Exoplanets

Lecture 11

Eric Agol, Autumn 2022

Transit timing overview

- For a single planet orbiting a star: transit times are precisely periodic (ignoring non-Newtonian effects)

GR, tidal/oblateness

- Residuals to linear fit to transit times are transit-timing variations or "TTVs"

Discover planets: KOI 872.02

Kepler object of interest

- TTVs scale with:

EXoMoons: eventually?

1). mass ratio of *companion planets* to star;

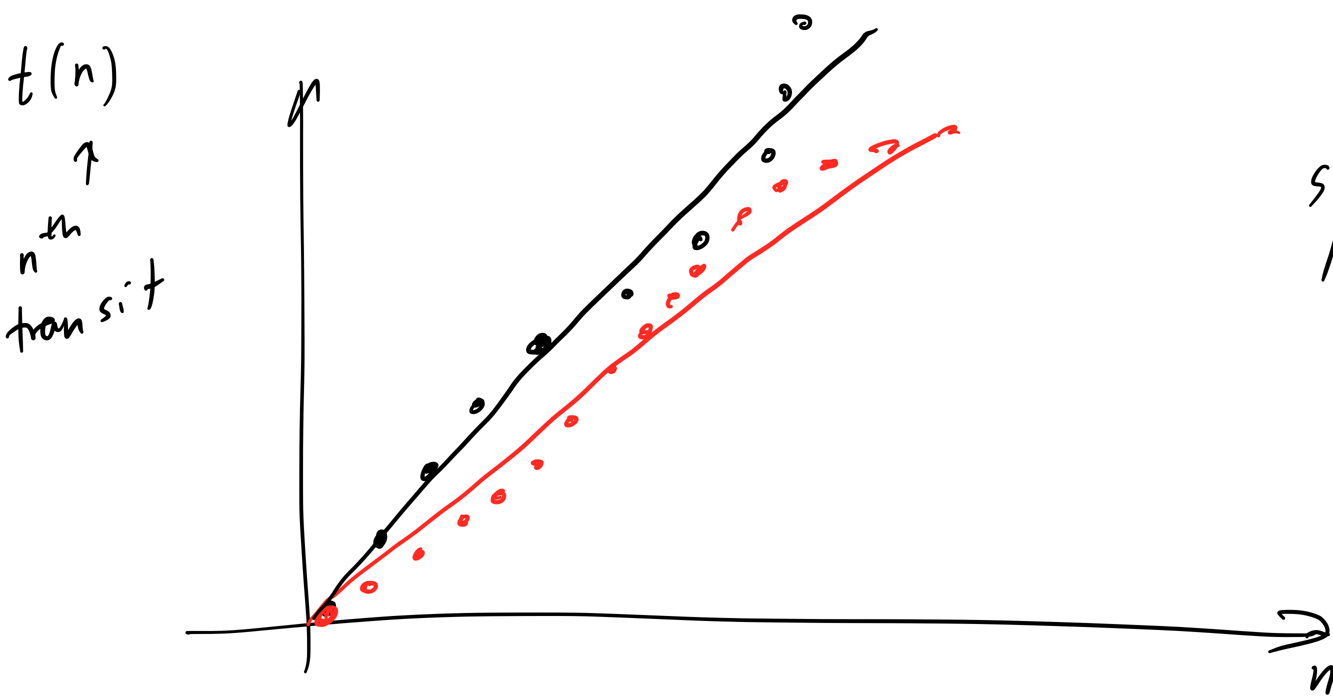
2). orbital per i ;

3). scale with proximity of planets to one another & to first-order mean motion resonances.

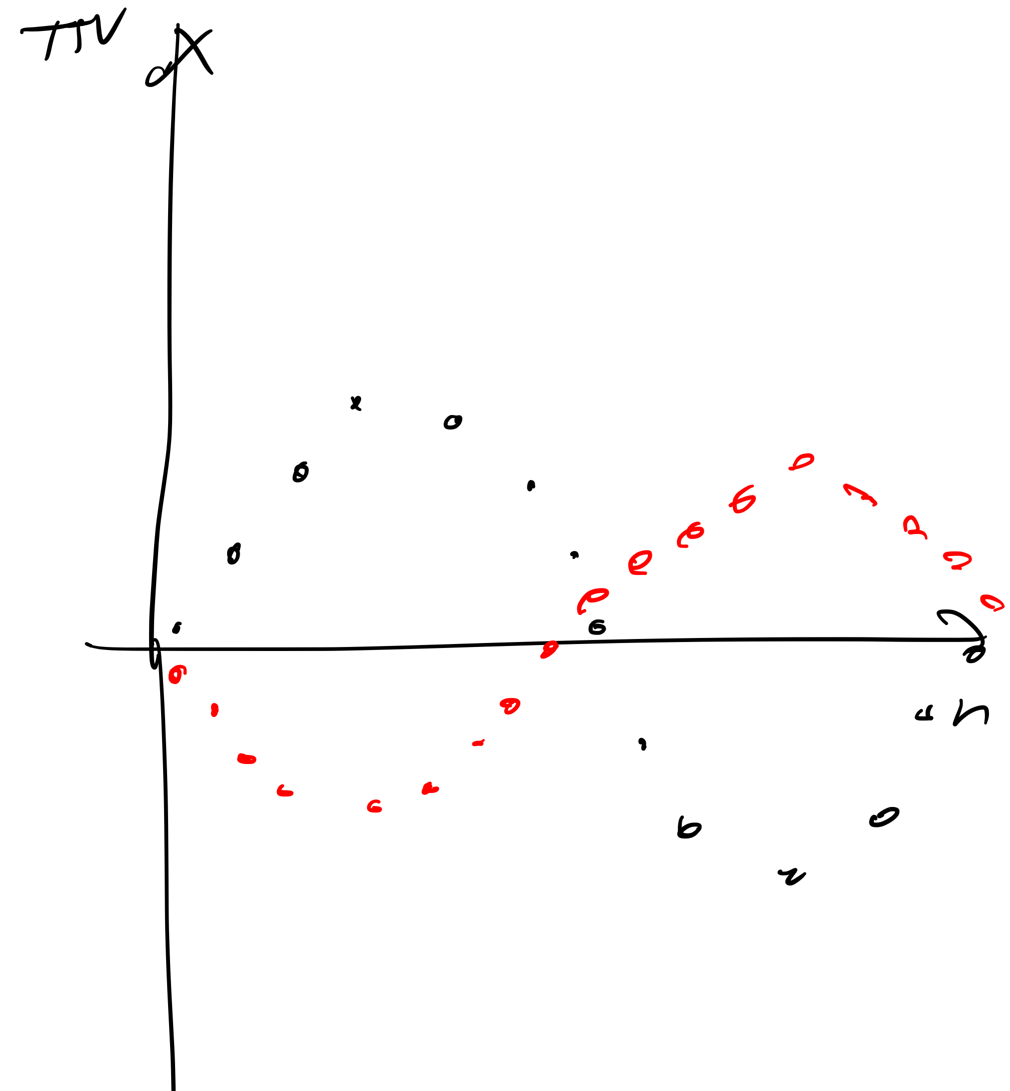
periods close to j:j+1 (j is an integer).

first-order

Transit-timing variations (TTV)



subtract line



1). Correct for light-travel time across solar system

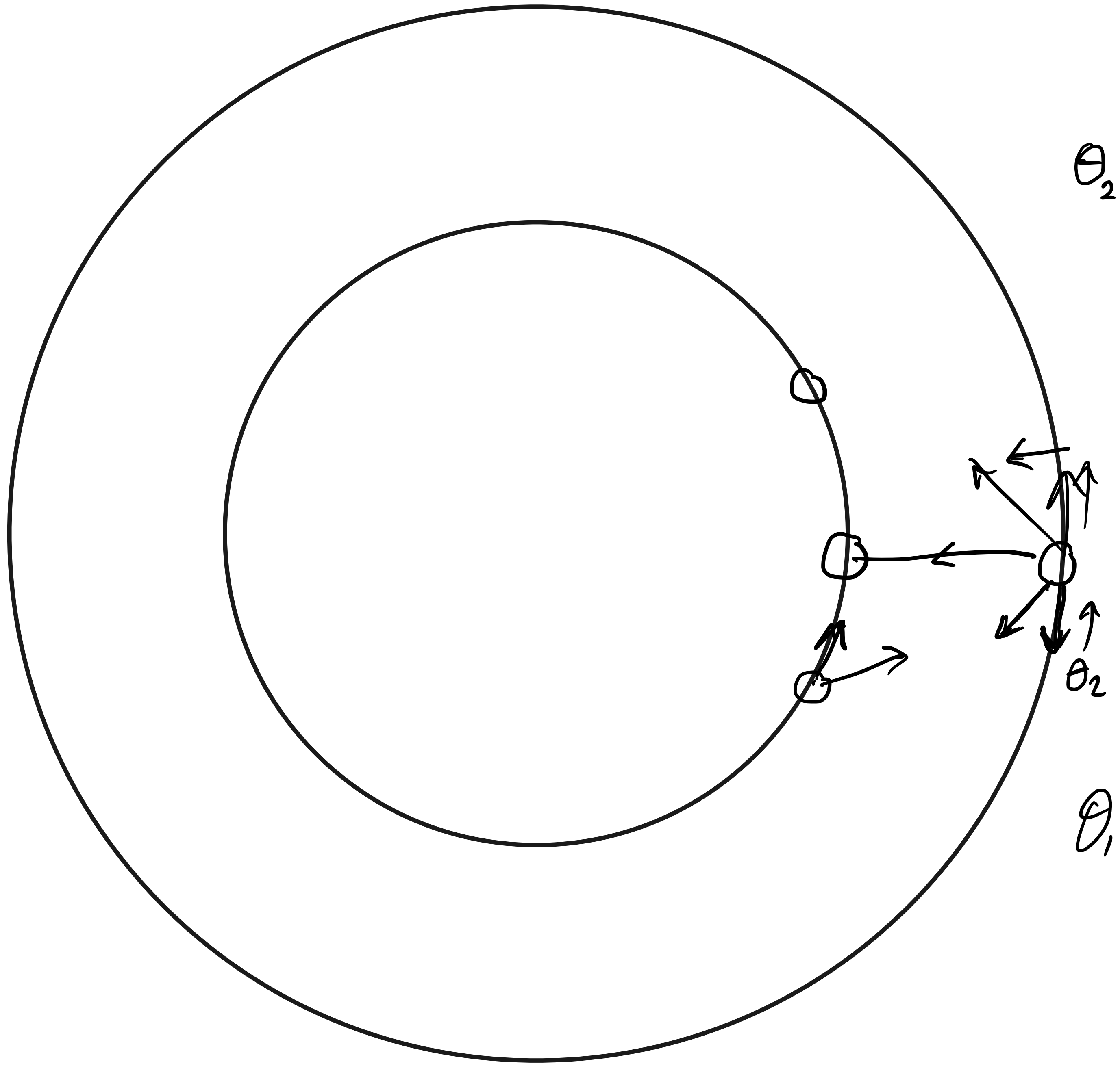
→ to barycenter of solar system.

