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Updated Masses for the Gas Giants in the Eight-planet Kepler-90 System Via Transit-timing Variation and Radial Velocity Observations

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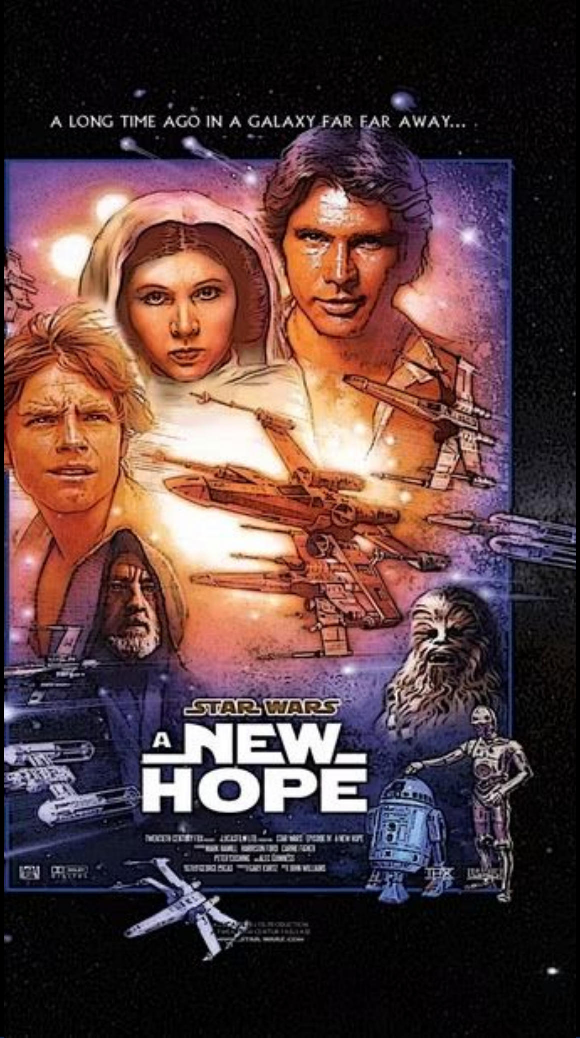
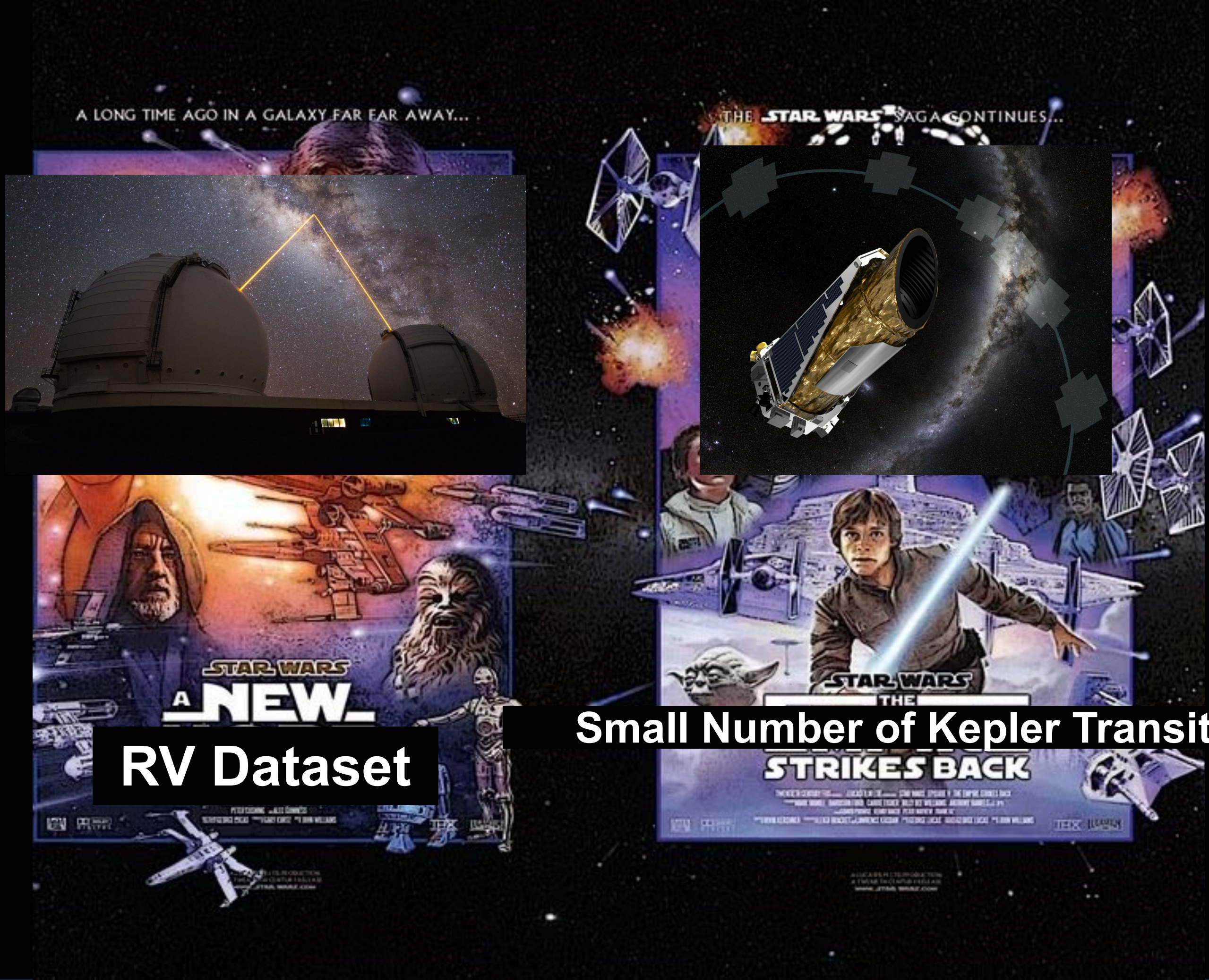
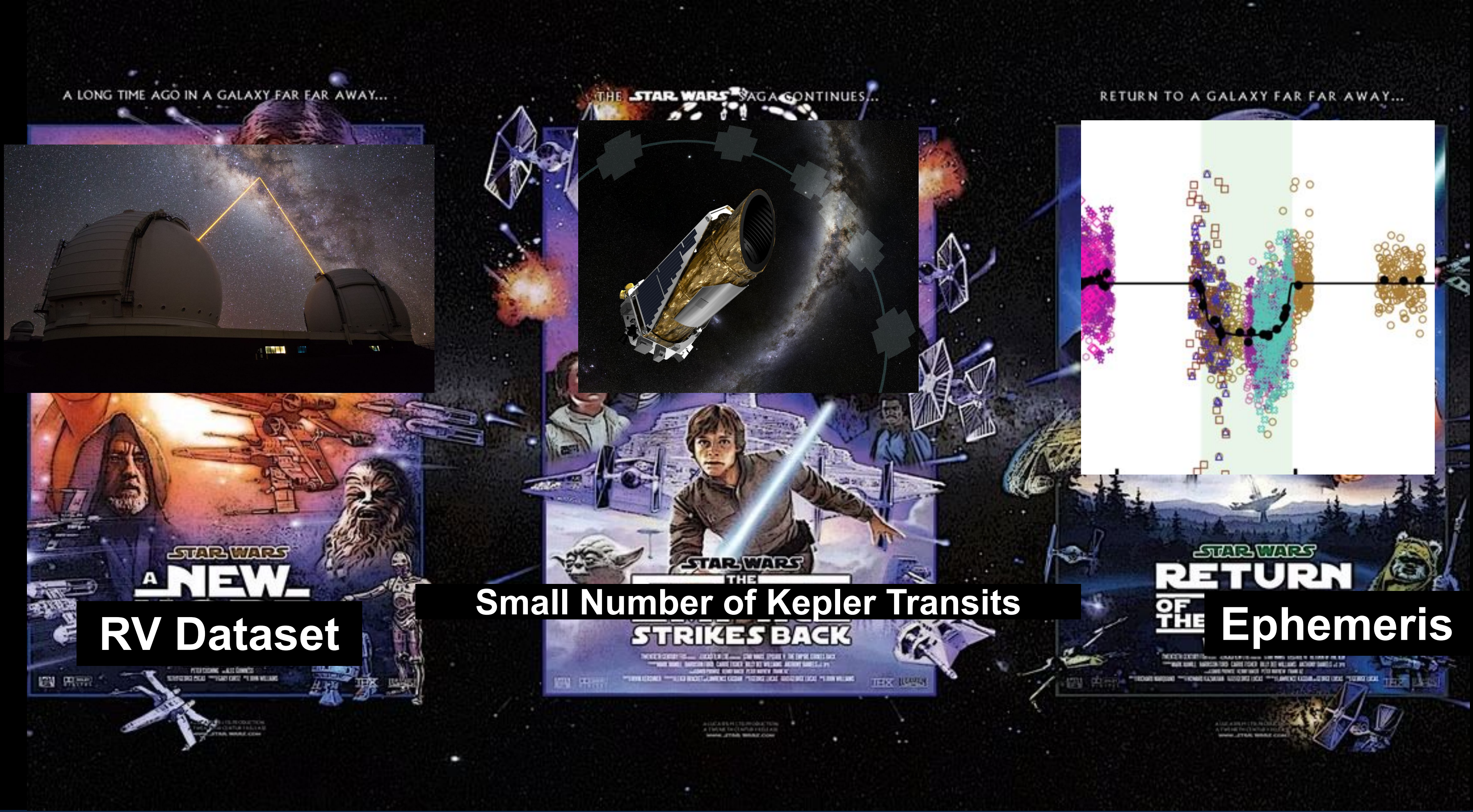

