UNIVERSITÉ DE GENÈVE

Swiss National Science Foundation

PlanetS

TTV data challenge of the Geneva Resonant State Workshop

PLATO ESP2025 – Marseille

A. Leleu, R. Mardling, K. Masuda, M. Rosenqvist, J. Korth, J. Almenara, I.-G. Jiang and L.-C. Yeh

TTVs precision

Agol & Fabrycky (2025)

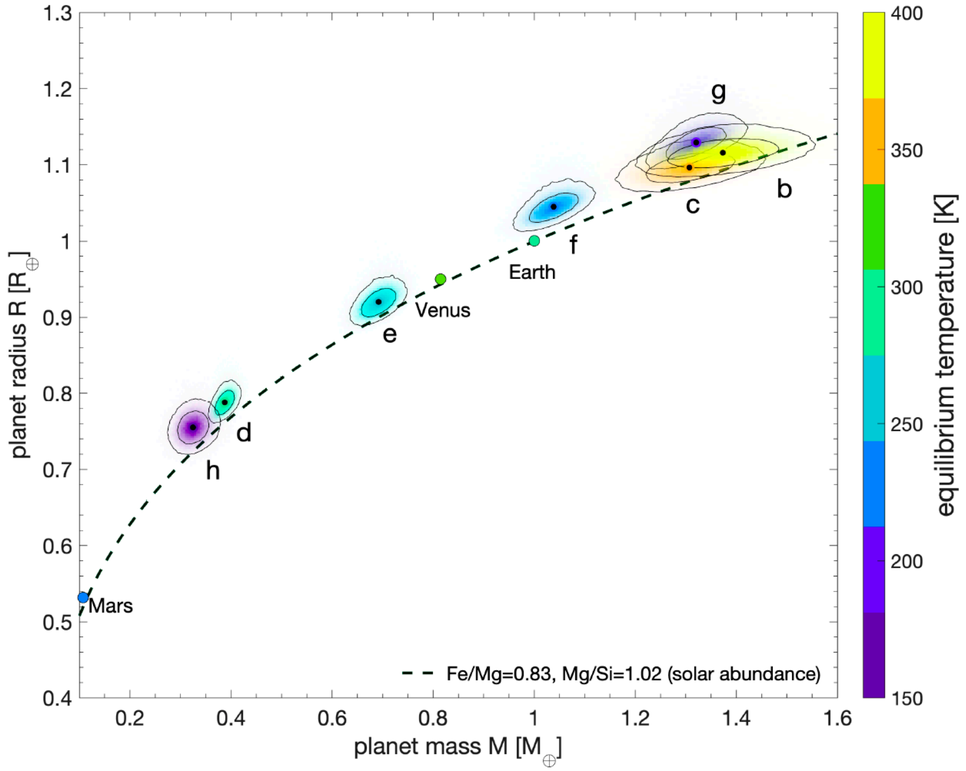
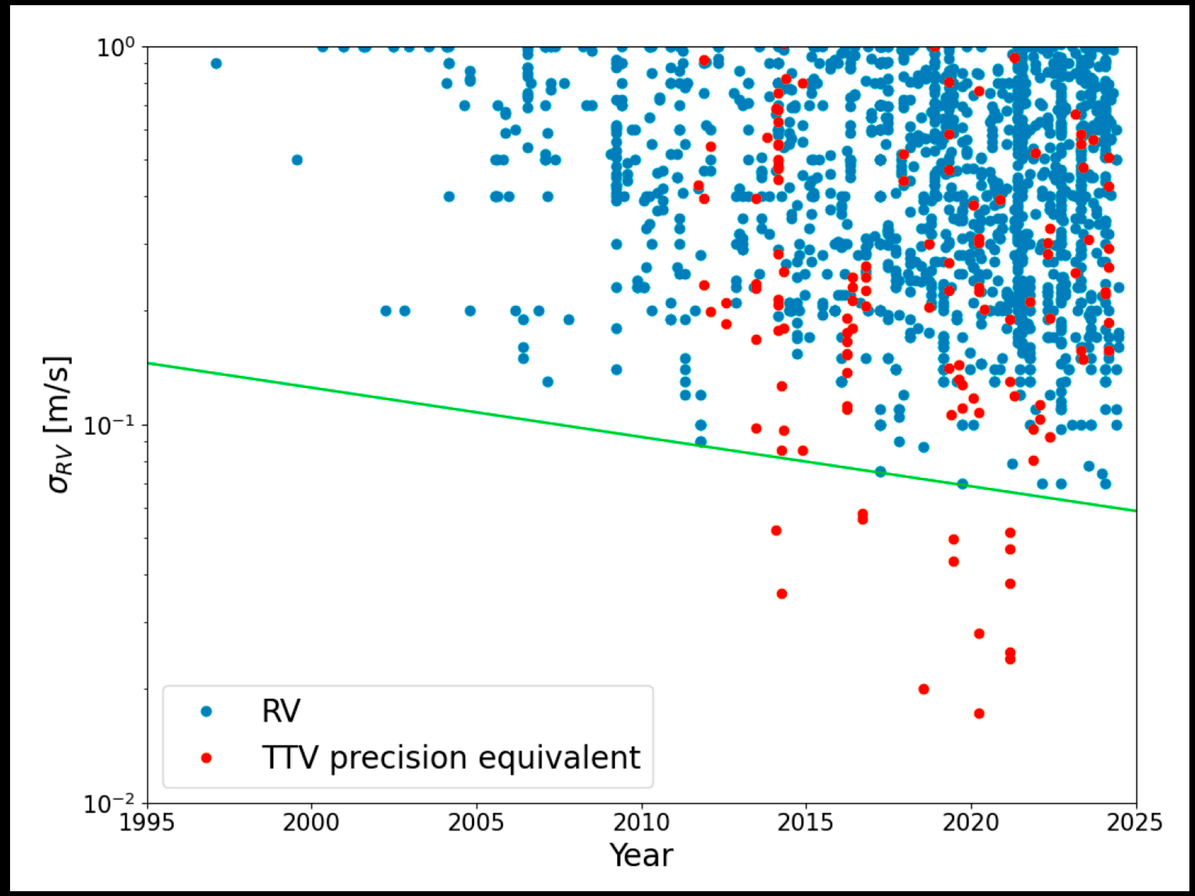
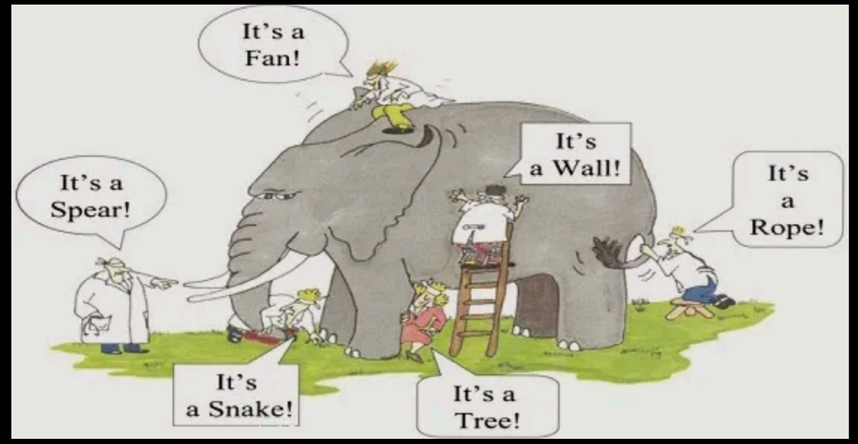


Fig. 4 Mass-radius relation of the TRAPPIST-1 planets based on Agol et al. (2021a).



TTVs is a very powerful method, but its applicability depends on the orbital configuration of the observed system

How to make sure of the accuracy of our measurements?



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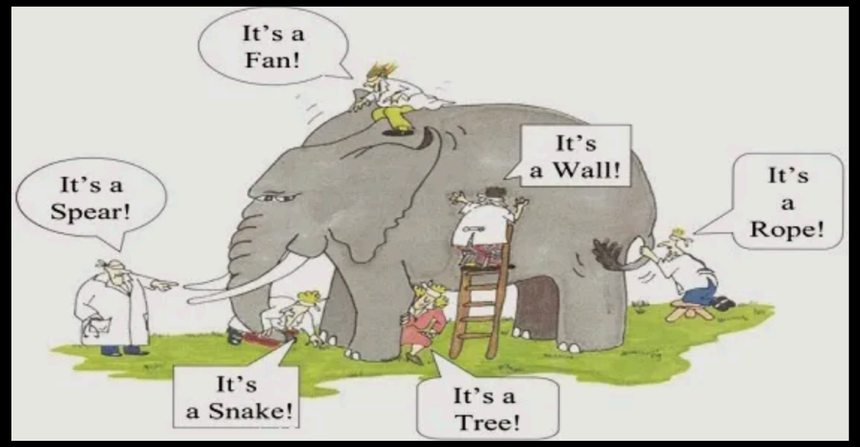

by comparing the results on different methods on the same targets …

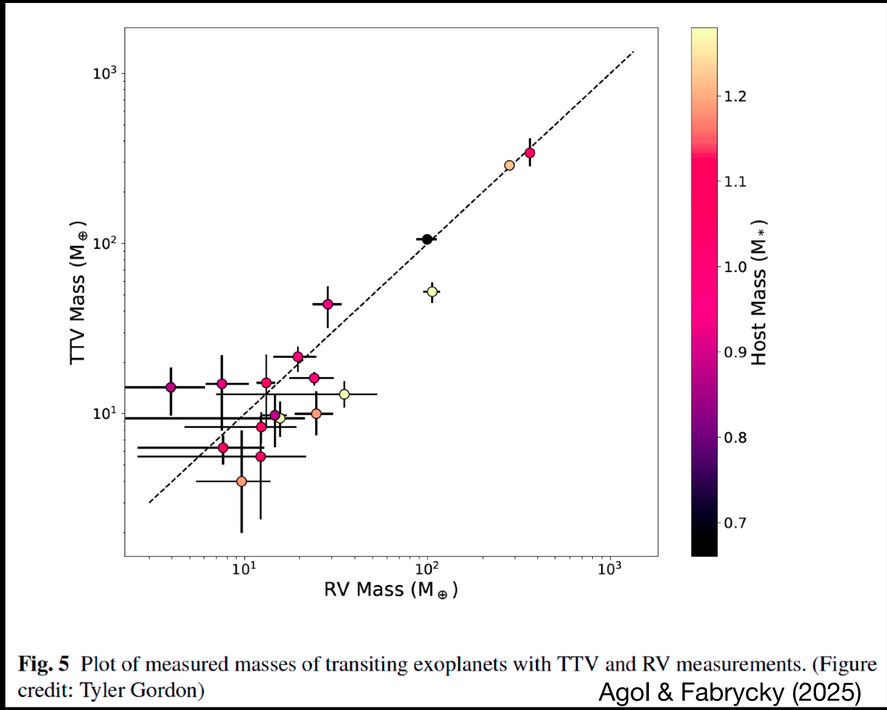

Fig. 5 Plot of measured masses of transiting exoplanets with TTV and RV measurements. (Figure credit: Tyler Gordon)

Agol & Fabrycky (2025)

Working on it… (**MAPS WG,** CHEOPS programs)

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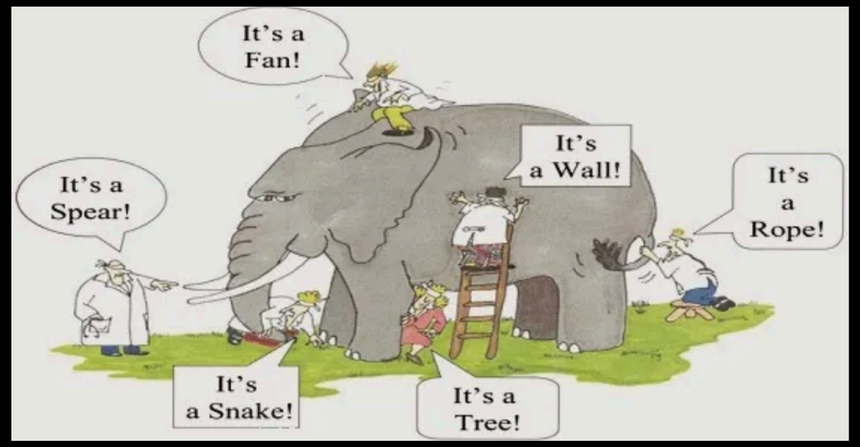

