

# DECODING HOT JUPITER SYSTEMS: Unveiling Formation Clues from Giant Planet Populations


Jon Zink

December 12<sup>th</sup>, 2023

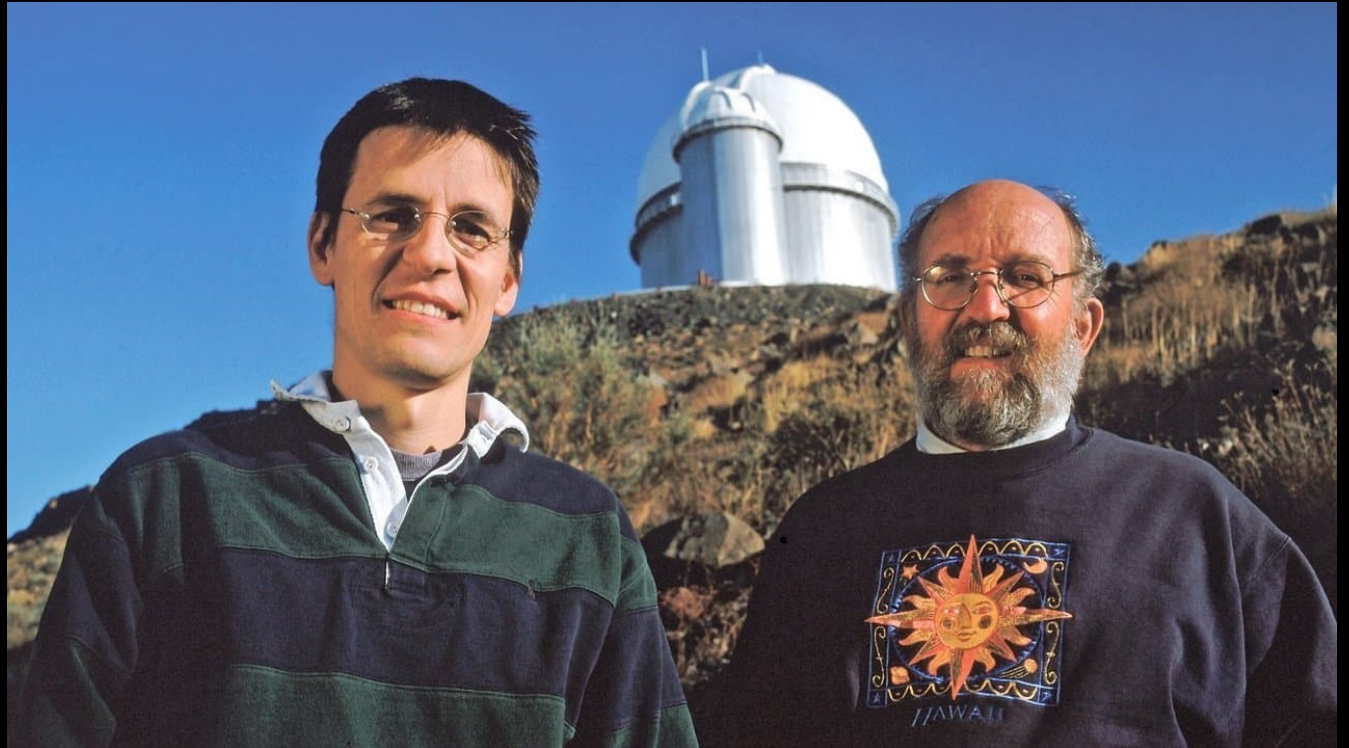
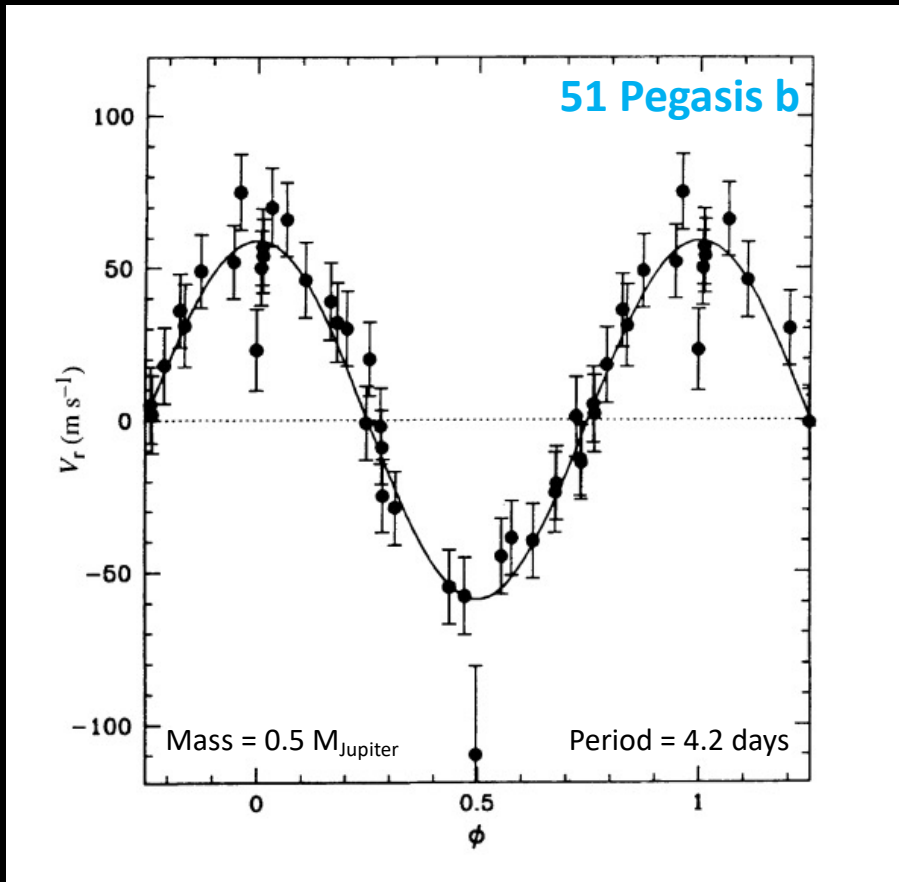
ExSoCal

NASA Hubble Fellow  
Caltech

[www.JonZink.com](http://www.JonZink.com)

 [@jonKzink](https://twitter.com/jonKzink)

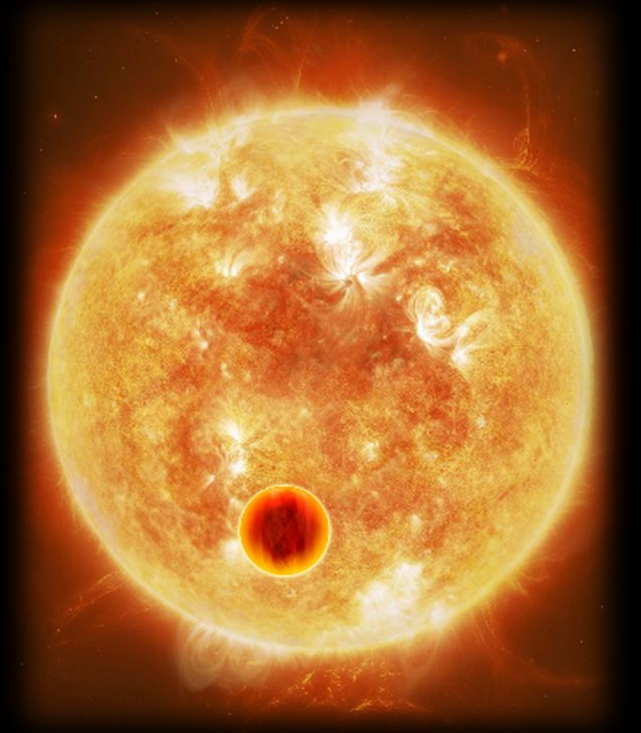
# 51 Peg. b: A Nobel Worthy Planet



Didier Queloz & Michel Mayor 1995

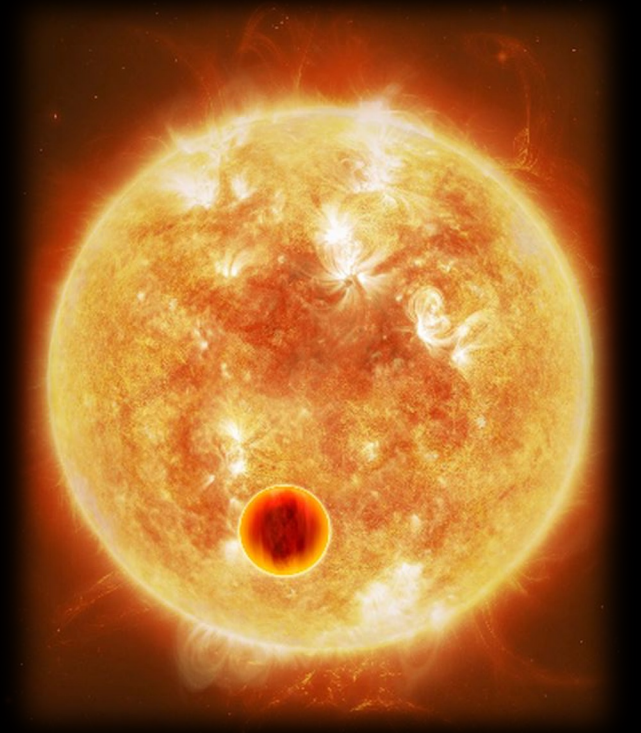
# Hot Jupiter Are Strange

- Orbital periods between 1 and 10 days  
(less than 25% the orbital radius of Mercury)
- Dayside temperature  $\sim 2700\text{K}$   
(hotter than many late M-dwarfs)



# Hot Jupiter Are Strange

- Orbital periods between 1 and 10 days  
(less than 25% the orbital radius of Mercury)
- Dayside temperature  $\sim 2700\text{K}$   
(hotter than many late M-dwarfs)
- How did they come to exist?

