PHYS055

NEPTUNE: N-body Exoplanet Prediction Using TTV for Unseen Exoplanets

Arushi Nath

CHALLENGE

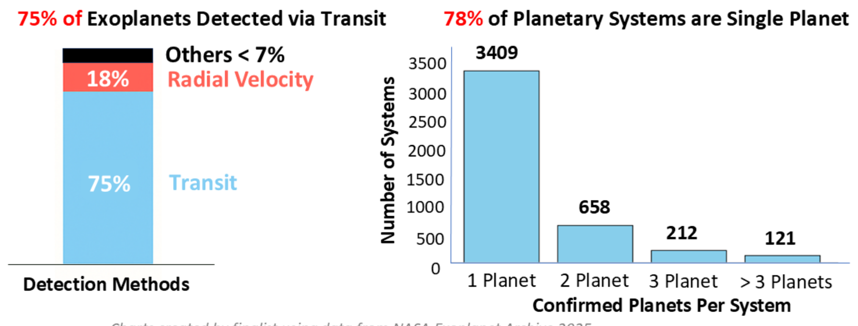
Exoplanet Detection Bias Distorts Our View of Planetary Systems

Most known exoplanets are detected using the **transit method**, which favors planets that orbit close and nearly edge-on to their stars

Outer planets often remain undetected:
- **Have longer orbital periods** → Fewer transits
- **May have slight inclination** → Prevents observable transits

Total Confirmed Exoplanets: 5845

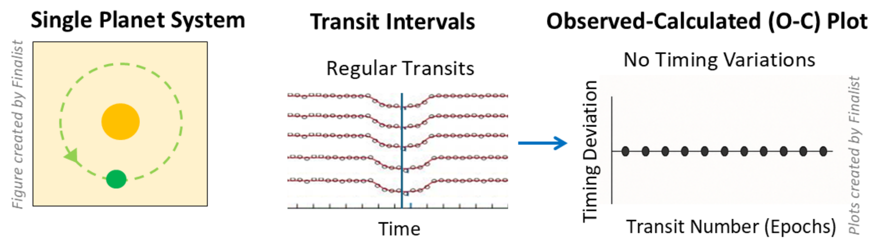
75% of Exoplanets Detected via Transit | 78% of Planetary Systems are Single Planet



Charts created by finalist using data from NASA Exoplanet Archive 2025

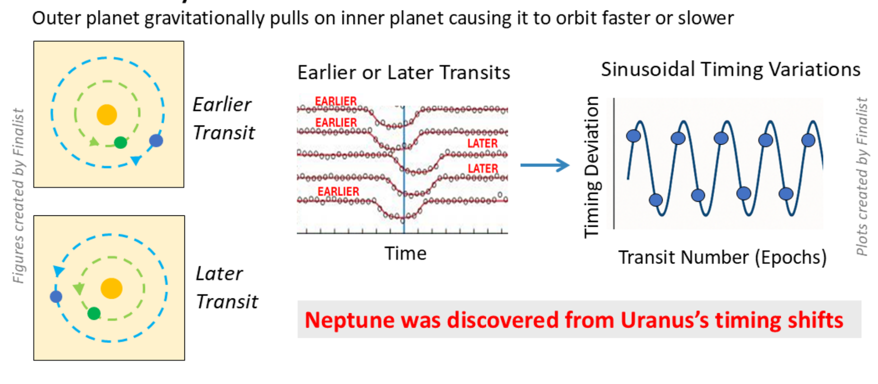
Missing outer planets significantly **undercounts** multi-planet systems, leading to an incomplete view of planetary system architectures

How Transit Timing Variations (TTVs) Reveal Multi-Planet Systems



Multi-Planet System

Outer planet gravitationally pulls on inner planet causing it to orbit faster or slower



Neptune was discovered from Uranus's timing shifts

Why Accelerate TTV Analysis?