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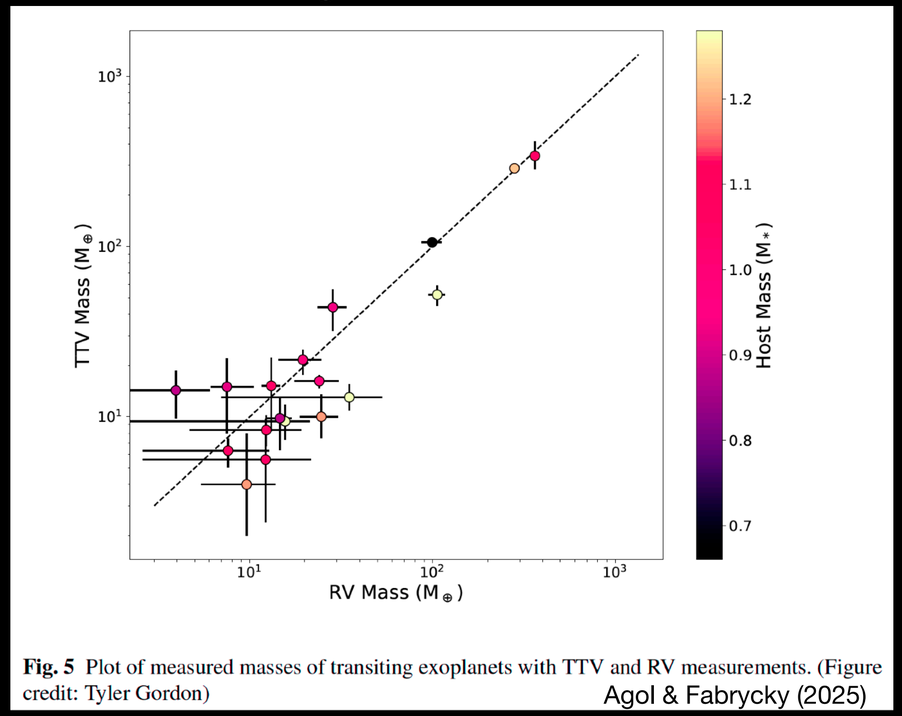

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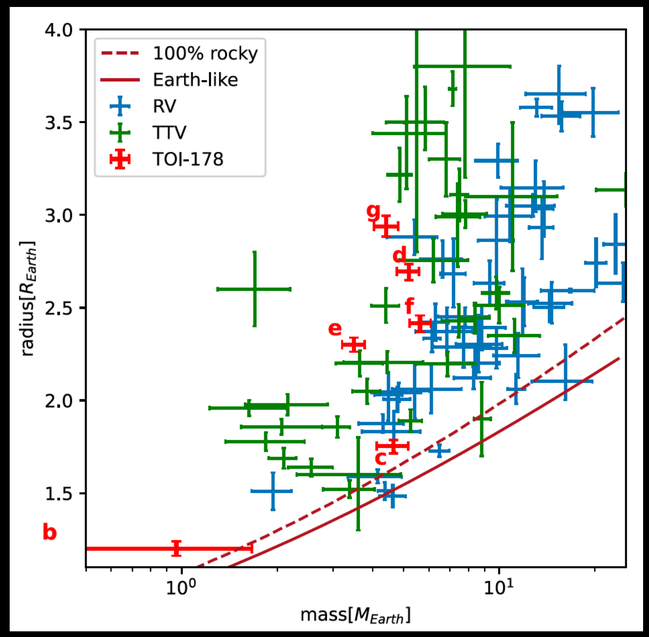
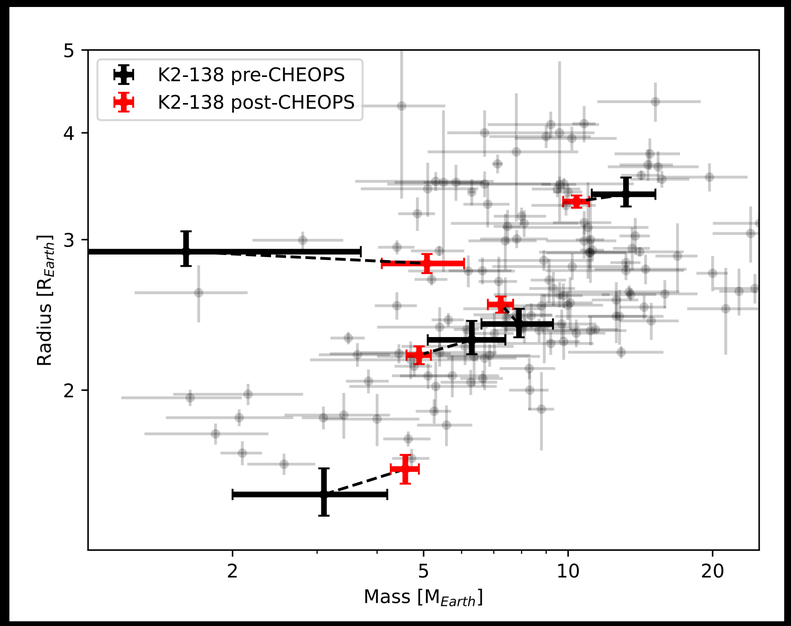
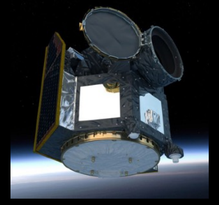
TOI-178



K2-138





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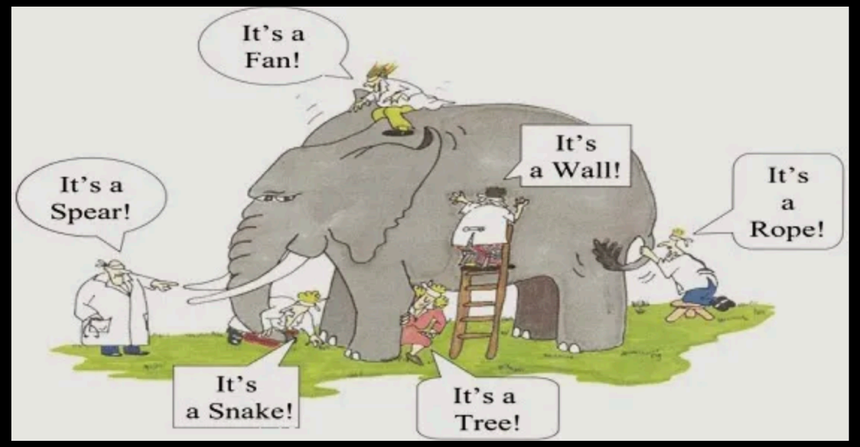

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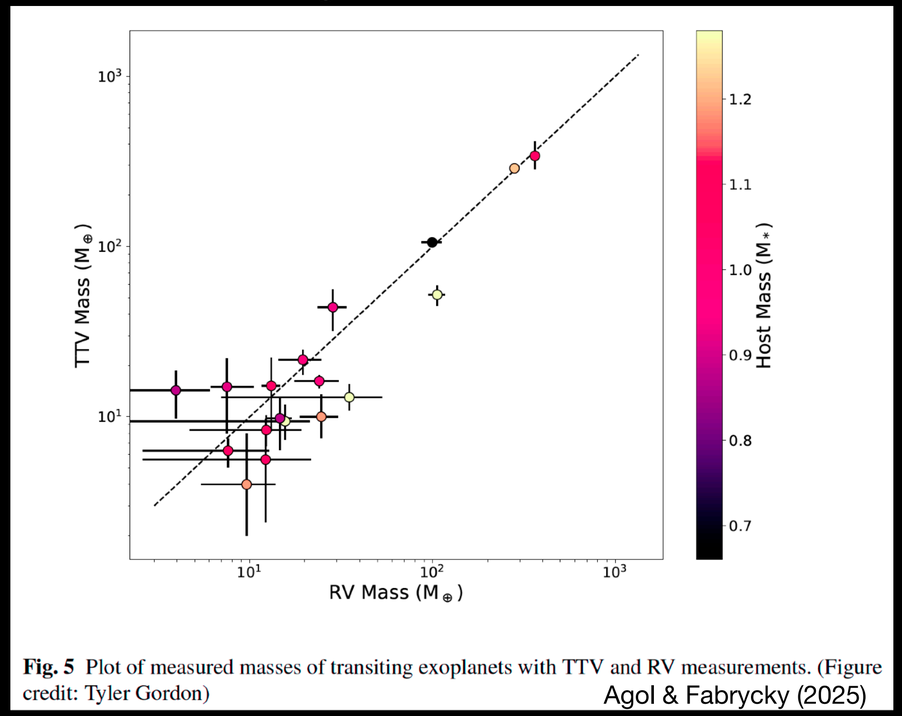

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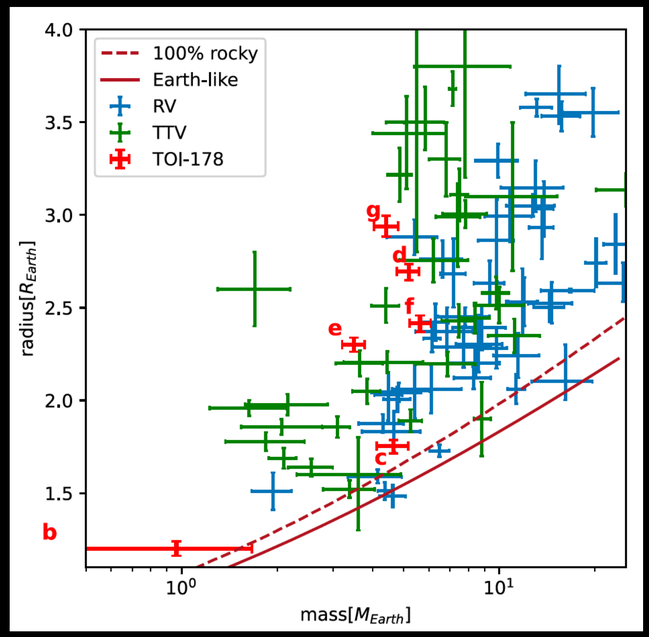

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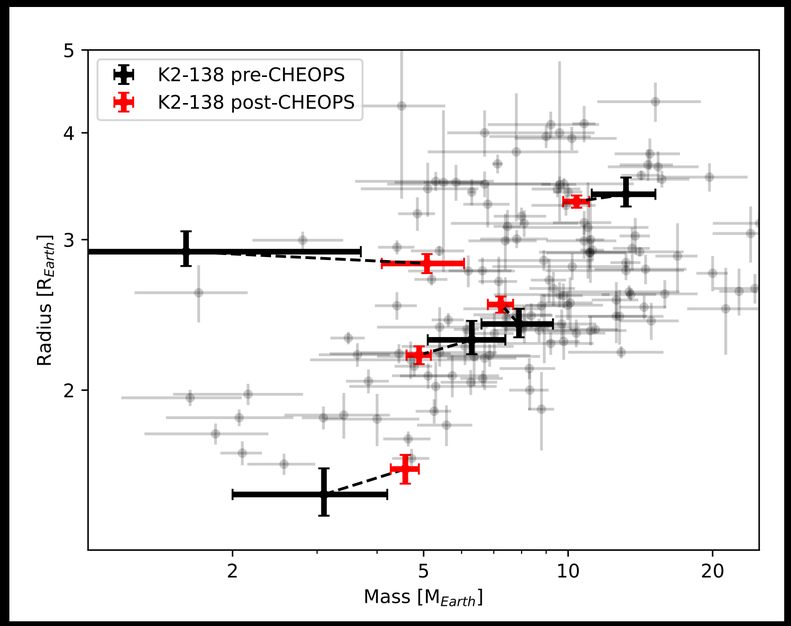

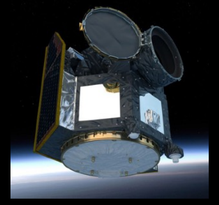

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… or by doing a data challenge!

Rationale for a TTV data challenge

Difficulties of TTV analysis:

1. The correct mode can have degeneracies.
2. The solution can be multi-modal.
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Goals of the data challenge:

- To identify unforeseen difficulties: solutions that are far off, but doesn't appear to be.
- To identify criteria to tackle aforementioned difficulties.

Scope of the data challenge

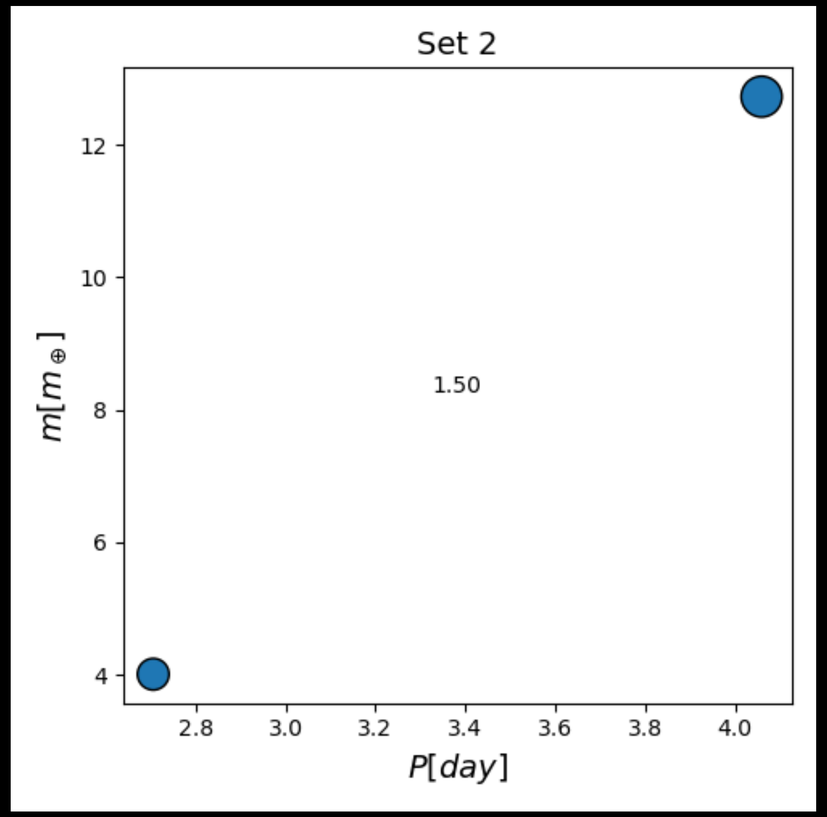
- 20 sets for TTV analysis, 6 of which were also selected for photo-dynamical analysis.
  - Sets 1 to 7 are 2-planet sets in various orbital configurations
  - Sets 7 to 18 are focussed on multi-planetary systems with some non-transiting planets
- TTV participants: Kento Masuda, Marylyn Rosenqvist, Ing-Guey Jiang and Li-Chin Yeh
- Photo-dynamical participants: Kento Masuda, Judith Korth and Jose Almenara

