

# Planetary system architecture and hot Jupiter formation

Melvyn B. Davies

Department of Astronomy and Theoretical Physics

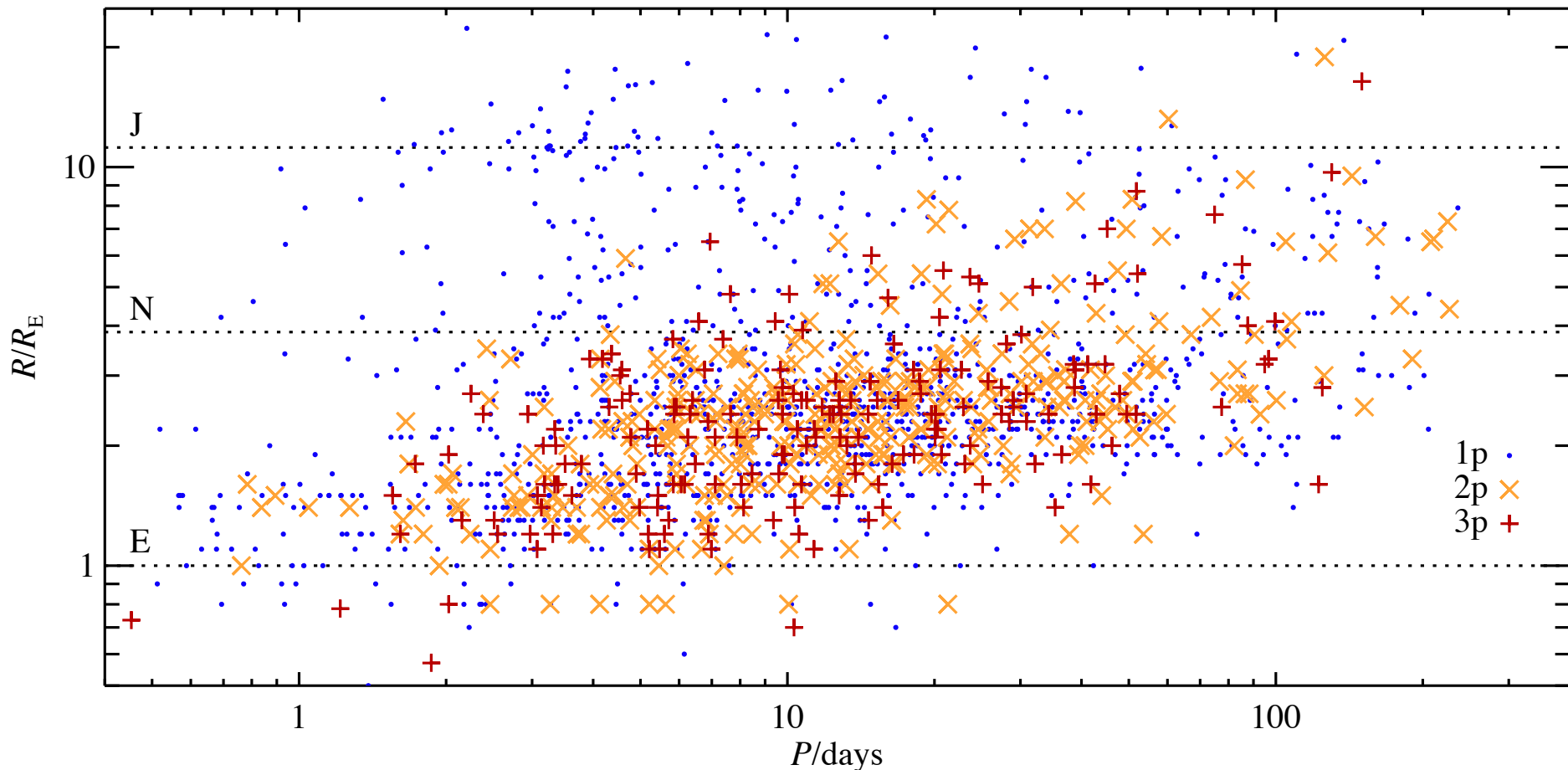
Lund University

**KEY IDEA #1:** *The relative rates of multiple transits for systems observed by Kepler tell us about the properties of these planetary systems.*