A LONG TIME AGO IN A GALAXY FAR FAR AWAY...
STAR WARS
A NEW HOPE

RV Dataset



RV Dataset

Small Number of Kepler Transits

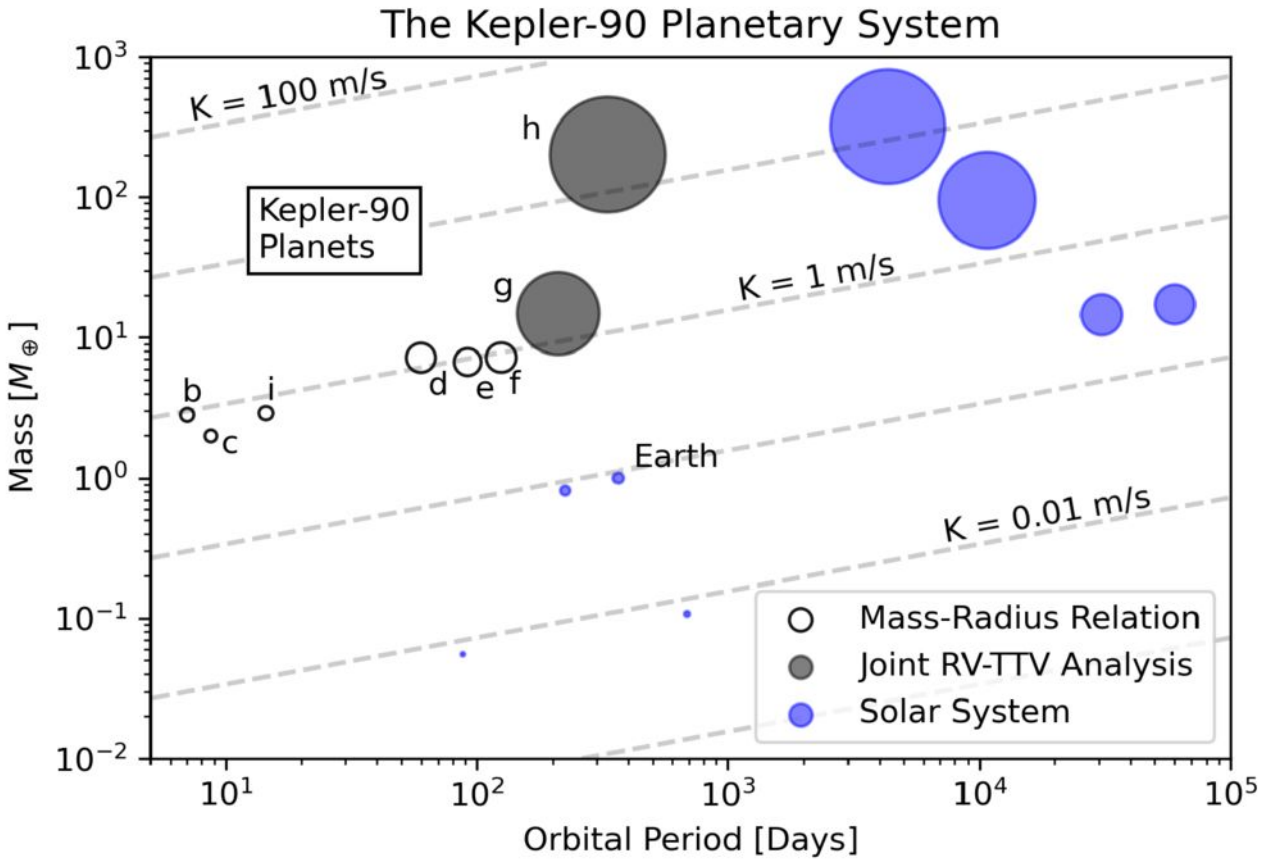


RV Dataset

Small Number of Kepler Transits

Ephemeris

An Introduction to the Kepler-90 System



<u>Many authors have built up our understanding of this system, including:</u>

Cabrera et al. 2014
Schmitt et al. 2014
Lissauer et al. 2014
Shallue & Vanderburg 2018
Liang et al. 2021
Weiss et al. 2024
Lissauer et al. 2024
Shaw et al. 2025

All Eight Planets Transited in the Kepler Photometry

Cabrera et al. 2014 presented **six transits of g** and **three transits of h** in the Kepler photometry

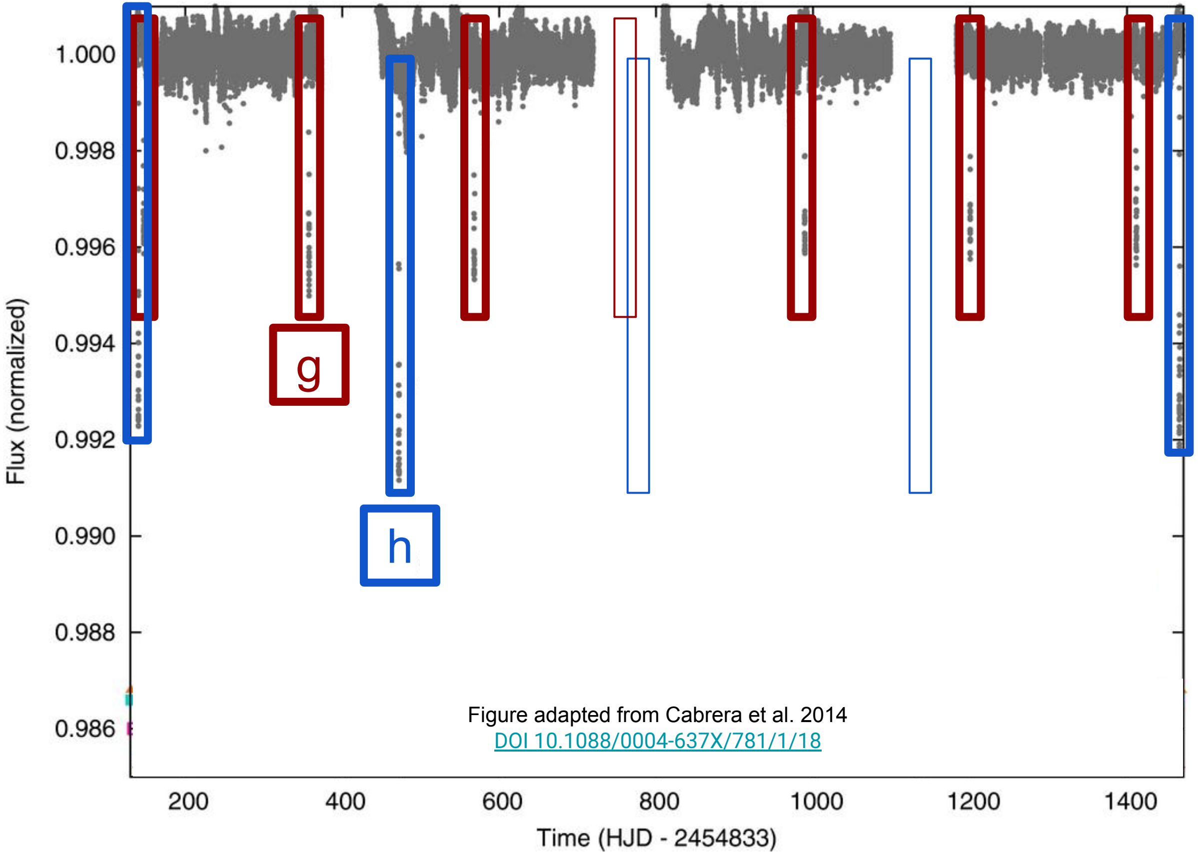


Figure adapted from Cabrera et al. 2014
DOI 10.1088/0004-637X/781/1/18

“The Force Is Strong With This One”

Variations in Kepler-90g’s times of transit (TTVs) are induced by planet-planet gravitational perturbations

Mass ratios of K90g and K90h can be inferred (Liang et al. 2021)

Dynamical interactions with K90h!

Transits of K90g From Kepler

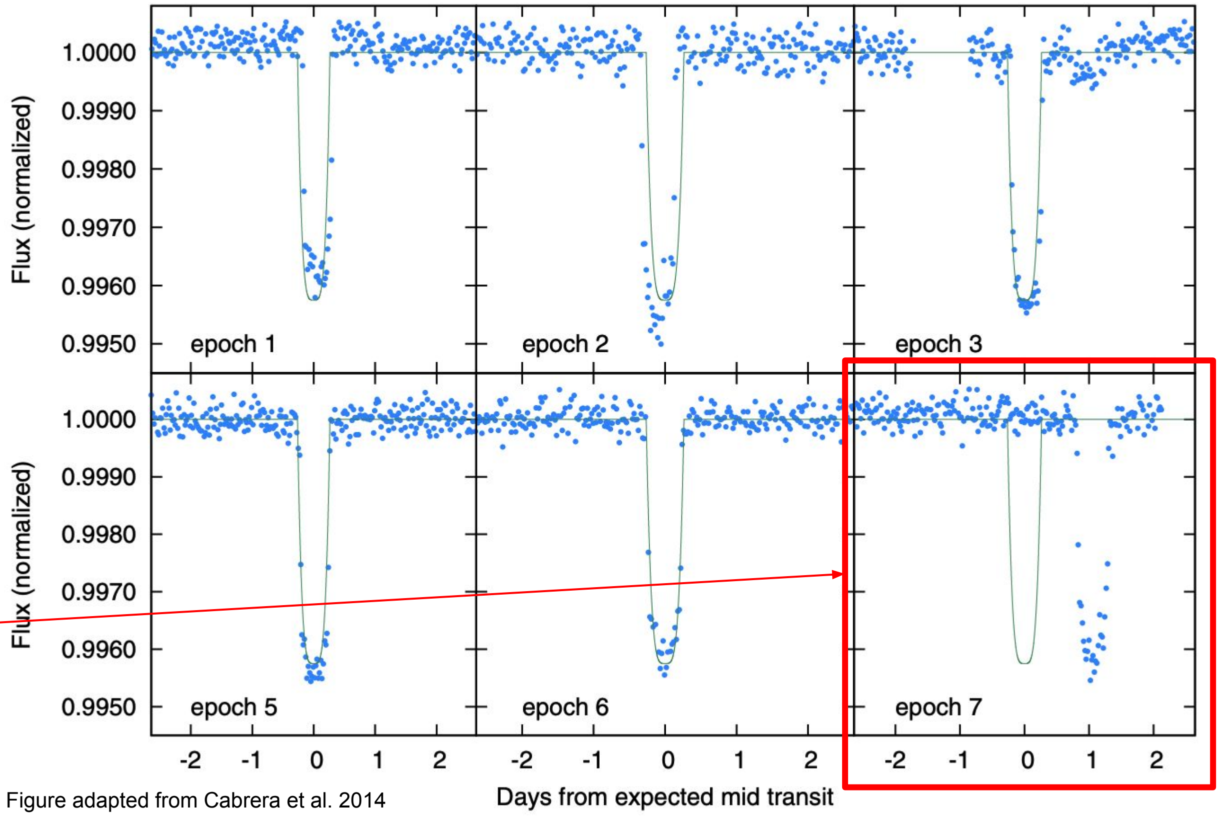


Figure adapted from Cabrera et al. 2014

DOI 10.1088/0004-637X/781/1/18

TTV-inferred masses are precise and powerful, but confirmation with radial velocity observations would be valuable!

