

TOI-1136: Measuring the Mass
of Exoplanets with TTVs, RVs,
and Stellar Activity (and ducks!)

TOI 1136

(h)



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TOI-1136? What's So Great About it?



- TOI-1136 was first observed by TESS in July 2019, where three candidate planets would be identified
- Later a fourth would be discovered, and community observers would identify a fifth and sixth
- Dai et al. published an analysis of TOI-1136 in 2023, identifying a seventh candidate and highlighting many of its important properties
- The TESS-Keck Survey (TKS; Chontos et al. 2022) prioritized this system as a part of its mission to measure the masses of 100 TESS systems
- TOI-1136 stands out from other systems due to its
 - Youth
 - High Multiplicity
 - Amenity to transmission spectroscopy
 - Well-defined evolutionary history

Young Systems

- TOI-1136's rotation period and magnitude suggest an age near 650 Myr
- Young systems are valuable because they allow us to constrain the timescales of various astrophysical processes
- TOI-1136 may be actively undergoing evolution, or perhaps, all evolutionary processes have ceased

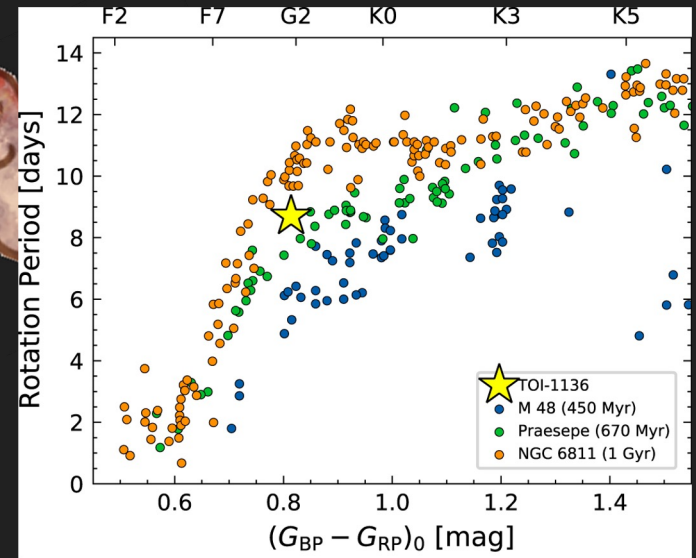


Figure: Dai et al., 2023

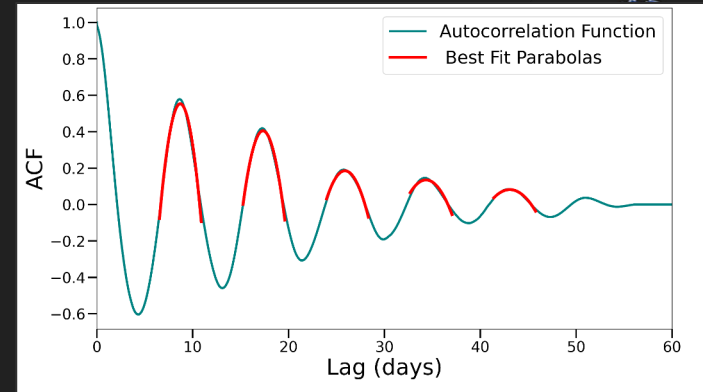


Figure: Beard et al., 2024



High Multiplicity

- TOI-1136 has among the highest multiplicity known among planetary systems, especially if we include the candidate seventh planet
- We can compare properties of planets in the same system and be certain that they had the same evolutionary history
- This allows us to remove dependence on things like stellar properties and system age

