
Taking the Dynamical Temperatures of Planetary Systems

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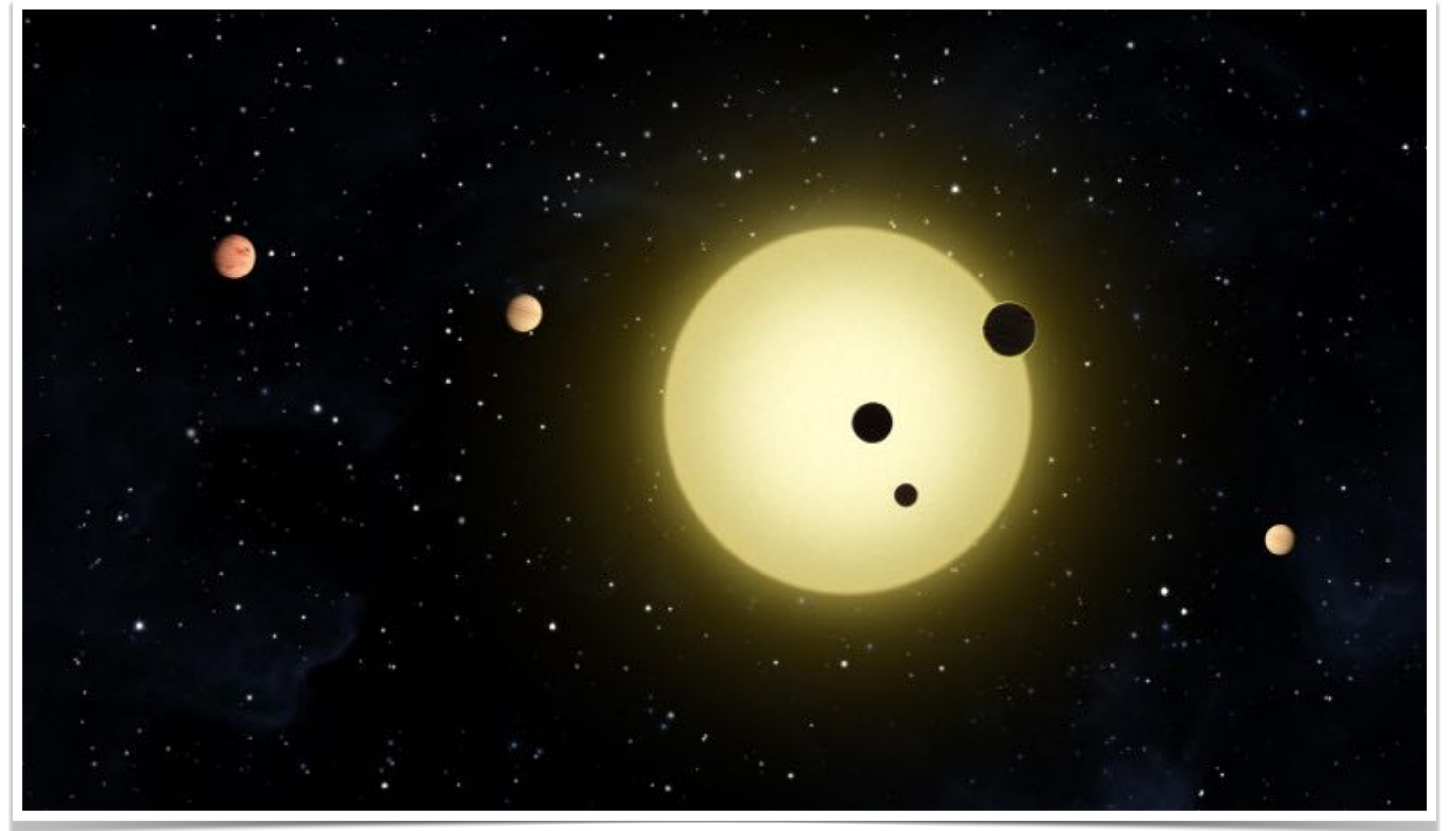
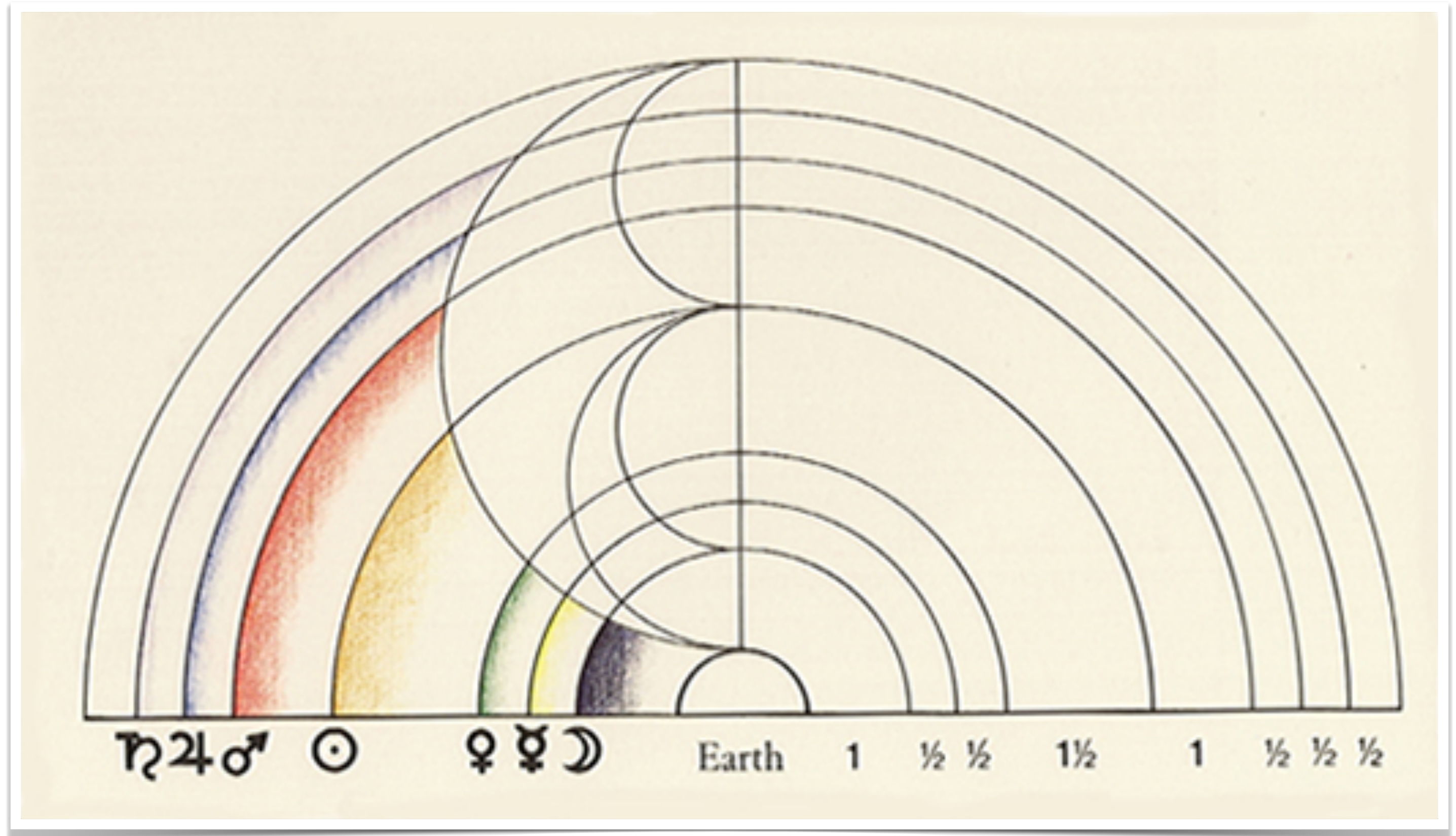


Image Credit: NASA

Harmony of the Worlds



Wikipedia

Harmony of the Worlds



HARMONICIS LIB. V. 207

omnia (infinita in potentiâ) permeantes actu : id quod aliter à me non potuit exprimi, quam per continuam seriem Notarum intermedia- CAP. VI

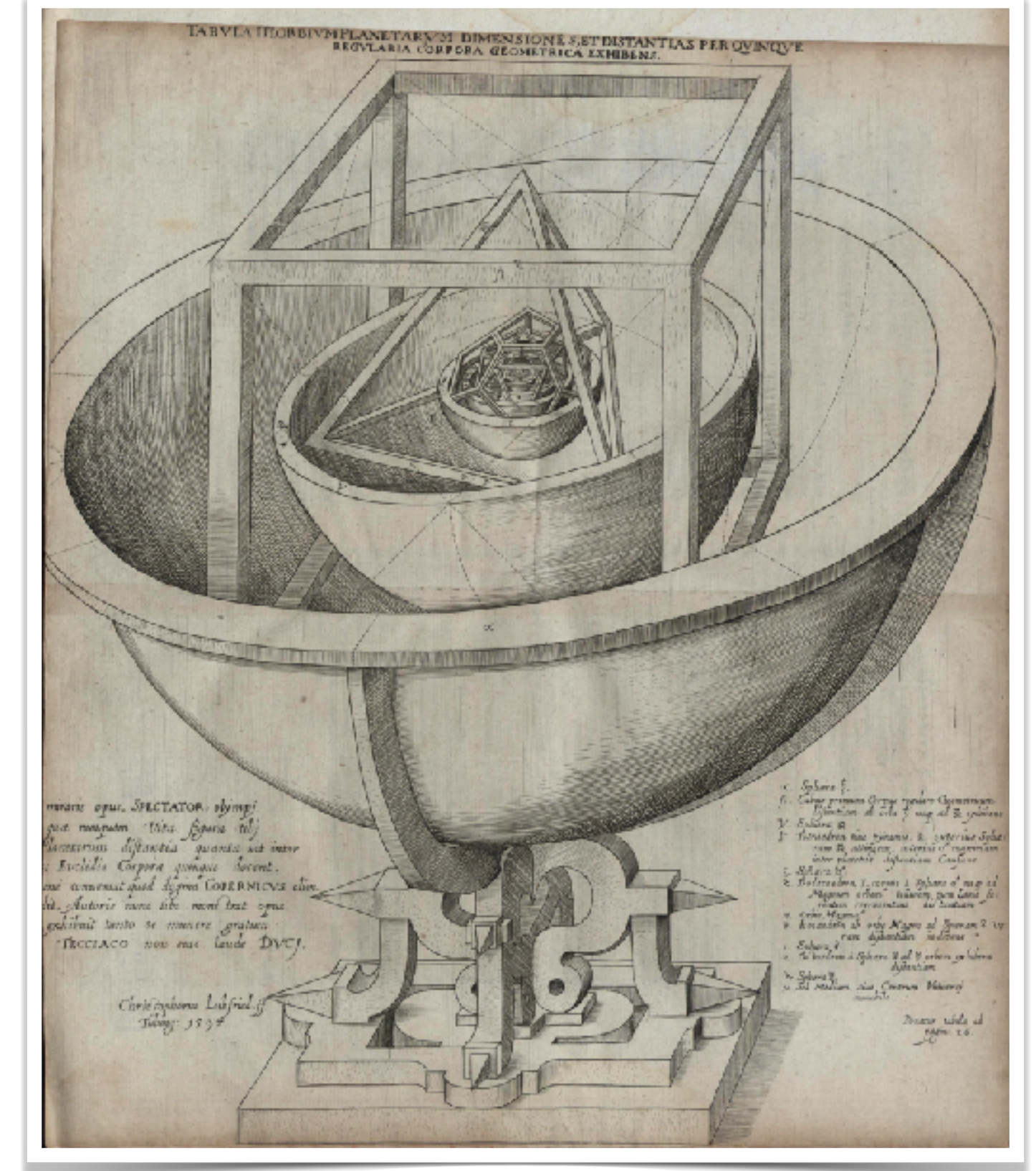
Saturnus Jupiter Mars ferè Terra

Venus Mercurius Hic locum habet etiam

rum. Venus ferè manet in unifono non æquans tensionis amplitudine vel minimum ex concinnis intervallis.

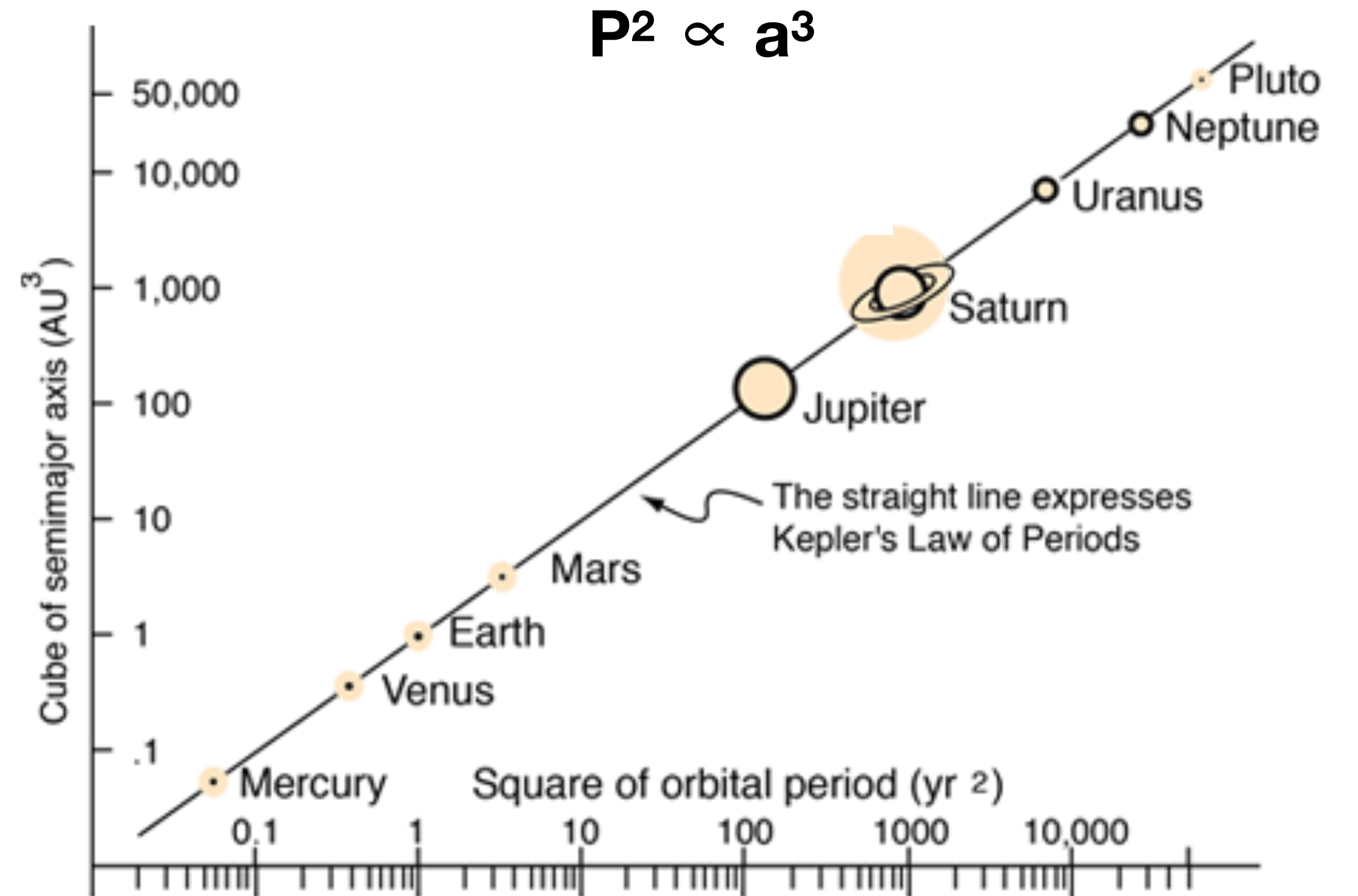
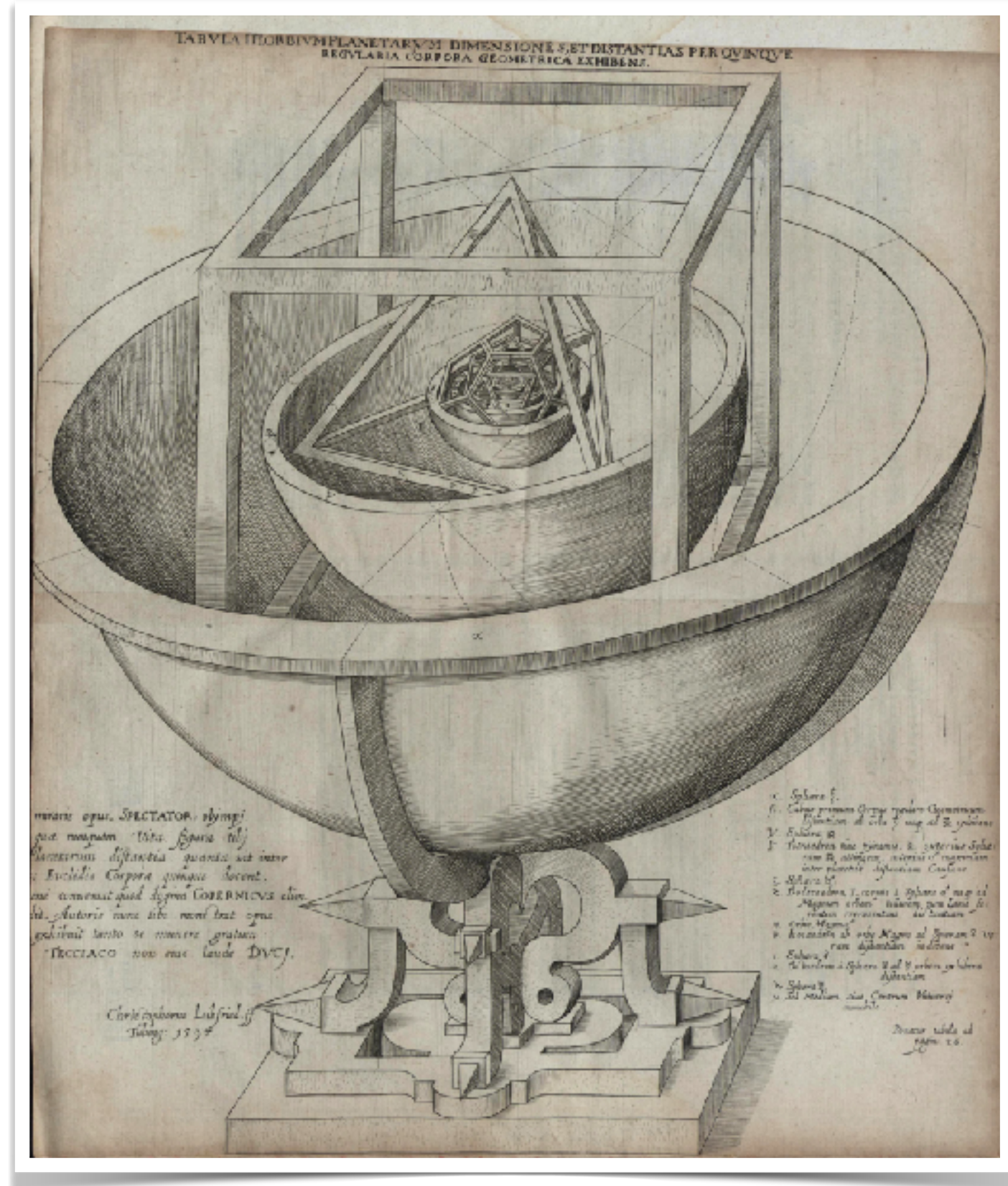
Atqui signatura duarum in communi Systemate Clavium, & formatio sceleti Octavæ, per comprehensionem certi intervalli concinni, est rudimentum quoddam distinctionis Tonorum seu Modorum: sunt ergò Modi Musici inter Planetas dispersiti. Scio equidem, ad formationem & definitionem distinctorum Modorum requiri plura, quæ cantus humani, quippe intervallati, sunt propria: itaque voce quodammodò sum usus.

