Constraining Scenarios of Planet Formation through Exoplanet Physics
從系外行星物理看行星形成理論

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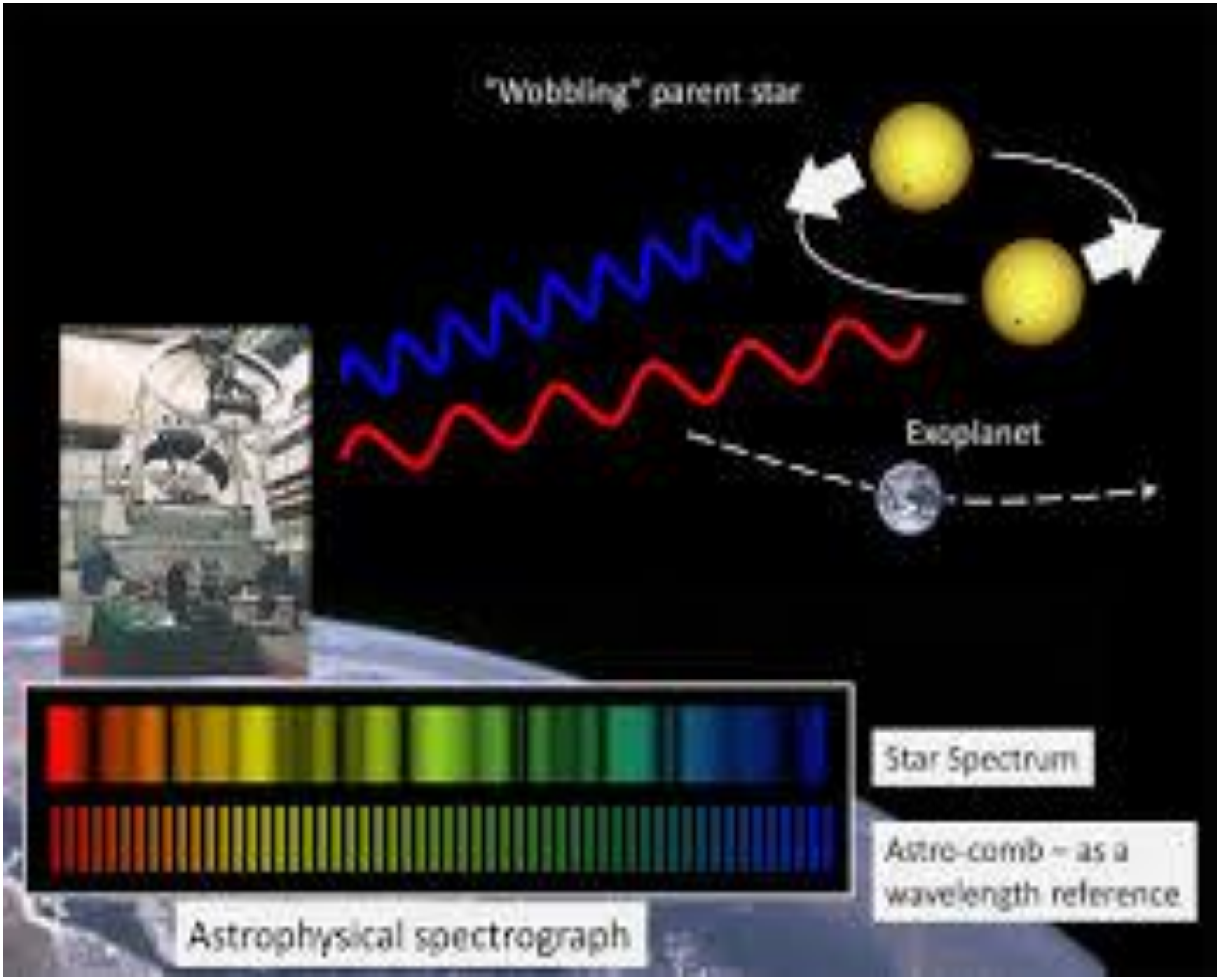
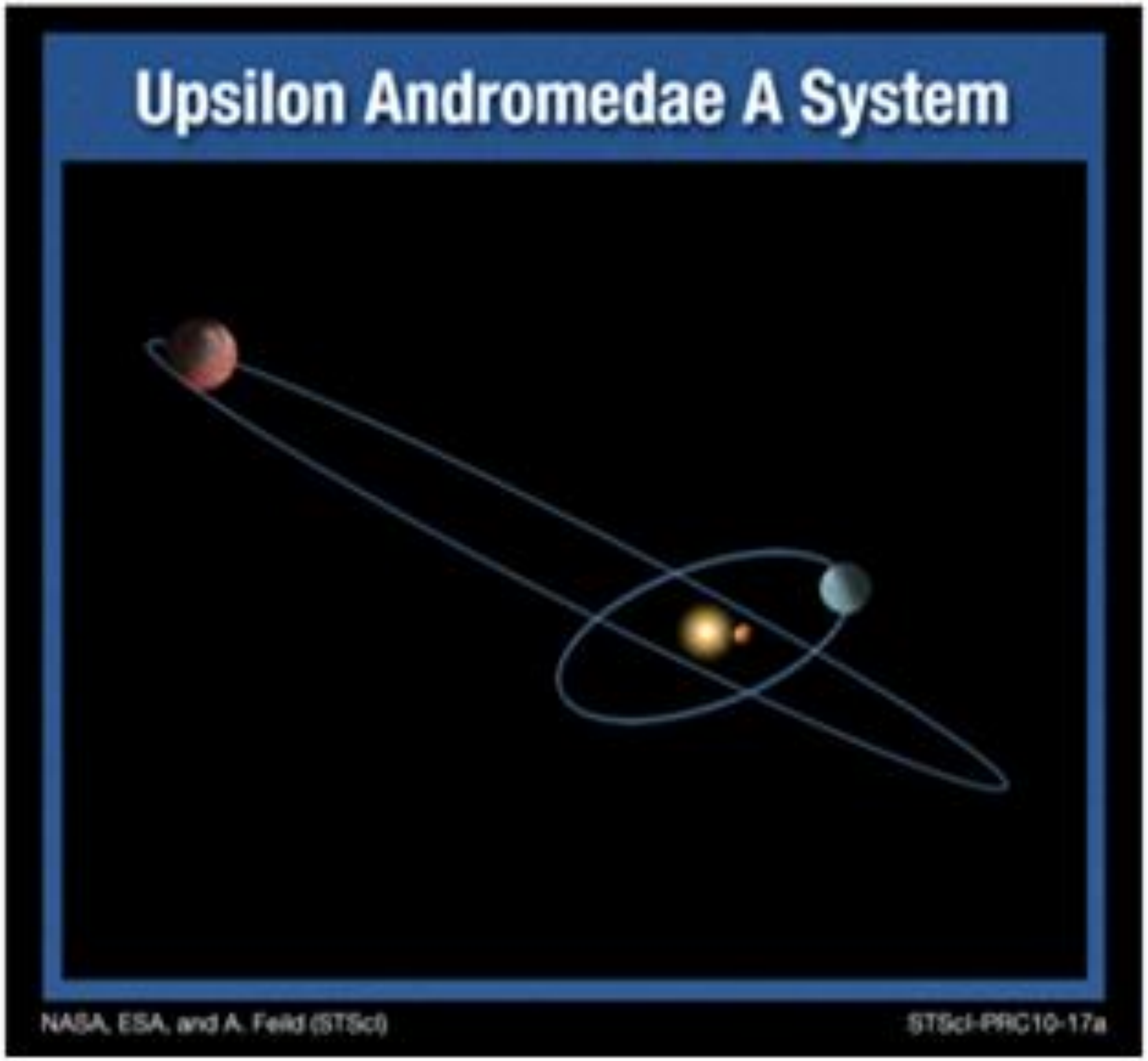
Outline

- Exoplanet Detections
- Exoplanet Statistics
- Witnessing Orbital Evolution
- Exoplanet Atmospheres
- Tracers of Formation History
- Summary
- Future

