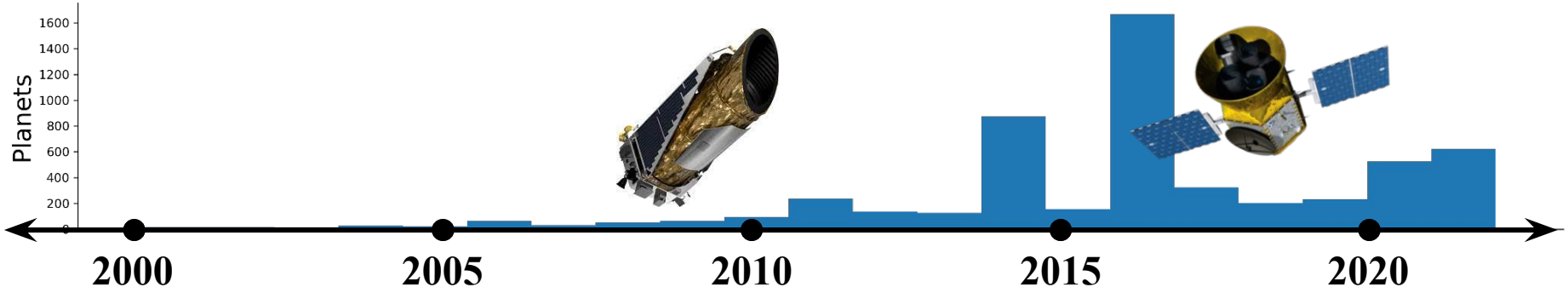
# Unveiling Orbital Architectures with the TESS-Keck Survey

Alex Polanski
and the TKS and CPS Team

# Transitioning into a new Era

Our field has made massive strides in past two decades.



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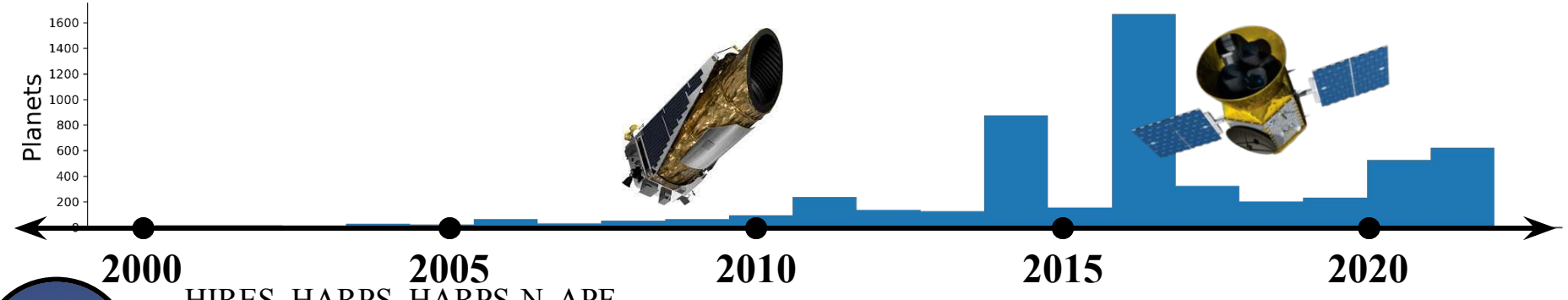


HIRES, HARPS, HARPS-N, APF

Long-term Radial Velocity Monitoring

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Long-term Radial Velocity Monitoring

KPF, EXPRES
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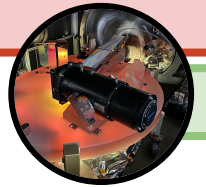

**The combination of new RV instrumentation and the maturation of long RV surveys means are we in the best position to investigate system architectures.**

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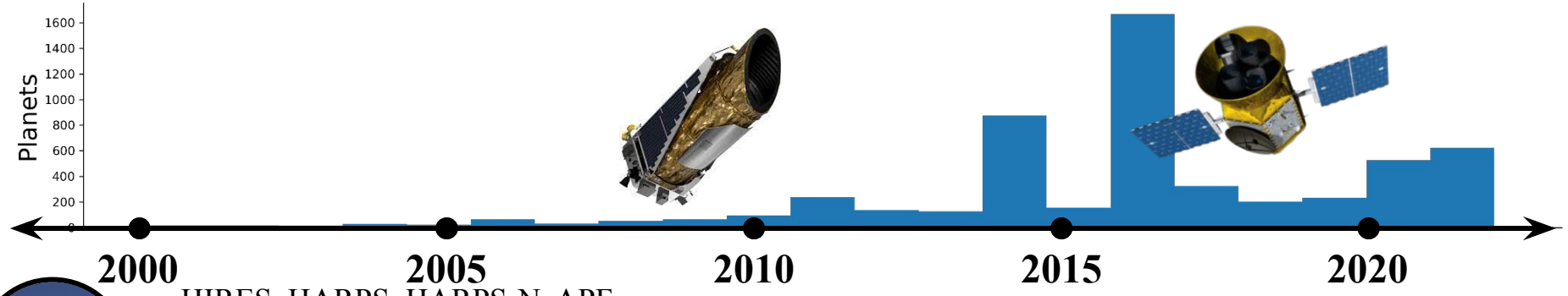


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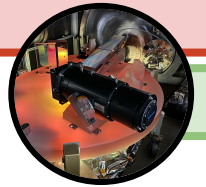

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**TFOP**

TESS Follow-up Observation Program

# TESS-Keck Survey

## A NASA-Keck Strategic Mission Support Program


**Andrew Howard***
**Arpita Roy***
Fei Dai
Aida Behmard
Sarah Blunt
Lee Rosenthal
Ryan Rubenzahl

**Benjamin Fulton***

**Erik Petigura***
Isabel Angelo
Mason MacDougall
Dakotah Tyler
Judah Van Zandt

**Courtney Dressing***
**Howard Isaacson***
Steven Giacalone
Emma Turtelboom
Andrew Mayo

**Paul Robertson***
Corey Beard
Rae Holcomb
Jack Lubin

**Stephen Kane***
Paul Dalba
Tara Fetherolf
Michelle Hill
Daria Pidhorodetska

**Natalie Batalha***
Joey Murphy
Nicholas Scarsdale

**Dan Huber***
Casey Brinkman
Ashley Chontos
Jingwen Zhang

**Lauren Weiss***

**Ian Crossfield***
Alex Polanski


* TKS Co-I

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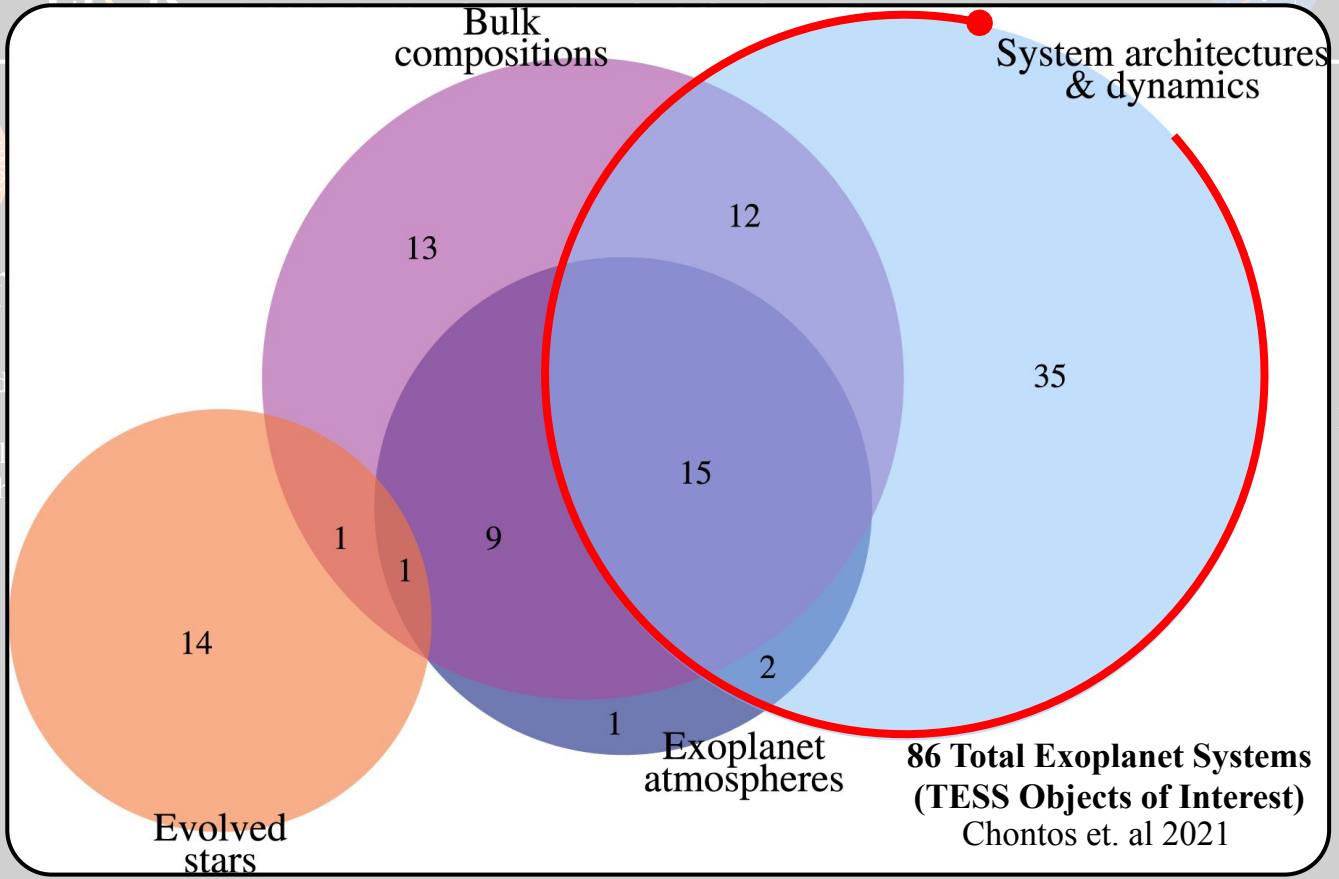



* TKS Co-I

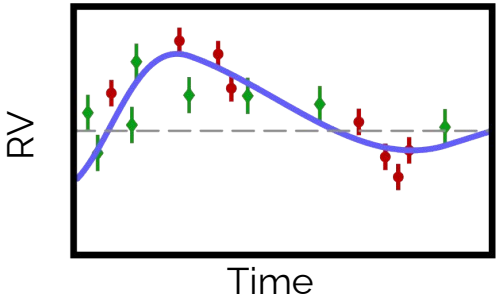
# The TKS Mass Catalog

Polanski et al. (*submitted*)

## Full Data Release

Nearly 10,000 radial velocity points from both Keck/HIRES and the Automated Planet Finder (APF, Lick Observatory)

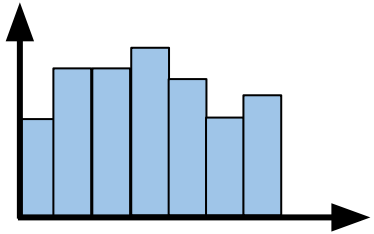
## Uniform RV Analysis




We perform a standardized analysis of all survey data to produce mass constraints for 126 planets.