Thus begins our saga…

IV. A New RV Dataset

IV: A New RV Dataset

Weiss et al. 2024 collected 34 radial velocity (RV) measurements of Kepler-90 for the Kepler Giant Planet Search

RVs were measured with HIRES at the W. M. Keck Observatory between April 2011 and June 2022

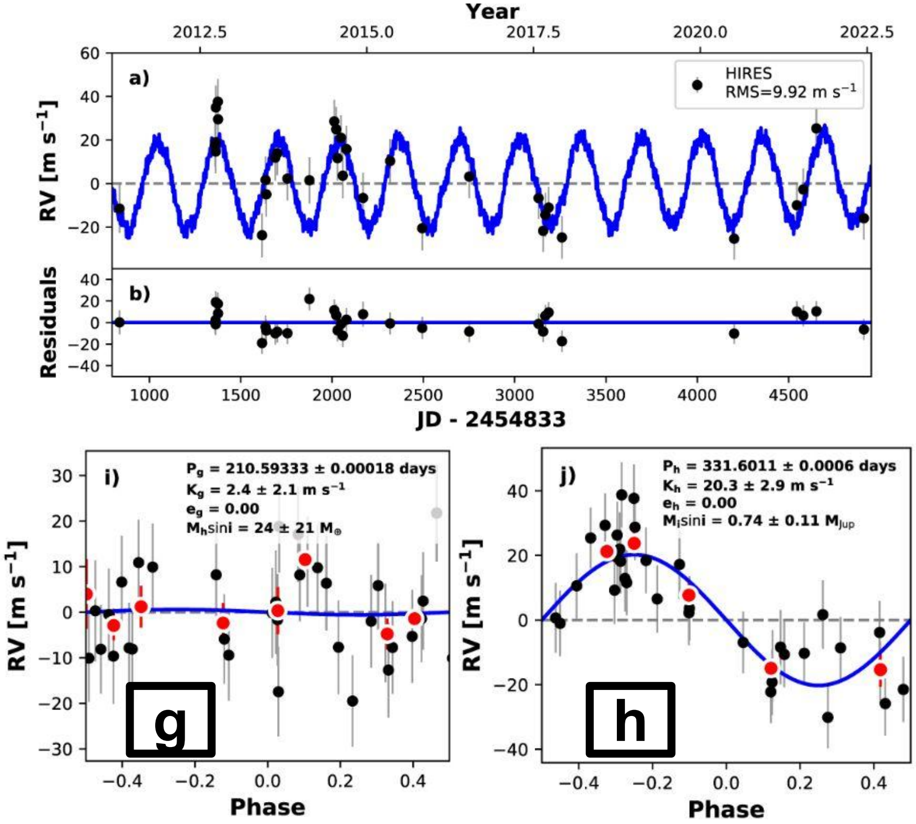


Figure adapted from Weiss et al. 2024
DOI: 10.3847/1538-4365/ad0cab

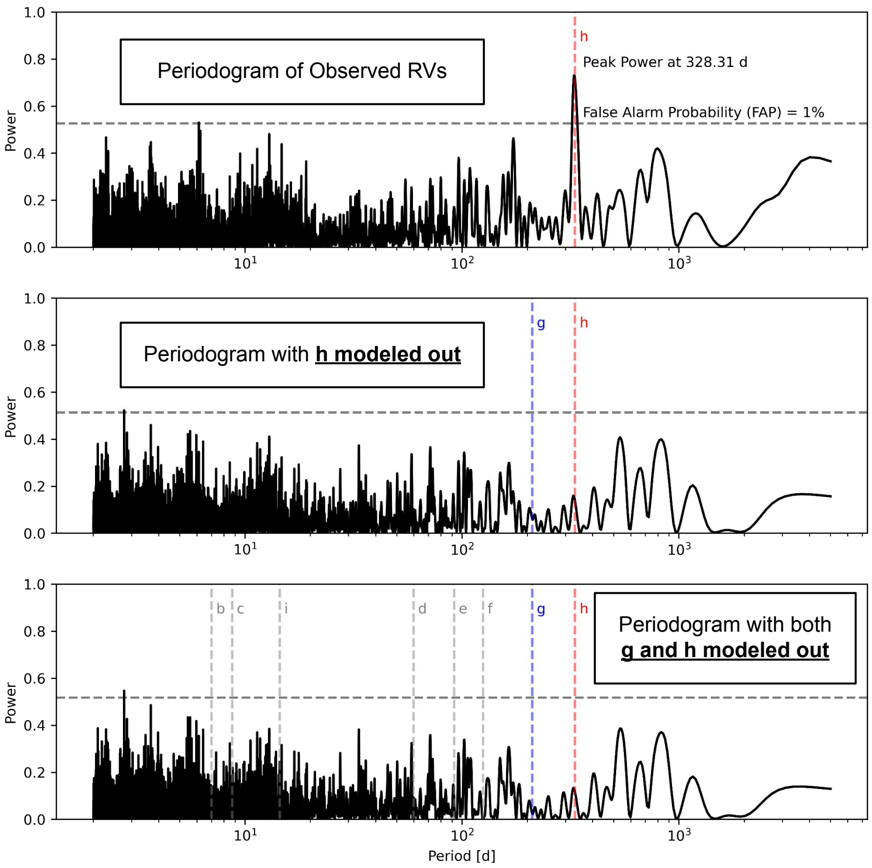
IV: A New RV Dataset

We computed the Lomb-Scargle Periodogram of the RVs to search for periodic signals

Clear signal from planet h

No clear signal from the other seven transiting planets

No signs of additional planets in the RVs



IV: A New RV Dataset

We can now jointly model the TTVs of K90g and K90h and the RVs of Kepler-90 for the first time!

V: The Small Number of Kepler Transits Strikes Back

V: The Small Number of Kepler Transits Strikes Back

Until now, only 6+3 transits available for K90g and K90h

Models of their interactions have more free parameters than transits!

Radial velocity data helps!