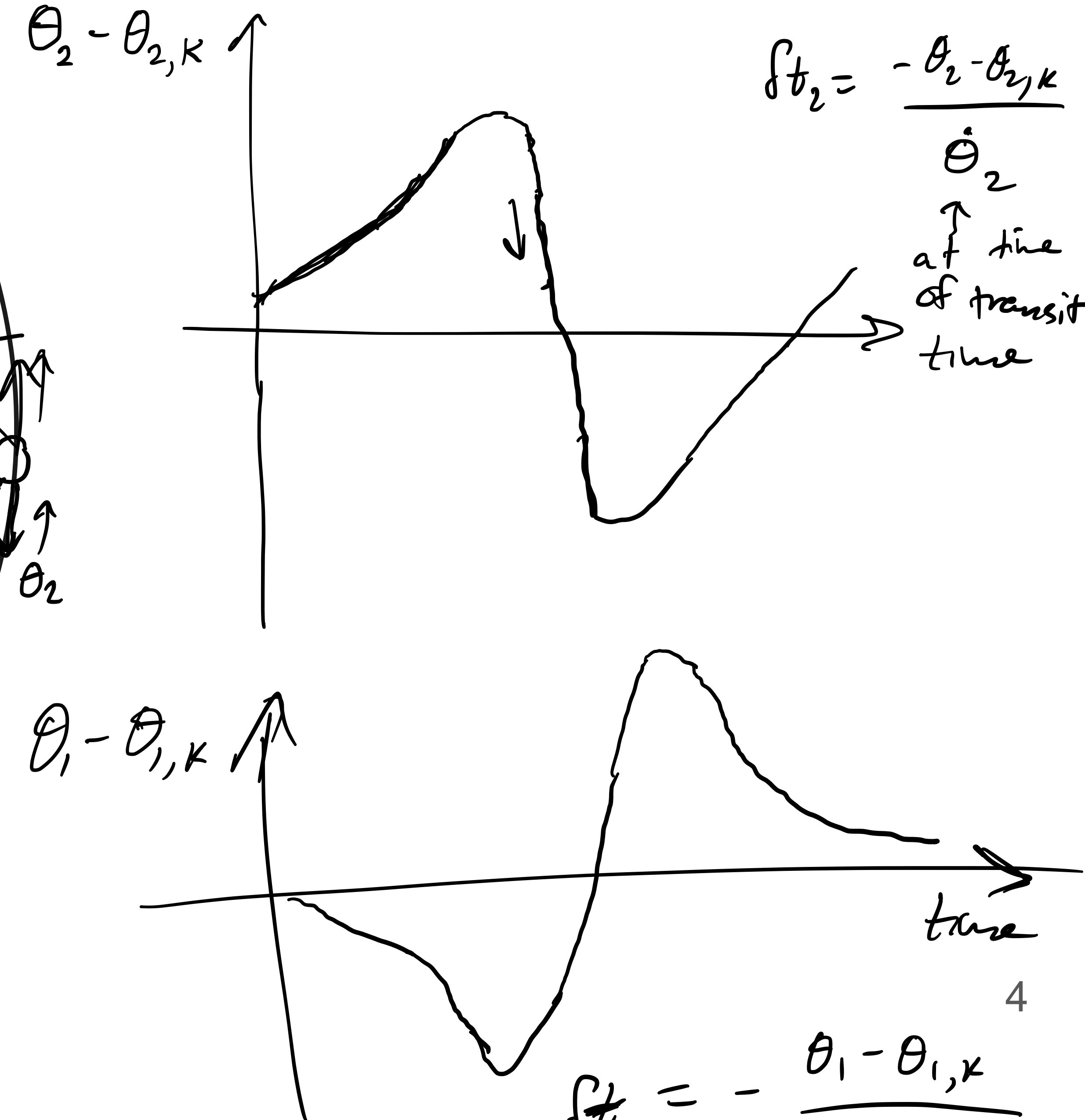
"Barycentric Julian Date"

↑ corrected for light-travel time

Perturbations at conjunctions

perturbations occur at harmonics of the conjunction timescale.



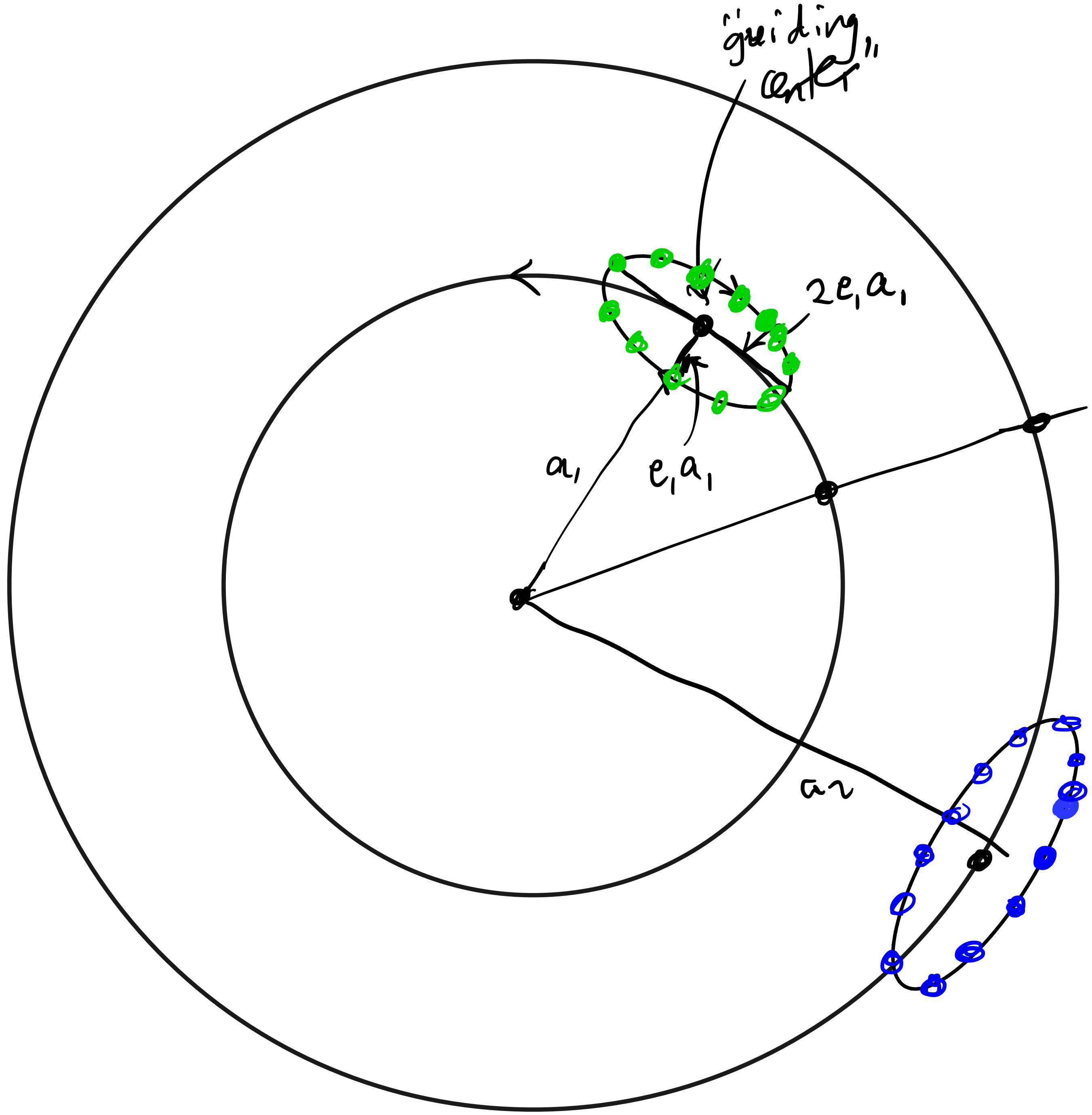


$$\delta t_2 = \frac{-\theta_2 - \theta_{2,K}}{\dot{\theta}_2}$$

at time of transit

$$\delta t_1 = - \frac{\theta_1 - \theta_{1,K}}{\dot{\theta}_1}$$

Resonant perturbations



- near-resonant interactions
  - Epicyclic frequency = orbital frequency for $1/r^2$ potential
  - If planets are close to resonance, $\frac{P_1}{P_2} \approx \frac{j}{j+1}$ $\neq$
  - Motion of conjunctions about epicycle determines how they interact
  - Oscillations in perturbations of orbits.

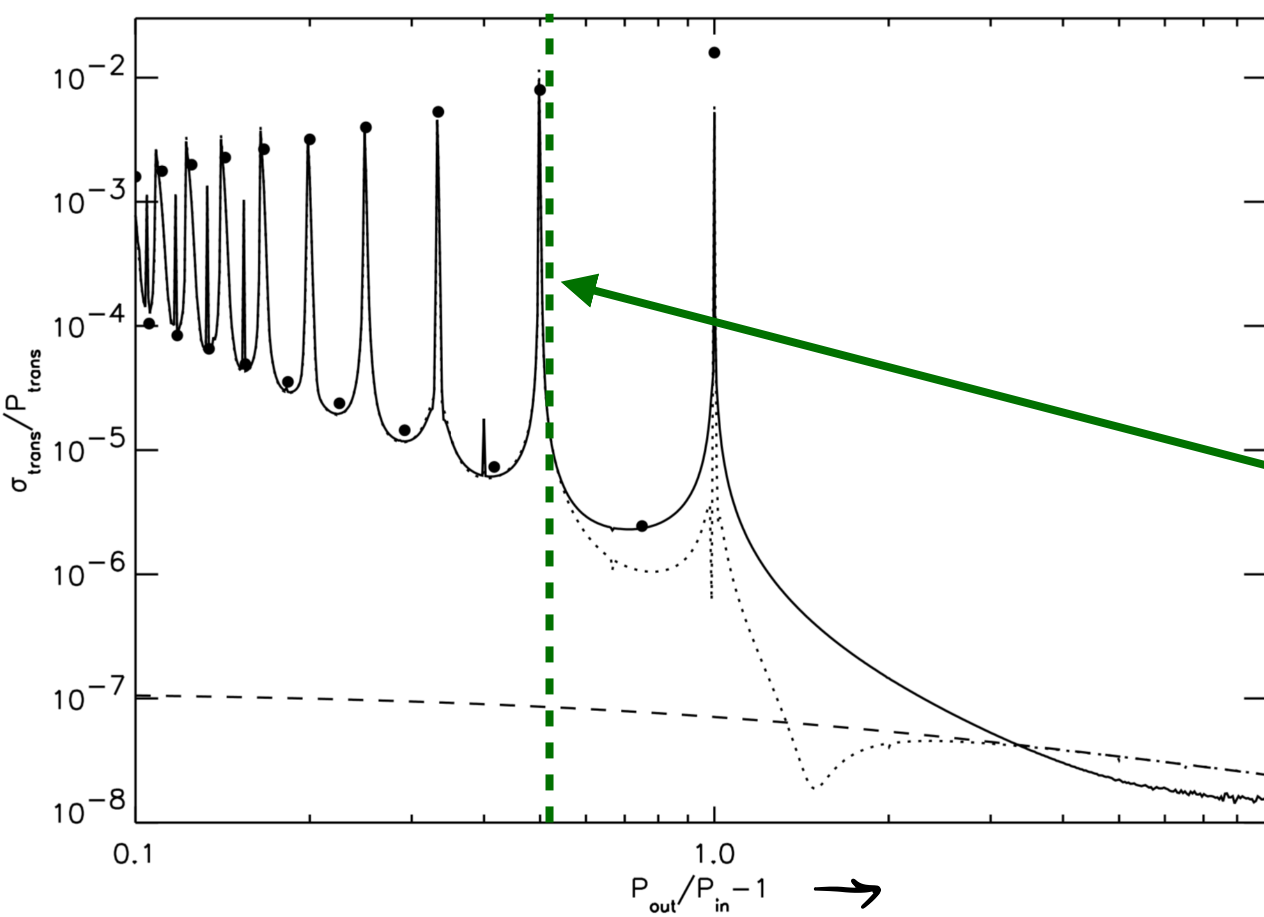
$$P_{TTV} = \frac{1}{\left| \frac{j}{P_1} - \frac{j+1}{P_2} \right|}$$