**The largest uniform RV analysis of TESS planets to date.**

## Assessment of Survey Performance



Take the opportunity to assess how well our survey achieved the goals we set out 3 years ago.

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Take the opportunity to assess how well our survey achieved the goals we set out 3 years ago.

Catch my dissertation talk!
Wednesday 2:30
Radial Velocities I

# RV Observations and System Architectures

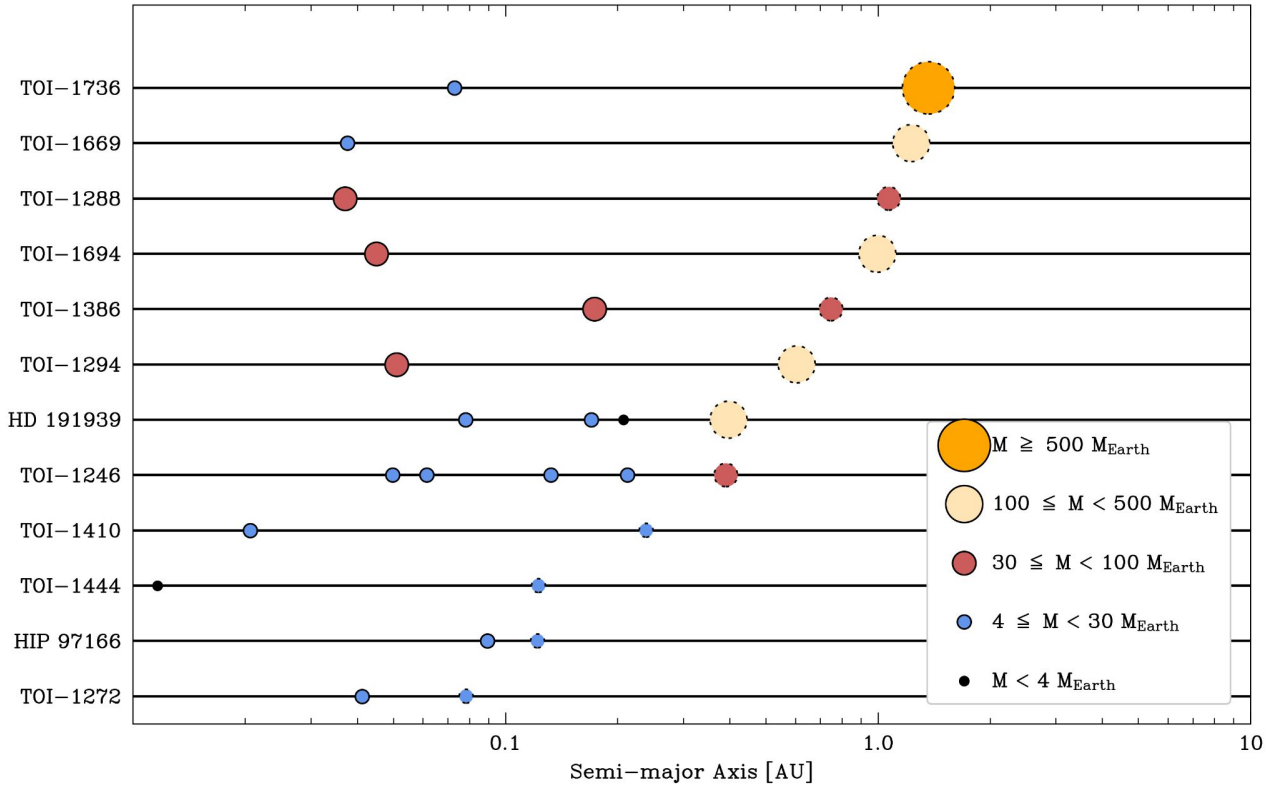
Detecting Non-Transiting Planets  Resolving Orbital Eccentricity  Measuring Planet Masses

# RV Observations and System Architectures

**Detecting Non-Transiting Planets** Resolving Orbital Eccentricity Measuring Planet Masses

TKS detected non-transiting planets in 12 of the 86 TOIs surveyed.

- ➢ Almost exclusively in systems with a single transiting planet (10/12). **Systems with large mutual inclinations?**



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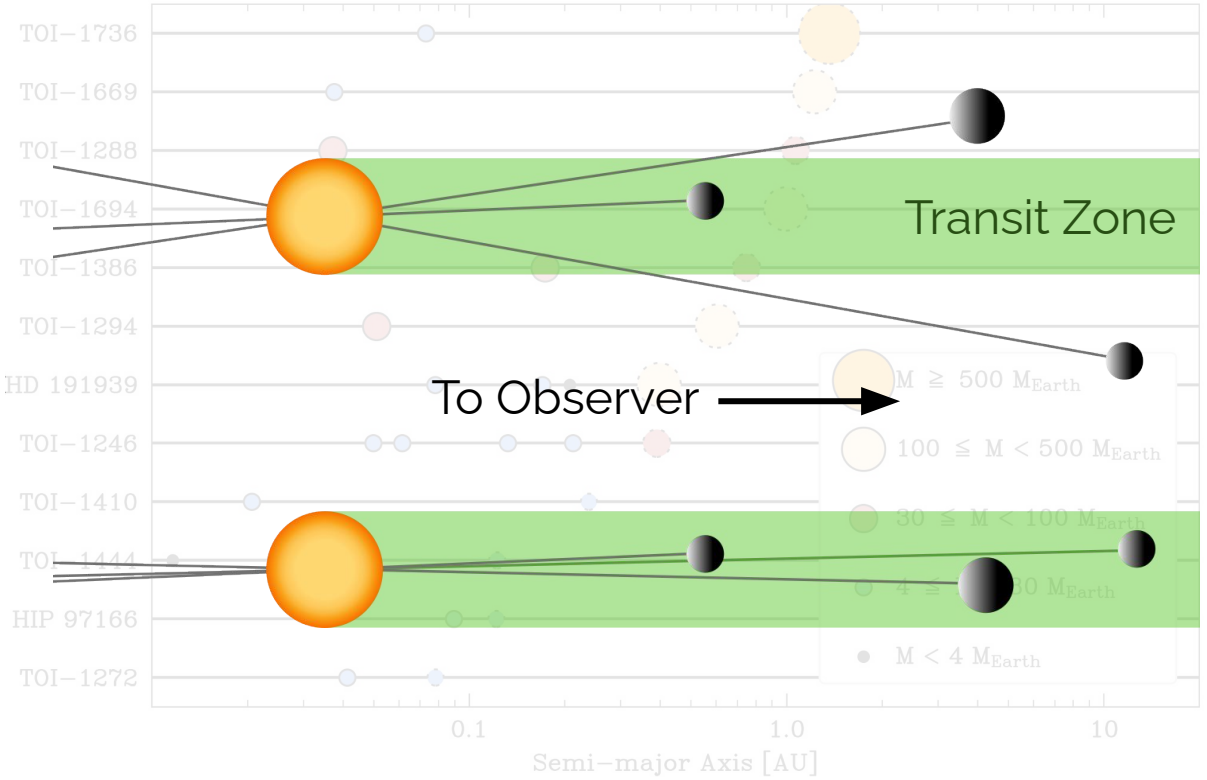

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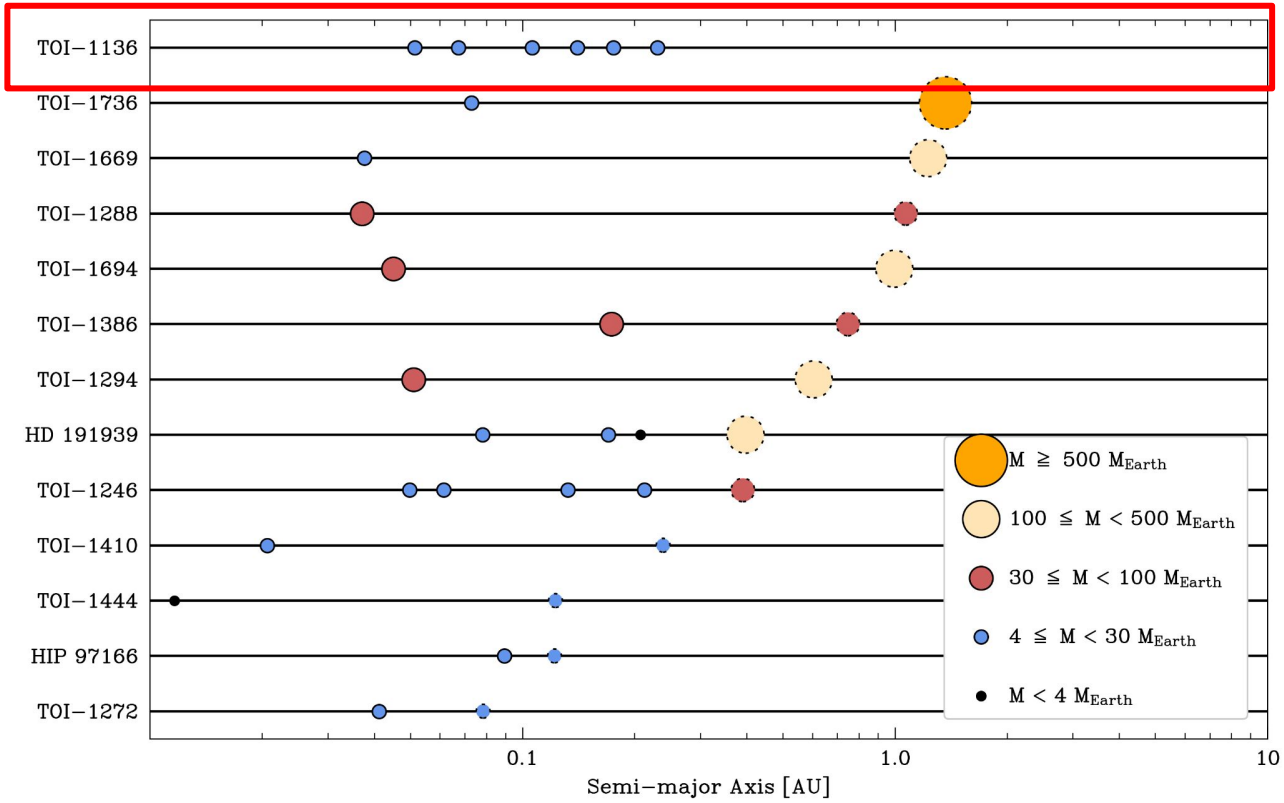