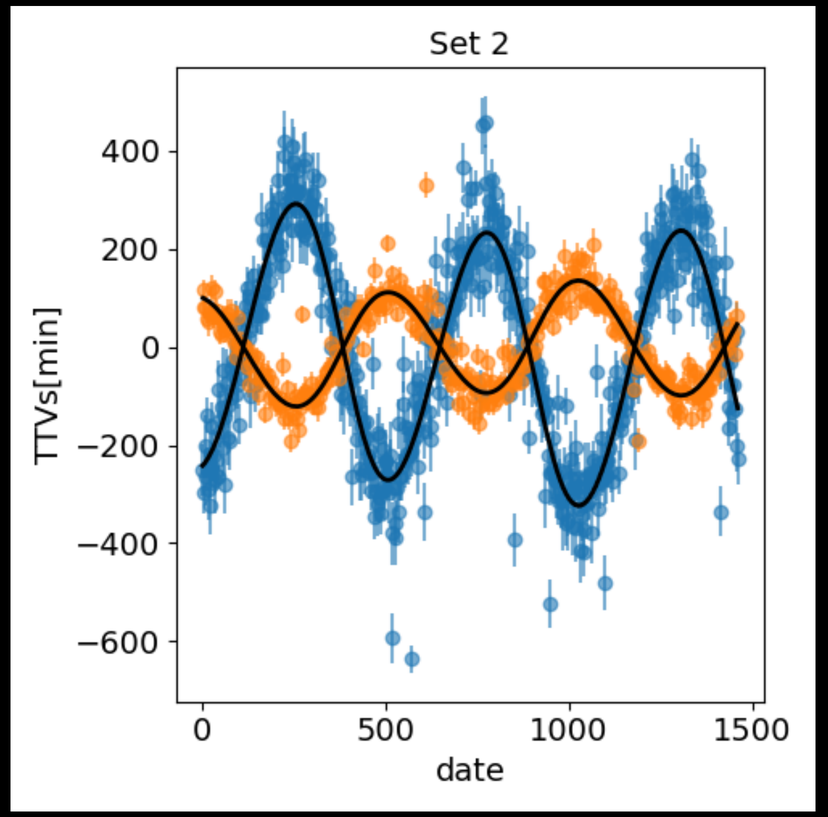
  → **154 planets analysed**

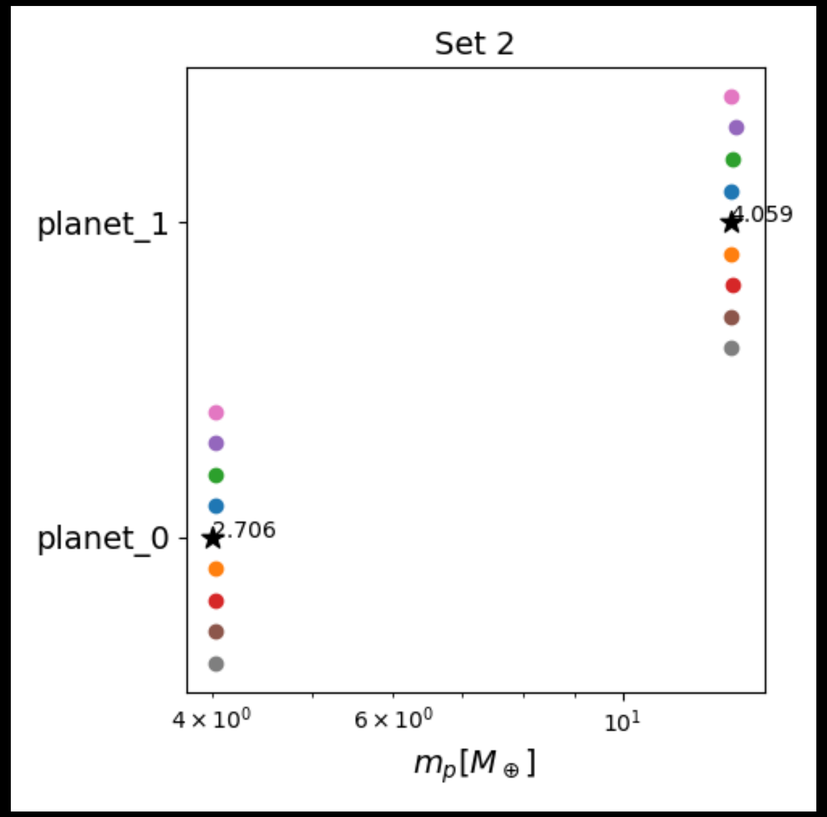
- Synthetical multi-planetary signal were injected in raw Kepler light curve. **The setup is ready to simulate PLATO systems as well.**

Some cases

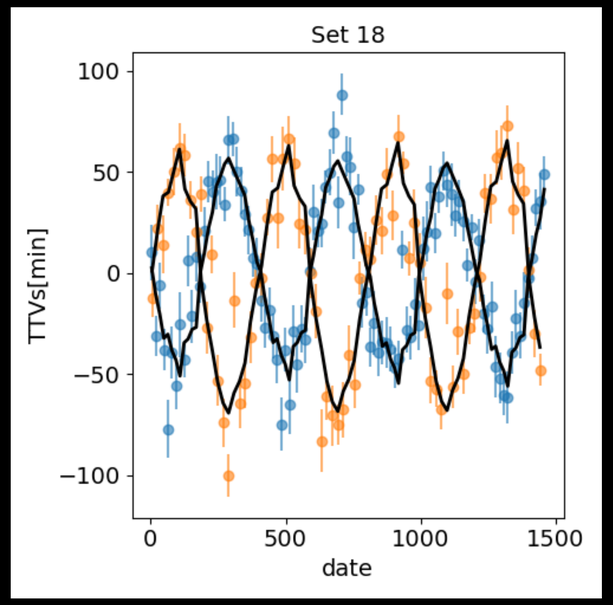
Example of an easy case

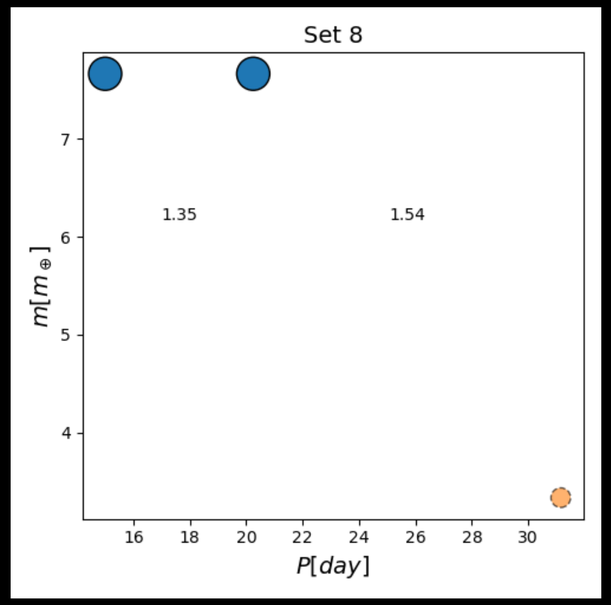


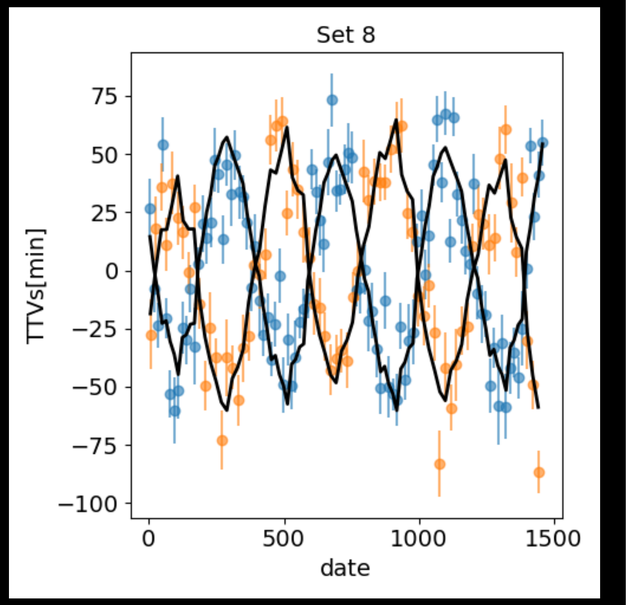


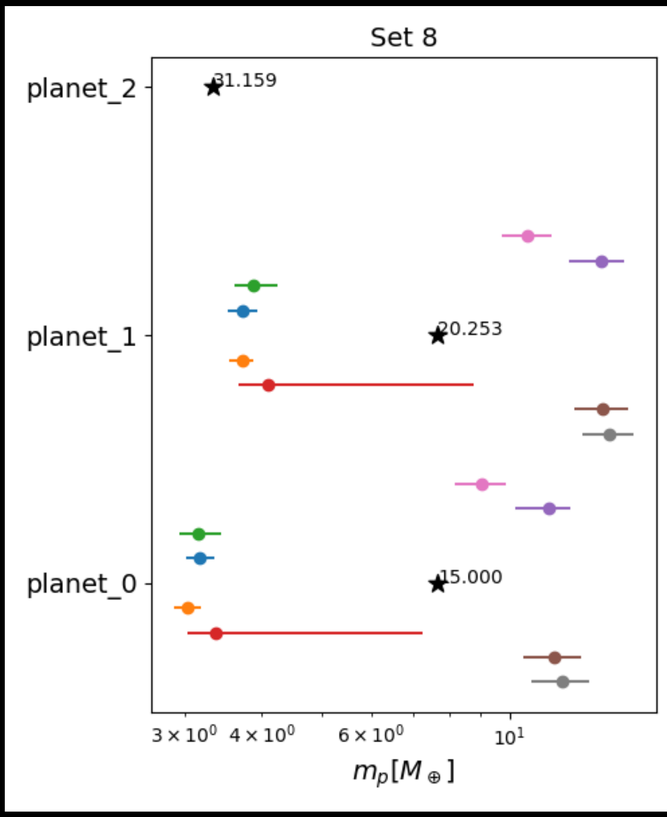


Sets 8





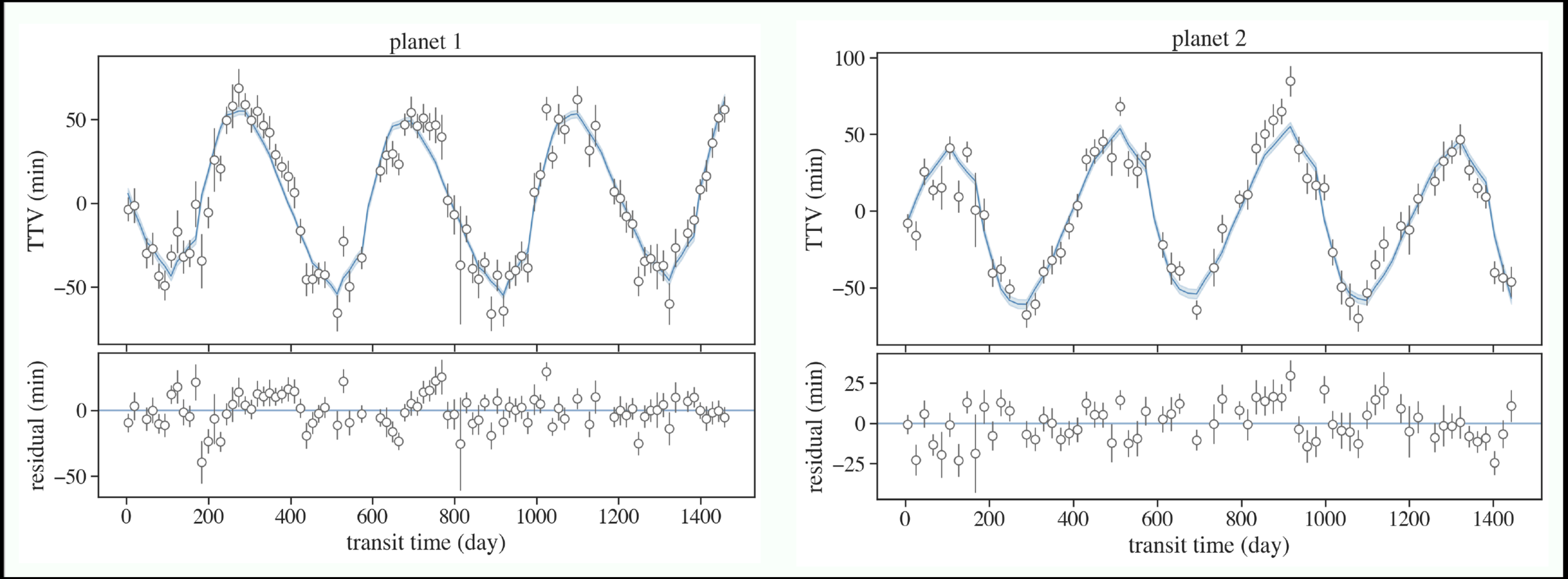




Same inner two planets, but set 8 has a 3rd outer planet **forming a resonant chain**
Since they have the same super-period than the inner pair, the TTV blends in