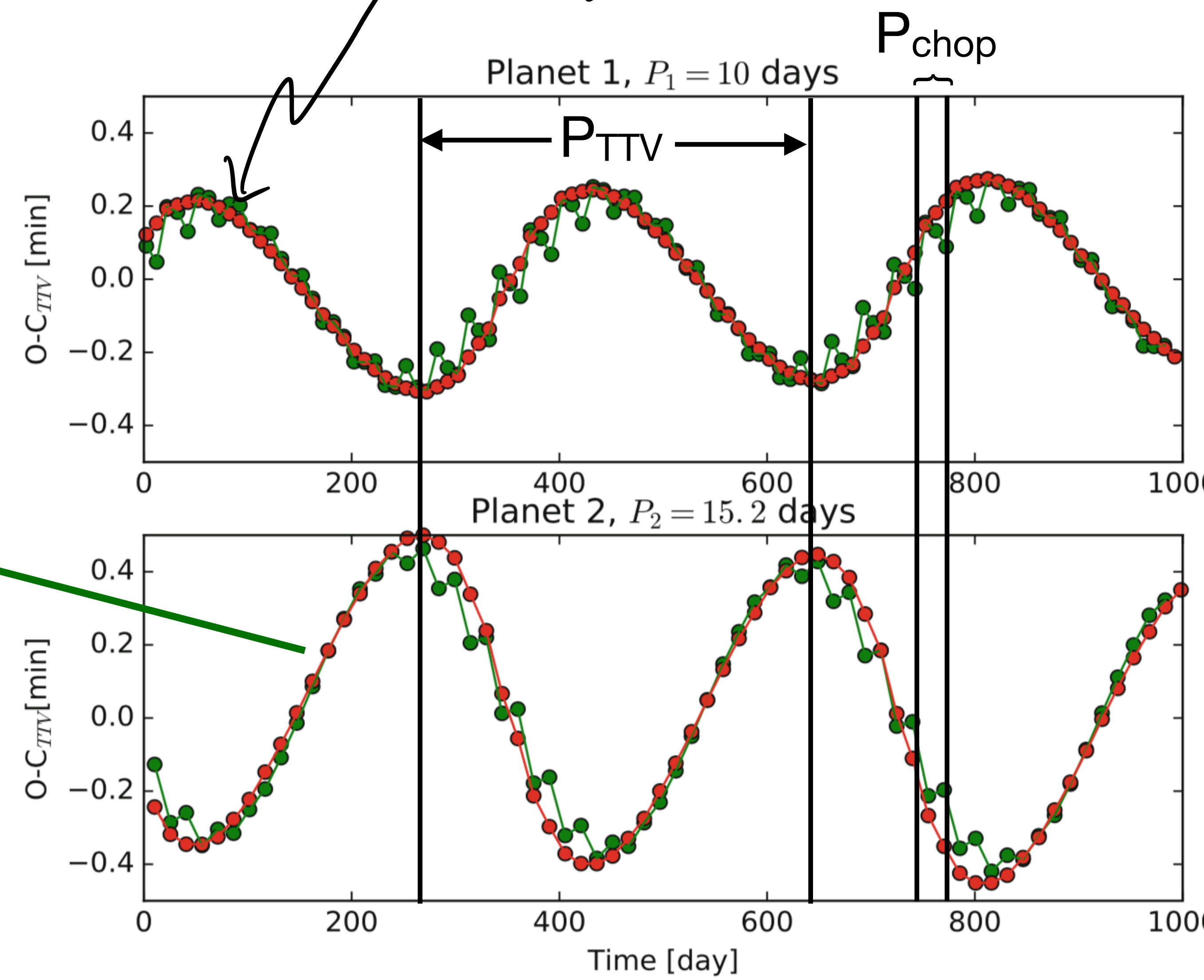
- Leads to sinusoidal transit timing variations on this longer timescale

Transit-timing anatomy

mass-eccentricity degeneracy

$$\frac{m_1}{m_*} = \frac{m_2}{m_*} = 10^{-7}$$





Agol Steffen Sari & Clarkson (2005)

$$P_{TTV} = |j/P_{in}-(j+1)/P_{out}|^{-1}$$

$$= |2/10-3/15.2|^{-1} = 380 \text{ d}$$

$$P_{chop} = |1/P_{in}-1/P_{out}|^{-1} = 29.2 \text{ d}$$

Agol & Fabrycky (2017)

Also eccentricity-eccentricity degeneracy

TTV applications

1. Confirm of multi-transiting planets. (not multiple stars or not diluted EBs)
2. Detection of non-transiting companions. KOI-872
3. Characterize of masses, eccentricities.
4. Discovery of exomoons.
5. With RV, measurement of absolute masses.

$$K_* \propto P^{-1/3} \frac{M_1 \sin i}{M_*^{2/3}}$$

RV + TTV → measure mass of star

$$\delta t_1 \propto P_1 \frac{m_2}{M_*}$$

$$\delta t_2 \propto P_2 \frac{m_1}{M_*}$$

TTV drawbacks

1. Requires long term monitoring of transits

2. Aliasing limits the dynamical information

3 ~~4~~. Degeneracy between mass and eccentricity (low precision)

4. ~~5~~. Degeneracy between planets' eccentricity and longitude of periastron of 2 planets.

5. Unknown planets (don't transit or shallow) which perturb TTVs.

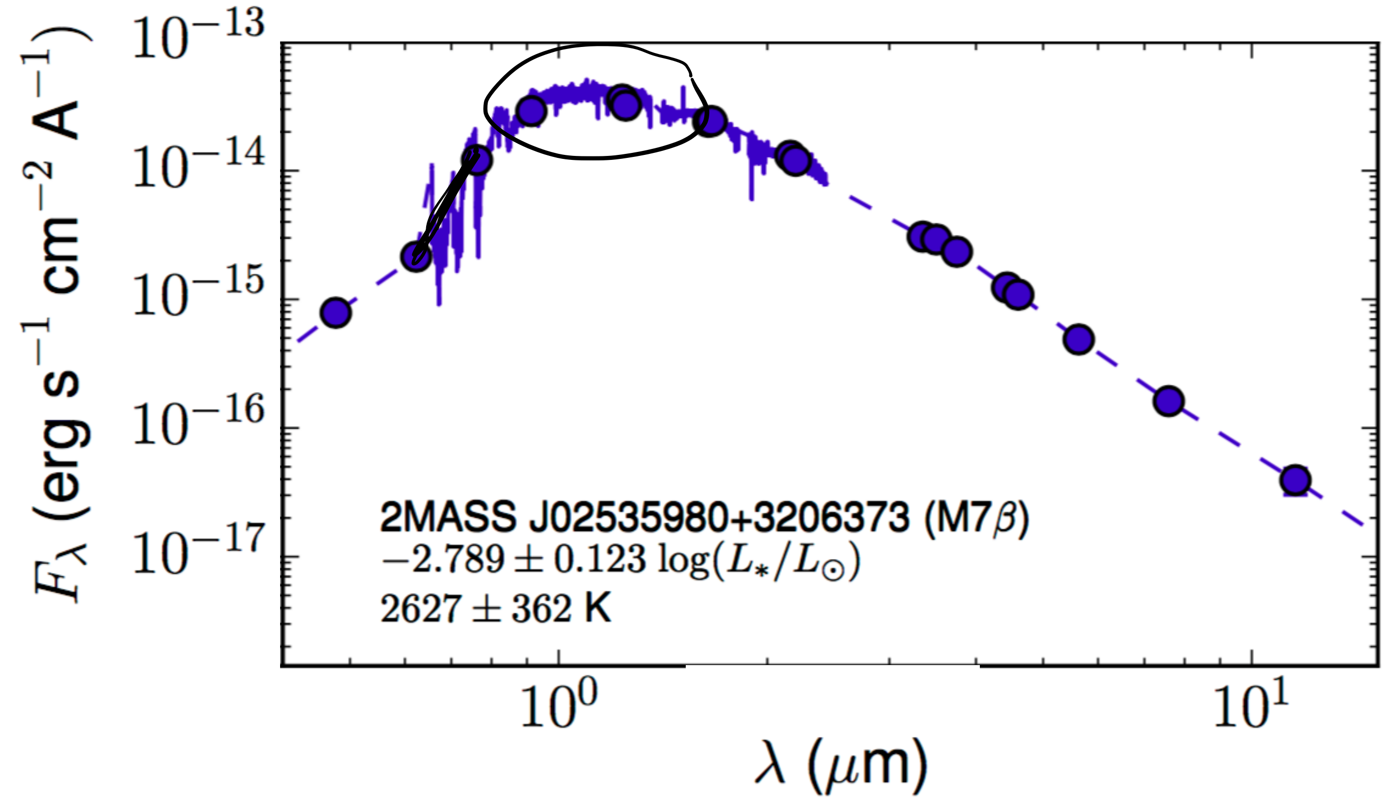
Trappist survey

- "Ultracool dwarfs": lamppost effect:
  - smallest stars
  - most common → close proximity
- Low-T stars have highest temperate transit probability (Charbonneau & Deming 2007) Gould 2003
- Two telescopes: La Silla, Morocco - 60cm, I+z (>700nm)

  2016: first planet system – TRAPPIST-1
- 50 stars surveyed

Trappist-1 host star

R = 0.12 $R_\odot$; M = 0.0~~8~~9 $M_\odot$; L = 0.00057 $L_\odot$



SED from Filippazzo (2016; PhD dissertation)

SDSS image

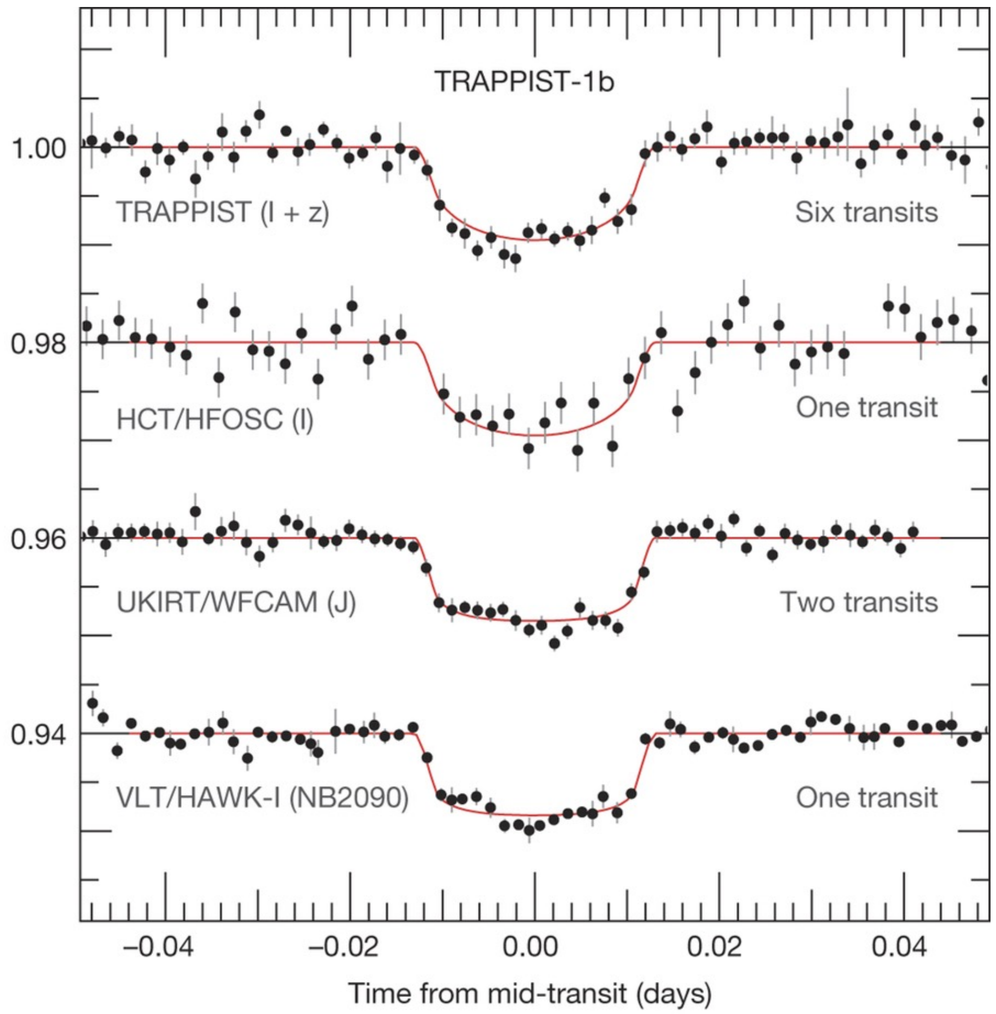
T_{eff} = 2560 K; d = 12.2 pc; 7.6+-2.2 Gyr (Burgasser & Mamajek 2017); [Fe/H]=0.04 ± 0.08