Liberum autem erit Harmonistæ, sententiam de promere suam: quem quisque planeta Modum exprimat propiùs, extremis hîc ipsi assignatis. Ego Saturno darem ex usitatis Septimum vel Octavum, quia si radicalem ejus clavem ponas G, perihelium motus ascendit ad h: Jovi Primum vel Secundum; quia aphelio ejus motu ad G accommodato, perihelium ad b pervenit; Marti Quintum vel Sextum; non eò tantum, quia ferè Diapente afflequitur, quod intervallum commune est omnibus modis: sed id eò potissimum. quia redactus cum cæteris ad



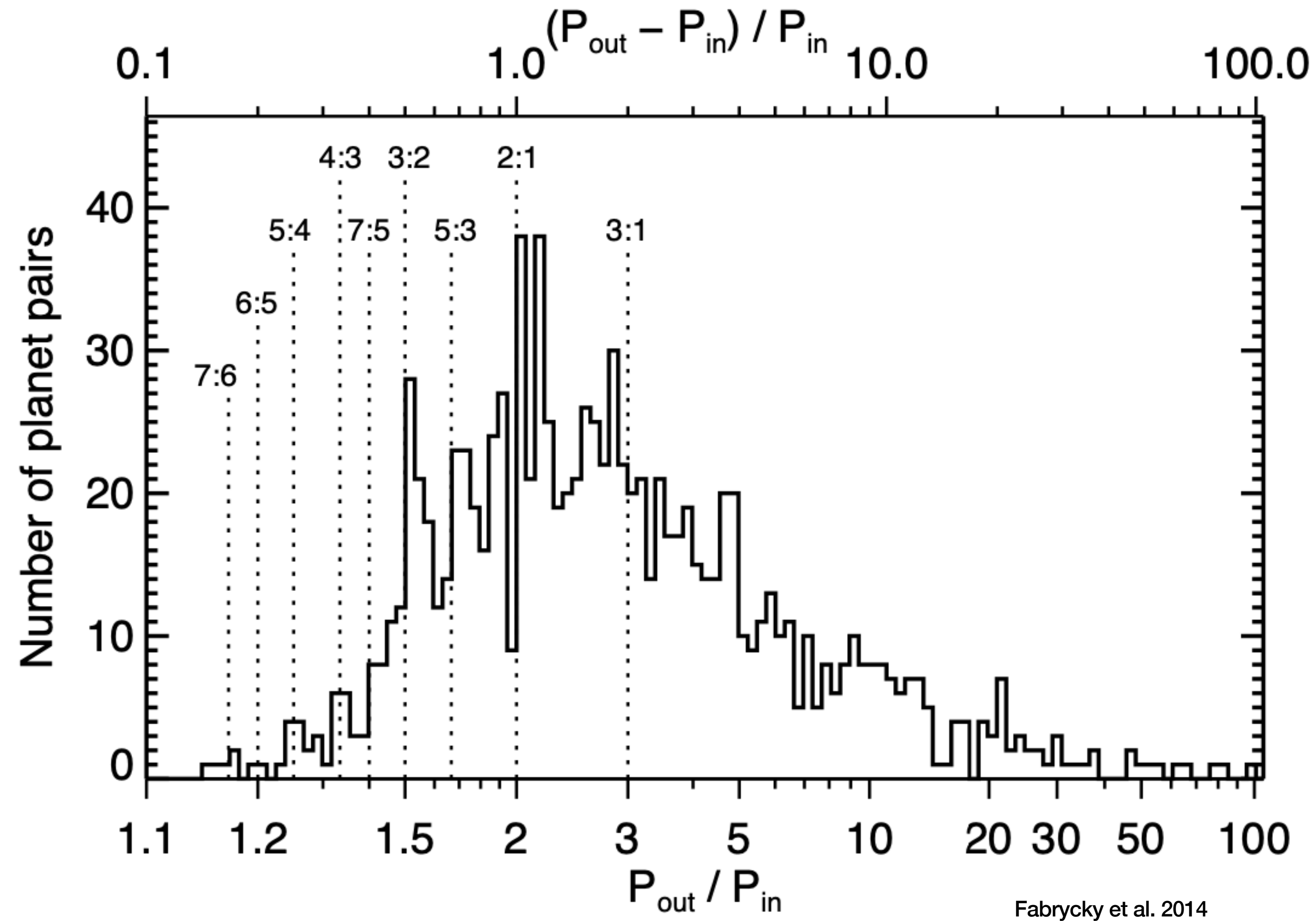
Wikipedia

Harmony of the Worlds



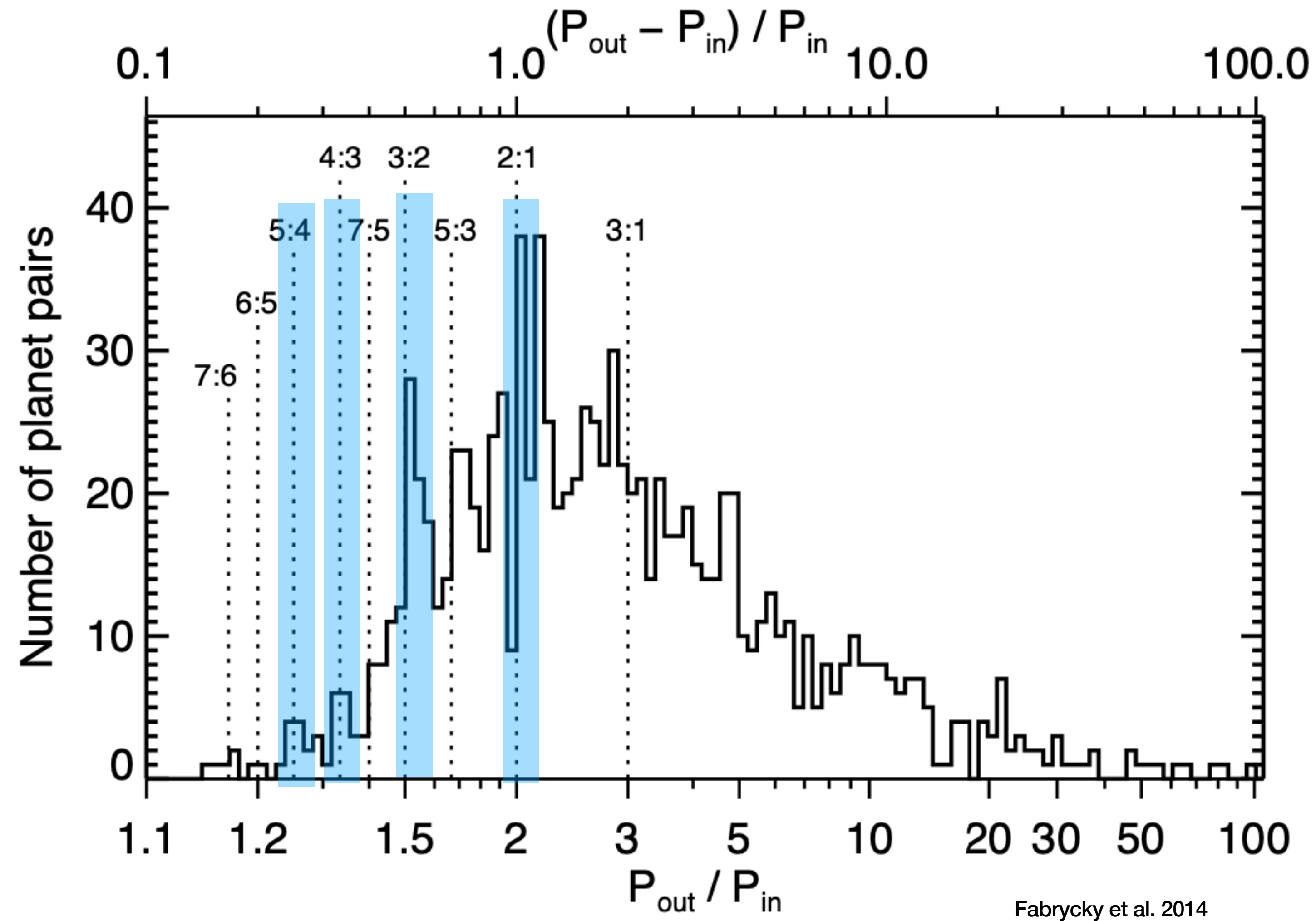
Wikipedia

Most Exoplanetary Systems are also Non-resonant



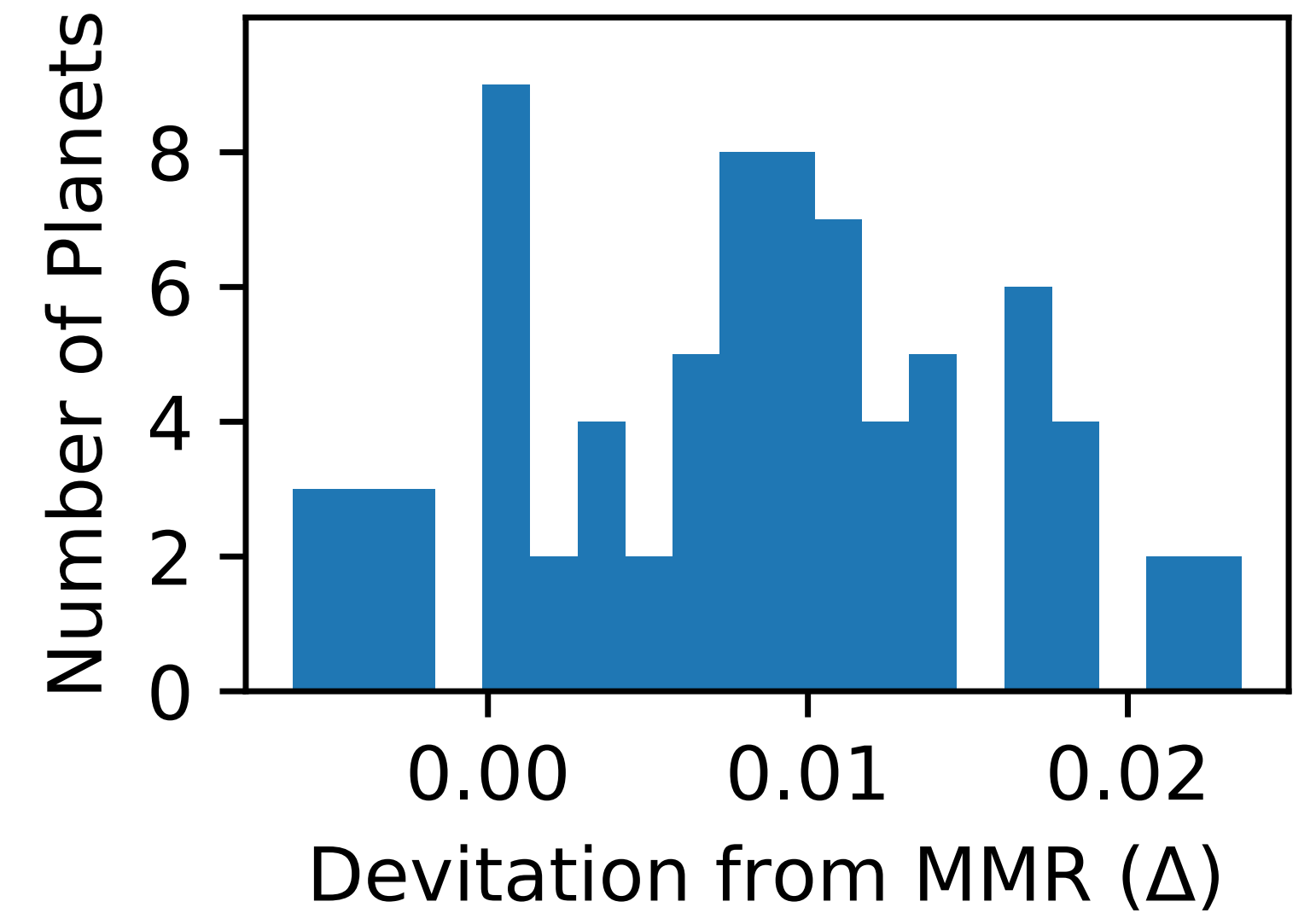
Fabrycky et al. 2014

Most Exoplanetary Systems are also Non-resonant

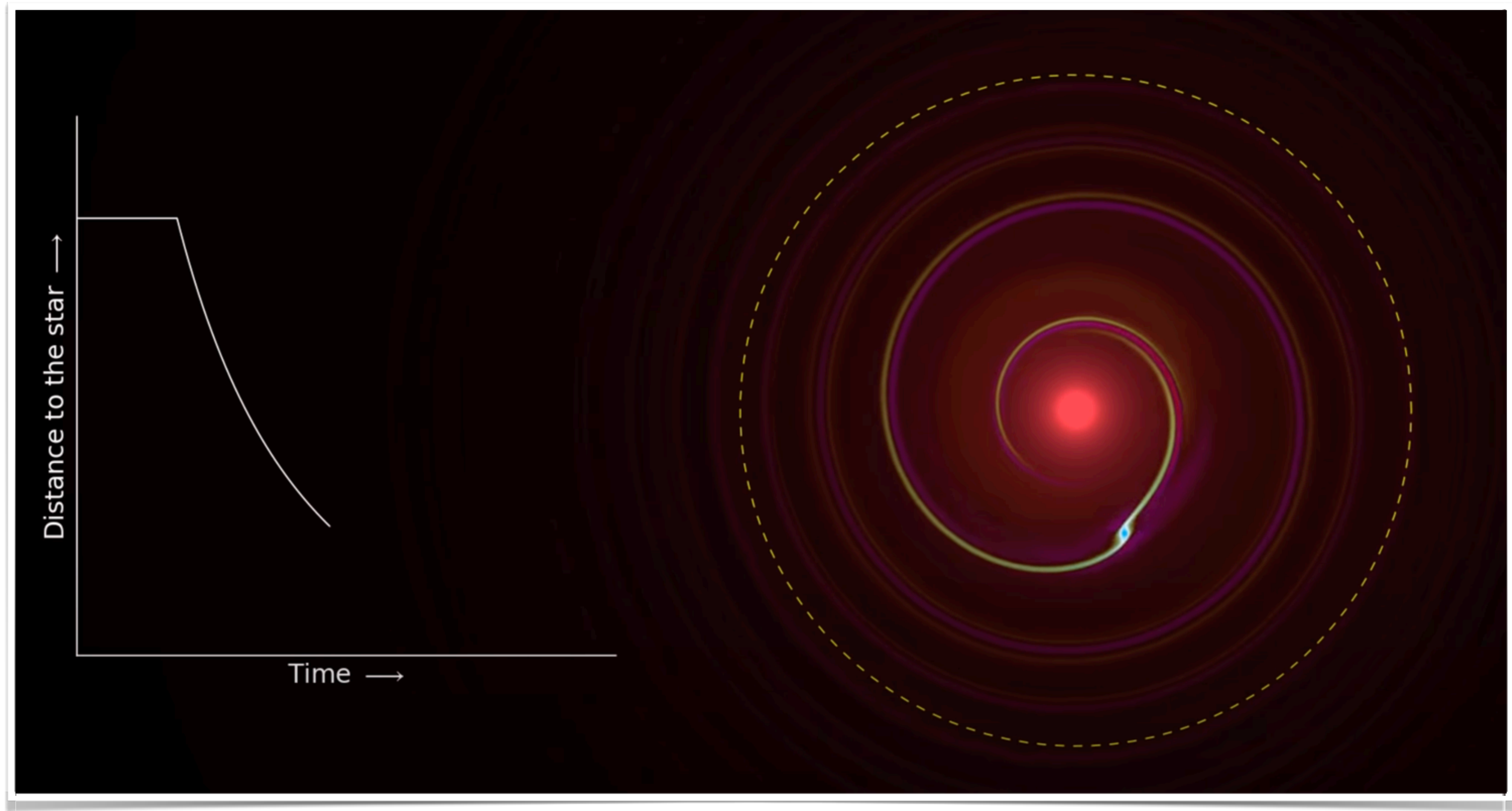


Fabrycky et al. 2014

$$\Delta \equiv \frac{P_{out}/P_{in}}{p/q} - 1$$



Planets Migrate in Disks



FARGO3D Benitez-Llambay

Planet Migration Readily Generates a Resonant Chains

Migration model

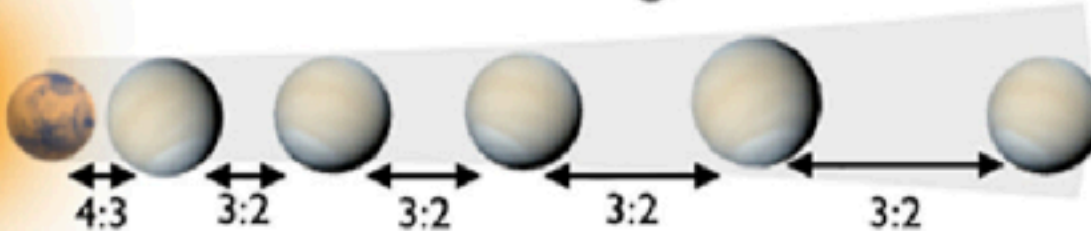
1. Planetary embryos grow in a gaseous planet-forming disk



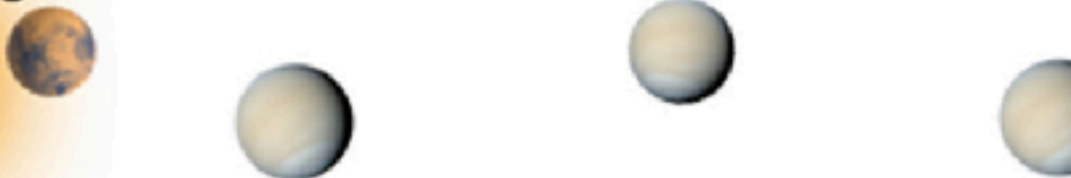
2. Ice-rich embryos migrate inward through rocky zone



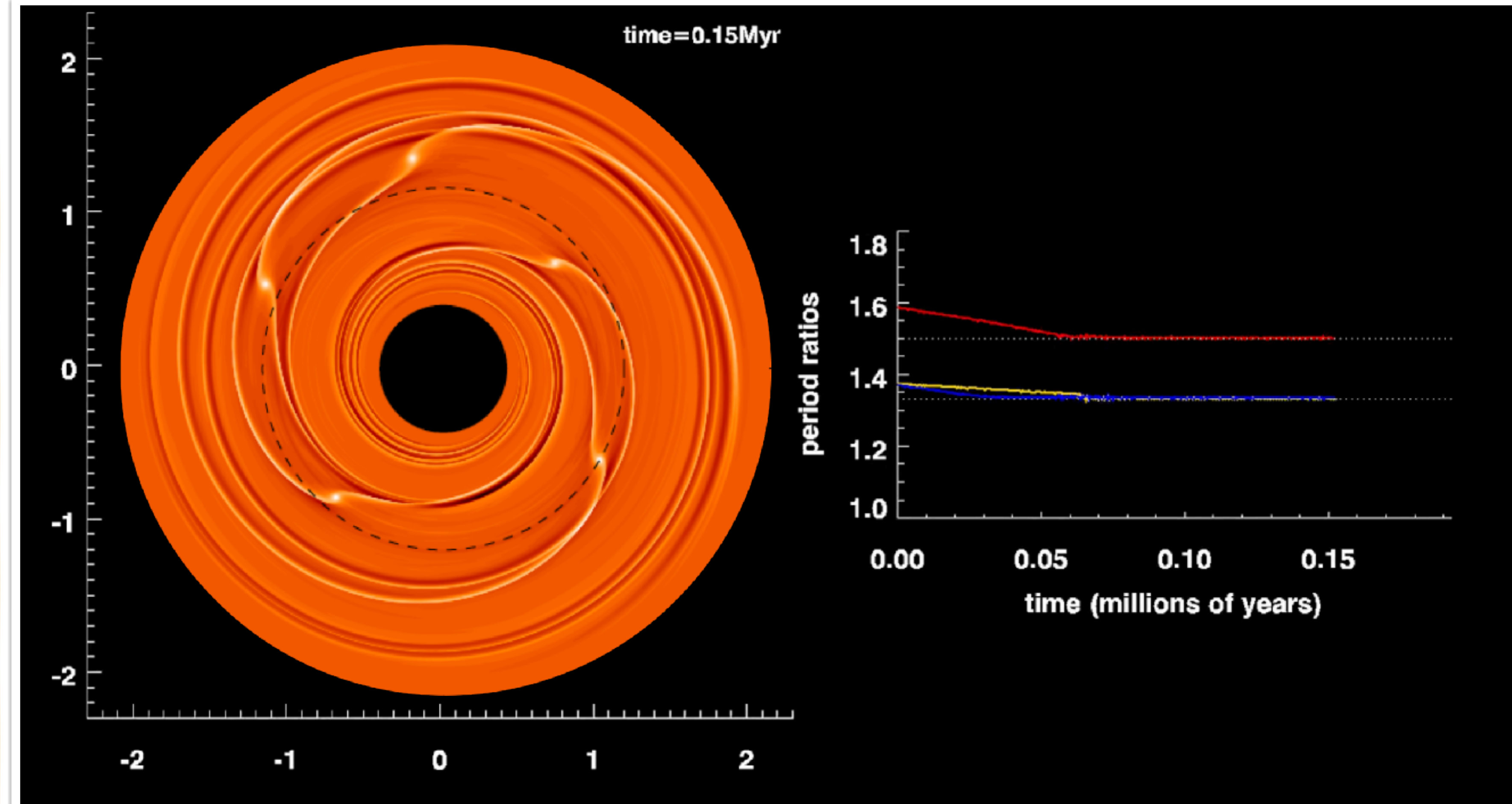
3. Planets form in orbital resonances* with their neighbors



4. After gas disk dissipates, most systems go unstable and resonances are broken



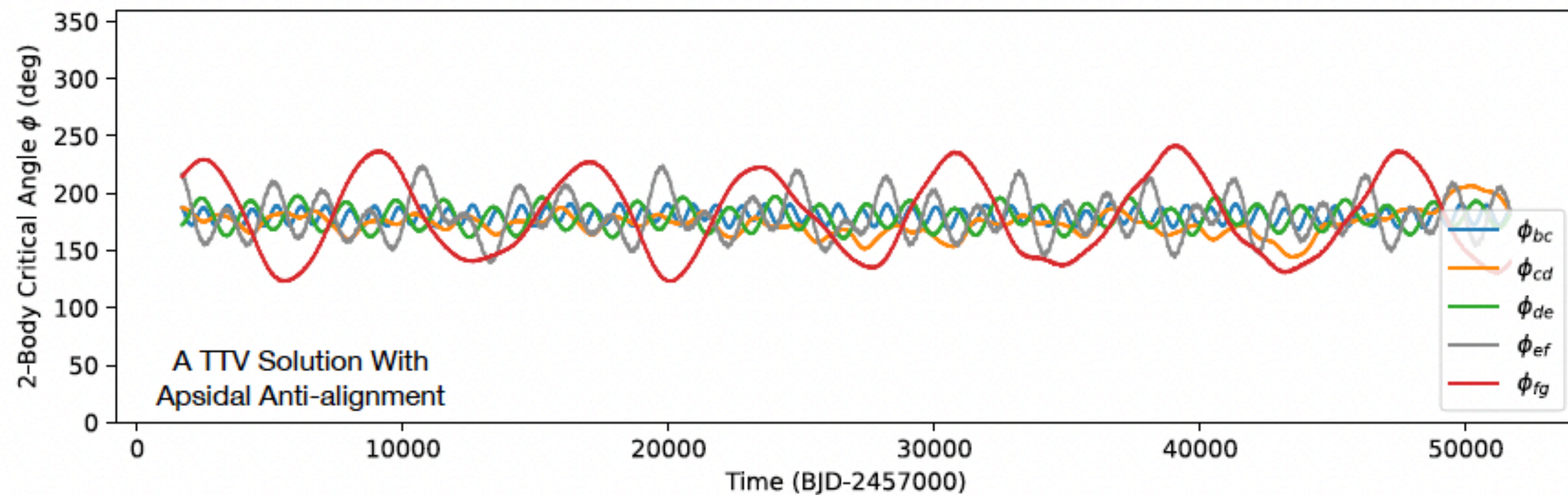
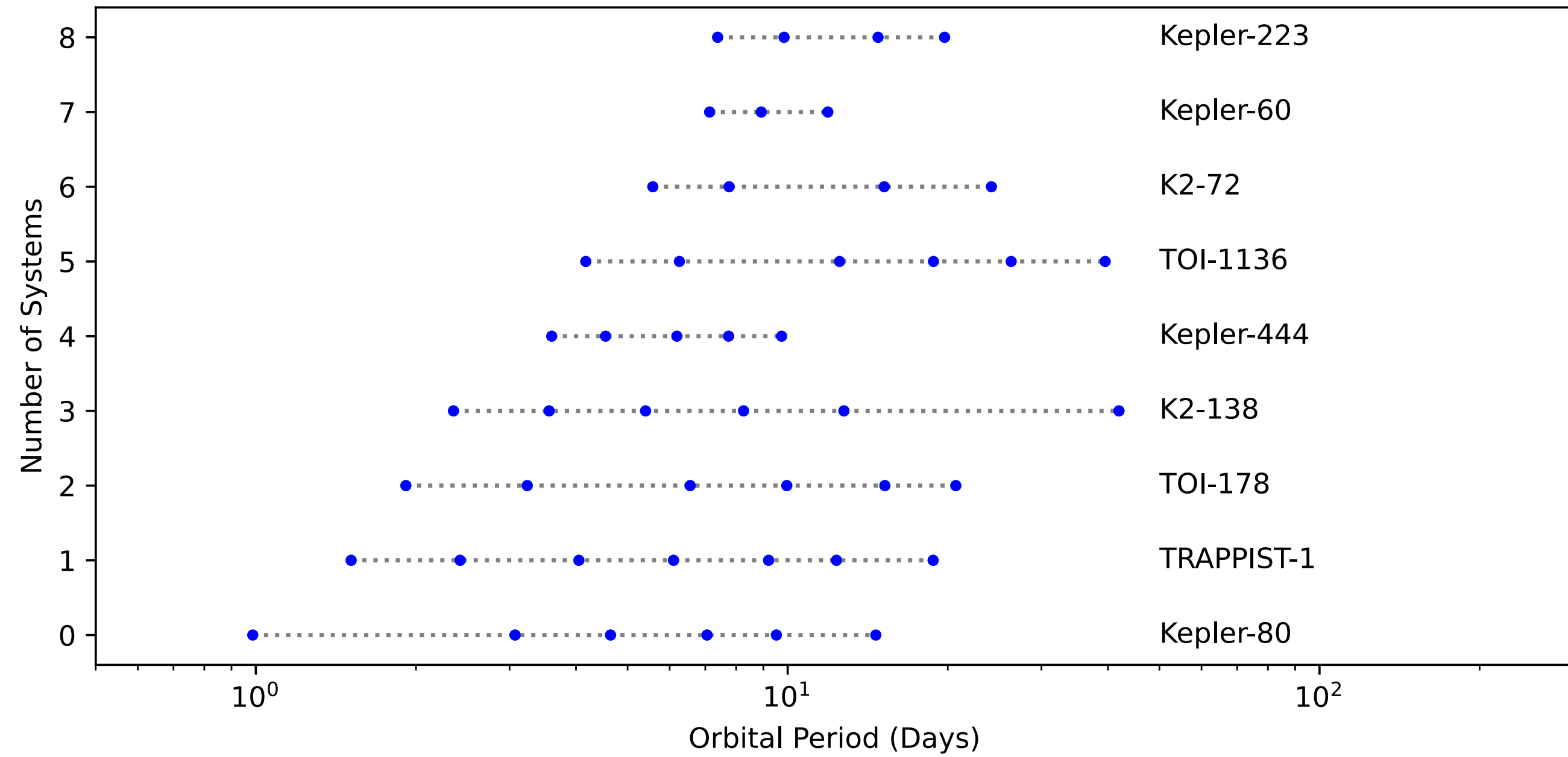
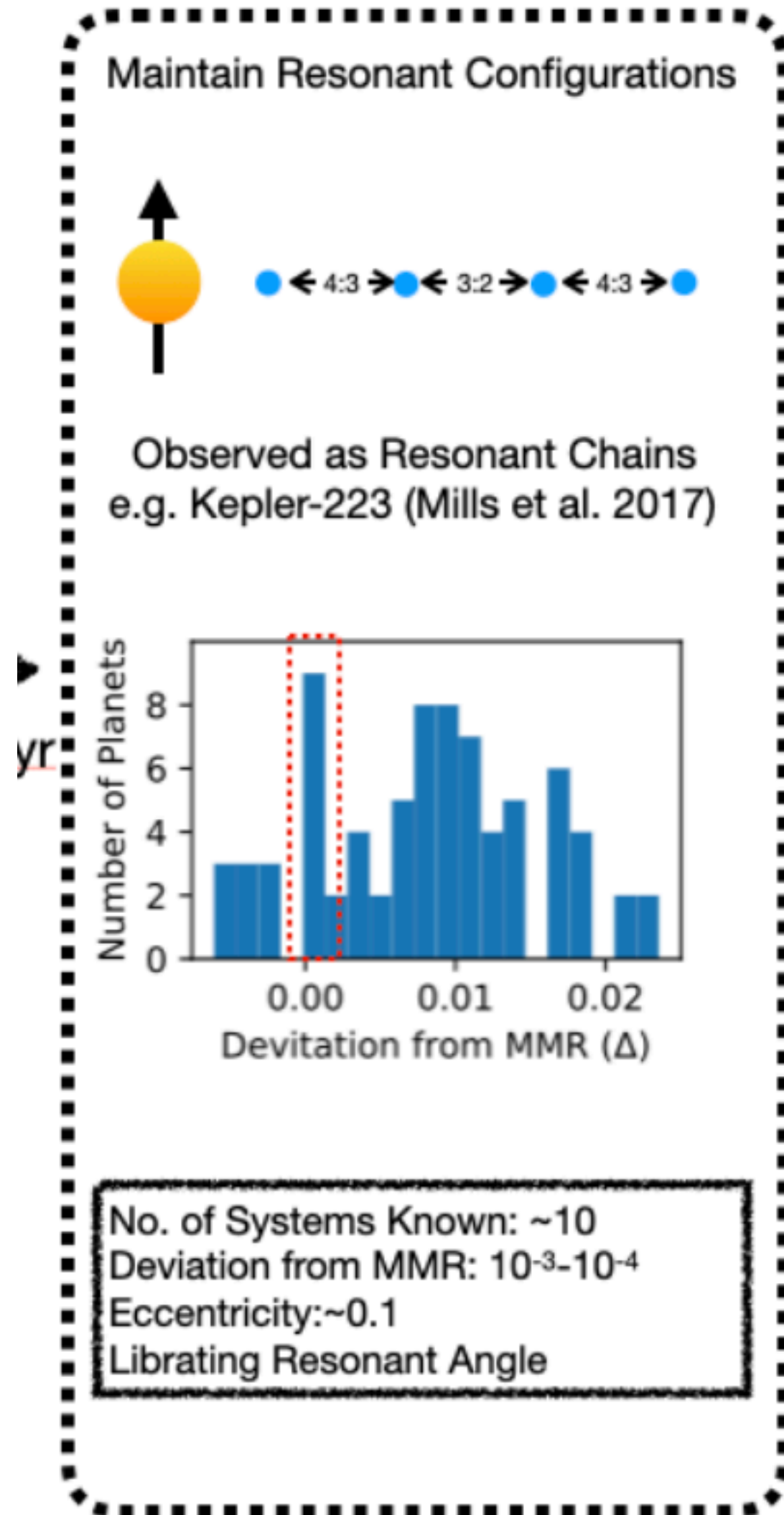
Time



