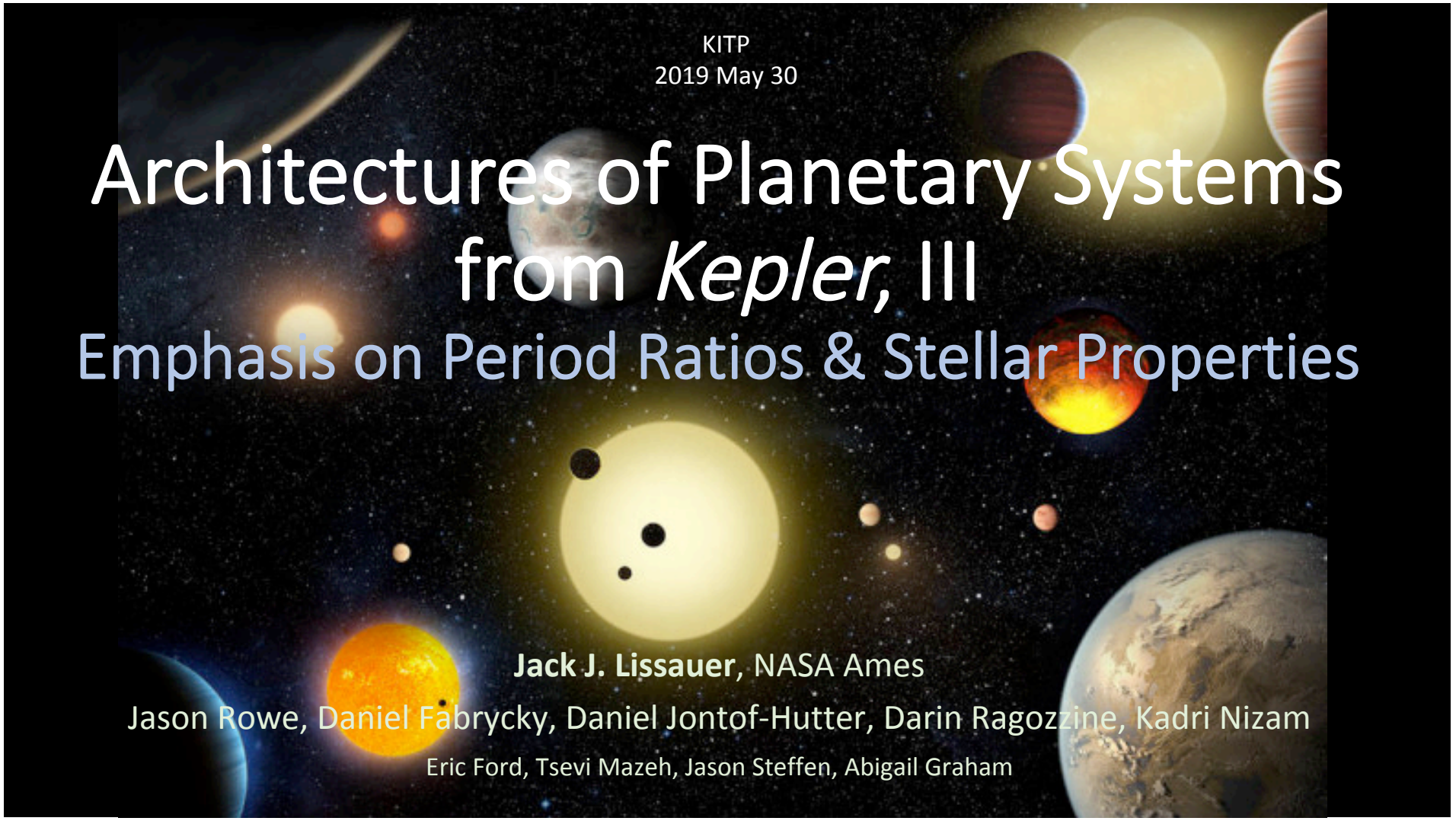
KITP
2019 May 30

Architectures of Planetary Systems from *Kepler*, III

Emphasis on Period Ratios & Stellar Properties



Jack J. Lissauer, NASA Ames

Jason Rowe, Daniel Fabrycky, Daniel Jontof-Hutter, Darin Ragozzine, Kadri Nizam

Eric Ford, Tsevi Mazeh, Jason Steffen, Abigail Graham

Goals of Architectures III

Use *Kepler*'s candidate multi-planet systems to understand architectures of planetary systems: spacing of planets, correlations of parameters with planetary multiplicity, etc.

Extend our previous studies to entire *Kepler* sample using refined statistical techniques

The Astrophysical Journal Supplement Series, 197:8 (26pp), 2011 November doi:10.1088/0067-0049/197/1/8

ARCHITECTURE AND DYNAMICS OF *KEPLER*'S CANDIDATE MULTIPLE TRANSITING PLANET SYSTEMS

Jack J. Lissauer[1], Darin Ragozzine[2], Daniel C. Fabrycky[3,14], Jason H. Steffen[4], Eric B. Ford[5], Jon M. Jenkins[1,6], Avi Shporer[7,8], Matthew J. Holman[2], Jason F. Rowe[6], Elisa V. Quintana[6], Natalie M. Batalha[9], William J. Borucki[1], Stephen T. Bryson[1], Douglas A. Caldwell[6], Joshua A. Carter[2,14], David Ciardi[10], Edward W. Dunham[11], Jonathan J. Fortney[3], Thomas N. Gautier, III[12], Steve B. Howell[1], David G. Koch[1], David W. Latham[3],

The Astrophysical Journal, 790:146 (12pp), 2014 August 1 doi:10.1088/0004-637X/790/2/146

ARCHITECTURE OF *KEPLER*'S MULTI-TRANSITING SYSTEMS. II. NEW INVESTIGATIONS WITH TWICE AS MANY CANDIDATES

Daniel C. Fabrycky[1,17,18], Jack J. Lissauer[2], Darin Ragozzine[3], Jason F. Rowe[2,4], Jason H. Steffen[5,6], Eric Agol[7], Thomas Barclay[2,8], Natalie Batalha[2,9], William Borucki[2], David R. Ciardi[10], Eric B. Ford[11,12,13], Thomas N. Gautier[14], John C. Geary[3], Matthew J. Holman[3], Jon M. Jenkins[2], Jie Li[2,4], Robert C. Morehead[11,12,13], Robert L. Morris[2,4], Avi Shporer[14,15,16,19], Jeffrey C. Smith[2,4], Martin Still[8], and Jeffrey Van Cleve[2,4]

Goals of Architectures III

Use *Kepler*'s candidate multi-planet systems to understand architectures of planetary systems: spacing of planets, correlations of parameters with planetary multiplicity, etc.

