Extending Exoplanet Ephemerides through TTV Analysis with NEPTUNE and Ground-Based Observations

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- 2023 EU Contest for Young Scientists – Grand Award
- 2022 & 2023: Canada's Top Young Scientist

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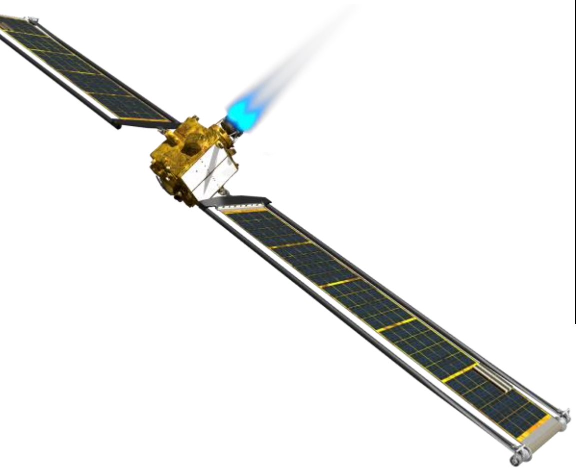
ExoClock 5th Annual Meeting

Madrid, Spain 4th October 2025



A quick background!

My photometry journey started in 2022 with **NASA DART Mission** where as a Citizen Scientist I developed algorithms to merge data from remote telescopes to measure the change in orbital period of asteroid Dimorphos

Led to research presentations, 2 peer reviewed publications, and wanting to have my own remote observatory for photometry!

February 2024

July 2024

Building a Remote Observatory at age 15:

~~IMPOSSIBLE~~

✓ **IS POSSIBLE**

Thanks to the

Masason Foundation Research Grant

For providing me an opportunity to implement bold ideas — **like building a remote observatory for planetary defense** and exoplanetary research

Presenting my project to Masayoshi Son and Masason Board Members in Tokyo, Japan

My Remote Observatory "Monitor My Planet" (Spain)

MPC Code R60

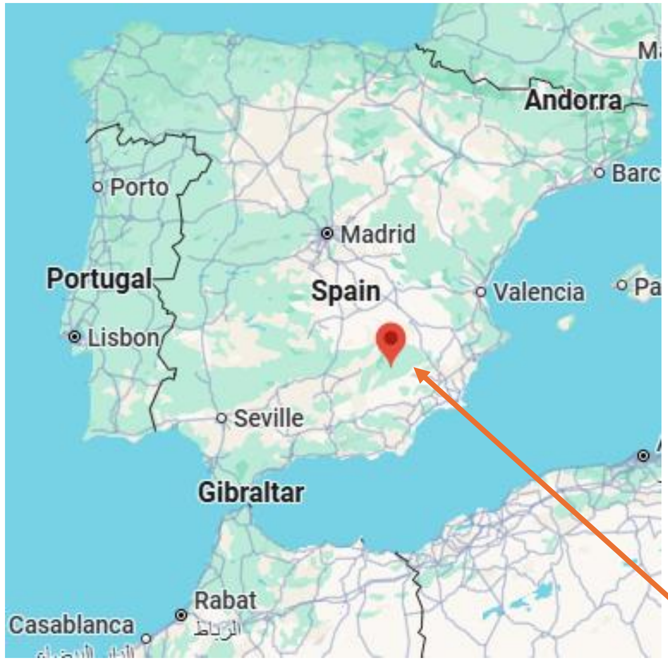
Location: Nerpio, Spain

Host: Astro Camp

Telescope: 12" Ritchey-Chrétien

Camera: ZWO ASI 2600 Mono

Filters: U, B, V, R, I, Lum

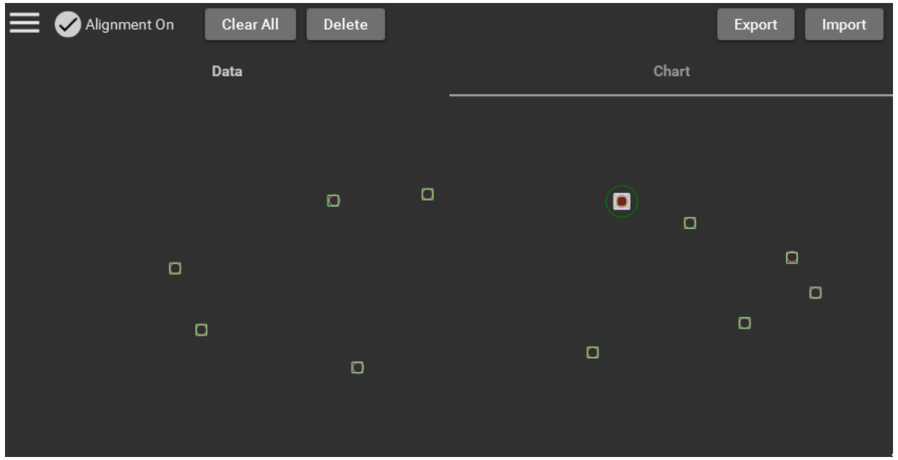


Around 400 kms South of us!

Assembly, Calibration, and Alignment of Telescope

Mount Installation on a Pier

Aligning Optics for Sharper Focus



Star Alignment of Telescope for Accurate Tracking

Telescope Setup Completed

FIRST IMAGE Eagle Nebula (M 16)

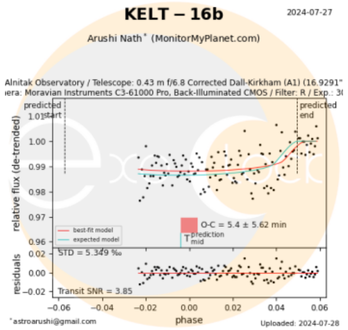
3-minute exposure, R filter

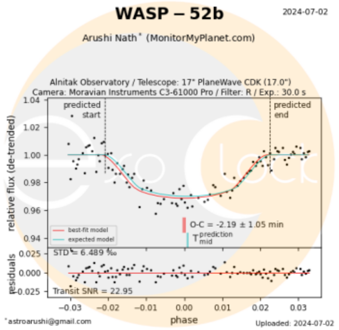
Passed the astrometry and photometry calibration tests.
Got an MPC Code for My Observatory!