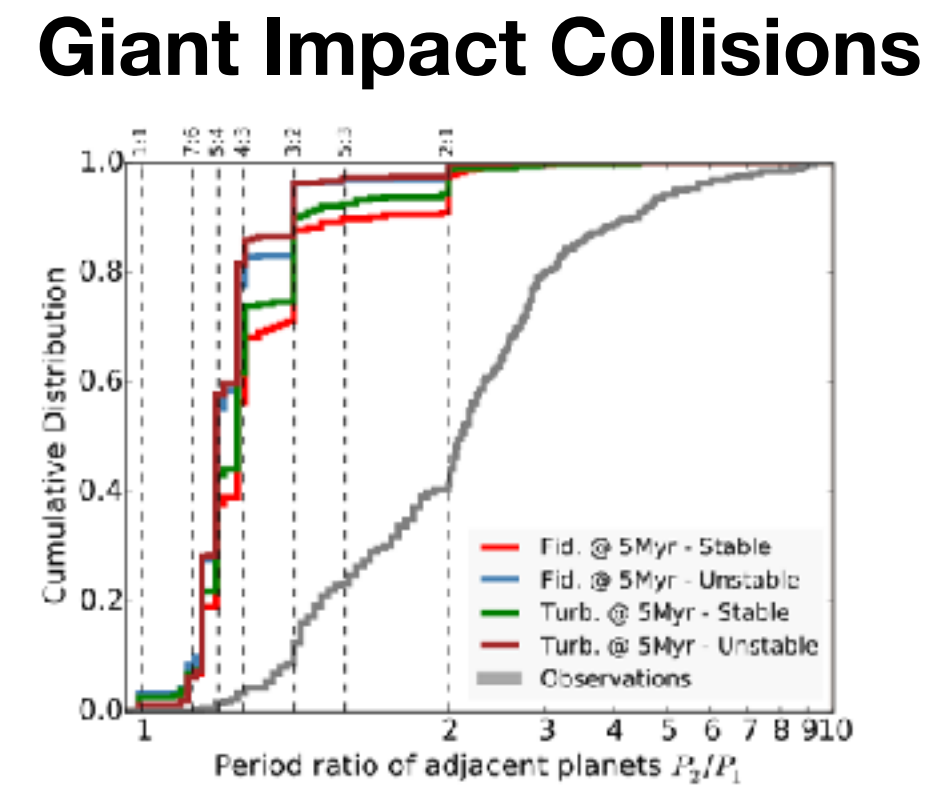
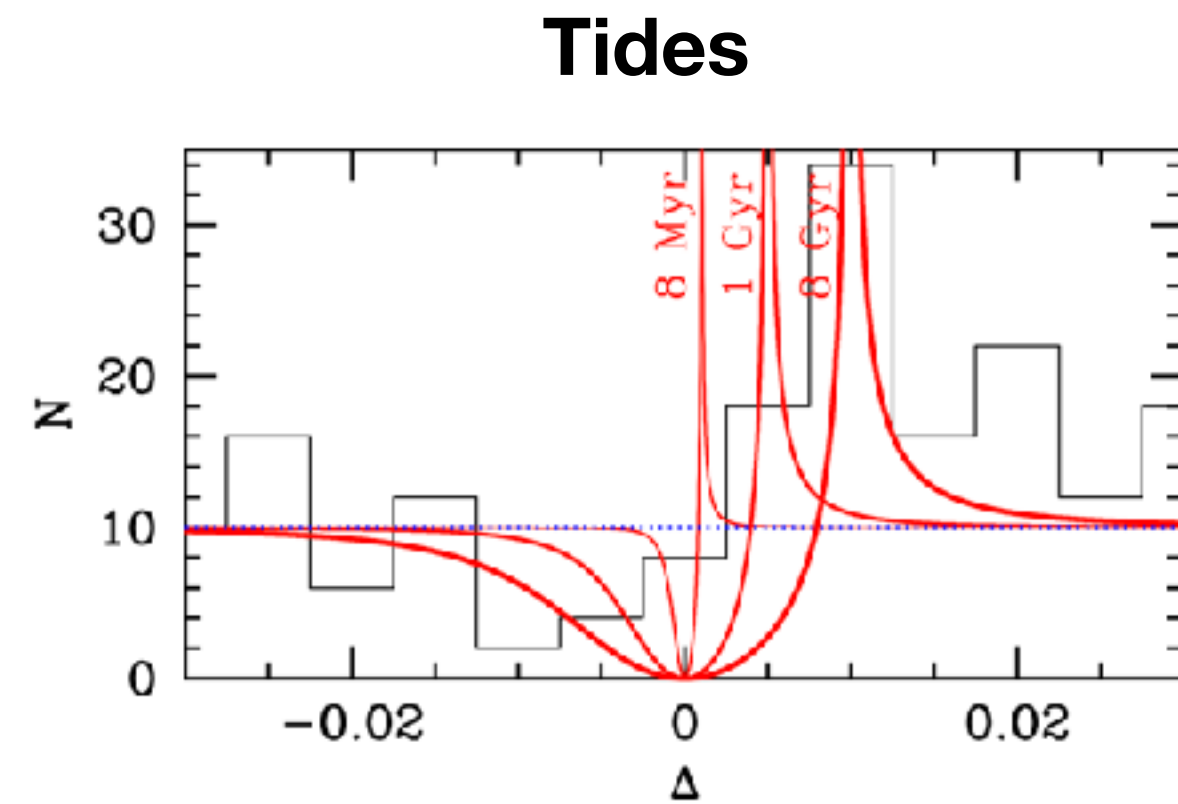
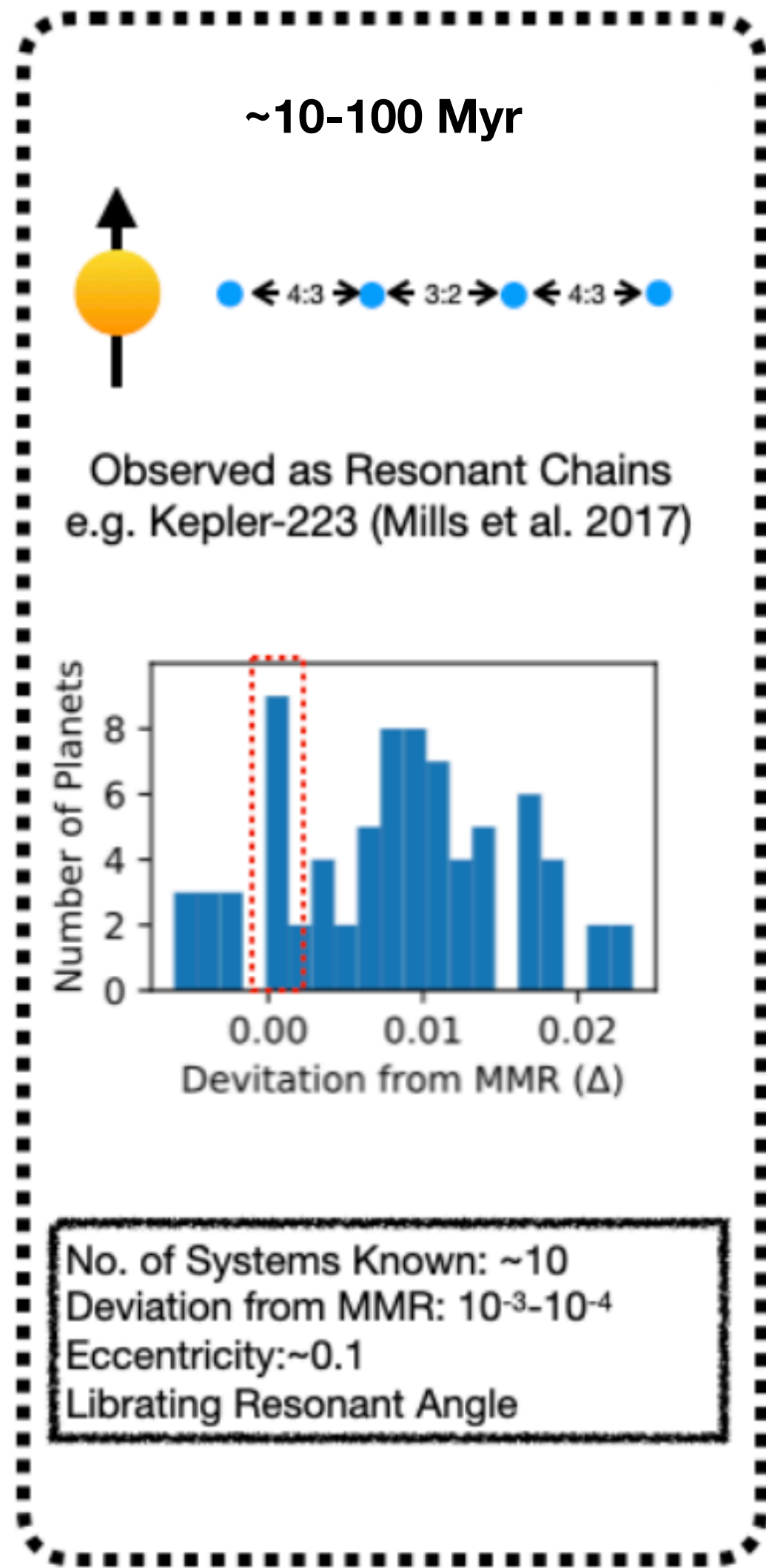
Bean et al. 2020

Mills et al. 2017

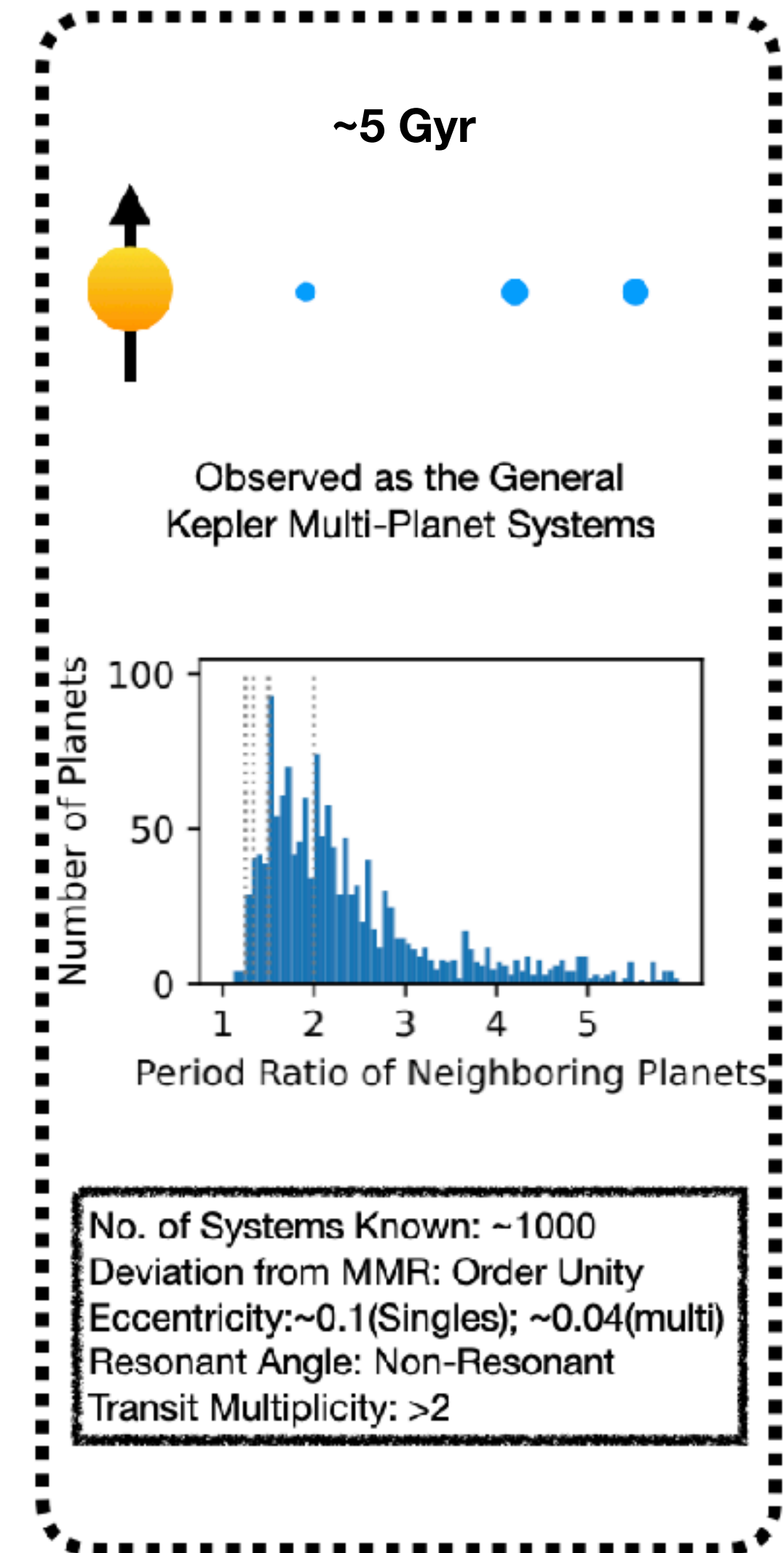
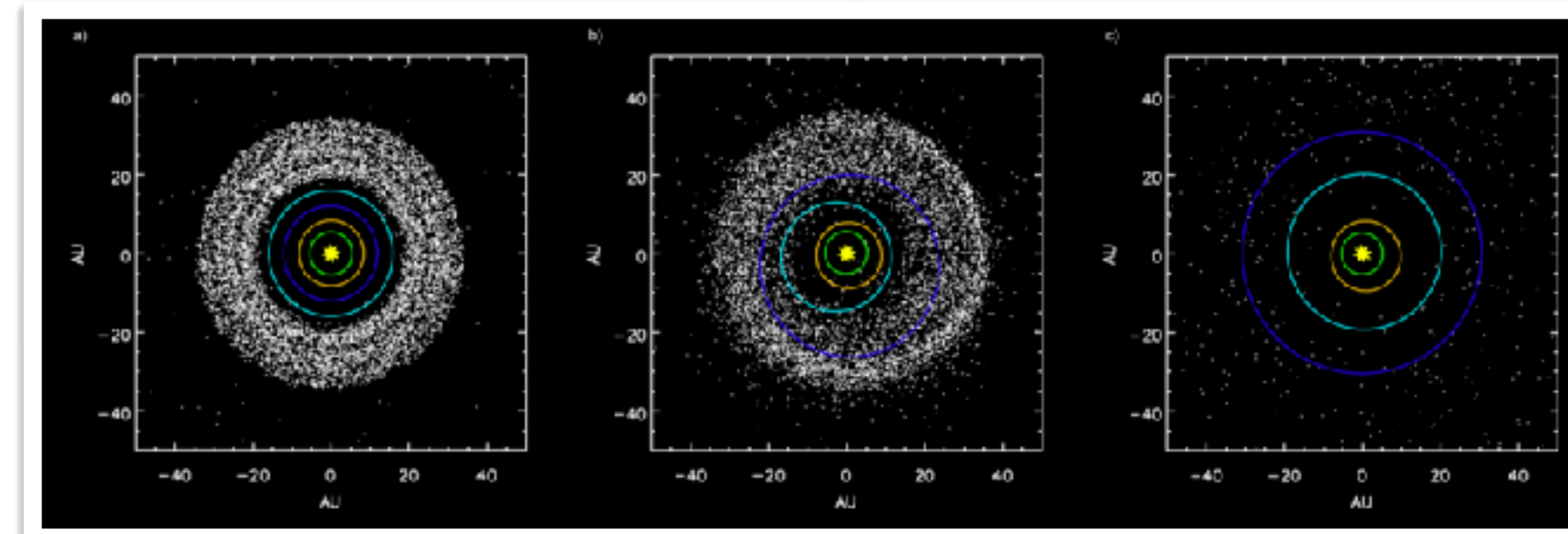
~10 Resonant-chain Systems have been Discovered



