Project EXPLORE 2000:
A Joint AAVSO/BAA Collaboration to Detect Additional Planets via TTVs

June 23, 2025

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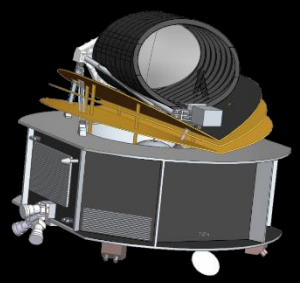
Topics:
EXPLORE – EXoPLanet Orbit REsearch

- Background
- Transit Timing Variations (TTVs)
  - their use in exoplanet discoveries
- The Discovery Process
- Supporting Resources
- Who, When, and How to Contribute

Background

- BAA's Exoplanet Division:
  - our counterparts in the British Astronomical Association (BAA)
  - Roger Dymock, Director

- Ariel Mission:
  - ESA space mission to study the atmosphere of approx. 1,000 exoplanets



- ExoClock Project:
  - currently supports ground-based observations of Ariel targets to help refine their planetary parameters, in particular periods

- The AAVSO/BAA collaboration will consist primarily of amateur astronomers observing ExoClock targets that exhibit TTV characteristics

ExoClock Modeling Software

- Accepts user photometry data about an ExoClock target from programs such as AstroImageJ and HOPS
- Conducts an MCMC exoplanet model fit
- Provides uncertainties on mid-transit times
- Assesses the quality of the observation
- If quality is acceptable, the results are included in a trend analysis, along with other observations of the same target
- Provides a best fit exoplanet model of user data and computes and tracks mid-transit Observed minus Calculated (i.e., predicted) (O-C) values

ExoClock Evaluation Report

Evaluation Report

Results

R_p/R_s = 0.1408 ± 0.006 (expected: 0.139 ± 0.003)

O-C = 3.95 ± 2.02 minutes

Quality check

Residuals STD (Standard Deviation) = 5.955 ‰

Based on your past observations, this is worse than expected (5.044 ‰). If the weather was good, the target was above 30 degrees from the horizon, and you used a broadband filter, then there is probably room for improvement. If you wish to try improving this result, use the tips below (especially points 3, 4, and 5).

Diagnostics

Step 1: Transit SNR = 11.91

Transit SNR is good (strong detection of the transit)!

Step 2: R_p/R_s drift = 0.27σ

The R_p/R_s drift is good (R_p/R_s in good agreement with the literature)!

Step 3: AutoCorrelation = 0.329

The AutoCorrelation is good (no systematics in the data)!

