AnalyticLC: Analytic Tool for Light Curve Modeling

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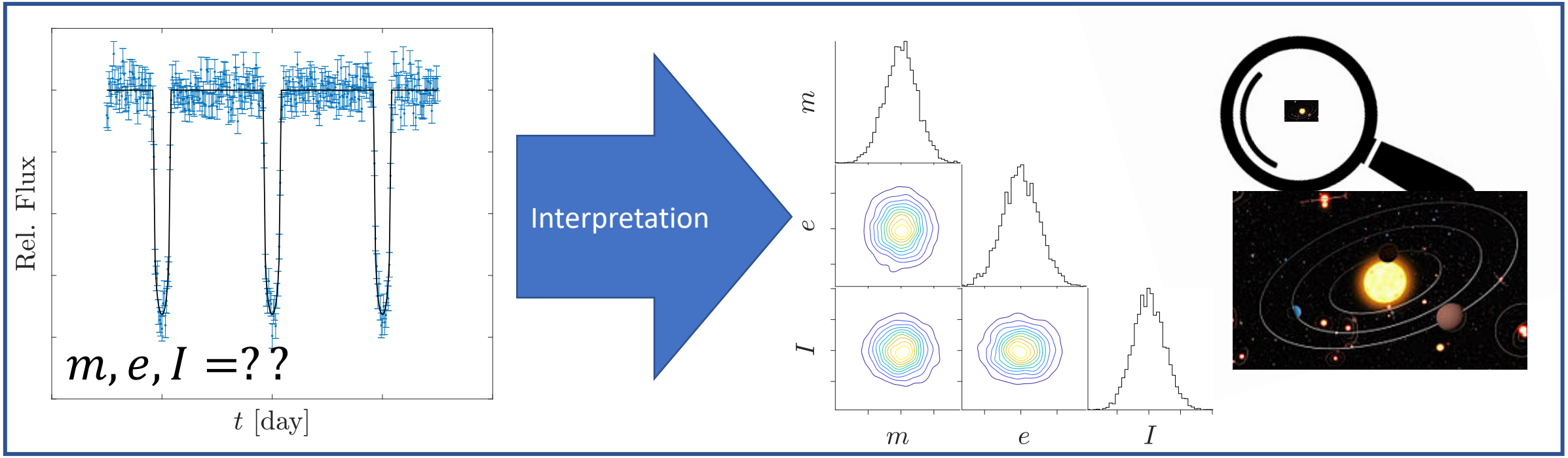

Existing modeling techniques:

- N-body integration (e.g. Chambers 1999, Deck et al. 2014)
- Analytic formulae for TTVs (e.g. Hadden & Lithwick 2016, Agol & Deck 2016)
- Spectral approach to TTVs (Ofir et al. 2018)
- TTV Modal decomposition (Linial et al. 2018)

Analytic LC:

- **Global light curve modeling**
- **Fast calculation**
- **Accuracy: fourth order in e, I**
- **Models also RV & Astrometry**

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AnalyticLC method

- Fast – efficiency-accuracy balance
- Global photometric modeling
- Analytic – elucidates orbital dynamics
- Applicable for RV/Astrometry