Johansen, Davies, Church & Holmelin, 2012, ApJ, 758, id. 39;  
arXiv:1206.6898v2

# Our selected sample (1t, 2t & 3t)

1t:2t:3t = 1183:187:62



Kepler data from Batalha et al. (2012)

# Could all planets be in multiple systems?

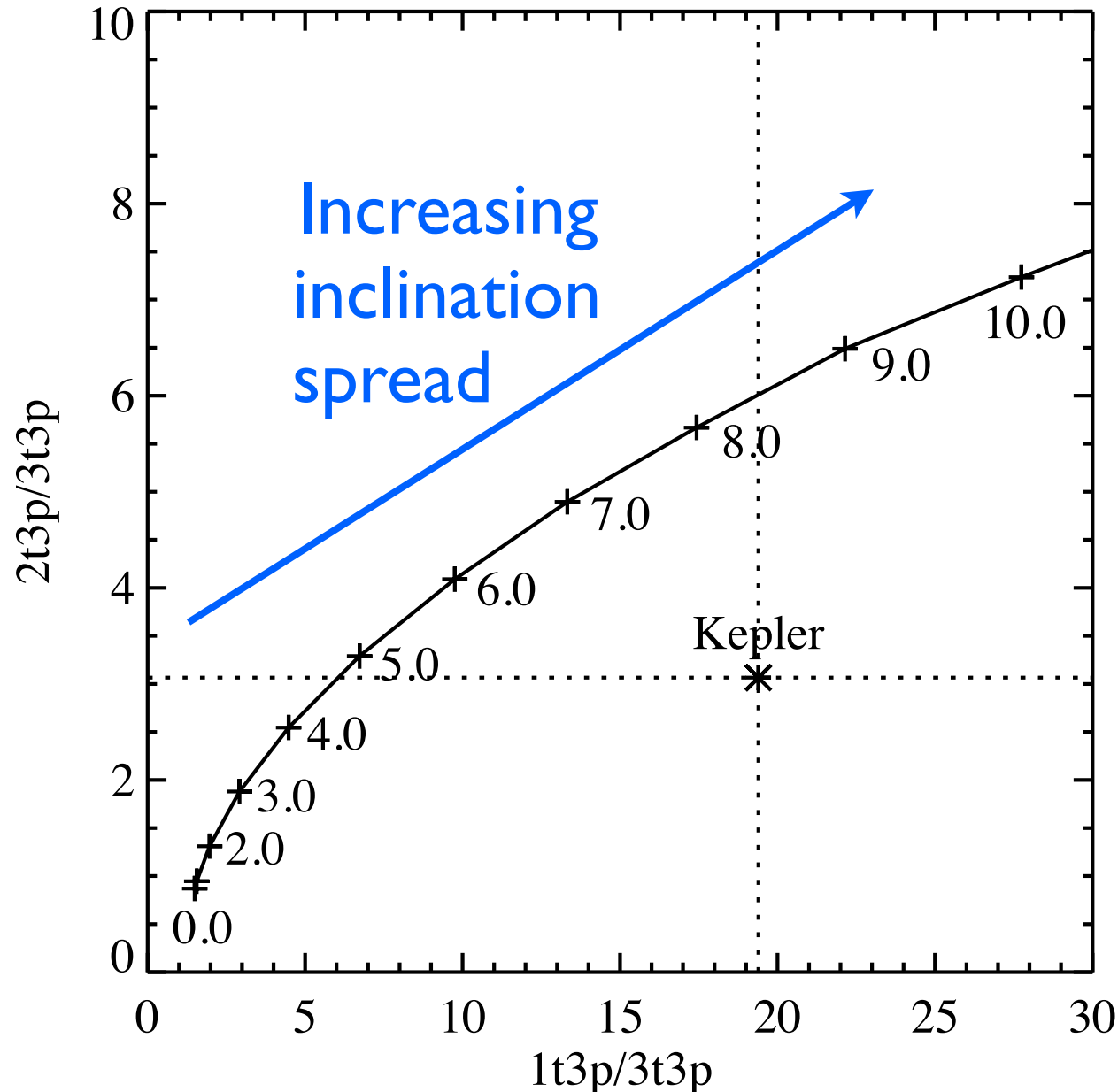
To test the idea, build a sample of intrinsically 3-planet (“3p”) systems