`R60 357.673440.787445+0.614750MonitorMyPlanet, Nerpio`

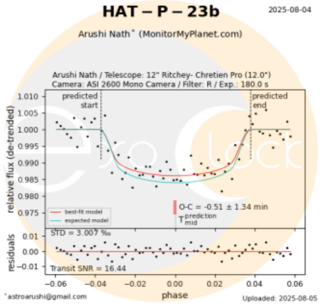
RESULT: 25+ Exoplanet Transits Observed and Published on ExoClock

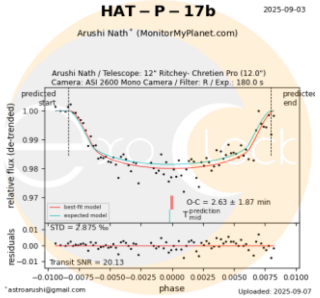
2024:
2 Transits Observed

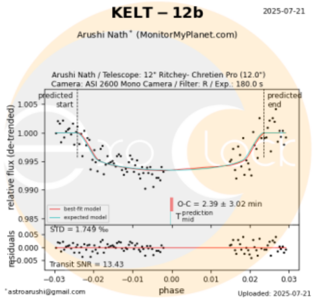


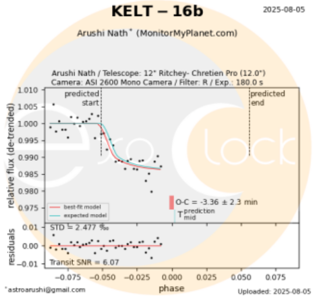


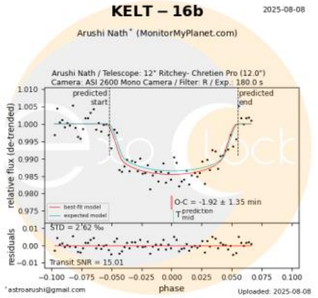
2025 (July - September)
~25 Transits

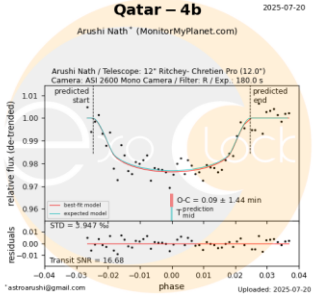


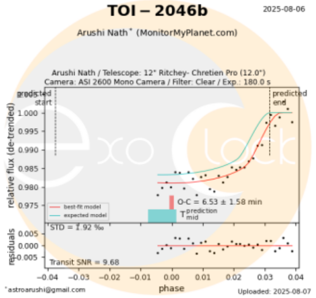


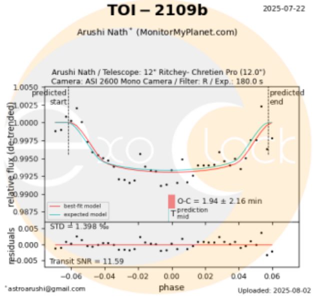


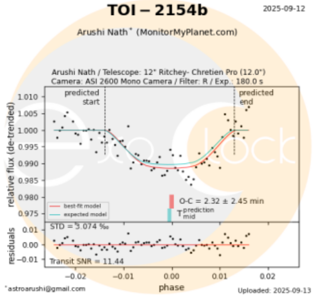


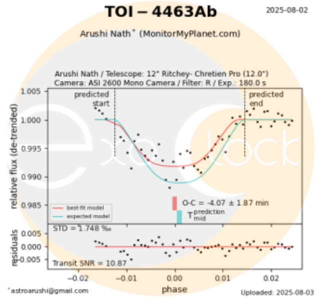


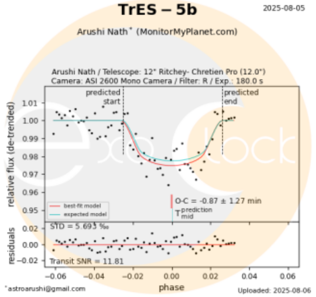


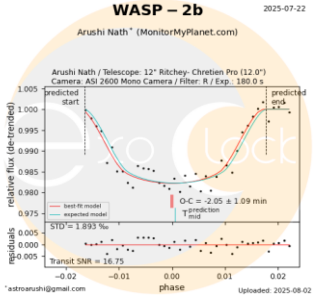


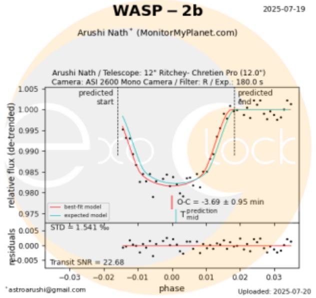


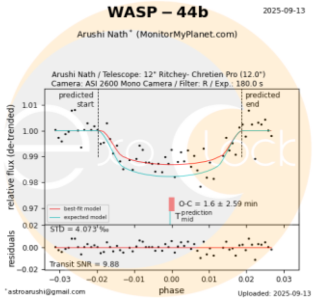


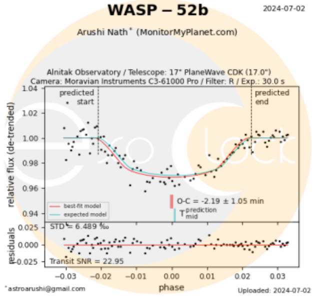








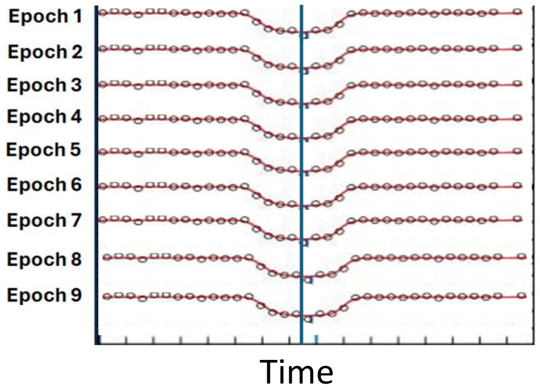




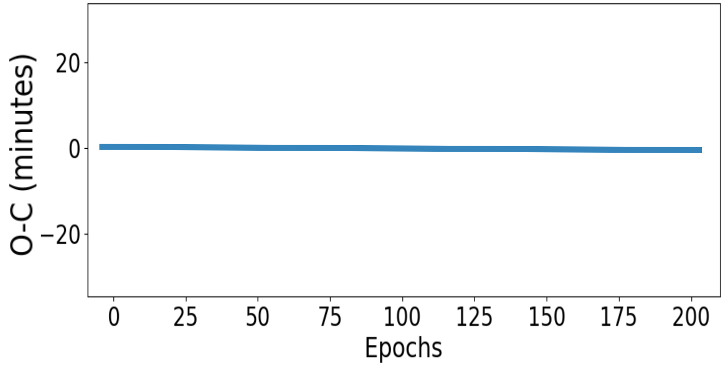
Current Focus: Transit Timing Variation (TTV) in Exoplanets