Orbit size, planet location

$$\frac{da}{dt} =$$

$$\frac{d\lambda}{dt} =$$

Orbit shape

$$\frac{de}{dt} = f(\mathcal{R})$$

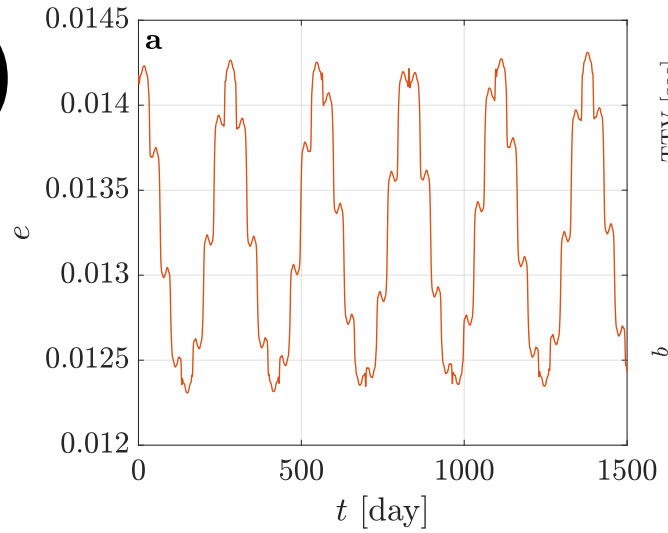
$$\frac{d\varpi}{dt} =$$

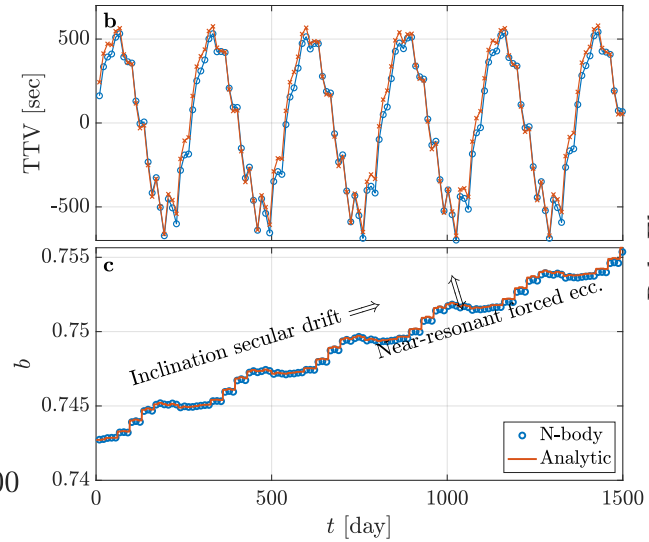
Orbit plane orientation

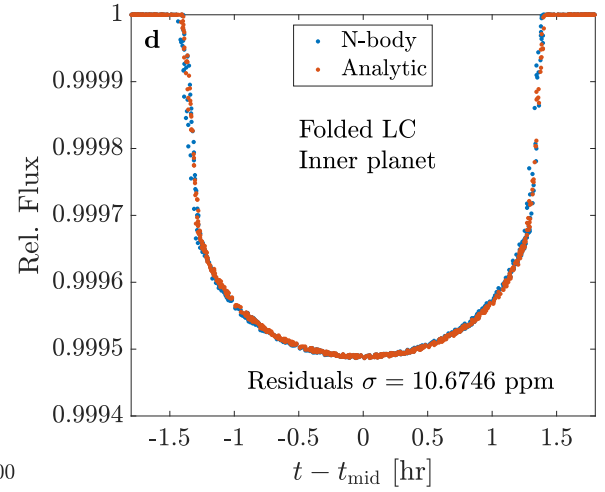
$$\frac{dI}{dt} =$$

$$\frac{d\Omega}{dt} =$$

Murray & Dermott, 1999