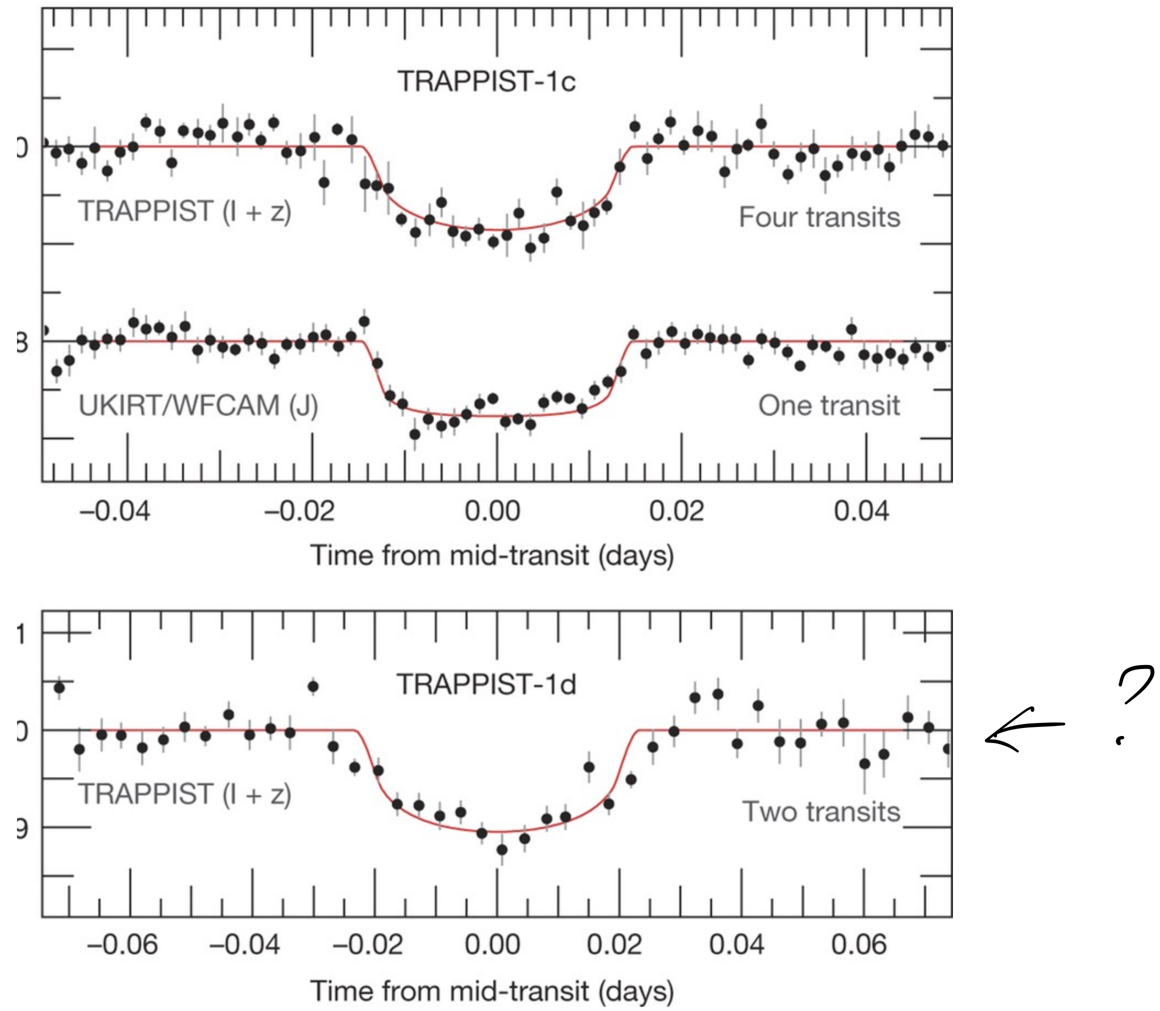
George Wallerstein notation

Trappist 1b,c

1,5 d

~2,4 d





Gillon et al. (2016)

Plus hints of other transits…

Size comparison

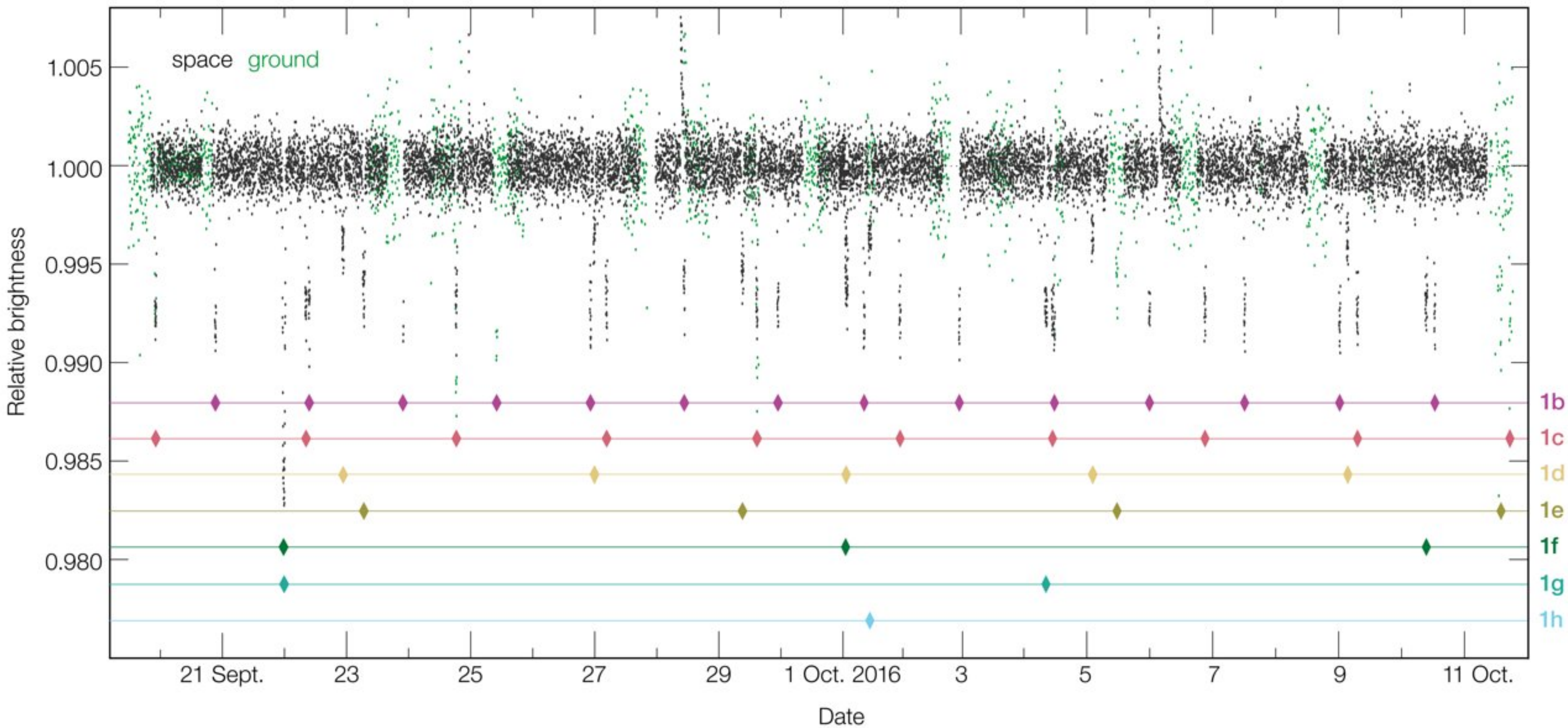
Sun:

29.5”

TRAPPIST-1: 1.1”

Planets b-h: 1/8”

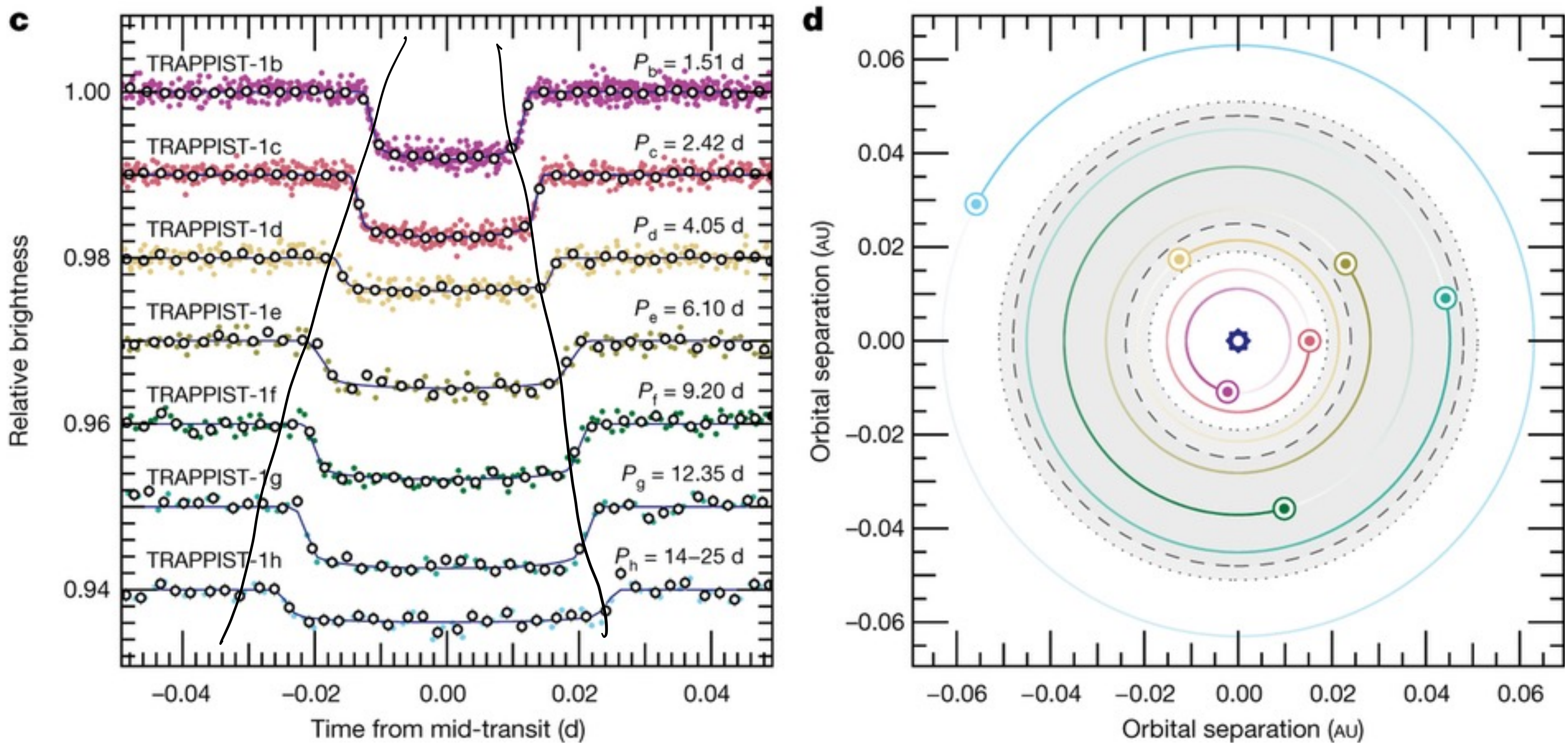
Spitzer light curve



Transits occur 6% of the time!