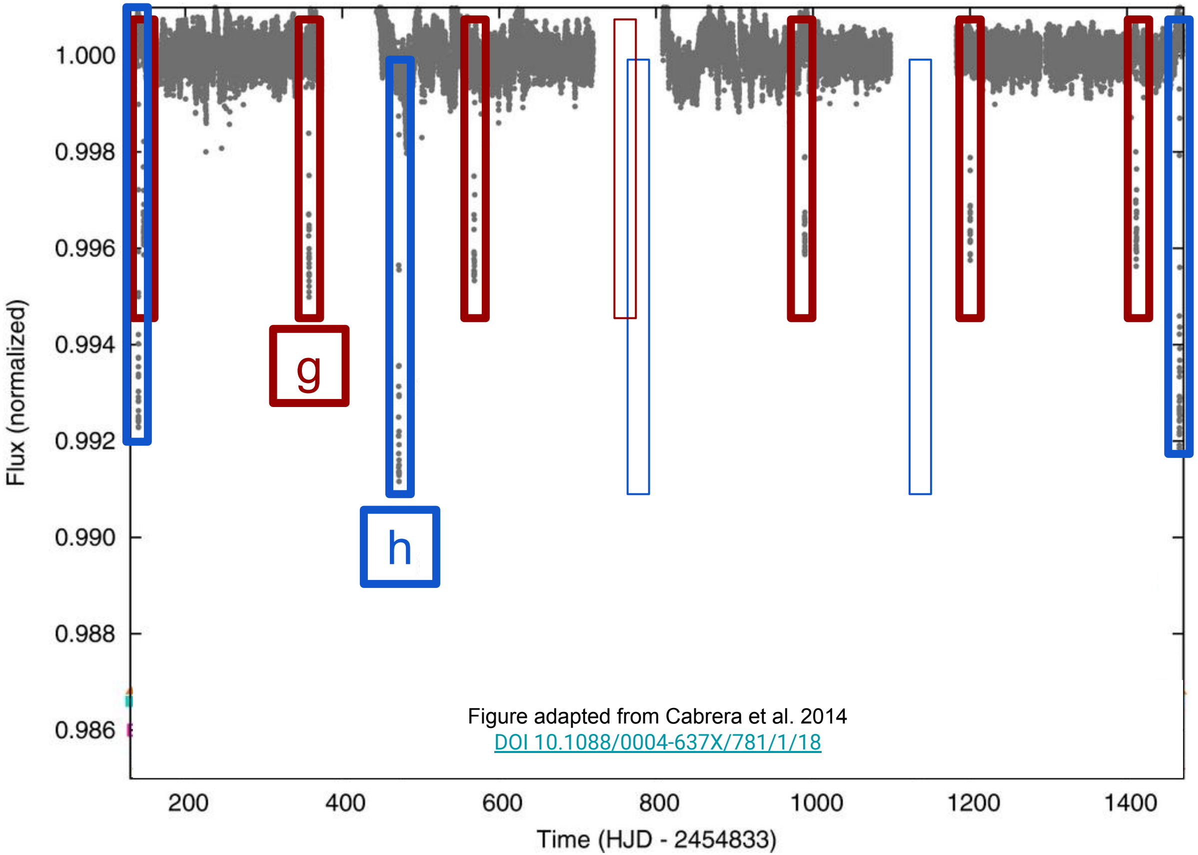


Figure adapted from Cabrera et al. 2014
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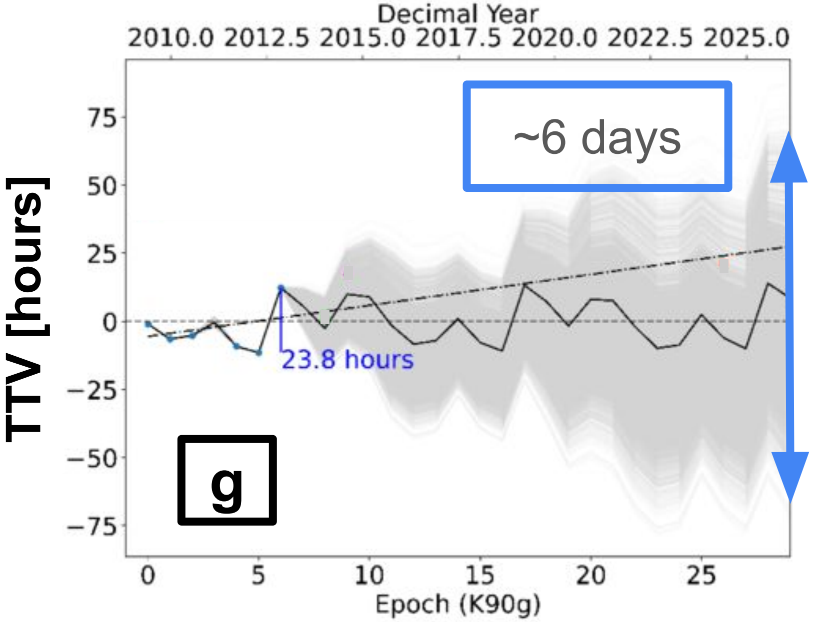
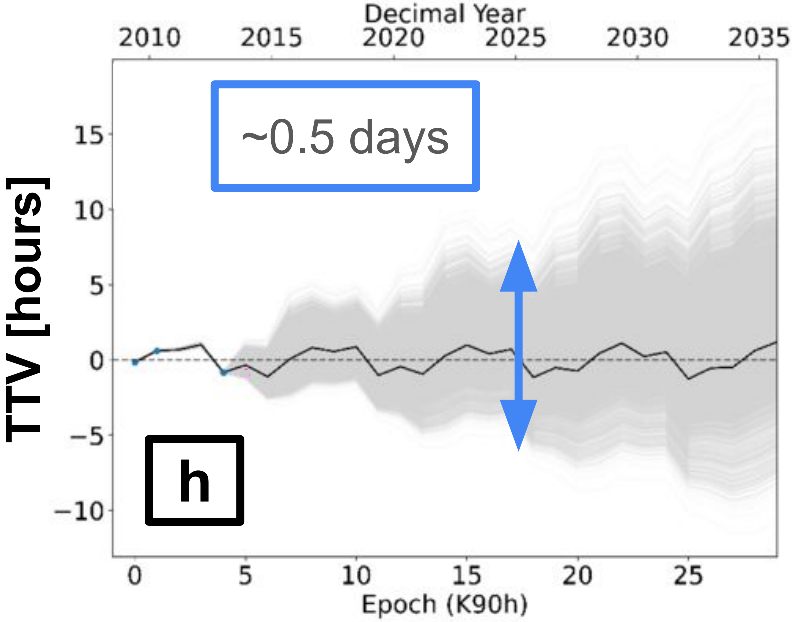
V: The Small Number of Kepler Transits Strikes Back

What is the uncertainty in transit times of K90g and K90h by 2025 based on Kepler TTVs and the RVs?





VI: Return of the Ephemeris

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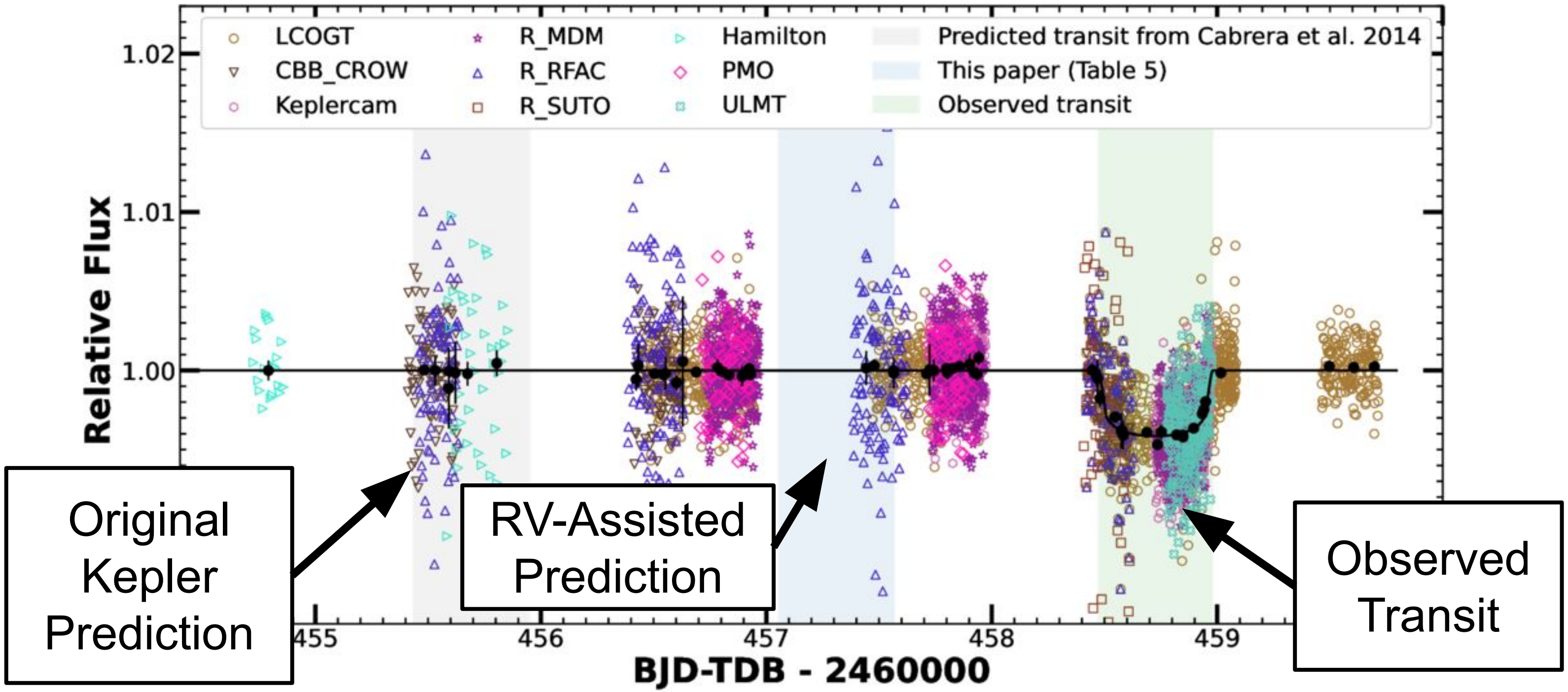
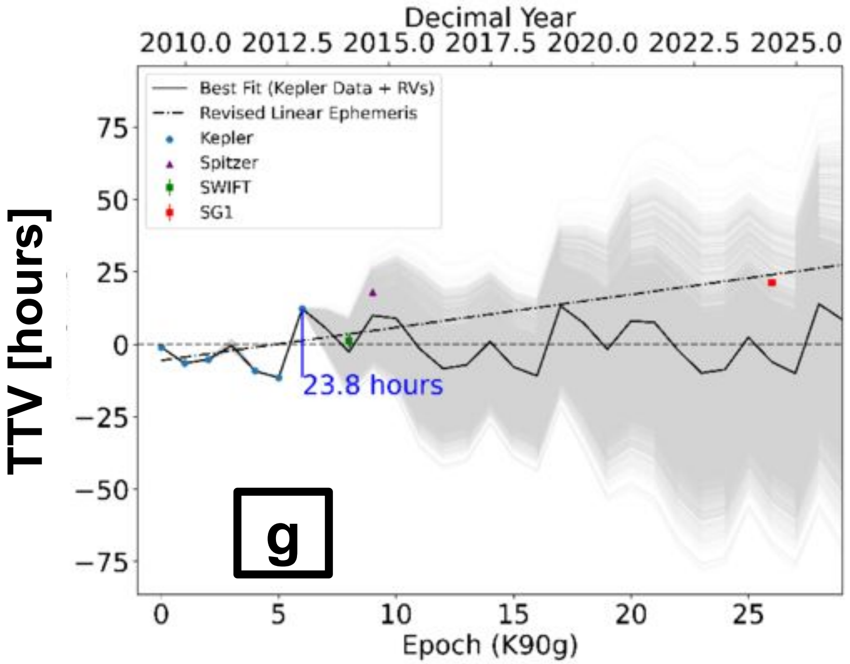
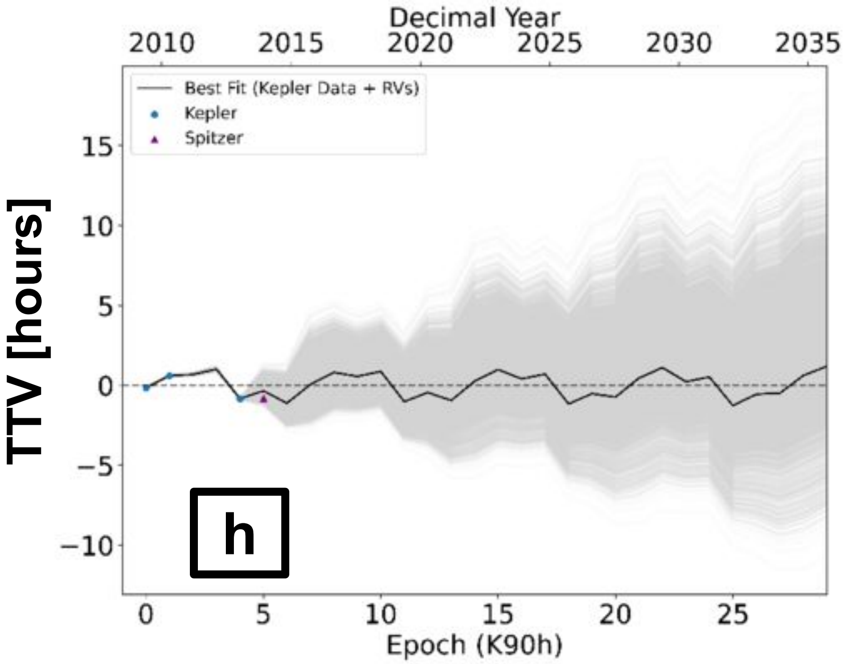
Our TTV + RV analysis enabled the TFOP SG1 ground-based recovery of K90g's 2024 May transit



VI: Return of the Ephemeris

Additional post-Kepler transits fall within the predicted range of our Monte Carlo ephemerides, but clearly show that the previous linear period was misinformed from the Kepler data alone!