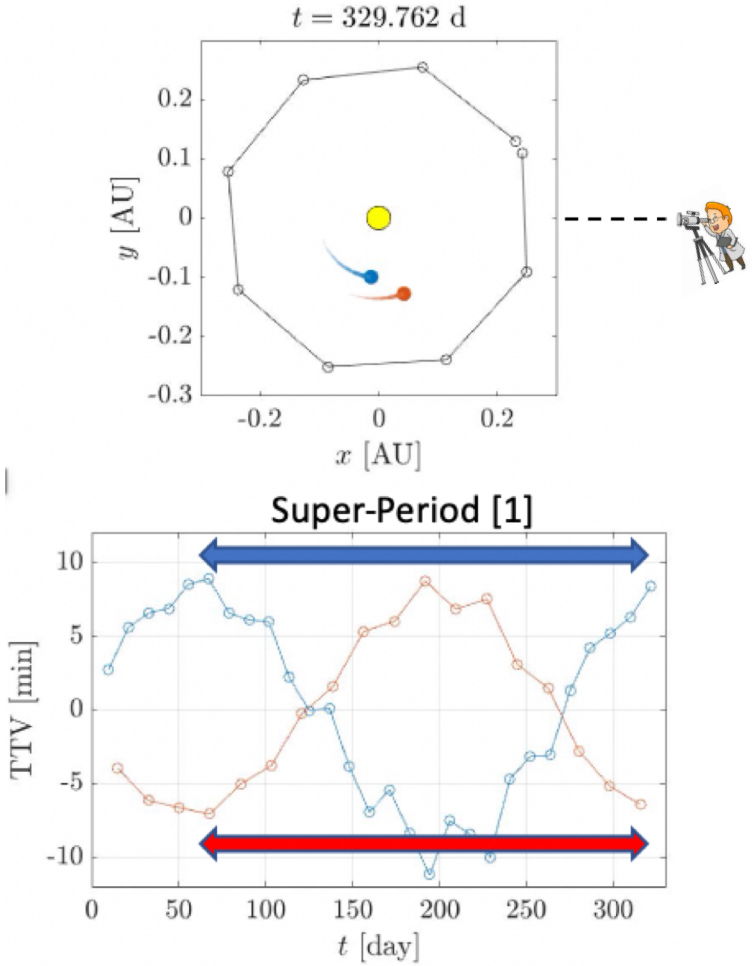


Lagrange's equations → Solve → Orbital elements variations → Translate → Individual Transit Properties → Compute → Global light curve

[1] Mandel & Agol, 2002

TTV near 1st order MMR

2 planets, periods ratio = 1.531

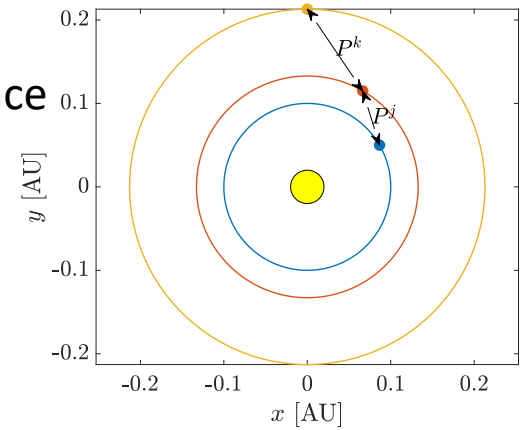


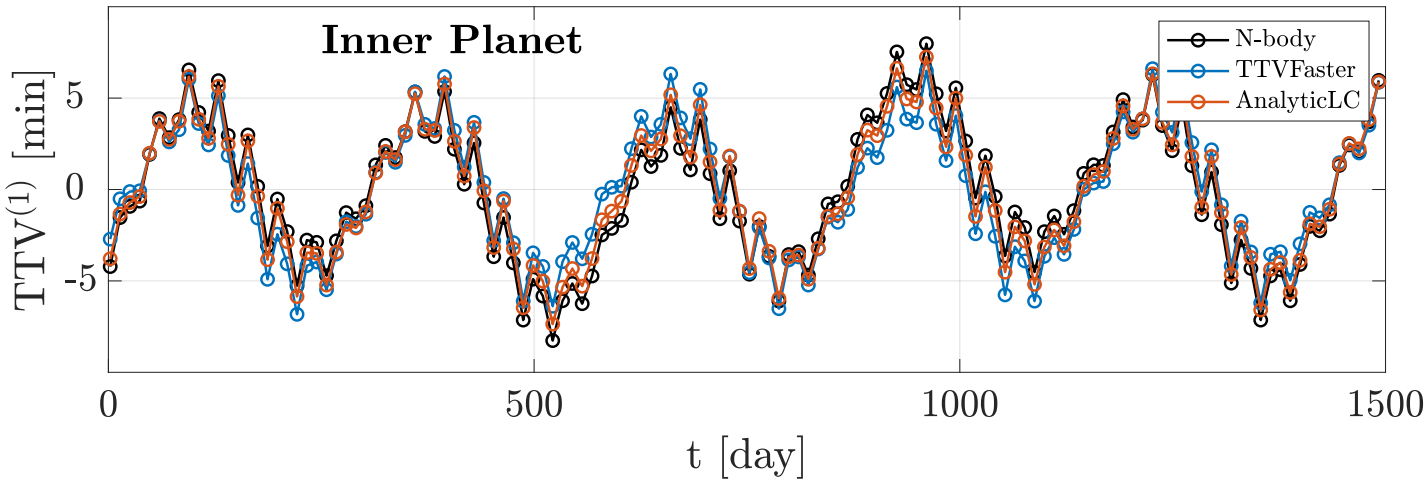
[1] Lithwick et al., 2012
[2] TTVFaster – Agol & Deck, 2016