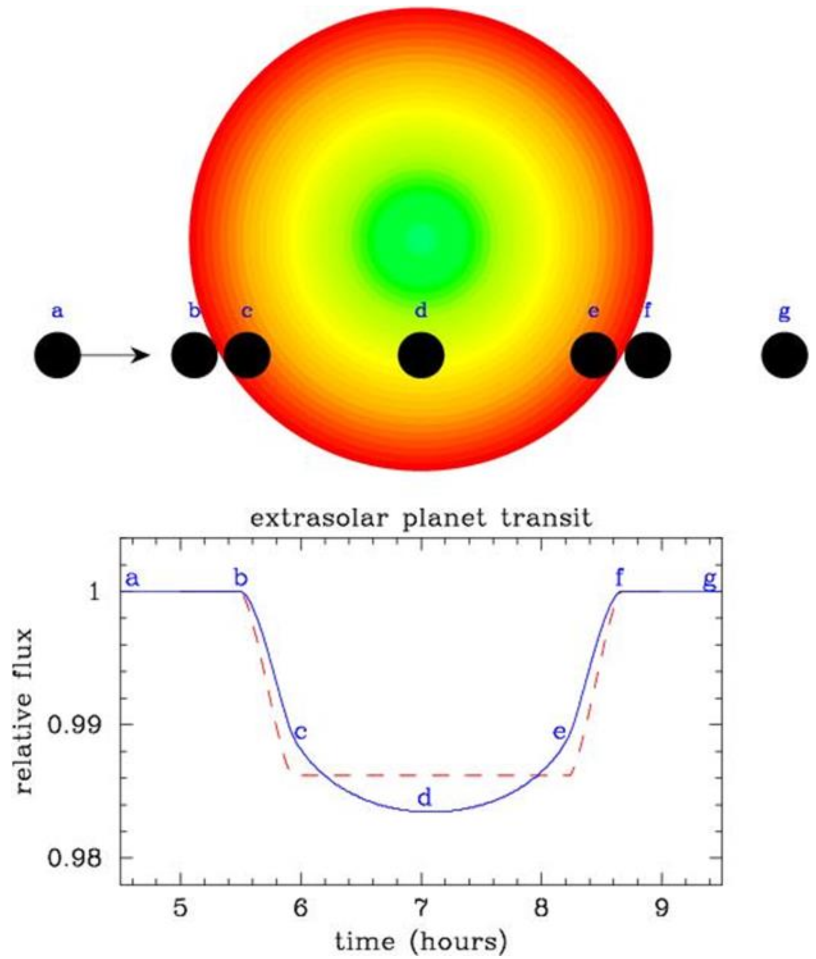
The Proof of Existence

Radial Velocity Method



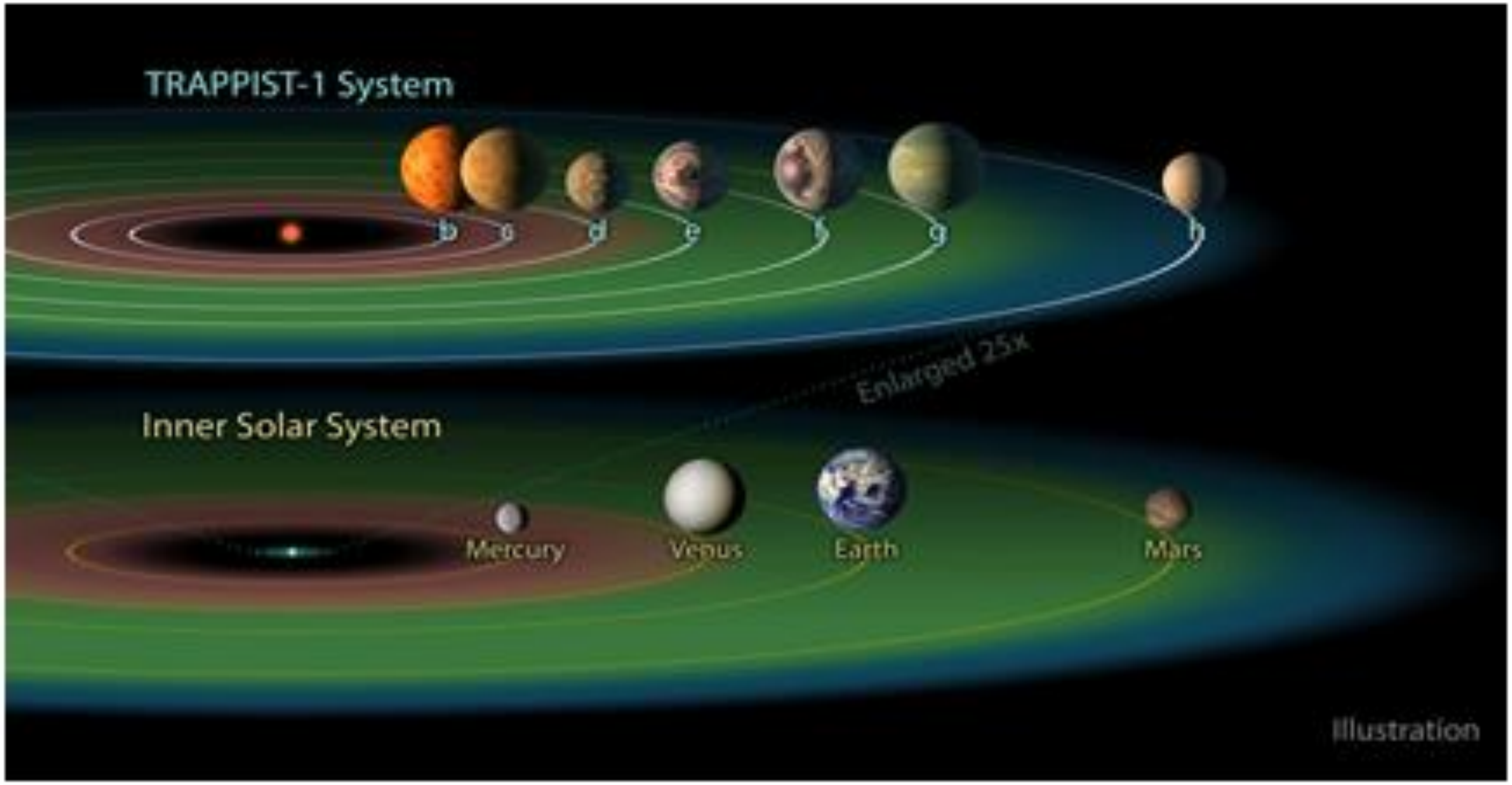

Upsilon Andromedae A System
NASA, ESA, and A. Feild (STScI)
STScI-PRC10-17a

Transit

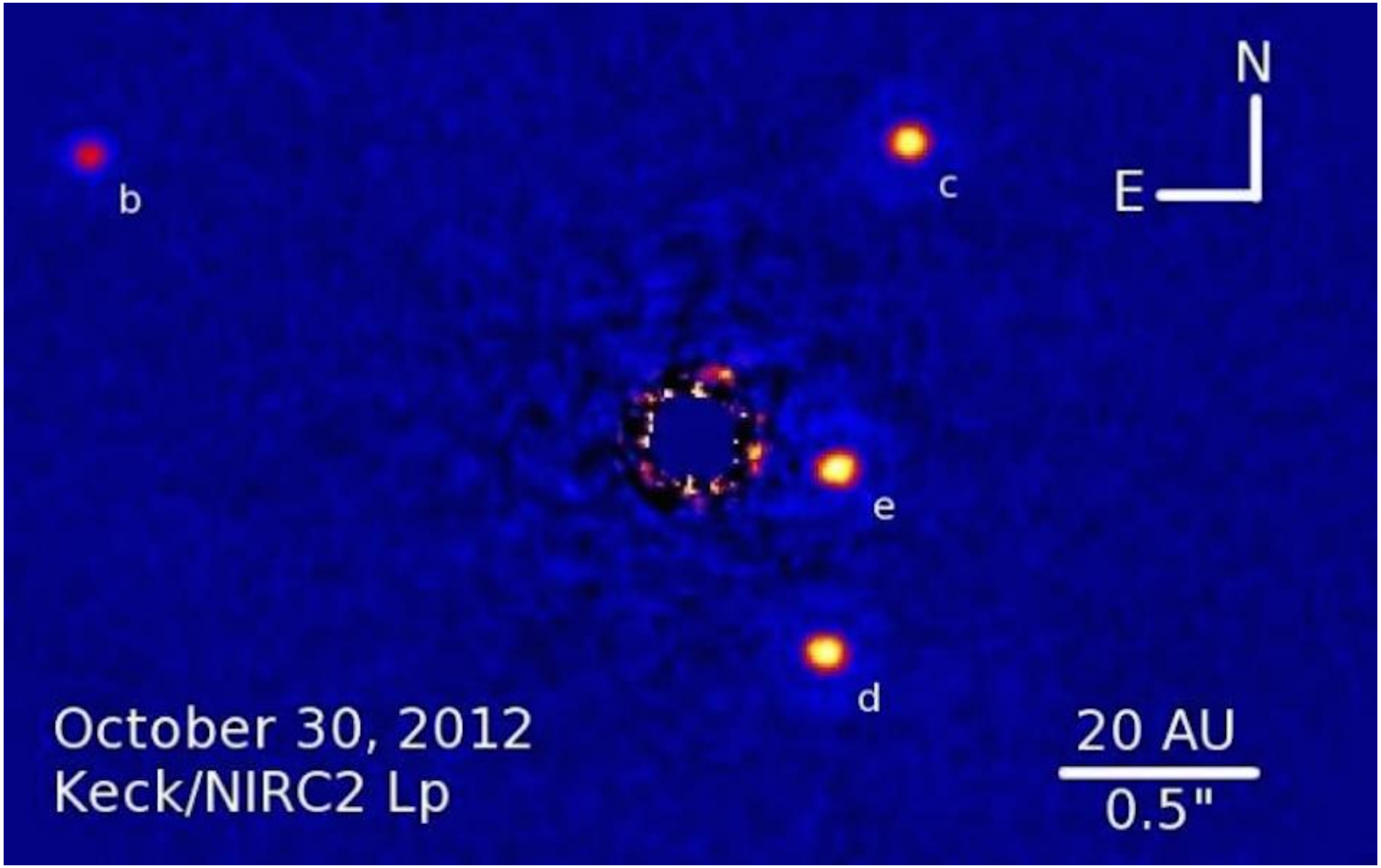


a
b
c
d
e
f
g
extrasolar planet transit
relative flux
1
0.99
0.98
5
6
7
8
9
time (hours)