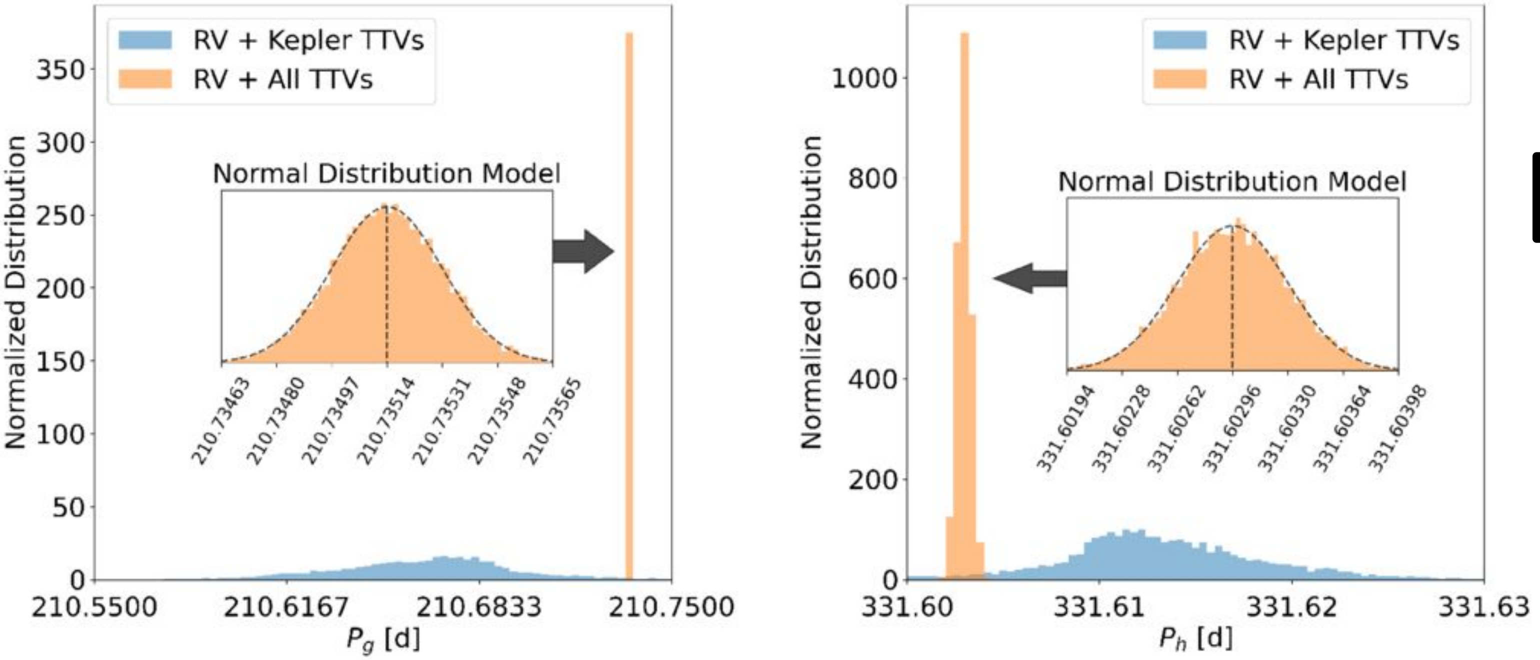




VI: Return of the Ephemeris

The linear ephemeris was more precisely determined with errors decreased by an order of magnitude

g

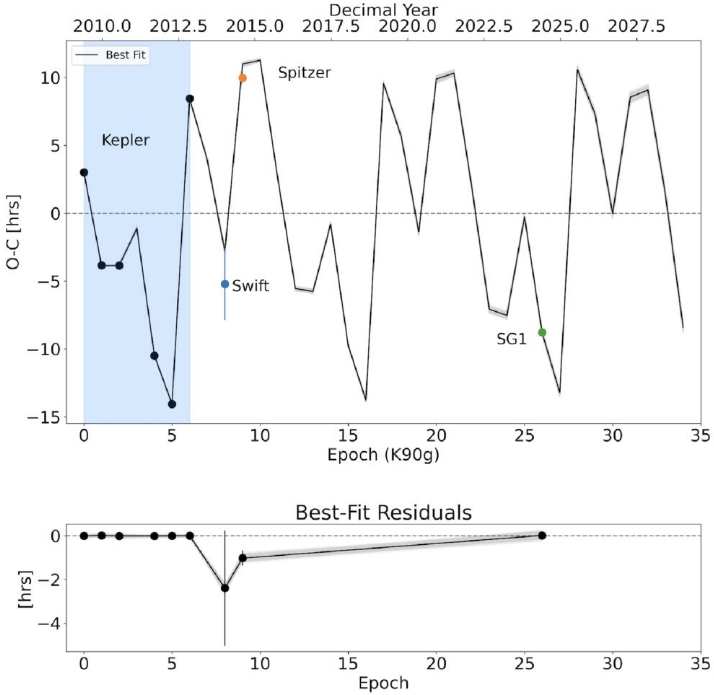


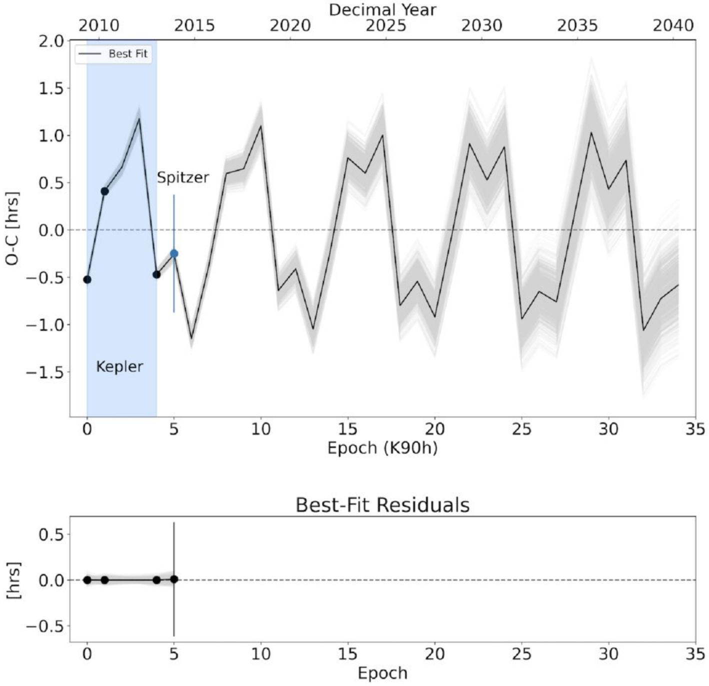
h

VI: Return of the Ephemeris

The augmented dataset enables much tighter constraints on the future times of transit for K90g and K90h

g





h

Conclusions

Long-term RV monitoring helped us improve the ephemeris of Kepler-90 g enough to observe a crucial **new transit in May 2024**

TTVs encode rich information about a system, and long-period giant planets can induce giant TTVs when near a mean-motion resonance. They must be well-understood for transit follow-up

Looking forward, high-precision spectrometers should be capable of **measuring masses and obliquities** (via the Rossiter-McLaughlin Effect) in the Kepler-90 system and other super puff systems, and **transmission spectroscopy** of K90g would give valuable insight into these mysterious super puffs

Check out the paper for more!

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Check out the paper for more!

This is my planet. Why?