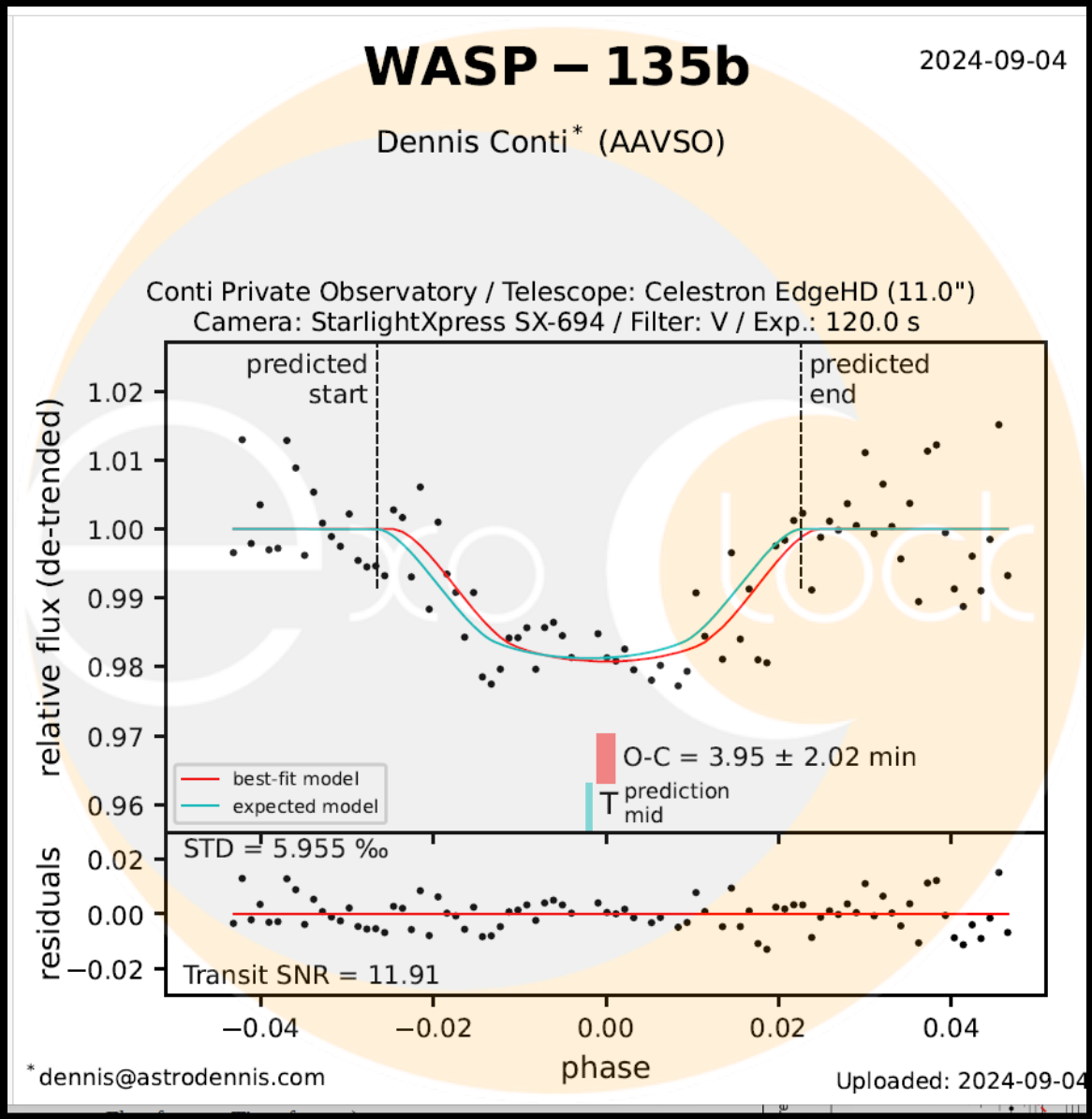
Step 4: Shapiro test = 0.014

The Shapiro test is good (few or no outliers in the data)!

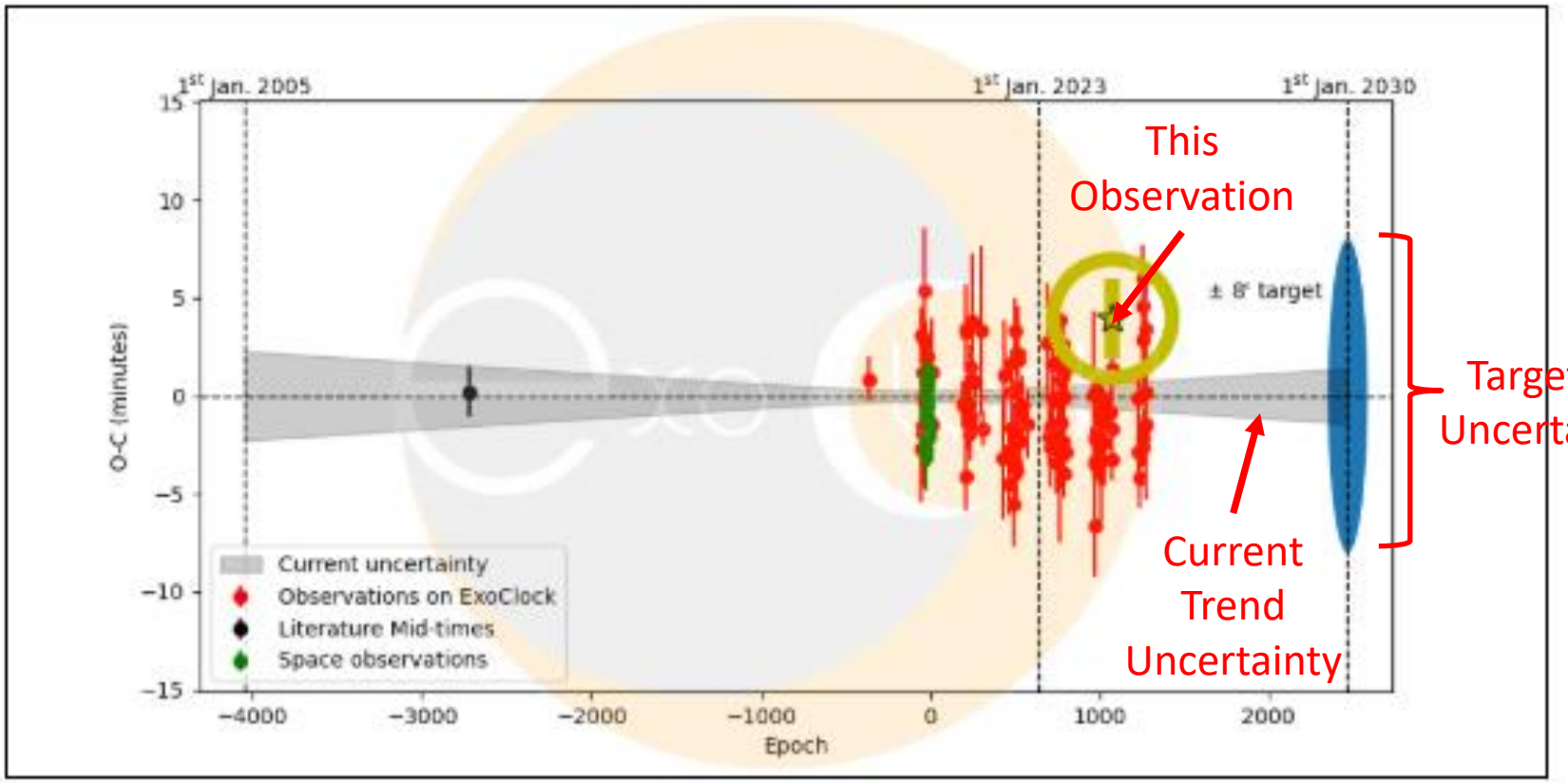
Tips to improve your results:

1. Check that you have given the correct inputs (Planet, Filter,

ExoClock Modeling



ExoClock O-C Diagram



ExoClock Database

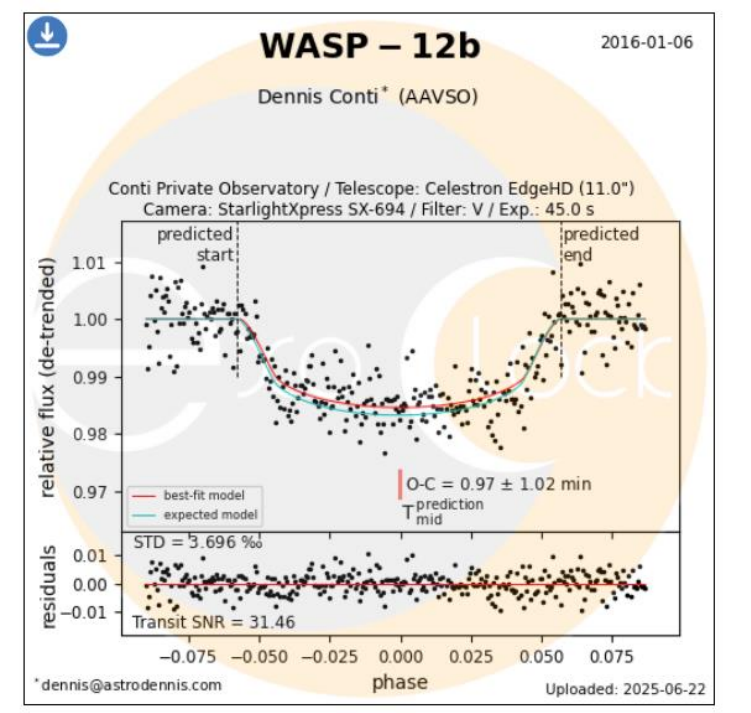
Transit Timing Variations (TTVs)