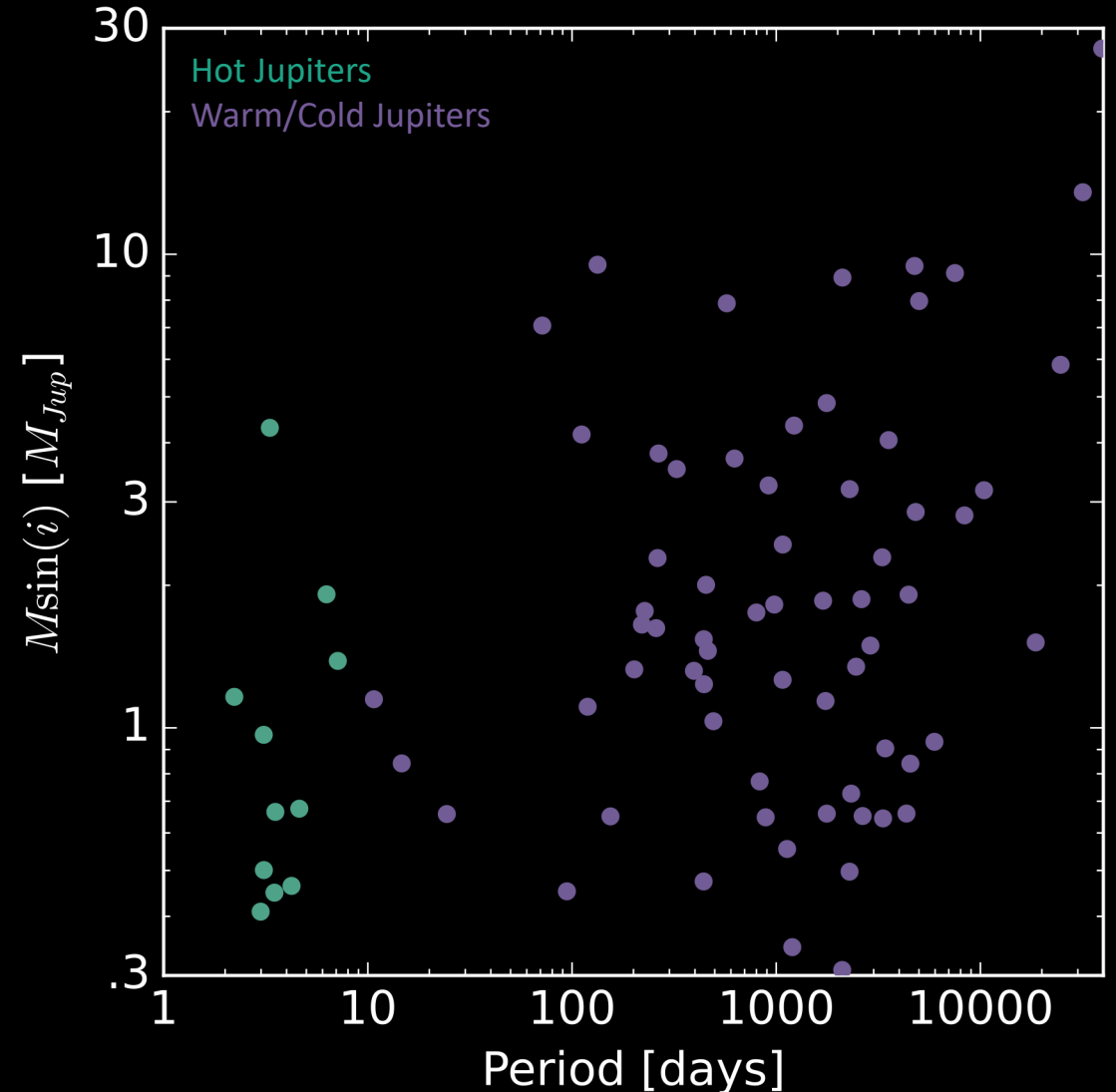


# A Homogenous RV Sample

- The California Legacy Survey (CLS) monitored the radial velocities of 719 stars over 30 years. (Rosenthal et al. 2021)

## Identified 127 Planets

- 11 Hot Jupiter systems
- 46 Warm/Cold Jupiter systems

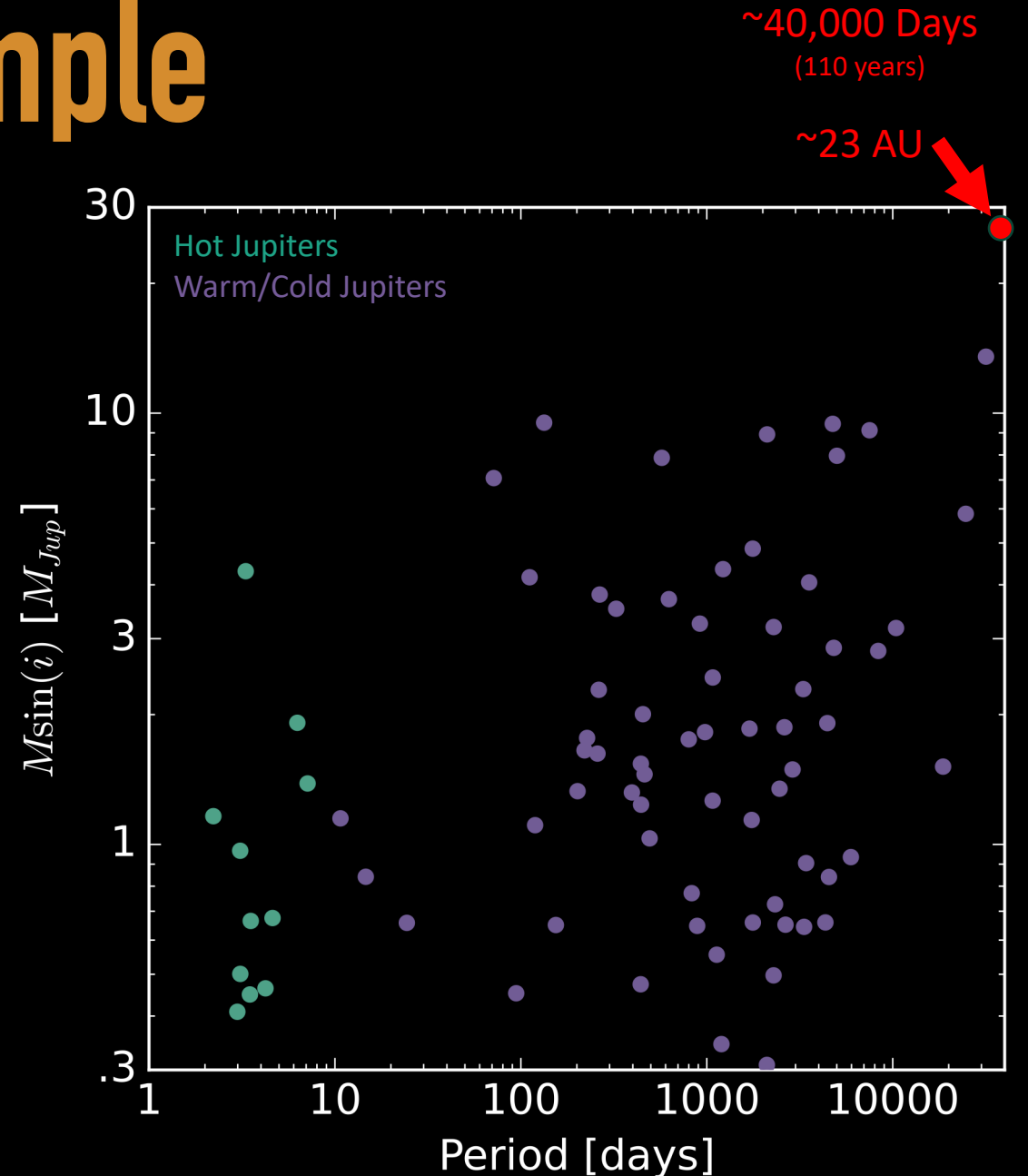


# A Homogenous RV Sample

- The California Legacy Survey (CLS) monitored the radial velocities of 719 stars over 30 years. (Rosenthal et al. 2021)