Extend the studies of Lissauer, Ragozzine, Fabrycky, et al. (2011, *ApJS* **197**, 8) & Fabrycky, Lissauer, Ragozzine, et al. (2014, *ApJ* **197**, 8) to the entire *Kepler* sample using refined statistical techniques

Uses planet candidates rather than verified planets to avoid biases in verification methods

Scope of Architectures III

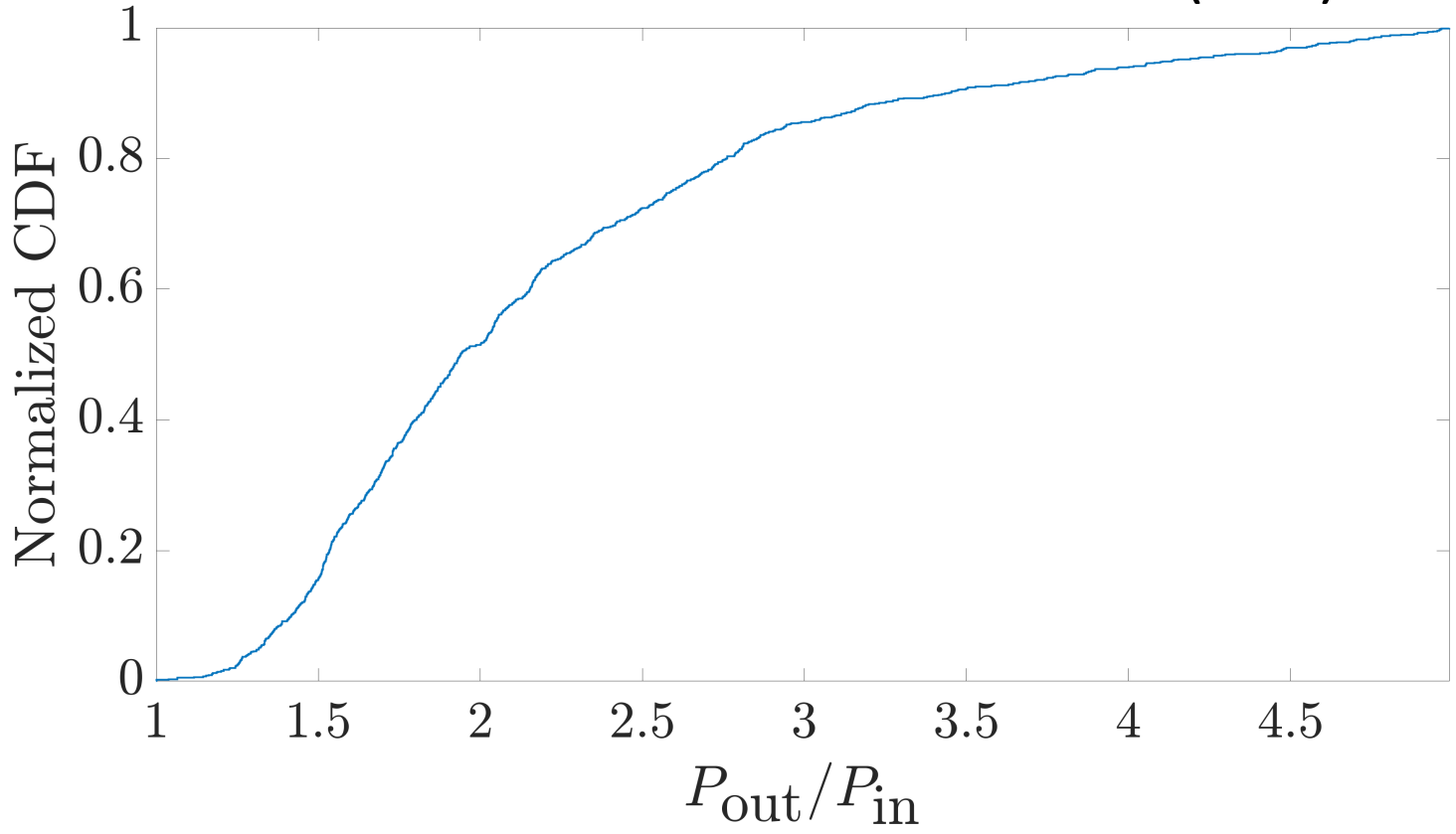
- Special-purpose catalog of planet candidates (under construction)
- Comparison of distributions of planetary properties for different multiplicities
- Period ratio studies
- Three-body resonances
- Relative inclinations
- Distribution of planetary system characteristics, including multiplicity
- Dependence of system architectures on planetary & stellar properties

Scope of Architectures III, Part 1

- Special-purpose catalog of planet candidates (under construction)
- Comparison of distributions of planetary properties for different multiplicities
- **Period ratio studies**
  - **Viewing the elephant from different perspectives & distances**
  - **Are (two-body) resonances overabundant?**
  - **How does the distribution depend on stellar properties**
- Three-body resonances
  - Abundance & characteristics
- Relative inclinations
- Distribution of planetary system characteristics, including multiplicity