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**Detecting Non-Transiting Planets** Resolving Orbital Eccentricity Measuring Planet Masses

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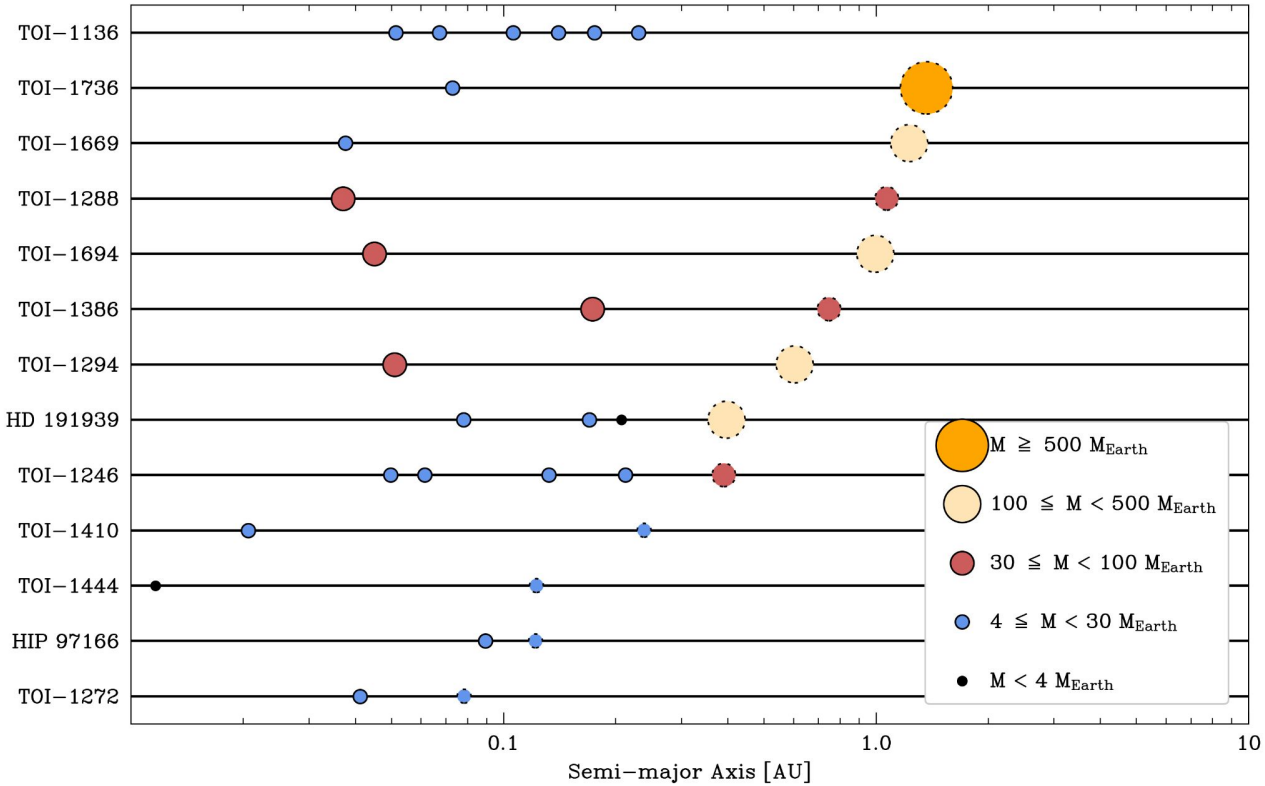
- Many of our detections are higher in mass.



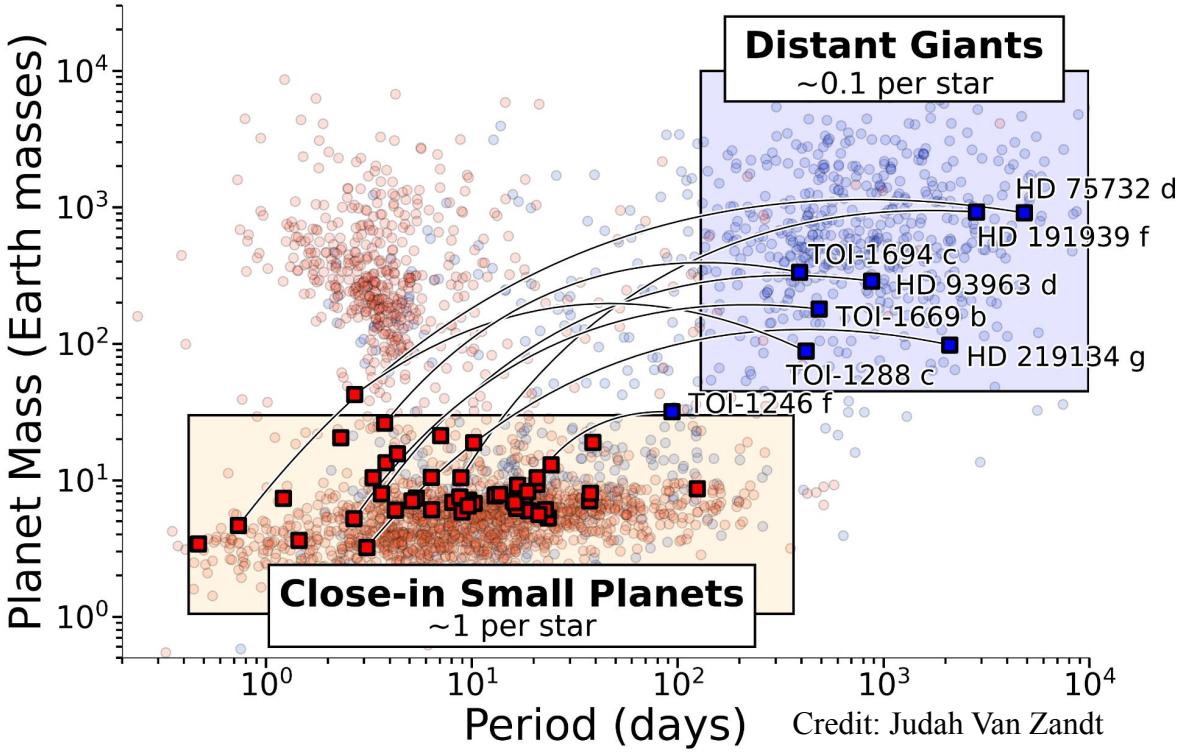
# RV Observations and System Architectures

**Detecting Non-Transiting Planets** Resolving Orbital Eccentricity Measuring Planet Masses

Distant Giants Program:

- 47 small-planet hosts observed for with 3 years with monthly RV cadence.
- 7 Jovian analogs, 1 sub-Jovian, 7 linear trends.

Judah Van Zandt's AAS talk:
Thursday, 10:00 AM
429 Radial Velocities II



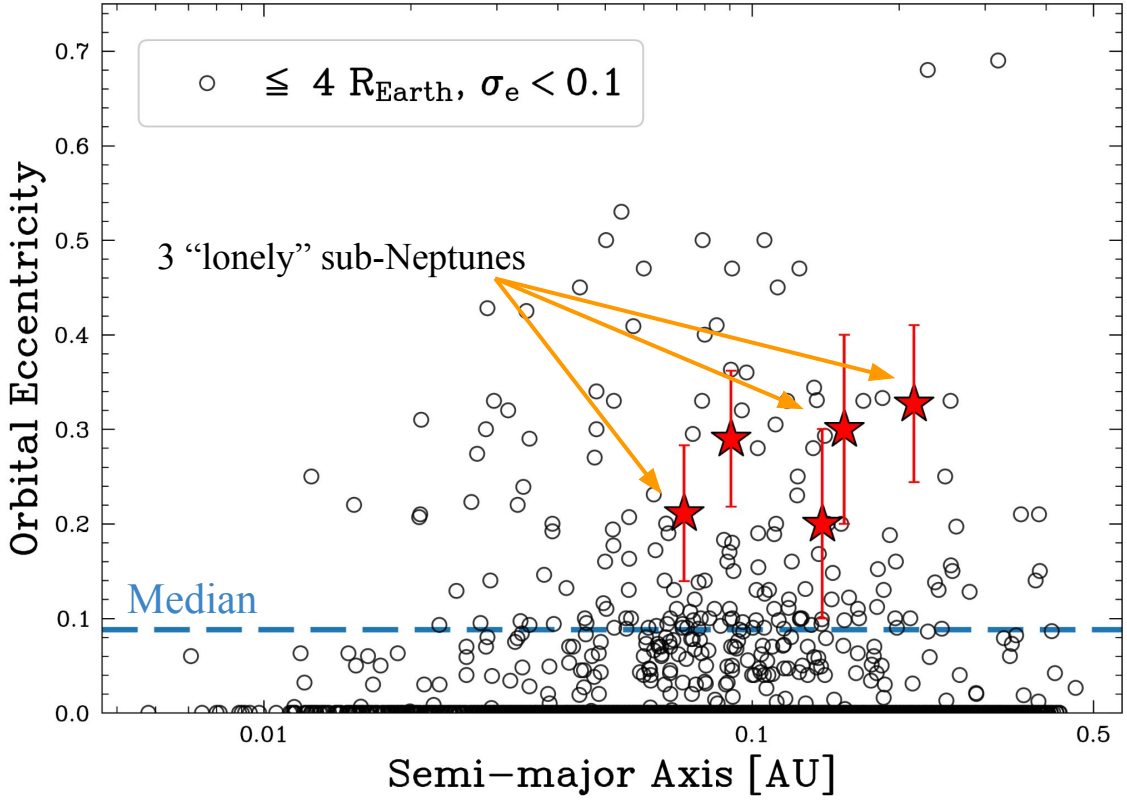
# RV Observations and System Architectures



The eccentricity of planets are records of their orbital evolution.