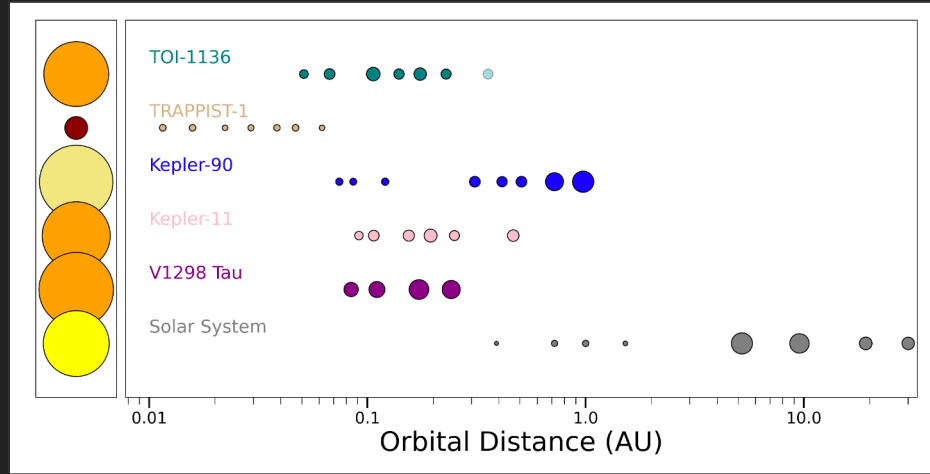


Figure: Beard et al., 2024

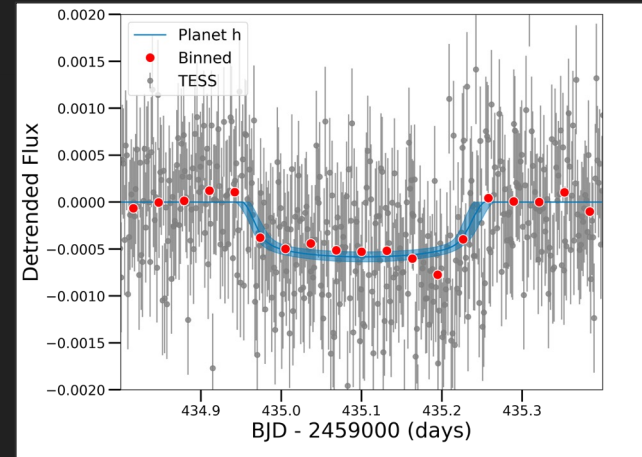
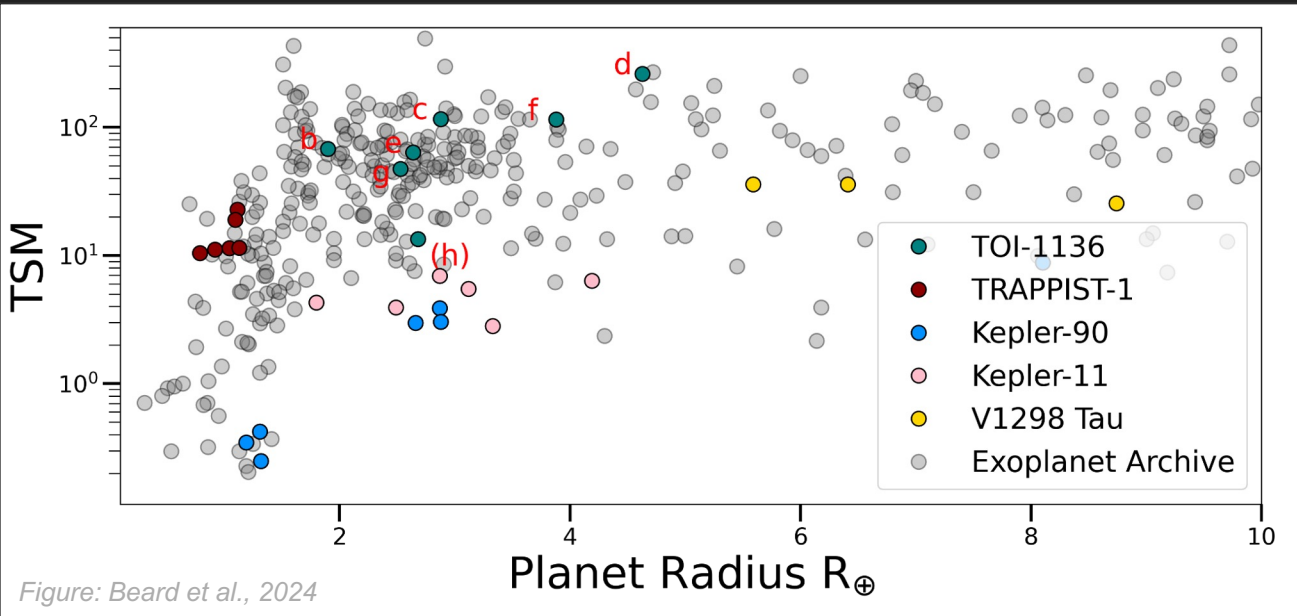