Non-additive 3 planets TTV

SMMR = Super-Mean-Motion-Resonance

- Time scale: $(\frac{1}{P^j} - \frac{1}{P^k})^{-1}$
- Second order in planetary mass





Pairwise models agree: Residual relative to full n-Body ~2 min

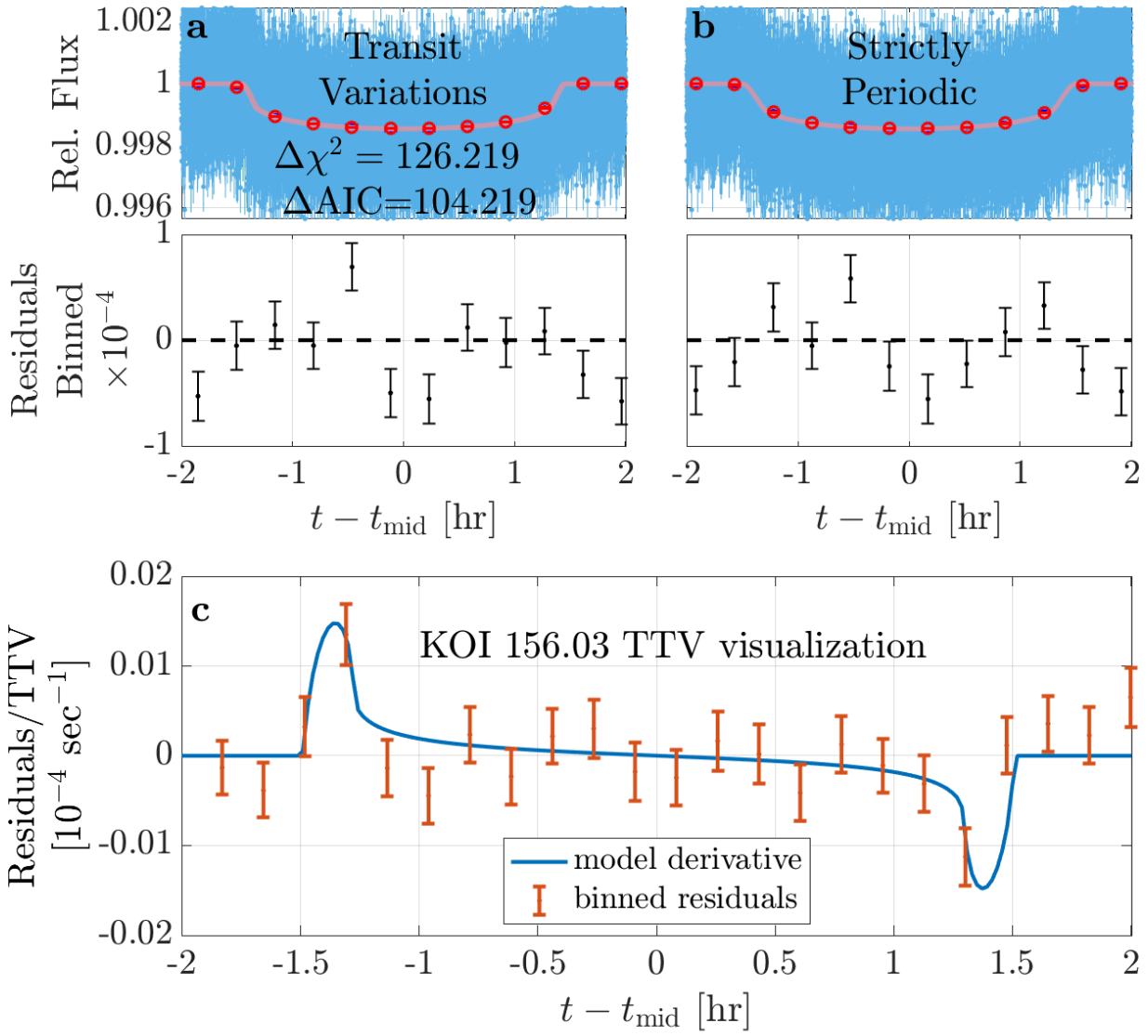
AnalyticLC with SMMR: Residual relative to full n-Body <1 min (!)