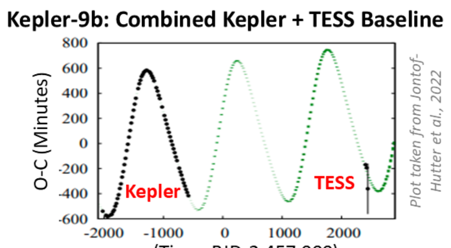
Breakthrough Discoveries
- **36** exoplanets confirmed via TTVs
- **22** single-planet systems upgraded to multi-planet status

Discovery Potential
- Kepler: **260** strong, **650** moderate TTVs
- TESS: **30+** planets with TTVs
- Ground telescopes constantly update TTV data

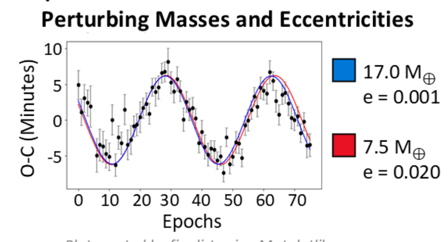
Key Challenges
- Requires multi-year monitoring
- Computationally demanding analysis
- Multiple planet parameters can produce same TTV signals (degeneracies)

e.g. High-mass + low-eccentricity, or Low-mass + high-eccentricity

Kepler-9b: Combined Kepler + TESS Baseline



Kepler-18c: Same O-C Curve for Different Perturbing Masses and Eccentricities



Plot created by finalist using Matplotlib

Decoding TTVs requires long baselines and breaking degeneracy

RESEARCH GOALS

Goal

Accelerate the detection and characterization of hidden (non-transiting) exoplanets in multi-planet systems using **Transit Timing Variations (TTVs)**

Objectives

1. **Simulate** realistic TTV signals to analyze gravitational interactions between planets in multi-planet systems
2. **Estimate** planet masses, orbital periods, and eccentricities by resolving degeneracies using **Machine Learning**, **Bayesian Inference**, and **multi-period fitting**
3. **Validate** the model by comparing predictions against known TTV systems and quantifying uncertainties
4. **Apply** the model to **Kepler** and **TESS** data to discover new exoplanet candidates

DATA SOURCES

NEPTUNE: Powered by Open Science, Open Source, Open Data

Data Sources
- TTV Catalog: Kepler and TESS Data Release
- Transit Timings: MAST Archive
- Ephemeris: NASA Exoplanet Archive
- Radial Velocity: HARPS Catalog

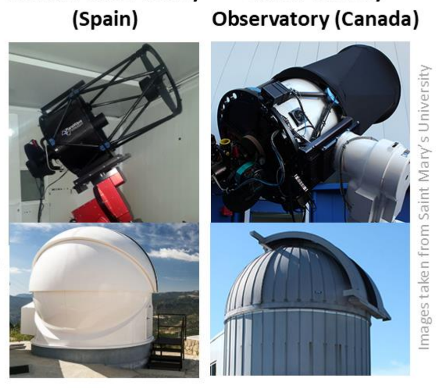
Open Robotic Telescopes Network
- Burke-Gaffney Observatory (Canada)
- Alnitak Observatory (Spain)

Modeling and Analysis Tools
- N-Body integrator: REBOUND (IAS15)
- Signal Processing: Scipy, Astropy
- Machine Learning: scikit-learn
- Bayesian Inference: emcee, corner

Networks and Forums
- Citizen Science: Ariel ExoClock, ExoFOP
- Forums: Royal Astronomical Society of Canada, Exoplanet Watch, British Astronomical Association

Robotic Telescopes I Used for Exoplanet Observations

Alnitak Observatory (Spain) | Burke-Gaffney Observatory (Canada)



Images taken from Alnitak | *Images taken from Saint Mary's University*

Aperture: 0.43 m, Focal Ratio: f/6.8 | Aperture: 0.61m, Focal Ratio: f/4

SELECTED REFERENCES

Deck, K. M., & Agol, E. (2015). Measurement of planet masses with transit timing variations due to synodic "chopping" effects. *The Astrophysical Journal, 802*(2), 116. https://iopscience.iop.org/article/10.1088/0004-637X/802/2/116