Figure: Beard et al., 2024



Great Targets for Transmission Spectroscopy



TSM_b	=	68
TSM_c	=	116
TSM_d	=	260
TSM_e	=	64
TSM_f	=	115
TSM_g	=	47

- Planets c and d are especially good for transmission spectroscopy, though all planets are accessible
- Systems with multiple targets amenable to transmission spectroscopy are especially useful for atmospheric comparisons between planets

Clear Evolutionary History

- The planets in TOI-1136 are in pristine orbital resonance, suggesting Type-I Migration
- The system is young, and still evolving
- In time, it may maintain its resonance, drift away from resonance, or lose it entirely

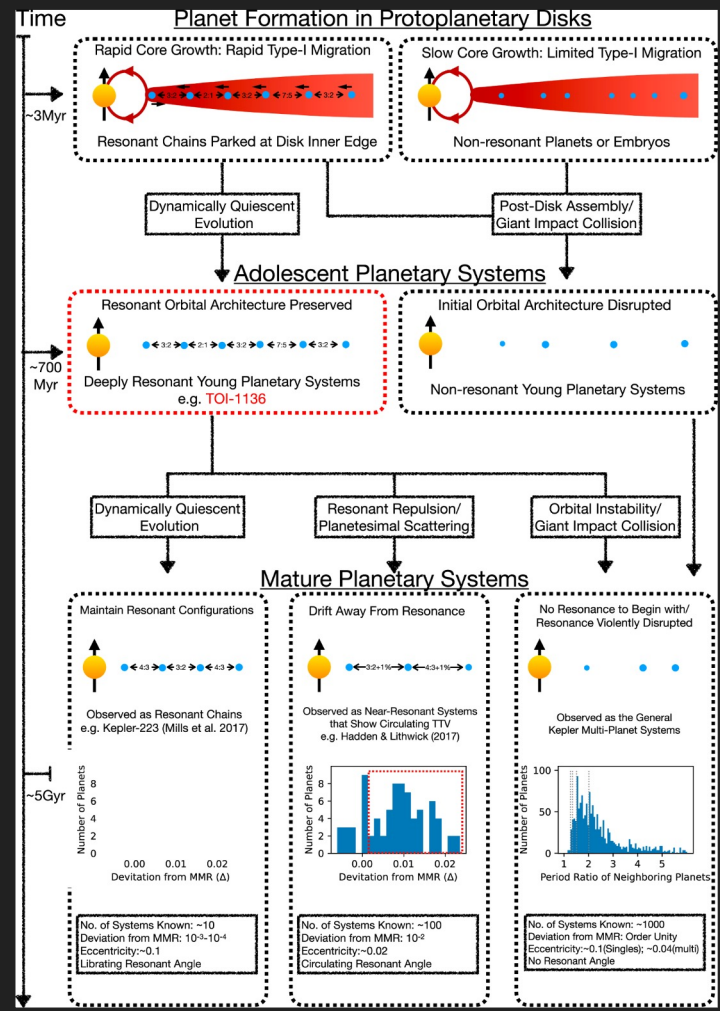


Figure: Dai et al., 2023

Our Analysis: Constraining the Mass with RVs and TTVs

- Plenty of analyses have been performed for other systems using **TTVs alone** (i.e. Lissauer et al. 2013, Agol et al. 2021)
- Or **RVs alone** (i.e. Santerne et al. 2019, Lubin et al. 2022)
- A number of analyses have been performed on systems with both **TTVs and RVs jointly**, though typically with **lower multiplicity** (i.e. Almenara et al. 2016, Weiss et al. 2017)
- The only other system we know of with an RV + TTV analysis on a high multiplicity (> 5 planets) system is for Kepler-11 (Weiss 2016)
- Our analysis appears to be the **first for which N-body forward model with Gaussian process is jointly fit to the TTVs and RVs**



RV Analysis - Do We See a Seventh Planet?