Example: KOI-567 (Kepler-184):

- Orbital periods 10.7, 20.3 and 29 days
- Super periods 202.4, 205.7 days
- SMMR period: 34.5 years

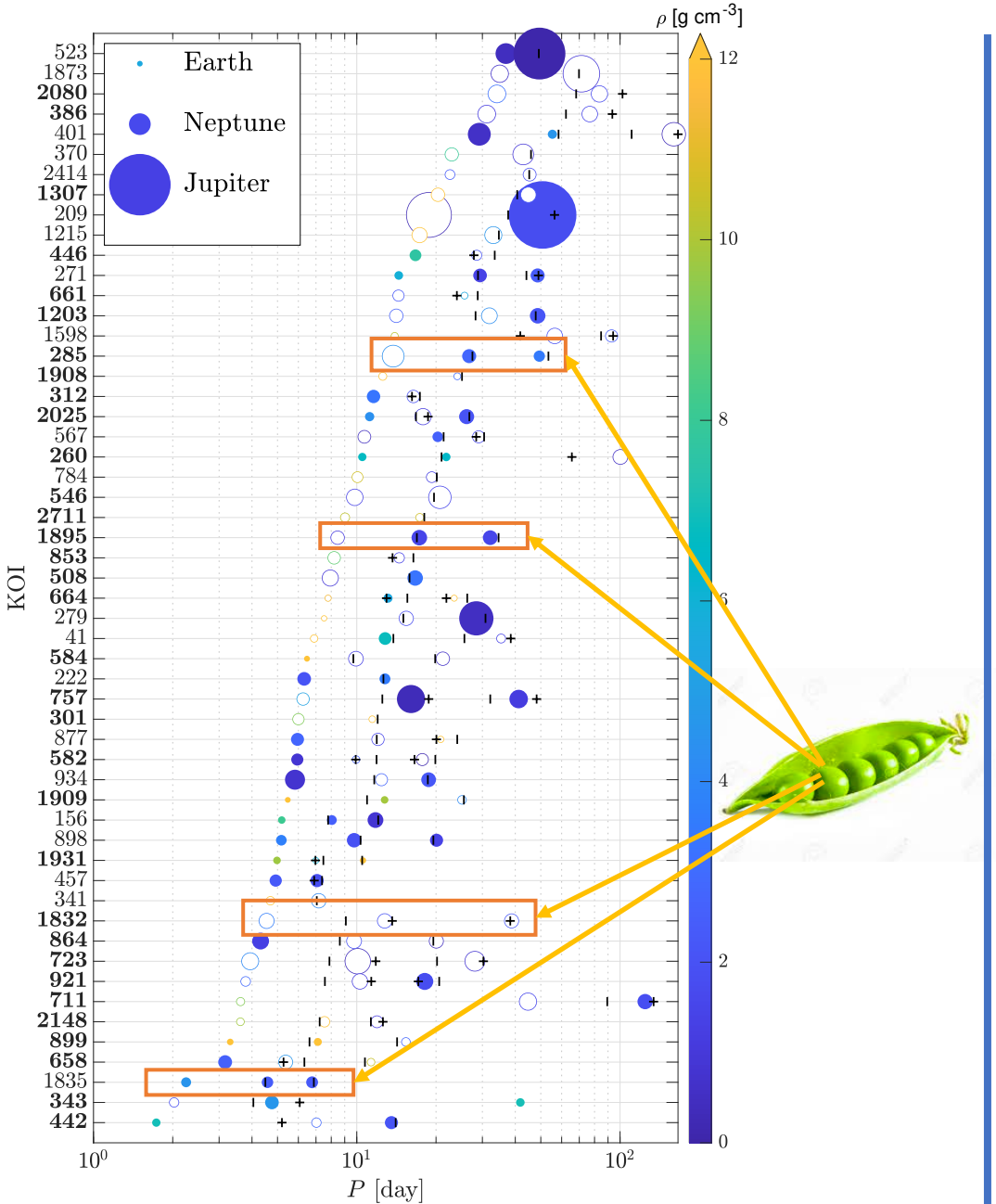
Usage of AnalyticLC - methods