We were able to constrain non-zero eccentricities for 5 small planets (< 4 $R_{Earth}$):

- 2 of these systems have additional sub-Neptunes
- Remaining 3 are "lonely" with hints of long-term trends. Indications of cold Jupiters? (see Bitsch & Izidoro 2023)



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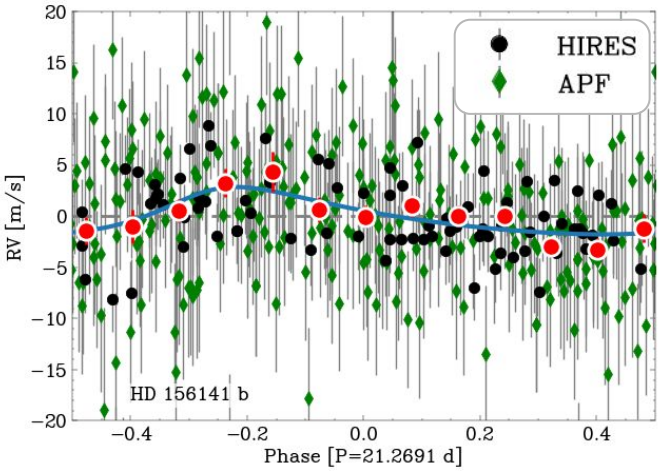
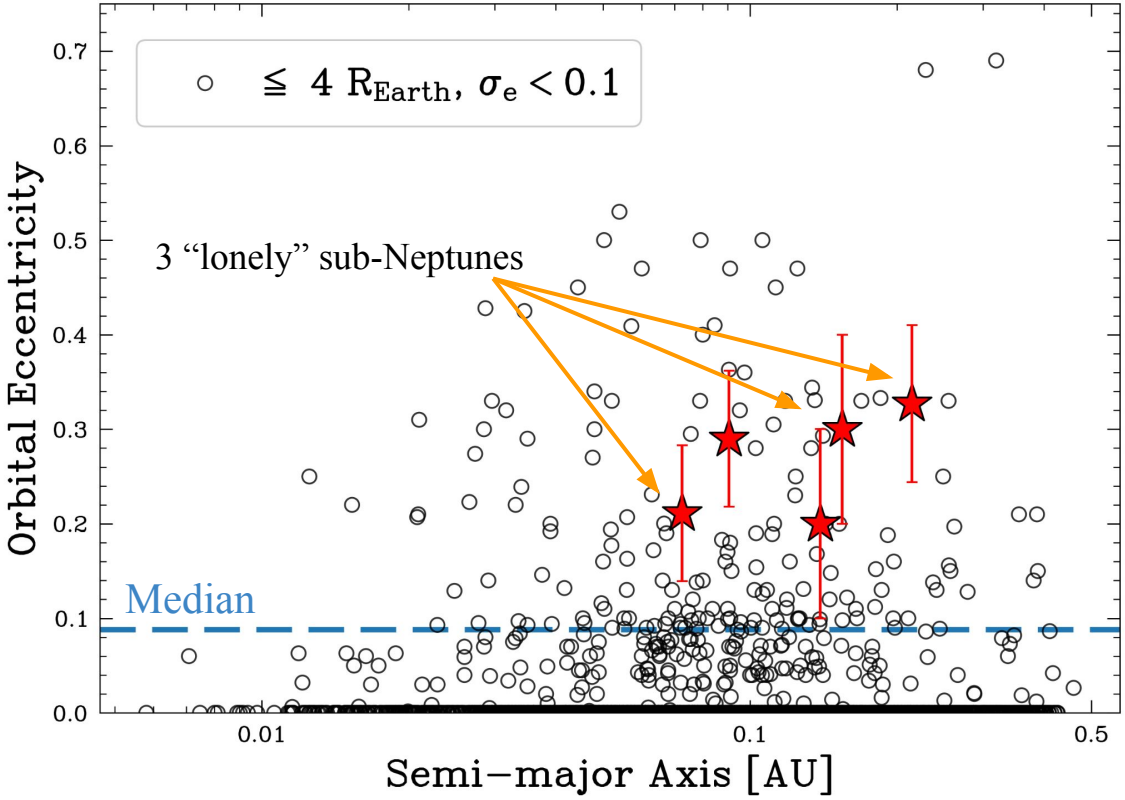
Detecting Non-Transiting Planets | **Resolving Orbital Eccentricity** | Measuring Planet Masses




High-cadence APF RVs provided tighter constraints on orbital eccentricity by providing fuller RV phase coverage.



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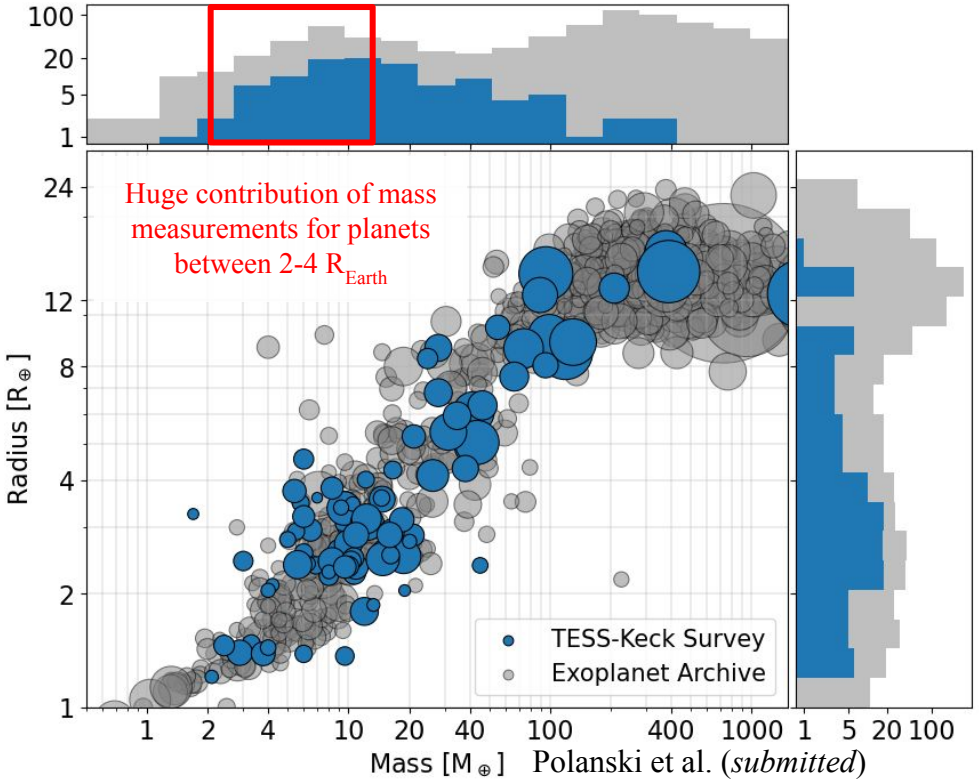
Detecting Non-Transiting Planets | Resolving Orbital Eccentricity | **Measuring Planet Masses**

TKS has resulted in mass constraints for 126 planets.



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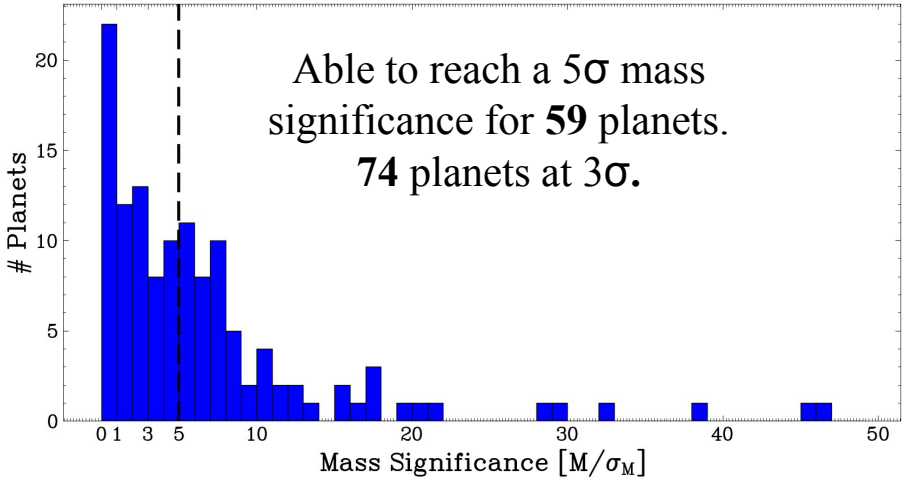