- We had to be careful when performing an RV fit: the stellar variability was an order of magnitude larger than our planet amplitudes
- We trained our activity model on contemporaneous TESS photometry, and we used this to recover planet masses
- Unfortunately, no strong detection of the seventh planet was possible

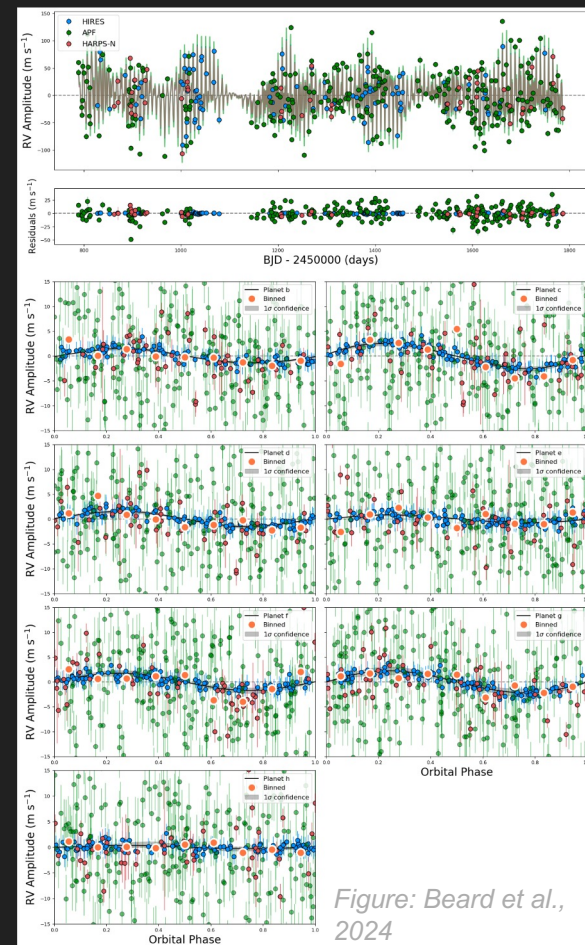


Figure: Beard et al., 2024

TTV Analysis - Do We See a Seventh Planet?



- TTV models saw slight differences when including a seventh planet or only six
- Outer planet fits in particular saw discrepancies
- TOI-1136 will be re-observed in Sector 75
- Six and seven planet models see significantly different TTV predictions in this sector

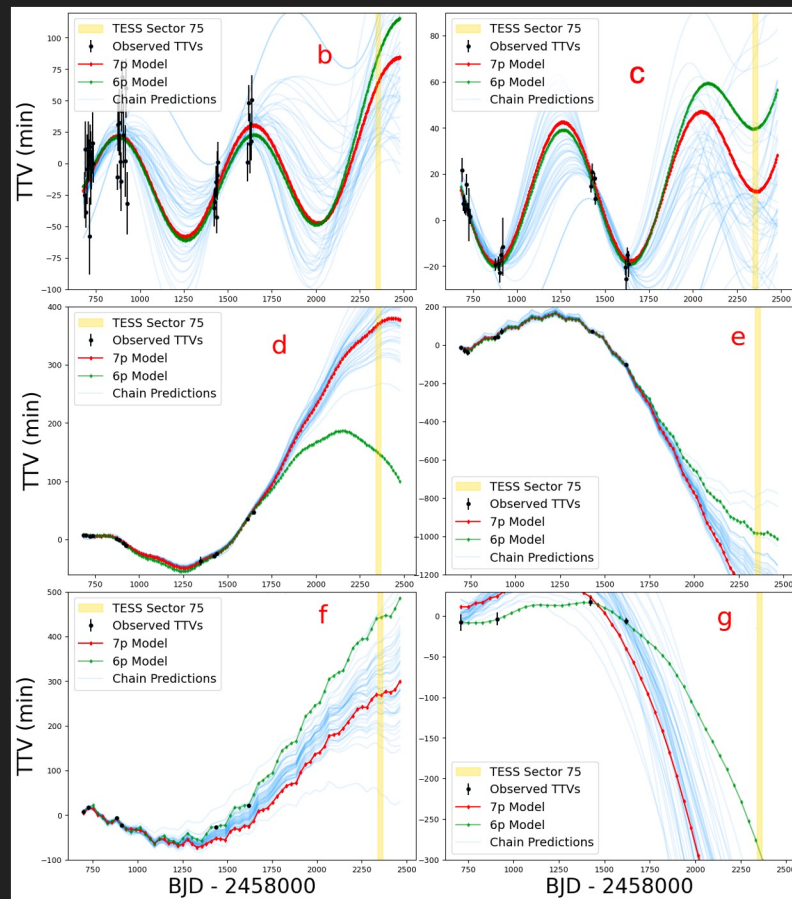


Figure: Beard et al., 2024

Atmospheric Prospects



- Most of the planets in the system are consistent with large H/He envelopes
- Planets d and f are noticeably “puffier” than the others, which is unexpected
- Planet b is an excellent candidate for a “water world”