Observe them from randomly chosen directions and see how many 1t, 2t, 3t systems we see

Use observed 3t systems as templates for our 3p systems

One free parameter: the distribution of inclinations

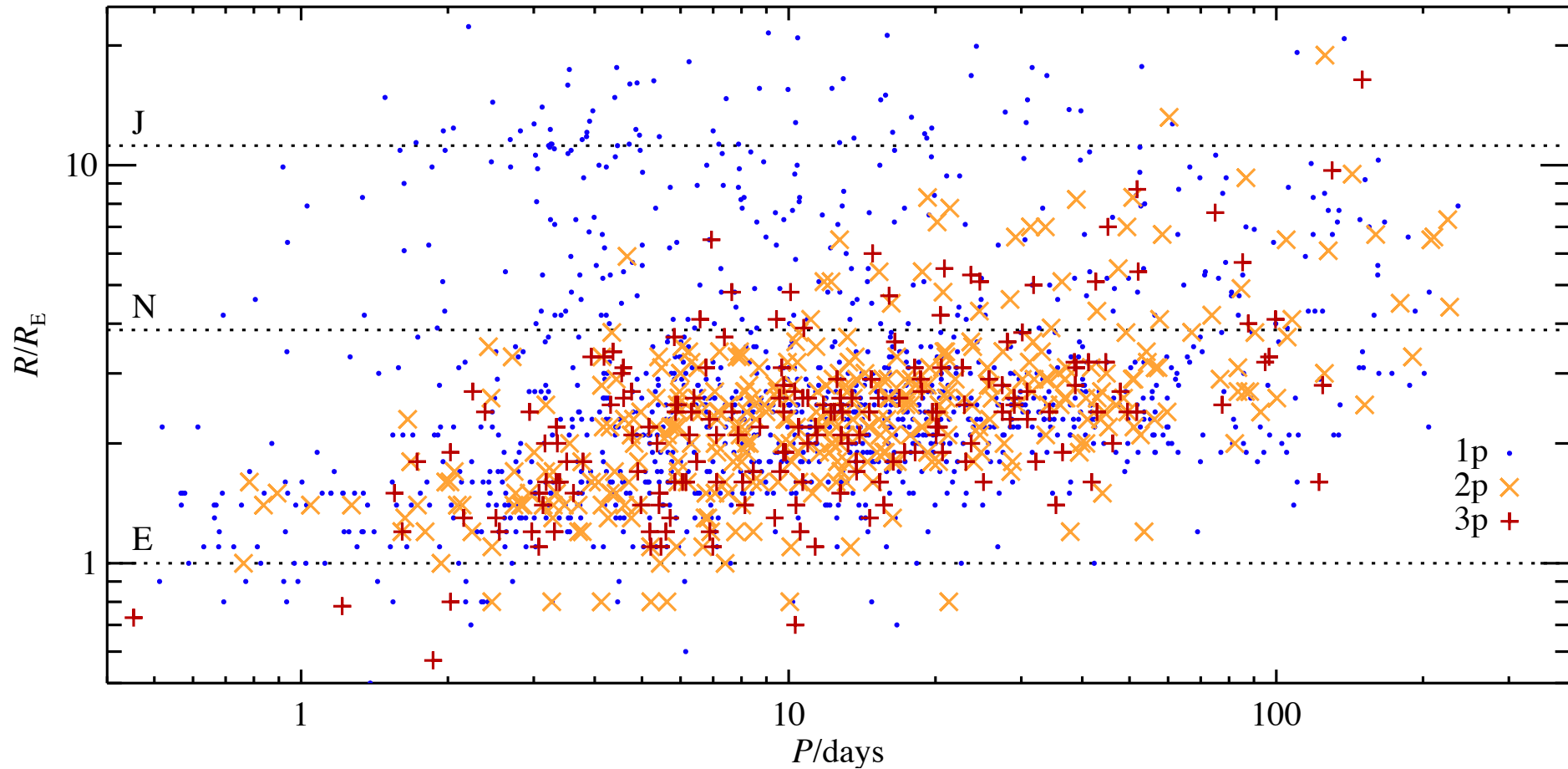
# Making everything from 3p systems



Kepler  
planetary  
systems are  
*FLAT*

Kepler sees  
more  $1t$   