GJ 357 d

Supplemental Material

Supplemental Material

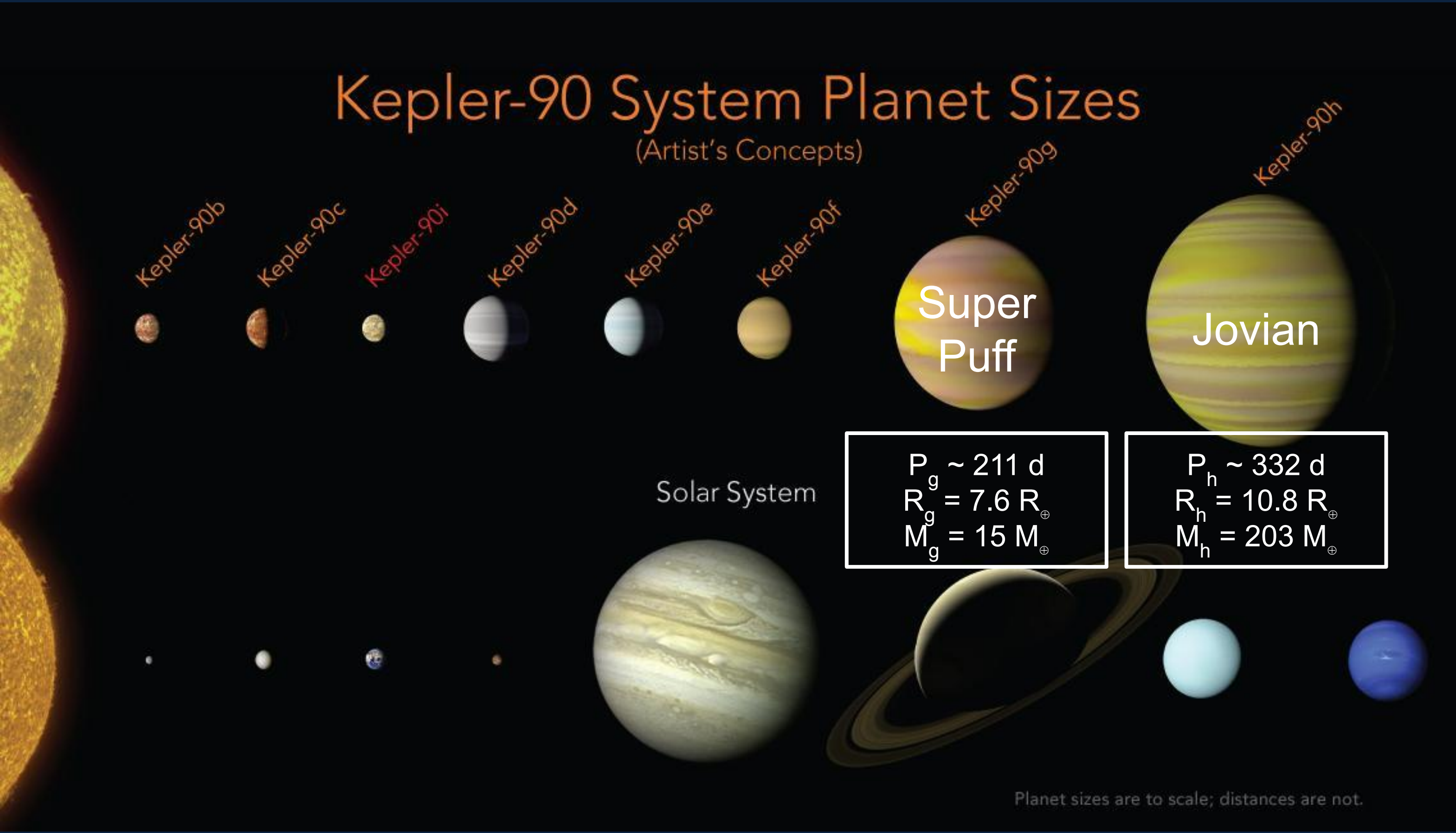


Image adapted from NASA

Supplemental Material

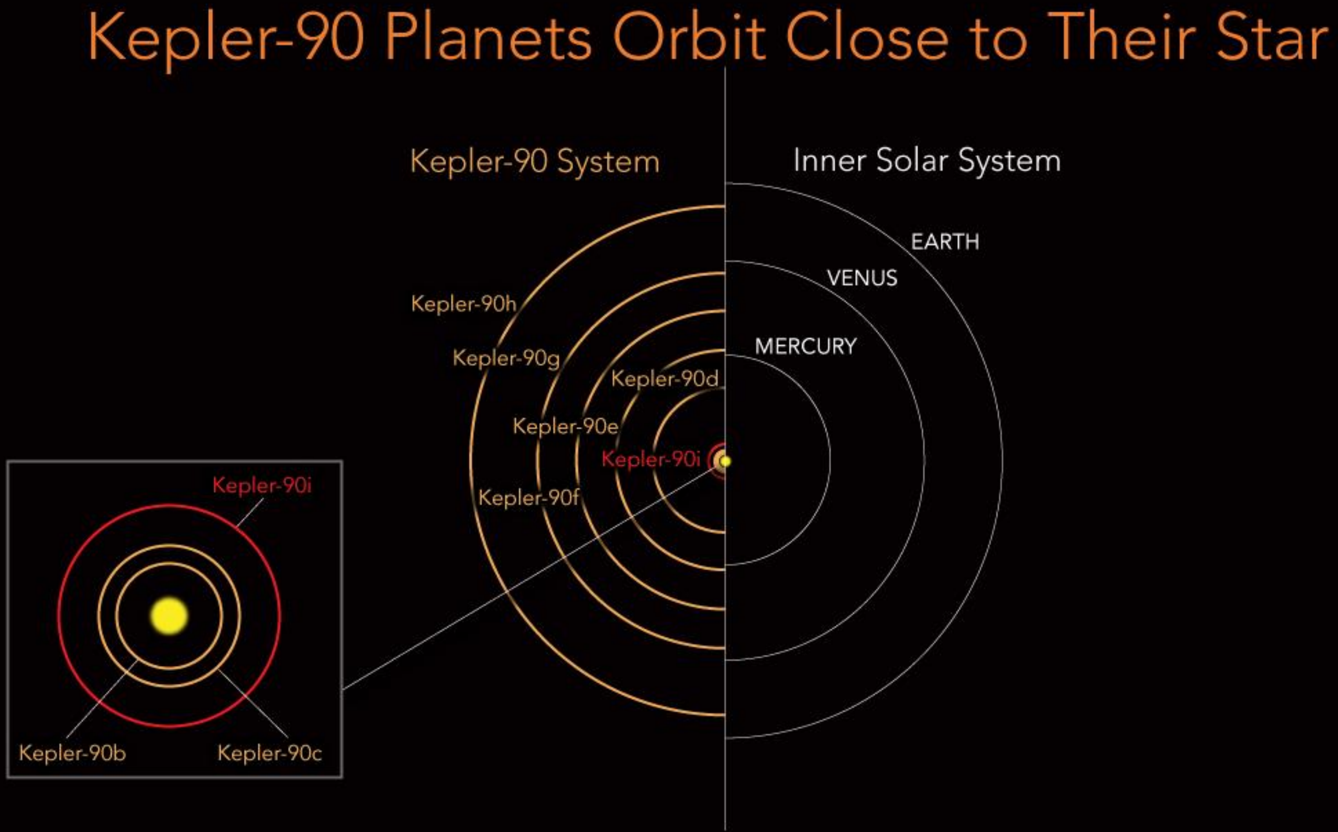
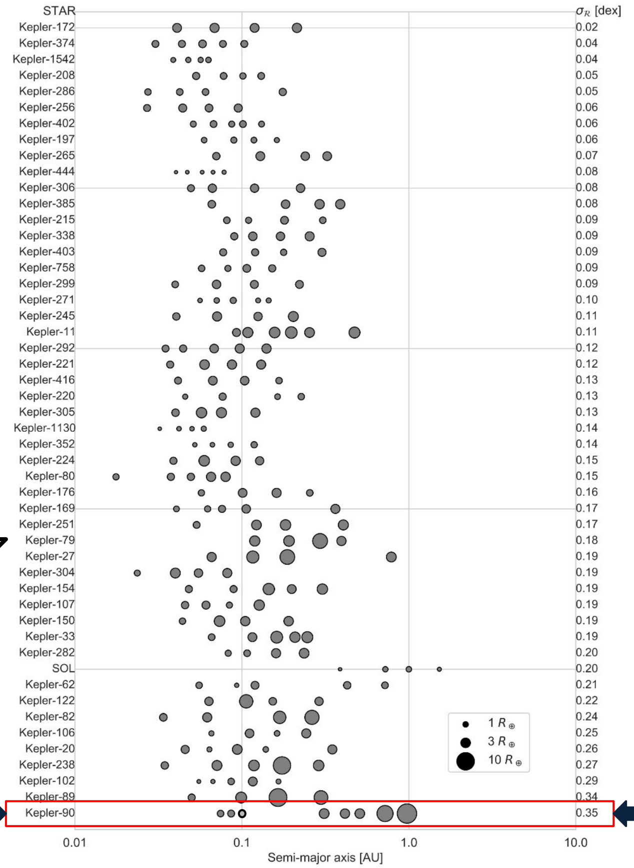


Image Credit NASA

Supplemental Material



More uniform sizes

Increasing diversity of sizes within compact multiplanet systems

Less uniform sizes

Figure adapted from *Protostars and Planets VII* Chapter 24: Architectures of Compact Multi-Planet Systems: Diversity and Uniformity (Weiss et al. 2023, [arXiv:2203.10076](https://arxiv.org/abs/2203.10076))

Supplemental Material

These “**transit timing variations**” (**TTVs**; also “transit duration variations”) allowed Liang et al. 2021 to infer dynamical masses for planets g and h.

K90h is a “**Jovian**”: $M_h = 203 \pm 5\ M_\oplus$

K90g is a “**Super Puff**”: $M_g = 15.0^{+0.9}_{-0.8}\ M_\oplus$

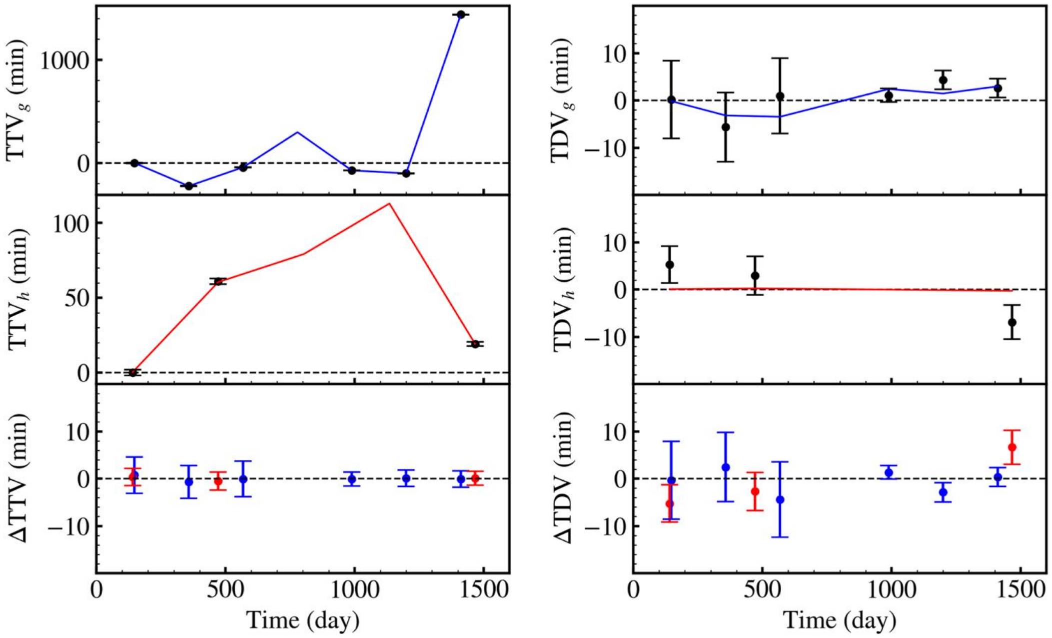
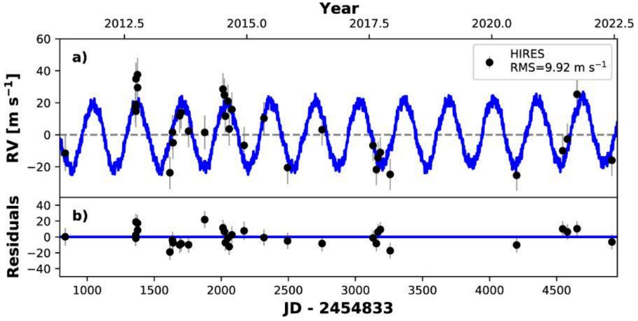
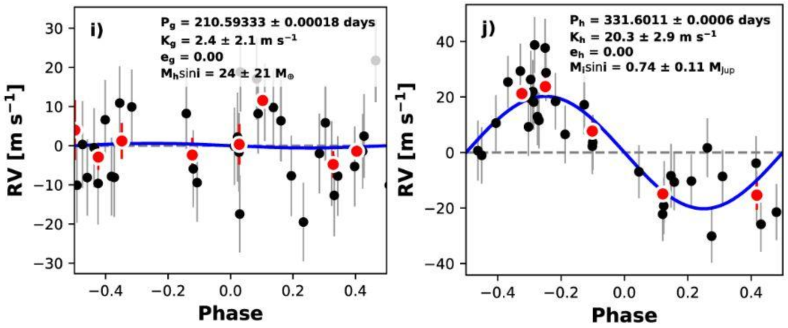


Figure from Liang et al. 2021
DOI 10.3847/1538-3881/abe6a7

Supplemental Material

The RVs alone allowed Weiss et al. 2024 to infer masses for the giant planets g and h which were consistent with the TTV/TDV analysis of Liang et al. 2021





