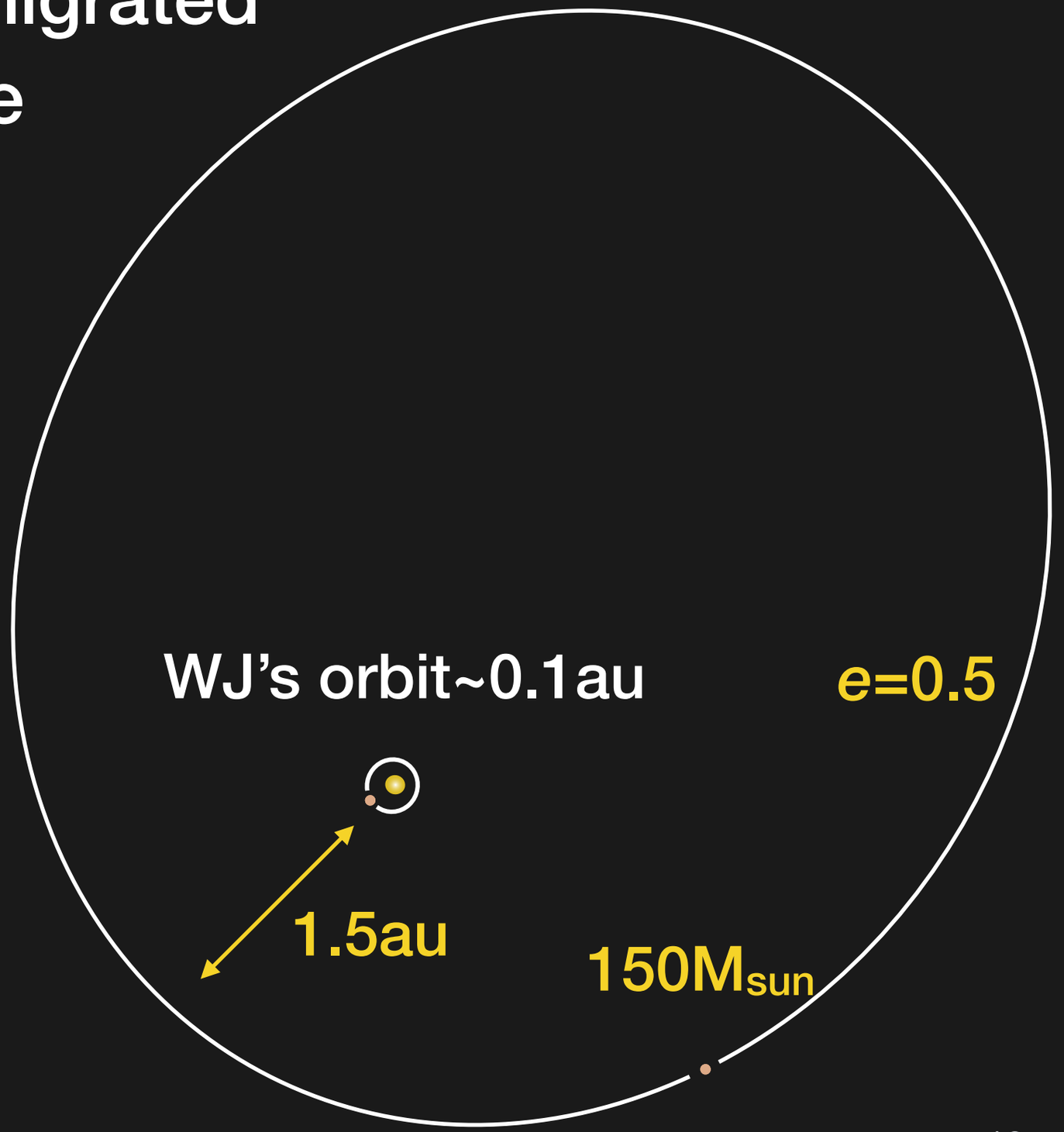
- Secular eccentricity excitation can bring $a(1-e)$ to <0.05au
- Possibly evolving to become a hot Jupiter



Masuda (2017)

How did the high-*e* migration start?

Outer companion is currently too close for the inner WJ to have migrated from beyond the snow line



How did the high-*e* migration start?