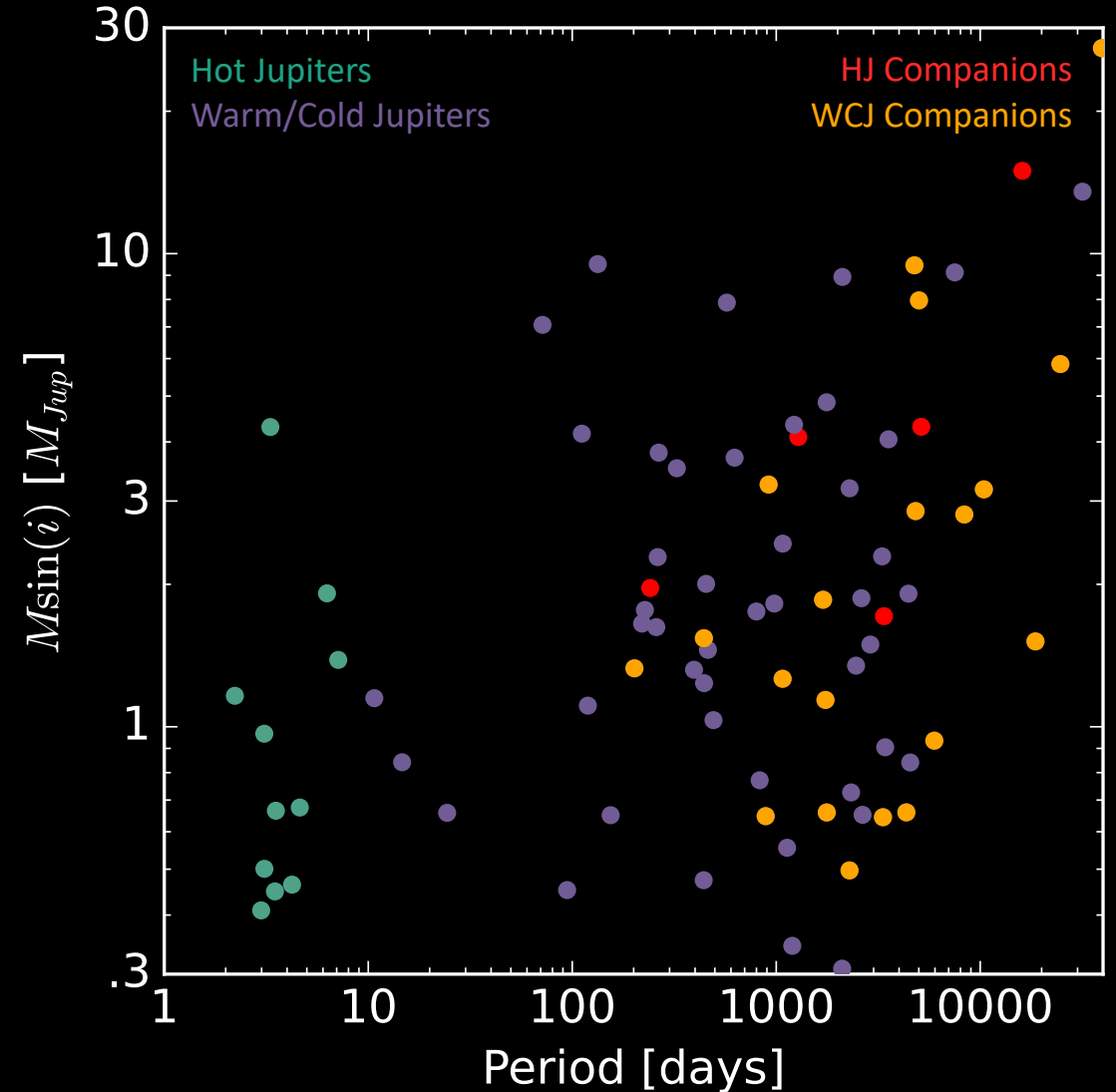
## Identified 127 Planets

- 11 Hot Jupiter systems
- 46 Warm/Cold Jupiter systems



# OUTER COMPANION SAMPLE

- 5 Hot Jupiter **Companions**
- 11 Warm/Cold Jupiter **Companions**



# Giant Multiplicity Is Ubiquitous

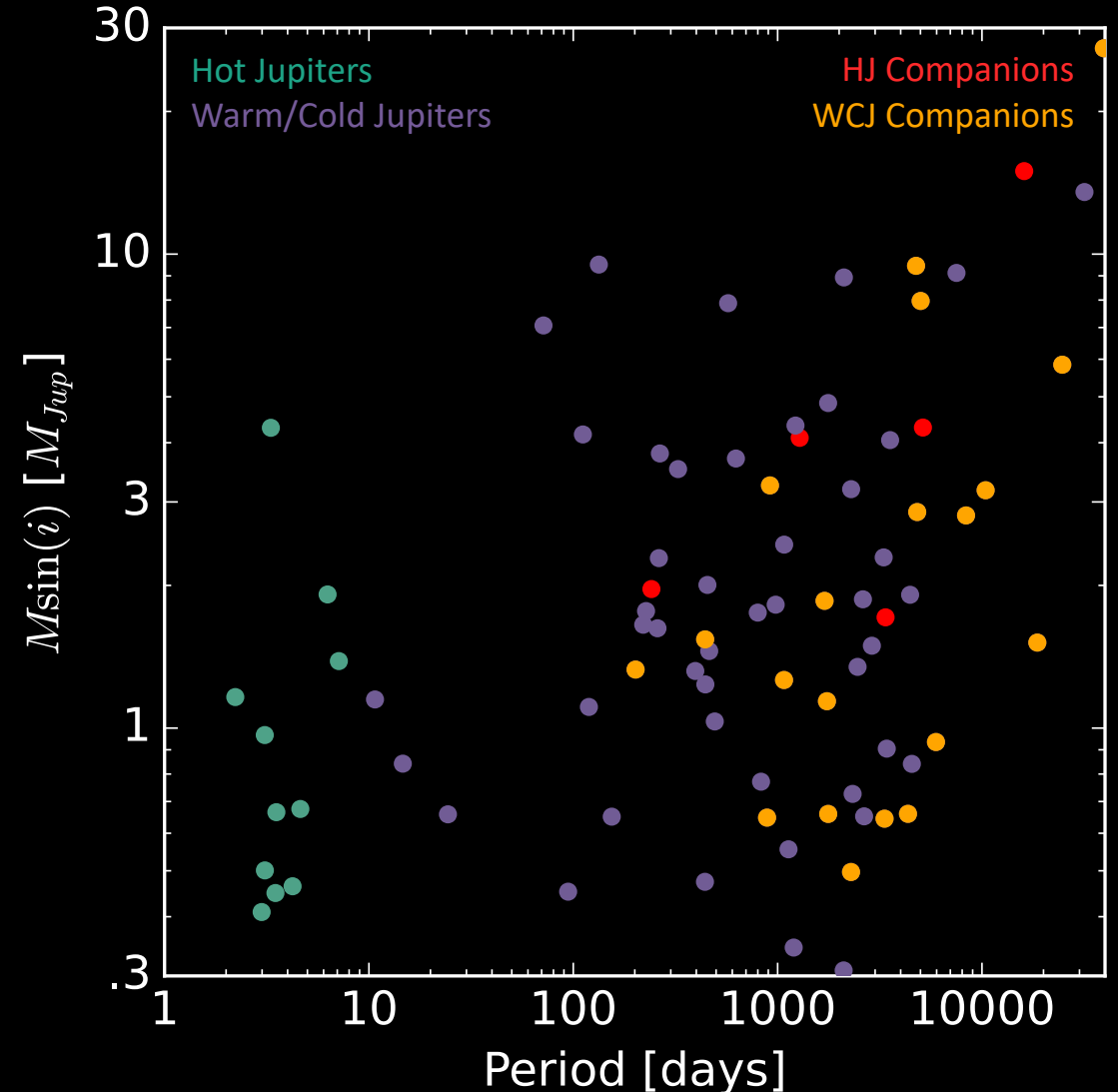
## OUTER COMPANION SAMPLE

- 5 Hot Jupiter **Companions**
- 11 Warm/Cold Jupiter **Companions**

## COMPANIONSHIP STATISTICS

$1.3 \pm_{0.6}^{1.0}$  Companions per HJ

$1.0 \pm_{0.3}^{0.3}$  Companions per WCJ



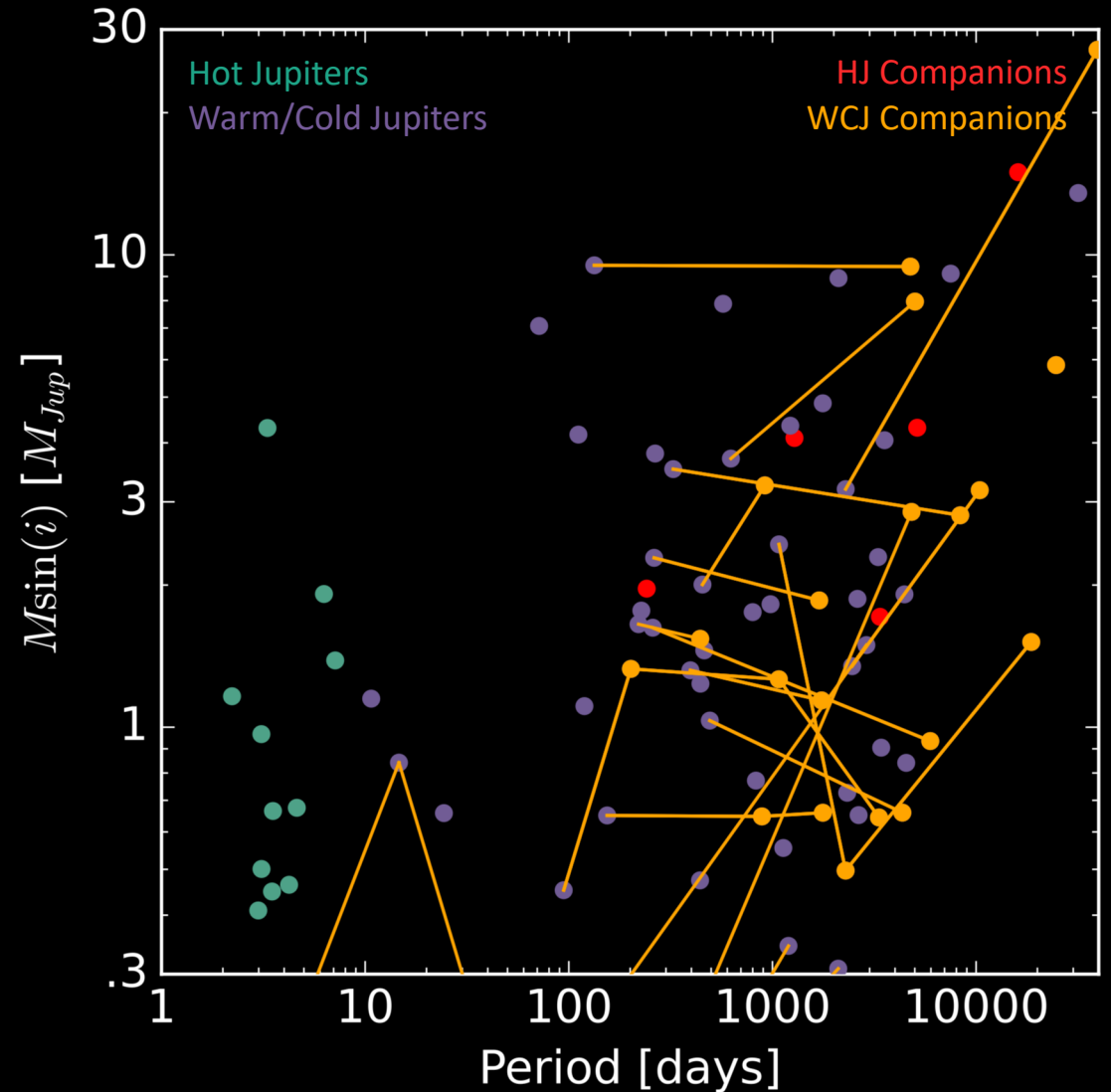