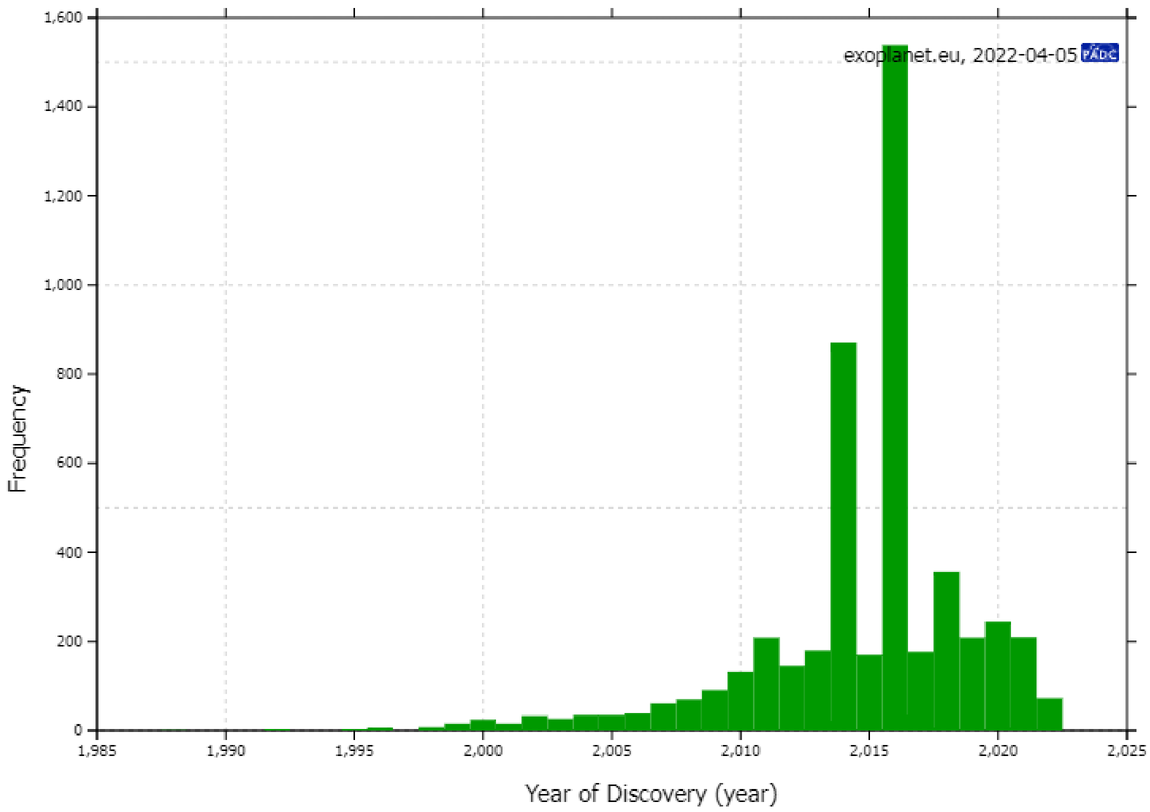
TRAPPIST-1 System



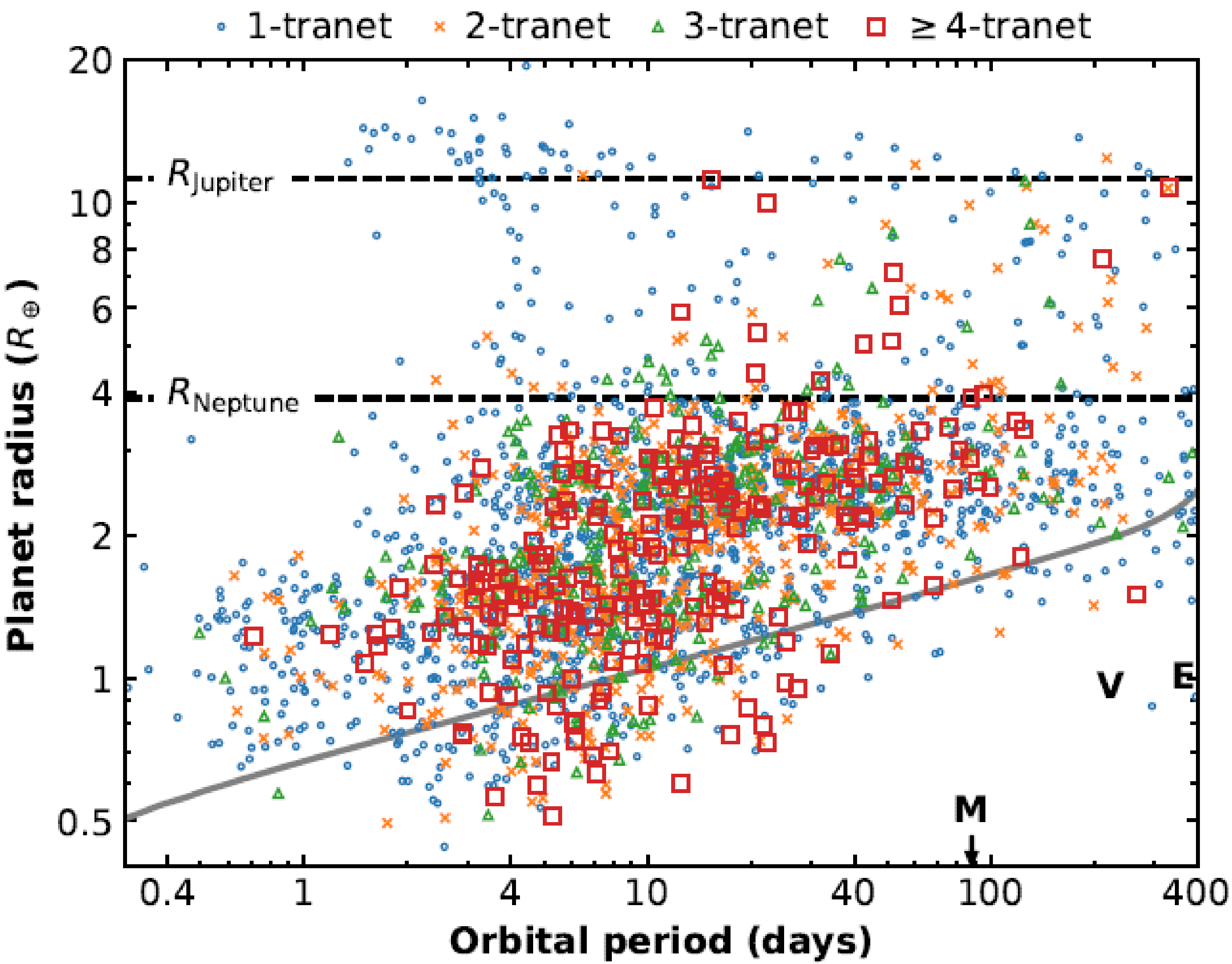
Direct Imaging
HR8799



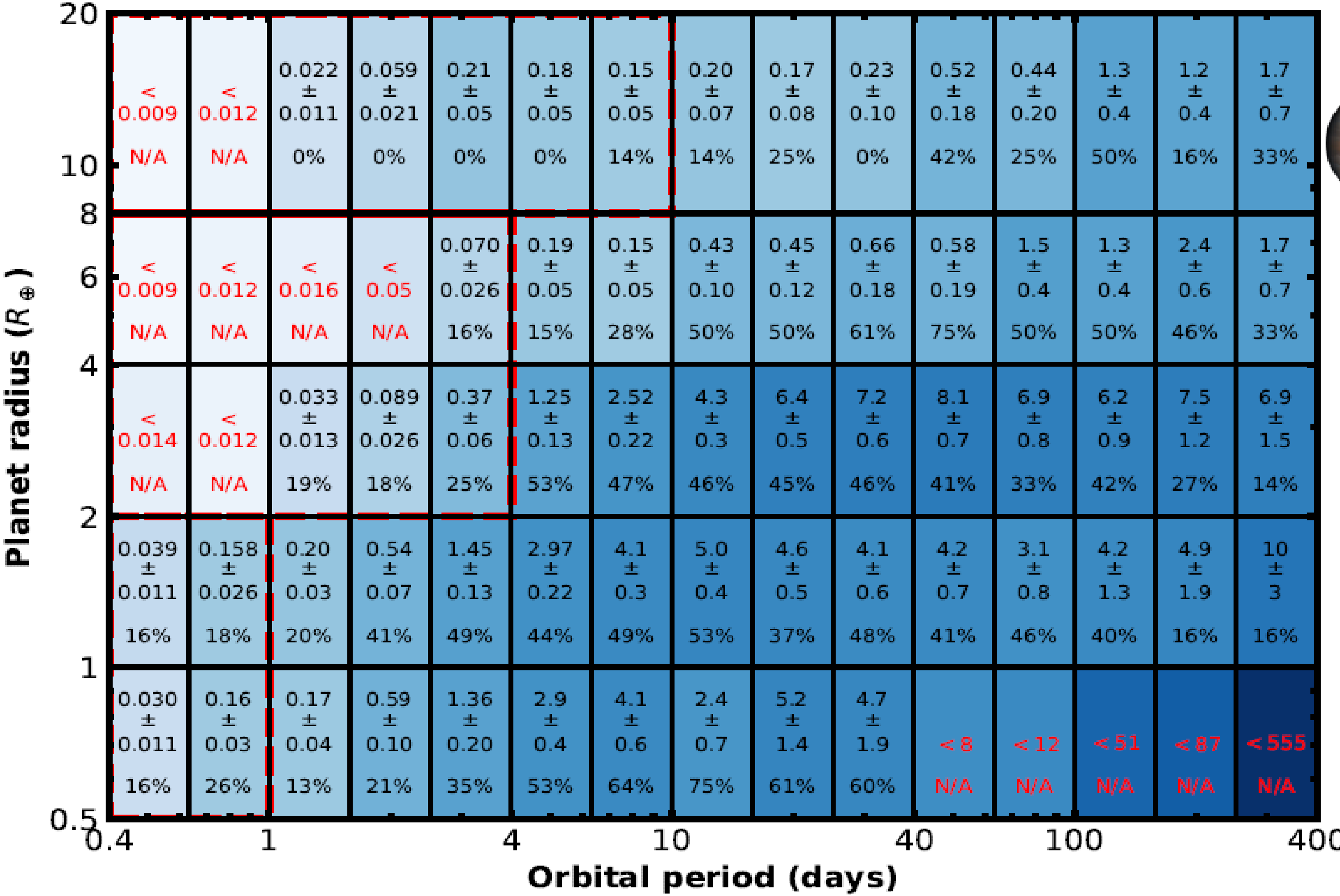
The Flow of Discoveries

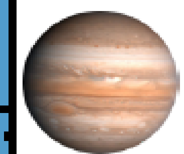


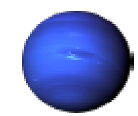
Zhu & Dong (2021)