than come  
from  $3p$

# Too many single planets



*...and essentially all Jupiters are single*

**KEY RESULTS #1:** *The relative rates of multiple transits for systems observed by Kepler tell us about the properties of these planetary systems:*

**Systems are flat**

**There is an excess of single planets**

**Hot Jupiters are single**

Johansen, Davies, Church & Holmelin, 2012, ApJ, 758, id. 39;  
arXiv:1206.6898v2

*KEY IDEA #2: One may produce a hot Jupiter by injecting a Jupiter-mass planet into a Kepler 3p system.*

**3p+J**

Mustill, Davies & Johansen, *ApJ*, in press; arXiv:1502.06971

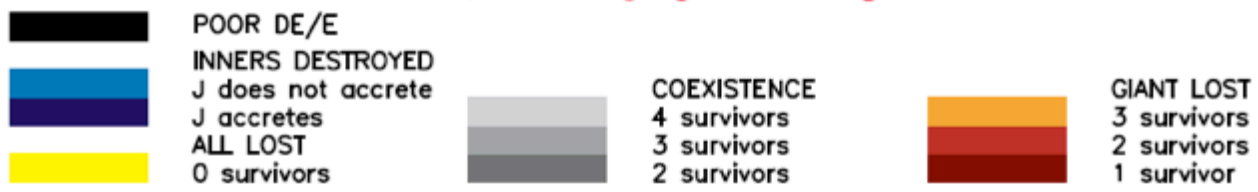
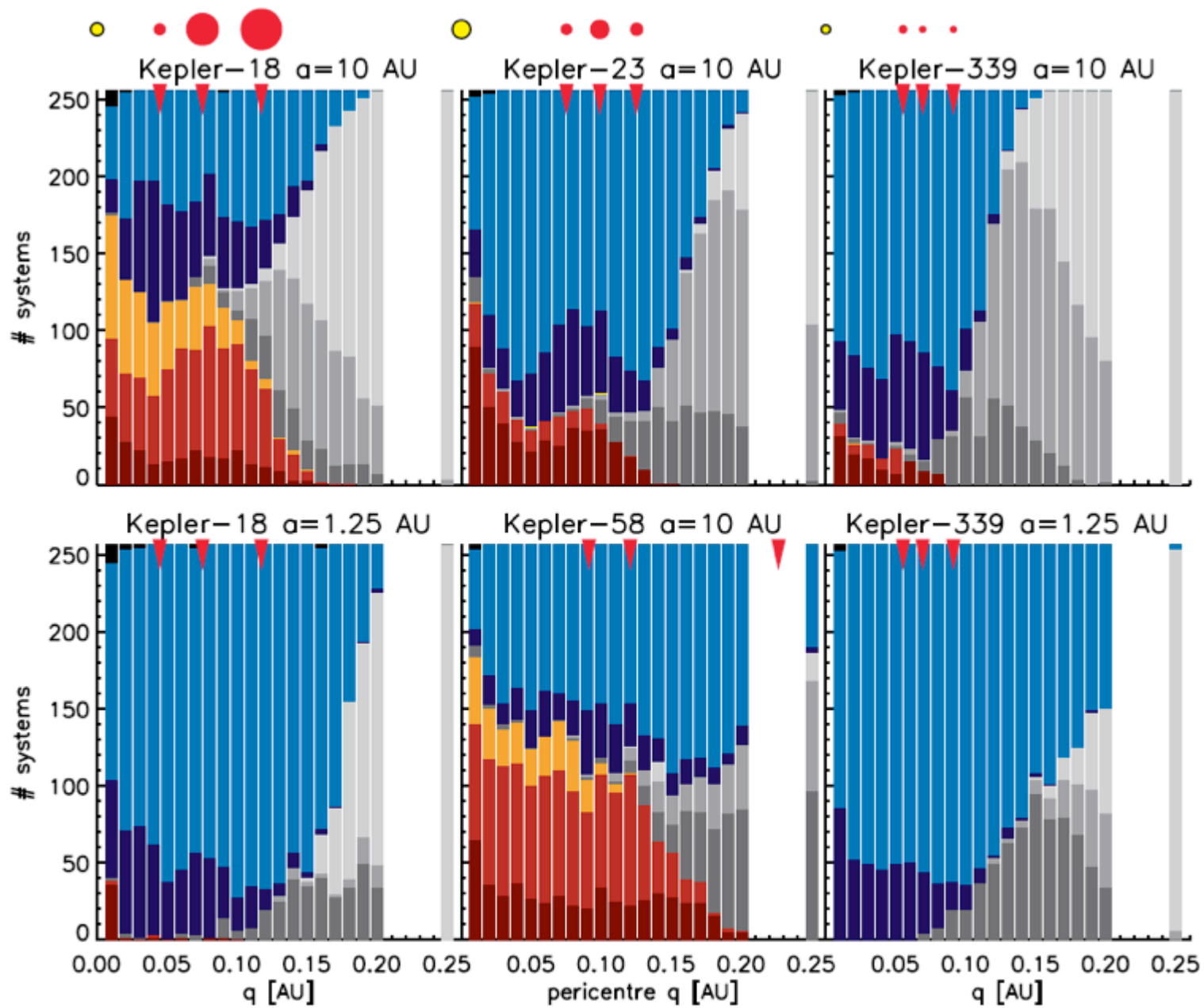


