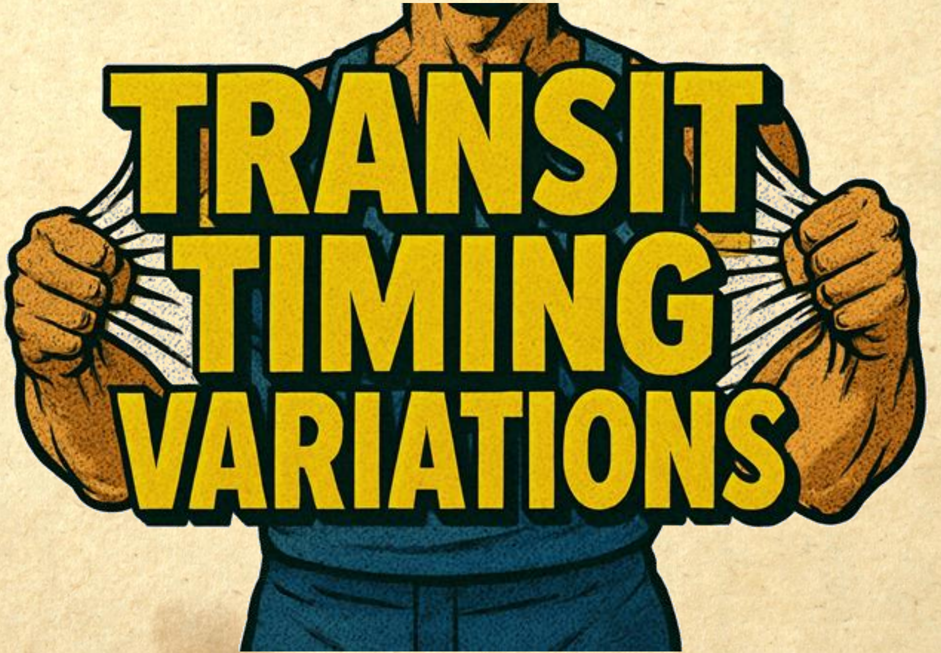
Stretching the limits of



Analysis

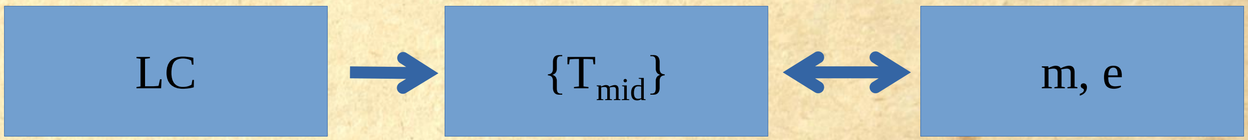
Aviv Ofir, Gideon Yoffe, Yair Judkovsky, Oded Aharonson, …

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

DDE, Coimbra – July 11, 25

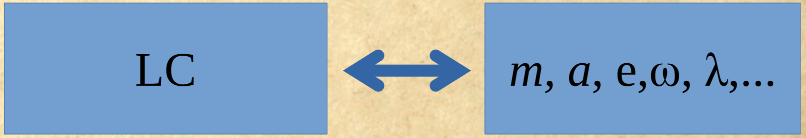
Two main avenues for TTV analysis

Classical:



Lithwick, Xi & Wu (2012)

Global modeling/ "Photodynamics"



Carter+(2011)

Global modeling outperforms Classical in:

- TTVs detection
- TTVs inversion
- Less biases in both detection and inversion

TTV Detection : Spectral Approach

(Ofir+2018)

Shortcomings of the Classical approach in:

- Low SNR individual events
- Short events
- Low-amplitude TTVs (swamped by many DOFs)

Is a global model of *unknown* TTV signal possible?