Kepler Results







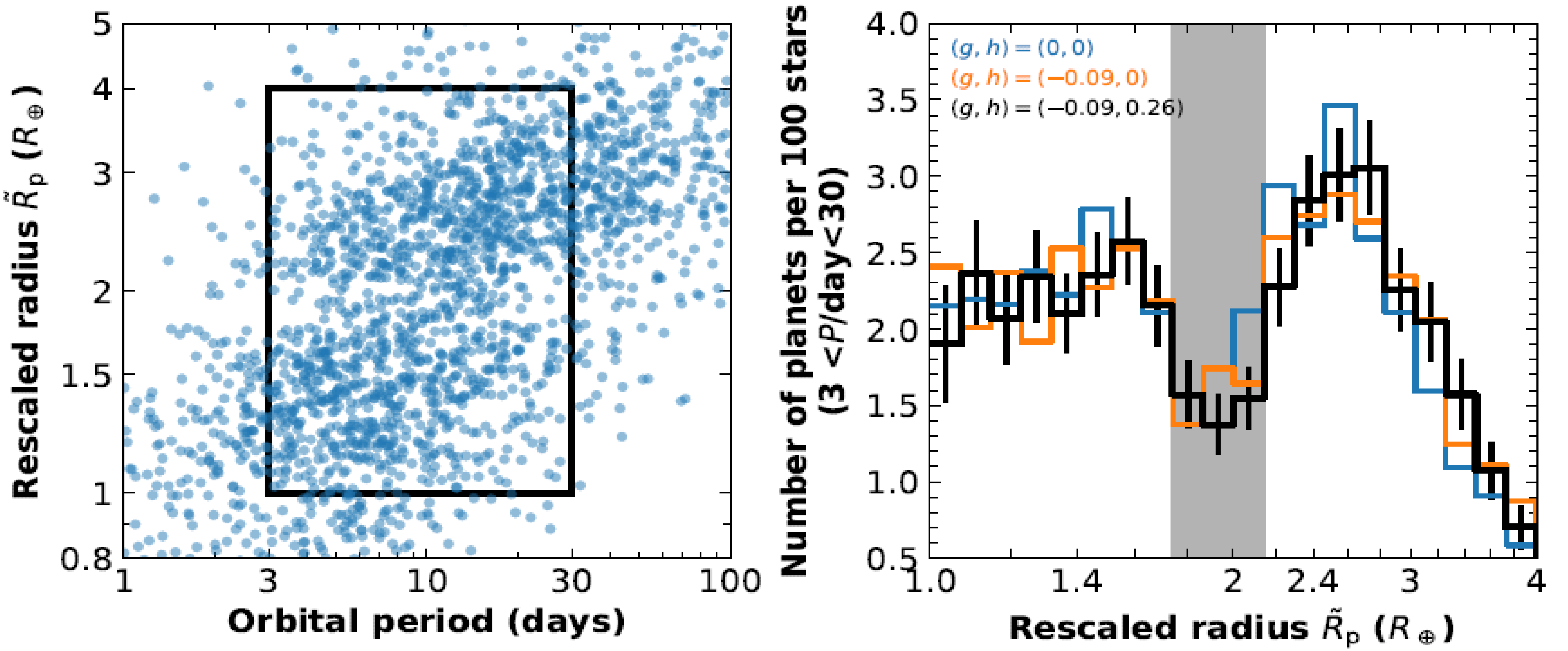
Hot Jupiters

- Occurrence Rates from Radial-Velocity and Transit Surveys are different
- About 0.6 % (Kepler results)
- About 0.7 % (Jiang et al. 2010)
- About 0.9 to 1.2 % (Mayor et al. 2011)
- Different stellar age ?
- Different stellar metallicity ?
- Typical exoplanet-host stars have [Fe/H] > 0.15

Hot Neptune Desert

- Under-populated for
  P< 4 day, Rp between 2 and 8 Earth Radius
- Due to formation or migration ?
- Different mass-radius relation for smaller planet and giant planet ?
- Photo-evaporation ? (Owen & Lai 2018)

Radius Valley



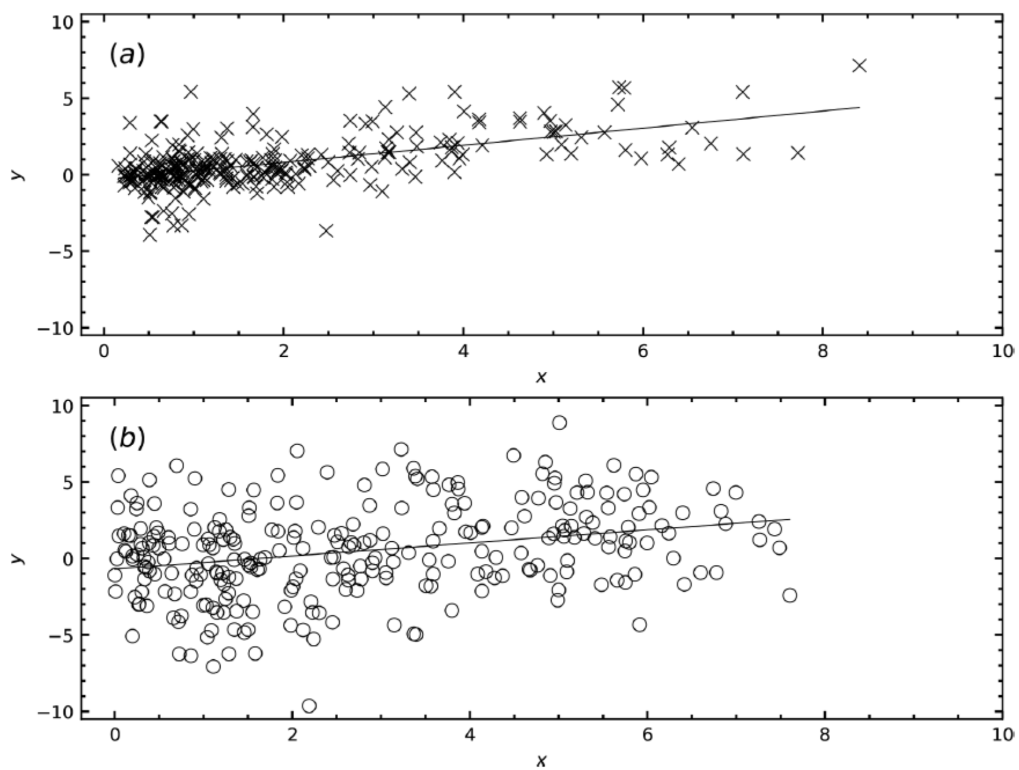
Radius Valley

- An important discovery
- Valley position: 1.9 Earth Radius (for P=10d)
- (1)Photo-evaporation
- Depending on distribution of core mass
- Core composition
- Atmosphere mass fraction
- (2)Core-powered mass-loss mechanism

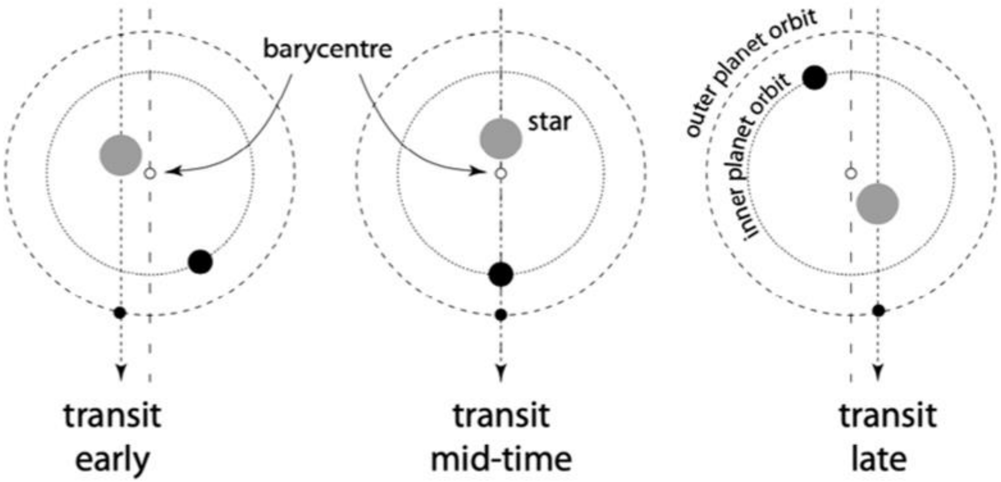
Peas in a Pod

- Planets in the same Kepler multi-planet systems have “similar” sizes (Lissauer et al. 2011)
- “similar” sizes and regular spacing (Weiss et al. 2018)
- Period-Ratio-Mass-Ratio Correlation (Jiang +2015, Yeh+2020, Gajendran+2021)

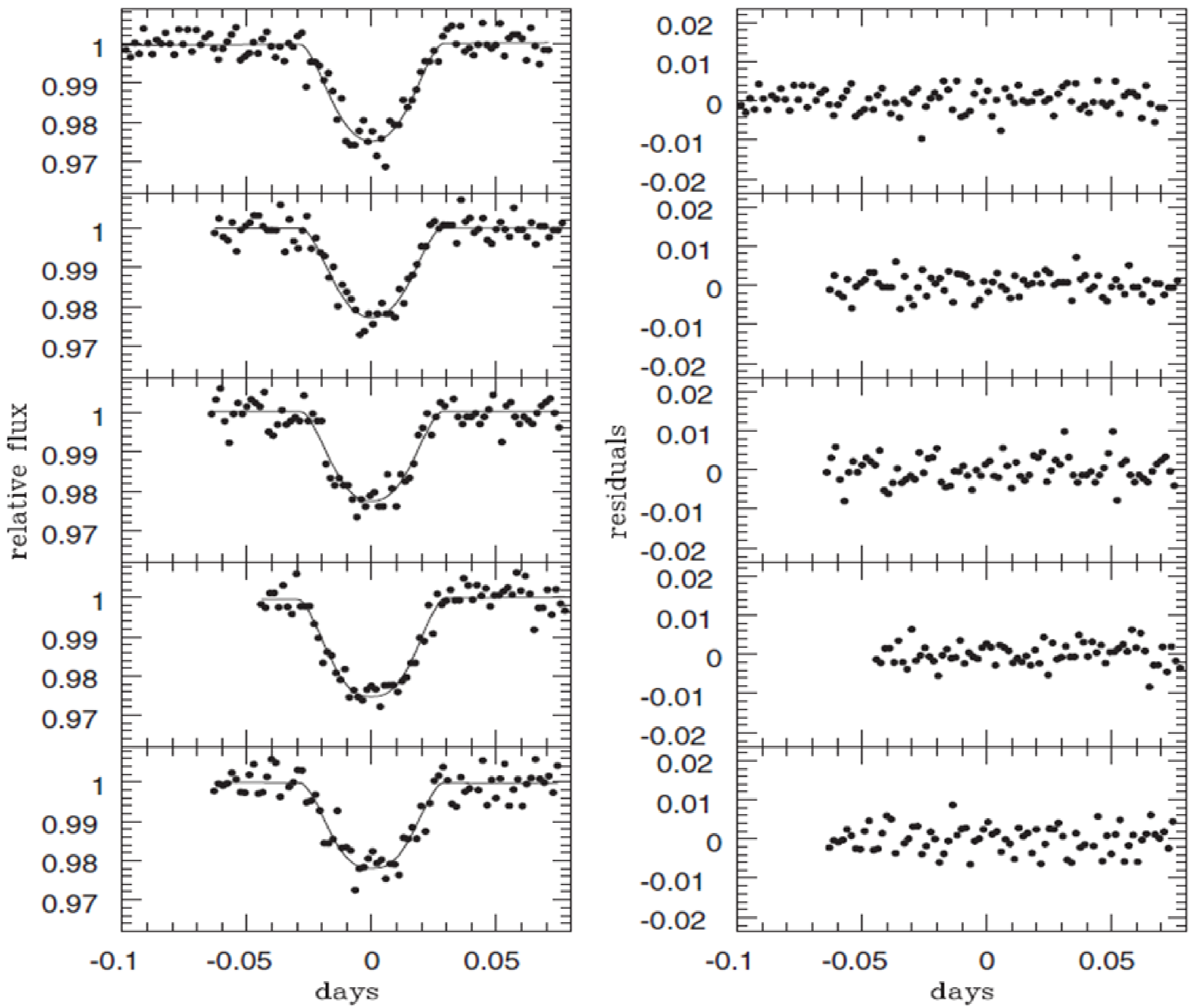
Period-Ratio vs Mass-Ratio of Adjacent and Non-Adjacent Pairs