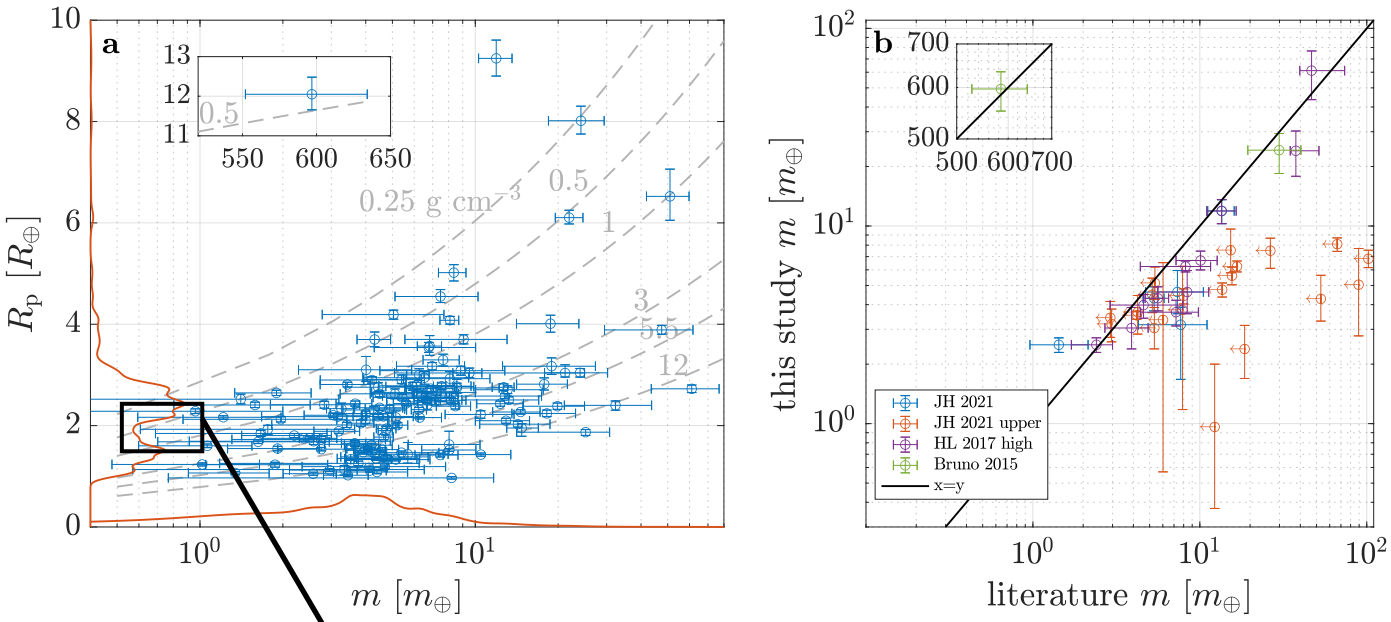
- Global fit using DE-MCzs [1]
- Analyzed Kepler data of 144 2- and 3- planets systems
- Performed tests to validate solutions
- 140 planets in 54 systems passed all tests