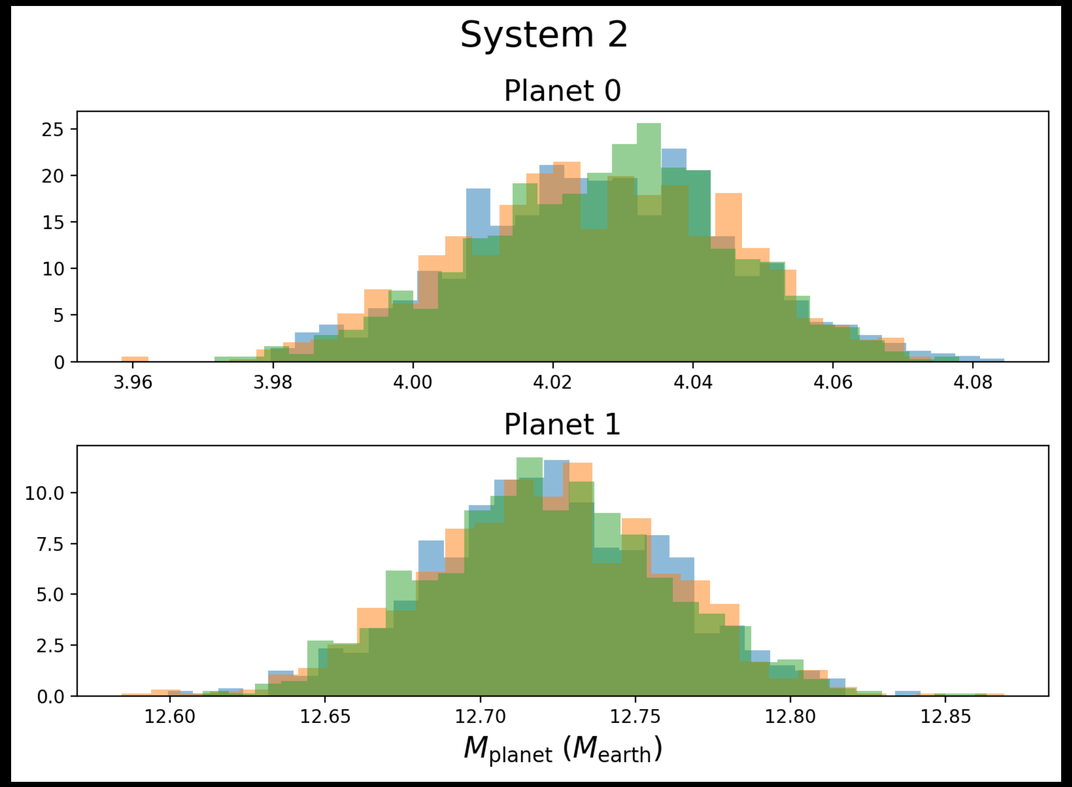
- 2 participants out of 4 considered a 3-planet model for set 8 based on residuals.
- 1 noticed bi-modality of the solution.
- **1 noticed a mass-eccentricity degeneracy.**

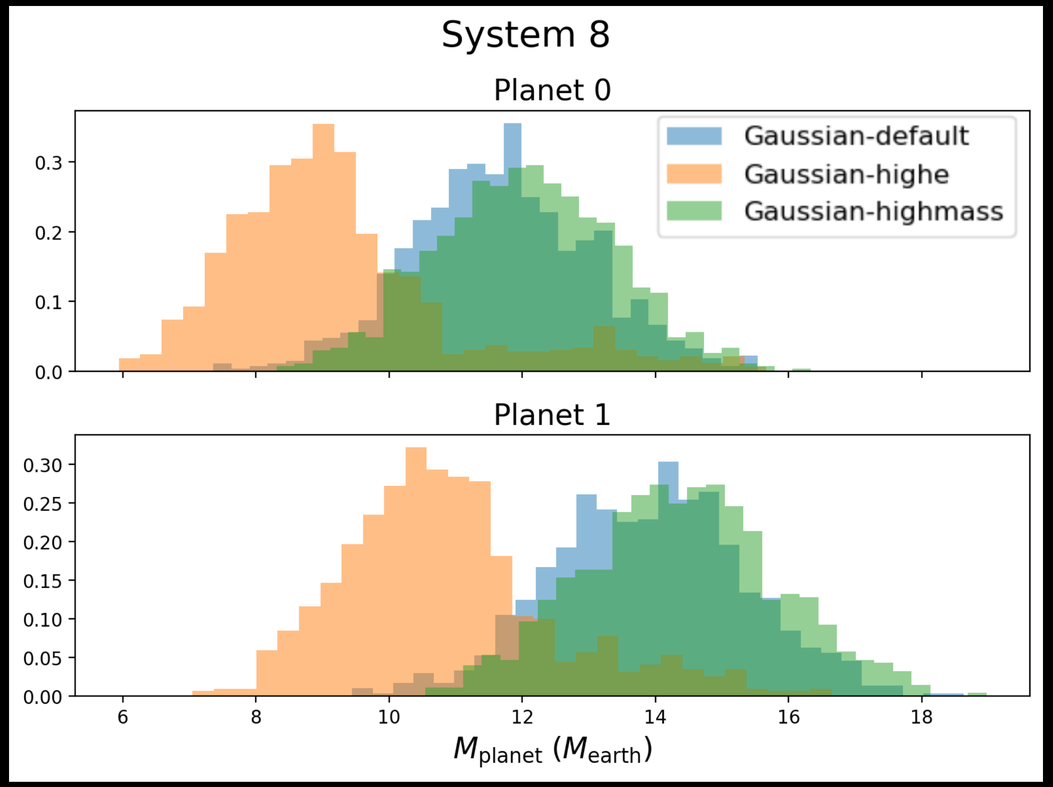
Set 8 - correlated residuals



plots by Kento Masuda

Prior test for mass-eccentricity degeneracy

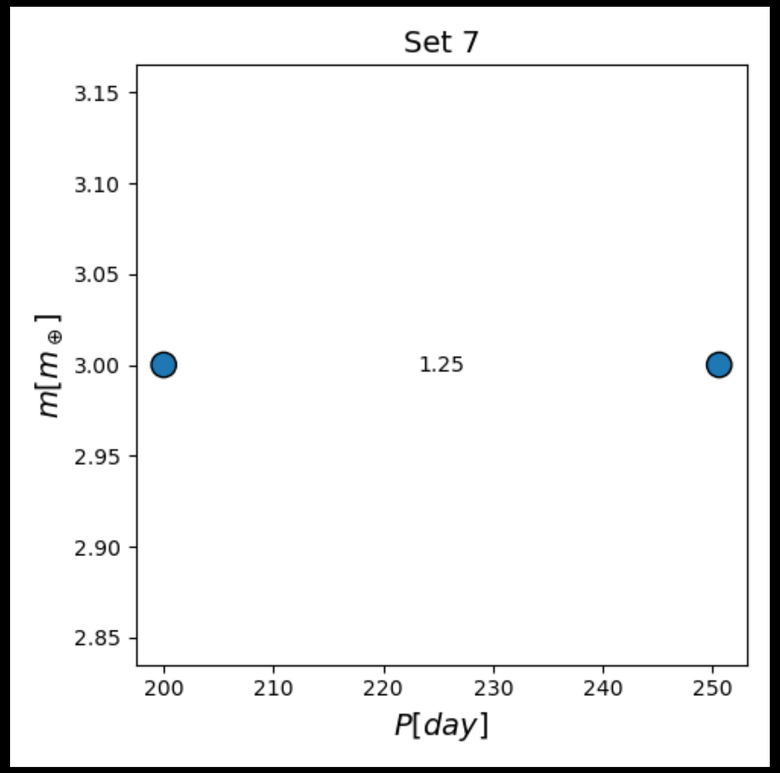


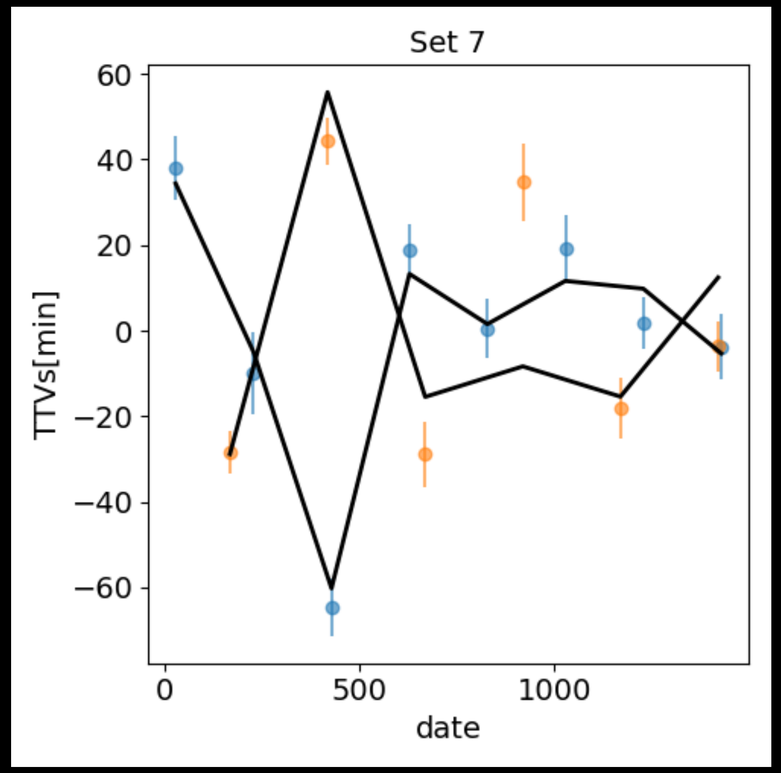


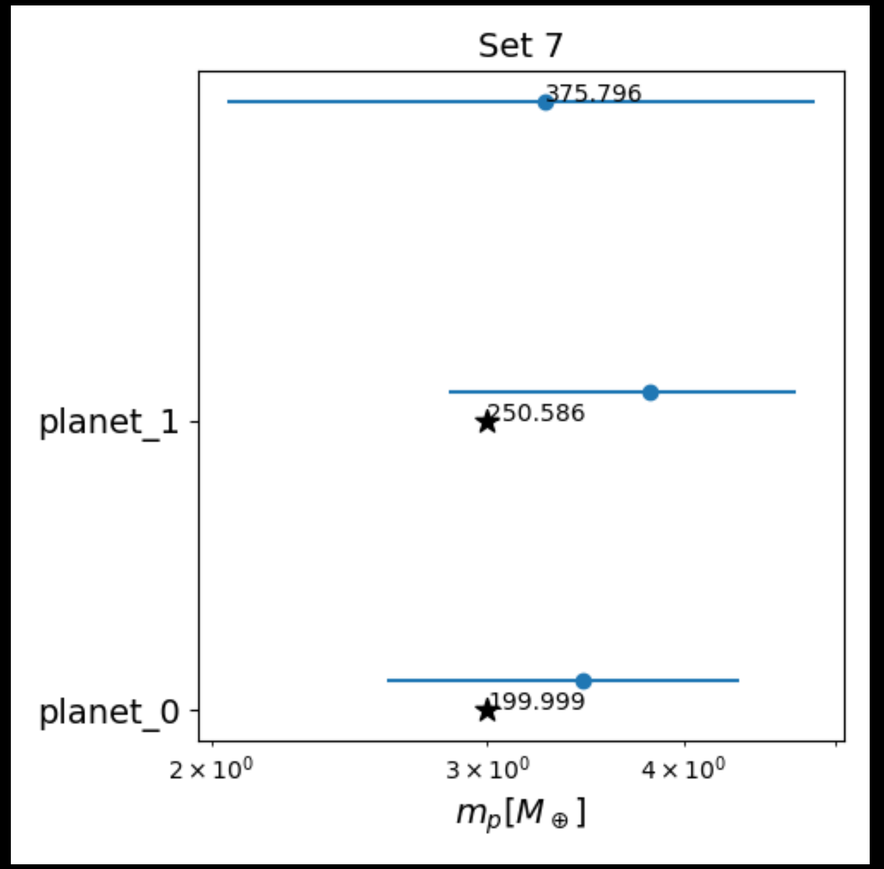
Analysis have different priors (uniform, log-uniform, beta distribution, etc.) for the masses and eccentricities

plots by Marylyn Rosenqvist

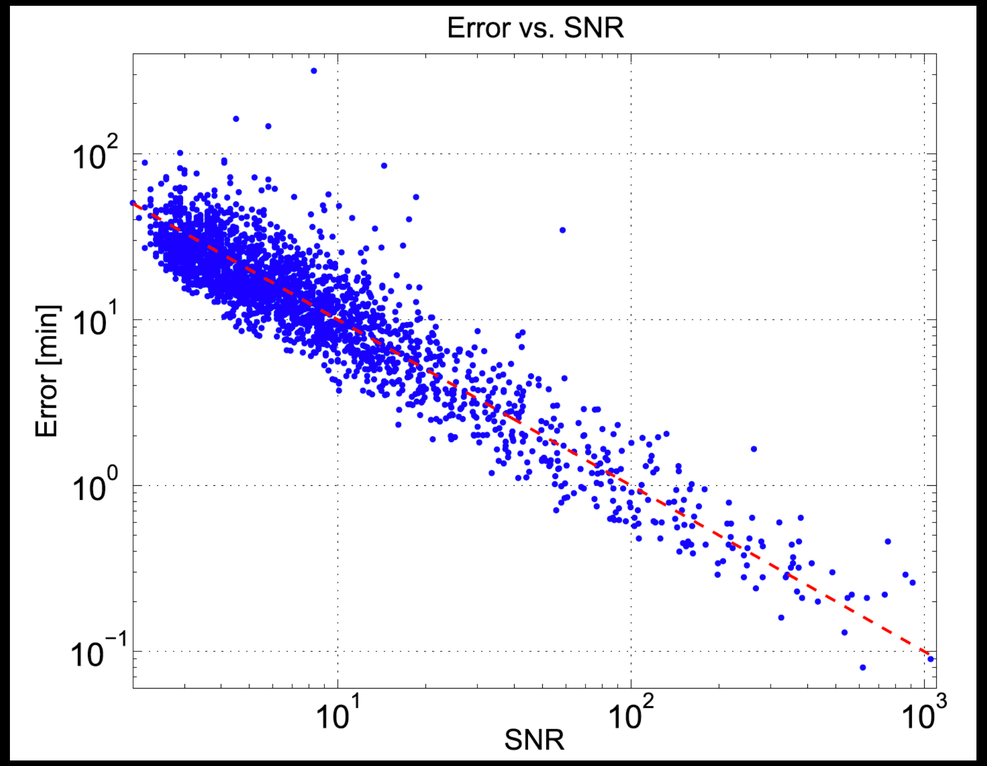
Set 7


Set 7
3.15
3.10
3.05
3.00
2.95
2.90
2.85
$m[m_\oplus]$
1.25
200
210
220
230
240
250
$P[day]$