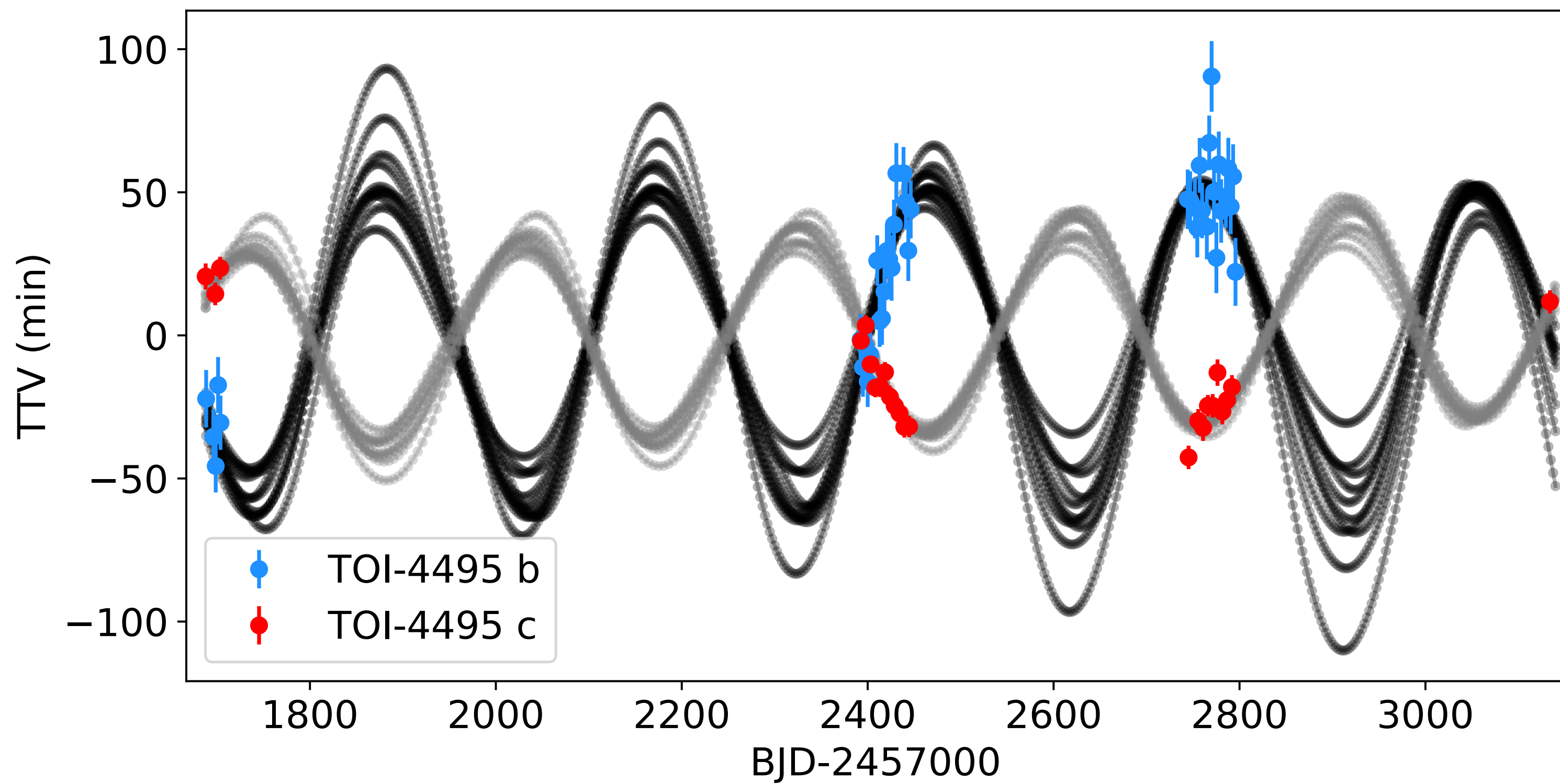
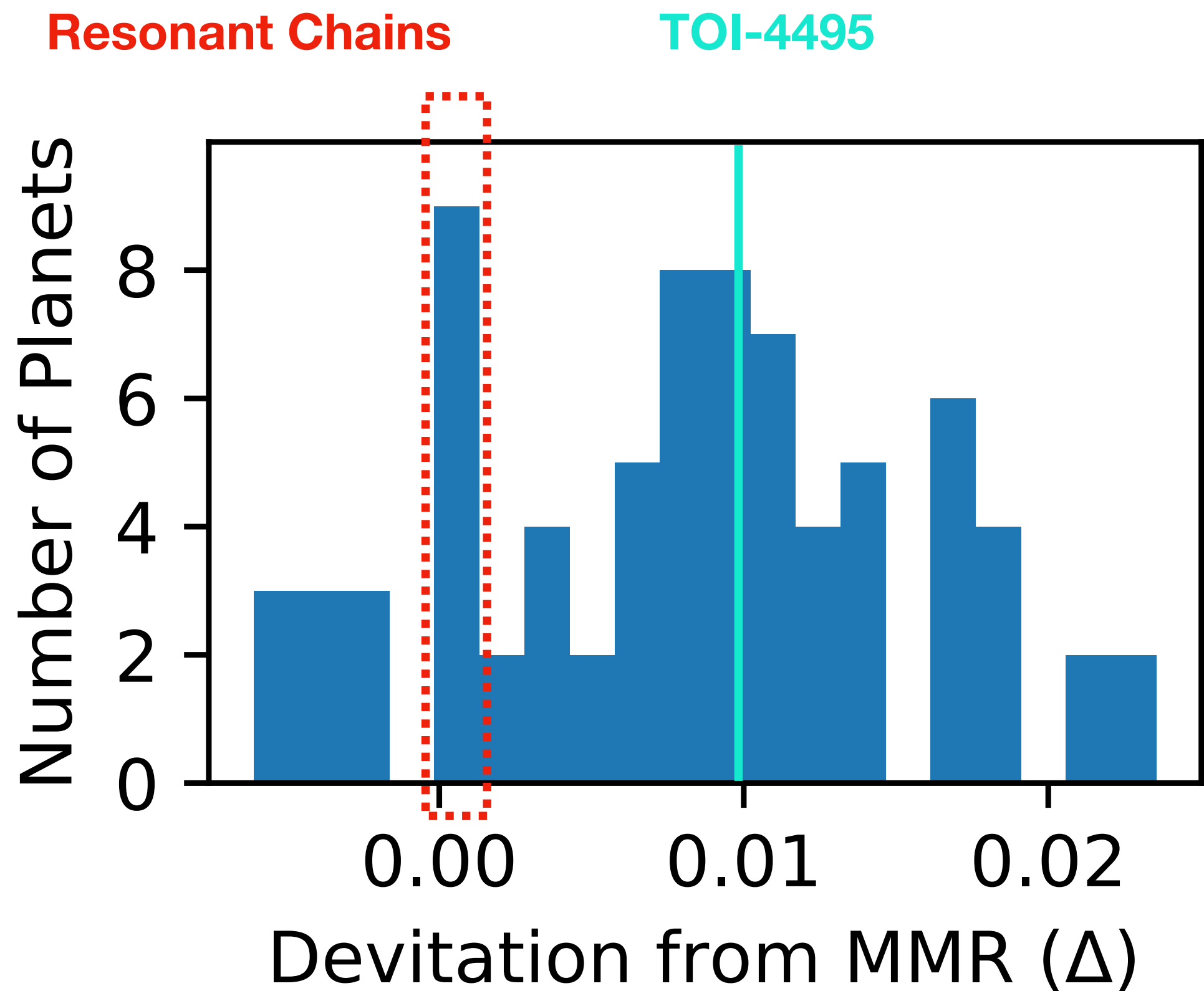
Are Resonant-chain Always Disrupted?