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METHODOLOGY

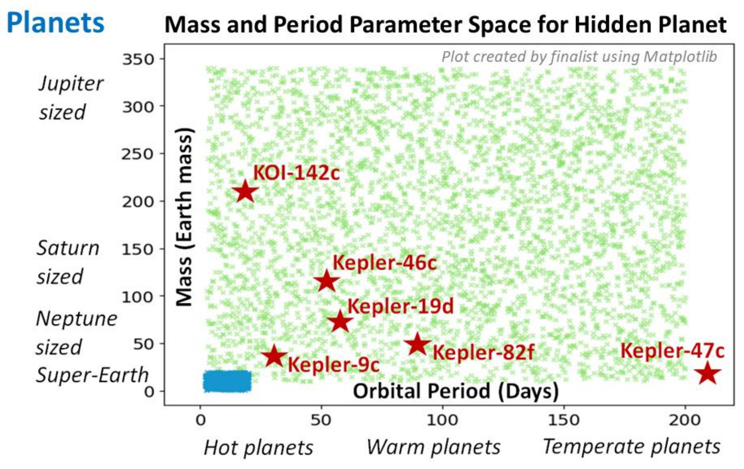
Step 1: 80,000 N-body Simulations Exploring 11 Parameters to Discover Hidden Planets

Parameter	Inner Planet (Transiting)	Outer Planet (Perturbing)
Stellar Mass	0.7 – 1.3 Solar Mass	
Planet Mass	1 – 20 $M_\oplus$ *(Earth – Neptune mass)*	1 – 320 $M_\oplus$ *(Earth – Jupiter mass)*
Orbital 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 Angle	-180° to +180°	-180° to +180°

Table created by finalist

Simulation Setup
- **Sampling:** Latin hypercube for uniform 11-D parameter space
- **Duration:** 1200 epochs (transits) per simulation
- **Output:** Transit Timing Variations (O-C Plot)
- **Stability Filter:** Systems must have ≥ 3.5 mutual Hill radii separation to avoid collisions/ejections

Mass and Period Parameter Space for Hidden Planet

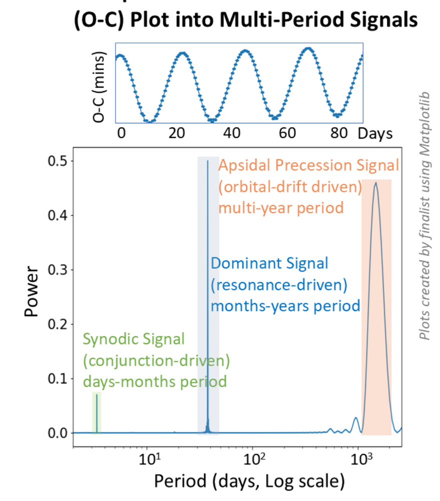


Blue: Known inner transiting planets simulated
Green: Outer planets simulated
★ Hidden planets discovered via TTV method

Step 2: Signals Extracted from Simulated TTVs

- **Dominant Period:** Detected via Lomb–Scargle periodogram
- **Secondary Period:** Detected by subtracting dominant period
- **Amplitude:** Estimated using sinusoidal fits
- **False Alarm Probability:** Signal kept if FAP < 0.01 (≥99% certainty)

Decomposition of Observed-Calculated (O-C) Plot into Multi-Period Signals



Step 3: Random Forest Regression to Predict Hidden Planet Priors

Applied machine learning to data from N-Body simulations

Training Data
- **80,000** N-body simulation parameters
- 10% Gaussian noise added *(transit timing uncertainty)*

Orbital Period Ratio Bins

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

Features Extracted
- TTV amplitude
- Dominant period
- Signal phase

Eccentricity Bins

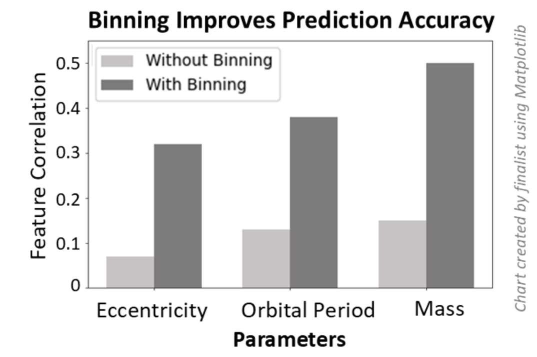
Low		Medium		High	
0 – 0.01	0.01 – 0.03	0.03 – 0.05	0.05 – 0.1	0.1 – 0.3	0.3 – 0.5