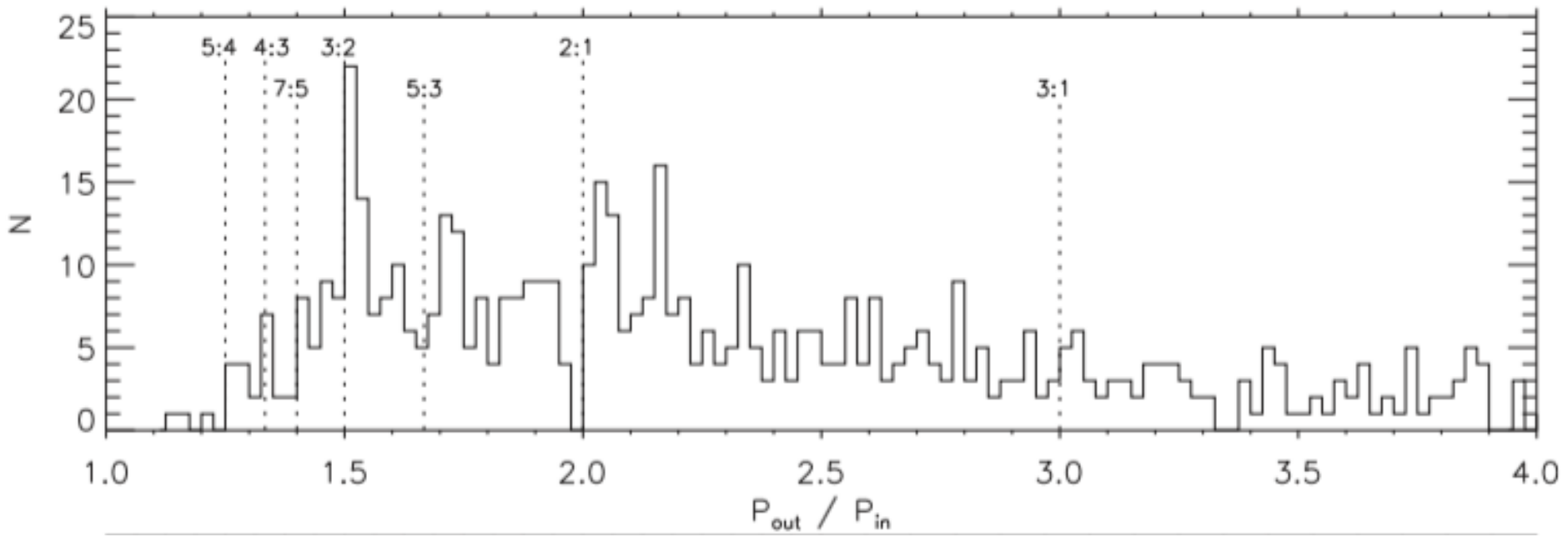
Period Ratios Adjacent Pairs of Planets

Cumulative Distribution Function (CDF)



Standard Period Ratio Histogram

(Arch II: Fabrycky et al. 2014)



Period Ratios Histogram – Bins of Different Width

Relative Number

P_{out}/P_{in}

Histogram – Same Width, Different Phase

Relative Number

P_{out}/P_{in}

Period Ratios Histograms – Width & Phase

- Appearance of histogram depends strongly on value of bin width used
  - Narrow bin resolve structure, but plagued with statistical noise
- Choice of phase also affects appearance of histogram
  - Unnecessary loss of information

Period Ratios Top-Hat KDEs, Various Widths

Relative Number

1 3 5

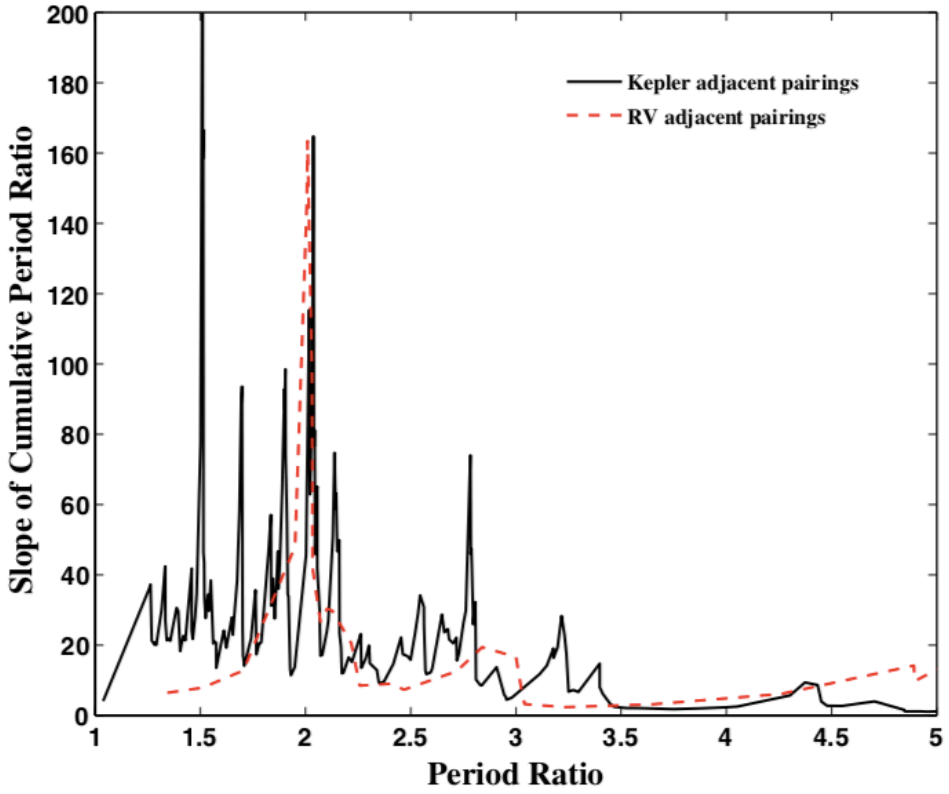
P_{out}/P_{in}

Period Ratios Histograms vs. KDEs

- Appearance of histogram depends strongly on value of bin width used
- Choice of phase also affects appearance of histogram
- Using Kernel Density Estimators (KDEs) shows all phases equally