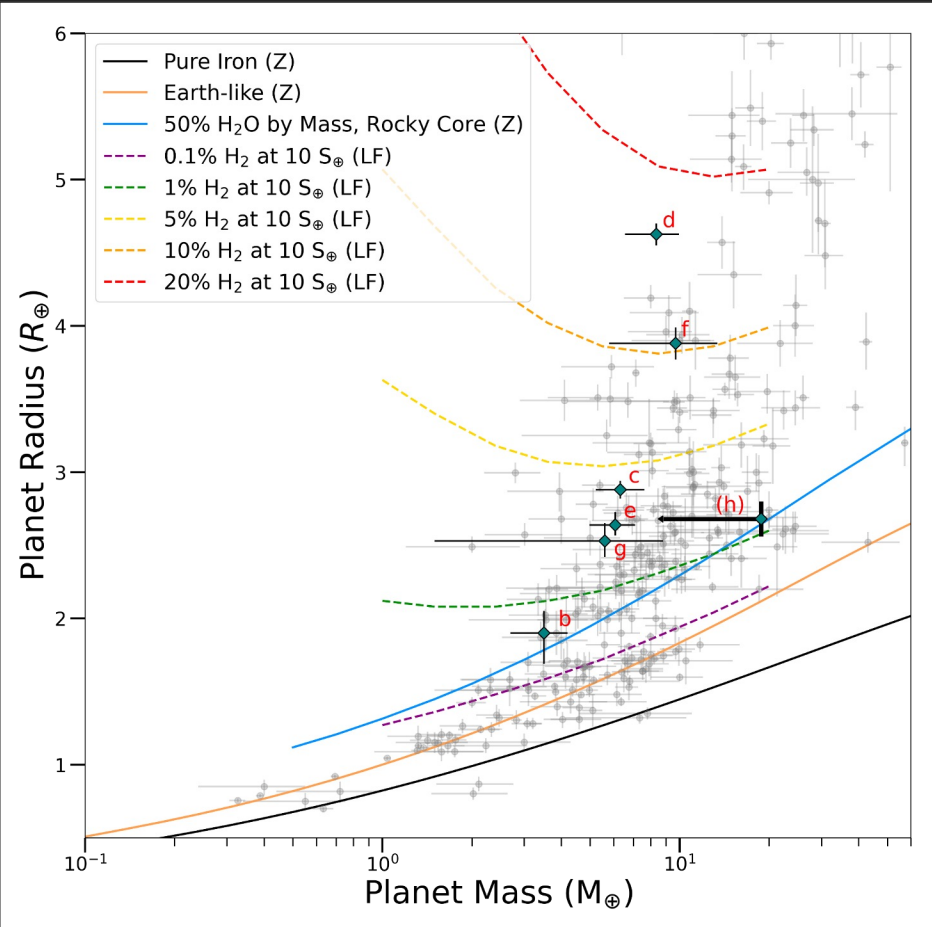
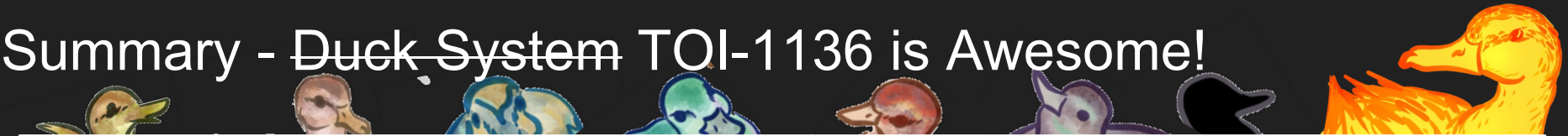


Figure: Beard et al., 2024

Summary - ~~Duck System~~ TOI-1136 is Awesome!

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- TOI-1136 is an excellent testing ground for a variety of open questions in exoplanet astrophysics
 - Its tight resonance makes it a clear example of Type-I migration
 - The youth allows us to constrain timescales of certain evolutionary processes
 - Its multiplicity allows us to perform intra-system comparisons of planetary parameters
 - Its brightness allows for RV study
 - TTVs allow for a detailed dynamical analysis
 - Expect to see much more about TOI-1136 in the future
 - Future TESS observations will likely further refine system properties
 - Future RV observations along with TTVs will help constrain the candidate planet's orbit
 - Future atmospheric studies are already planned!