# AVERAGE MASS RATIO FOR EACH ARCHITECTURE

Warm/Cold Jupiter Systems

$$\frac{M_{Outer}}{M_{Inner}} \sim 1$$

Random Draw



# HJs Require 3X Mass Companions

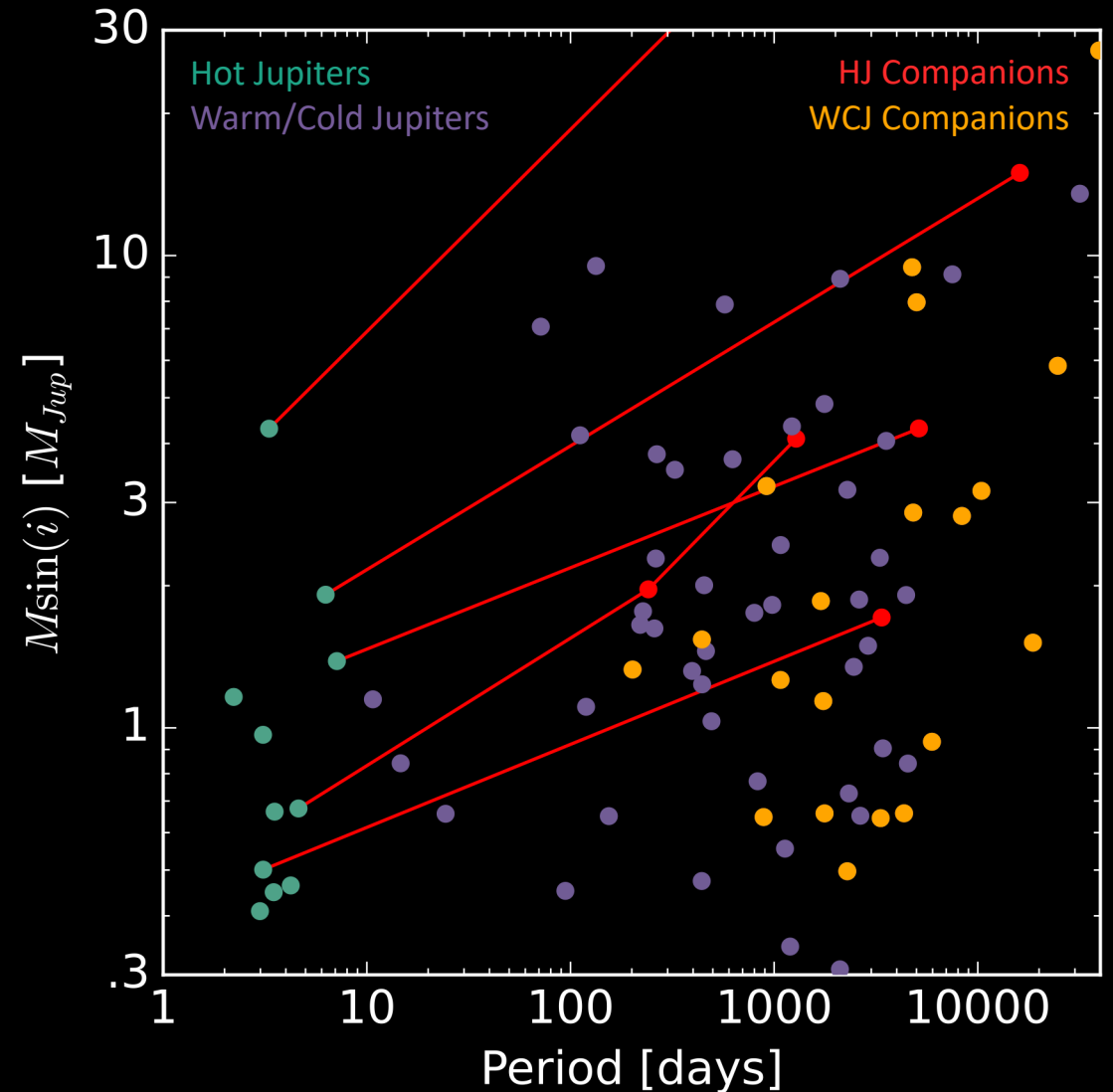
## AVERAGE MASS RATIO FOR EACH ARCHITECTURE

Warm/Cold Jupiter Systems

$$\frac{M_{Outer}}{M_{Inner}} \sim 1 \quad \text{Random Draw}$$

Hot Jupiter Systems

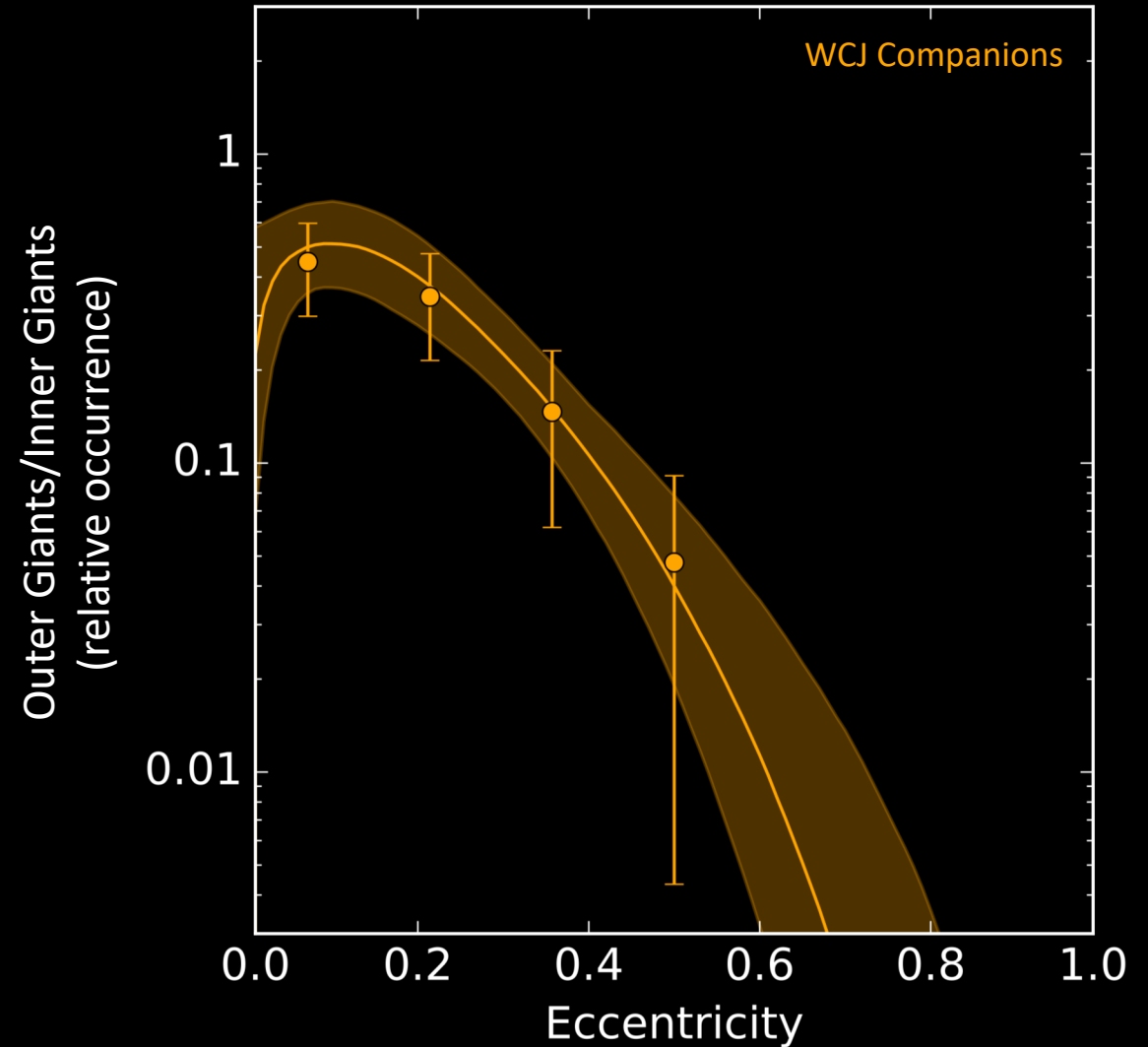
$$\frac{M_{Outer}}{M_{Inner}} > 3 \quad \text{Highly Order}$$



# AVERAGE ECCENTRICITY FOR EACH ARCHITECTURE

Warm/Cold Jupiter Companions