Set 7
60
40
20
0
−20
−40
−60
TTVs[min]
0
500
1000
date


Set 7
375.796
250.586
199.999
planet_1
planet_0
2×10^0
3×10^0
4×10^0
$m_p[M_\oplus]$

Timing precision as function of SNR



Statistics for Kepler - Holczer et al (2016)

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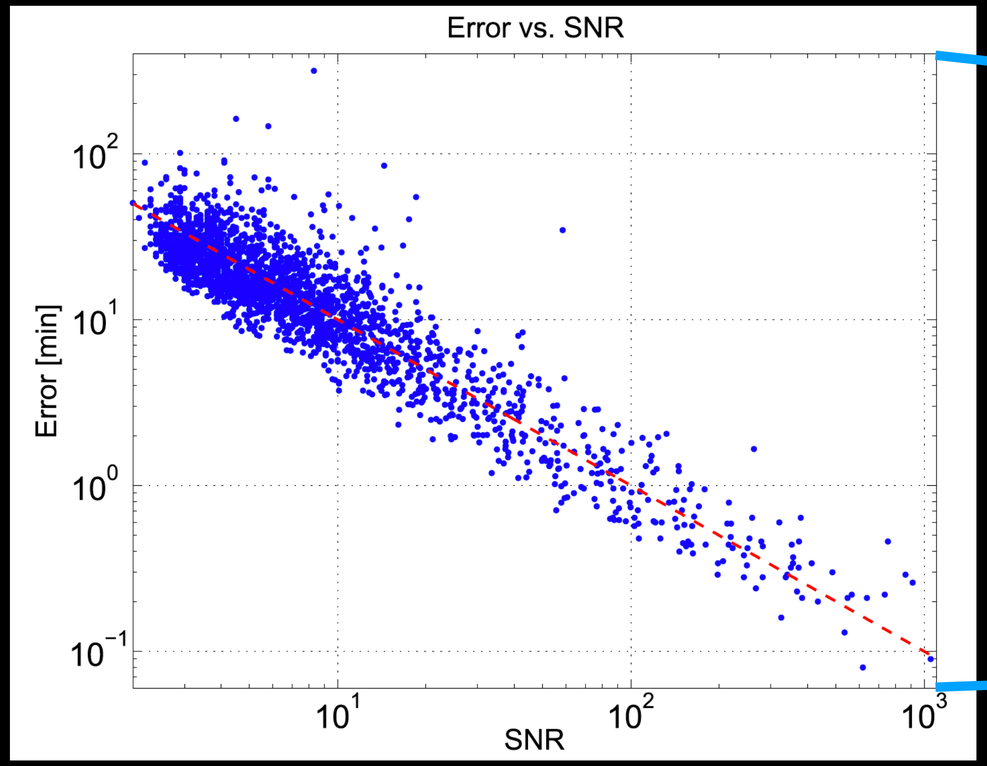

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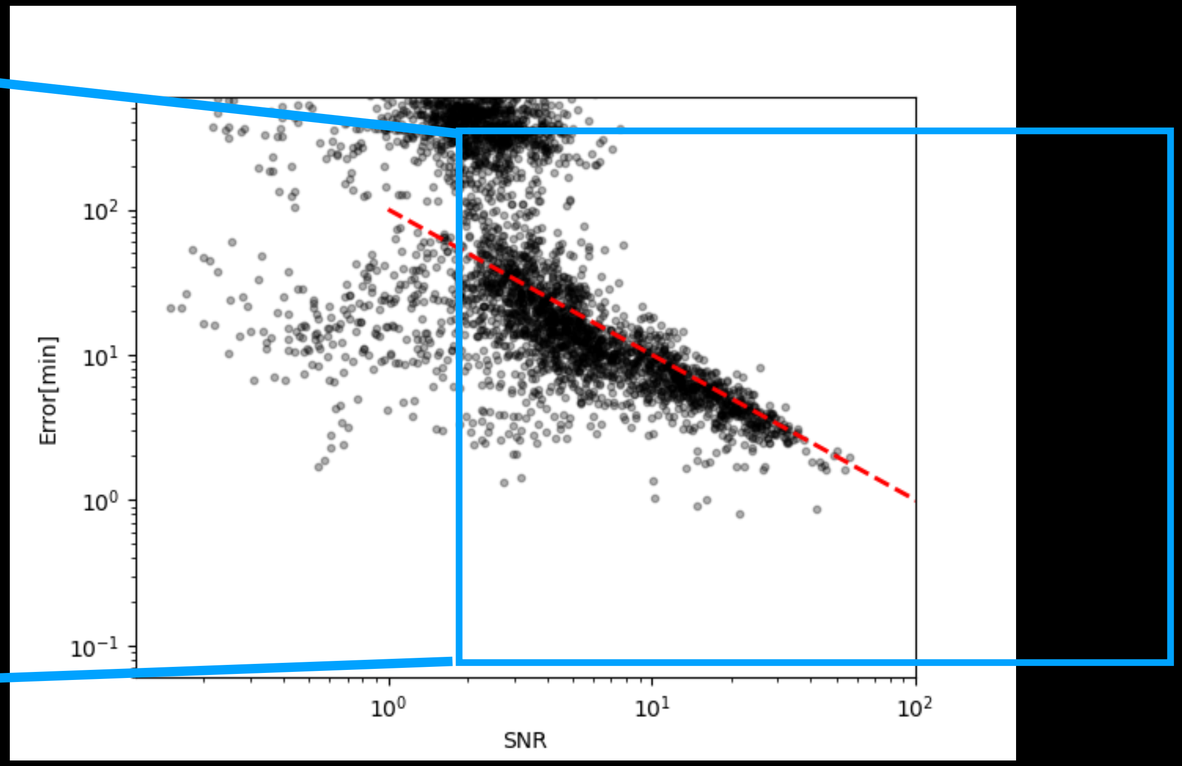
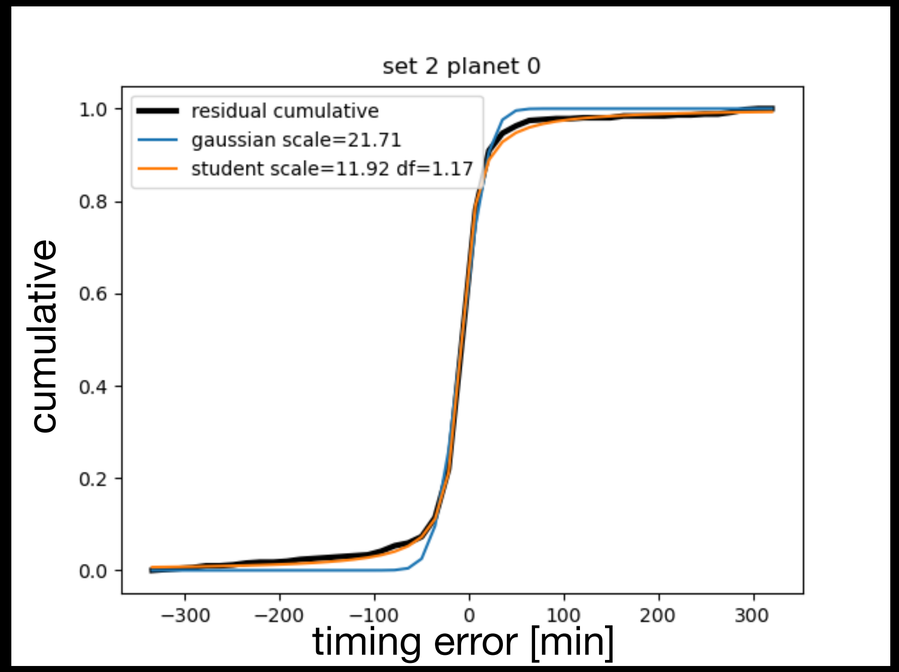
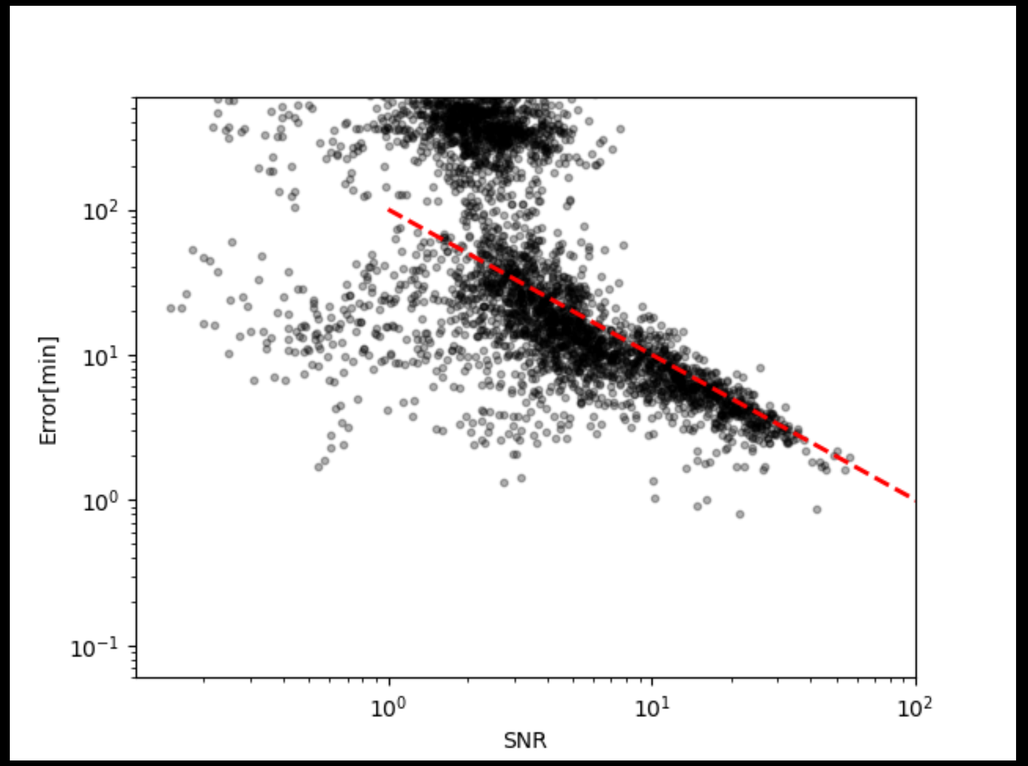


my attempt at reproducing the results :
- 200 Kepler lc tried
- 4 transit shapes tried (from the data challenge)

Timing precision as function of SNR





The distribution for a given planet in a given dataset can be found by injection-recovery.