Single Planet System

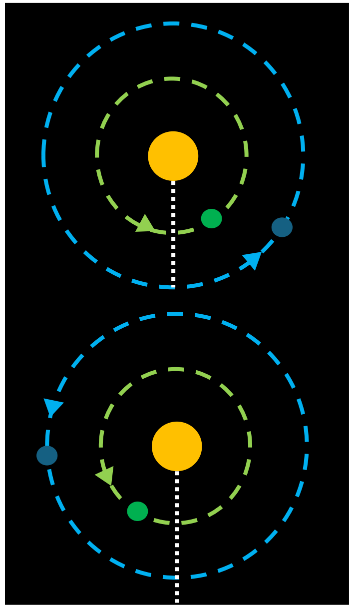
Transits happen at regular intervals



Observed-Calculated (O-C) transit time plot: **no variations**



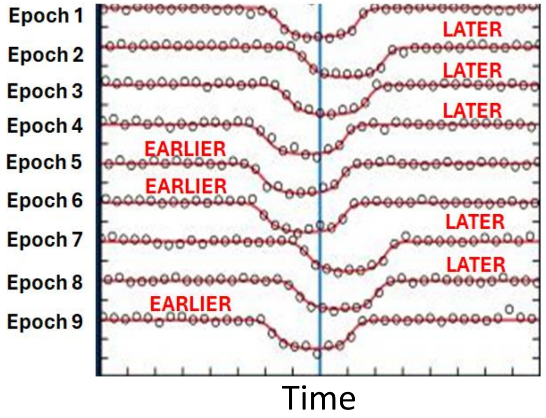
Multi-Planet System



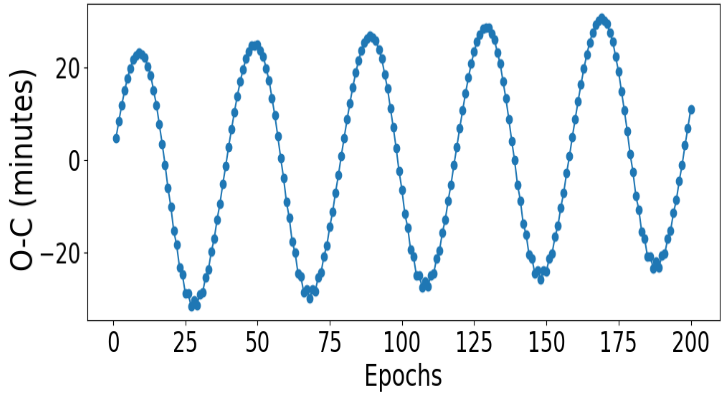
Transit is Earlier

Transit is Later

Outer planet gravitationally pulls on inner planet **causing earlier or later transits**



Observed-Calculated (O-C) transit time plot: **sinusoidal variations**



Why TTVs Matter?

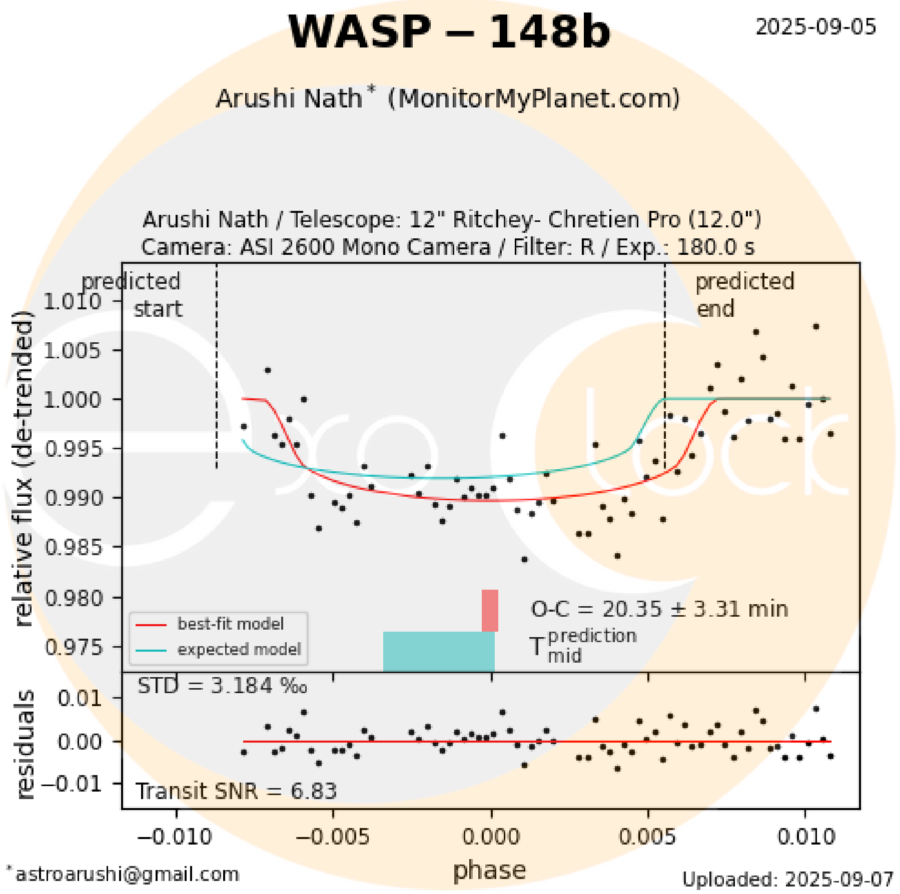
May reveal non-transiting, long-period planets in multi-planet systems.

Inner planet is transiting

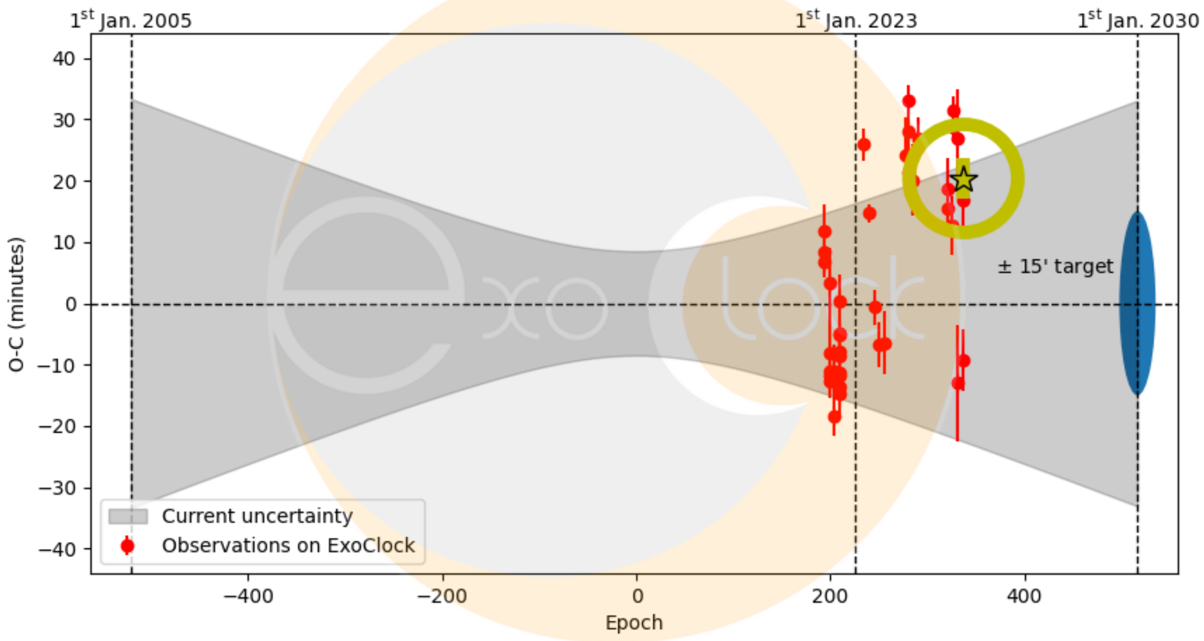
Example: WASP – 148: Two-Planet System

Experiencing Variations in Transit Timings

Transit Lightcurve from My Telescope



Observed – Calculated (O-C) Transit Time of WASP-148B



Challenges: TTV Analysis

- Requires **long-term timing baselines** — data often missing or with gaps
- **Traditional methods** are computationally intensive, taking **weeks to months** for parameter exploration
- **Degeneracies**: multiple possible solutions can arise from the same TTV signals