TTVs are ~sinusoidal ➔ assume a TTV = $(f, \varphi, A)_{TTV}$

➔ generate model LC

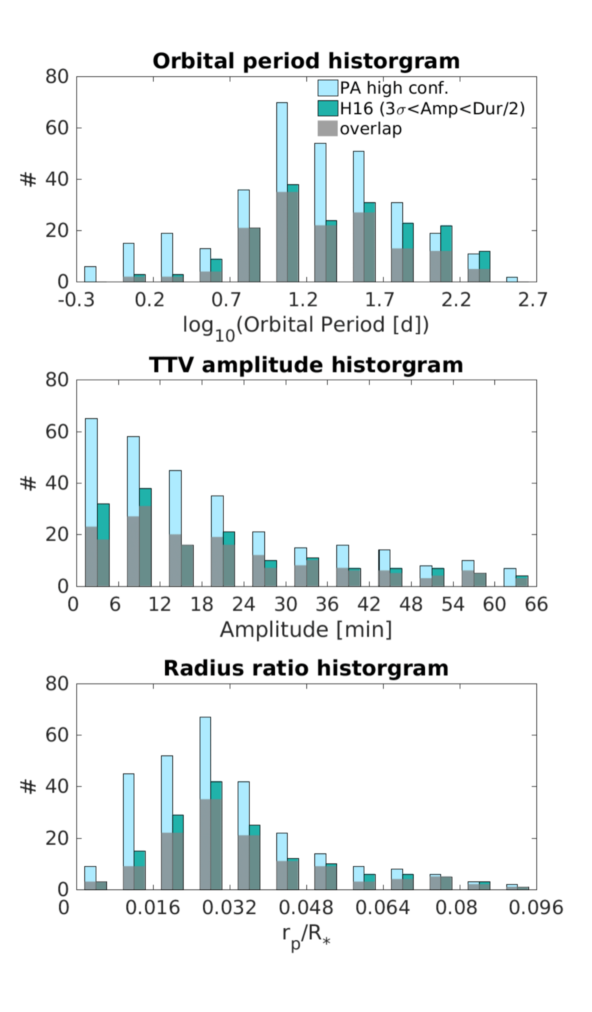
➔ compare with the linear LC

Perturbative approx. ➔ $(\varphi, A)_{TTV}$ solved linearly

Spectral Approach to TTVs

(Ofir+2018)

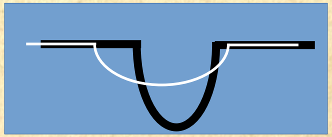
- Detected 129 new periodic TTVs in Kepler data (an increase of ~2/3 over a previous TTV catalog)
- Excess detections at short ***P***, low ***A***, small r_p – as predicted
- Unbiased: our extended TTV sample shows no deficit of short-period or low-amplitude transits
- What about TTV inversion?



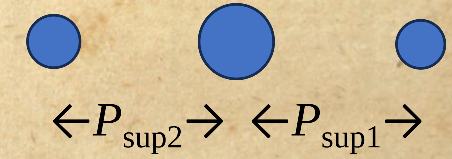
TTVs inversion I : **AnalyticLC**

Judkovsky, Ofir and Aharonson (2022a)

- A 3D analytic model based on a disturbing function expansion to 4th order in ***e*** and ***i***

LC =  ⟷ a, e, ϖ, λ, Ω, I, m/M, r/R

- New dynamical phenomenon: $\boldsymbol{P_{sup1}} \sim \boldsymbol{P_{sup2}}$ ➔ super-mean-motion resonance (SMMR)