Planetesimal Scattering

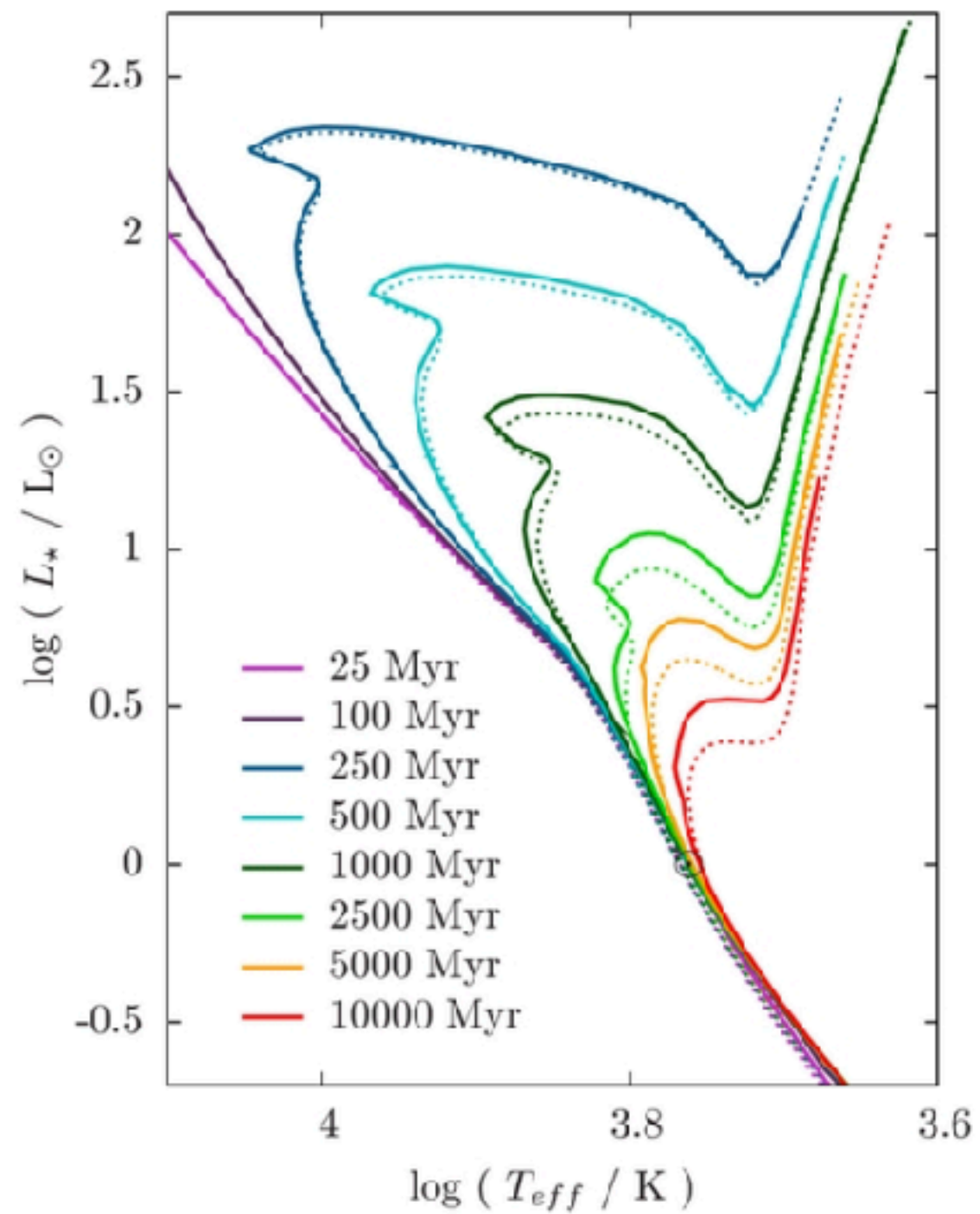


TOI-4495

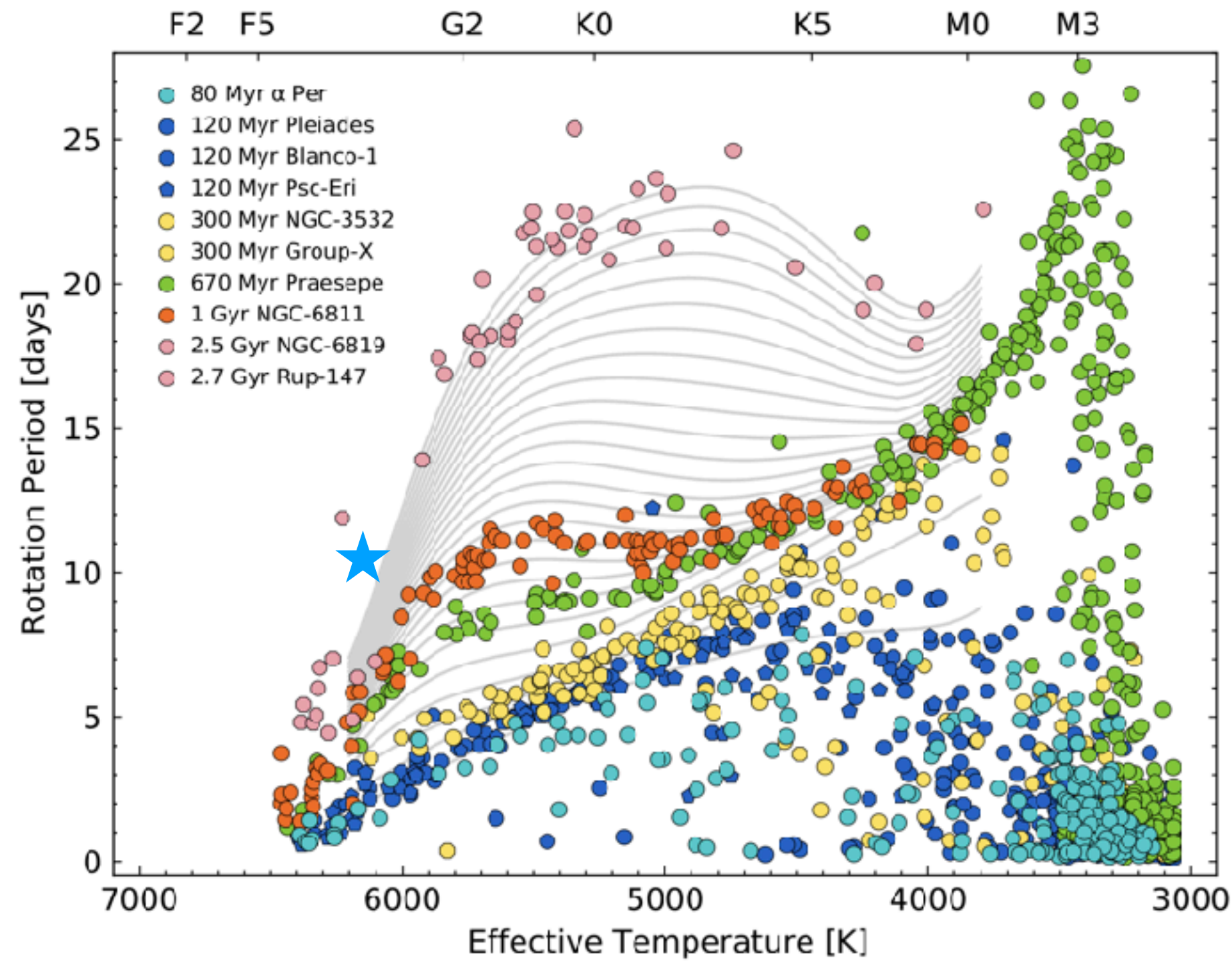


-F-type Host
-2.6-day and 5.2-day orbit
-2.7 Re and 4.1 Re

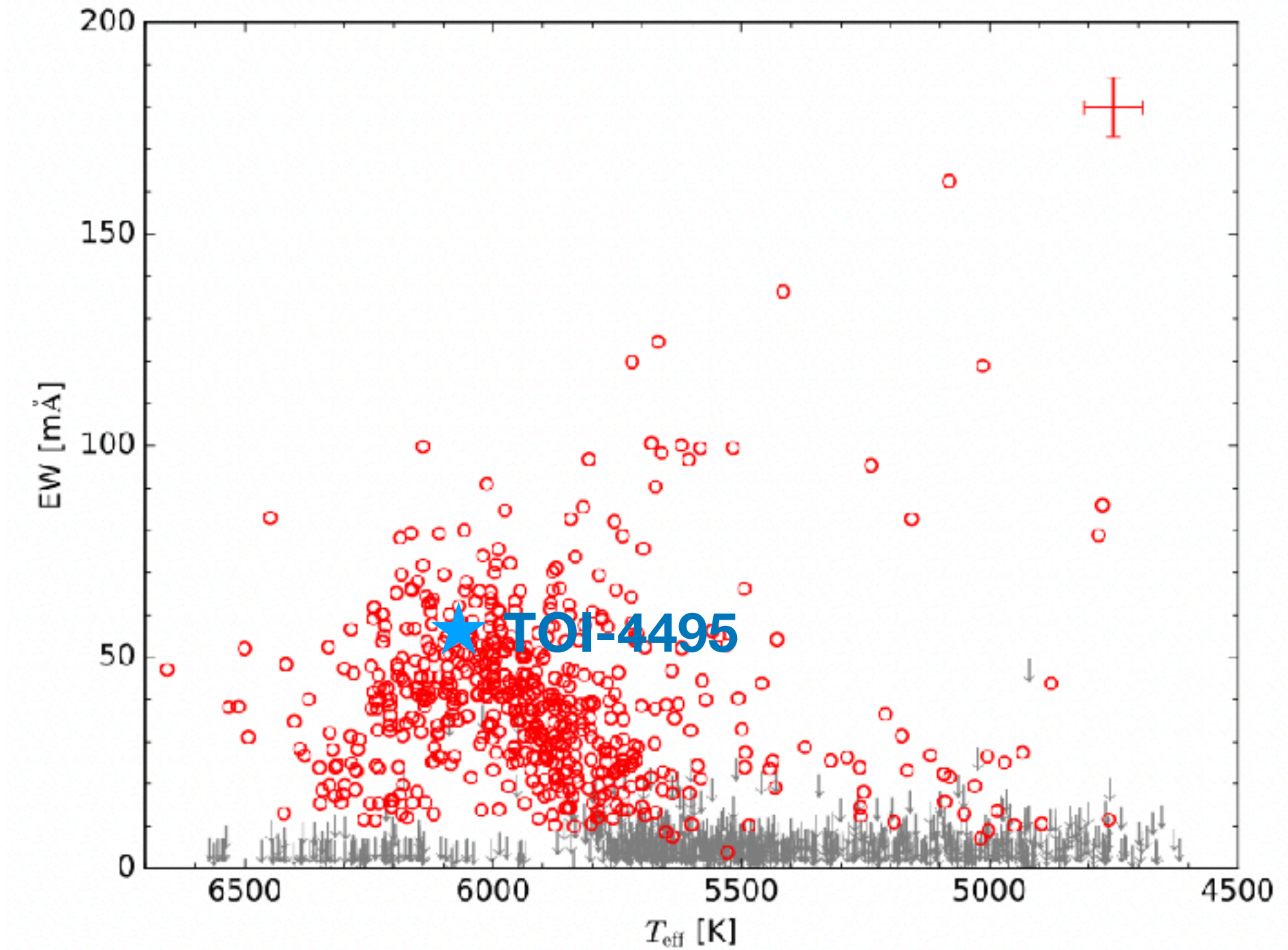
An Adolescent System about 1.8-Gyr-old



Casanellas & Lopes 2011

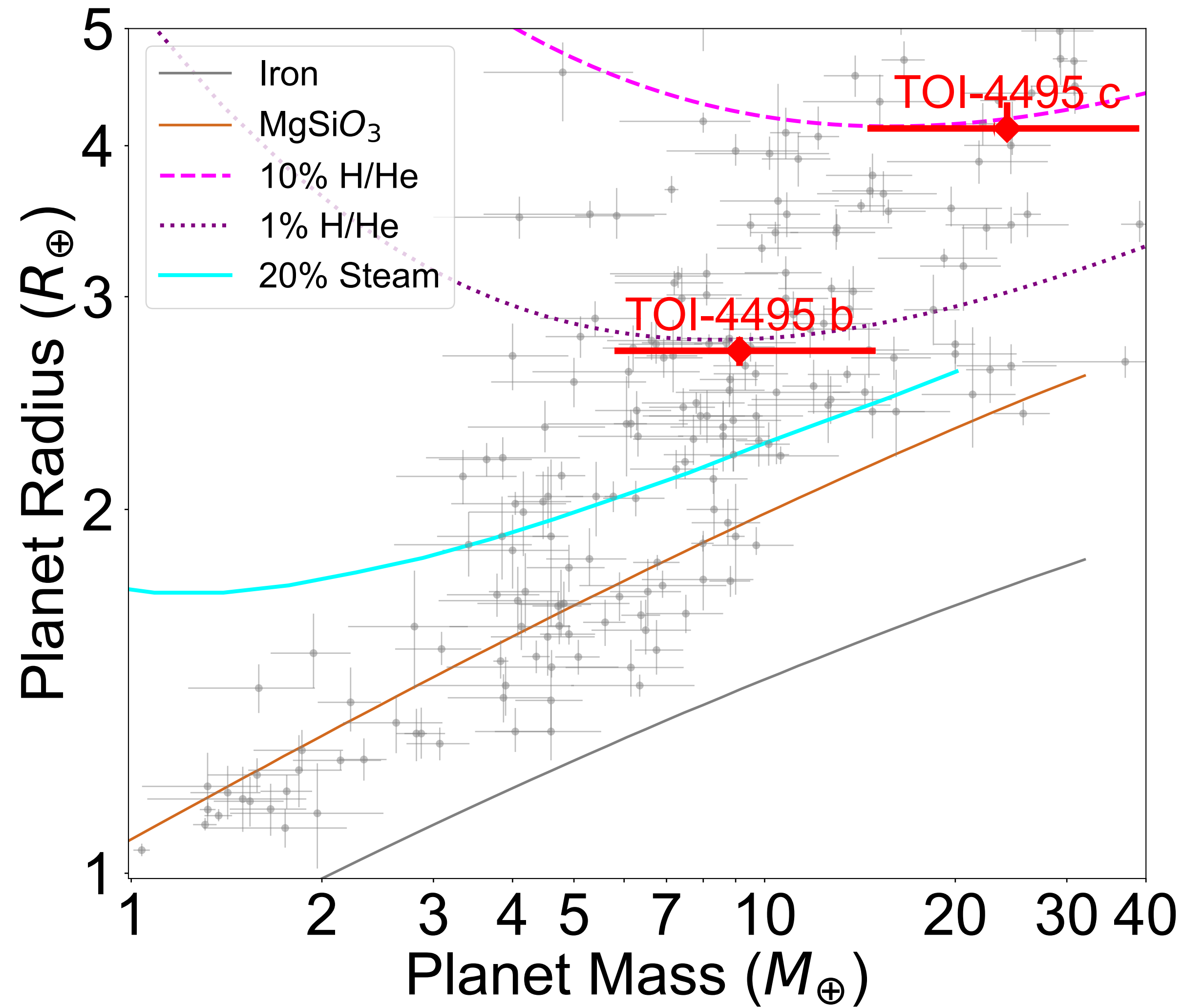


Bouma et al. 2023



Berger et al. 2018

Photoevaporation should have Concluded



Stellar Obliquity (Orbit Tilt)