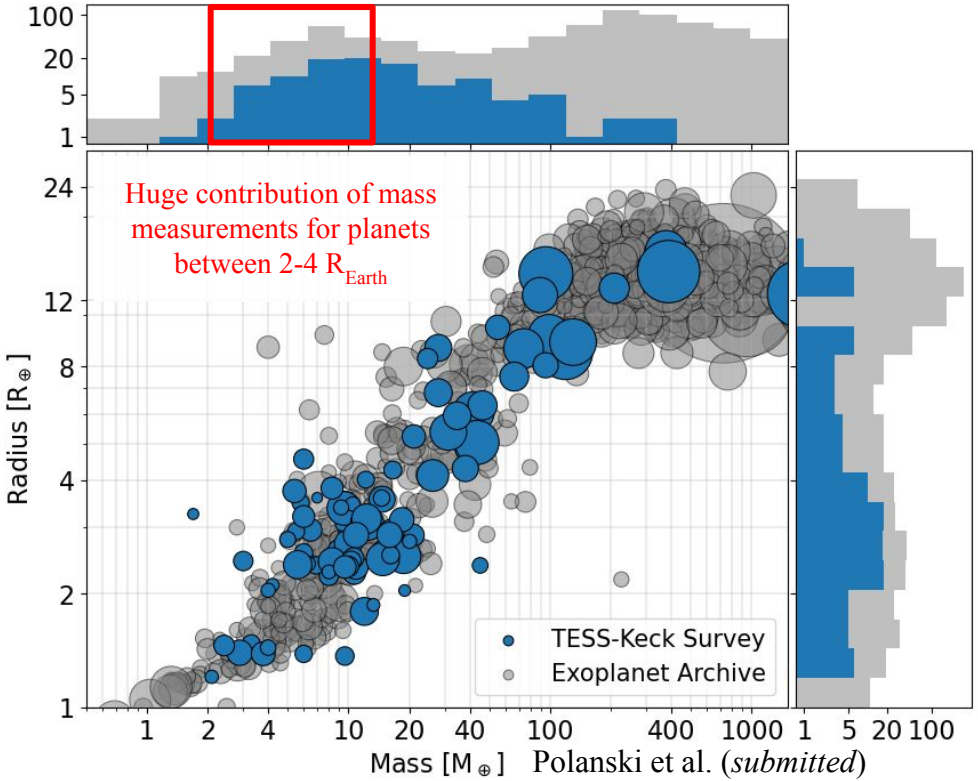

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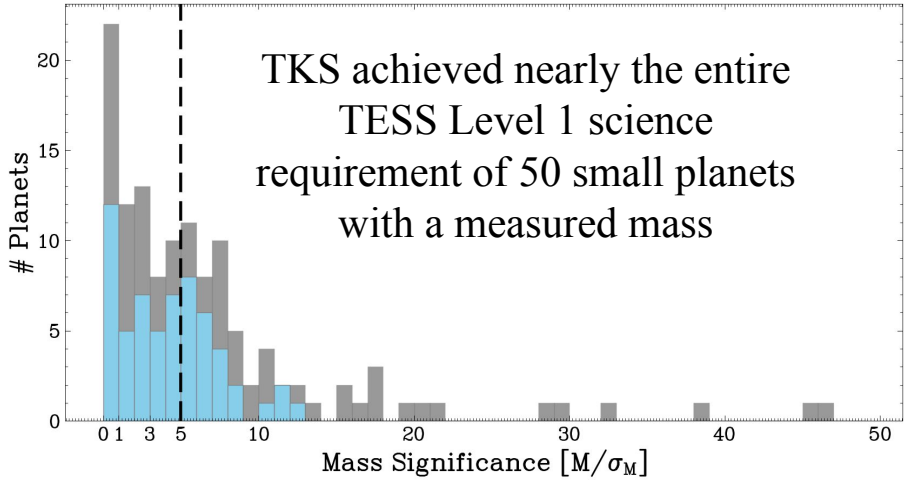
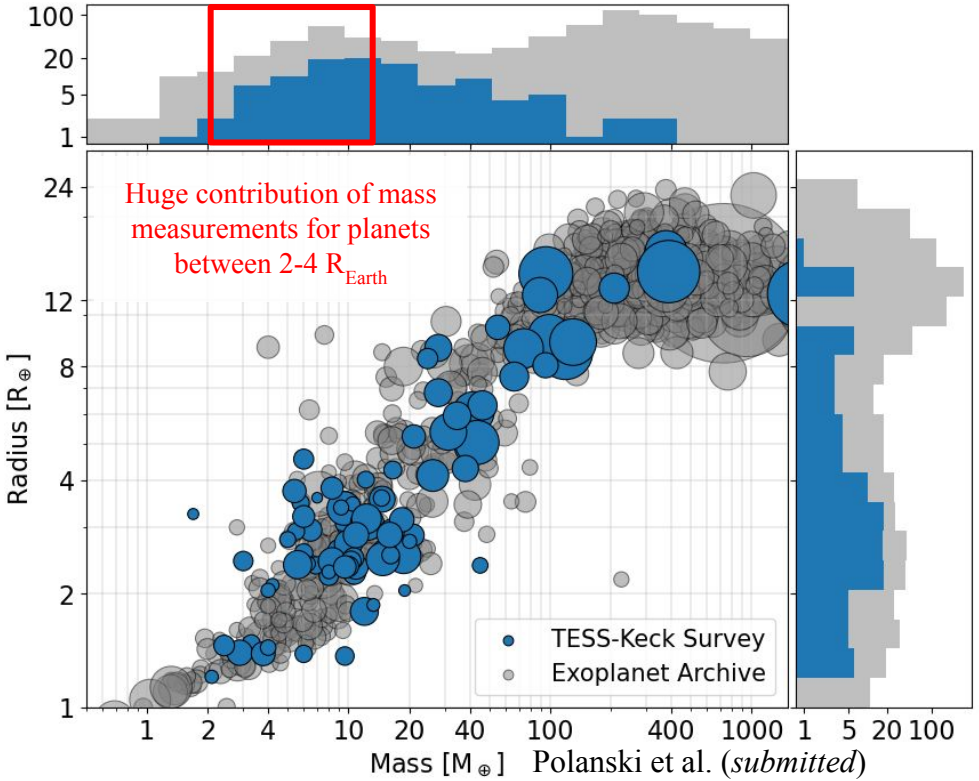
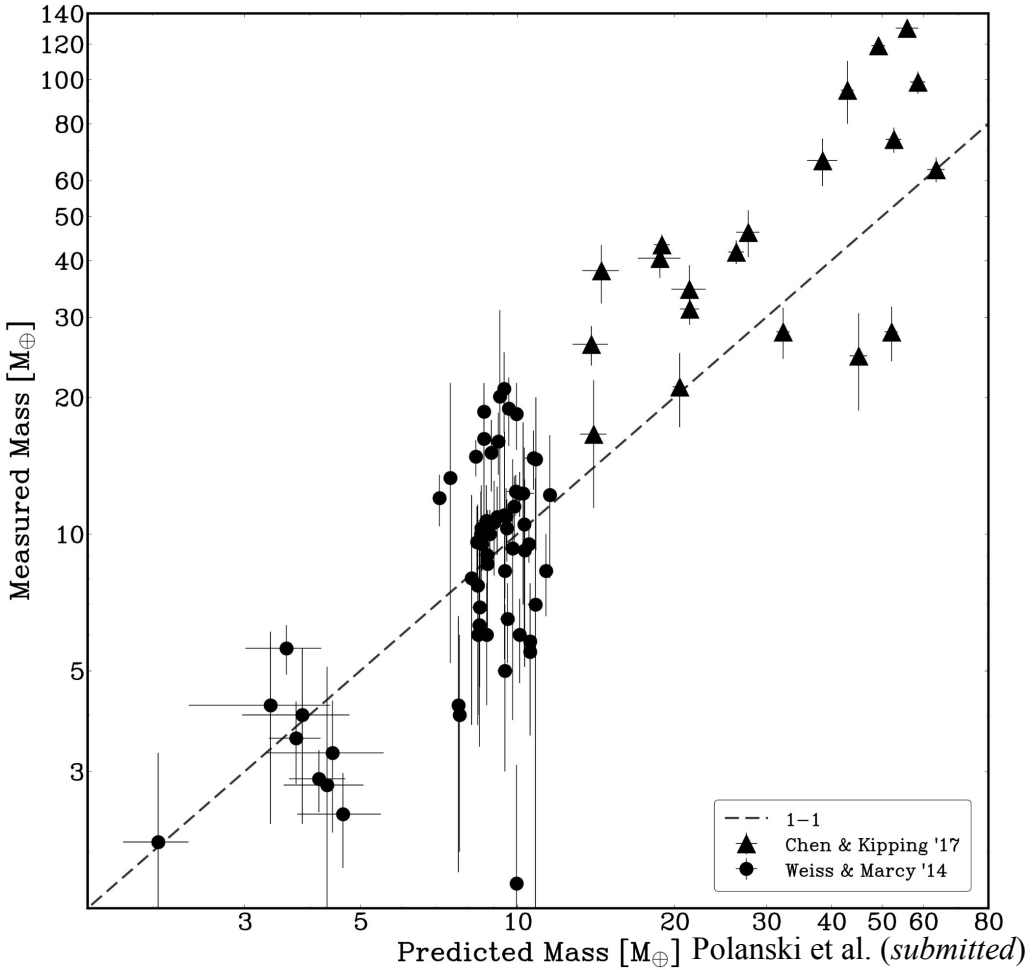


# Testing Empirical Mass-Radius Relations

We can use TKS masses to test if mass-radius relations are still holding up.