Numerical Derivative of CDF, Mask Size = 4

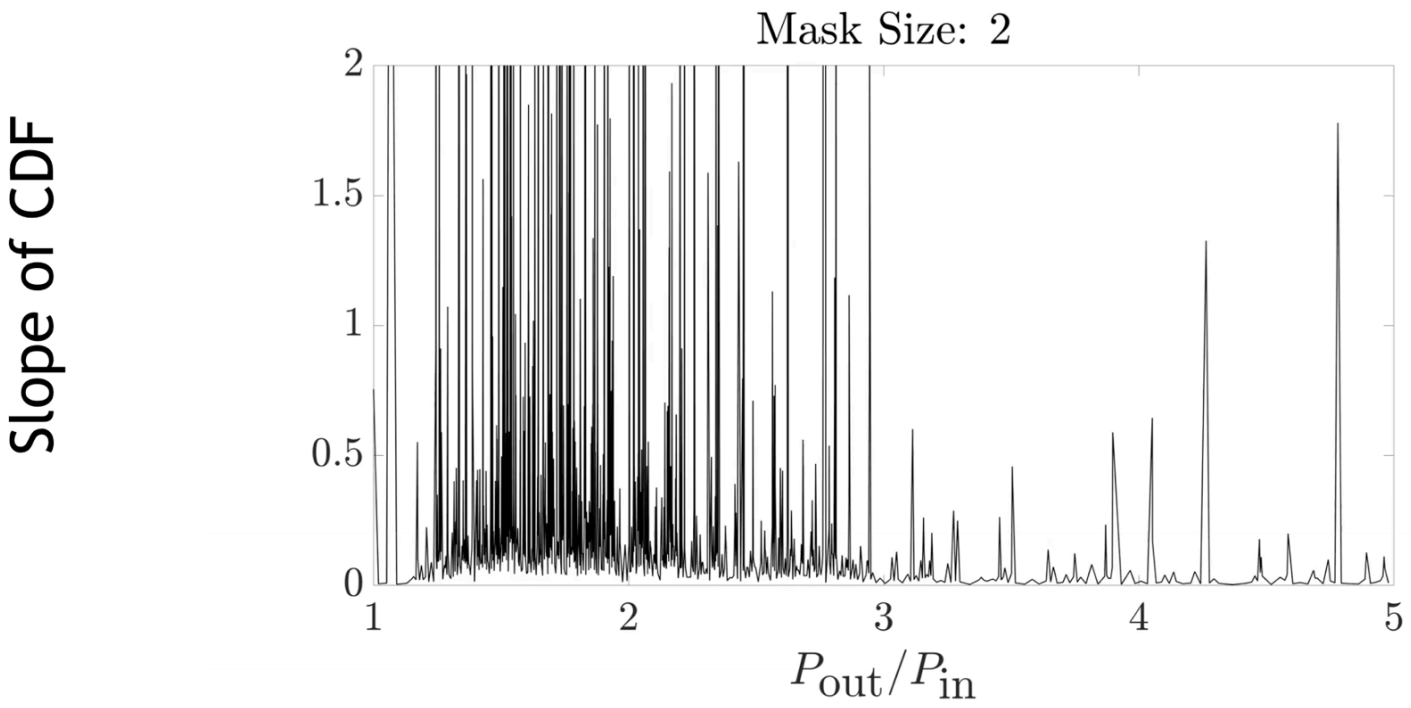
(Arch I: Lissauer et al. 2011)