Mass upper limits were placed on the inner six planets

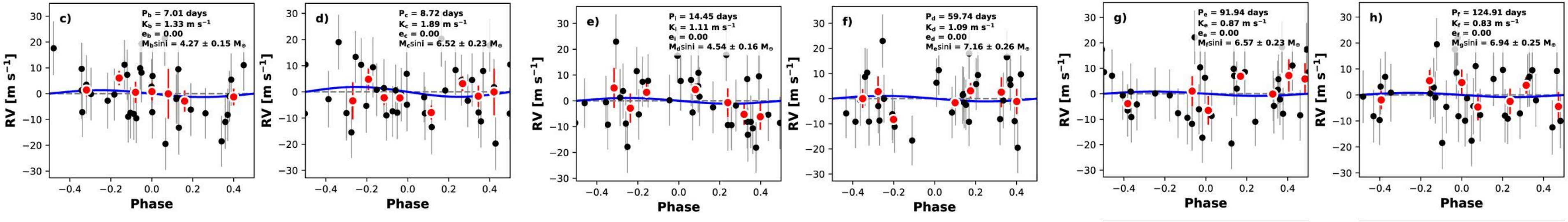


Figure adapted from Weiss et al. 2024

DOI: 10.3847/1538-4365/ad0cab

Supplemental Material

Modeled transit times with TTVFaster

- Assumes co-planar, edge-on orbits

Modeled RVs with RadVel

12 total free parameters

- 2x planet
  - Mass (M)
  - Average period (P)
  - Nominal time of conjunction (T0)
  - Eccentricity components ($\sqrt{e}\cos(\omega)$, $\sqrt{e}\sin(\omega)$)
- RV parameters
  - Offset γ
  - Jitter σ_{jitter}

Later included stellar mass a free parameter with a Gaussian prior

Supplemental Material

Assuming uniform priors, we find optimal parameters by maximizing the joint log-likelihood function:

$$
\begin{aligned}
\ln \mathcal{L} \quad = \quad & -\frac{1}{2}\left(\boxed{\chi^2_{\mathrm{RV}}} + \Sigma_{i=1}^{N_{\mathrm{RV}}} \ln \left[2\pi(\sigma^2_{\mathrm{RV},i} + \sigma^2_{\mathrm{jitter}})\right]\right) \\
& -\frac{1}{2}\left(\boxed{\chi^2_{\mathrm{TT}}} + \Sigma_{i=1}^{N_{\mathrm{TT}}} \ln \left[2\pi\sigma^2_{\mathrm{TT},i}\right]\right)
\end{aligned}
$$

$$
\chi^2_{\mathrm{RV}} = \sum_{i=1}^{N_{\mathrm{RV}}} \frac{(\mathrm{RV}_{\mathrm{obs},i} - \mathrm{RV}_{\mathrm{mod},i})^2}{\sigma^2_{\mathrm{RV},i} + \sigma^2_{\mathrm{jitter}}}
$$

$$
\chi^2_{\mathrm{TT}} = \sum_{i=1}^{N_{\mathrm{TT}}} \frac{(\mathrm{TT}_{\mathrm{obs},i} - \mathrm{TT}_{\mathrm{mod},i})^2}{\sigma^2_{\mathrm{TT},i}}
$$

Supplemental Material

We attempted to estimate the uncertainties on our model parameters using the Markov Chain Monte Carlo (MCMC) sampler implemented in the python package “emcee”

Problem: The MCMC chains would not converge!

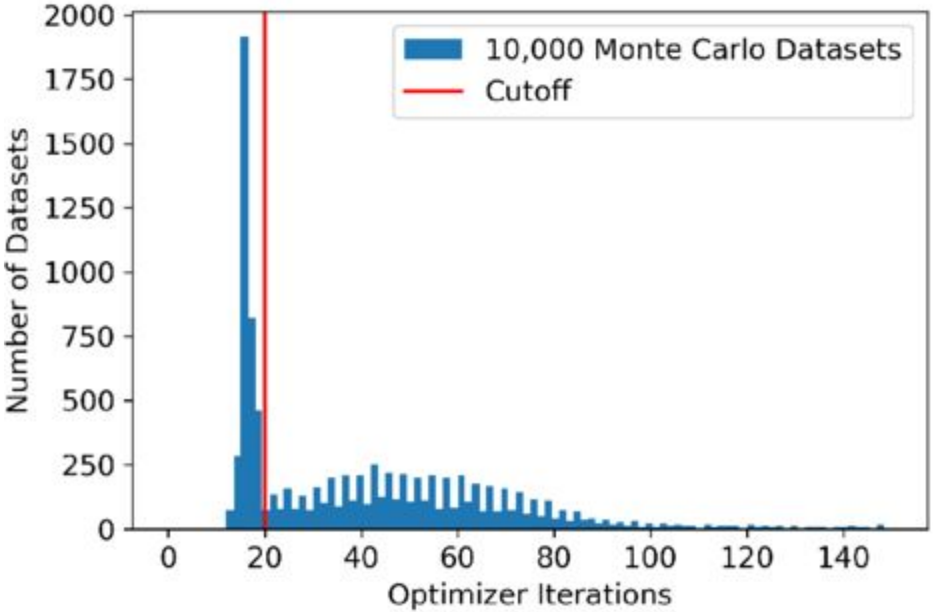
- K90g is not strongly detected in the RVs
- There are only 6 + 3 transit data points
- There are 12 model parameters (2x5 planet masses/coplanar orbits + 2 RV hyperparameters: offset and jitter)
- Difficult to adequately sample the posterior given this dataset

Supplemental Material

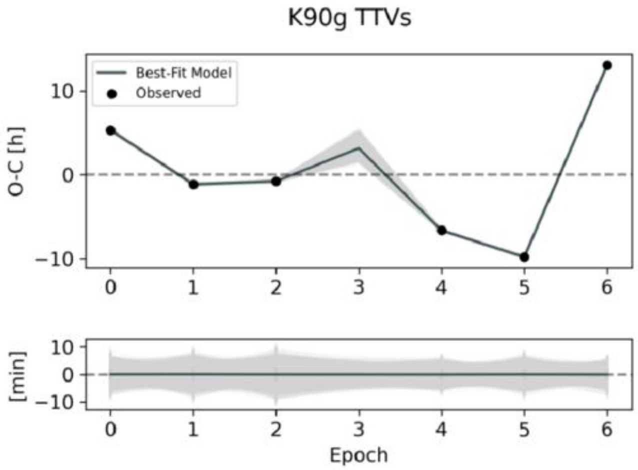
We used a Monte Carlo method to draw synthetic transit and rv “observations” from the existing dataset treating their measurements as a normal distribution with observed value as the mean and measurement uncertainty as the standard deviation

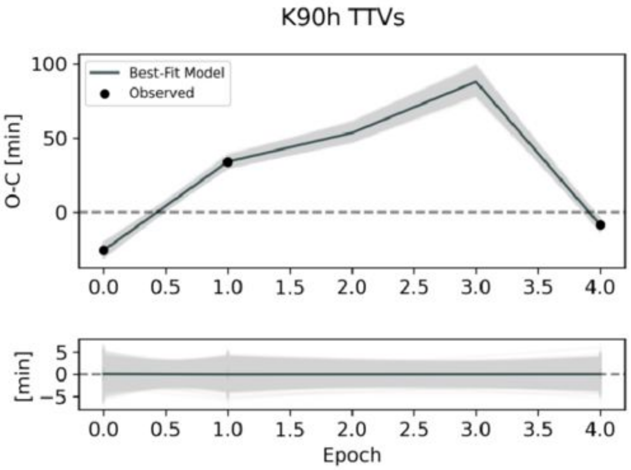
For each of these synthetic datasets, we repeated our optimization procedure to find the maximum a posterior distribution

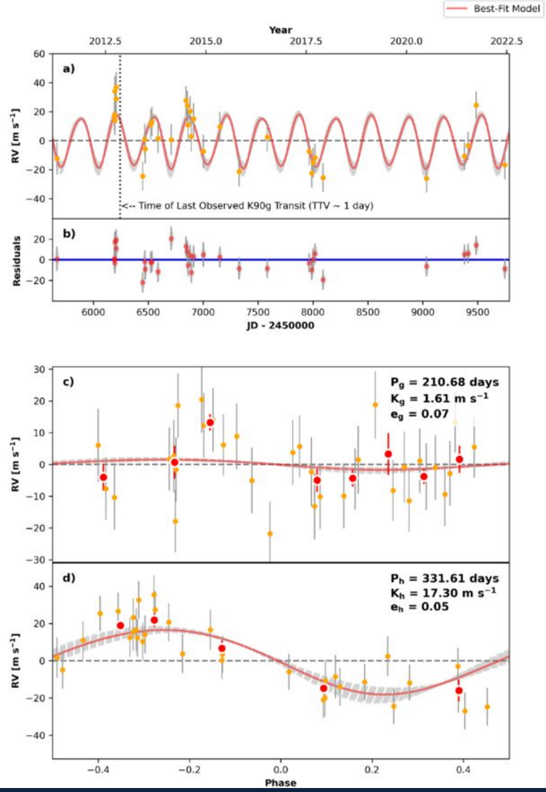
We removed synthetic data sets for which the optimizer stopped in less than 20 iterations, resulting in a final set of 6438 optimizations



Model fits from our Monte Carlo strategy with the Kepler + RV dataset







Supplemental Material

Two very important developments regarding the ephemerides:

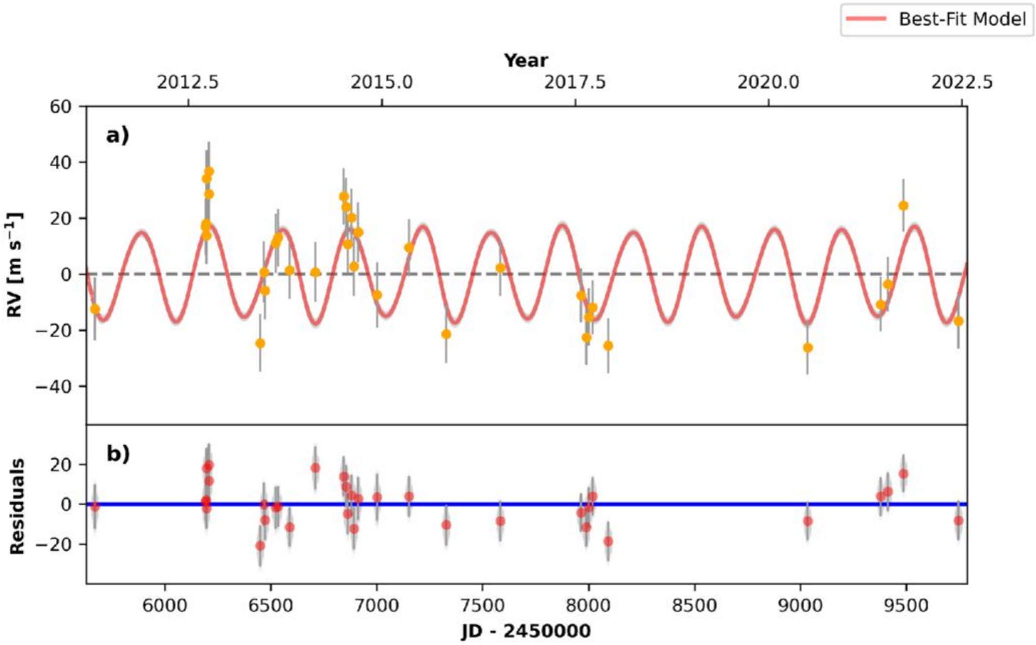
1. Several previously unpublished transits of K90g and K90h observed after the Kepler prime mission were brought to our attention. Some of these transits have background stories worthy of their own mini-series!