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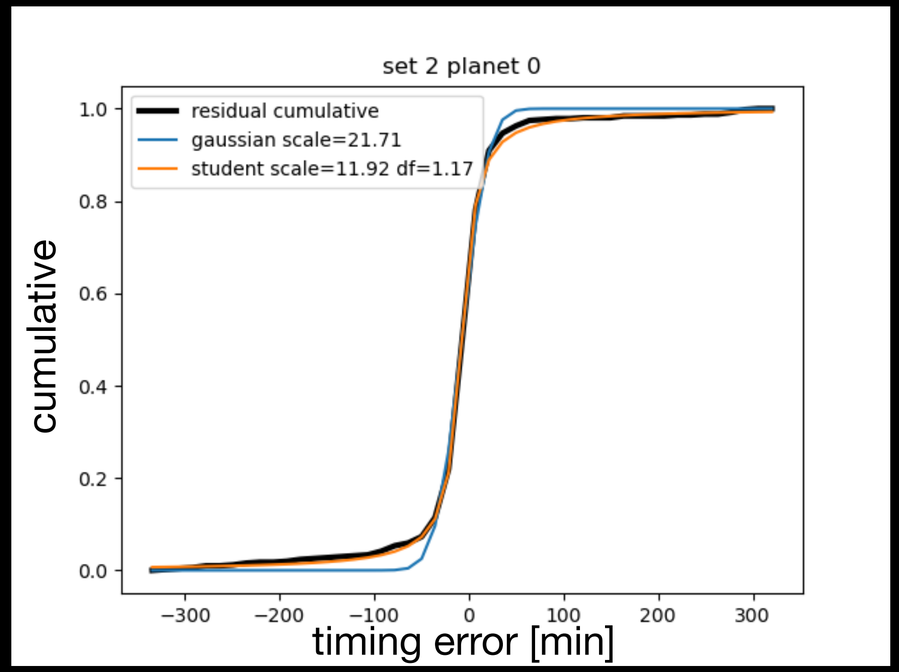

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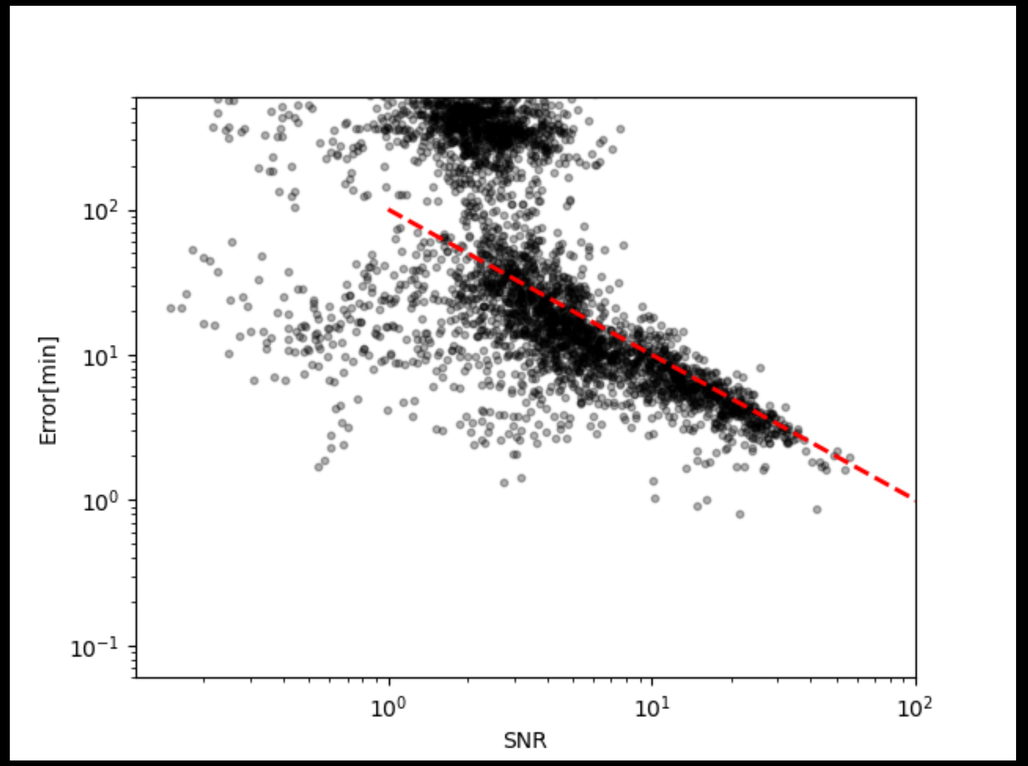

To measure the mass of an Earth in the habitable zone (inducing TTVs 4 ~ 10s of mins) we need to have am SNR of ~10 for its companion

→ For the P1 sample (< 34 ppm in 1 hour), the SNR of a single transit for an Earth-Sun analogue is 9

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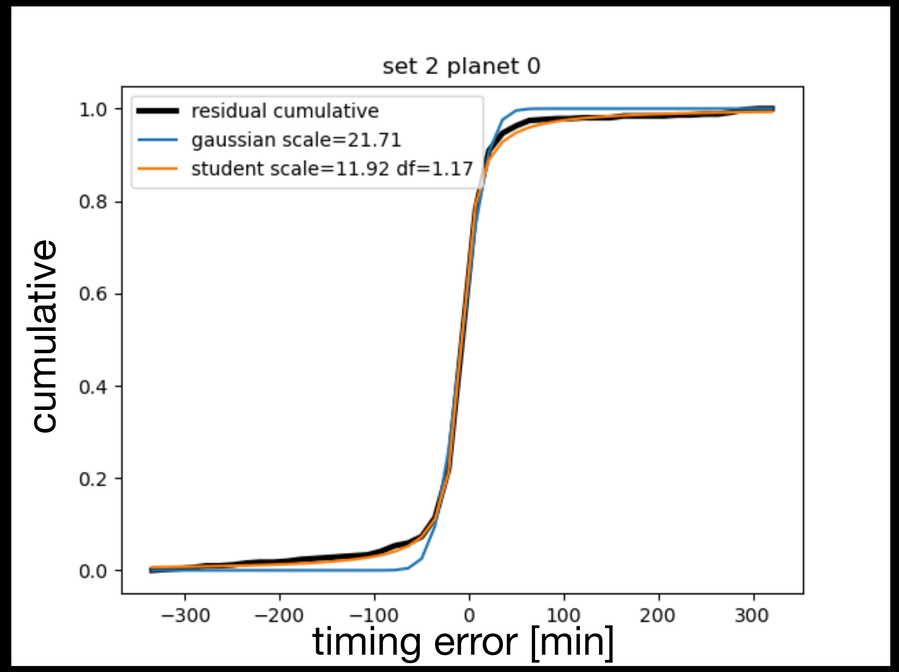

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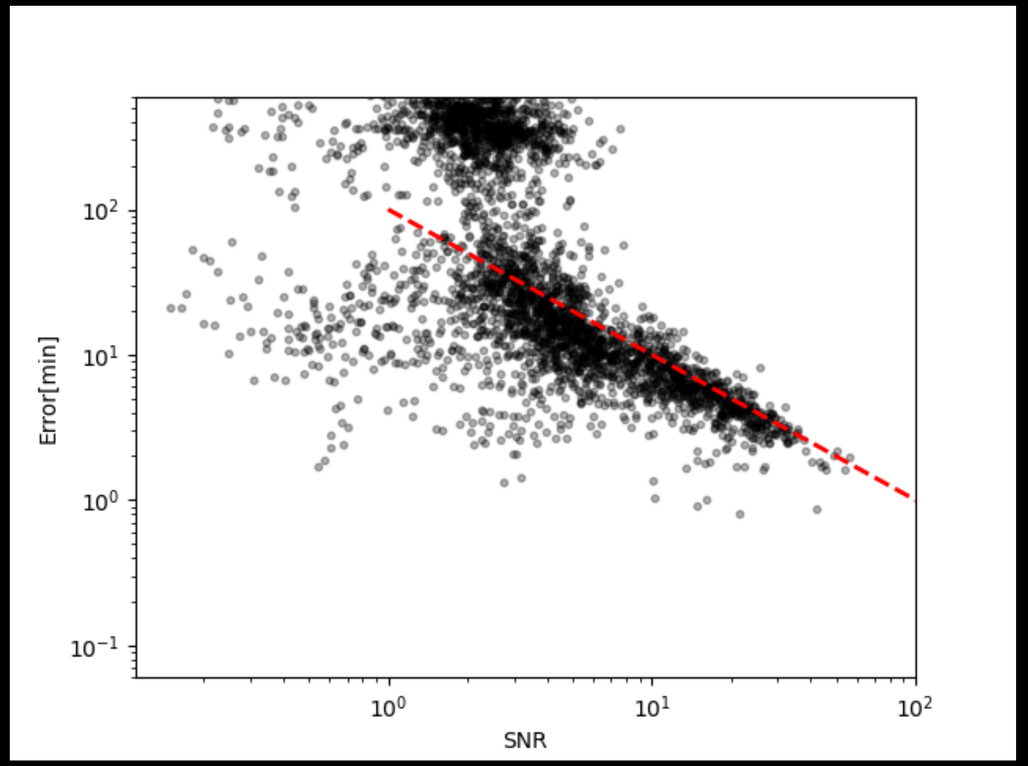

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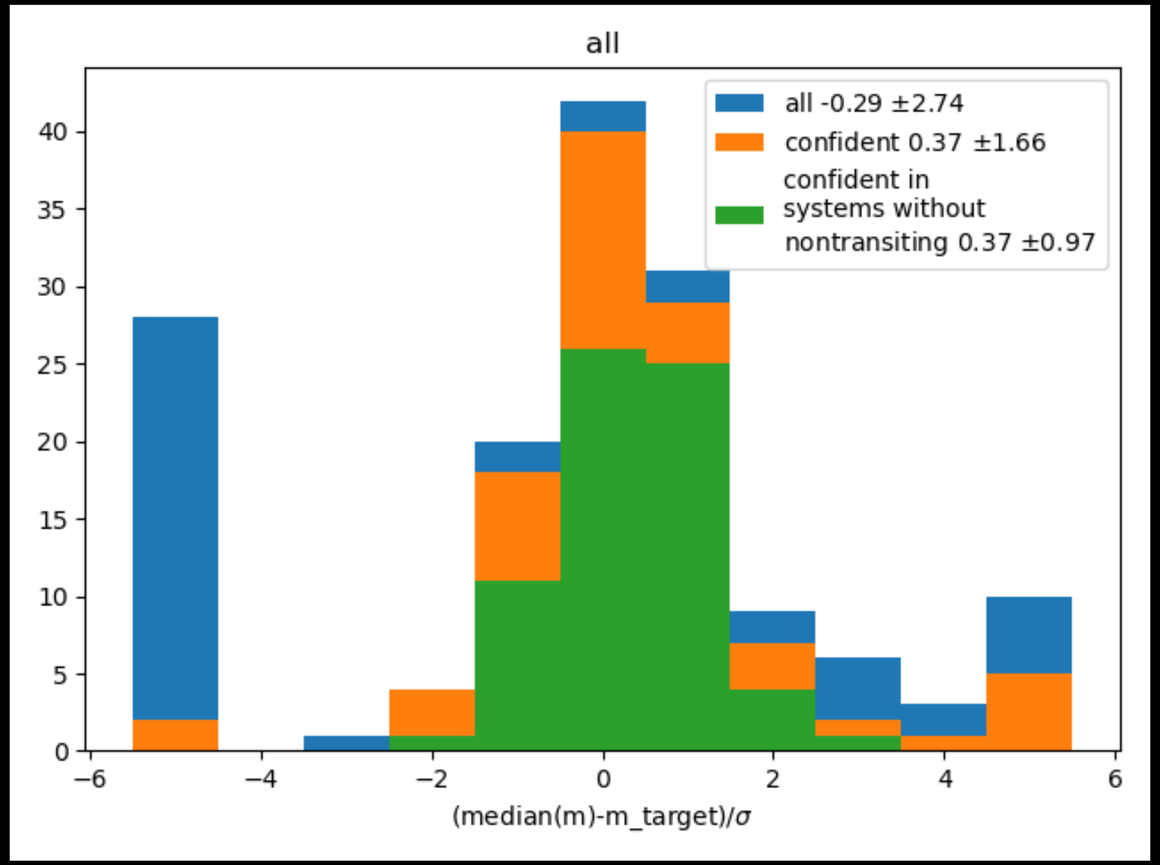
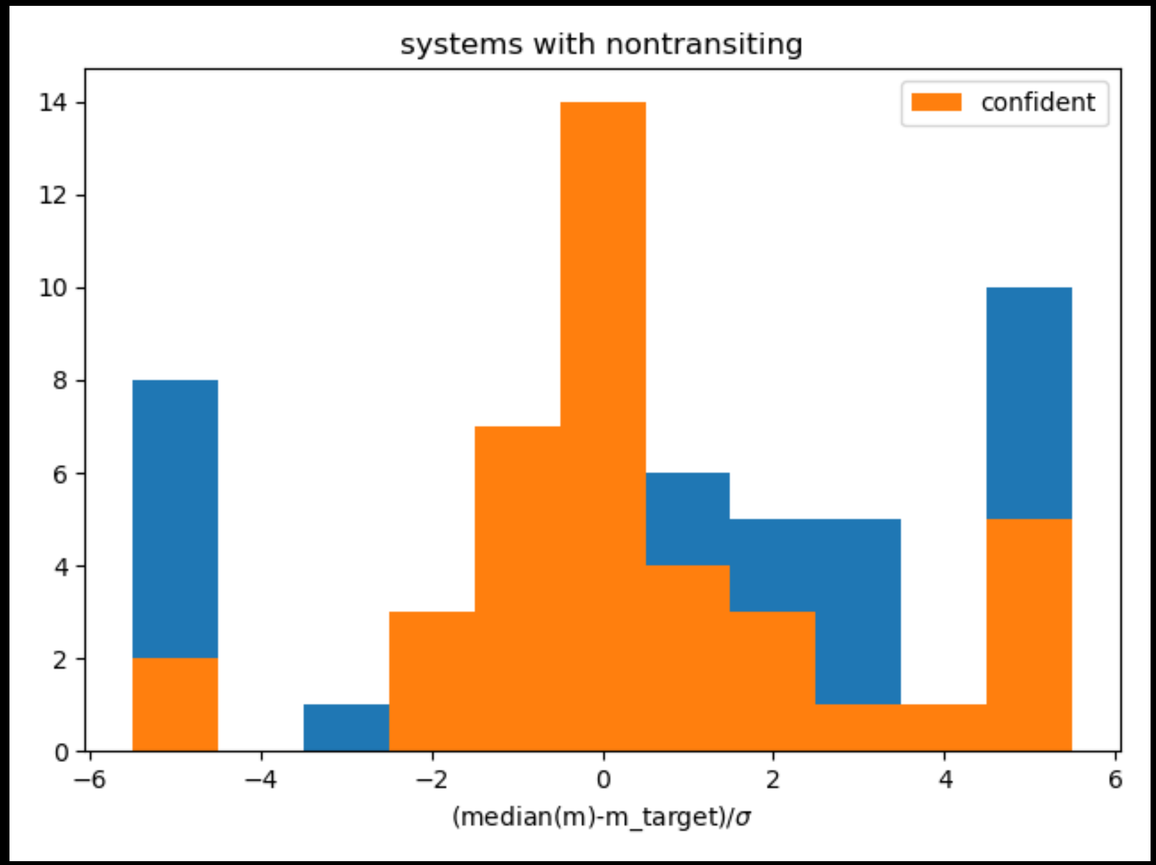
For geometrical reasons, the most probable case might be a non-transiting Earth Twin perturbing a transiting planet.