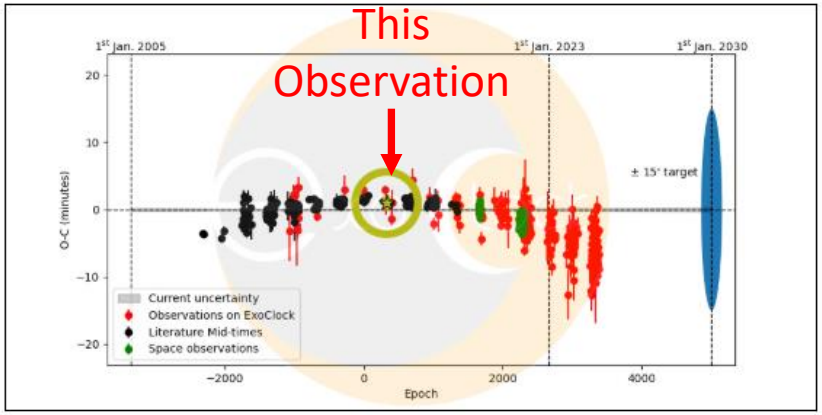
- What they are:
  - variations in an exoplanet's period potentially caused by gravitational interactions with another body, or
  - change in period due to orbital decay

- How we determine TTVs of a potential secondary planet:
  - measure over time the mid-transit times of a confirmed exoplanets
  - determine any regular variation in the O-C mid-transit values
  - a program such as Exoplanetpie can be used to conduct TTV analysis

- Radial velocity (RV) measurements also will be helpful in determining planet mass and confirming discovery

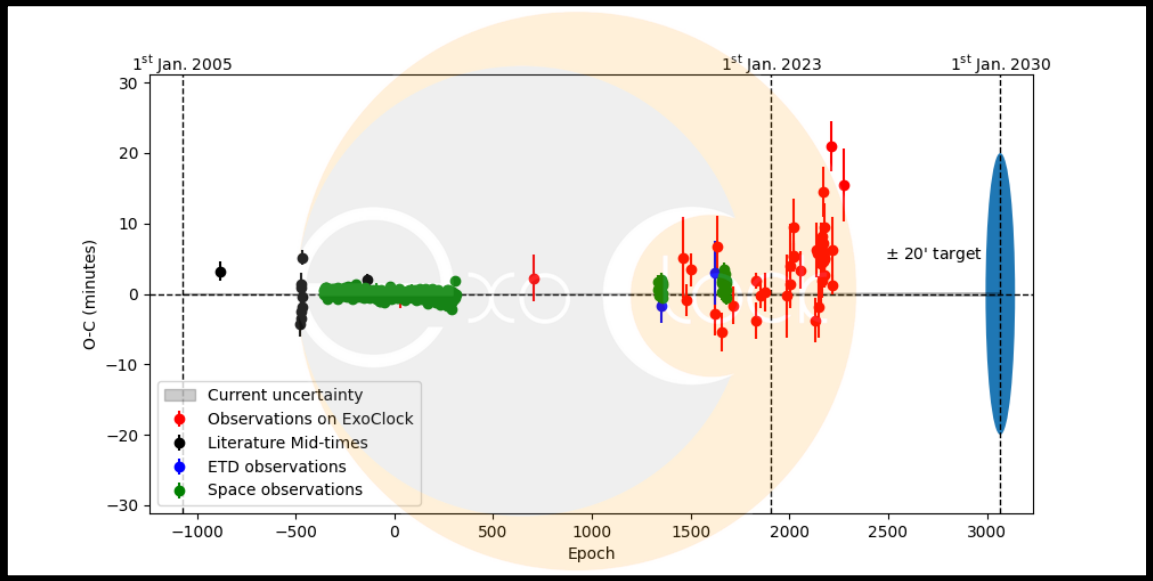
TTV Example: WASP-12b





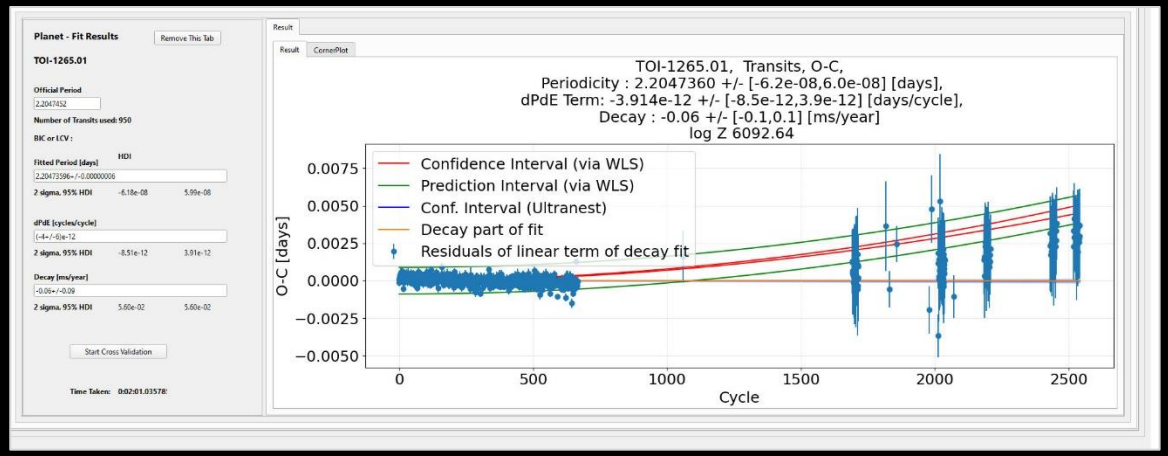
Decaying Orbit?