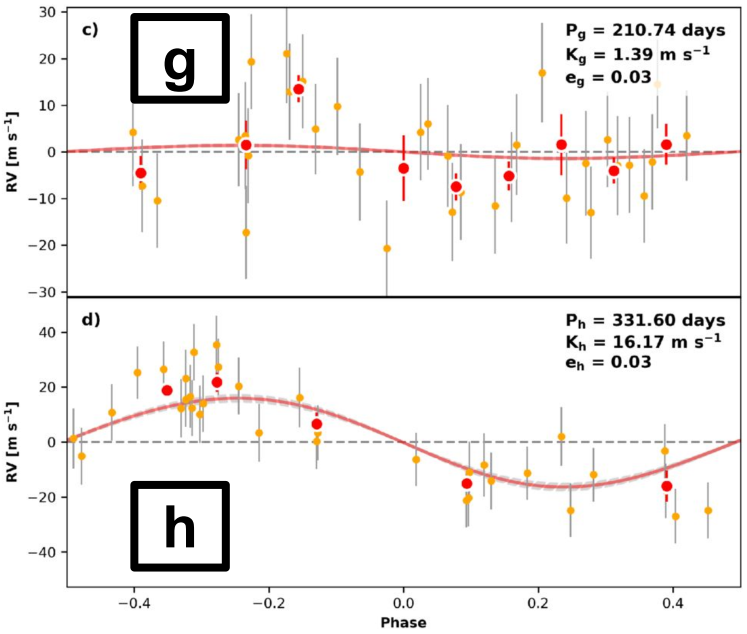
2. We reached out to the TESS Follow-up Observing Program Working Group (Sub Group 1) who heroically managed to observe a transit of K90g in 2024 May through a coordinated network of ground-based observers around the globe

Planet & Epoch	Transit Time (BJD_{TDB})	Observatory
g 0	2454980.1013 ± 0.0015	Kepler
g 1	2455190.5512 ± 0.0017	Kepler
g 2	2455401.2858 ± 0.0018	Kepler
g 4	2455822.4796 ± 0.0012	Kepler
g 5	2456033.0663 ± 0.0014	Kepler
g 6	2456244.7389 ± 0.0013	Kepler
g 8	2456665.64 ± 0.11	Swift[a]
g 9	2456877.007 ± 0.015	Spitzer[b]
g 26	2460458.7241 ± 0.0033	Ground-Based[b]
h 0	2454973.4787 ± 0.0011	Kepler
h 1	2455305.12063 ± 0.00092	Kepler
h 4	2456299.89279 ± 0.00088	Kepler
h 5	2456631.505 ± 0.026	Spitzer[b]

Supplemental Material

The RV model also has a smaller “spread” thanks to the augmented dataset





Supplemental Material

Our mass results were consistent with literature values (Liang et al. 2021, Weiss et al. 2024)

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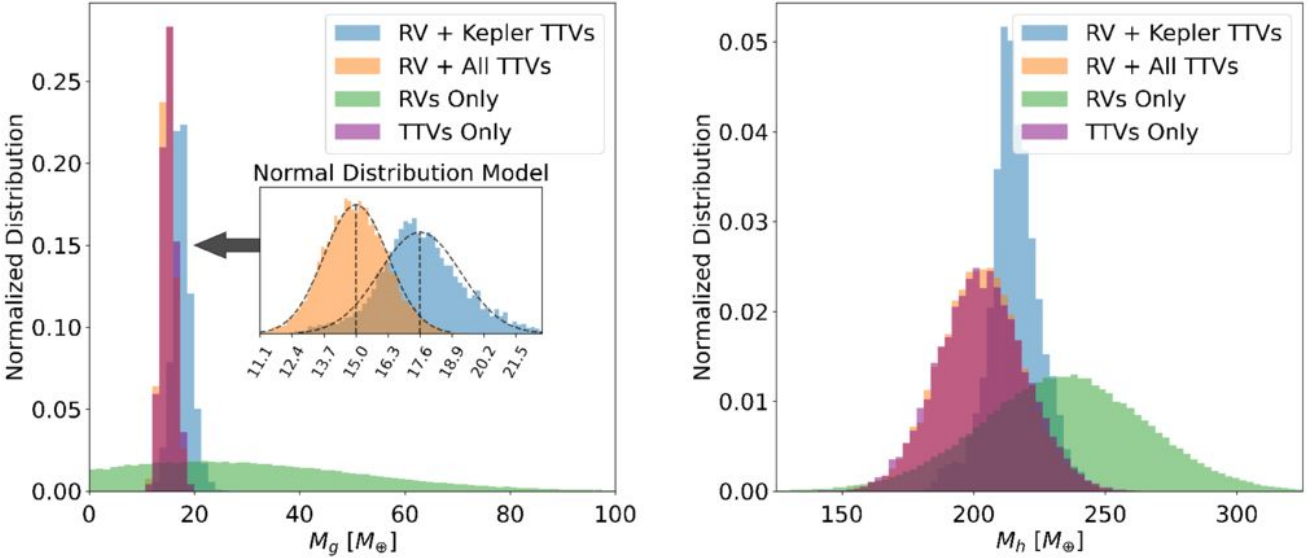

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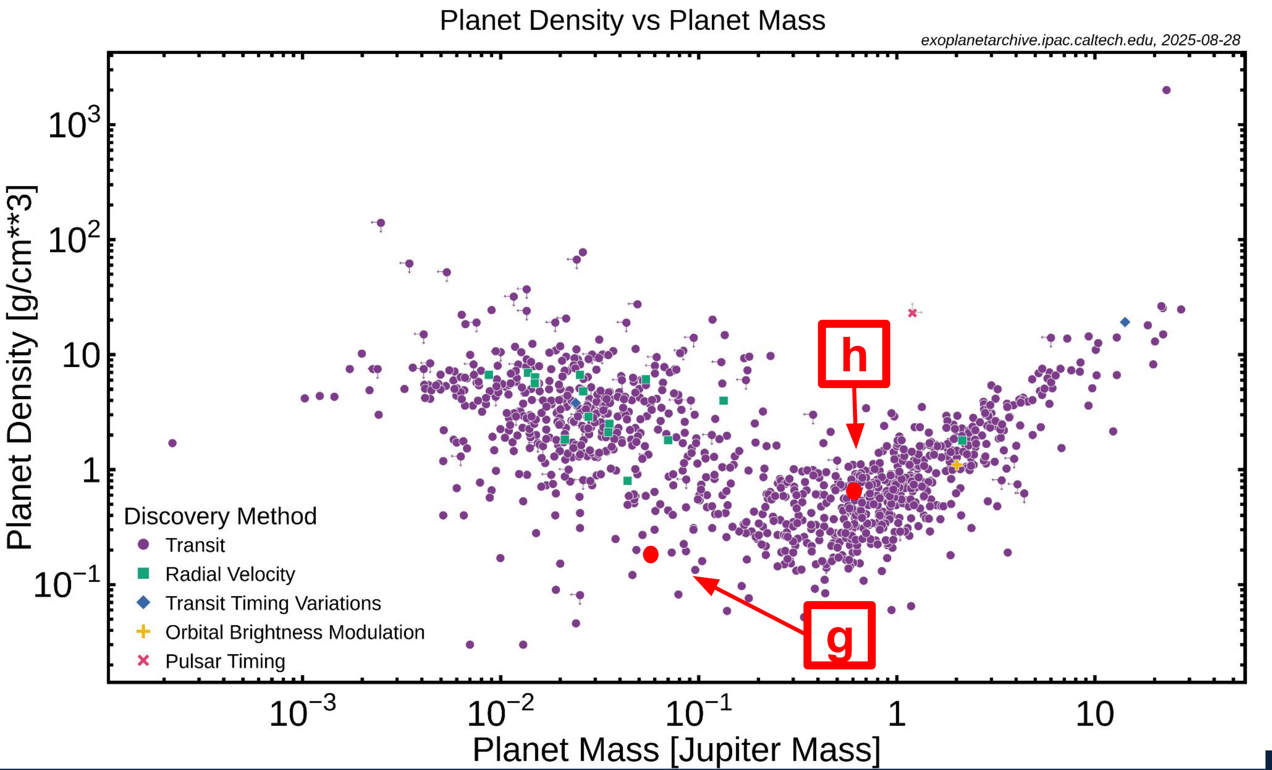
Supplemental Material

Kepler-90 g is a member of the enigmatic super puffs, which are in need of further investigation



Supplemental Material

Some open questions for the Kepler-90 system:

1. Super Puff Mechanism for K90g
   a. Could be answered by atmospheric transmission spectroscopy

2. (Mis)Alignment of the planets' orbital planes with the host's spin axis (stellar obliquity)
   a. Could be answered via the Rossiter-McLaughlin effect, i.e. detecting the RV anomaly induced by a transiting planet occulting portions of a rotating star

3. Masses of inner planets
   a. Secure detections would inform compositional modeling and allow for a more complete picture of the system's physical properties

4. Additional Planets
   a. Continued doppler monitoring informs us of potential long-period massive companions
   b. Small non-transiting planets could be found interior to the giants
      i. Implications for dynamical modeling of planets, i.e. mass/orbital inference and timing of future transits