Meta-analysis of the results

Mass distributions





154 planets analysed
Significant outliers due to mass-eccentricity degeneracy and non-transiting planets.
In absence of non-transiting planets, existing tests allow to recover a gaussian-like distribution

Robustness criteria

reasons why an analysis was not deemed robust

	Mass-eccentricity degeneracy prior test	Residuals	Mass-radius
underlying: without nontransiting	6	2	1
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1 planet wrongly added

6 (out of 15) analysis didn't notice planet(s) were missing

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Systems with non transiting planet:

- **4 were found robust to the mass-eccentricity prior test** while a planet was missing.
- **1 was found not robust to the mass-eccentricity prior test** while a planet was missing.
- 2 analysis added planet to systems with non transiting planet:

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- **1 was found not robust to the mass-eccentricity prior test** while a planet was missing.

- 2 analysis added planet to systems with non transiting planet:
    - 1 was added to the wrong side and biased the masses recovered.
    - 1 was added to the correct side (but wrong MMR) and yield good mass estimates.

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Future exploration by the MAPS working group in order to prepare recommendations for PlanetPipe

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- **Checking for additional planets** (Rosenqvist et al 2025, in prep)**:**
  - **Residuals analysis:**
    - Is the TTV residual distribution the same as the injection-retrieval one ?
    - Are the residuals correlated ? (FAP, etc.), at the level of the lightcurve?
  - **Injection of additional planets :** what is the minimum number of test necessary?

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- There is **currently no well-established method to robustly identify a non-transiting perturber**. Potential solutions : residuals analysis, testing several models.
- **In absence of non-transiting planets, the population that the participants were confident in was unbiased.**

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Conclusions

All the details in Leleu et al (2025), in prep

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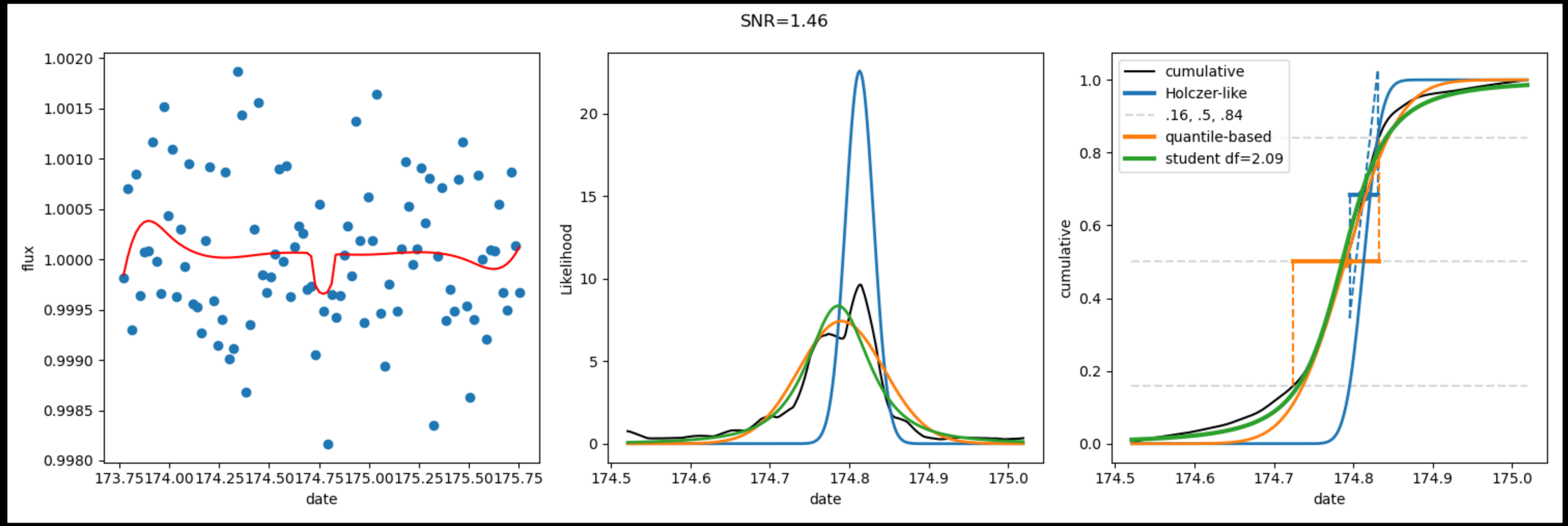
- To explore further :
  - **TTV+RV synergies**

timing extraction method

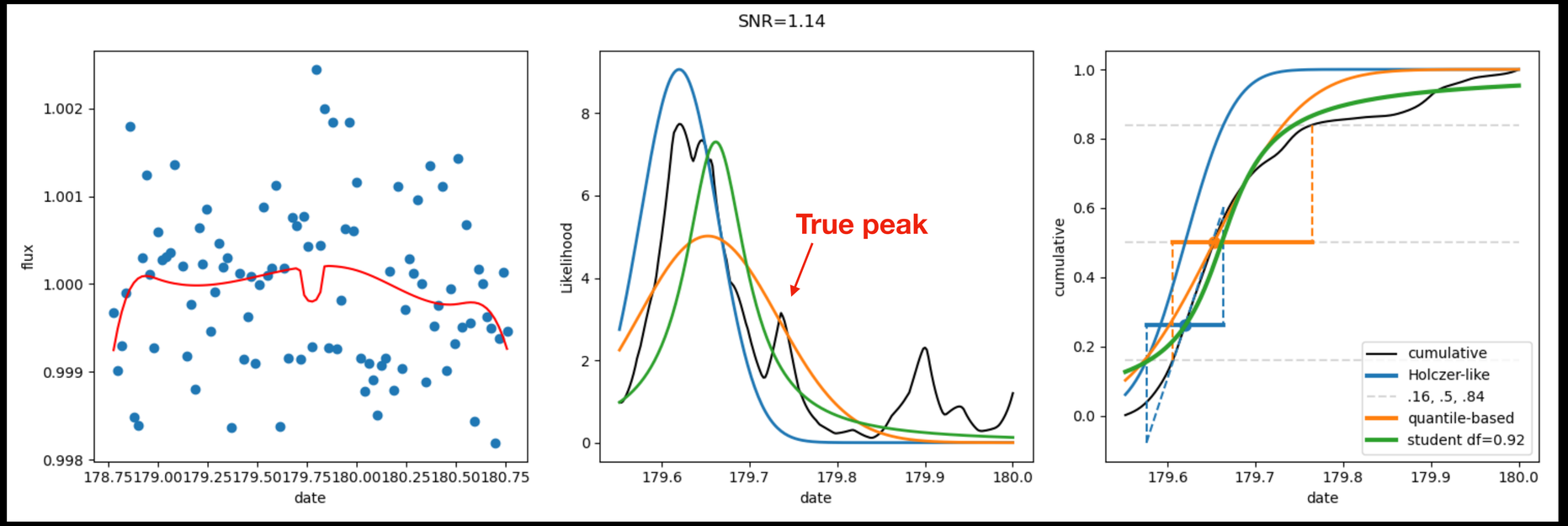
Holczer et al (2016) : find maximum Likelihood,
then compute the local slope around it to estimate the error

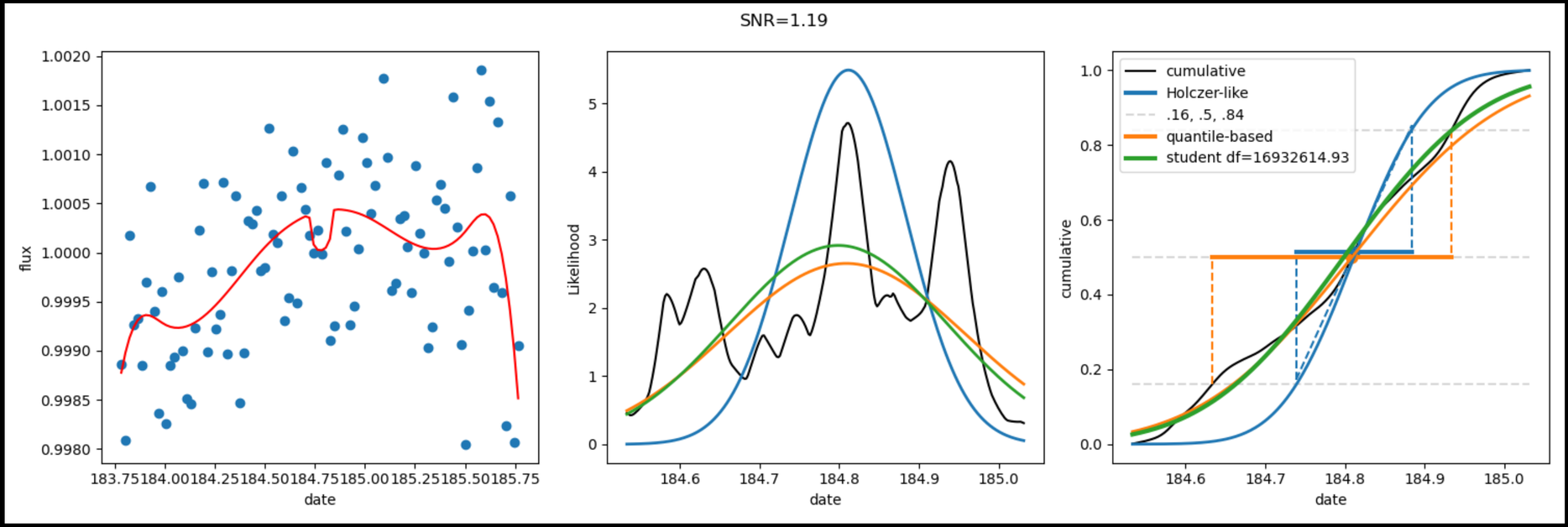


quantile-based : find the median and the .16
the .84 quantile

fit a student distribution

Other examples





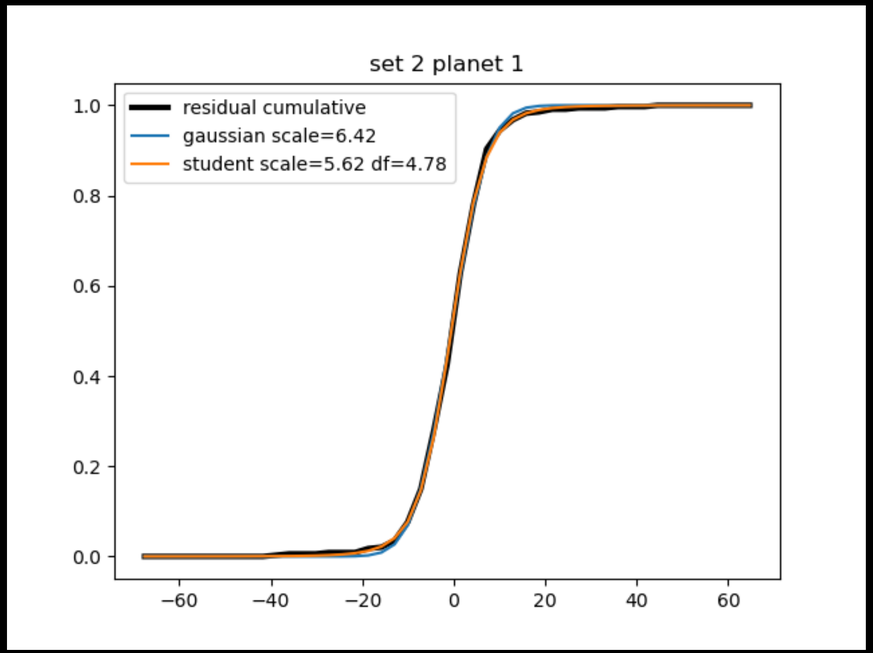
For low snr, the likelihood near each transit is multi-modal and the derived parameters depend on the size of the search window.