TTV Example: HAT-P-7b



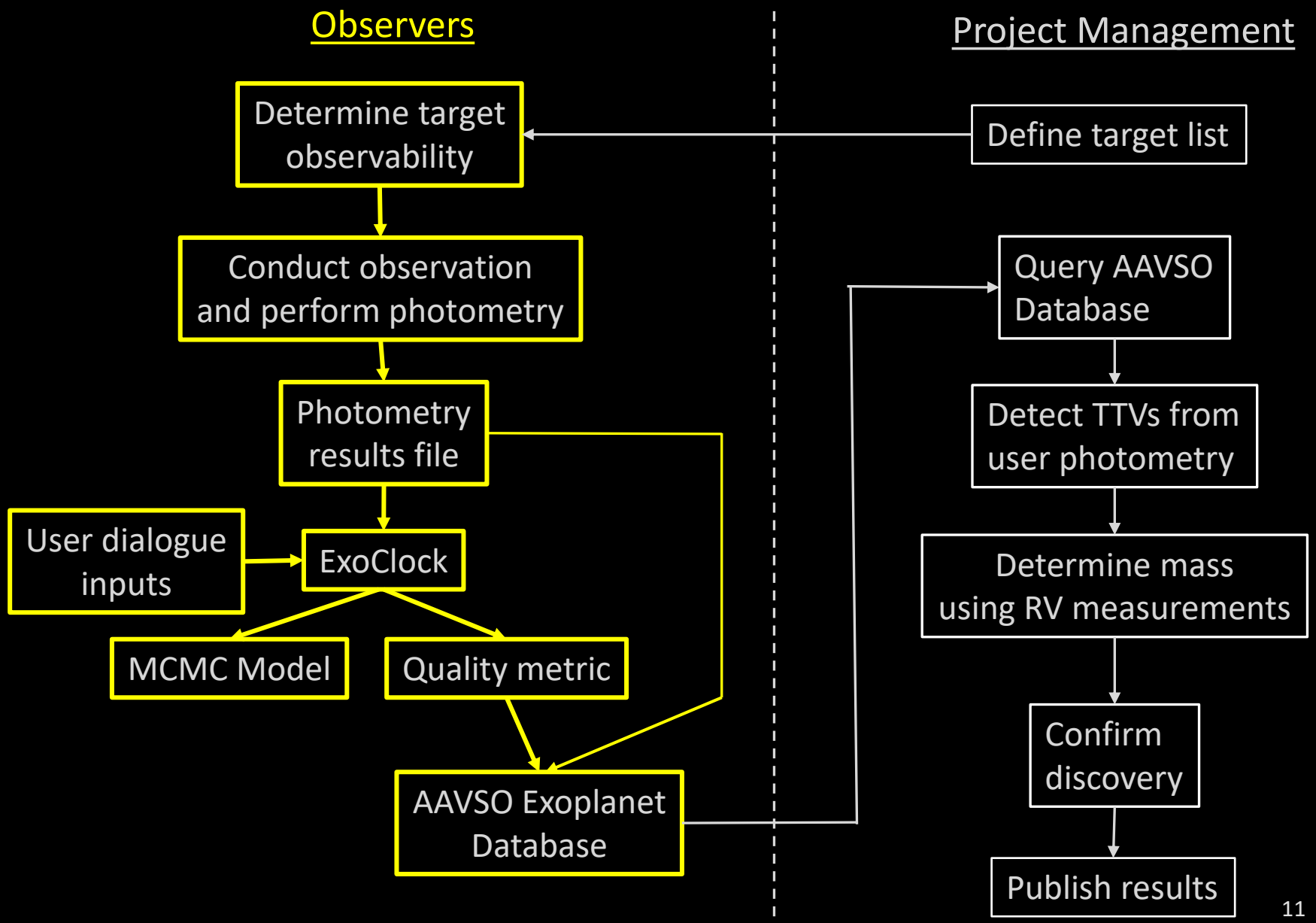
ExoClock Database

Companion planet or another star?