- Weiss & Marcy for planets < 4 $R_{Earth}$
- Chen & Kipping for planets > 4 $R_{Earth}$




Polanski et al. (*submitted*)

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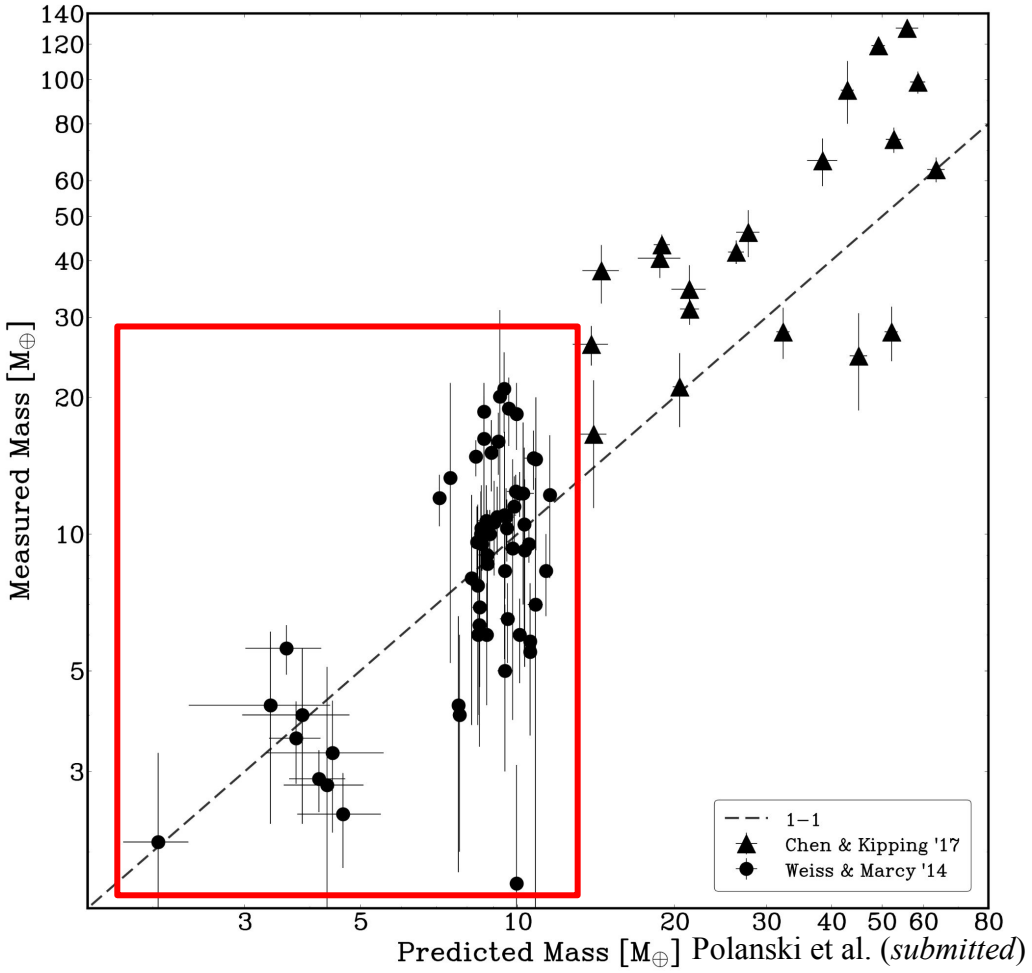

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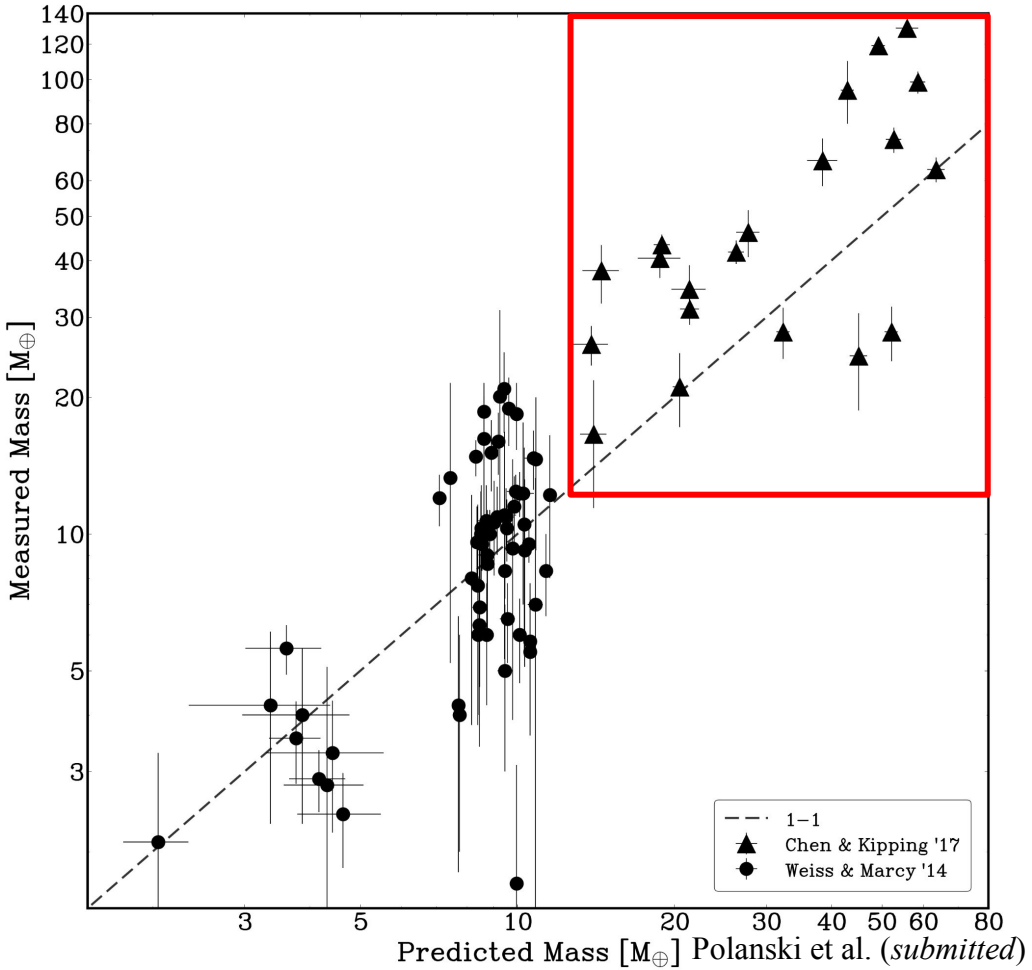
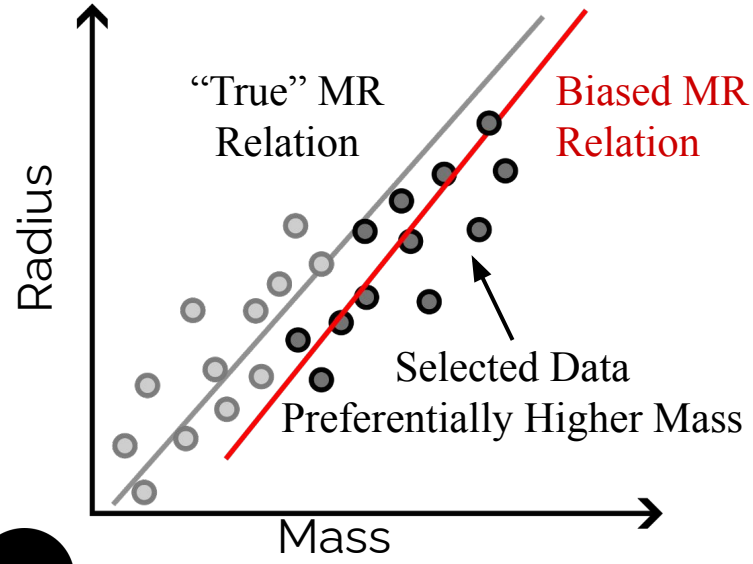
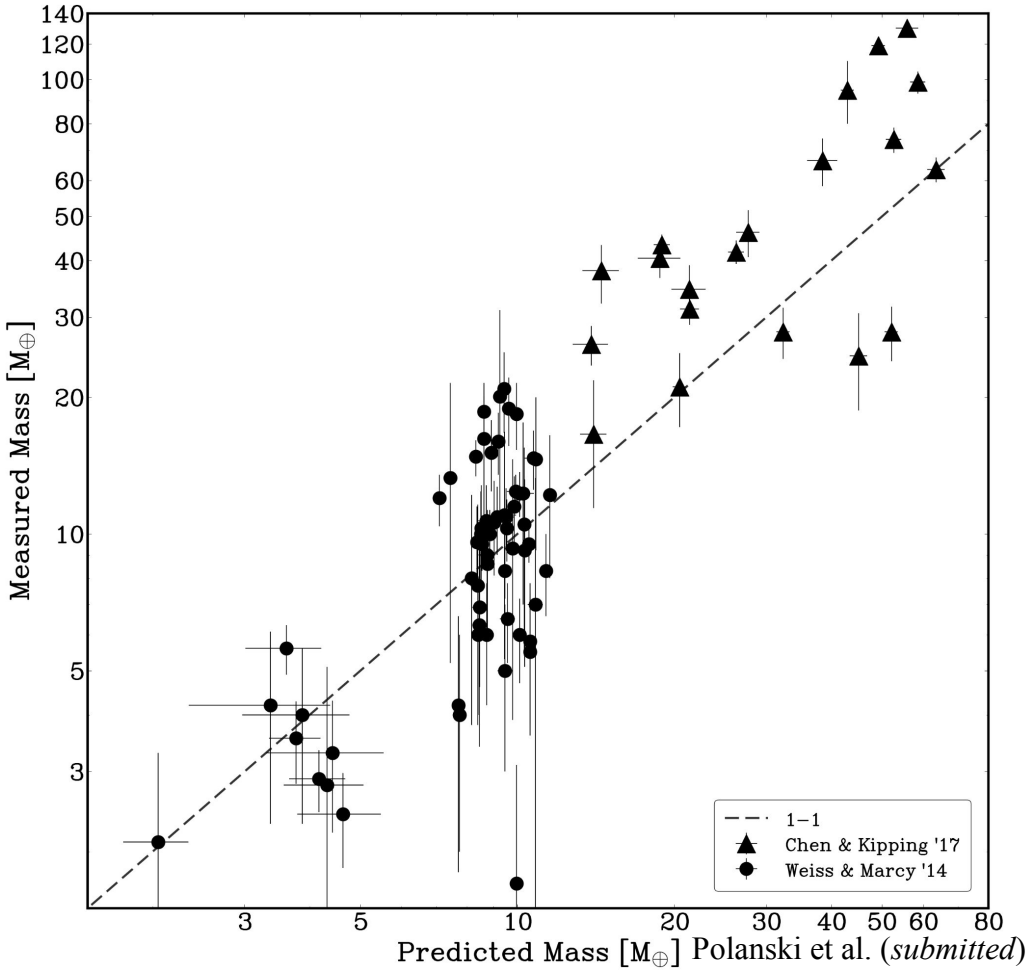
**CK'17 tend to *underestimate* planet mass by a factor of ~2.**