GILLON ET AL. 2017

P_c/P_b, P_d/P_c, P_e/P_d, P_f/P_e & $P_g/P_f \approx 8/5, 5/3, 3/2, 3/2$ & $4/3$



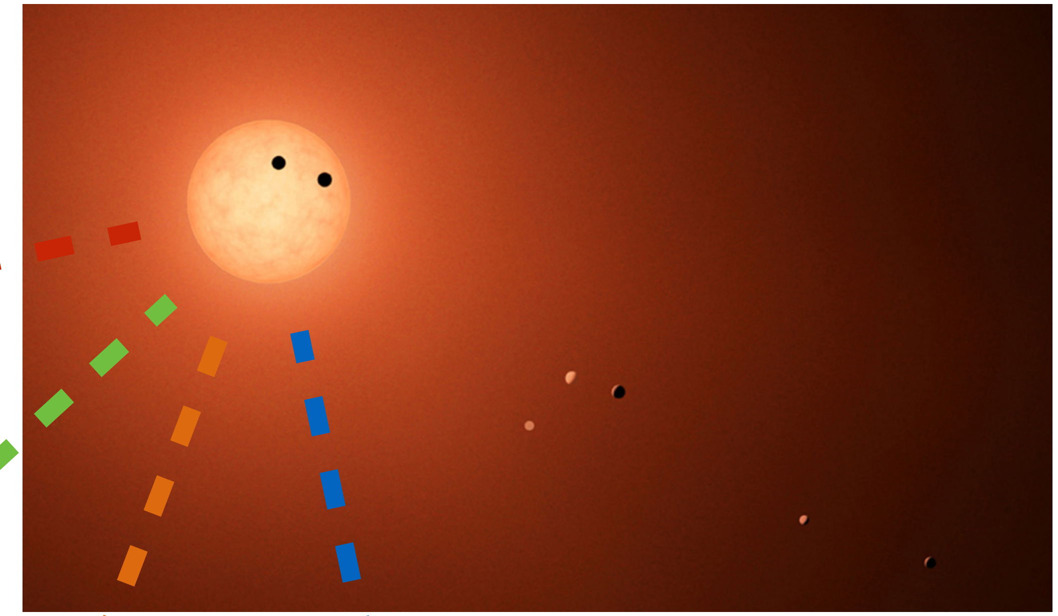
$T \propto P^{1/3}$

GILLON ET AL. 2017

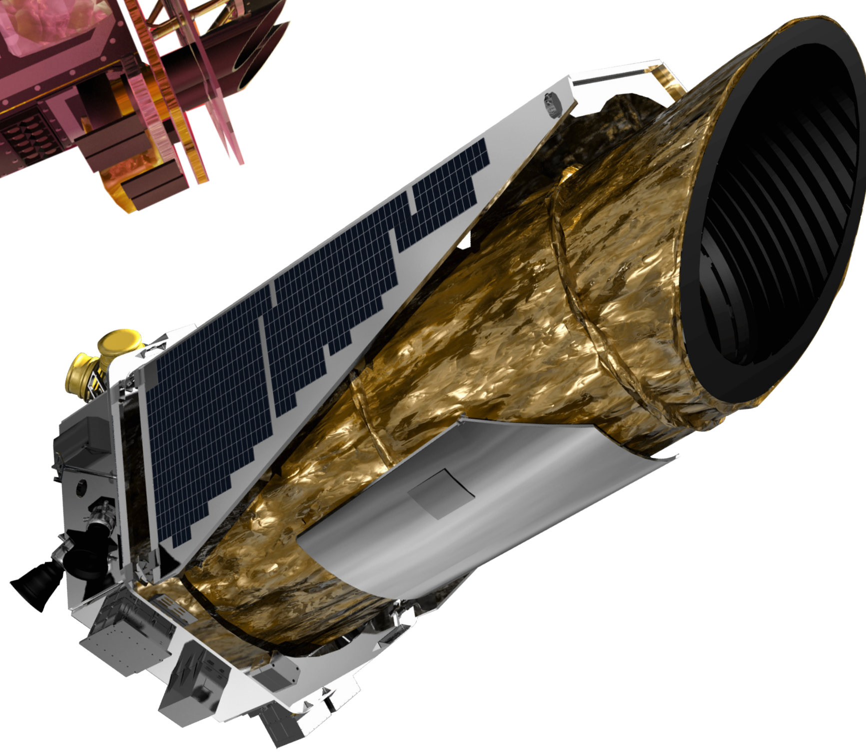
Transit timing survey

Spitzer: **188**

1 star:
$0.09 M_\odot$,
$0.12\ R_\odot$
2570 K
12 pc



7 planets:
1.5-19 days
0.75-1.1 $R_\oplus$
0.3-1.4 $M_\oplus$
0.1-4 $S_\oplus$

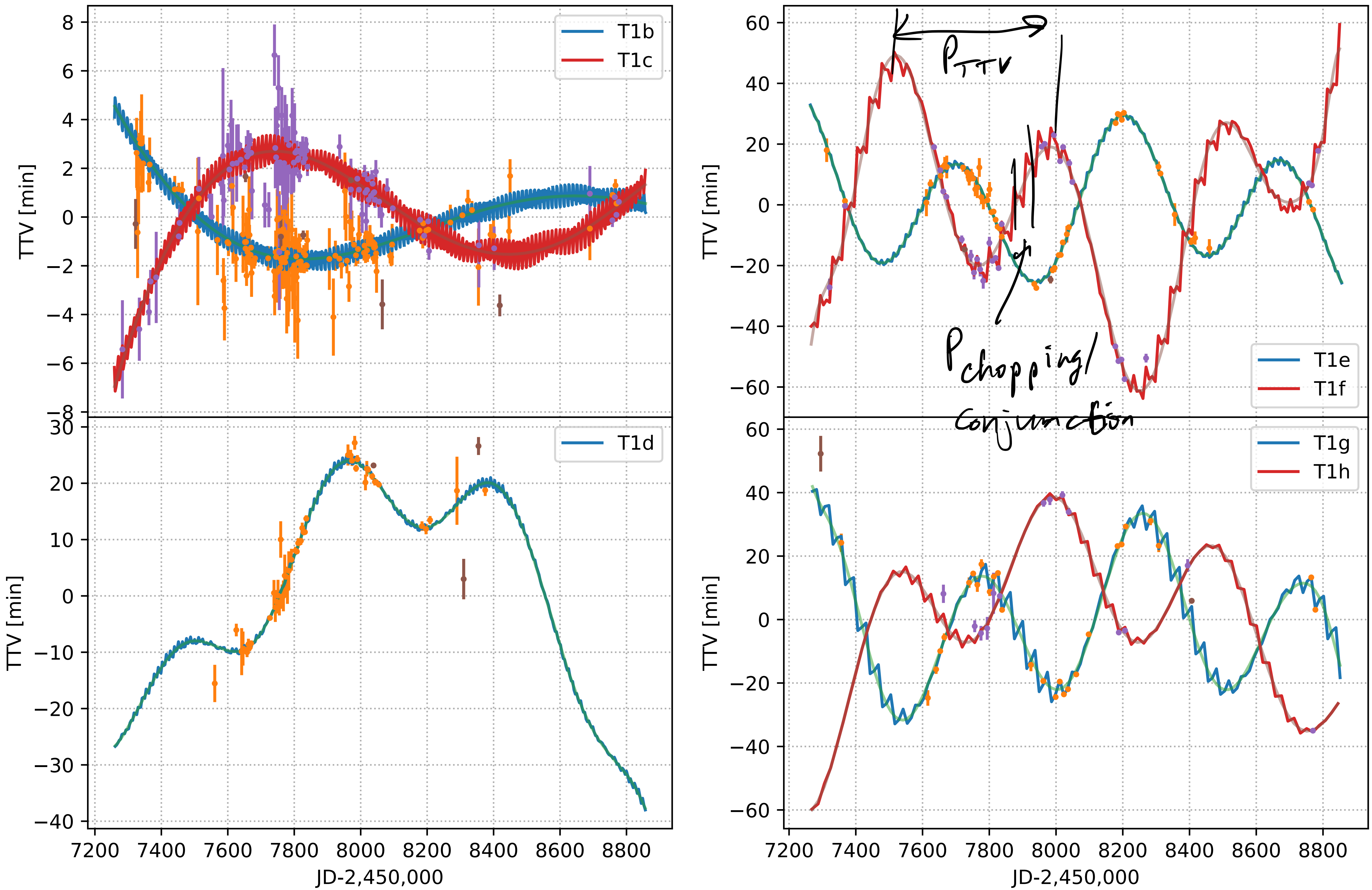


K2: **126**

SPECULOOS,
TRAPPIST-N/S: **125**

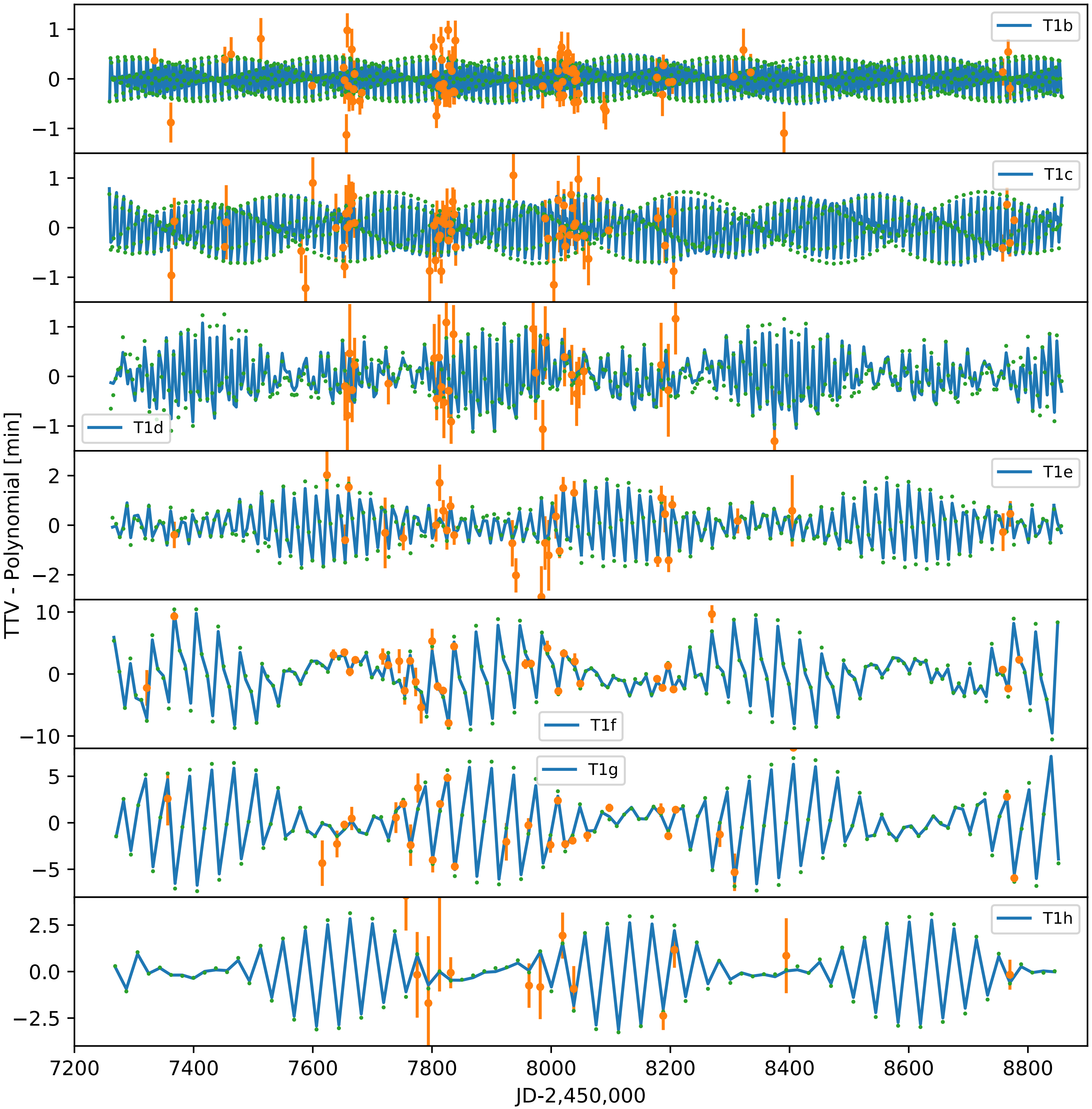
+Other: **69**
-**61** duplicates
= **447** transits