[1] DE-MCzs - ter Braak and Vrugt, 2008
[2] Akaike, 1974

Results – overview of 140 planets

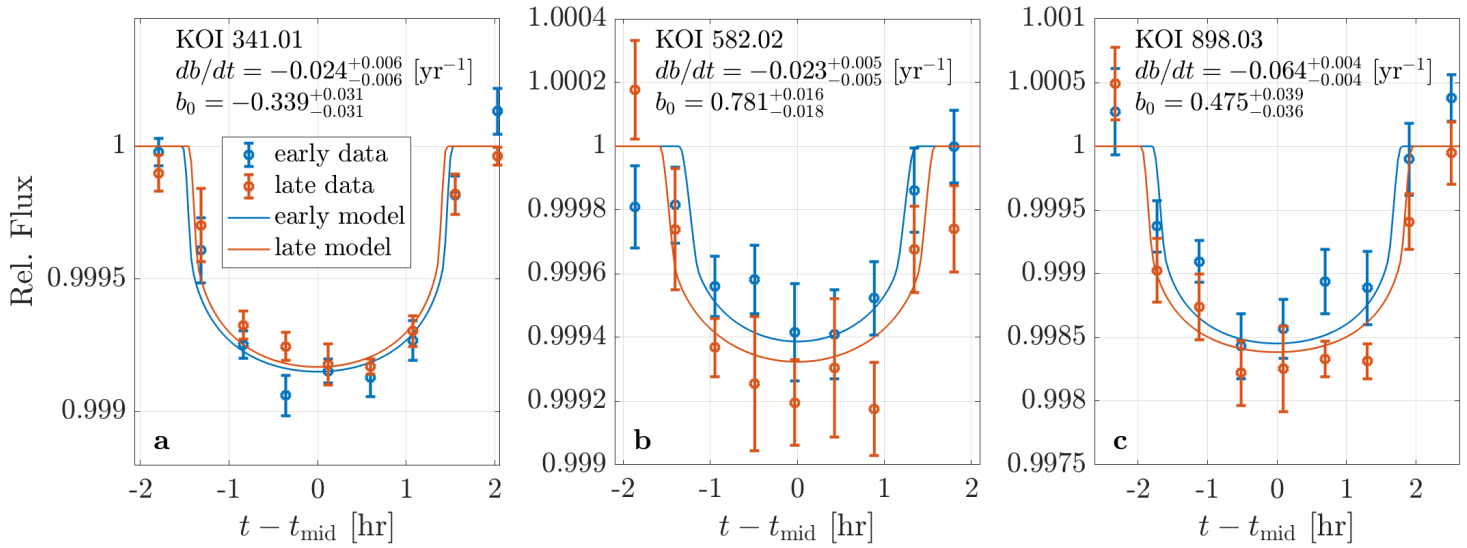


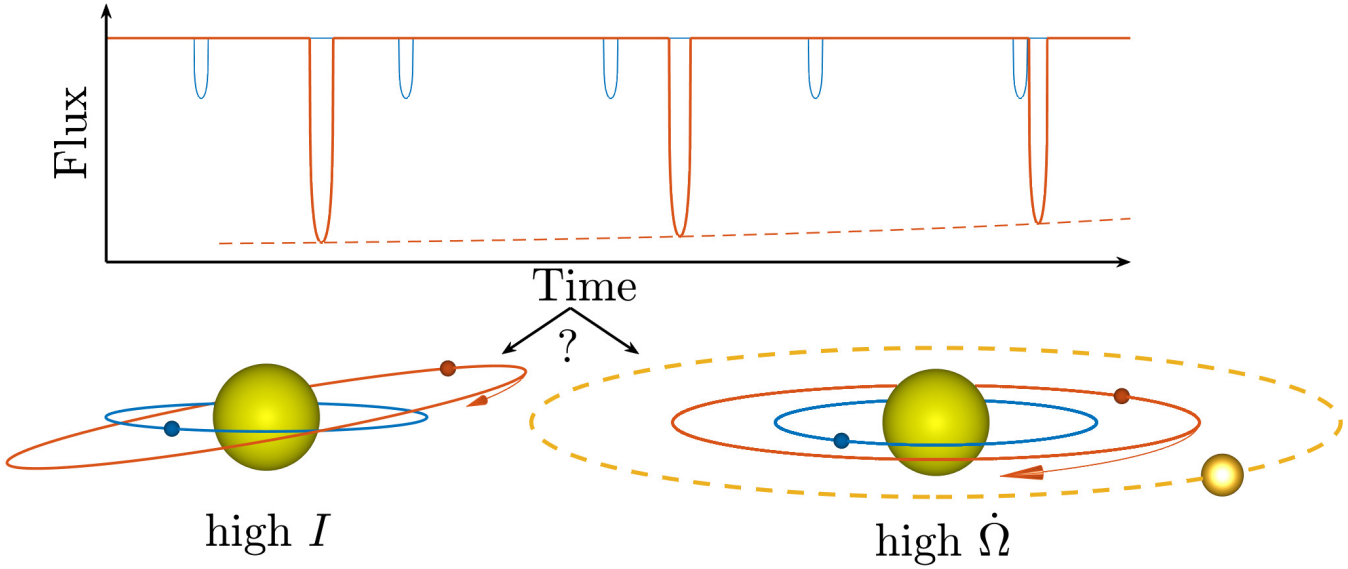


[1] Weiss et al., 2018
[2] Fulton et al., 2017
[3] Jontof-Hutter, 2021
[4] Hadden & Lithwick, 2017
[5] Bruno et al., 2015