Model Setup

Random Forest machine learning algorithm with
- Trees = 500
- Max depth = 15

Model Output (Informed Priors):
- Mass
- Orbital period
- Eccentricity

Binning Improves Prediction Accuracy



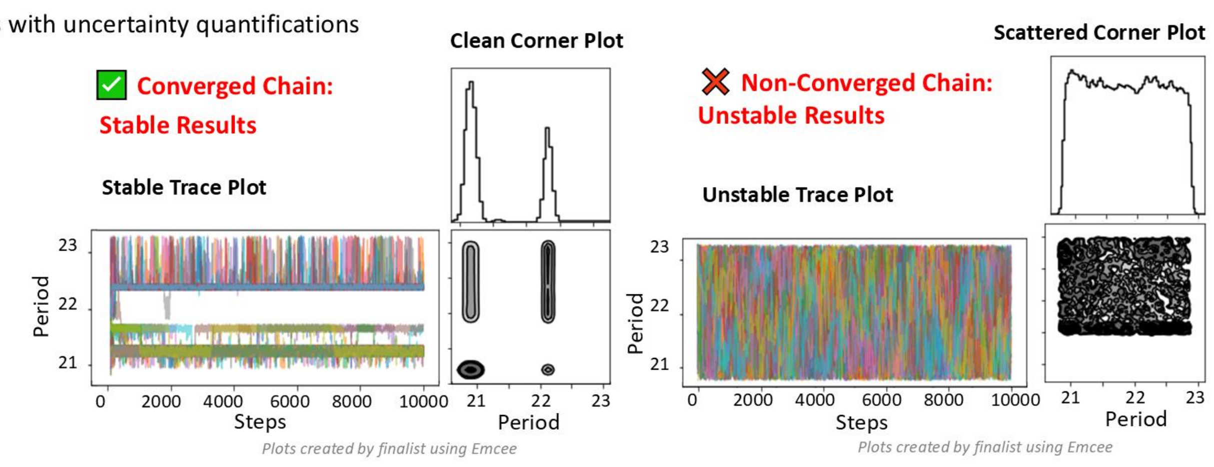
Step 4: Bayesian Inference Recovers Hidden Planet Parameters

Using informed priors to sample posterior distributions with uncertainty quantifications

Markov Chain Monte Carlo (MCMC) Setup
- **Walkers**: 100 (explores parameter space)
- **Steps**: 10,000 (ensures full sampling)
- **Convergence Checks**
  - Trace Plots: Assess parameter stability
  - Autocorrelation time: Shorter = Independent samples
  - Gelman-Rubin statistic (R̂): Converged if R < 1.1

Outputs
- **Posterior distributions** of mass, period, and eccentricity
- **Uncertainties:** 1σ confidence intervals
- **Degeneracies:** Identify solutions with similar TTV fits