Final Spitzer TTV analysis

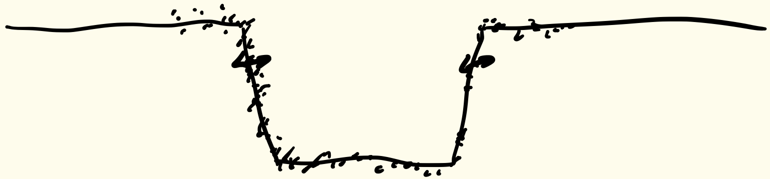


- Times through Oct 2019.
- Plane-parallel analysis

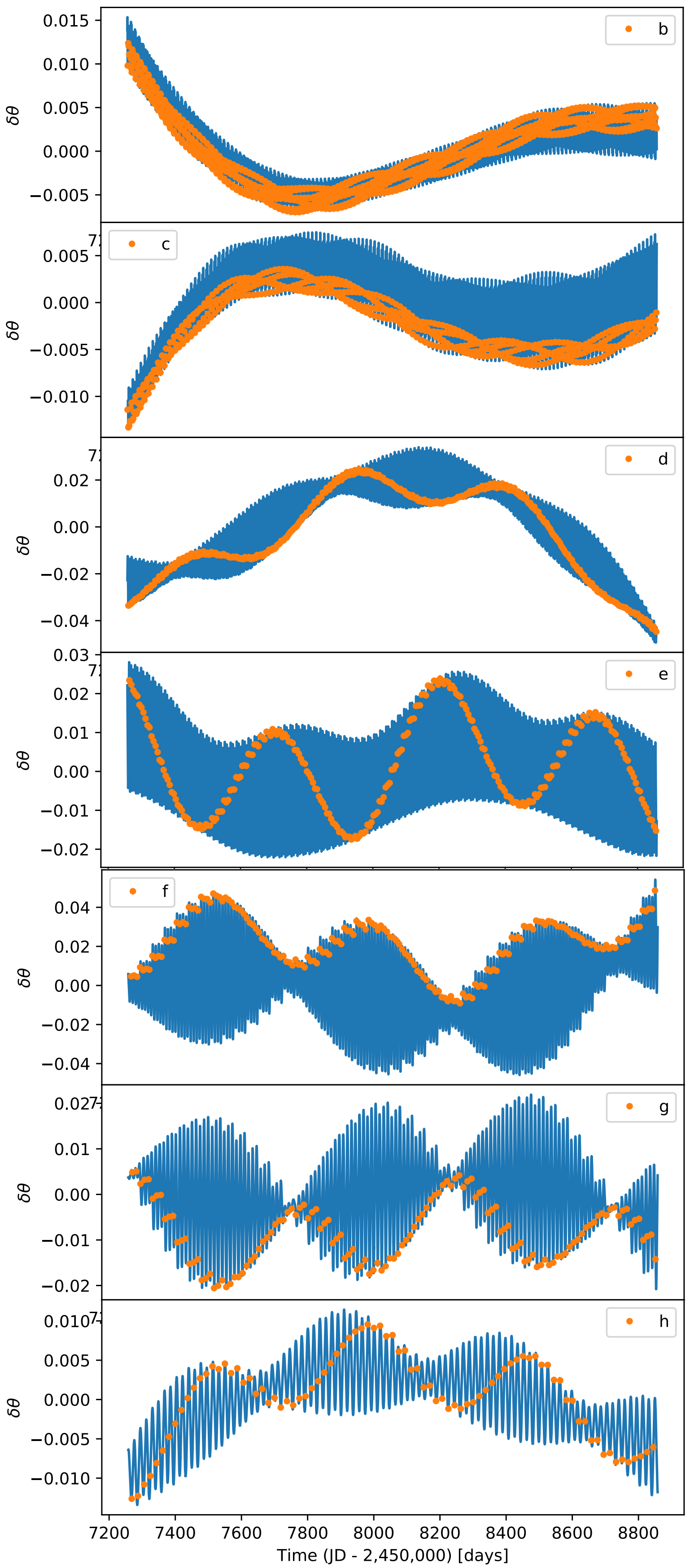
“Chopping” TTV: sensitive to mass-ratios

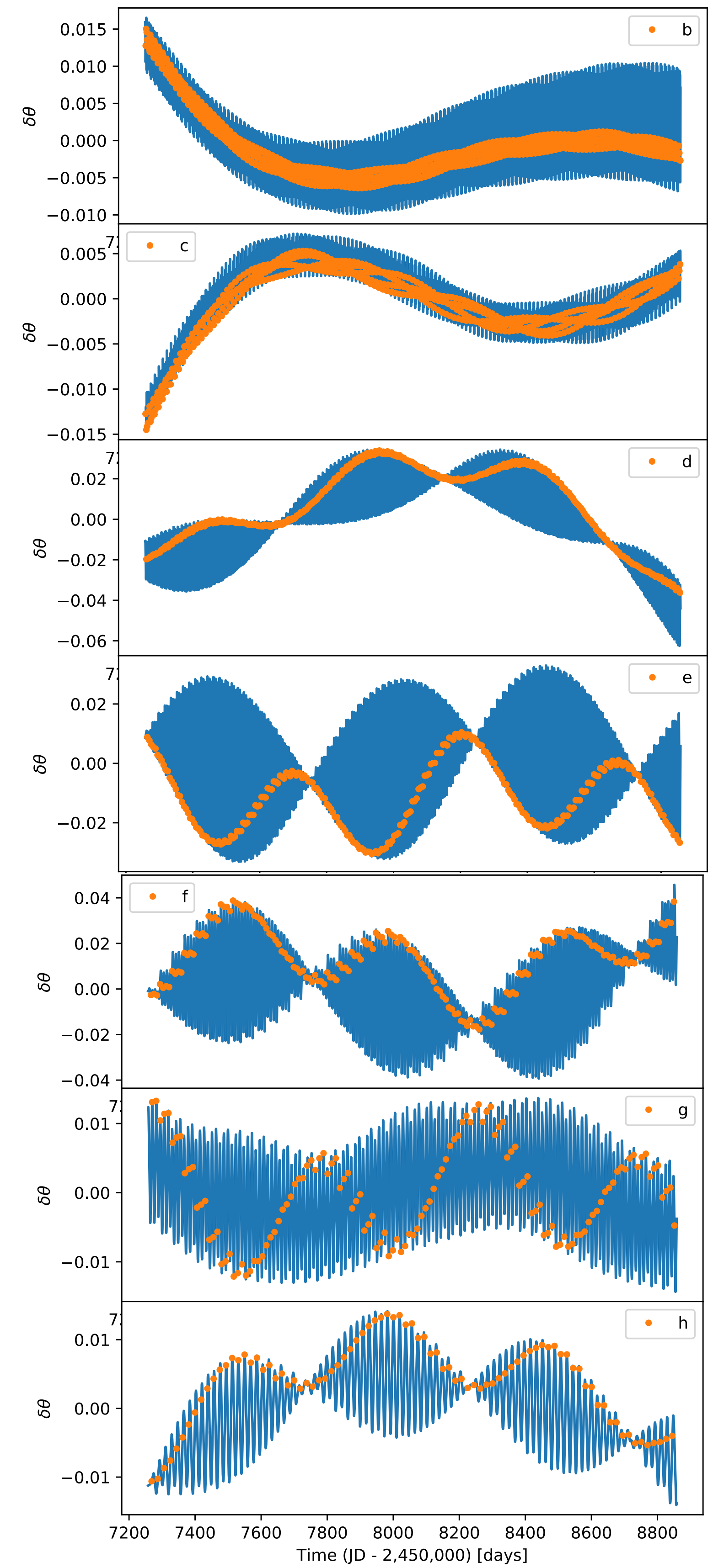


Blue lines: TTV model with polynomial removed
Orange error bars: data.
Green dots: analytic chopping model



Aliasing

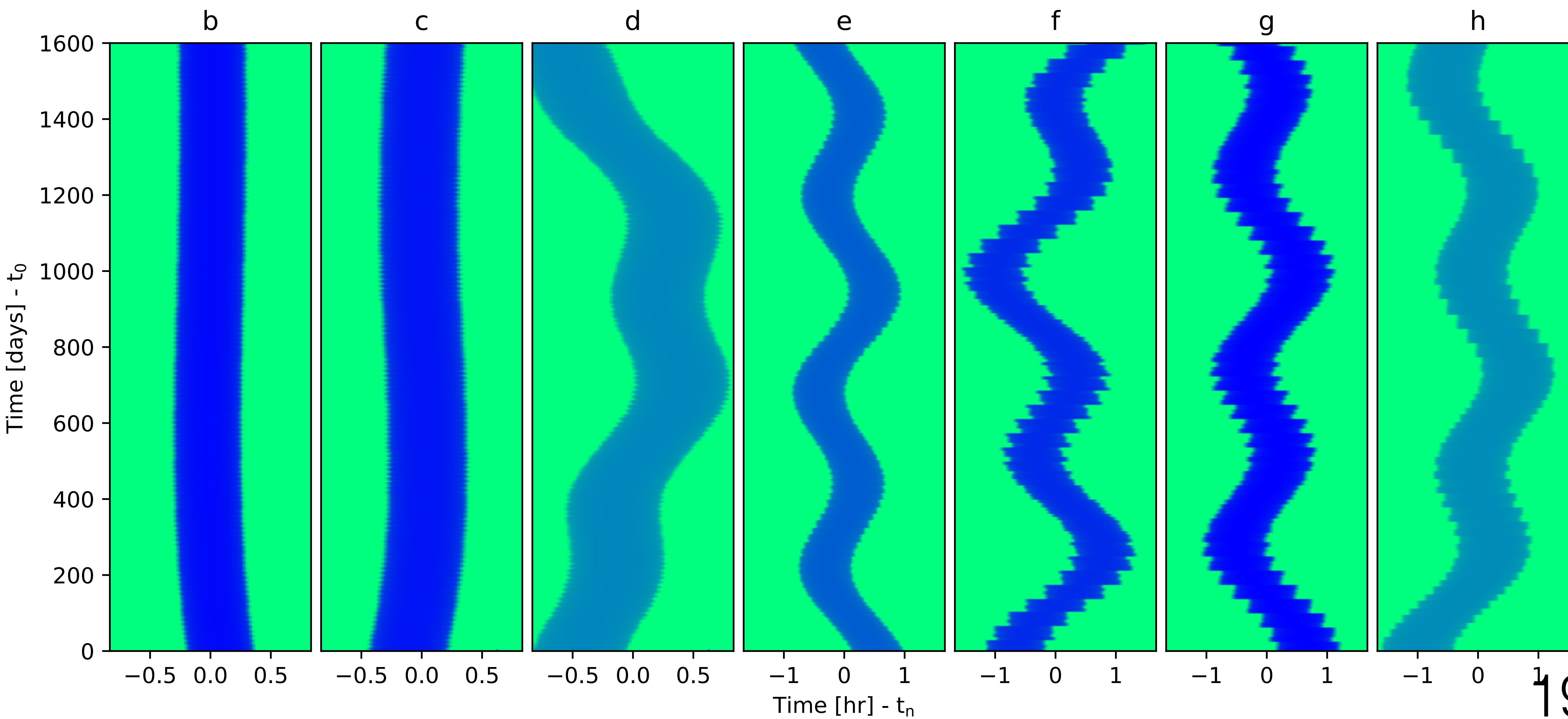

b
c
d
e
f
g
h
δθ
Time (JD - 2,450,000) [days]


b
c
d
e
f
g
h
δθ
Time (JD - 2,450,000) [days]