Period Ratios – Numerical Derivatives

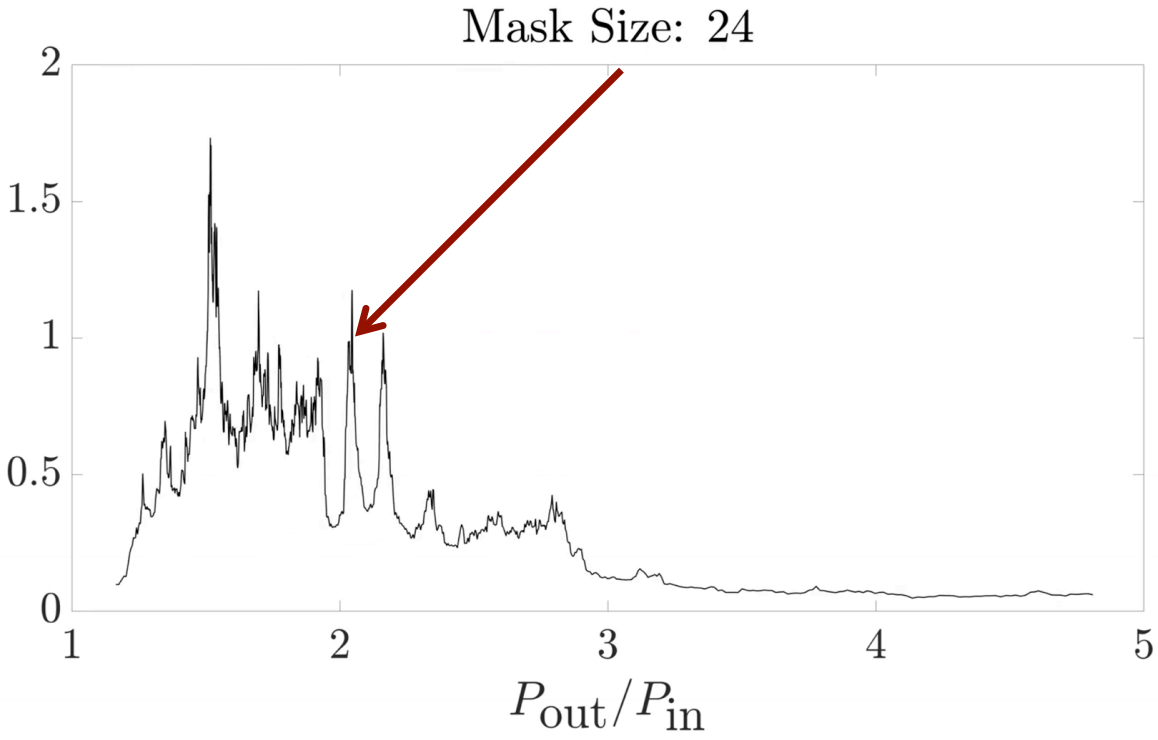
Slope of CDF

Period Ratios – Numerical Derivatives



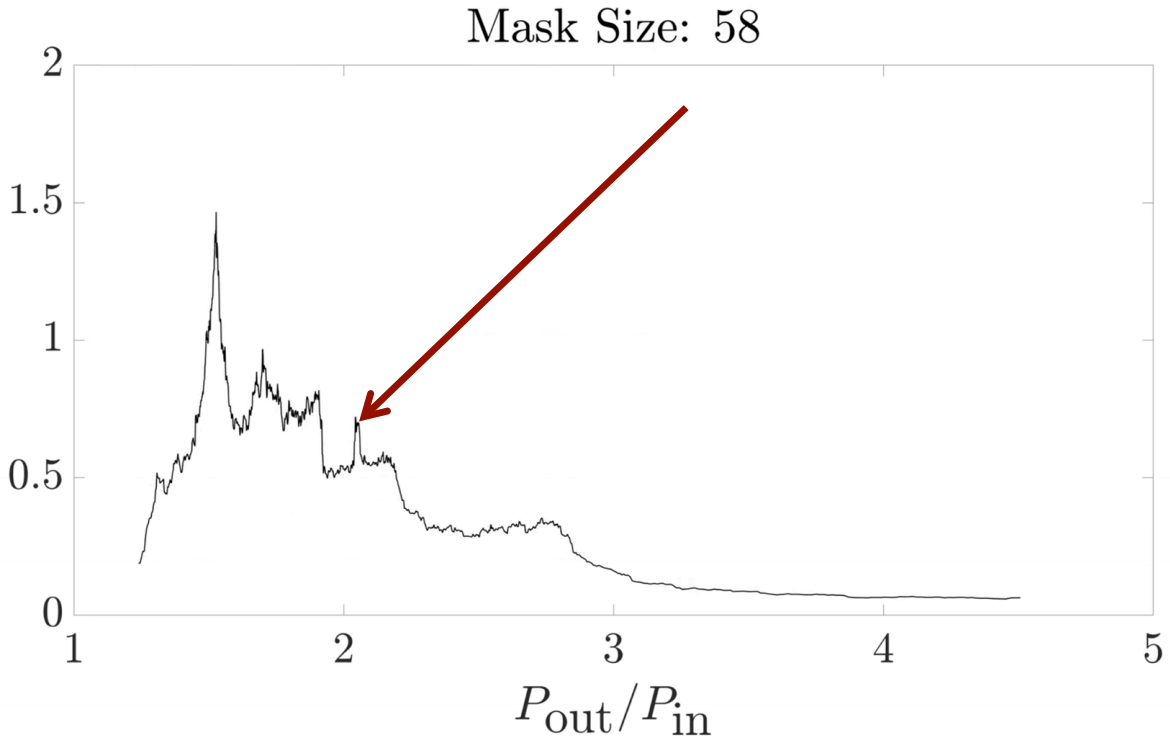
Period Ratios – Numerical Derivatives

Slope of CDF



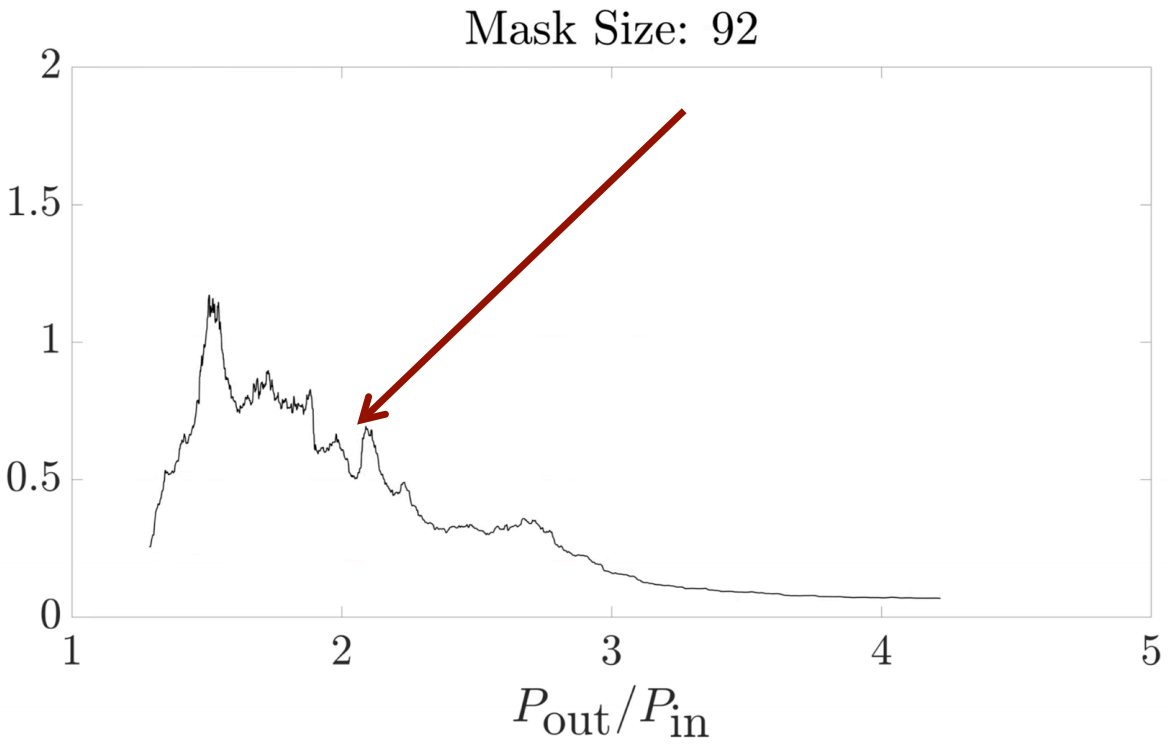
Period Ratios – Numerical Derivatives

Slope of CDF



Period Ratios – Numerical Derivatives