- Quicker than **TTVFast** for Kepler, Analytic – scales better

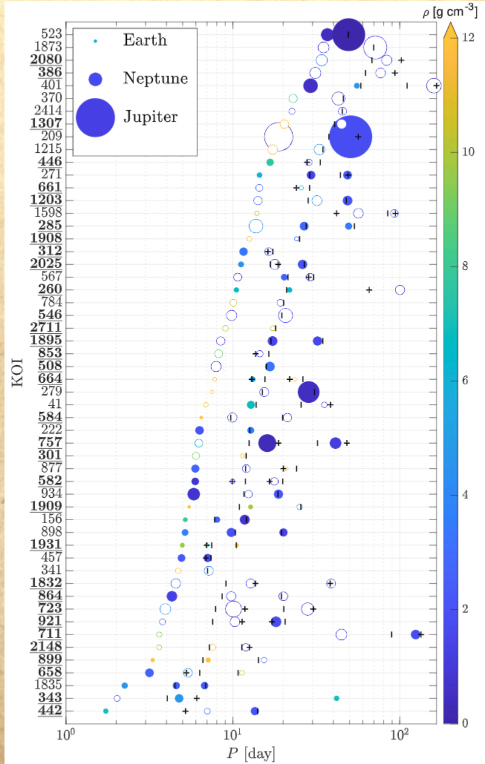
AnalyticLC Results:

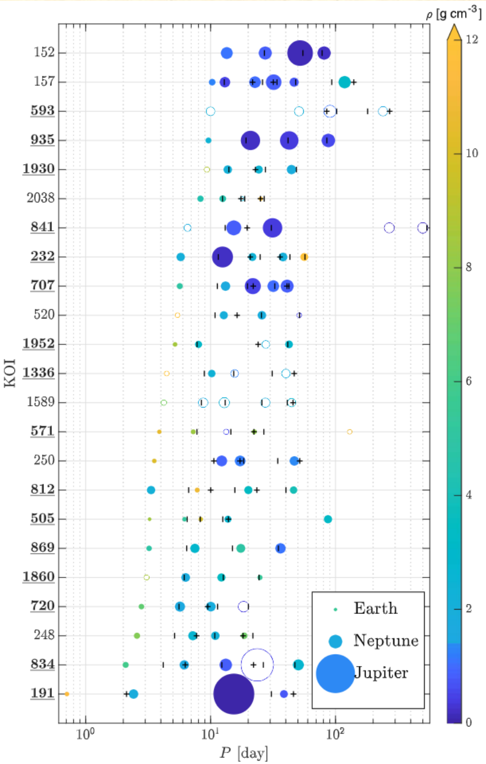
Judkovsky, Ofir and Aharonson (2022b, 2024)

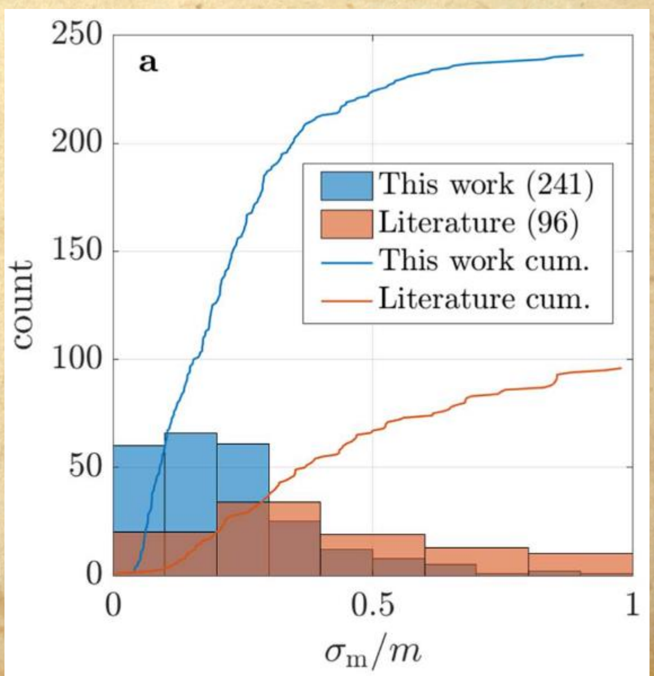
- >200 masses – mostly new, improved precision on rest

2,3 planes

4+ planets







AnalyticLC Results:

Judkovsky, Ofir and Aharonson (2022b, 2024)