TABLE 2  
PLANETARY PARAMETERS USED IN OUR INTEGRATIONS

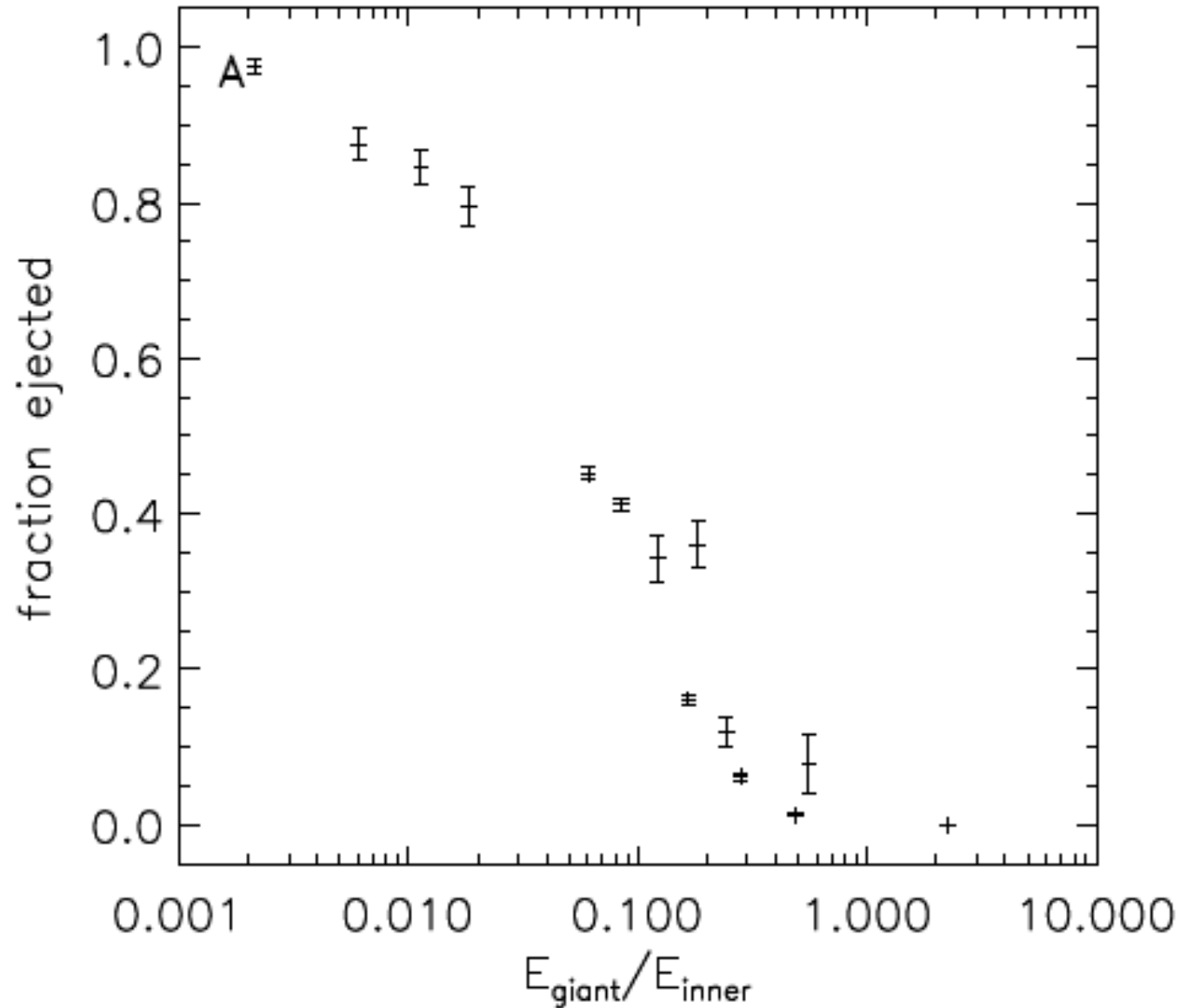
Name	$a/\text{AU}$	$M_{pl}/M_{\oplus}$	$R_{pl}/R_{\oplus}$	Reference
Kepler-18 b	0.0477	6.9 <sup>a</sup>	2.00	1
Kepler-18 c	0.0752	17.3	5.49	1
Kepler-18 d	0.1172	16.4	6.98	1
Kepler-23 b	0.0749	4.86 <sup>a</sup>	1.89	2
Kepler-23 c	0.0987	8.05 <sup>a</sup>	3.25	2
Kepler-23 d	0.125	5.60 <sup>a</sup>	2.20	2
Kepler-58 b	0.0909	18.0	2.78	3
Kepler-58 c	0.1204	17.5	2.86	3
Kepler-58 d	0.2262	7.33 <sup>a</sup>	2.94	4
Kepler-339 b	0.0551	3.76 <sup>a</sup>	1.42	4
Kepler-339 c	0.0691	1.74 <sup>a</sup>	1.15	4
Kepler-339 d	0.0910	1.86 <sup>a</sup>	1.17	4

REFERENCES. — (1) [Cochran et al. \(2011\)](#); (2) [Ford et al. \(2012\)](#); (3) [Wu & Lithwick \(2013\)](#); (4) [Rowe et al. \(2014\)](#)