# Testing Empirical Mass-Radius Relations

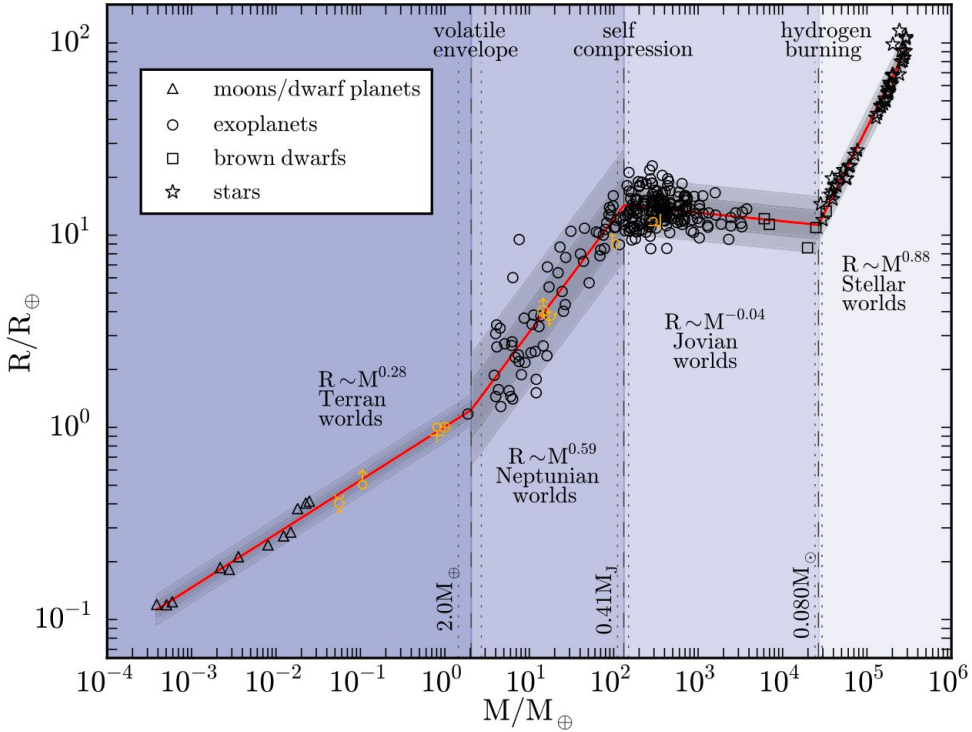
Wouldn't Chen and Kipping 2017 be suffering from publication bias?
See Burt et. al 2018 or Montet 2018



# The Need for Updated Mass Radius Studies

Pre-TESS MR Relations are outdated - we're now benefiting from a massive increase in the number of well-characterized planets.




Chen & Kipping 2017

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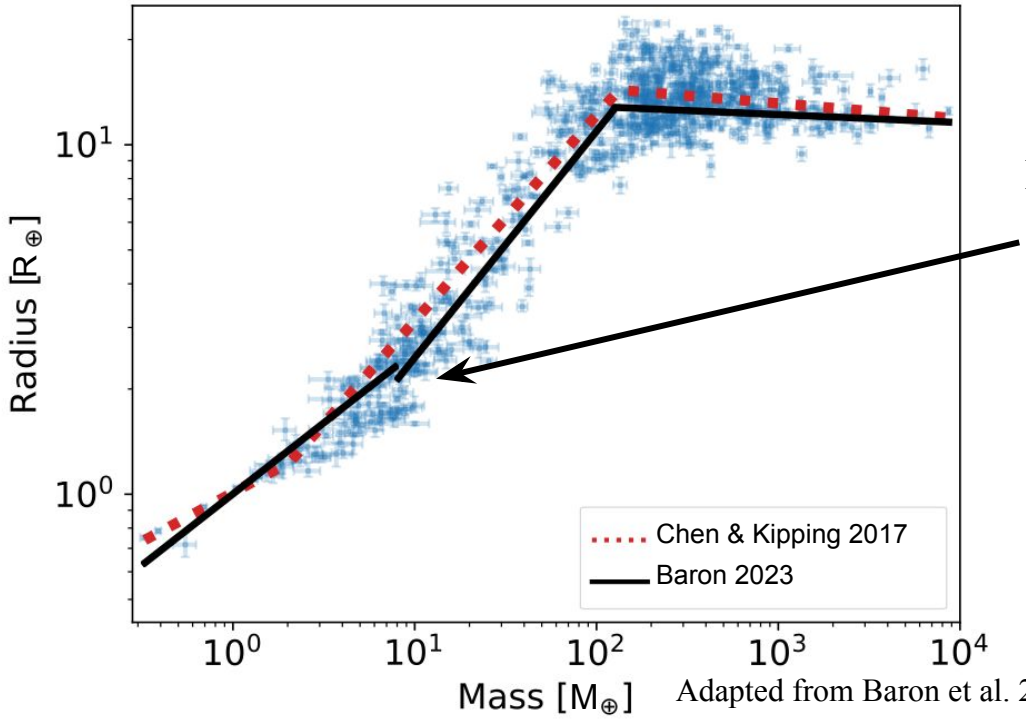


Break point at higher mass results in a steeper MR slope.

Adapted from Baron et al. 2023

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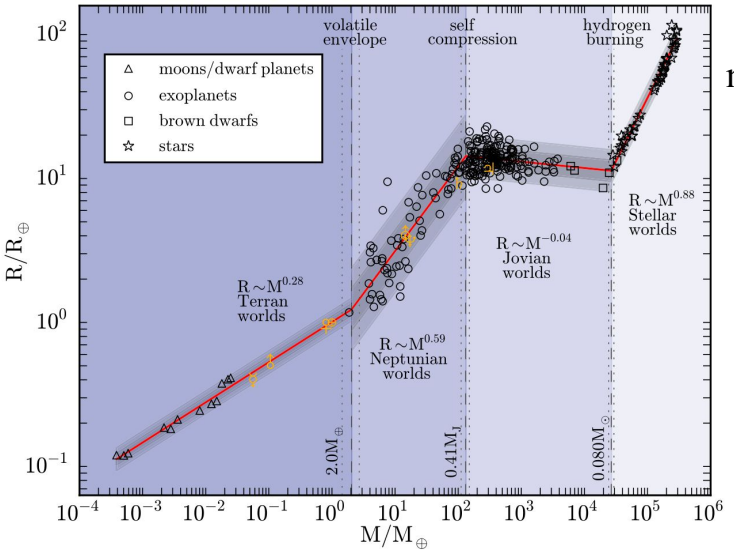
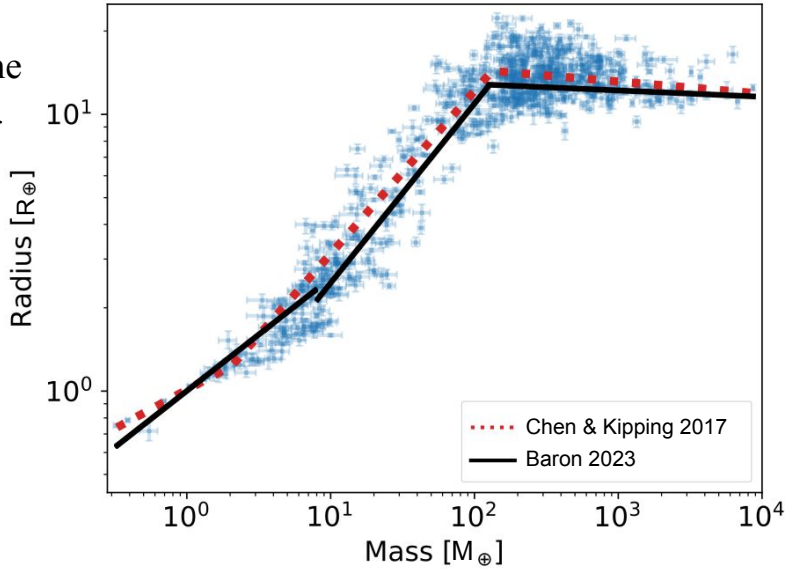



More than double the number of planets in the Neptunian range now.




We will be discovering more non-transiting planets…not just with RVs: Roman!

**Multi-dimensional MR Relations, in conjunction with methods to constrain inclination, will be critical to characterizing these new planets.** Polanski et al. (*submitted*)

# The Jovian Architectures Survey (JAS)

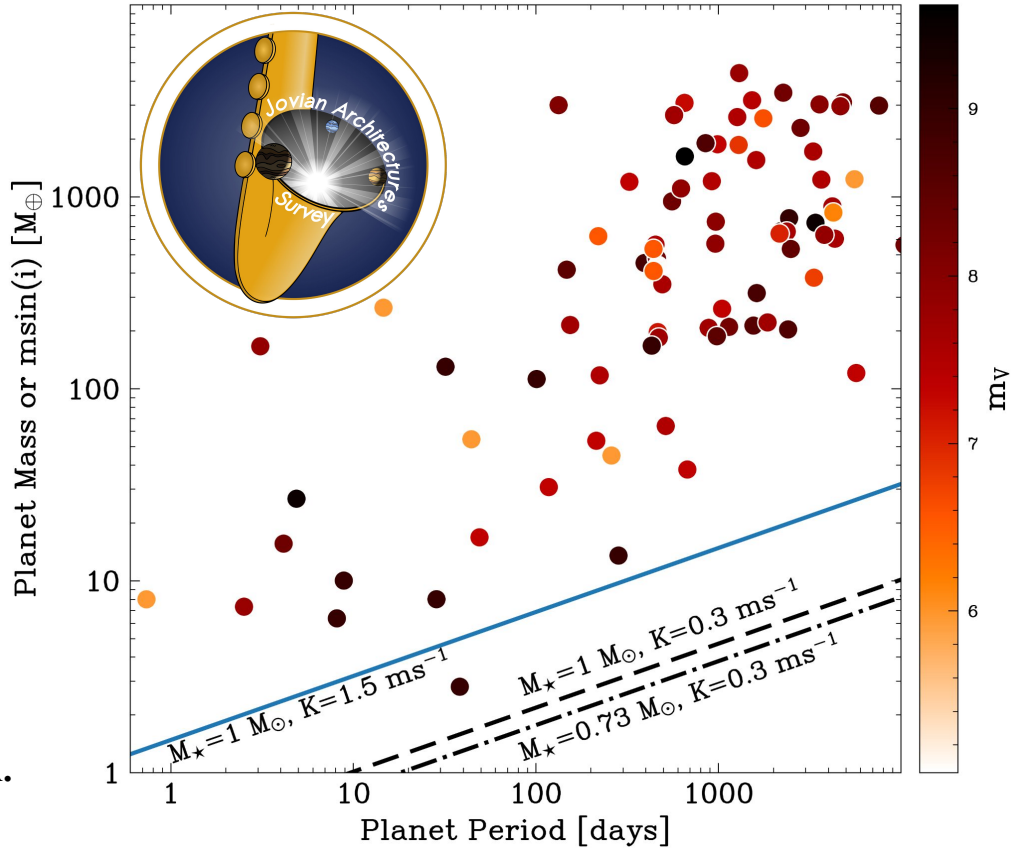
**Stephen Kane (PI), Alex Polanski, Diana Dragomir, Howard Isaacson, Sadie Welter**

A new survey targeting 51 nearby systems with known Jovian analogs (CLS I: Rosenthal et al. 2021) to search for smaller interior planets.