Exoplanetpie Analysis

The Discovery Process



Defining the Target List

- Targets: warm Jupiters, Neptunes, and Super-Earths with 10-100 day periods

- Target selection:
  - done by lead members of the collaboration
  - criteria:
    - exhibiting TTVs
    - ideally an ExoClock target
    - observable by amateur astronomer telescopes

Determining Target Observability

- Swarthmore Target Finder
  - can reduce selection to only TTV targets via a Perl expression of TTV targets – example:

    HAT-P-7 b|HAT-P-13 b|HAT-P-18 b|K2-19 b|Qatar-1 b|TOI-216.01|TOI-1130 c|TrES-3 b|WASP-4 b|WASP-12 b|WASP-19 b|WASP-43 b|WASP-148 b

- ExoWorlds Spies
  - shows all ExoClock targets observable for a given telescope size

Swarthmore Transit Finder

Search: | Show if visible transit % + baseline % > 0 | V_{max}: | $Depth_{min}$: 0 ppt | Overlap: 0 m. | Other Site

Local evening date	Name	V or Gaia mag	Start—Mid—End	Duration	BJD_{TDB} start-mid-end	Elev. at start, mid, end ±1 hrs	% of transit (baseline) observable, Suggested obs. start, end	Az. at start, mid, end ±1 hrs	HA at start, mid, end ±1 hrs	RA & Dec (J2000)	Period (days)	Depth (ppt)	Comments
Fri. 2025-06-13 Nautical twilight 21:38 – 04:30 (EST5EDT)	☐ Qatar-1 b Finding charts: Annotated, Aladin, SkyMap; Airmass plot, ACP plan Info: Exoplanet Archive, Simbad, Gaia, TIC	12.7 Moon 92% @91°	22:03 23:03—23:53—00:43 01:43 ±0:00	1:40	10840.6275 10840.6621 10840.6967	36° 42°, 47°, 52° 57°	 100% (100%) 22:03—01:43	31° 32°, 32°, 29° 24°	-5.7 -4.7, -3.9, -3.1 -2.1	20:13:31.65 +65:09:44.39	1.42	21.4	Ephemeris from Ivshina & Winn 2022.
Fri. 2025-06-20: Nautical twilight 2025-06-20 21:40 — 2025-06-21 04:30 local time / 2025-06-21 01:40 — 2025-06-21 08:30 UTC													
Fri. 2025-06-20 Nautical twilight 21:40 – 04:30 (EST5EDT)	☐ Qatar-1 b Finding charts: Annotated, Aladin, SkyMap; Airmass plot, ACP plan Info: Exoplanet Archive, Simbad, Gaia, TIC	12.7 Moon 23% @75°	00:27 01:27—02:17—03:07 04:07 ±0:00	1:40	10847.7276 10847.7622 10847.7968	53° 58°, 61°, 63° 62°	 100% (100%) 00:27—04:07	29° 22°, 14°, 3° 349°	-2.9 -1.9, -1.0, -0.2 +0.8	20:13:31.65 +65:09:44.39	1.42	21.4	Ephemeris from Ivshina & Winn 2022.
Sat. 2025-06-21: Nautical twilight 2025-06-21 21:41 — 2025-06-22 04:30 local time / 2025-06-22 01:41 — 2025-06-22 08:30 UTC													
Sat. 2025-06-21 Nautical twilight 21:41 – 04:30	☐ TrES-3 b Finding charts: Annotated, Aladin, SkyMap; Airmass plot, ACP plan Info: Exoplanet Archive, Simbad, Gaia, TIC	12.4 Moon 14% @109°	00:38 01:38—02:21—03:04 04:04	1:25	10848.7386 10848.7682 10848.7978	87° 81°, 73°, 65° 53°	 100% (100%) 00:38—04:04	97° 270°, 275°, 279° 284°	-0.3 +0.7, +1.4, +2.2 +3.2	17:52:06.99 +37:32:46.78	1.31	27.4	Ephemeris from Kokori et al. 2022.