NEPTUNE: Open Science, Open Source, Open Data for TTV Analysis

Data Sources

- Transit Timings Data: MAST (Kepler, TESS, Exoclock)
- TTV Catalog: Kepler Data Release, Holczer (2016)
- Ephemeris: NASA Exoplanet Archive

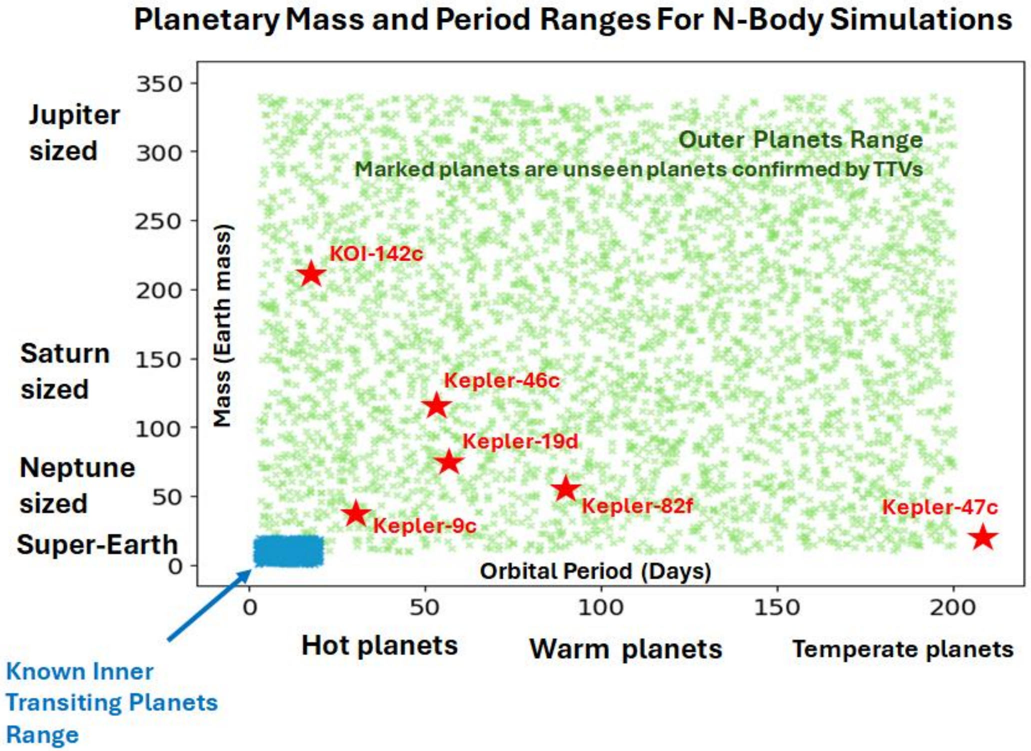
Modeling and Analysis

- N-Body integrator: REBOUND IAS15
- Signal Processing: Scipy, Astropy
- Machine Learning and Bayesian: scikit-learn, emcee, corner

Step 1: Generated N-Body Simulations

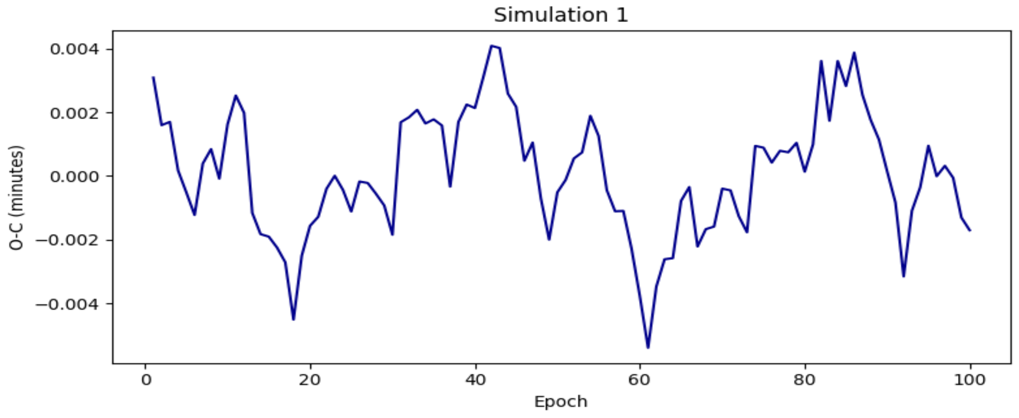
Stellar & Planetary Parameters Simulated: 11

Parameter	Inner (Transiting)	Outer (Perturbing)
Stellar Mass	$0.7\ M_\odot - 1.3\ M_\odot$	
Mass	$1\ M_\oplus - 20\ M_\oplus$ *Earth → Neptune mass*	$1\ M_\oplus - 320\ M_\oplus$ *Earth → Jupiter mass*
Period	2 – 20 days, *Short*	3 – 240 days, *Long*
Eccentricity	0 – 0.07, *Low - Medium*	0 – 0.5, *Low - High*
Inclination	87° – 90°, *In-transit*	50° – 90°, *Out-of-transit*
Periastron	-180° to +180°	-180° to +180°



N-Body Simulations

Observed minus calculated (O-C) mid-transit times

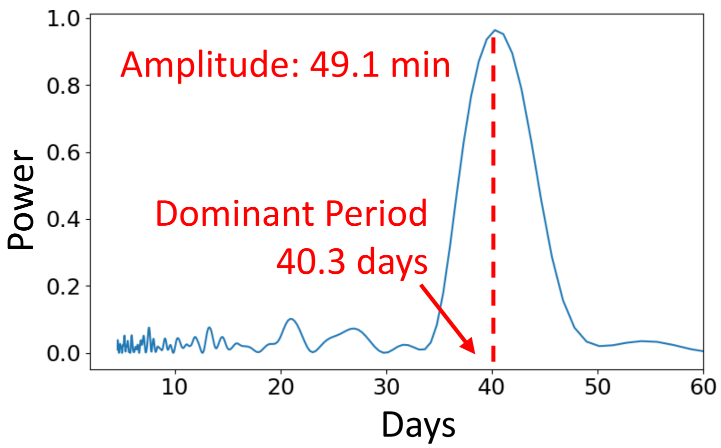


Step 2: Analyzes TTV Signals

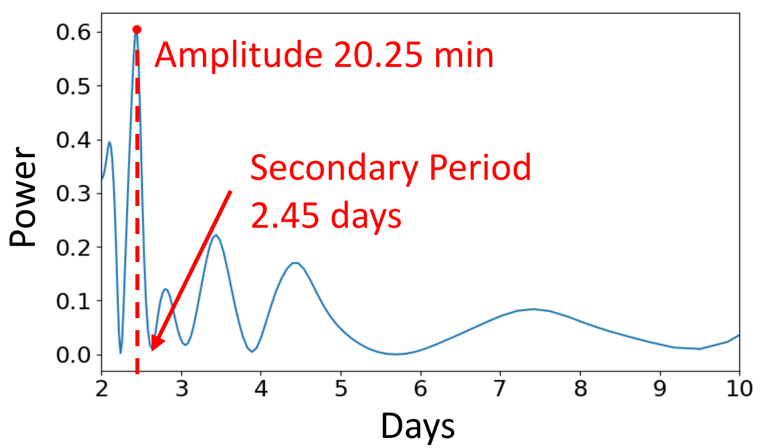
Methodology applied to simulated O–C plots of transiting planets:

- Determined dominant periods via Lomb–Scargle periodogram
- Dominant sinusoid removed to identify secondary periodicities
- Measured TTV amplitudes by fitting sinusoids
- **Retained peaks with False Alarm Probability (FAP)** ≤ 0.01 showing ≥99% confidence that the detected period is not due to noise

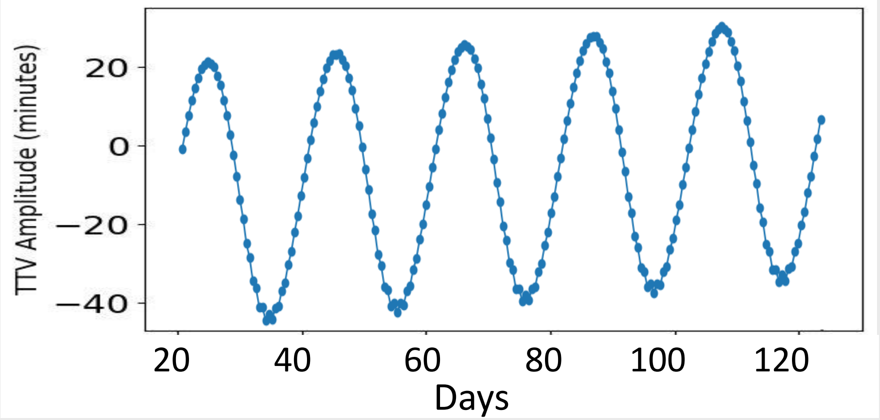
Dominant TTV Signal

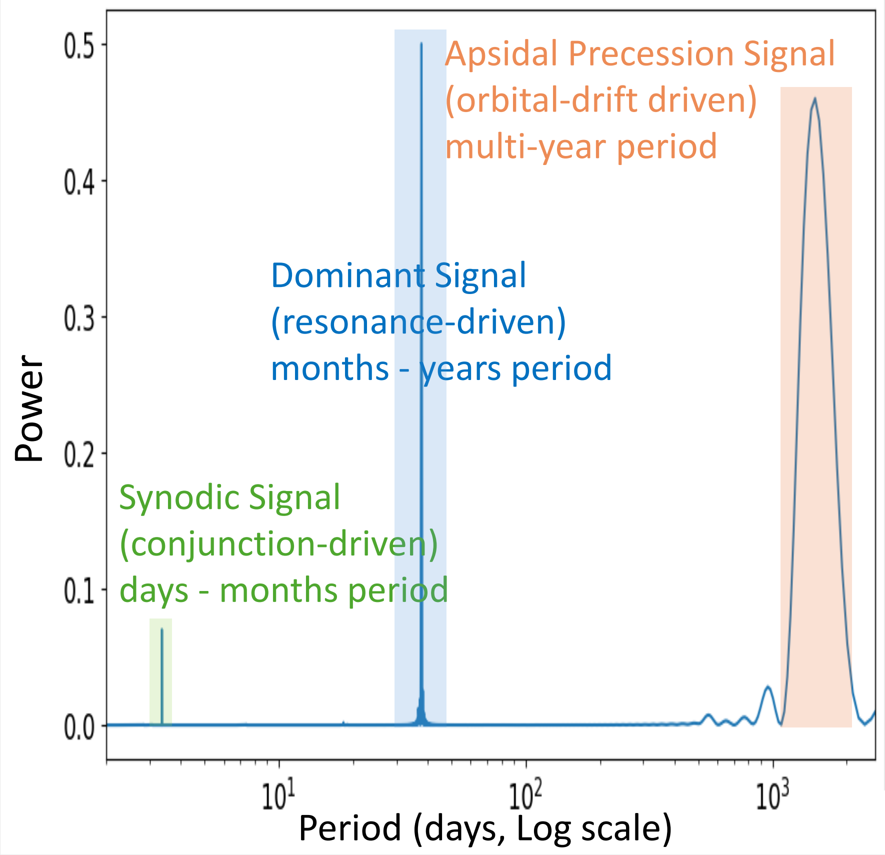


Secondary TTV Signal
(Dominant Signal Removed)



O-C Plot and its Multi-Period Decomposition





Step 3: Trained Random Forest on Simulated TTV Data

Applied machine learning (ML) to get informed priors of the hidden planet

Training Data
- 90 million N-body simulation data points
- 10% Gaussian noise added to transit timing data

Feature Extraction
- TTV amplitude
- Dominant TTV period
- TTV signal phase

Model Hyperparameters
- Number of Estimators = 500
- Maximum Random Forest Tree Depth = 15

Random Forest Outputs/Informed Priors

Mass, Orbital period, Eccentricity

Orbital Period Ratio Bins (6)

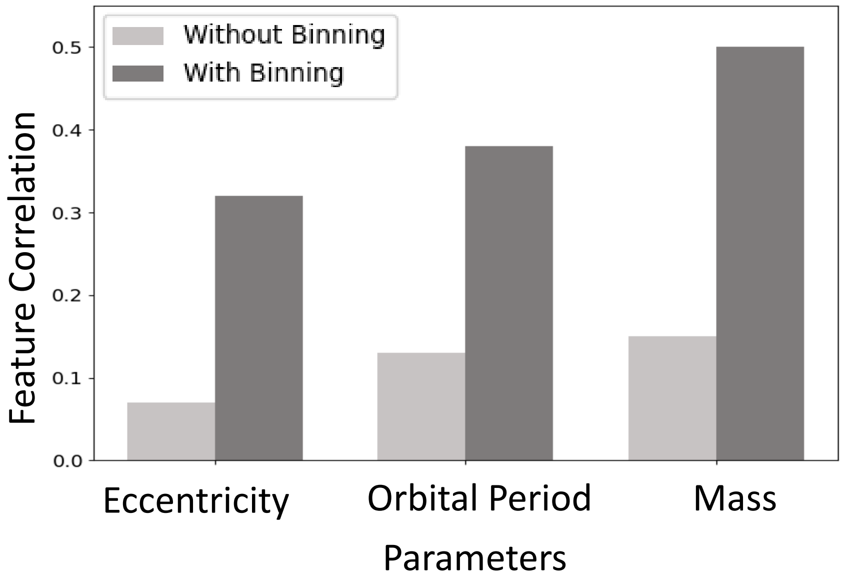
2:1 Resonance	3:2 Resonance	5:3 Resonance	3:1 Resonance	Non-Resonant	6:1 – 12:1 Long Period

Eccentricity Bins (6)

0 – 0.01	0.01 – 0.03	0.03 – 0.05	0.05 – 0.1	0.1 – 0.3	0.3 – 0.5

low moderate high

Binning of Parameters Improved Feature - Parameter Correlation



Step 4: Bayesian Parameter Estimation

Refine planetary parameters using Markov Chain Monte Carlo (MCMC) to sample posterior distributions