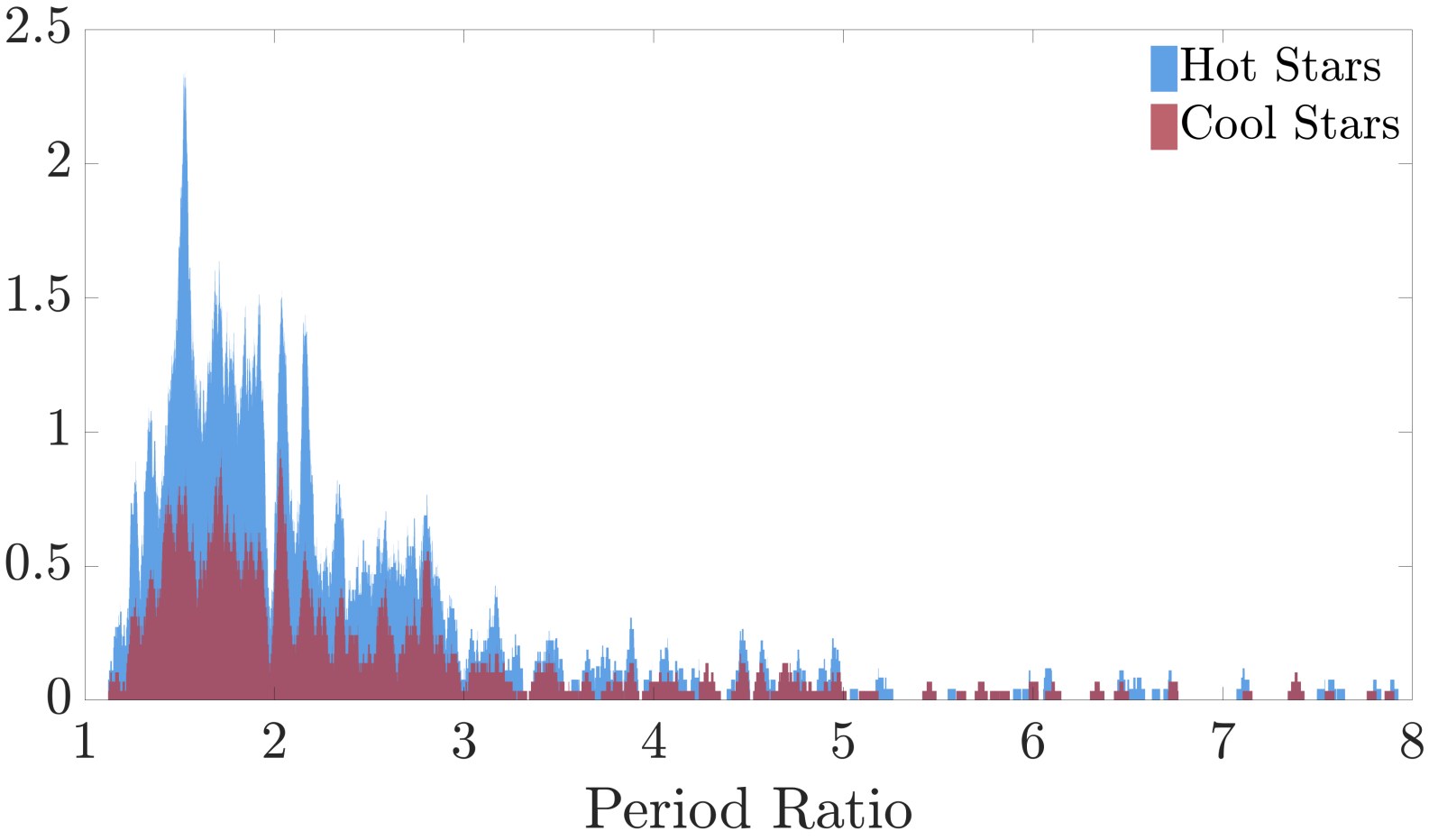
Slope of CDF



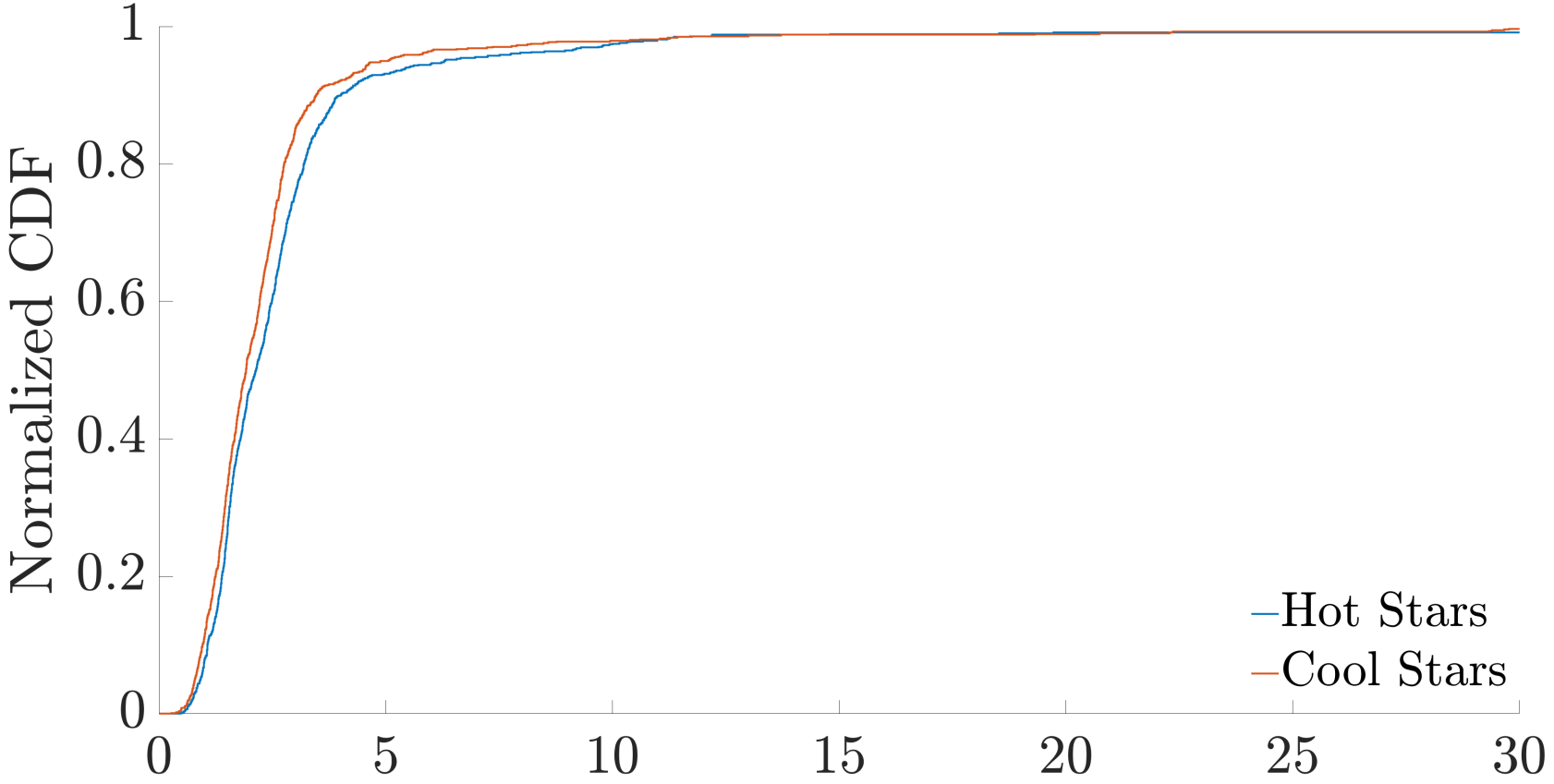
Period Ratios Histograms vs. Derivatives of CDF

- Appearance of histogram depends strongly on value of bin width used
- Choice of phase also affects appearance of histogram
- Using Kernel Density Estimators (KDEs) shows all phases equally
- Numerical derivatives of CDF shows finer structure in regions with many planet pairs