✅ Converged Chain: Stable Results | ❌ Non-Converged Chain: Unstable Results

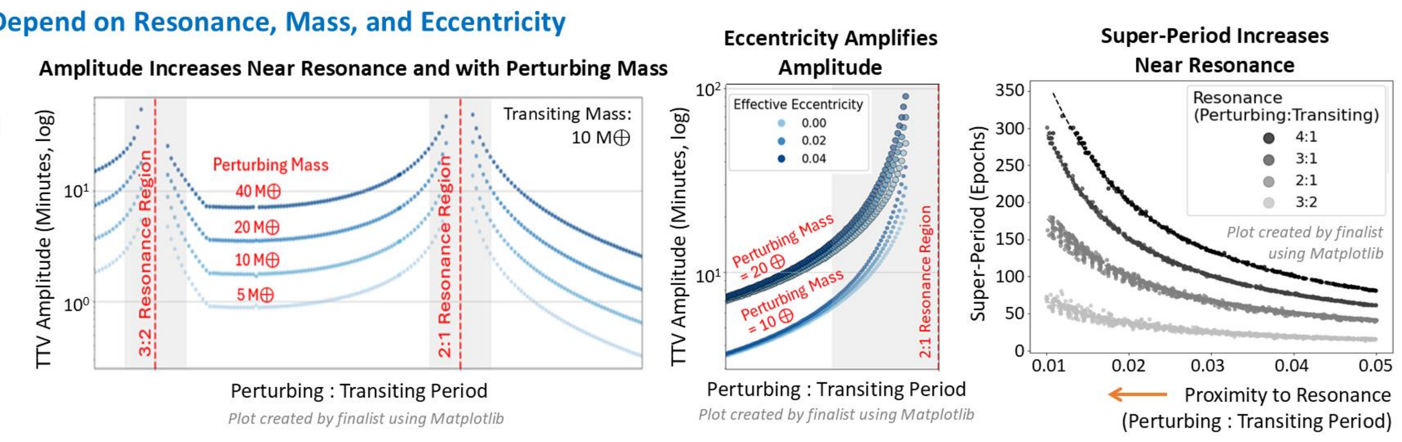


RESULTS

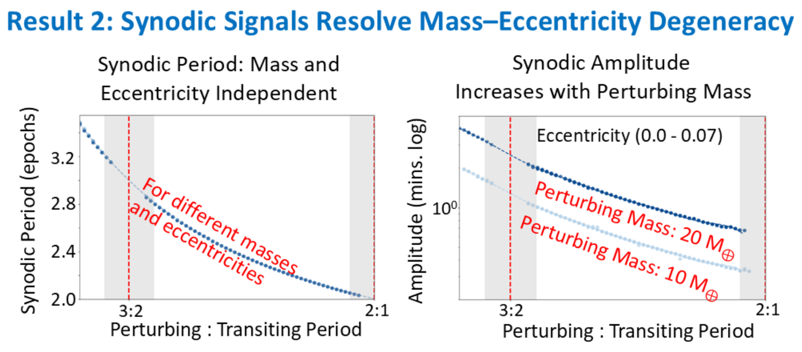
Result 1: TTV Amplitude & Period Depend on Resonance, Mass, and Eccentricity

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

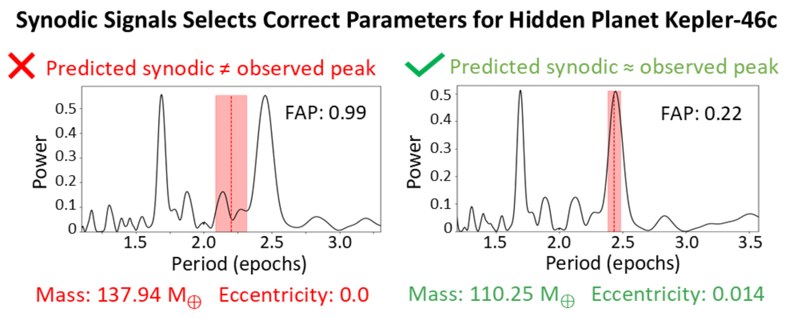
TTV Period
- **Resonant systems:** long-period, high-amplitude *super-period* signals
- **Non-resonant systems:** shorter-period, synodic signals from conjunction timing



Result 2: Synodic Signals Resolve Mass–Eccentricity Degeneracy



Synodic Signals Selects Correct Parameters for Hidden Planet Kepler-46c



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

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

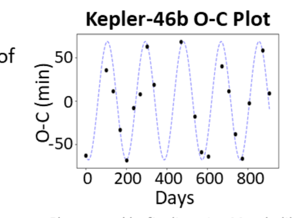
TTV Signal (Kepler-46b)
- Period: 191.5 ± 0.2 days
- Amplitude: 59.1 ± 1.8 min
- FAP: 10^{-7} (Highly significant)

Initial Guess from Random Forest
- Period ratio: 5:3 | far from resonance
- Eccentricity: 0.00 - 0.03
- Mass: 80 - 200 $M_\oplus$

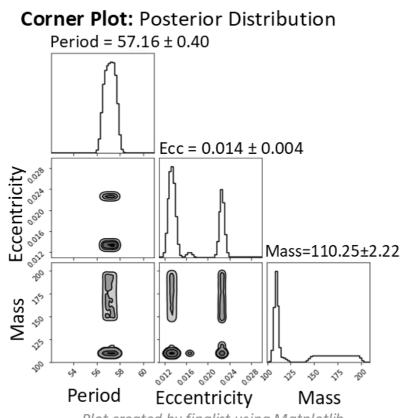
Bayesian Inference (MCMC)
- Gelman–Rubin R < 1.1 (converged)
- Chain length > 20× autocorrelation
- Posteriors: 9 degenerate solutions

Synodic Signal (Unique Solution)
- Period: 82.32 ± 0.2 days
- Amplitude: 20.25 ± 1.9 min