MCMC Setup

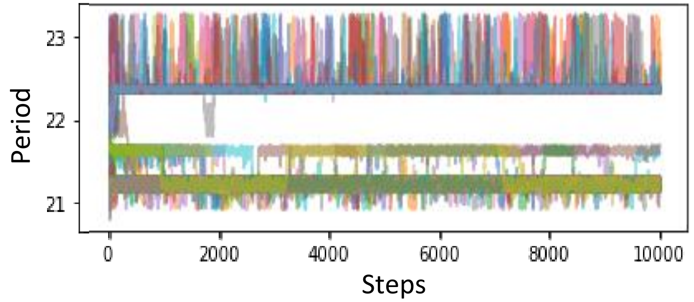
- **Algorithm:** emcee
- **Walkers**: 100 (explores parameter space)
- **Sampling Steps**: 10,000 (ensures adequate exploration)
- **Convergence Checks**
  - Trace Plots: Visual confirmation of parameter stability
  - Autocorrelation time: Ensures independent samples (shorter is better)
  - Gelman-Rubin statistic ($\hat{R}$): Confirms convergence across chains ($\hat{R} \approx 1$)

Outputs

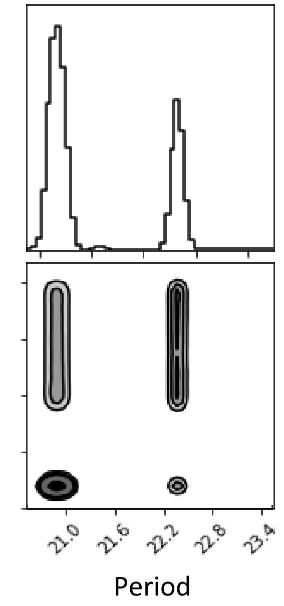
- **Posterior Distributions** of planetary parameters
- **Uncertainties:** Shown by 1-sigma (σ) deviations
- **Degeneracies:** Parameter combinations with similar solutions

MCMC Convergence: Clear Solutions

Stable Trace Plot

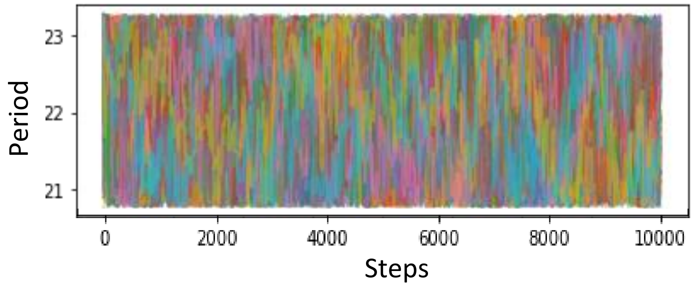


Corner Plot

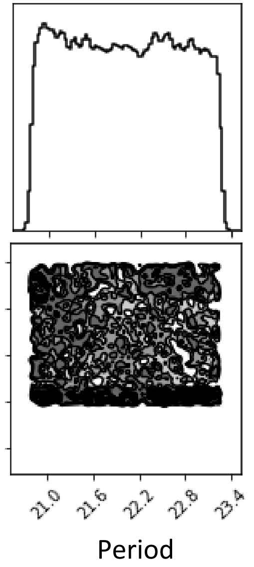


MCMC Non-Convergence: Poor Solution

Unstable Trace Plot



Corner Plot



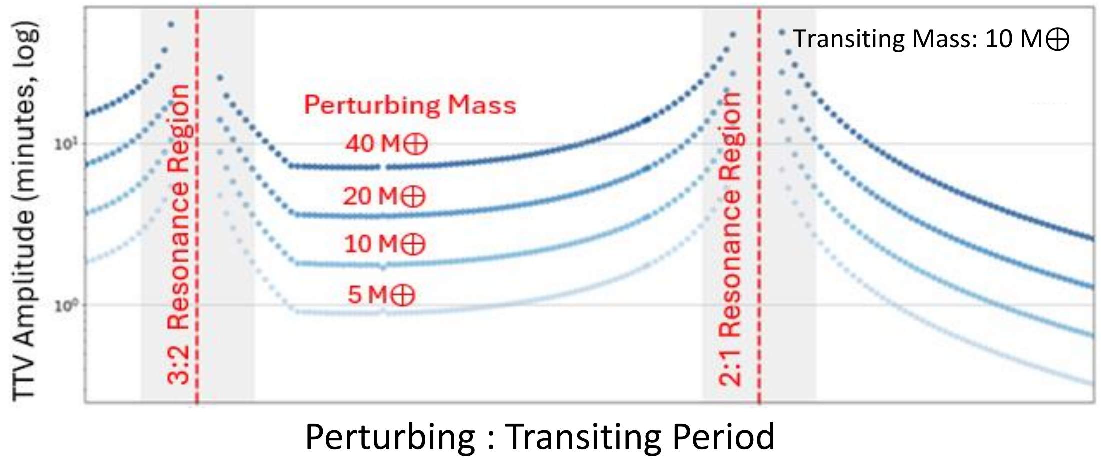
Result 1: TTV Amplitude & Period Depend on Resonance, Mass, and Eccentricity

TTV Amplitude:
- **Peaks** near resonances (e.g., 2:1, 3:2) due to cumulative gravitational interactions
- **Increases** with greater perturbing mass
- **Amplified** by eccentricity near resonance

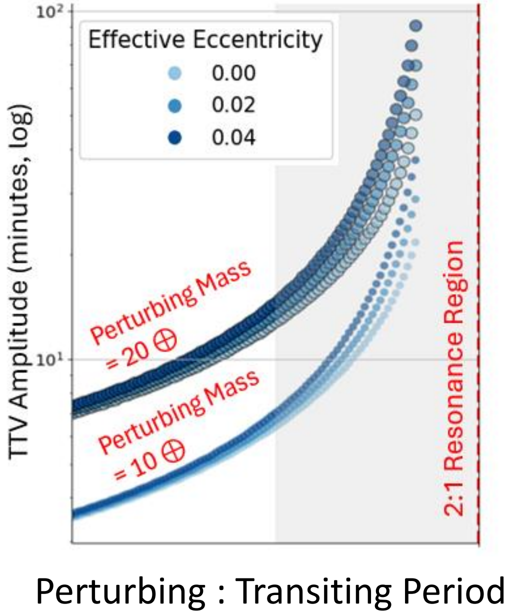
TTV Period:
- **Resonant systems** yield long-period, high-amplitude "super-period" signals
- **Non-resonant systems** reveal short-period synodic signals tied to planetary conjunctions

Degeneracies:
Different parameter combinations can produce similar TTV signals:
- **High-mass / low-eccentricity**
- **Low-mass / high-eccentricity**