- Stellar obliquity: the angle between the orbital axis of a planet and the rotation axis of its host star.
- Can be measured by the shadow of the planet on the host star.

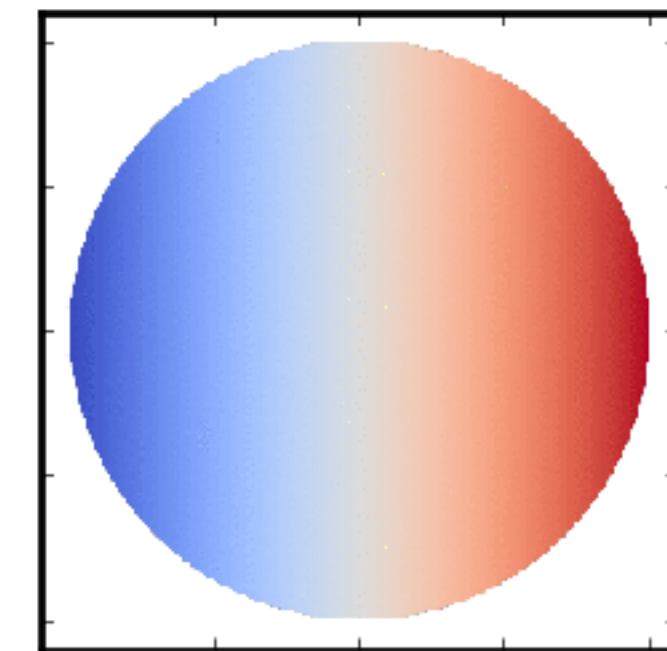
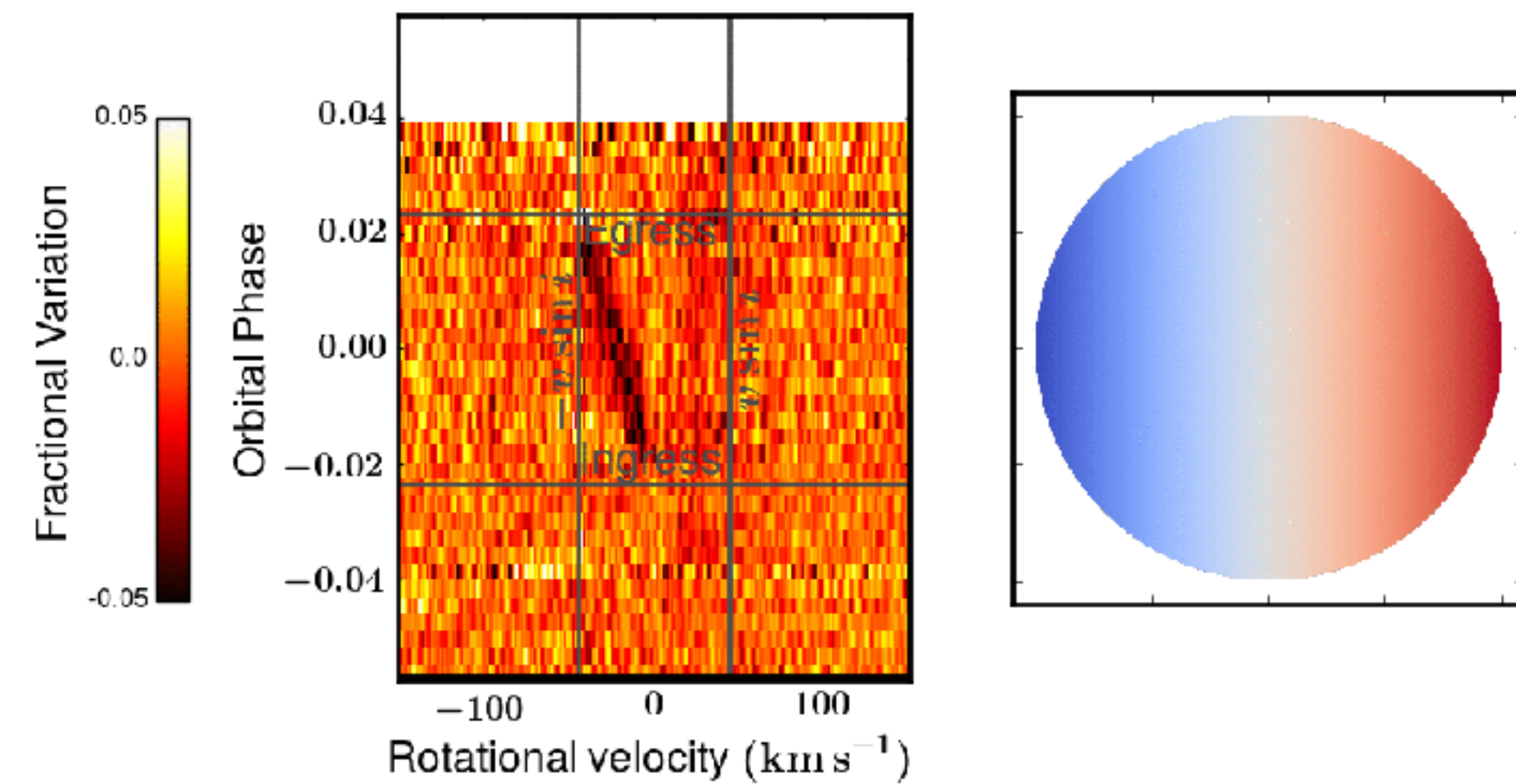
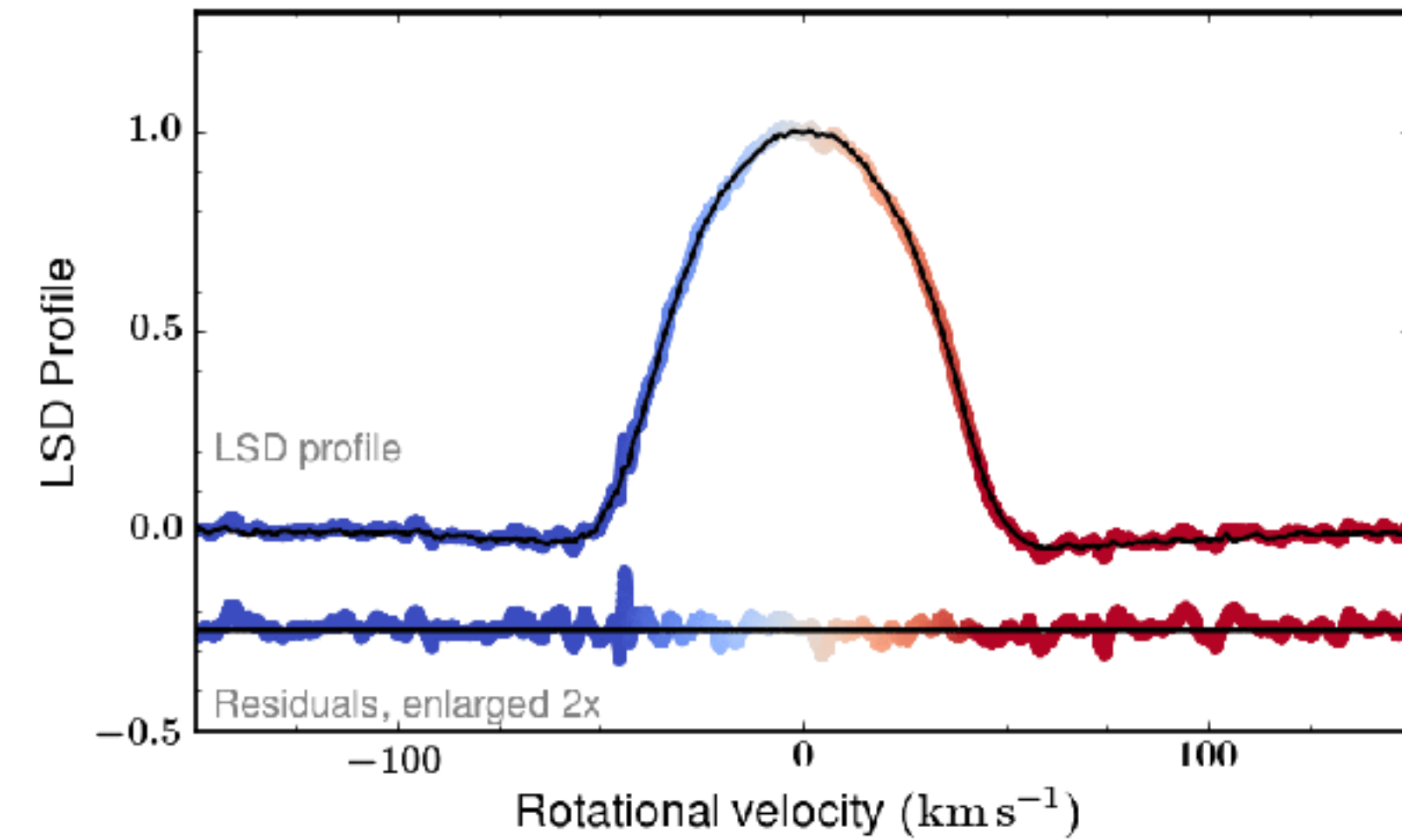
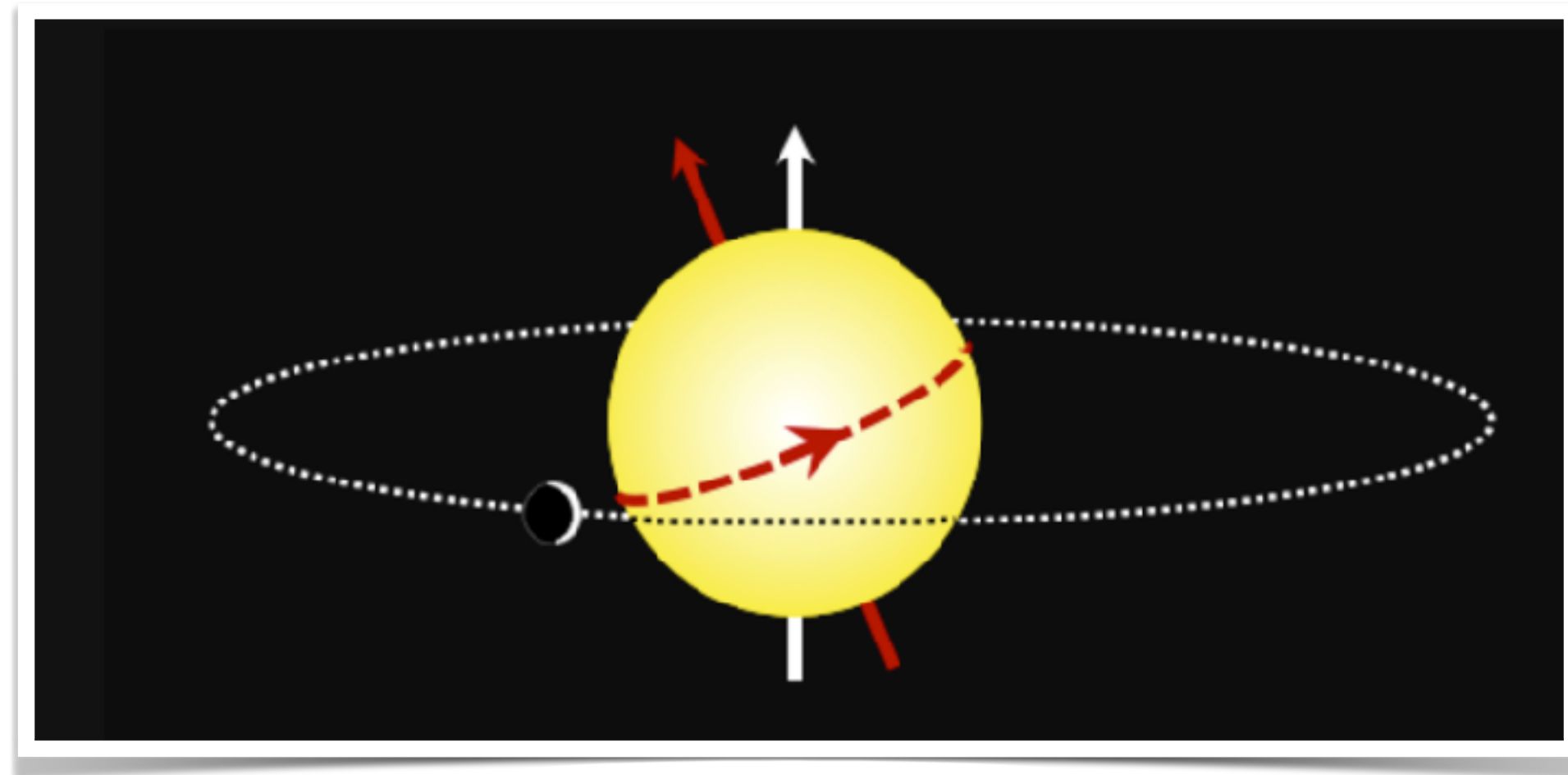
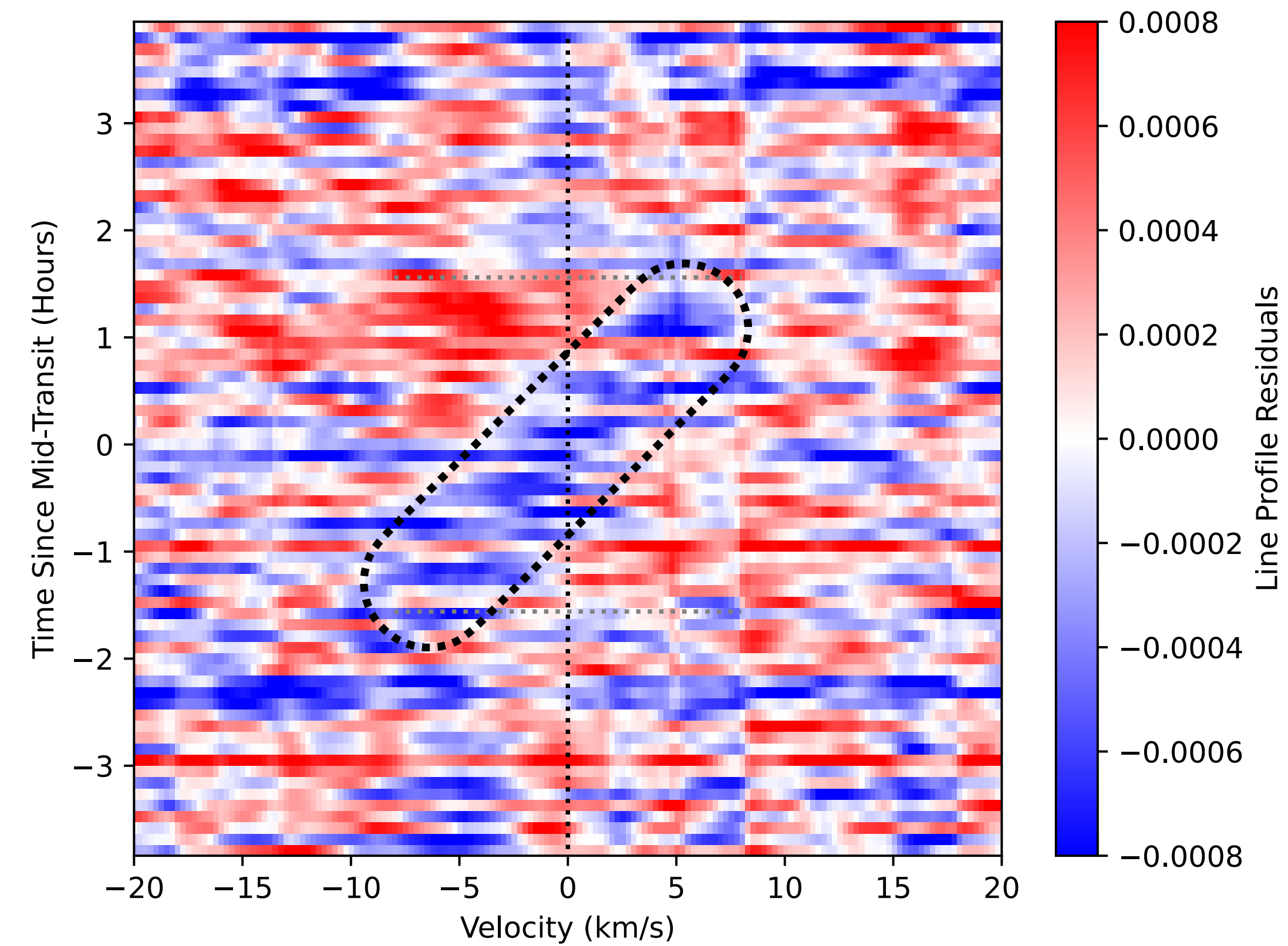
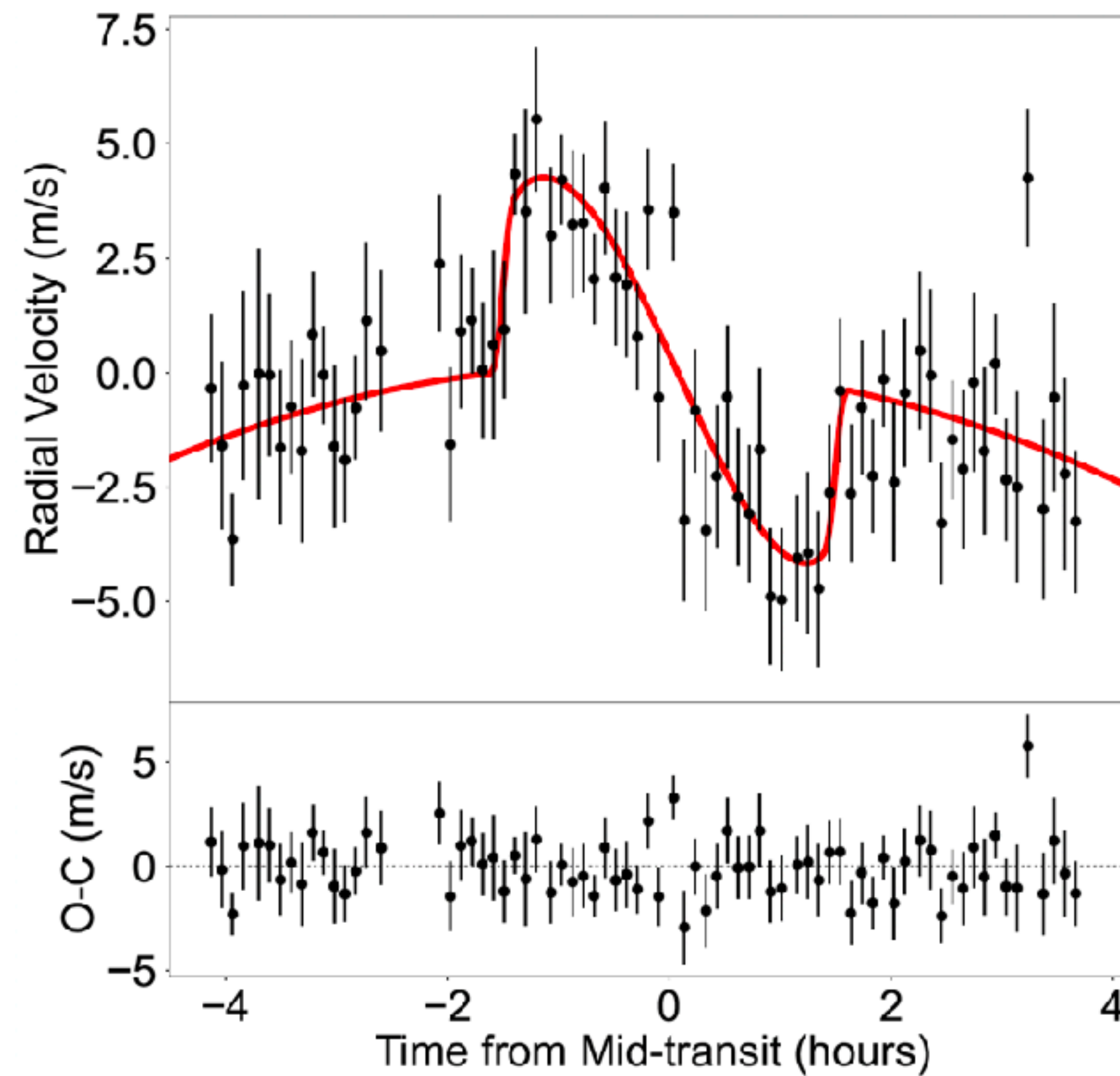
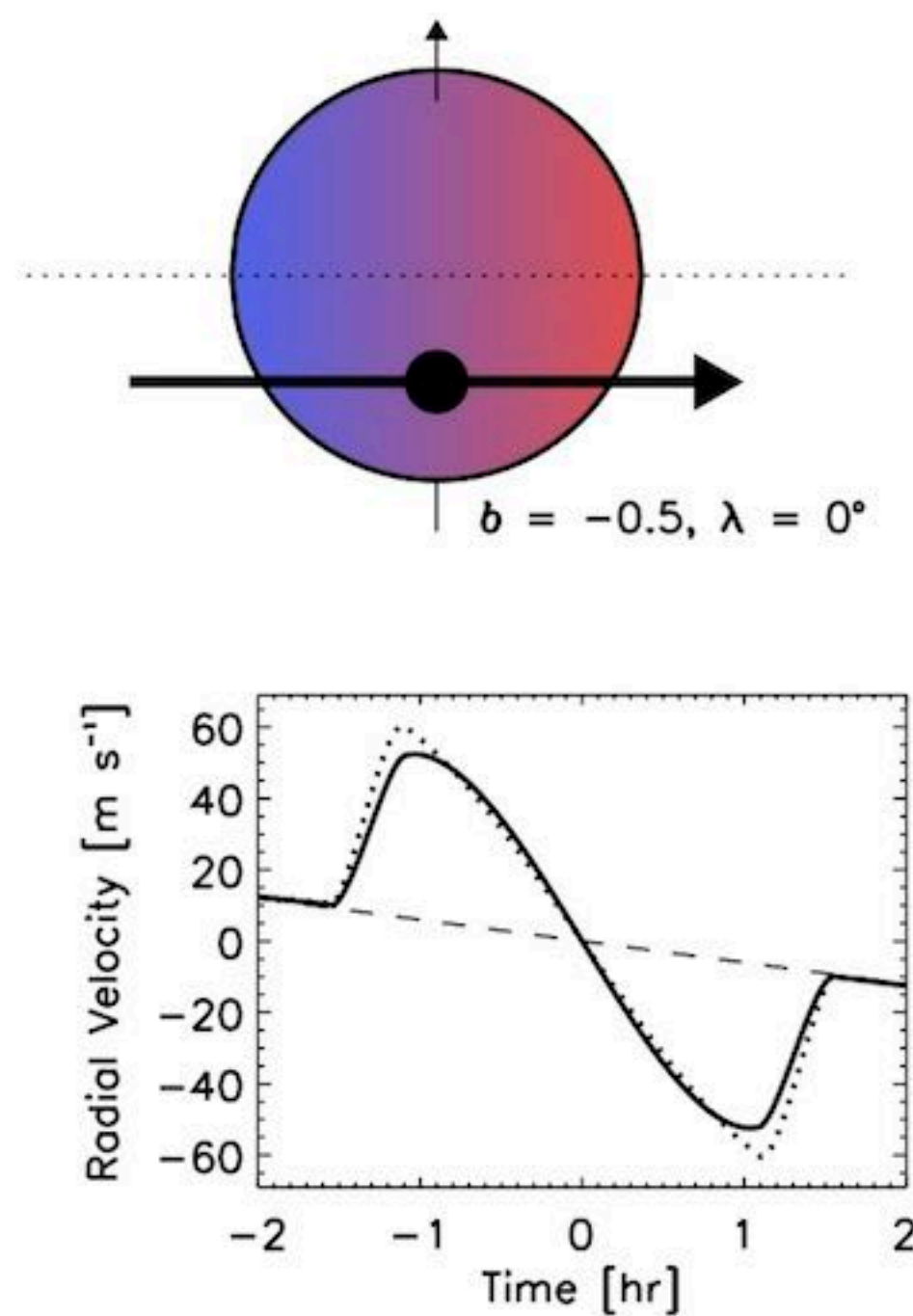