Kepler-46b O-C Plot



Corner Plot: Posterior Distribution



Predicted Parameters of Kepler 46c 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%

Result 4: Discovery of Possible Candidate Exoplanet in Single-Planet System Kepler-1710

Target: Kepler-1710b (Transiting, Period: 14.9 days)
Single-planet system with TTVs (*Kepler DR 25*)

Data and Light Curve Processing
- 70+ **Target Pixel Files (TPF)** from NASA **MAST**
- Custom apertures via **EXOTIC**
- Mid-transit times → O-C curve

TTV Signal Analysis (Kepler-1710b)
- Sinusoidal O-C → likely gravitational perturbation
- Dominant Period: 259.43 ± 0.3 days
- Amplitude: 37.6 ± 0.2 min
- FAP: 10^{-11} (Highly significant)

Initial Guess from Random Forest
- Period ratio: 2:1 | 3:2
- Eccentricity: 0.00 - 0.03
- Mass: 5 - 80 $M_\oplus$

Bayesian Inference (MCMC)
- Gelman–Rubin R < 1.1 (converged)
- Chain length > 20× autocorrelation
- Posteriors: 1 solution (others rejected > 10% Sum of Squared Errors)

Star in Kepler Field of View

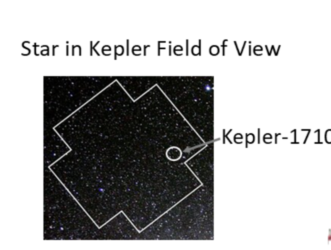
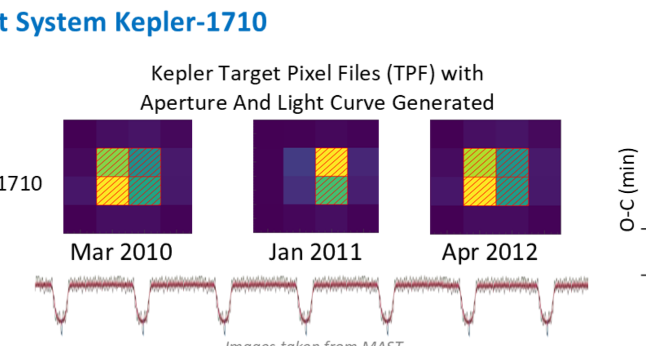


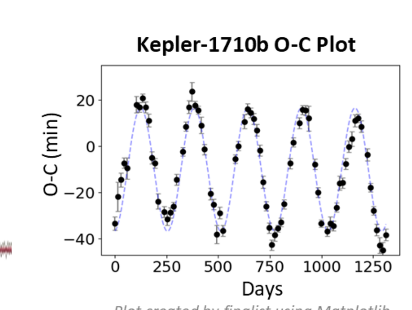
Image taken from NOAO, 2014

Kepler Target Pixel Files (TPF) with Aperture And Light Curve Generated



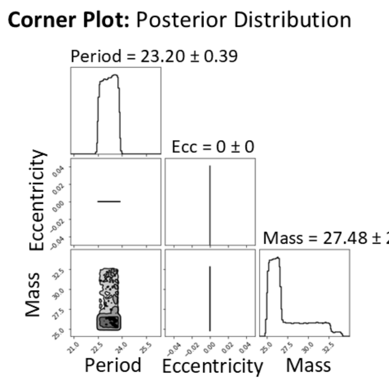
Images taken from MAST

Kepler-1710b O-C Plot



Plot created by finalist using Matplotlib

Corner Plot: Posterior Distribution



Plot created by finalist using Matplotlib

Likely Parameters of Candidate Exoplanet

Parameter	NEPTUNE
Period (days)	23.20 ± 0.73
Resonance	3:2
Eccentricity	0 ± 0
Mass ($M_\oplus$)	27.48 ± 2.38

Meets Radial Velocity Constraints
- **RV baseline:** 12.2 years, 21 RV points
- **No RV trend:** Excludes distant giant companions
- **RV mass limit:** *<1.23 Jupiter Mass at 10 AU*

✅ **Consistent with proposed Neptune-sized candidate** (27.5$M_\oplus$ at ~0.15 AU)