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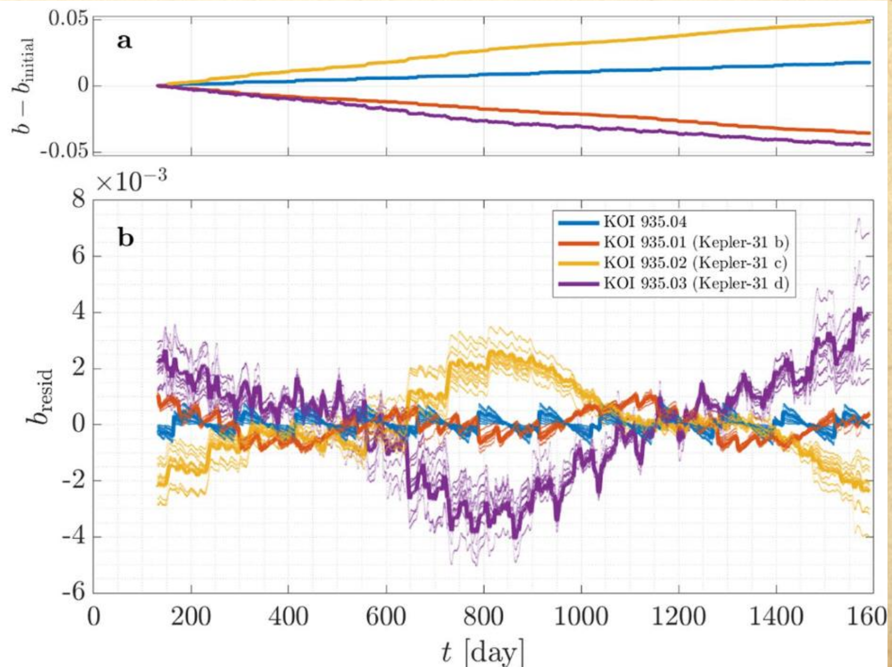
- TbV signals of 130 planets, typical detectable $\dot{b} \sim 10^{-2}$ yr^{-1}

KOI-935 (Kepler-31)



AnalyticLC Results:

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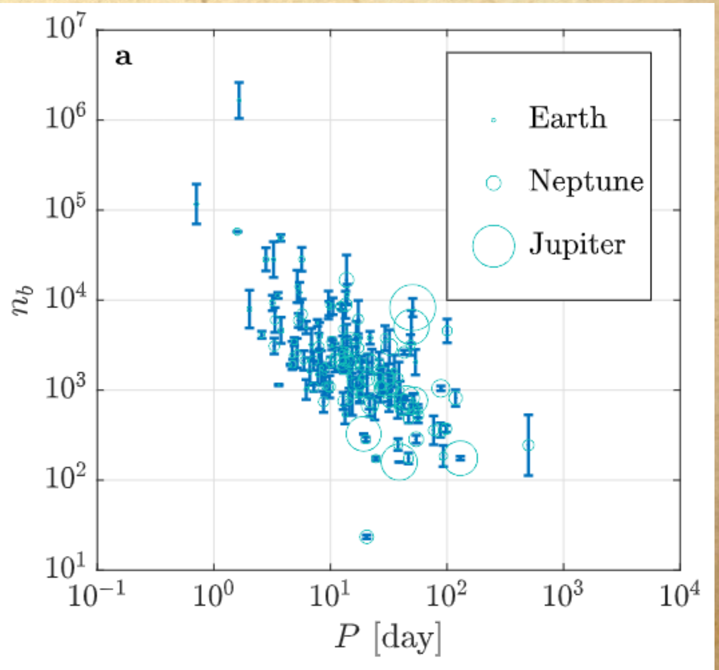


AnalyticLC Results:

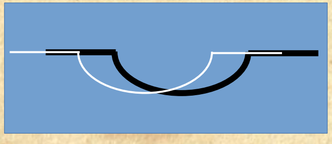
Judkovsky, Ofir and Aharonson (2022b, 2024)

- >200 masses – mostly new, improved precision on rest
- TbV signals of 130 planets, typical detectable $\dot{b}\sim 10^{-2}$ yr $^{-1}$
- Only a ~single transit at $P\sim 10^4$ d
- Supports AMD : more planets ➔ less mutual inclination
- …
- Not all systems *have* that much information to be extracted