$$\langle e \rangle = 0.19 \pm 0.02$$



# HJs Companions Are More Eccentric

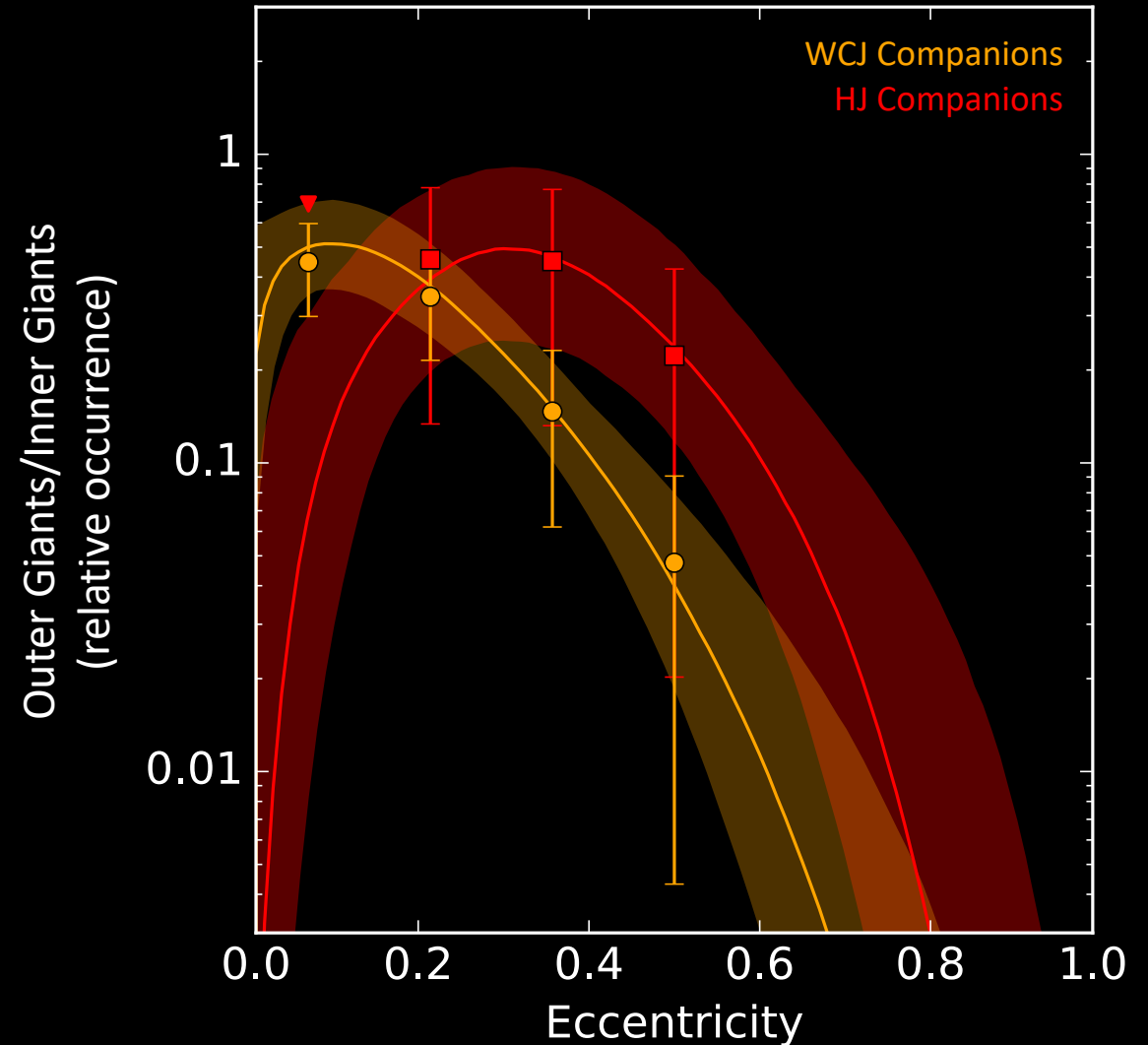
AVERAGE ECCENTRICITY  
FOR EACH ARCHITECTURE

Warm/Cold Jupiter Companions

$$\langle e \rangle = 0.19 \pm 0.02$$

Hot Jupiter Companions

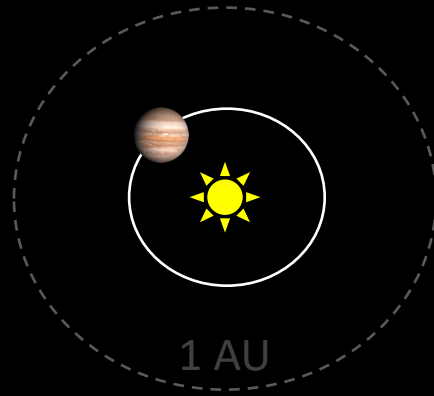
$$\langle e \rangle = 0.34 \pm 0.05 \quad 3\sigma \text{ Higher}$$



# Formation Pathways:

## In-Situ (Batygin et al. 2016)

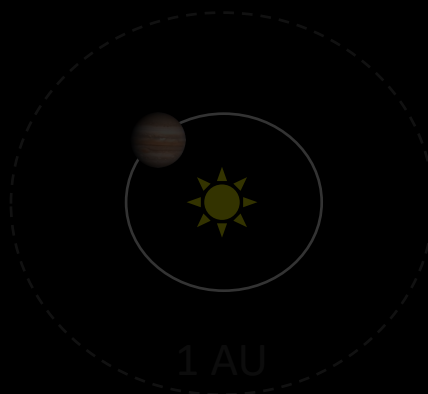
HJs form within 1 AU and undergo minimal migration.