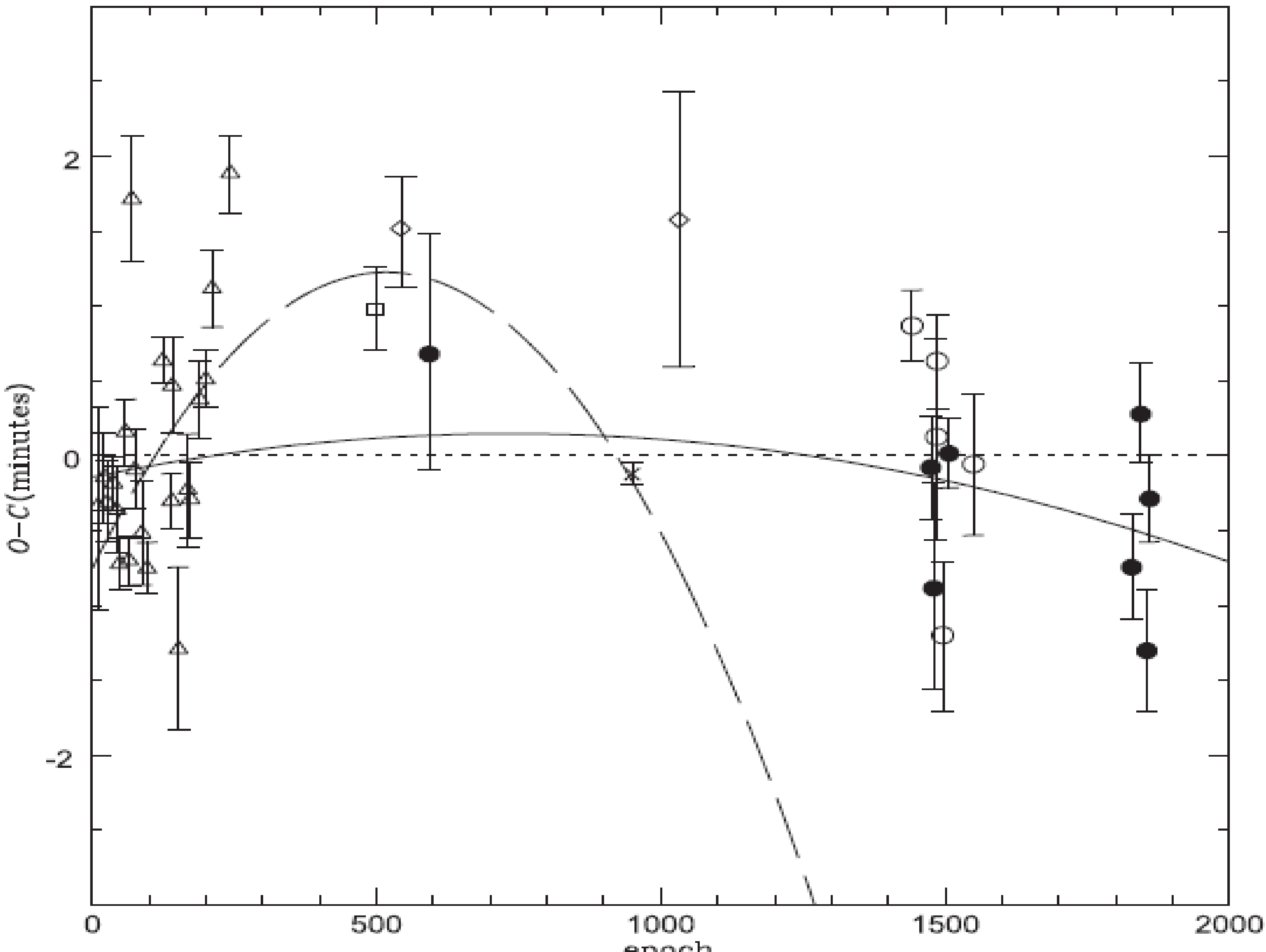
Transit Timing Variation (TTV)



TrES3 Light Curves (Jiang+2013)



Witnessing Orbital Evolution



WASP-43b (Chernov et al. 2017)

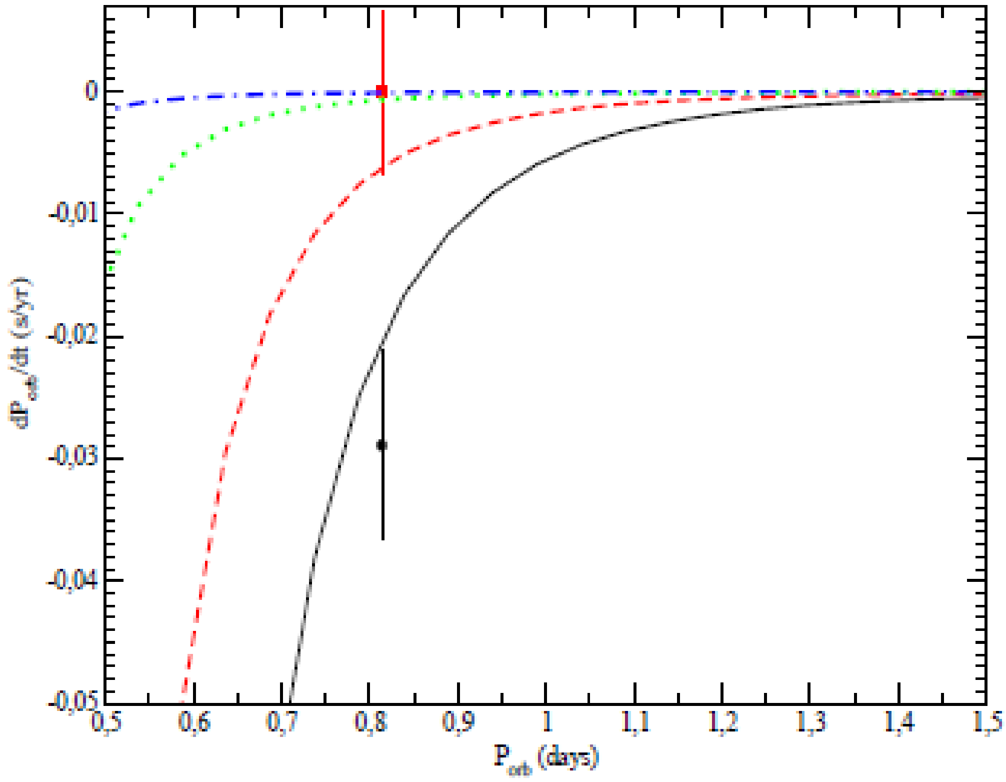
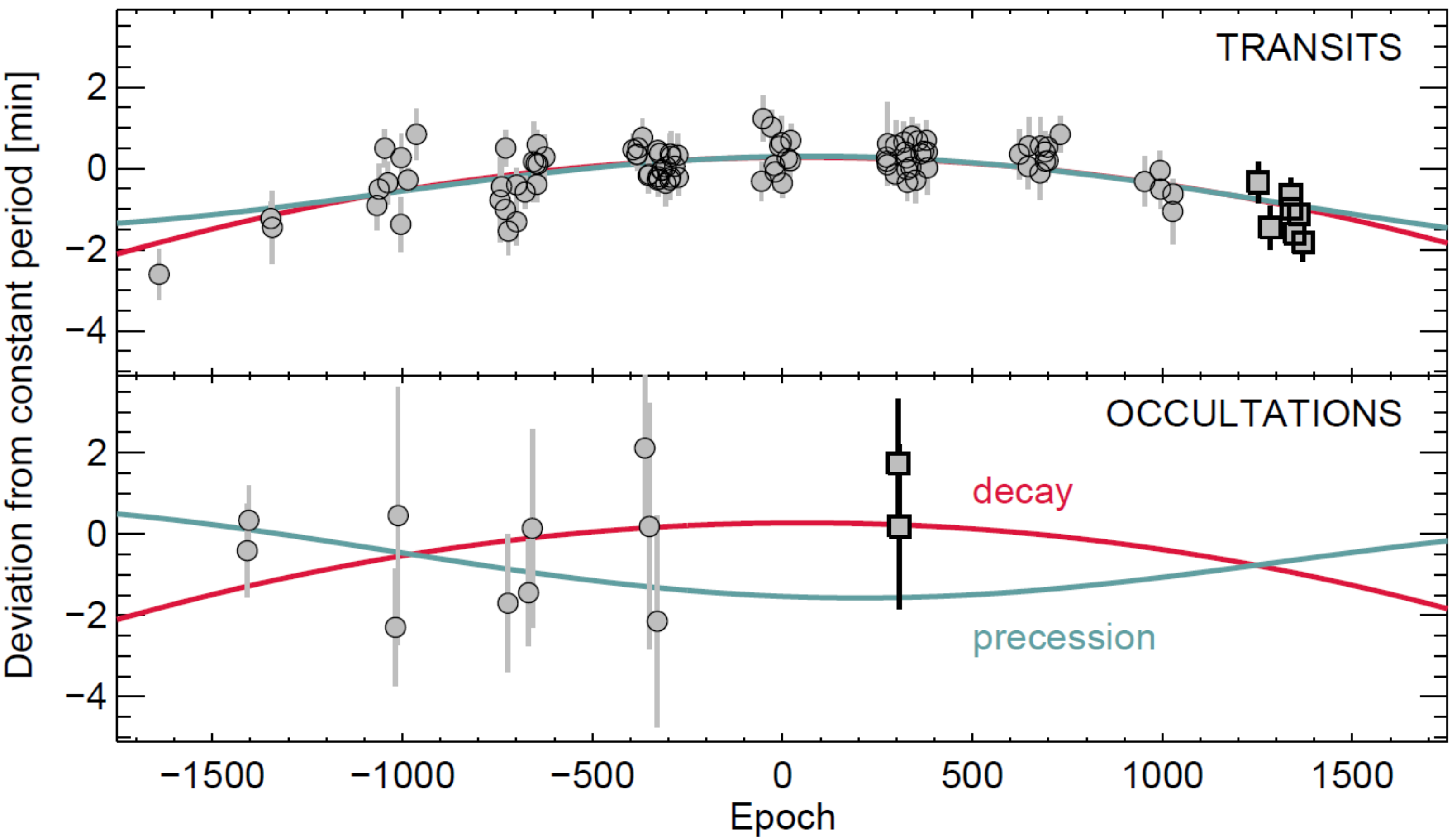
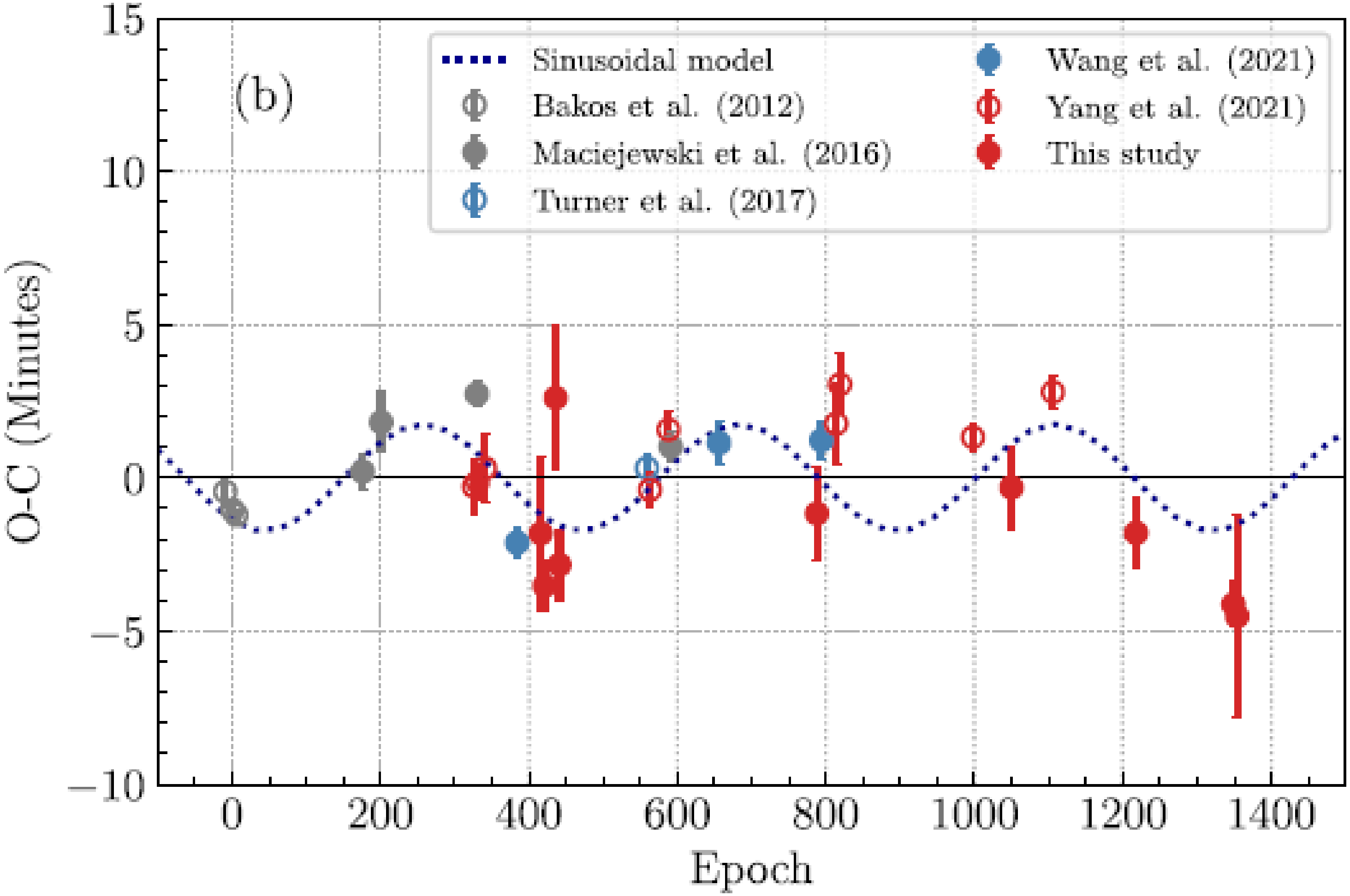