Results - Impact parameter variations (TbVs)

- Tabulated TbV catalog
- 59 KOIs with >2σ TbV detection, 35 of which better than 3σ



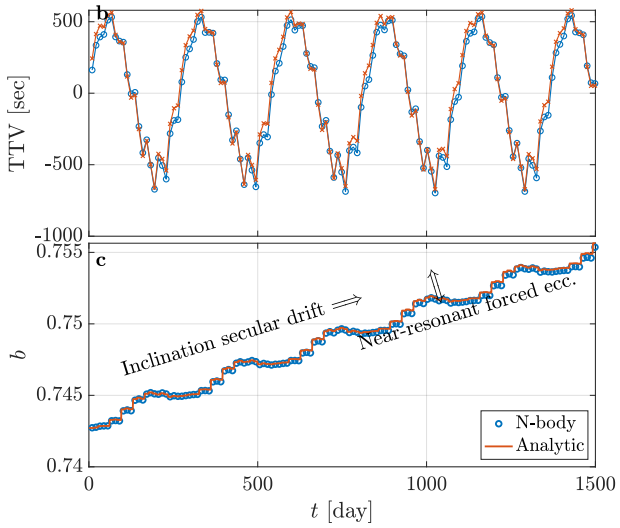


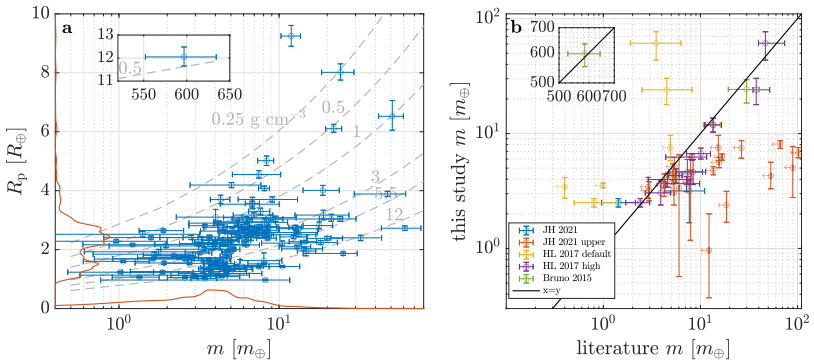
Summary

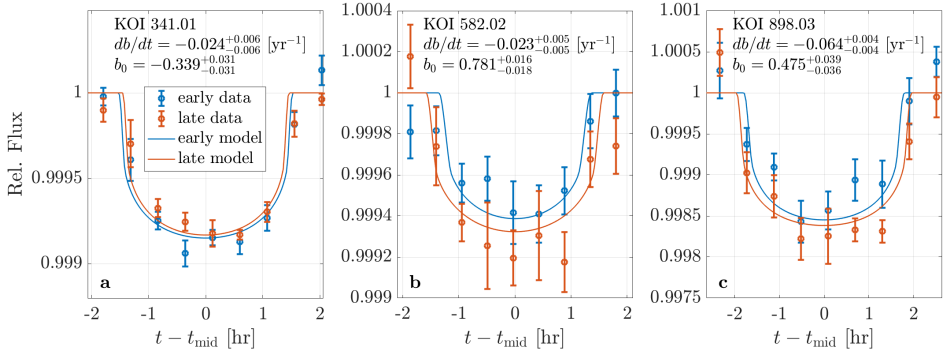
- **AnalyticLC** [1]
  - a novel analytic method for global multi-data 3D modeling

- **Main results from Kepler data** [2]:
  - 140 planets properties, 72 new masses
  - TbVs catalog of 59 planets (35 better than 3σ)

- **Future prospects**:
  - Future data, particularly PLATO
  - Joint data types analysis
  - Search for non-transiting companions







[1] Judkovsky et al. 2021a, submitted
[2] Judkovsky et al. 2021b, submitted

ERC proposal EXOPLANETS
PI: Aharonson