# Formation Pathways:

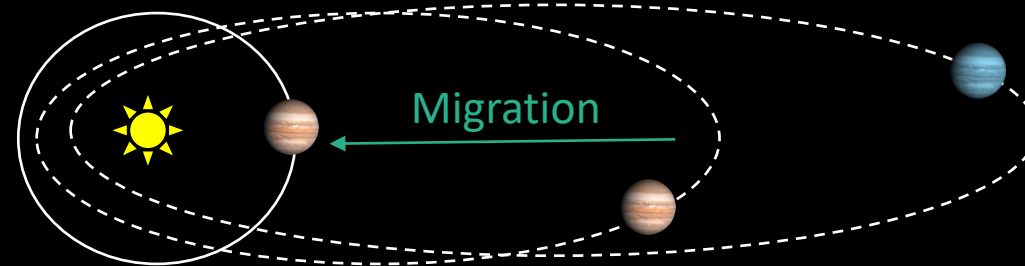
## In-Situ (Batygin et al. 2016)

HJs form within 1 AU and undergo minimal migration.



## Coplanar High-Eccentricity Migration (Petrovich 2015)

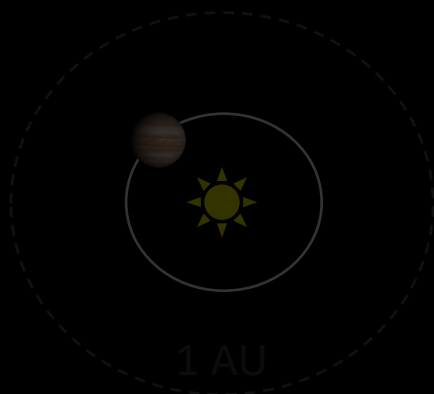
Two cold giants exchange angular momentum and tidally interact with the host star, culminating in a HJ.



# Formation Pathways:

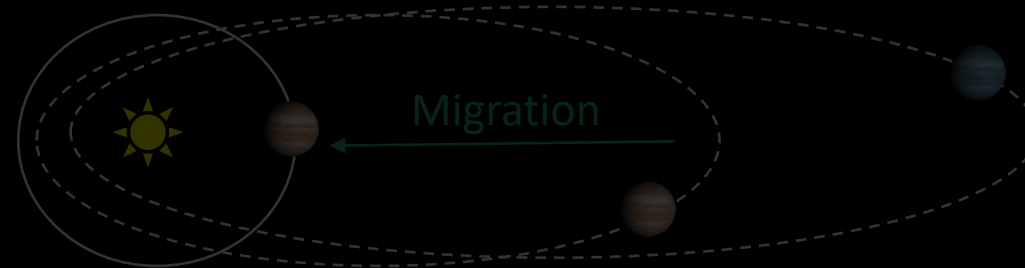
## In-Situ (Batygin et al. 2016)

HJs form within 1 AU and undergo minimal migration.



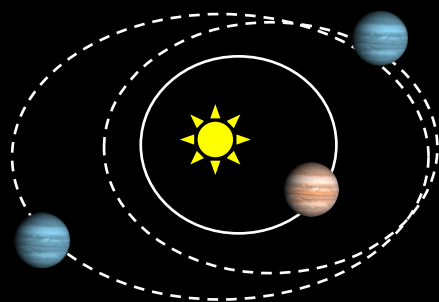
## Coplanar High-Eccentricity Migration (Petrovich 2015)

Two cold giants exchange angular momentum and tidally interact with the host star, culminating in a HJ.



## Secular Chaos (Wu & Lithwick 2011)

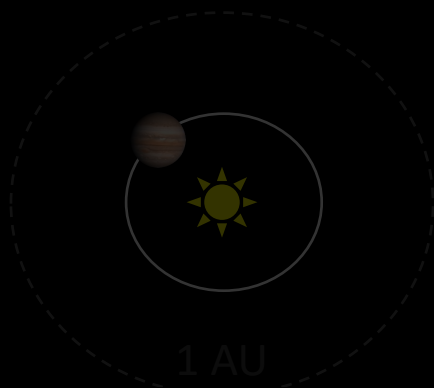
Three or more cold giants dynamically interact to produce a HJ.



# Formation Pathways:

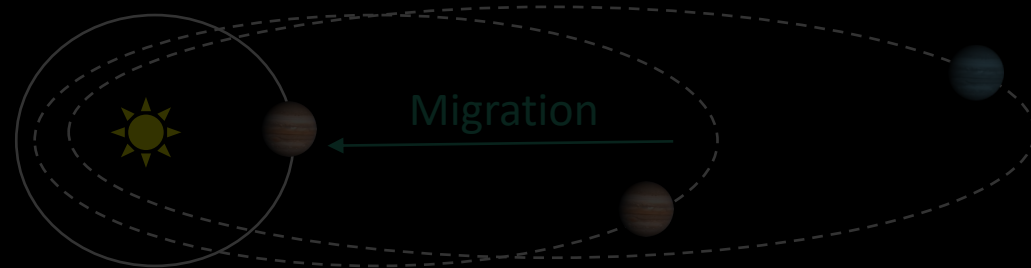
## In-Situ (Batygin et al. 2016)

HJs form within 1 AU and undergo minimal migration



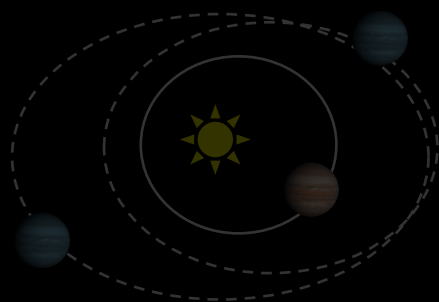
## Coplanar High-Eccentricity Migration (Petrovich 2015)

Two cold giants exchange angular momentum and tidally interact with the host star, culminating in a HJ.



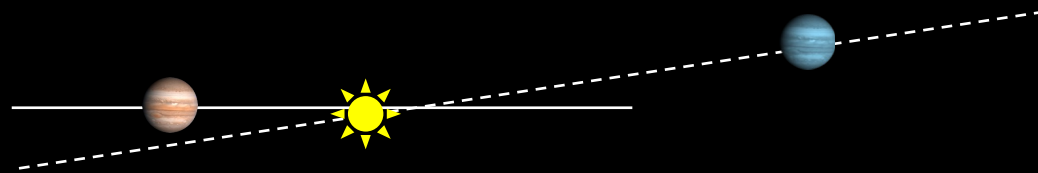
## Secular Chaos (Wu & Lithwick 2011)

Three or more cold giants dynamically interact to produce a HJ.



## Lidov-Kozai Cycling (Wu & Murray 2003)

Two cold giants with high initial mutual inclination undergo oscillations in eccentricity and inclination, yielding a HJ.





# Formation Pathways

Mechanism:	2 Giant Multiplicity:	3X Mass Companion:	Enhanced E. Companion:	Obliquity Distribution:
In-Situ				
Coplanar High-E.				
Secular Chaos				
Kozai Oscillations				

# Formation Pathways

Mechanism:	2 Giant Multiplicity:	3X Mass Companion:	Enhanced E. Companion:	Obliquity Distribution:
In-Situ	X	X	X	O
Coplanar High-E.	O	O	O	O
Secular Chaos	X	O	O	X
Kozai Oscillations	O	O	O	X

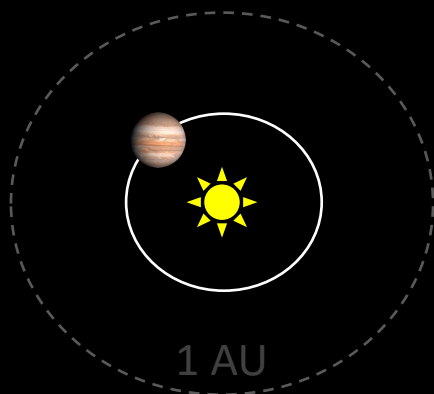
# Formation Pathways

Mechanism:	2 Giant Multiplicity:	3X Mass Companion:	Enhanced E. Companion:	Obliquity Distribution:
In-Situ	X	X	X	O
Coplanar High-E.	O	O	O	O
Secular Chaos	X	O	O	X
Kozai Oscillations	O	O	O	X