ExoWorlds Spies

Planet	Star RA/DEC J2000	R_{mag} mag	Transit Depth mmag	Transit Duration hours	Observing times [UTC−4.0] and target position: 1h Before Ingress	Transit Start	Mid Transit	Transit End	1h After Egress
WASP-3b ExoClock Priority: LOW Min. aperture: 5.0"	18:34:31.6255 +35:39:41.489	10.52	13.56	2.8	2025/06/11 20:35 25° NE	2025/06/11 21:35 35° E	2025/06/11 22:59 51° E	2025/06/12 00:23 67° E	2025/06/12 01:23 79° E
KOI-13b ExoClock Priority: LOW Min. aperture: 5.0"	19:07:53.1049 +46:52:06.004	9.8	9.39	3.2	2025/06/11 21:07 30° NE	2025/06/11 22:07 39° NE	2025/06/11 23:43 55° NE	2025/06/12 01:19 72° NE	2025/06/12 02:19 80° NE
HAT-P-59b ExoClock Priority: LOW Min. aperture: 6.33"	19:29:50.0700 +62:31:45.177	11.64	10.98	2.35	2025/06/11 21:11 34° NE	2025/06/11 22:11 40° NE	2025/06/11 23:21 49° NE	2025/06/12 00:32 56° NE	2025/06/12 01:32 62° NE
TrES-5b ExoClock Priority: LOW Min. aperture: 10.43"	20:20:53.2483 +59:26:55.574	13.77	24.73	1.82	2025/06/11 21:14 27° NE	2025/06/11 22:14 34° NE	2025/06/11 23:08 41° NE	2025/06/12 00:03 48° NE	2025/06/12 01:03 55° NE
HAT-P-4b ExoClock Priority: MEDIUM Min. aperture: 5.11"	15:19:57.9205 +36:13:46.737	10.848	9.84	4.25	2025/06/11 22:26 82° E	2025/06/11 23:26 85° SW	2025/06/12 01:34 60° W	2025/06/12 03:41 36° W	2025/06/12 04:41 25° NW
HAT-P-36b ExoClock Priority: LOW Min. aperture: 6.21"	12:33:03.9061 +44:54:55.197	12.27	20.66	2.22	2025/06/11 23:25 55° NW	2025/06/12 00:25 44° NW	2025/06/12 01:31 33° NW	2025/06/12 02:38 23° NW	2025/06/12 03:38 14° NW
WASP-177b ExoClock Priority: LOW Min. aperture: 7.85"	22:19:11.3367 −01:50:03.079	12.13	11.28	1.61	2025/06/12 00:58 10° E	2025/06/12 01:58 21° E	2025/06/12 02:47 30° SE	2025/06/12 03:35 37° SE	2025/06/12 04:35 45° SE
Kepler-17b ExoClock Priority: LOW Min. aperture: 9.79"	19:53:34.8643 +47:48:54.049	13.6	22.48	2.29	2025/06/12 01:13 63° NE	2025/06/12 02:13 73° NE	2025/06/12 03:22 81° N	2025/06/12 04:30 77° NW	2025/06/12 05:30 67° NW

Remaining Observer Steps

1. A best practices guide will be developed specific to TTV-related target observations

2. Exoplanet observation and reduction done in the normal way

3. Photometry done using AstroImageJ (AIJ) - note: many ExoClock users use HOPS

4. An AIJ or HOPS dataset output of time, relative flux, and associated errors is used as input to ExoClock

5. A quality measure (residuals STD?) from ExoClock and the photometry results from 3. are input into the AAVSO Exoplanet Database

Supporting Resources to be Developed

- Target selection guide
- Best practices guide
- Supporting software (e.g., Exoplanetpie, HOPS-to-AAVSO database front-end)
- EXPLORE website

Who, When, and How to Contribute

- Ideally, “experienced” exoplanet observers – example: have submitted observations as part of TESS or Exoplanet Watch, have submitted observations to AAVSO Exoplanet Database
  - although newcomers not discouraged
- A guide will be developed on how to contribute
- We will hold online, joint AAVSO-BAA support meetings
- Project will probably not be in full swing until the Fall
- Let me know of your interest:
  dennis@astrodennis.com