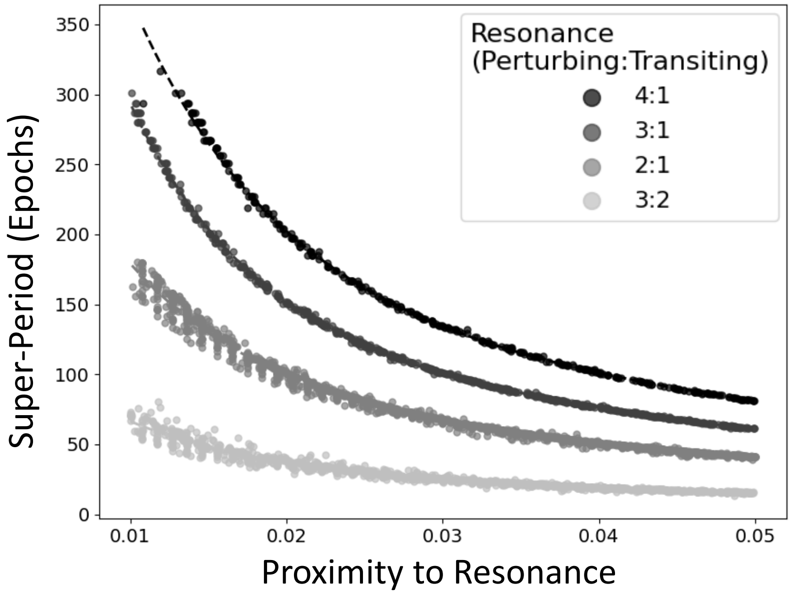
Amplitude Increases Near Resonance and with Perturbing Mass



Eccentricity Amplifies Amplitude

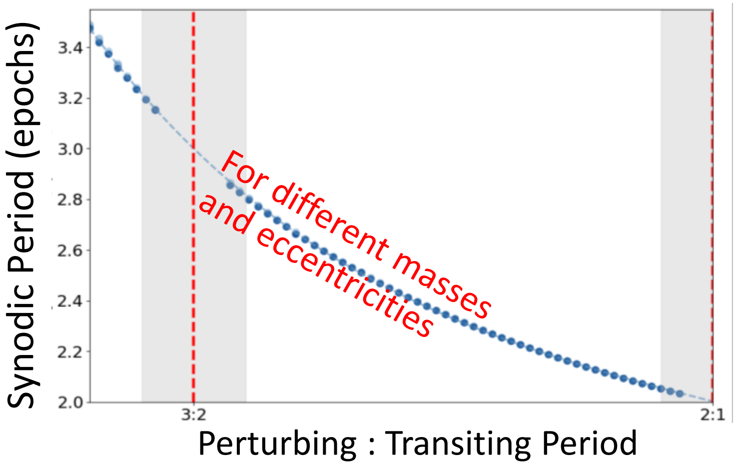


Super-Period Increases Near Resonance

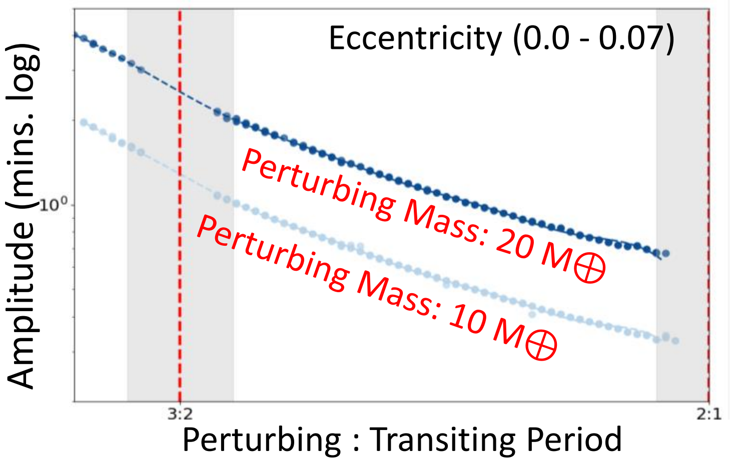


Result 2: Synodic Signals Resolve Mass–Eccentricity Degeneracies

Synodic Period is Independent of Mass and Eccentricity



Synodic Amplitude Increases with Perturbing Mass

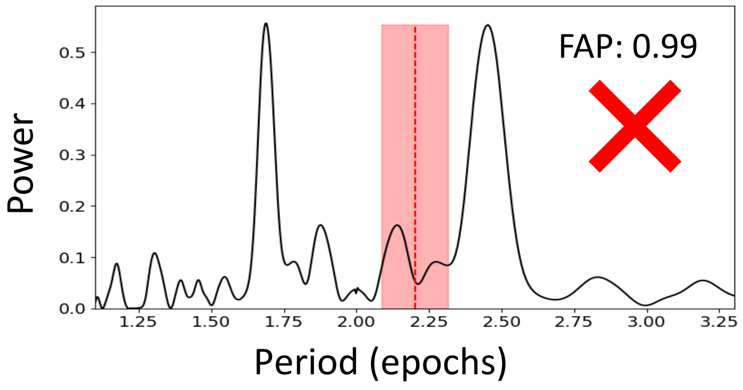


High-mass planets:
Strong, detectable synodic signals

Low-mass planets:
Weak, undetectable synodic signals

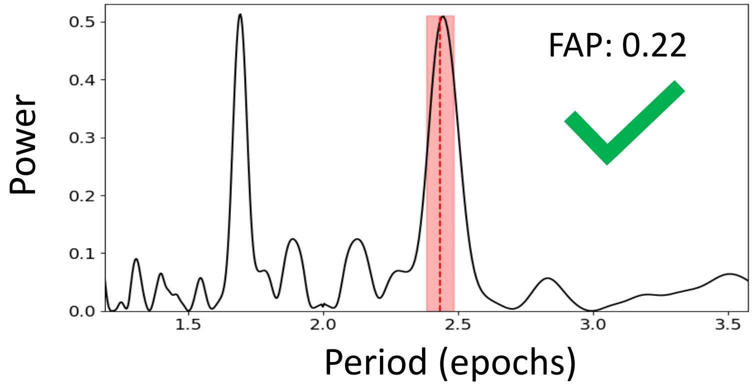
NEPTUNE Identifies Correct Planetary Parameters for Hidden Planet Kepler-46c

Mismatch between predicted synodic and observed peak



Mass: 137.94 $M_\oplus$ Eccentricity: 0.0

Agreement between predicted synodic and observed peak



Mass: 110.25 $M_\oplus$ Eccentricity: 0.014

Result 3: Parameters Recovered for Hidden Planet Kepler-46c

Data Input: 30 mid-transit observations of Neptune-sized transiting planet Kepler-46b (Period: 33.6 days)

Dominant Signal
- Period: 191.5 ± 0.2 days
- Amplitude: 49.1 ± 1.8 min
- FAP: 10^{-7} (Highly significant signal)