Figure 9. Results related to our model of WASP-43 are shown. Differen s/yr as functions of orbital period in days, for different values of the qua of particular curves. The black circle and red square show the positions of by Jiang et al. (2016) and Hoyer et al. (2016b), respectively.

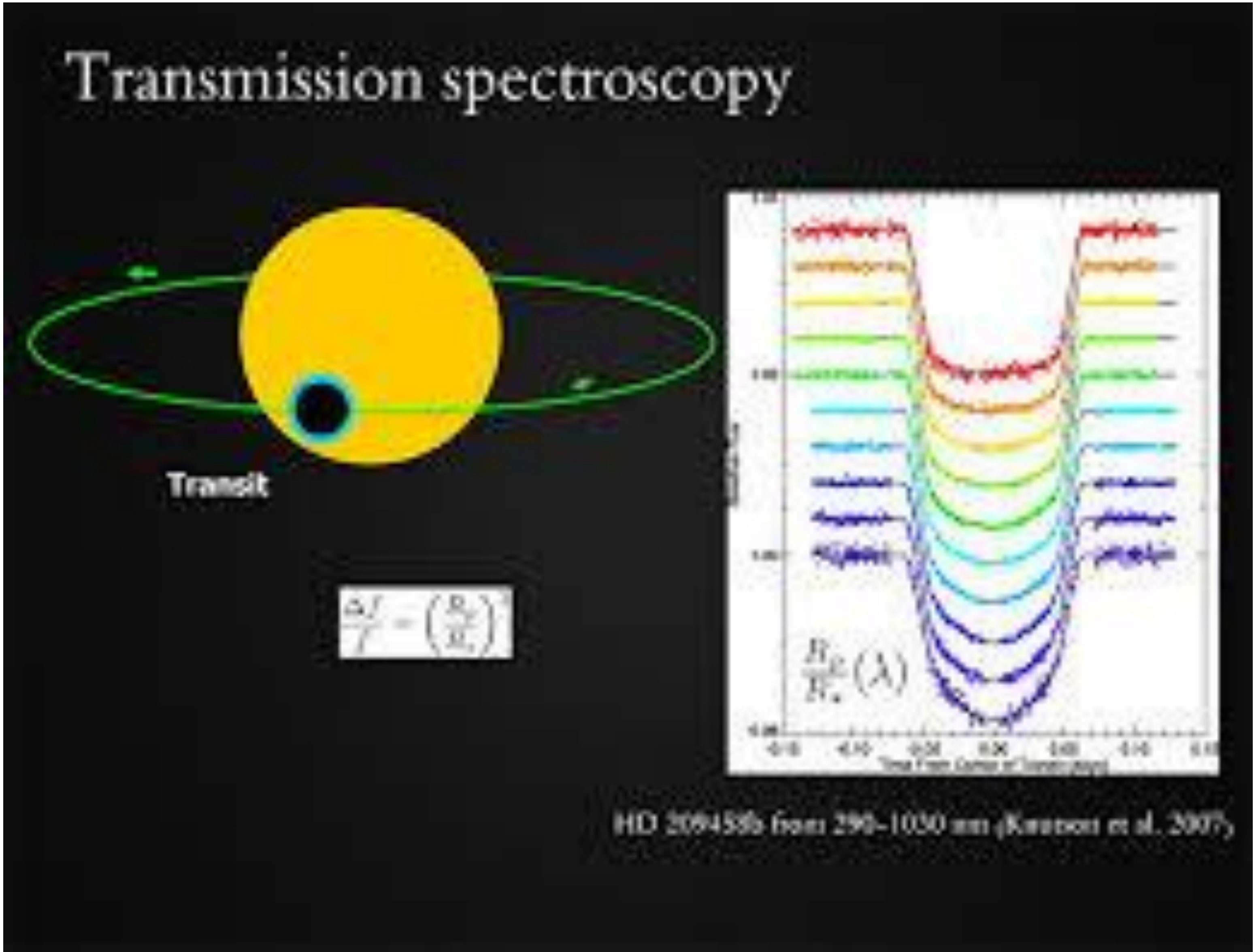
WASP-12b (Patra et al. 2017)



HAT-P-37b (A-thano+2022)



Transmission Spectroscopy



HAT-P-37b (A-thano+2022)