Science Drivers:

- Investigate gap complexity of small, multi-planet systems in the presence of Jovians.
- Explore how massive companions affect the delivery and retention of volatiles for inner terrestrial planets.
- How can we characterize stellar activity on (very) long timescales?
- Discover and highlight potential targets for future direct imaging missions.

**Initial allocation of 3 nights on KPF starting in 2024A.**



# Summary & Take Aways

- This is an exciting time to study exoplanet architectures - many pieces are starting to come together!
- The TESS Keck-Survey is contributing to our understanding of how systems arrange themselves:
  - 12 systems with non-transiting planets, many of which are single-transiting planet TOIs
  - Able to resolve the eccentricity of 5 additional small planets - the APF was crucial to do this!
  - **We present the TKS Mass Catalog: the Largest uniform RV analysis of TESS-discovered planets to date providing mass constraints for 126 planets.**

# Spares

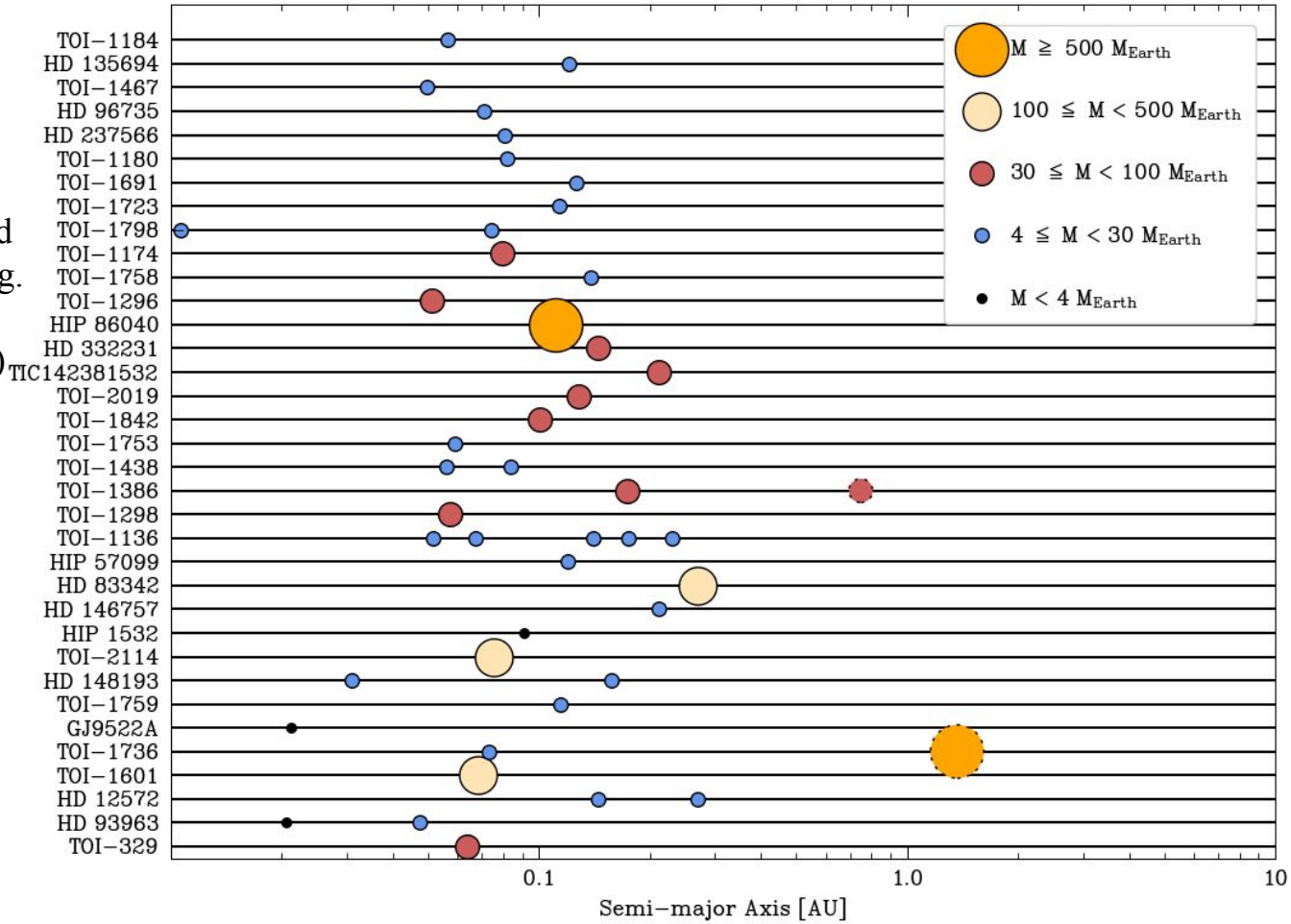
# Acknowledgments

Much of the data used in astronomical research, especially research on exoplanets, is obtained using observatories in Hawai'i. These telescopes reside on the mountain of Mauna Kea; a place of significant cultural importance to native Hawaiians. We are deeply grateful to have the opportunity to conduct observations from this mountain.

I also want to thank the Co-Is and many observers, especially junior researchers, who spent hundreds of hours collecting the data that made this survey possible.

# Future Work with TKS Data

- More single-system papers and the TKS Evolved Stars Catalog.
- Derivation of a TKS mass-radius relation (ongoing)



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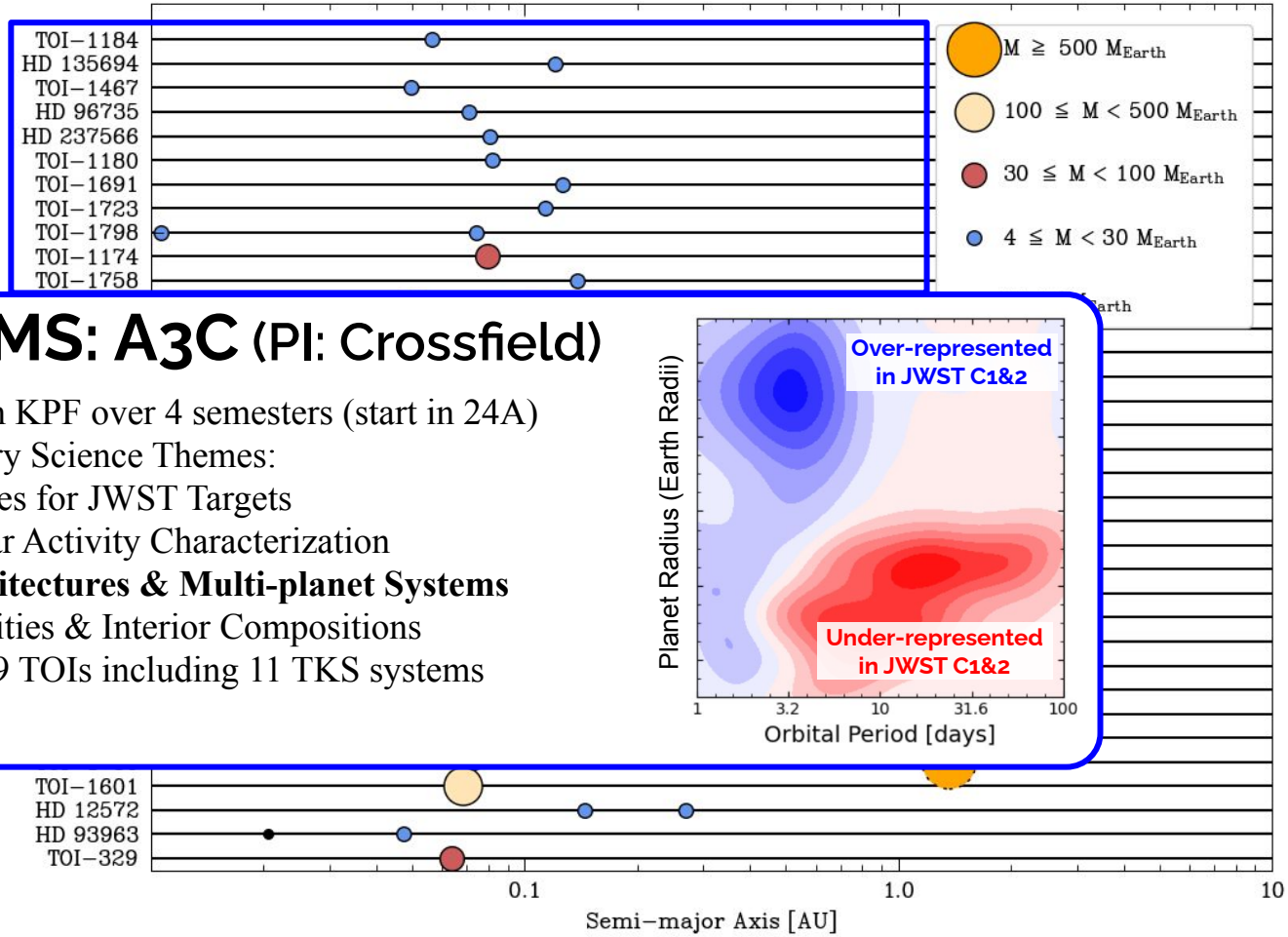


## New KSMS: A3C (PI: Crossfield)

- 10 nights on KPF over 4 semesters (start in 24A)
- Four Primary Science Themes:
  - Masses for JWST Targets
  - Stellar Activity Characterization
  - **Architectures & Multi-planet Systems**
  - Densities & Interior Compositions
- Targeting 19 TOIs including 11 TKS systems