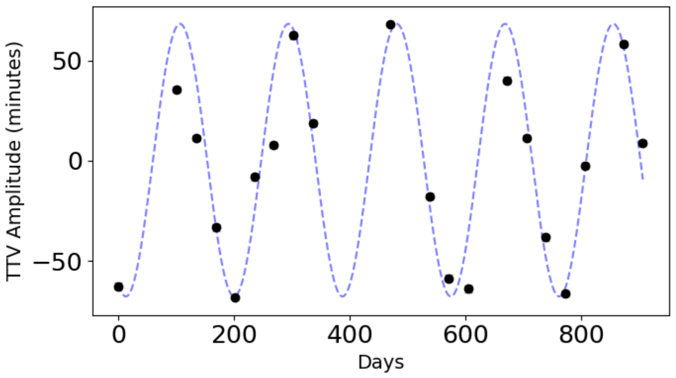
Random Forest Priors (Initial Guess)
- Period ratio: 5:3 or far from resonance
- Eccentricity: 0.00 - 0.03
- Mass: 80 - 200 $M_{\oplus}$

Bayesian (MCMC) Convergence:
- Gelman–Rubin $\hat{R}$ < 1.1 (chains converged)
- Chain length > 20× autocorrelation (well-sampled)
- Posteriors: 9 degenerate solutions

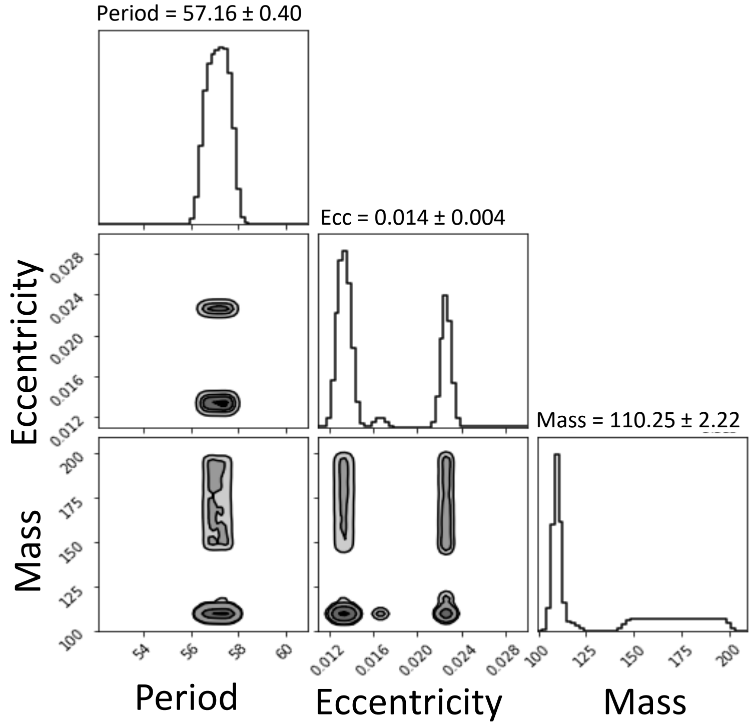
Synodic Signal (unique solution):
- Period: 82.32 ± 0.2 days
- Amplitude: 20.25 ± 1.9 min

NEPTUNE confirms unique solution for non-transiting planet Kepler-46c inferred from Kepler-46b's TTV

Kepler-46b O-C Plot



Corner Plot: Posterior Distribution

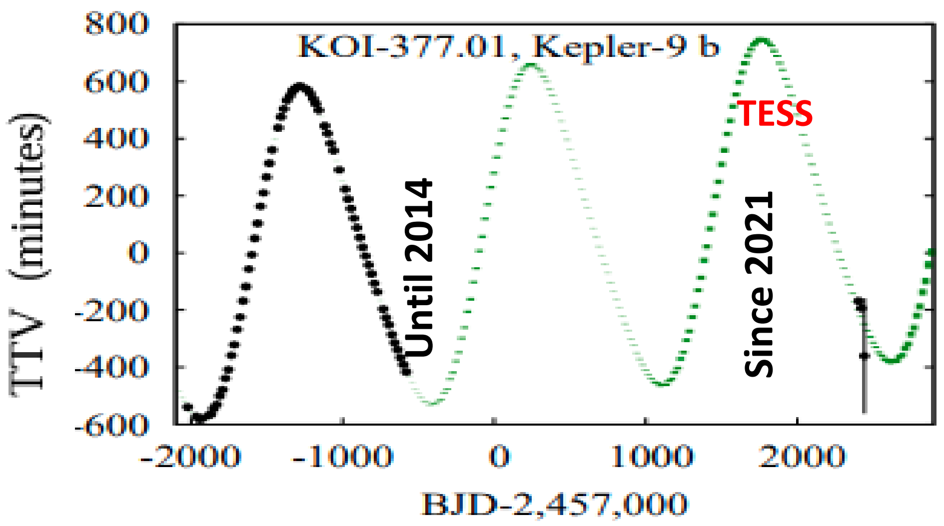


Predicted Parameters Matched NASA

Parameter	NEPTUNE	NASA	Accuracy
Period (days)	57.16 ± 0.40	57.01 ± 0.06	99.74%
Resonance	5:3	5:3	100%
Eccentricity	0.014 ± 0.004	0.0146 ± 0.003	95.89%
Mass ($M_{\oplus}$)	110.25 ± 2.22	119.49 ±6.67	92.27%

How Exoclock Data Can Improve NEPTUNE?

- **18,000+ transit mid-times** across 450+ planets (2023, and growing)
- **Vetted long-term data** extends baselines for feature extraction, synodic signals, and breaking degeneracies
- **Validates ML + Bayesian pipelines** on real, heterogeneous datasets
- Provides **negative signals** (non-planetary TTVs) to refine classifications

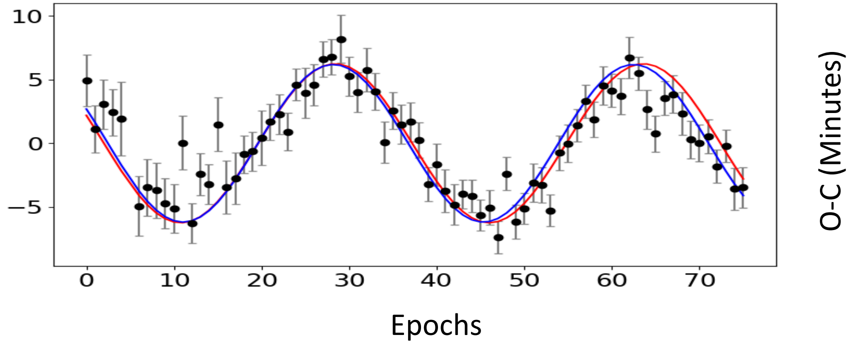


Exoclock can provide new data for some exoplanets

How NEPTUNE Can Help Ariel/ ExoClock

- **Accelerates** ephemeris predictions with hybrid N-body + ML + Bayesian modeling
- **Resolves degeneracies**: separates true planetary TTVs from noise, or small-mass eccentric vs. large-mass circular
- **Extends forecasts** beyond baselines, keeping predictions sharp during Ariel operations

Kepler-18d:
Two Solutions with Identical TTV Fits



Solution 1:
Mass = 17.0 $M_\oplus$
Eccentricity = 0.001

Solution 2:
Mass = 7.5 $M_\oplus$
Eccentricity = 0.020

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Arushi Nath
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- Grade 11 Student, Toronto, Canada

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- 2024 Masason Scholar
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- 2022 & 2023: Canada's Top Young Scientist

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ExoClock 5th Annual Meeting

Madrid, Spain 4th October 2025