# Formation Pathways:

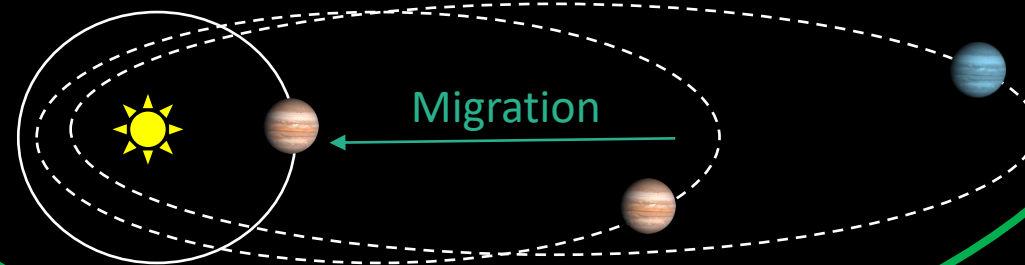
## In-Situ (Batygin et al. 2016)

HJs form within 1 AU and undergo minimal migration



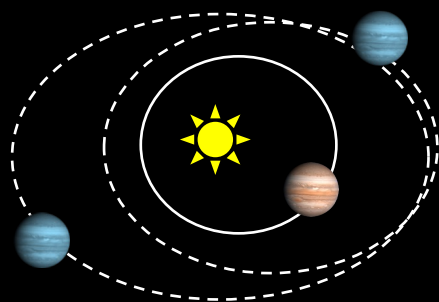
## Coplanar High-Eccentricity Migration (Petrovich 2015)

Two cold giants exchange angular momentum and tidally interact with the host star, culminating in a HJ.



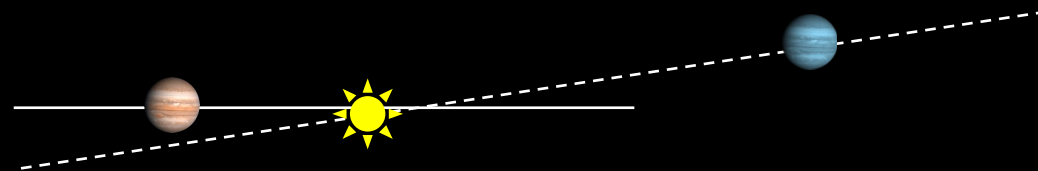
## Secular Chaos (Wu & Lithwick 2011)

Three or more cold giants dynamically interact to produce a HJ.



## Lidov-Kozai Cycling (Wu & Murray 2003)

Two cold giants with high initial mutual inclination undergo oscillations in eccentricity and inclination, yielding a HJ.



# JZ & ExSoCal: A Joint History

Presented as a  
CSUN Student

TIME



2015

2016

2017

2018

2020

2023

First ExSoCal

# JZ & ExSoCal: A Joint History

Got Engaged



TIME

2015

2016

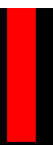
2017

2018

2020

2023

First ExSoCal



# JZ & ExSoCal: A Joint History

Got Engaged



2015

2016

First ExSoCal



TIME



2023

# JZ & ExSoCal: A Joint History

Got Engaged

Attended as a  
UCLA Grad

TIME

2015

2016

2017

2018

2020

2023

First ExSoCal





# JZ & ExSoCal: A Joint History

Got Engaged

Presented as a  
UCLA Grad

TIME

2015

2016

2017

2018

2020

2023

First ExSoCal



# JZ & ExSoCal: A Joint History



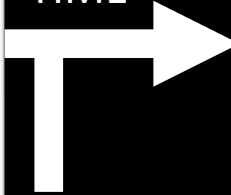
Got Engage

T

2015

First ExSoC

TIME

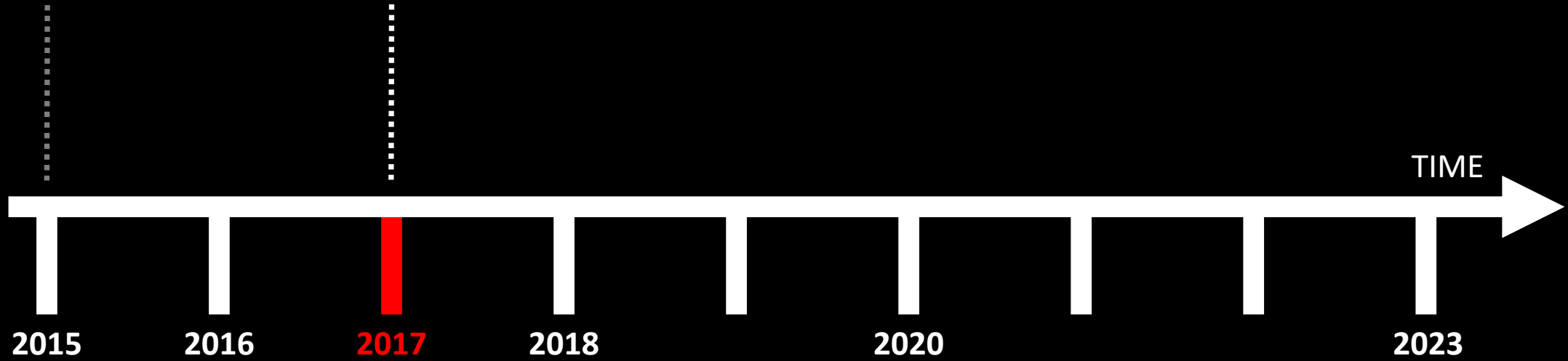


2023

# JZ & ExSoCal: A Joint History

Got Engaged

Got Married



First ExSoCal

# JZ & ExSoCal: A Joint History

Got Engaged

Got Married

Presented as a  
UCLA Grad

TIME

2015

2016

2017

2018

2020

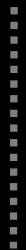
2023

First ExSoCal



# JZ & ExSoCal: A Joint History

Got Engaged



2015

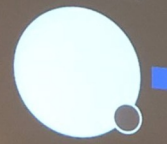
20

First ExSoCal

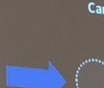
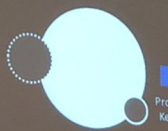


Some Planets are Lost Due to Injections

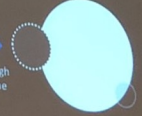
START with 4,034 Kepler Candidates



Inject One Planet Into Each System



ONLY 3,965 Kepler Candidates Returned



Process Through Kepler Pipeline

69 Candidates are Lost

TIME



2023

# JZ & ExSoCal: A Joint History

Got Engaged

Got Married

Presented as a  
UCLA Grad

TIME

2015

2016

2017

2018

2020

2023

First ExSoCal



# JZ & ExSoCal: A Joint History

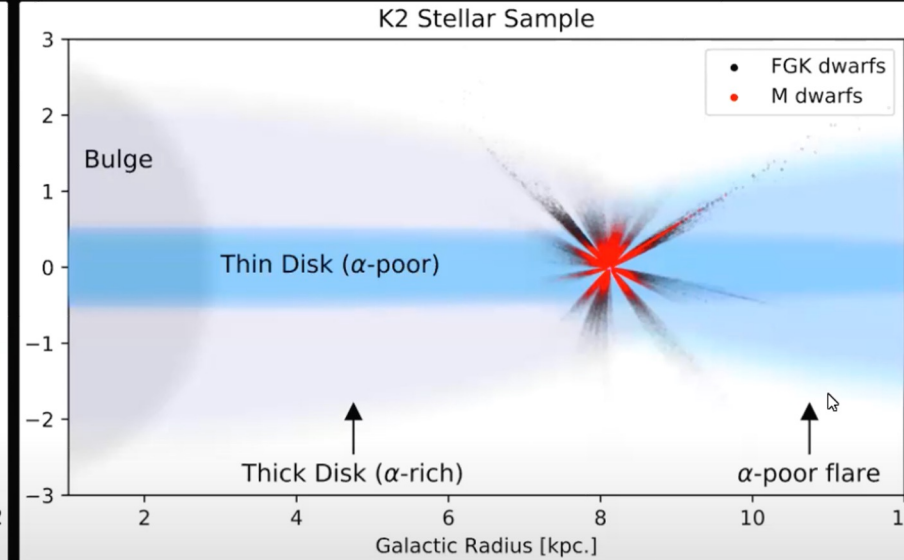
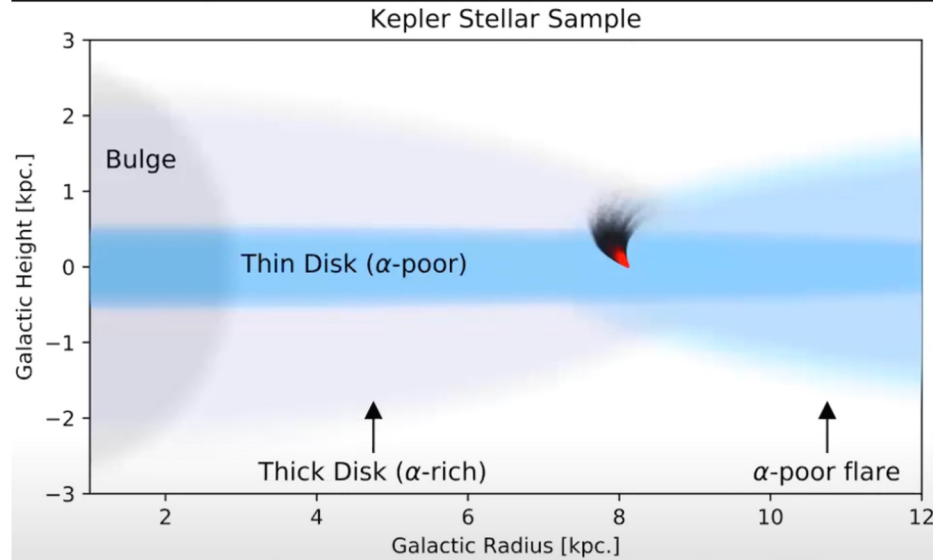
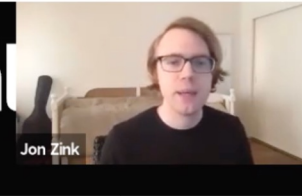
Got Engage