Planet Period Ratios – Split at $T_* = 5543$ K



Radius distribution of planets in multis (T_{split}=5543 K)



Period Ratios split at $T_* = 6100$ K

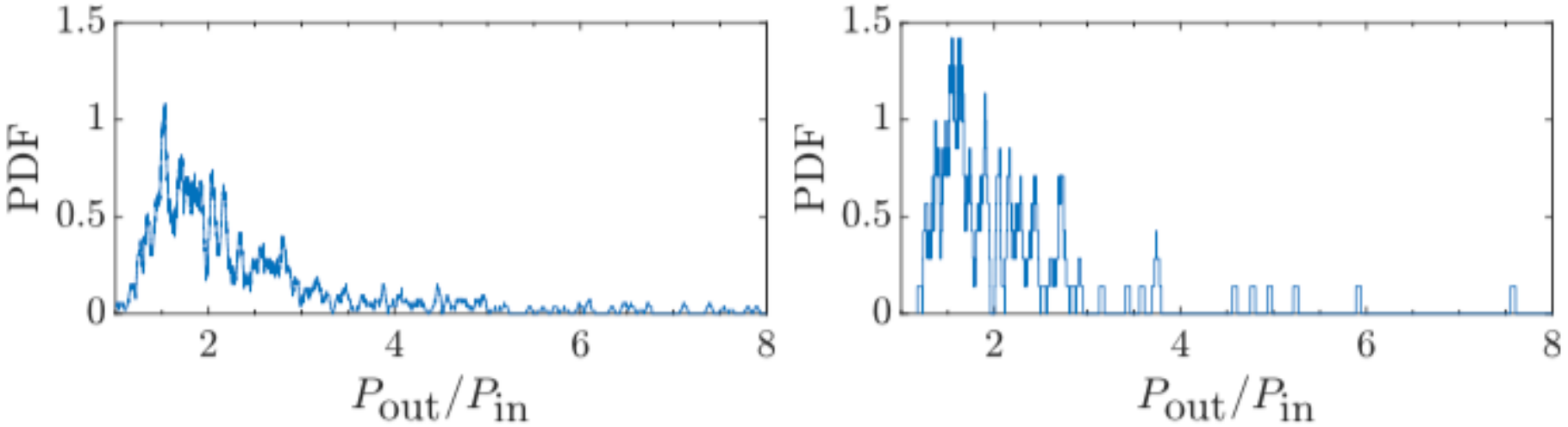


Figure 20. KDE: Period ratio of cold (left, $<$ 6100K) and hot star (right, $\geq$ 6100K) multis. Data taken from `koiprops_20190116.csv`