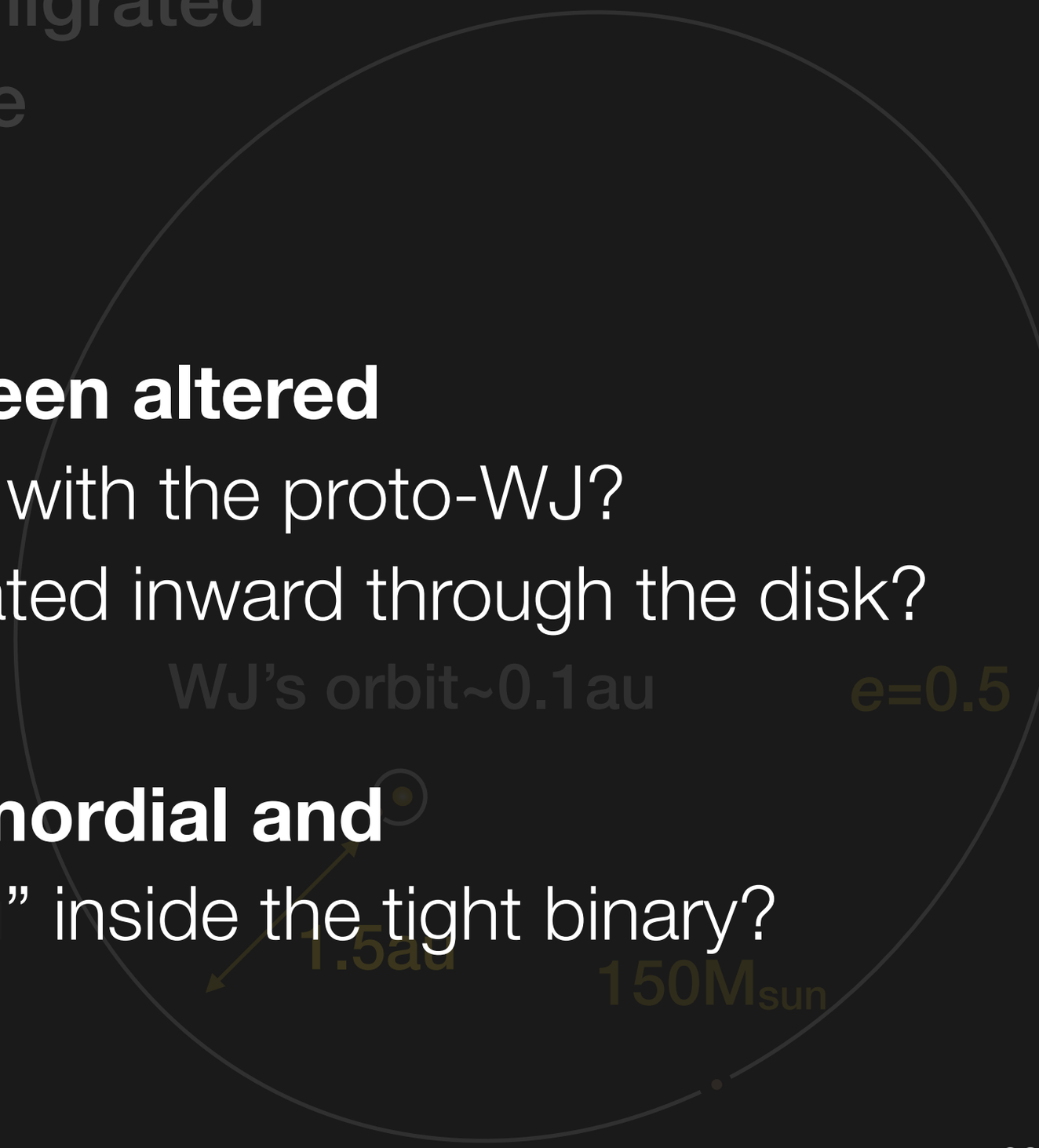
Outer companion is currently too close
for the inner WJ to have migrated
from beyond the snow line

Companion's orbit has been altered

1. via dynamical scattering with the proto-WJ?
2. after the proto-WJ migrated inward through the disk?

Companion's orbit is primordial and

3. proto-WJ formed "in situ" inside the tight binary?



Summary

- Two transiting & eccentric warm Jupiters with non-transiting, (sub-)stellar companions with ***a*(1-*e*)=1.5au**

- Kepler-448: **20M_J** companion, mutual inclination=?

- Kepler-693: **low-mass star (150M_J)** inclined by **50deg**
  - eccentricity oscillation demonstrated
  - tidal dissipation may turn it into a hot Jupiter

- Support the “proto-hot Jupiter” picture, but companion’s small *a*(1-*e*) suggest some other process (e.g. disk migration) contributing to the inward migration