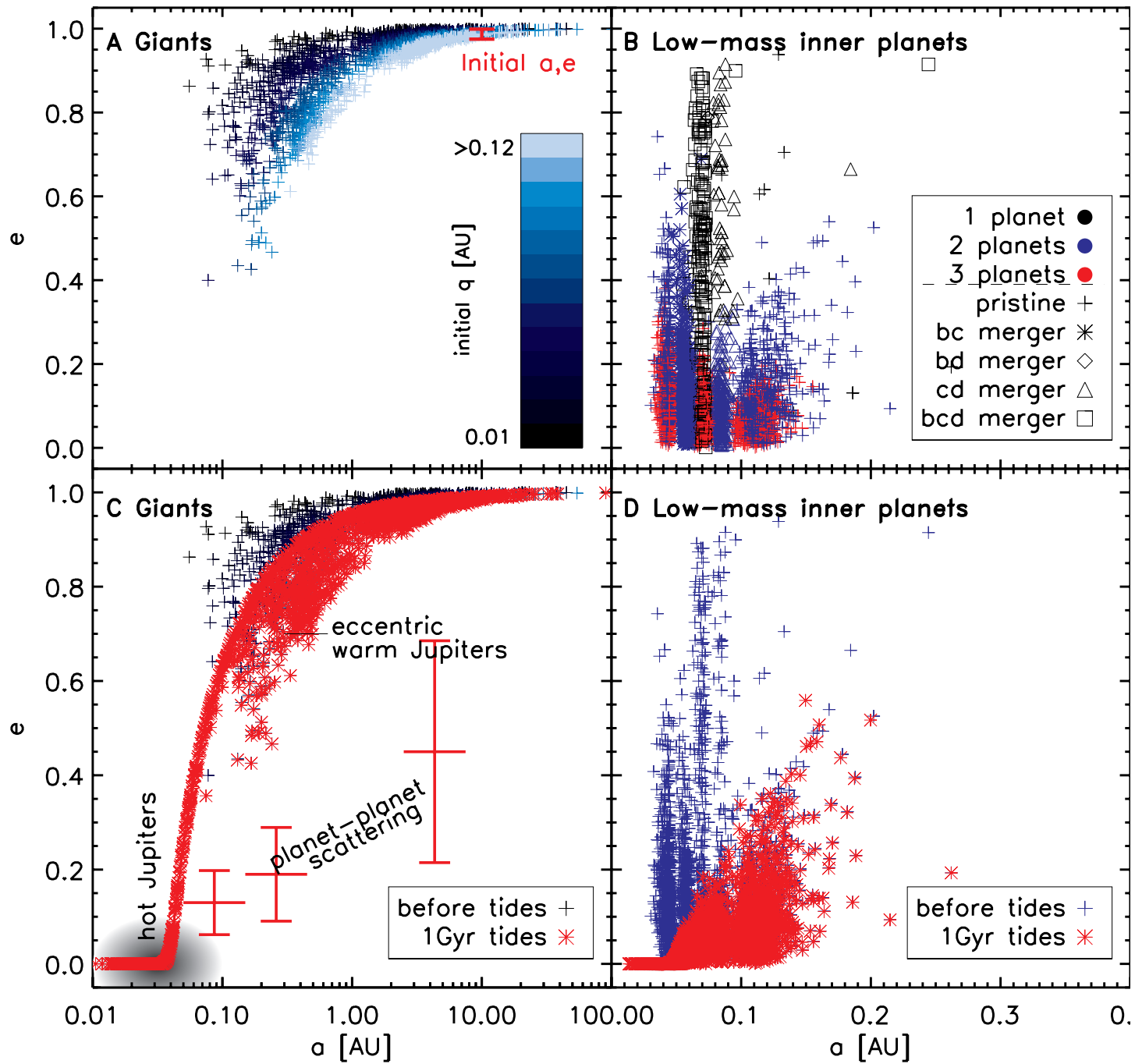
<sup>a</sup> Mass is not measured directly: estimated from a mass–radius or density–radius relation ([Weiss & Marcy 2014](#)).



# Outcome depends on binding energies



# Some captured Jupiters produce hot Jupiters



**KEY RESULTS #2: *One may produce a hot Jupiter by injecting a Jupiter-mass planet into a Kepler 3p system.***

**Jupiter-mass planets are often captured**  
**Tidal interaction produces hot and warm Jupiters**  
**3p planets either collide with star or with Jupiter**  
**1p produced relatively rarely**

**Mustill, Davies & Johansen, ApJ, in press; arXiv:1502.06971**

# Summary

Planetary systems are flat

There is an excess of single planets

Hot Jupiters are single

$3p+J$  encounters can produce Hot Jupiters

$3p$  planets collide with star or Jupiter

$3p+p$  encounters in Alex Mustill talk