DISCUSSIONS

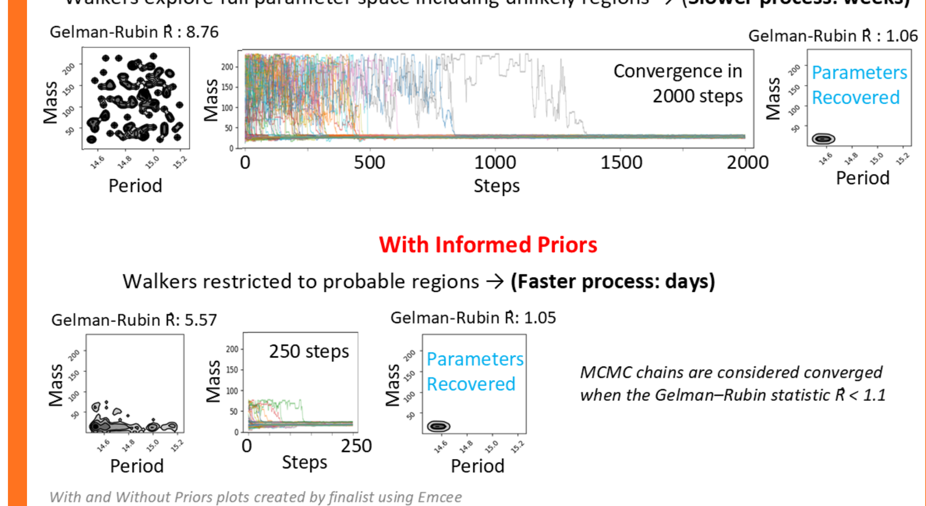
Discussion 1: Informed Priors Accelerate Parameter Recovery 8x Faster

With Uniform Priors

Walkers explore full parameter space including unlikely regions → **(Slower process: weeks)**

With Informed Priors

Walkers restricted to probable regions → **(Faster process: days)**



With and Without Priors plots created by finalist using Emcee

Discussion 2: NEPTUNE Characterizes Hidden Exoplanets

Planet Classification
- Rocky Super-Earths: < 10 $M_\oplus$
- Neptune/super-Neptune like: 10 – 100 $M_\oplus$
- Gas Giants: > 100 $M_\oplus$

Surface Temperature Estimation (T_{eq}):
*Calculated using orbital distance (**d**, in AU) and stellar luminosity (**L★**)*

$$T_{eq} \approx 278 \times \frac{L_\star^{1/4}}{d^{1/2}}$$

Habitable Zone: Defined by potential liquid water conditions (~200–400 K)

Kepler-46c Hidden Planet *(orbiting K-type Star)*

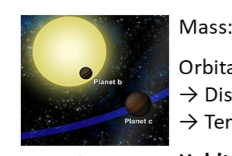


Image from NASA

Mass: **110 $M_\oplus$ (Gas Giant)**
Orbital Period: **57 days**
→ Distance: **0.28 AU**
→ Temperature: **472 K**
Habitable Zone: ❌

Kepler-1710b's Possible Hidden Companion *(orbiting G-type Star)*

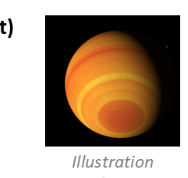


Illustration Image from NASA

Mass: **27.5 $M_\oplus$ (Neptune-like)**
Orbital Period: **23 days**
→ Distance: **0.15 AU**
→ Temperature: **658 K**
Habitable Zone: ❌

Discussion 3: NEPTUNE Analyzes Planetary Migration in Multi-Planet Systems

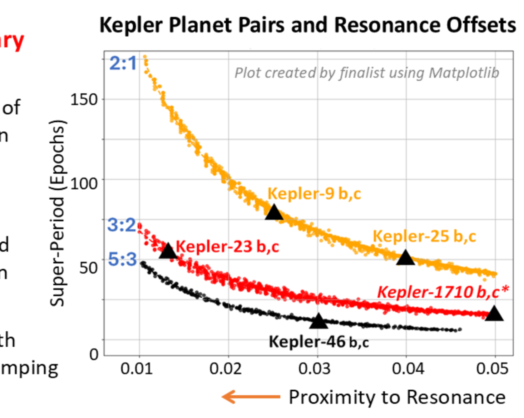
Resonance Offsets Trace Planetary Migration & Tidal Evolution