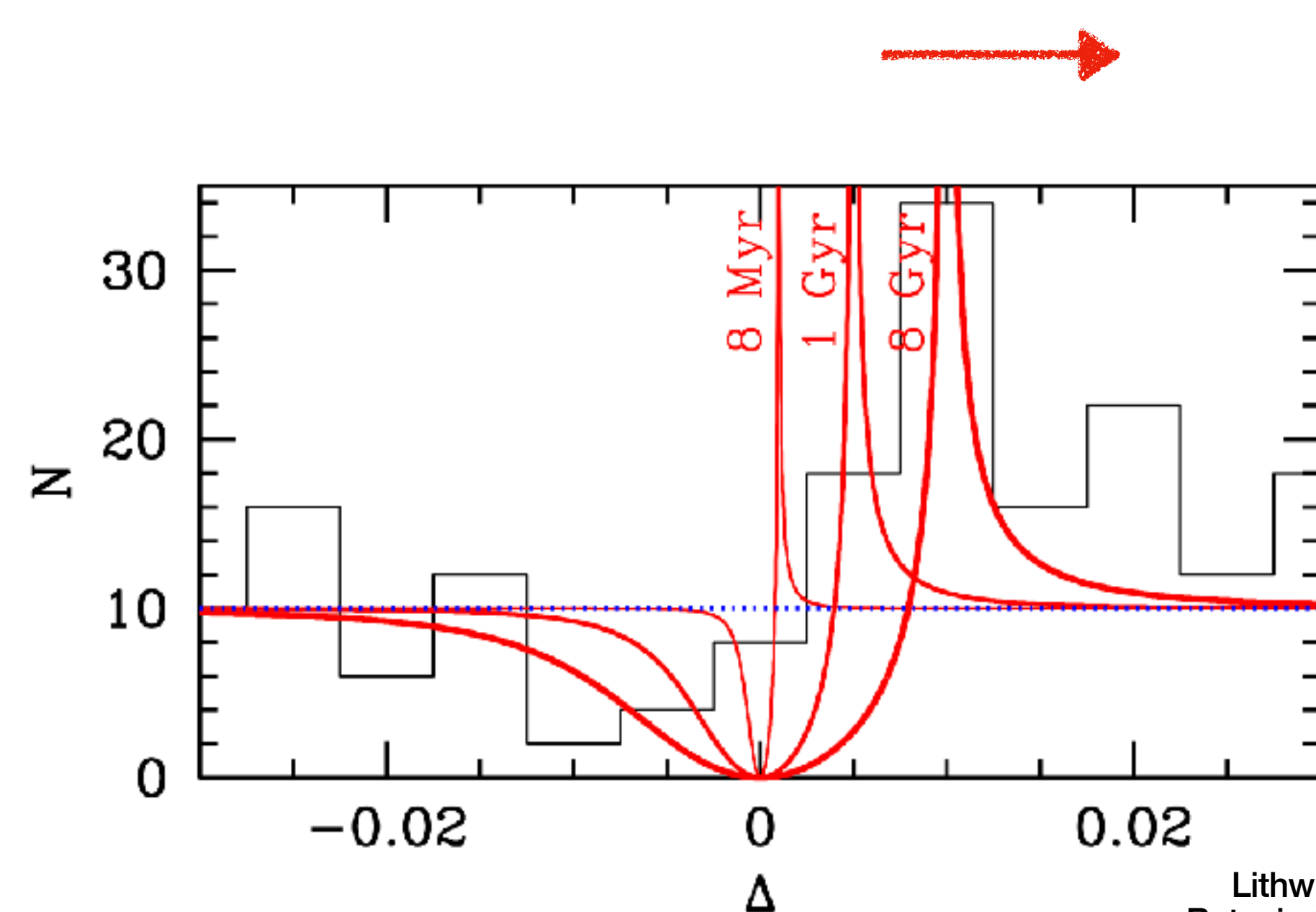
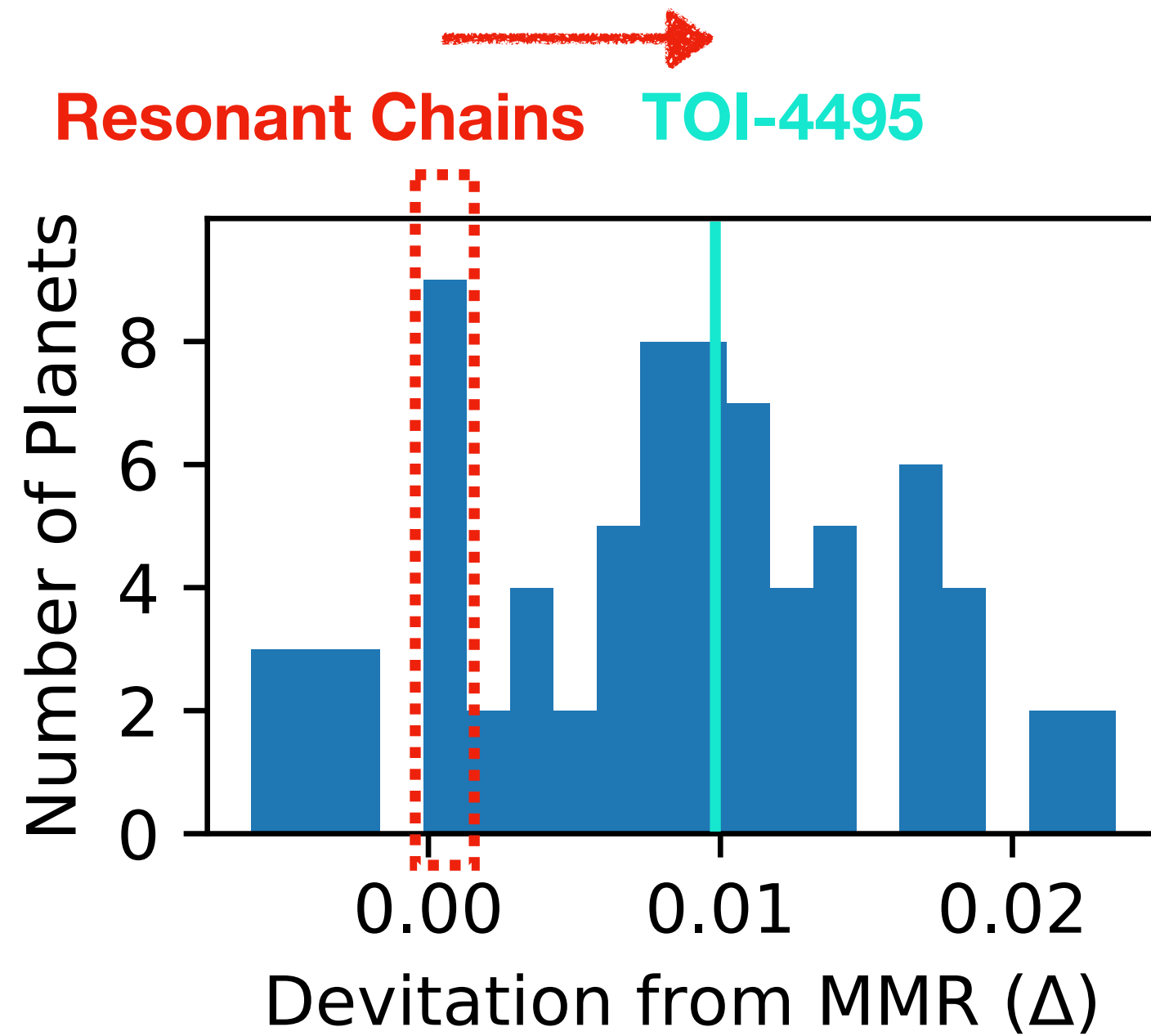
Image Credit: George Zhou