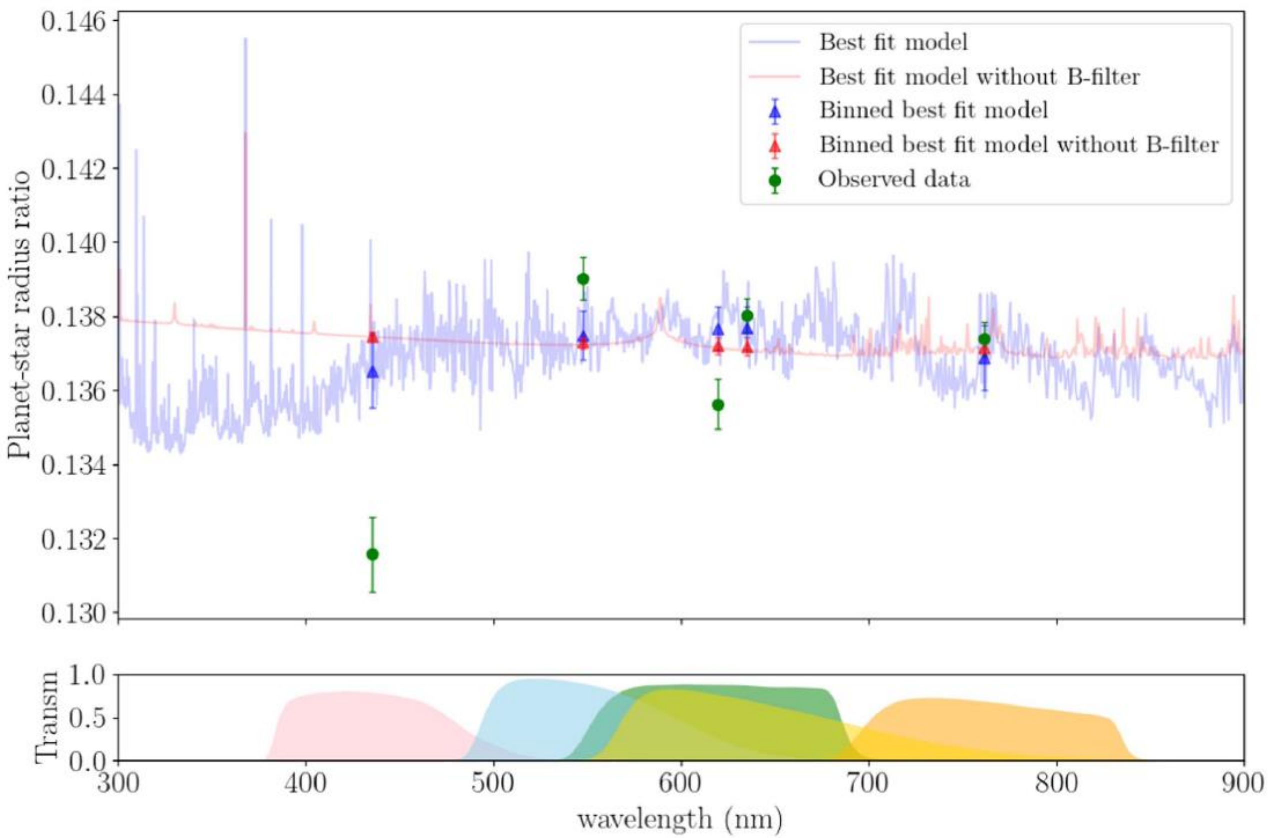
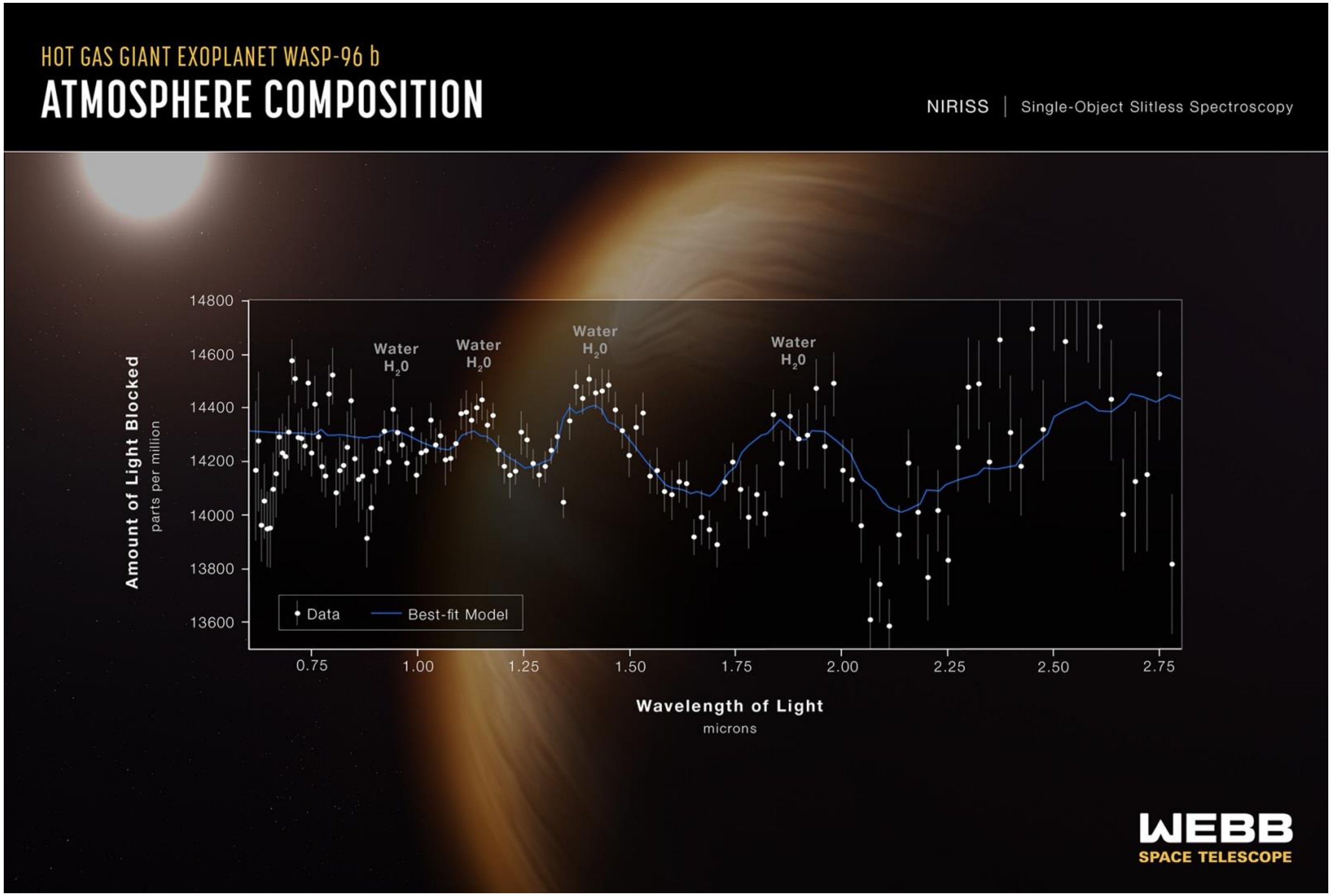


Figure 5. The best-fit transmission spectrum of HAT-P-37b with synthetic models generated from PLATON retrieval (top) and the bandpass filters: *B*, *V*, *R*, *r*, and *i* band (from left to right; bottom).

WASP-96b by JWST



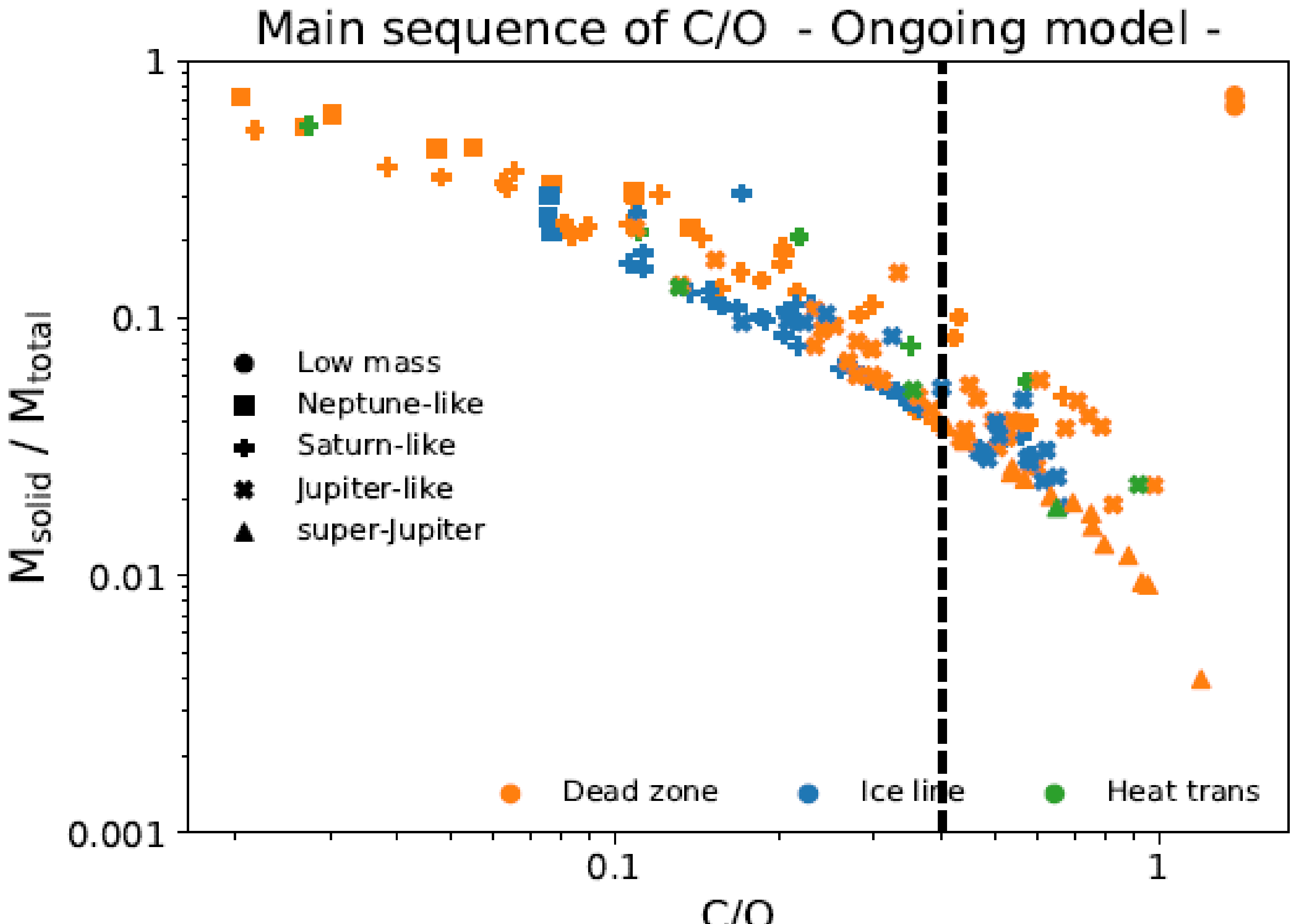
Exoplanet Atmosphere

- Na, H_2O, CO, CO_2, CH_4 were detected
- Planet metallicity
- Jupiter is enriched in C by a factor 4 to Sun
- Enrichment depends on the planet formation
- Core accretion or direct collapse
- Enrichment depends on planet migration
- Mordasini+(2018), Cridland+(2019)