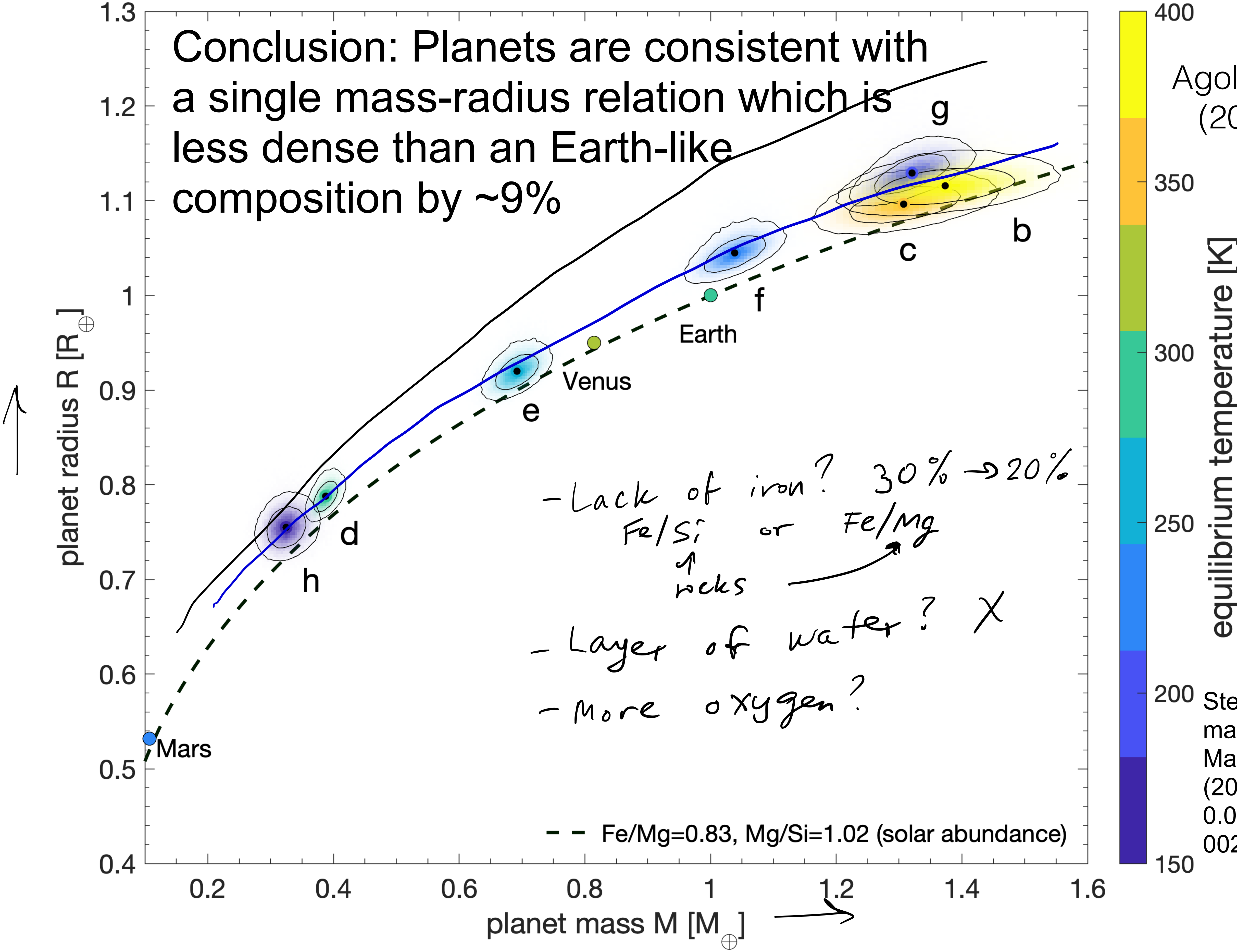
Photodynamic model

$E = -\frac{GM_*}{2a_1} - \frac{GM}{2a_2}$

- Varied the stellar density, limb-darkening parameters, impact parameters, and radius-ratios.
- Held fixed the dynamical parameters at best-fit model.



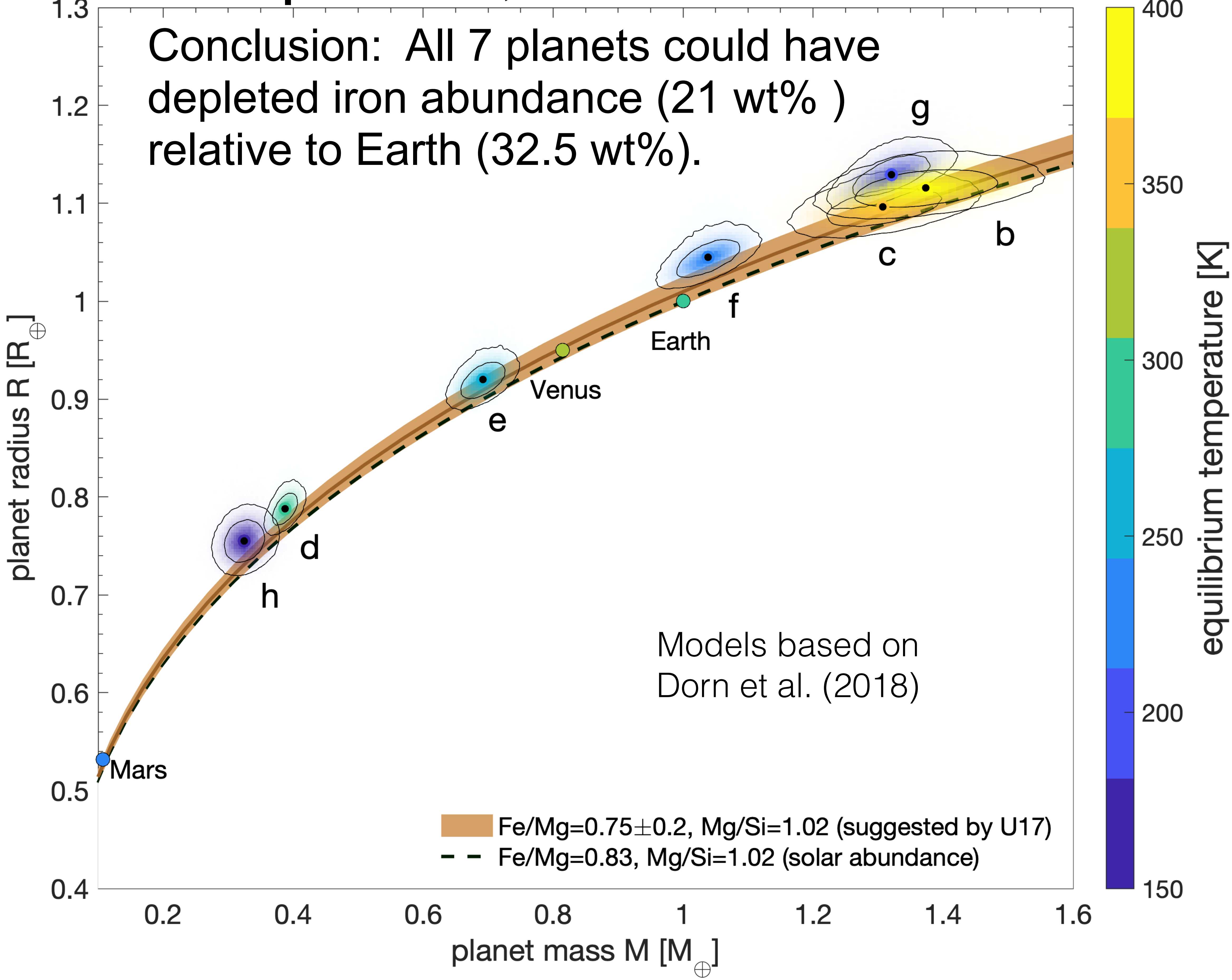
New mass-radius relation



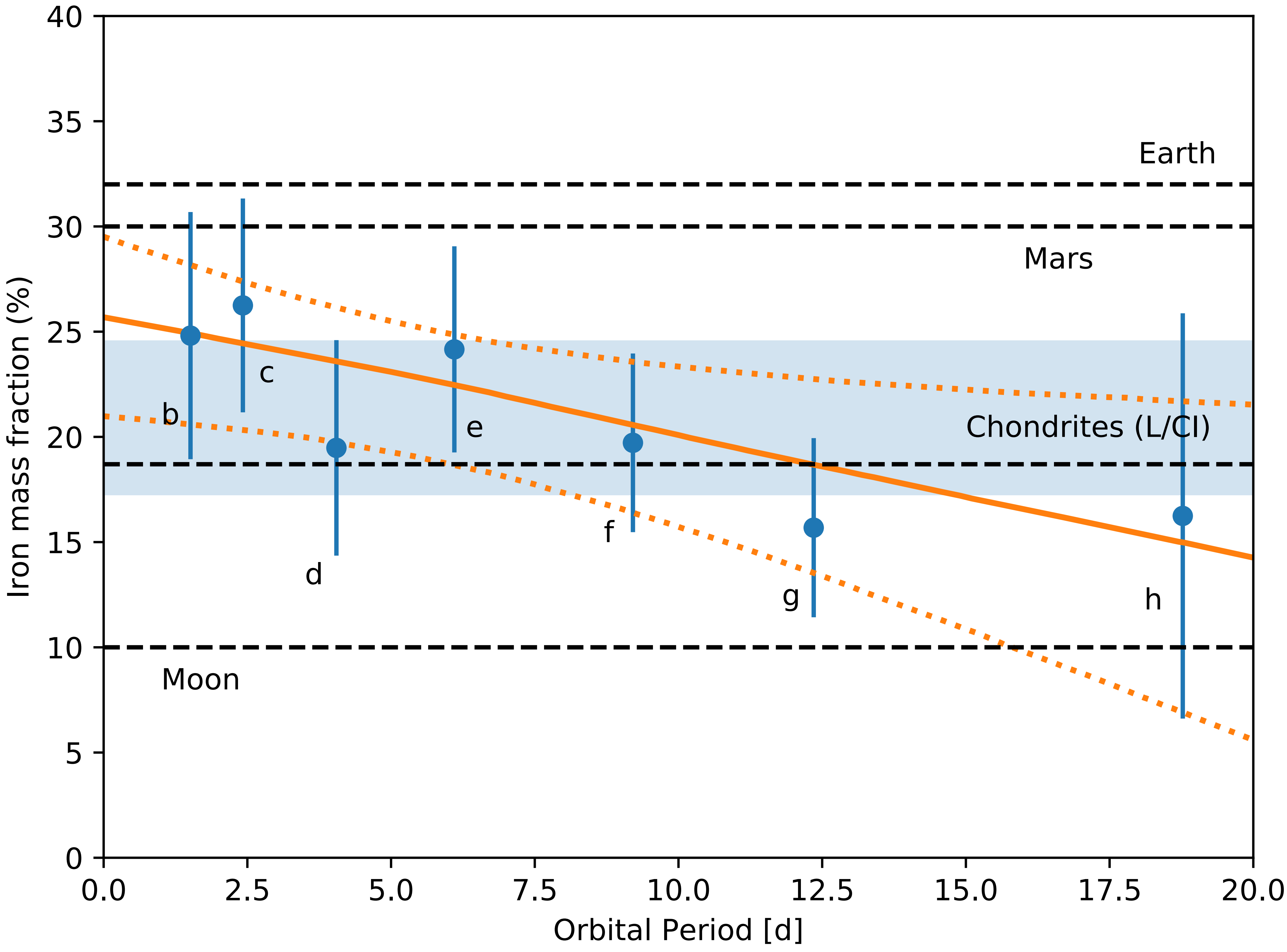
Agol et al. (2020)