Stellar Obliquity From Keck Planet Finder

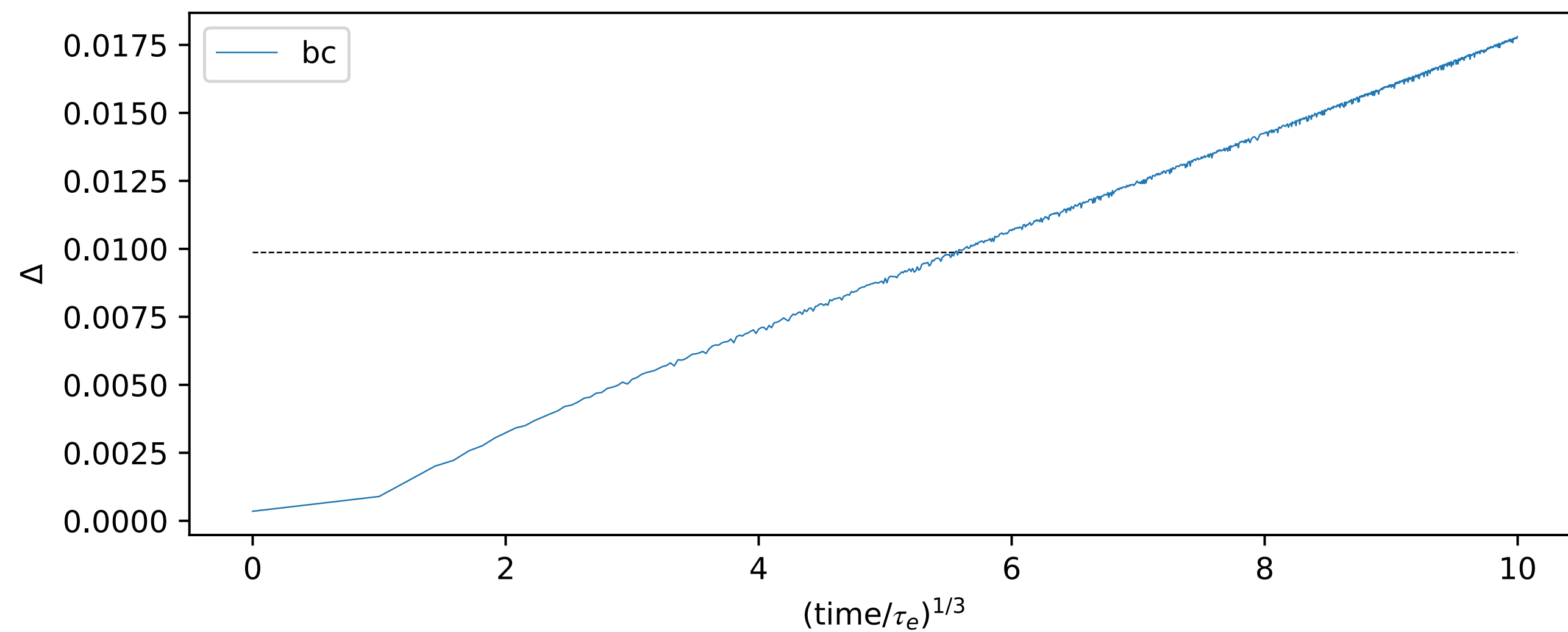
Stellar Obliquity: 3 ± 12 degrees



Resonant Repulsion



Lithwick & Wu 2012
Batygin & Morbidelli 2013
Millholland & Laughlin 2019



A surprisingly low $Q' < 1200$

c.f. Q' of Mars = 1000
 Q' of Neptune = 30000

Planet Migration in a Turbulent Disk?

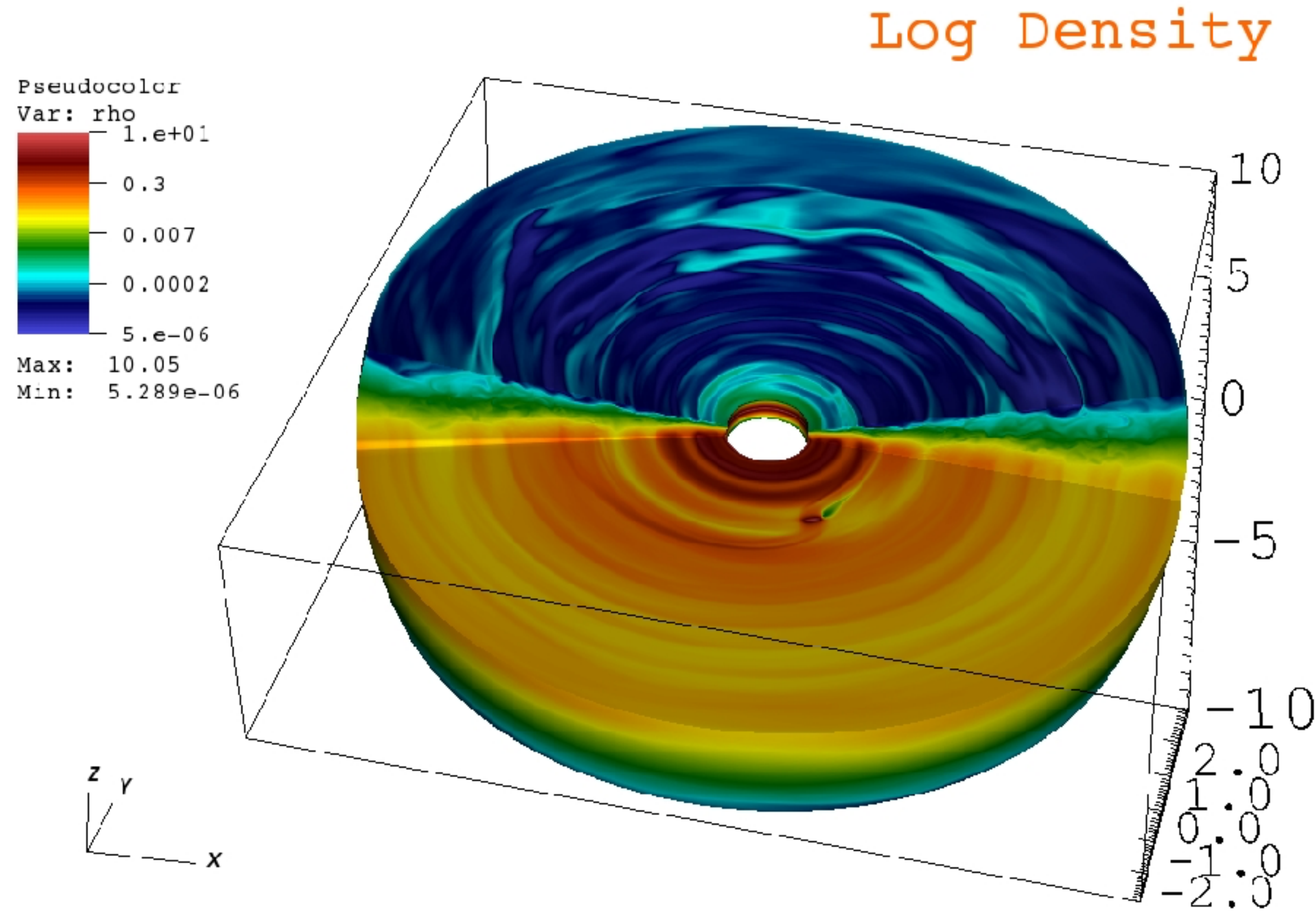
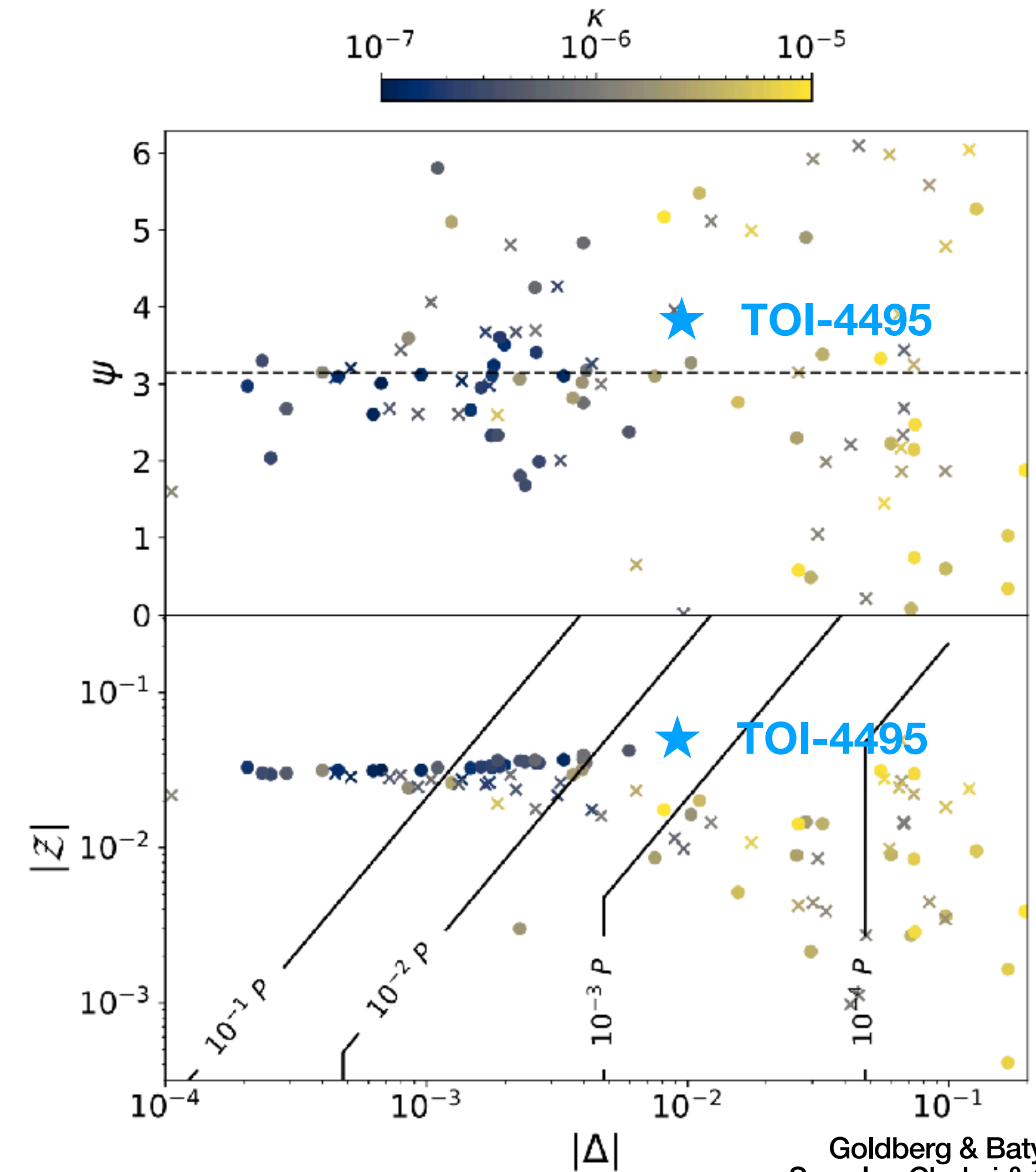


Image Credit: Uribe



Goldberg & Batygin 2023
See also Choksi & Chiang 2020

Conclusion

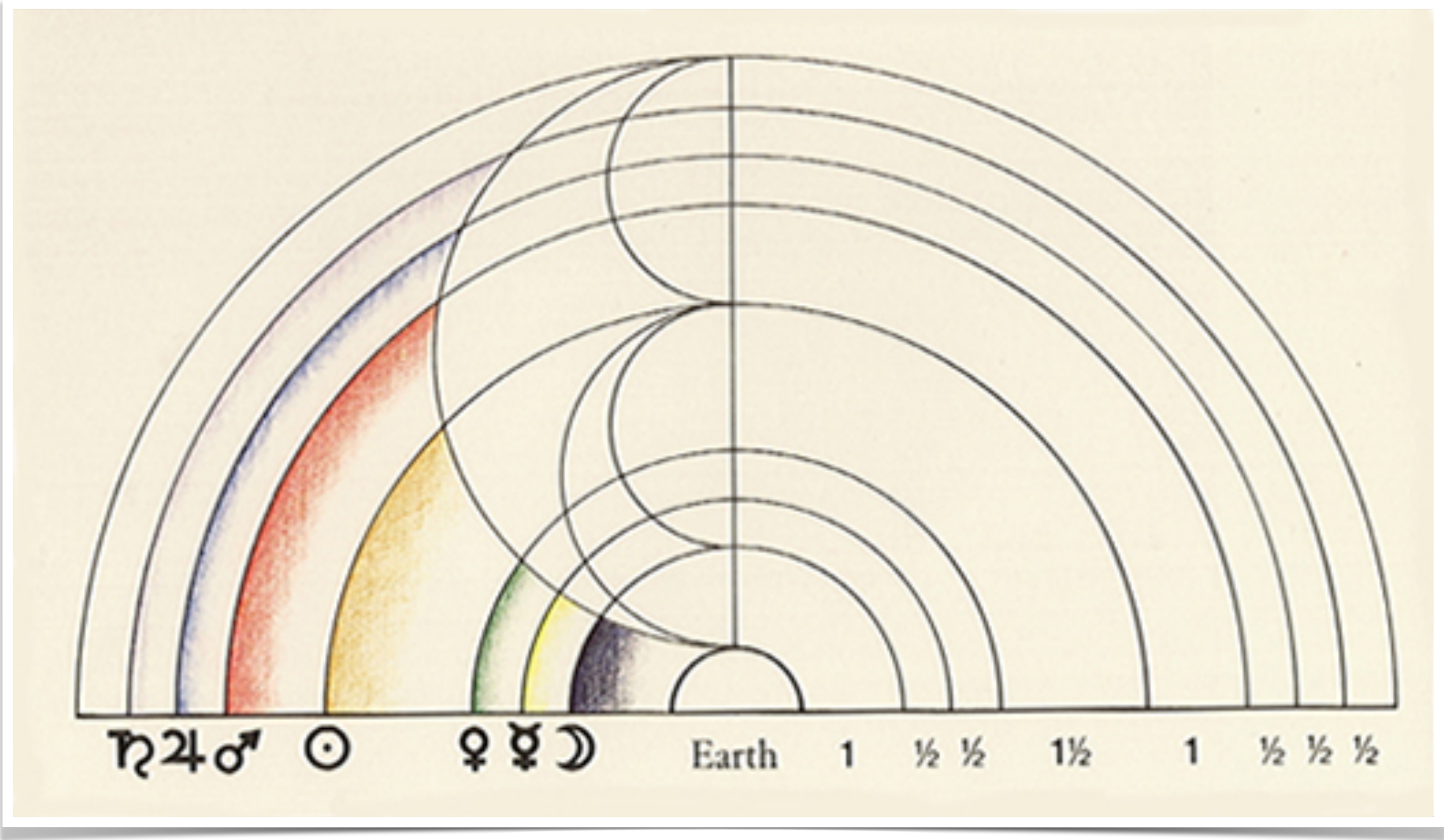


Image Credit: Arnaud Pierens