Kepler planet pairs often lie just wide of resonance, indicating migration-driven capture and tidal divergence

Kepler-25 b,c: Period ratio ≈ 2.04
Likely captured into 2:1 resonance and diverged due to tidal orbital expansion

Kepler-46 b,c: Period ratio ≈ 1.70
Likely captured into 5:3 resonance with small divergence due to weak tidal damping

Kepler Planet Pairs and Resonance Offsets

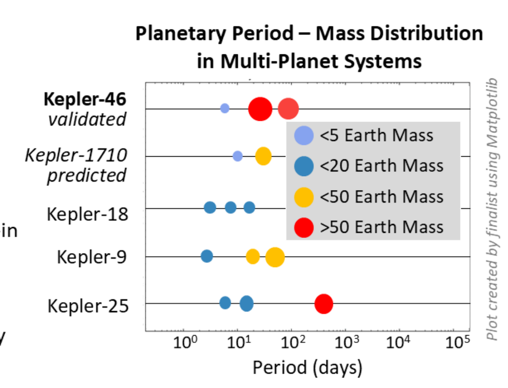


Planetary Architecture Patterns

Planet masses and periods used to characterize planetary system architectures:
- **Peas-in-a-Pod:** Planets with uniform spacing and similar masses, typically found in non-resonant systems
- **Hot Jupiter Systems**: Massive, close-in planets (<0.1 AU) and usually lack outer companions

Kepler-25 & Kepler-46: Shaped by early resonance capture and tidal evolution

Planetary Period – Mass Distribution in Multi-Planet Systems



Errors and Limitations

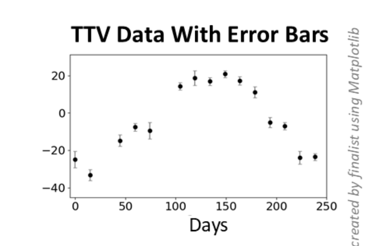
1. Mid-Transit Time Uncertainty
Transit times from Kepler/TESS light curves included measurement uncertainties derived using EXOTIC

2. Confidence Intervals of Parameter Estimates
MCMC sampling produced **1-σ** credible intervals, capturing both best-fit parameter values and the likelihood of different outcomes

3. Model Selection using Sum of Squared Errors
Models were ranked by Sum of Squared Errors (SSE); **lower SSE** indicated a better fit to TTV data

4. Numerical Integration Limitations
Limited processing capabilities of my home computer meant N-body simulations using the IAS15 integrator were restricted to 200 steps/orbit resulting in **~1% cumulative error** after 1200 epochs

TTV Data With Error Bars



CONCLUSIONS

1. Accelerated TTV Analysis
- Integrates machine learning + Bayesian inference to rapidly detect and characterize hidden exoplanets
- With informed priors, NEPTUNE achieves 8x faster analysis vs. current methods

2. Degeneracy Resolution
- Uses multi-period fitting to resolve degeneracies in planetary mass, period, and eccentricity

3. Model Validation and Uncertainty Quantification
- Model accuracy validated by comparing results with well-studied TTV systems
- Includes uncertainty estimates for reliable predictions

4. Applications to New Systems and Scalability
- Successfully applied to discover possible exoplanet candidate in Kepler-1710 system and potentially transform it from a single-planet into a multi-planet system
- Open-source tool enables broader use by researchers and citizen scientists

PROJECT IMPACT AND FUTURE

1. Contributed to ESA Ariel/ExoClock Mission
NEPTUNE observations added to **ExoClock** to improve TTV baseline

2. Expanding to Mono-Transit Analysis
Huge demand for NEPTUNE to characterize long-period planets with only 1 transit observation (**eg: KOI 4307**, **KOI 1271**) and where future observations are unlikely

3. NEPTUNE is Open-Source
Posted on GitHub and training modules created to crowdsource analysis of hundreds of unstudied TTVs

4. International Talks Delivered on NEPTUNE
4th ExoClock Annual Meeting, Portugal (Oct 2024)
31st Youth Scientists Conference, Ukraine (Apr 2025)

NEPTUNE Analysis Added to ExoClock to Improve TTV Baseline

KELT-16b Transit Curve and O-C Plot