T

2015

First ExSoC

## K2 – Probing Different Regions of the Local Gal



Zink et al. 2020b

Adibekyan et al. (2012) – Evidence of alpha–element abundance surplus in exoplanet-hosting stars

K2 provides an opportunity to further consider the alpha elements effect planet on occurrence

2:20 / 15:41 • K2 - Probing Different Regions of the Local Gal >

# JZ & ExSoCal: A Joint History

Got Engaged

Got Married

Defended PhD

TIME

2015

2016

2017

2018

2020

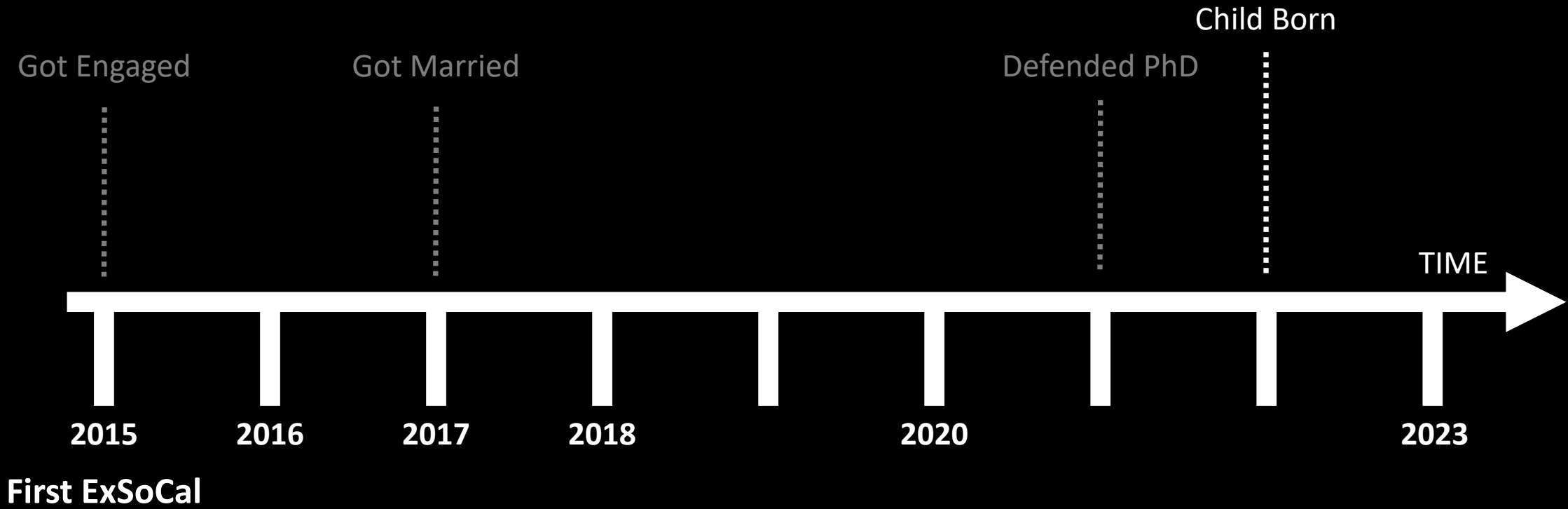
2023

First ExSoCal

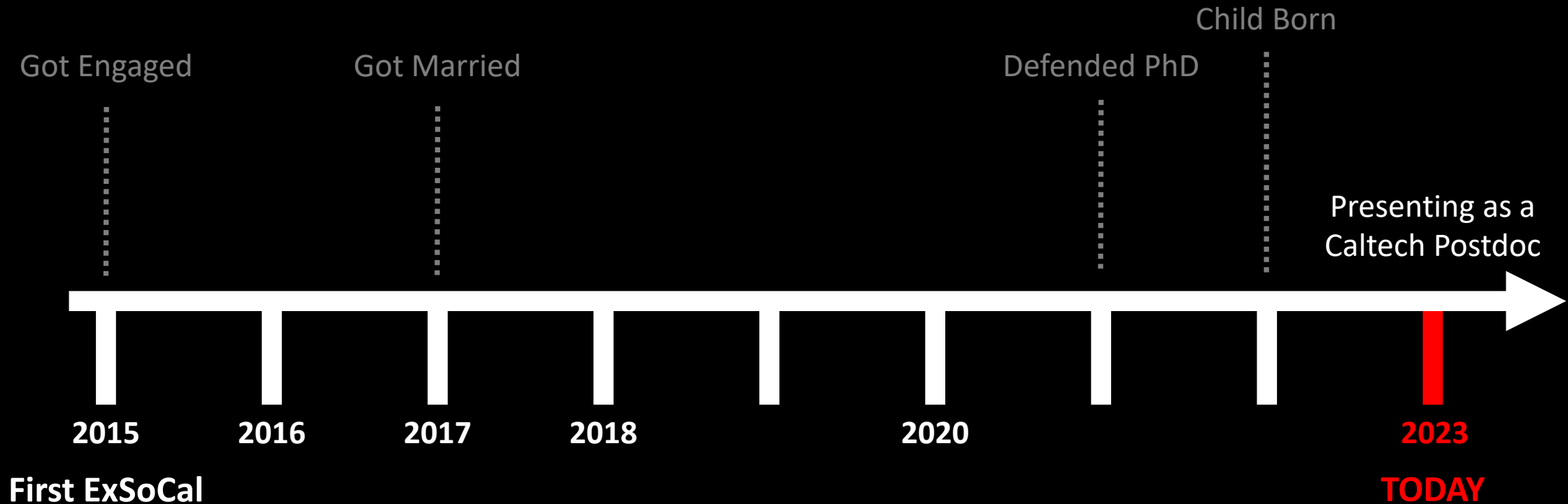




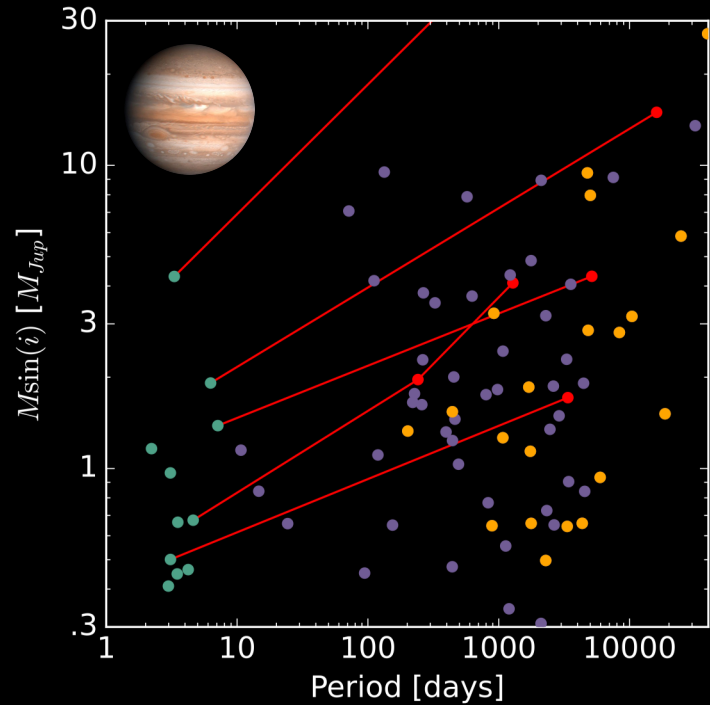
# JZ & ExSoCal: A Joint History



# JZ & ExSoCal: A Joint History



# Summary: DECODING HOT JUPITER SYSTEMS



Hot Jupiters have 3X more massive outer companions.



Thank you!