Period Ratios split by $R_{inner\ planet}$ =1.7 R_E

- R < 1.7 R_E

R > 1.7 R_E

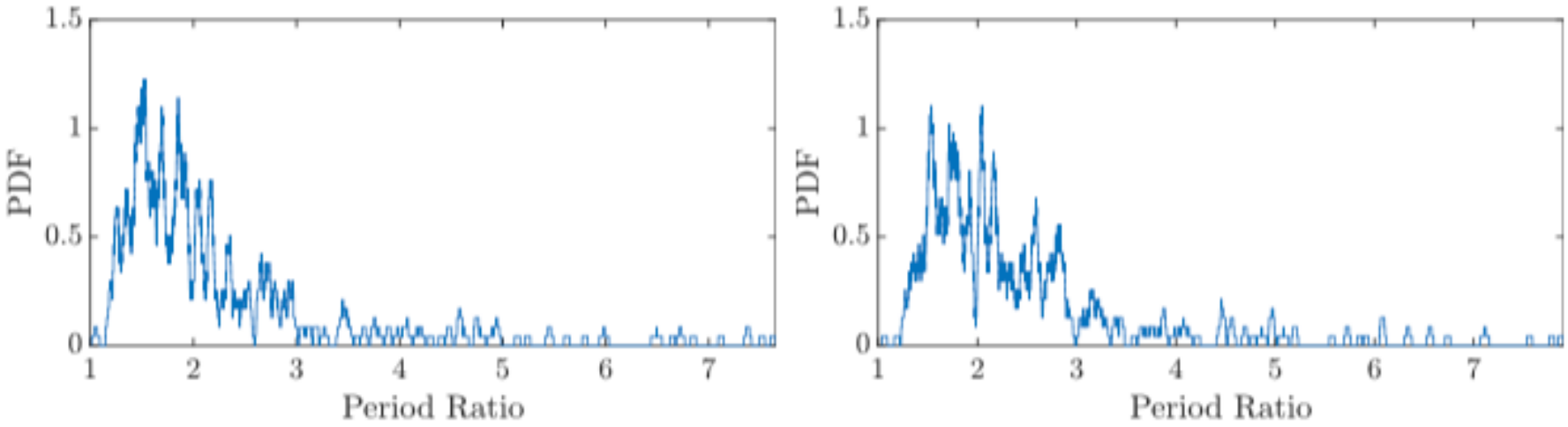
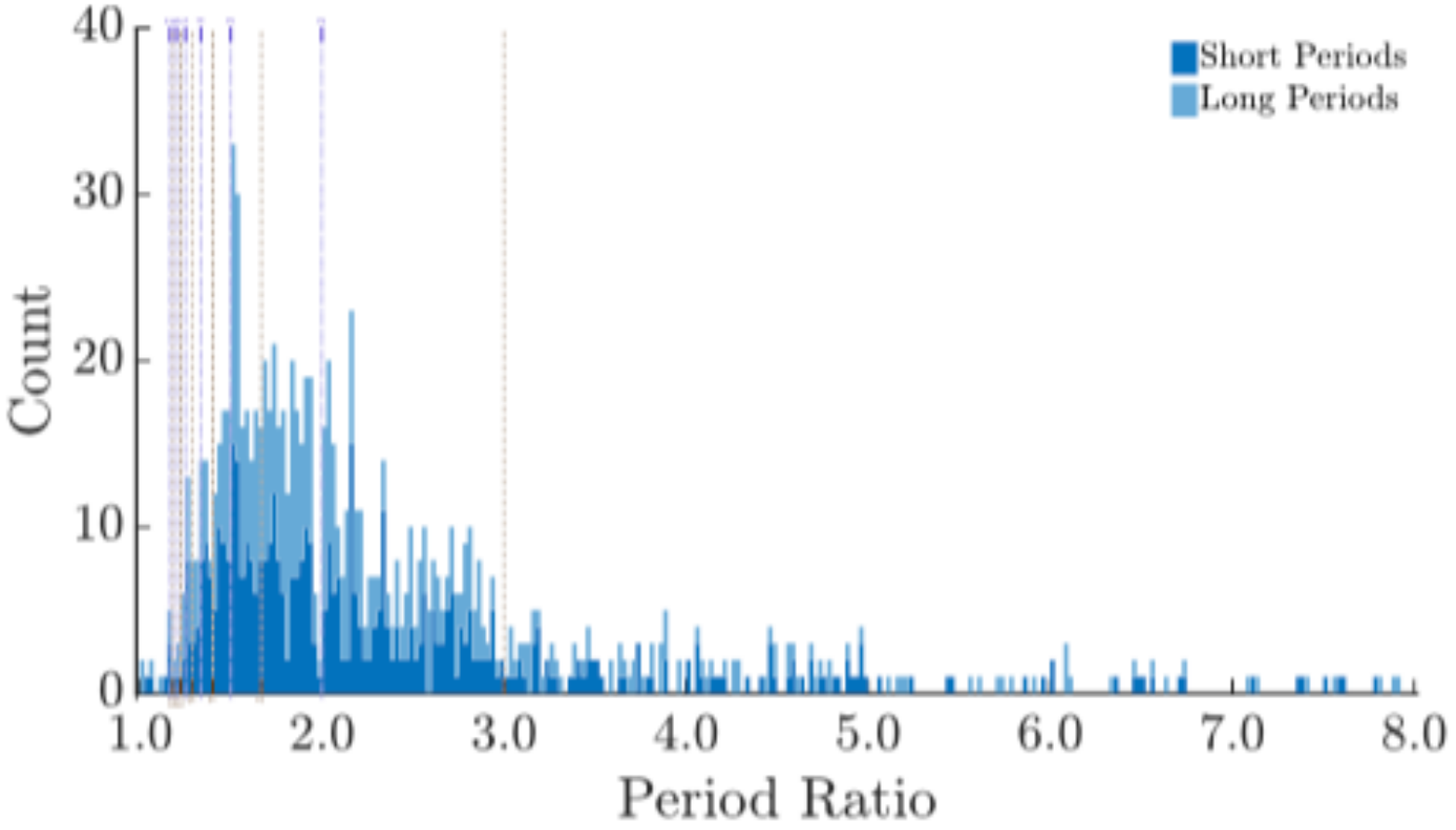


Figure 17. The period ratio distribution split by the median radius (1.69 $R_\oplus$) of the inner planet of all adjacent planet pairs, displayed as a kernel density estimator with a top hat kernel of width 1/64. There are 475 pairs where the inner planet is smaller or equal to the median, with smaller inner planets in the left panel and larger inner planets on the right.

Period Ratios split by median period



Results for 1st-order Mean Motion Resonances

- Significant excess of planet pairs just wide of MMRs
- Significant deficit of planet pairs just narrow of MMRs
- Dips and peaks near MMRs almost cancel out
  - only slight net excess of planet pairs near MMRs
  - most *Kepler* planets are neither in nor near resonance