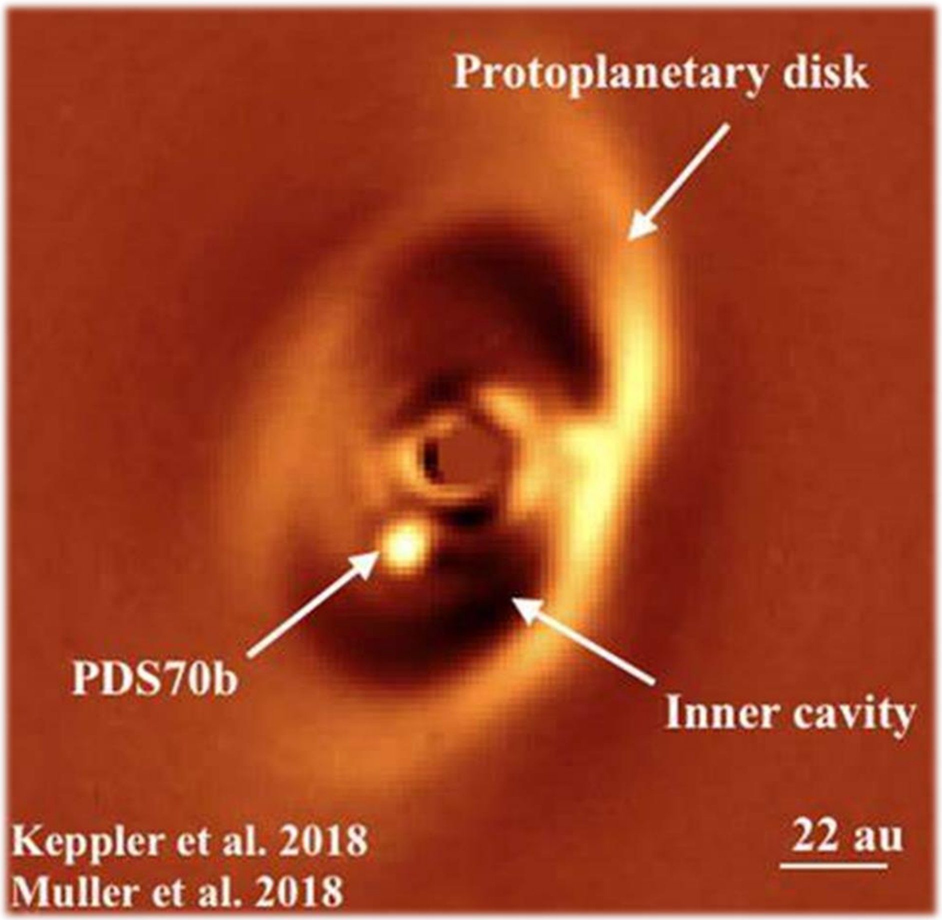
Planet Population Synthesis

- Set a host star with assumed metallicity
- With assumed C/O, set a disk with chemistry
- A set of initial position/mass of proto-planets
- Experience different migration & accretion
- Settle to be currently observed planets
- Determine the planet atmosphere chemical abundance

C/O Main Sequence



Real Time Planet Formation



Witnessing Active Minor Bodies

LETTER

doi:10.1038/nature13849

Two families of exocomets in the β Pictoris system

F. Kiefer[1,2,3], A. Lecavelier des Etangs[1,2], J. Boissier[4], A. Vidal-Madjar[1,2], H. Beust[5], A.-M. Lagrange[5], G. Hébrard[1,2] & R. Ferlet[1,2]

The young planetary system surrounding the star β Pictoris harbours active minor bodies[1–6]. These asteroids and comets produce a large amount of dust and gas through collisions and evaporation, as happened early in the history of our Solar System[7]. Spectroscopic observations of β Pictoris reveal a high rate of transits of small evaporating bodies[8–11], that is, exocomets. Here we report an analysis of more

Given the HARPS resolution and sensitivity, each *β* Pictoris spectrum shows an average of about six variable absorption features that are due to exocomets. These features have radial velocities ranging from −150 to +200 km s^{-1} with respect to the *β* Pictoris heliocentric radial velocity (~20 km s^{-1}). We fitted each feature with a Gaussian profile and obtained the estimates of p_K and p_H (their depths in the Ca II K and H

Absorption by Exocomet Ca+ Clouds

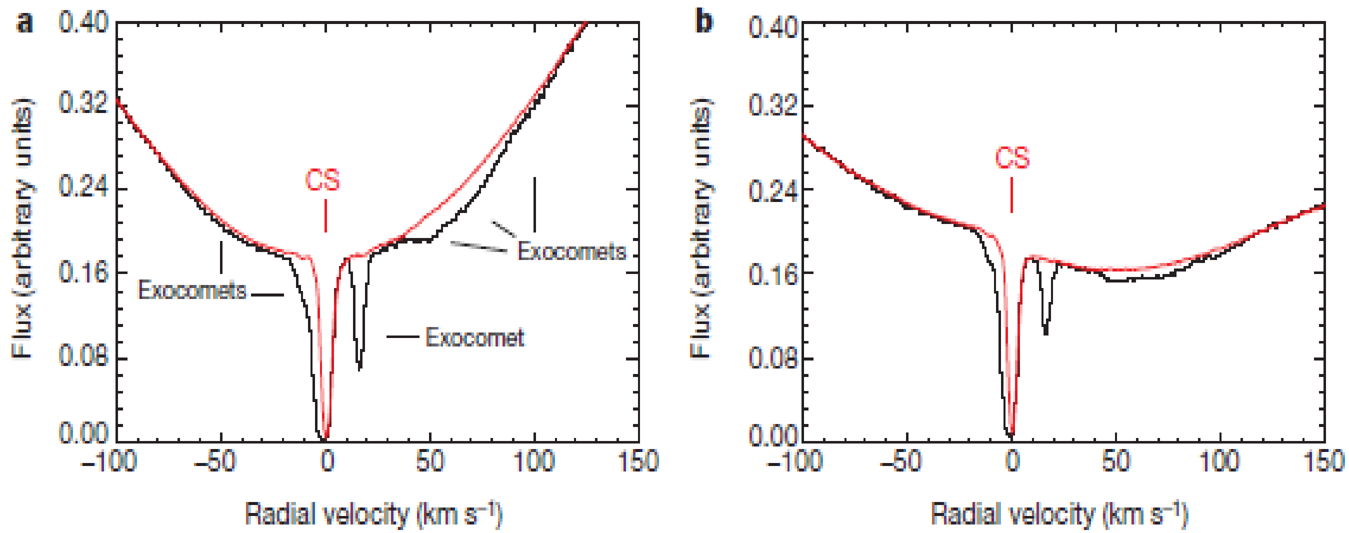
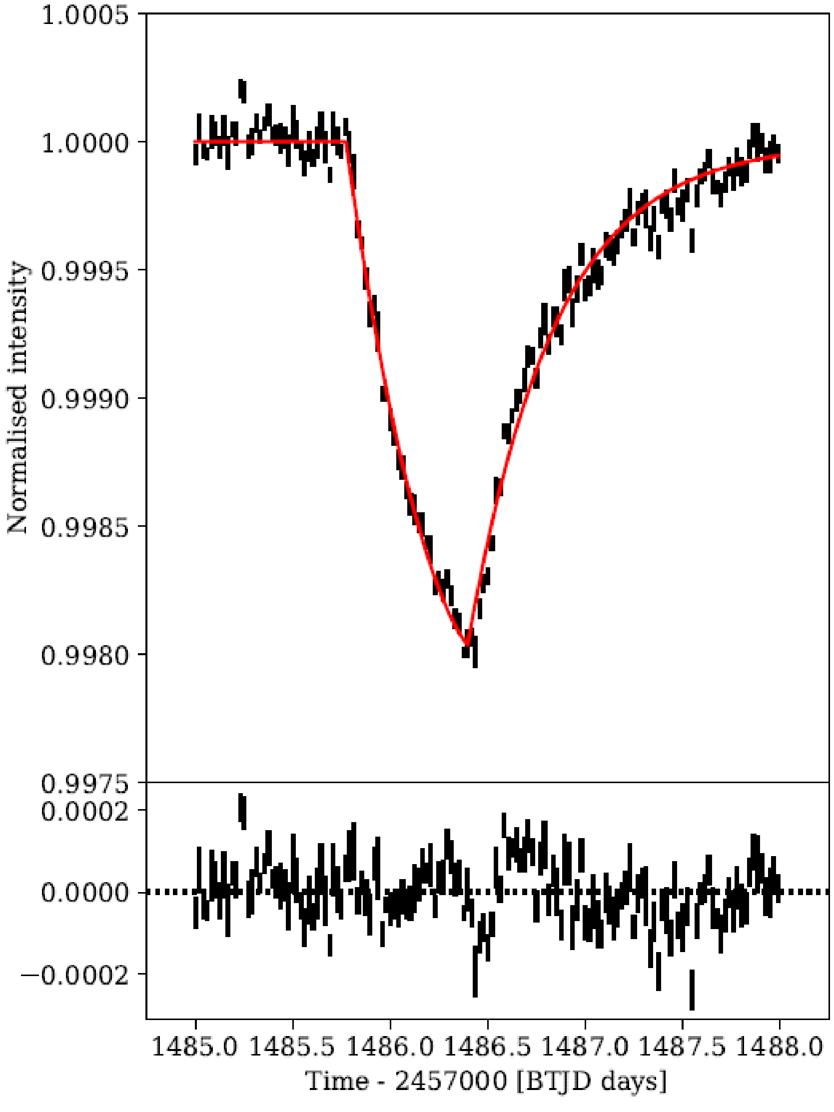


Figure 1 | A typical Ca II spectrum of β Pictoris. **a**, Ca II K-line (3,934 Å). **b**, Ca II H-line (3,968 Å). A typical Ca II spectrum of β Pic (black line) collected on 27 October 2009 is shown together with the derived β Pic stellar spectrum (red line) used as the reference spectrum free of variable absorption features. Radial velocities are given with respect to the star's rest frame. CS indicates the circumstellar disk contribution, while solid black lines indicate the changes in flux caused by the transiting exocomets. Each transiting exocomet produces an absorption signature detected at the same radial velocity in both Ca II lines.

Exocomet (Zieba+2019)



Exomoon 系外月球

Light Curve

Summary

- Discoveries of exoplanets motivate and excite the field of planet formation
- Characterizing detected exoplanets and architecture of multi-planet systems gives imprint of planet formation
- Exoplanet atmosphere gives implication of planet formation and migration
- Theoretical Work/Simulations on different stages of all the above are important
- More observational results could lead us to the right directions

Future

- Future facility will reveal more results on Exoplanet Physics
- Giving more implication for Planet Formation
- High resolution theoretical simulations for detail processes of different stages are important
- Stability Analysis of different configurations of multi-planet systems