TTVs inversion II : PyDynamicaLC

Yoffe, Ofir and Aharonson (2021), Ofir, Yoffe and Aharonson (2025)

- A simplified photodynamical Model: flat, low-eccentricity, based on TTVFaster. Agol & Deck (2016)
- Least— and the least correlated— DOFs: relies only on the *average* Keplerian elements



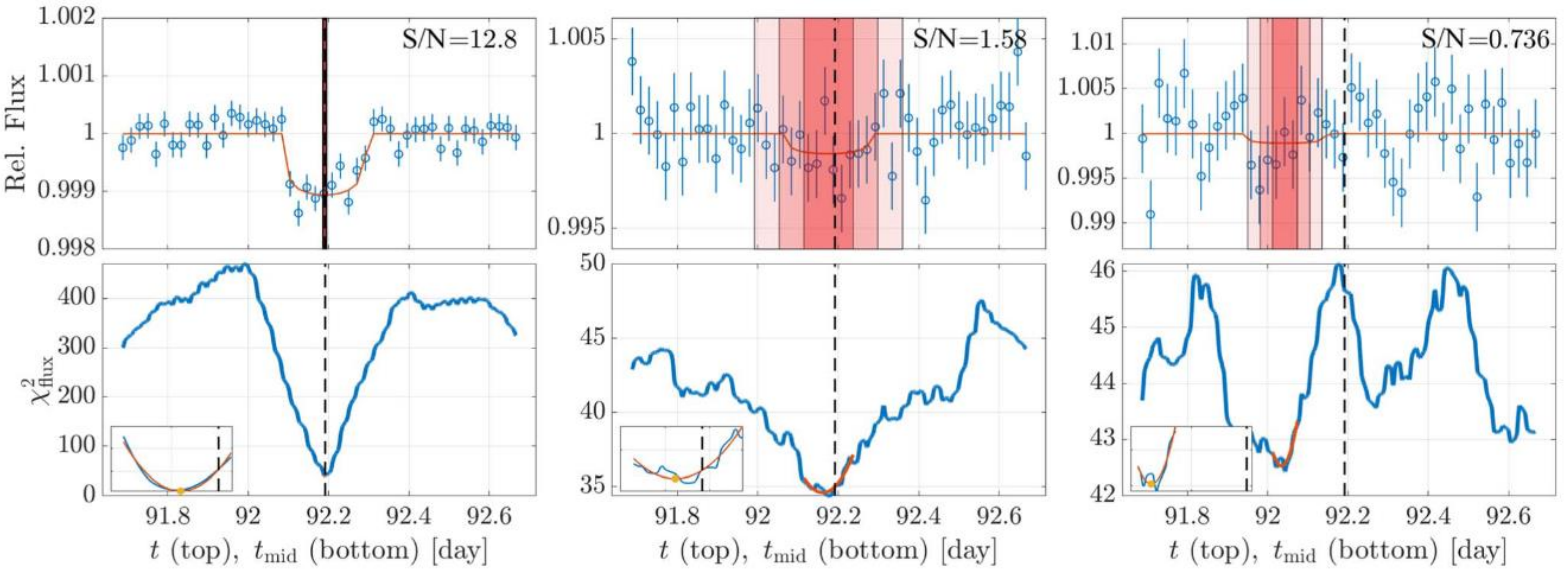
$\leftrightarrow$ $\Delta e_x, \Delta e_y, m/M$

- 88 masses, of them 23 new, down to **<1M**$_\oplus$ & **<1R** $_\oplus$ (Kepler-345 b)

Theoretical Explanation

Judkovsky, Ofir and Aharonson (2023)

- White-noise photometry ≠ white-noise timings



Conclusions

- Global modeling is advantageous both for TTV detection & TTV inversion
- Source of advantage: non-Gaussianity of timings, fewer DOFs
- Allowed us to detect more TTVs in a nearly unbiased way, more significant masses, more significant TbVs, and other effects.

Thank you.