Stellar mass from Mann et al. (2018): 0.0898±0.0023 M☉

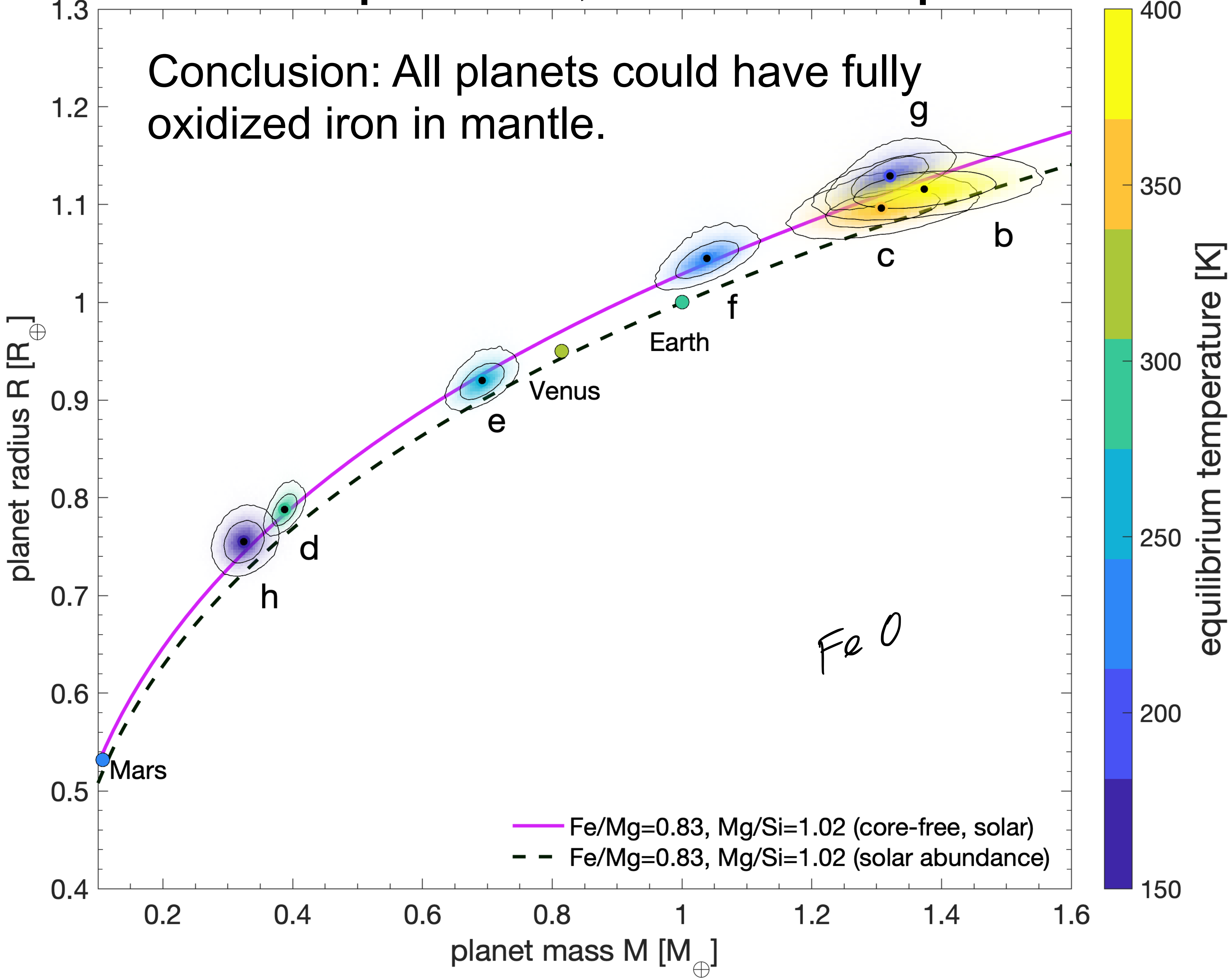
Cored planets, variable iron content



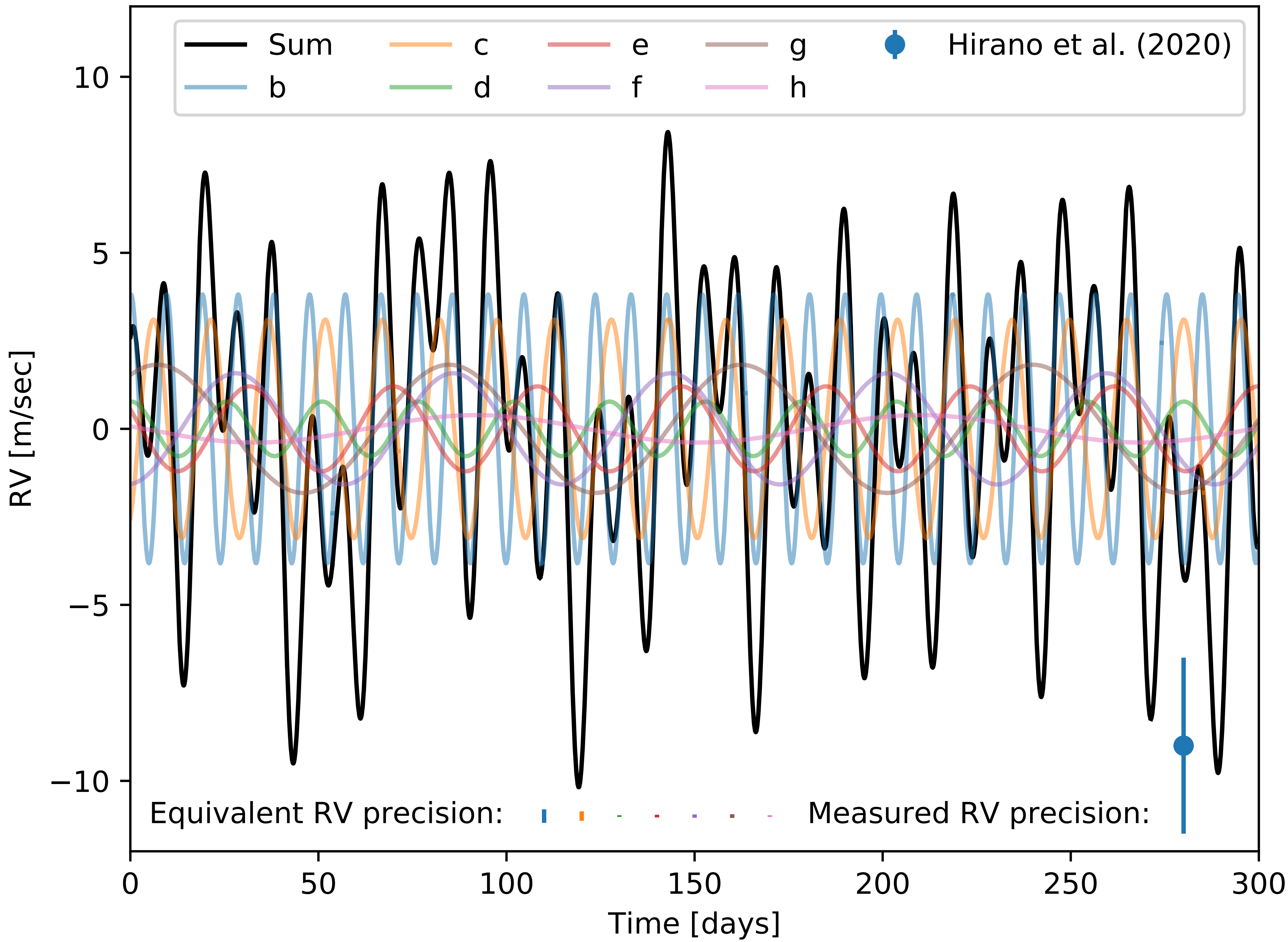
Iron mass fraction versus orbital period



Coreless planets, Solar composition

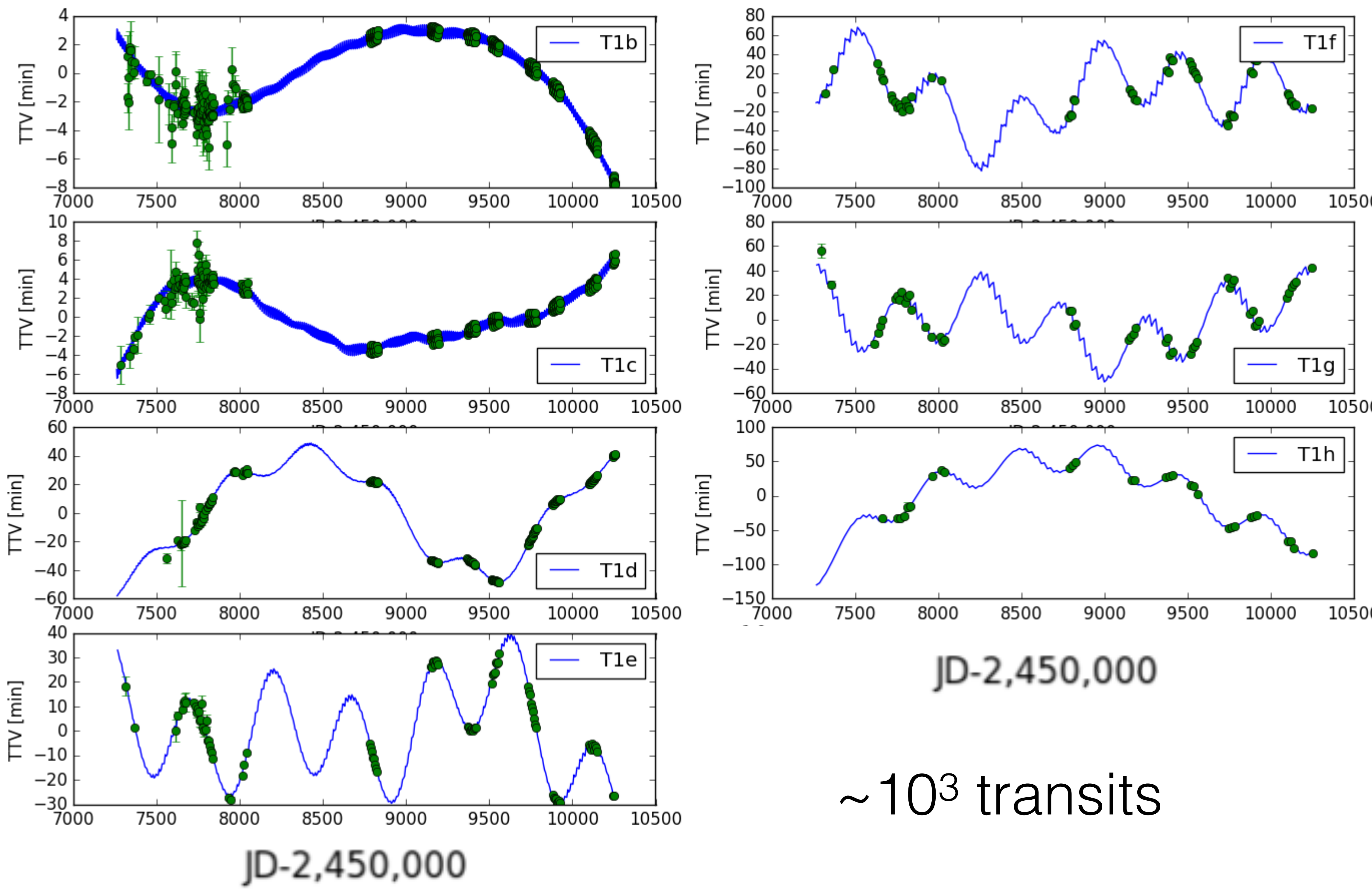


Radial velocity comparison



Simulate “pirated” JWST

~second timing precision → part-per-thousand mass ratios



~10^3 transits

Next time:

Astrometry & direct imaging

Reading:

"Direct Imaging of Exoplanets" Traub & Oppenheimer;

"Astrometric Detection and Characterization of Exoplanets" Quirrenbach