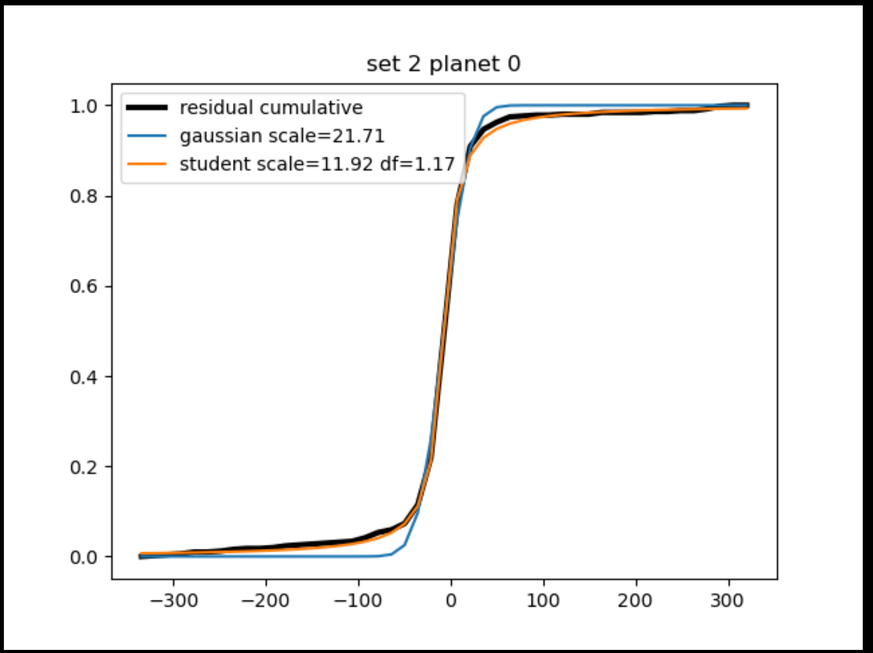
The likelihood gain due to having the transit at the correct place is not necessarily higher than using the transit to absorb noise.

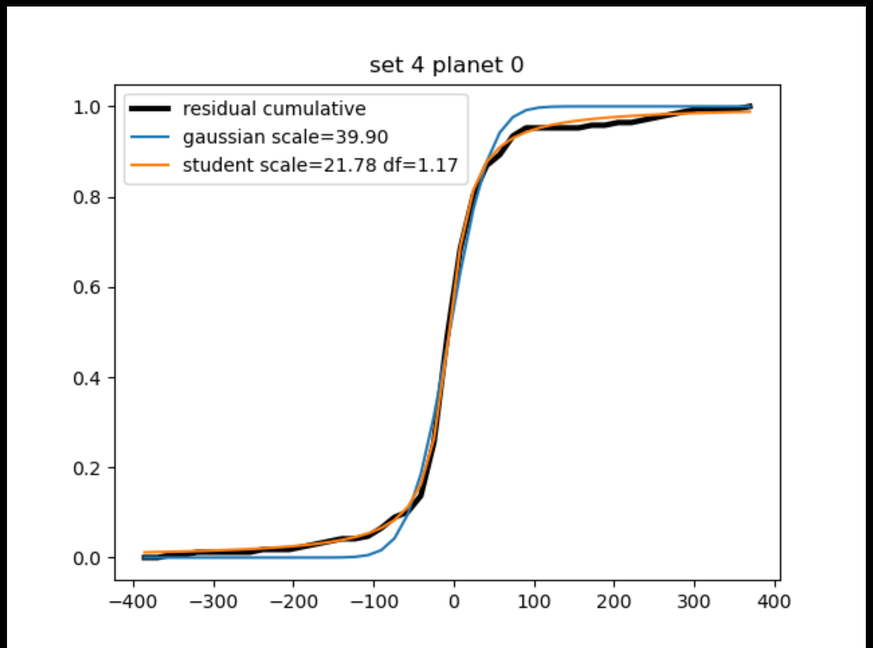
data challenge : TTV extraction vs injected solution

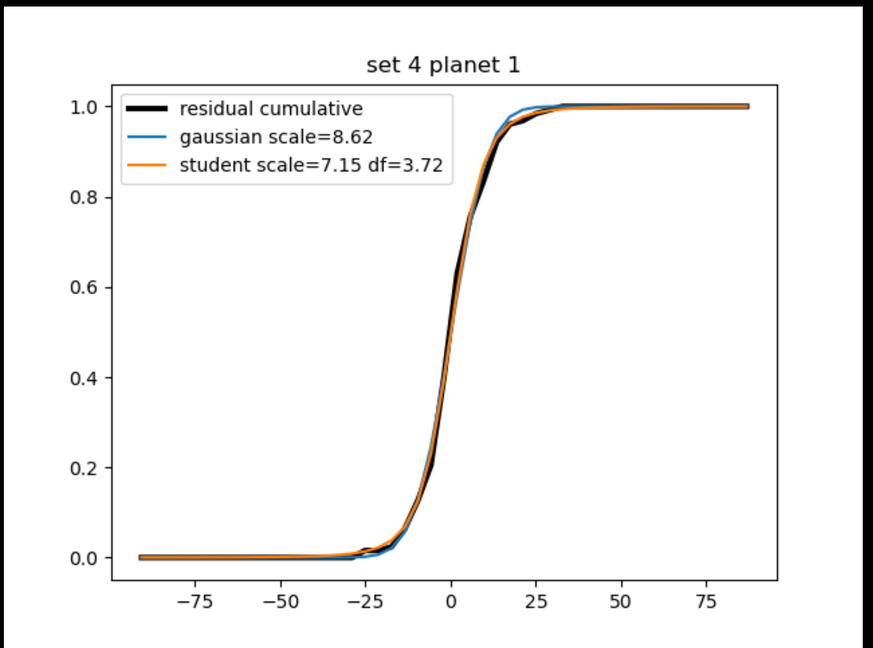
When re-extracting the individual timings from the photo-dynamical challenge cases, the residuals are well approximated by a student law.
(See also Agol et al 2021).

Two way possible: let the dof parameter free as in Agol et al (2021), **but with one value of scale parameter and dof per planet**, or derive a law for the dof as function of the SNR.





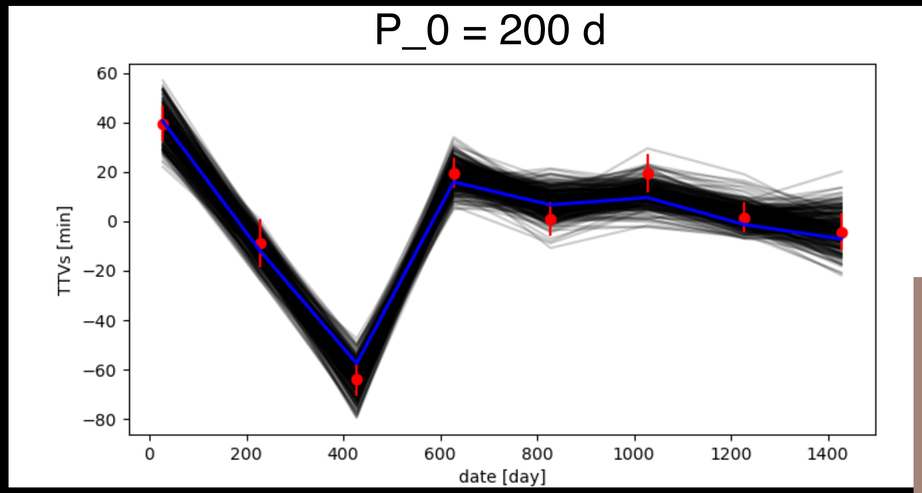


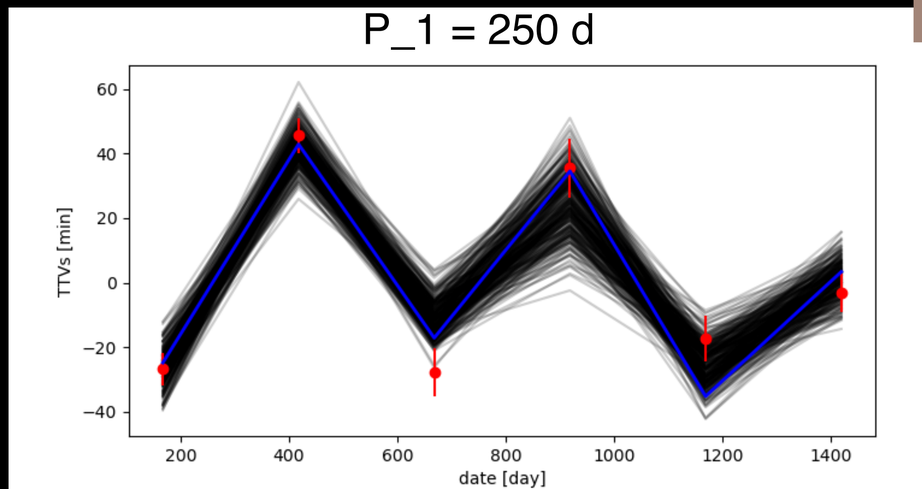


Adrien Leleu

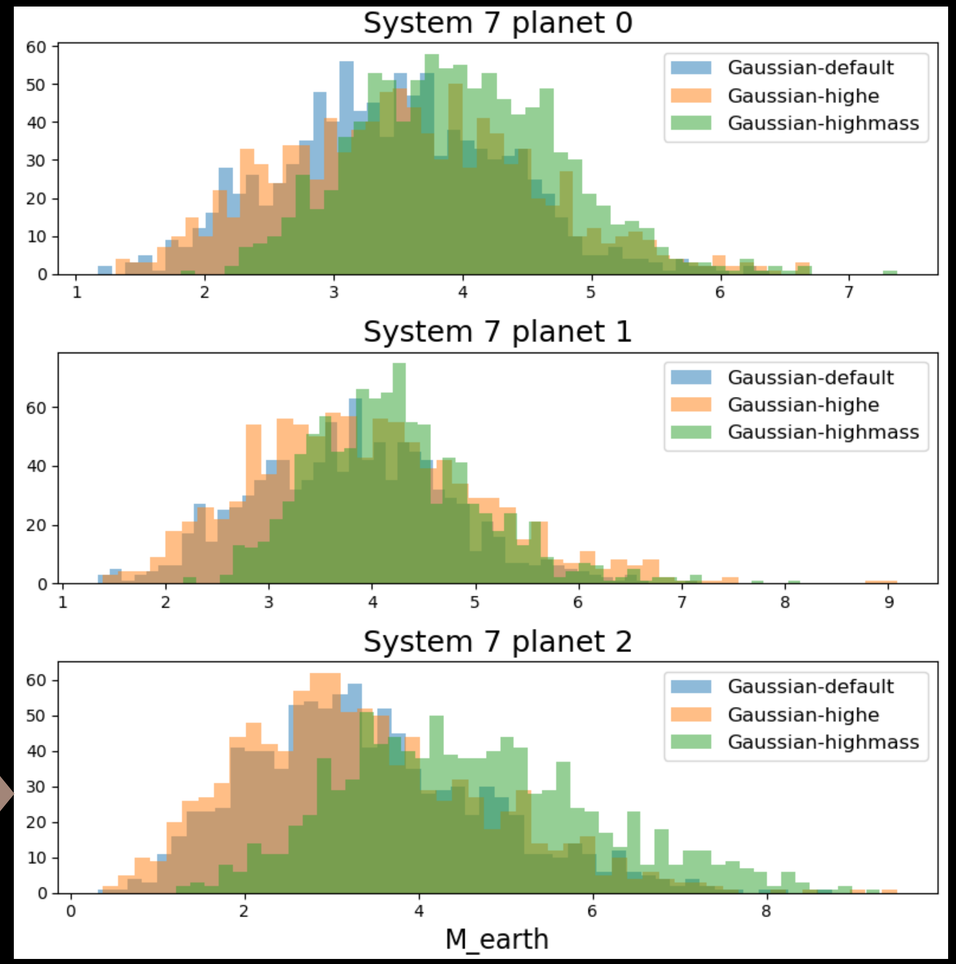
System 7

- 2-planet model did not fit all points in TTV curve
- Model: outer planet in **3:2 resonance** (P_3 = 375 d)
- TTVs fitted with **Gaussian** errors



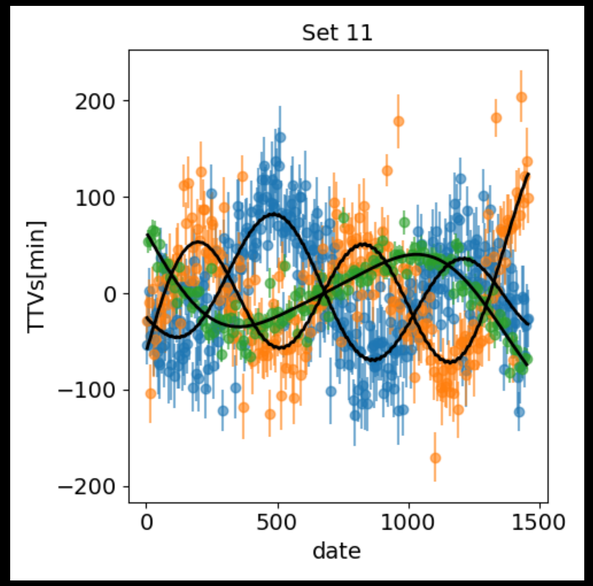


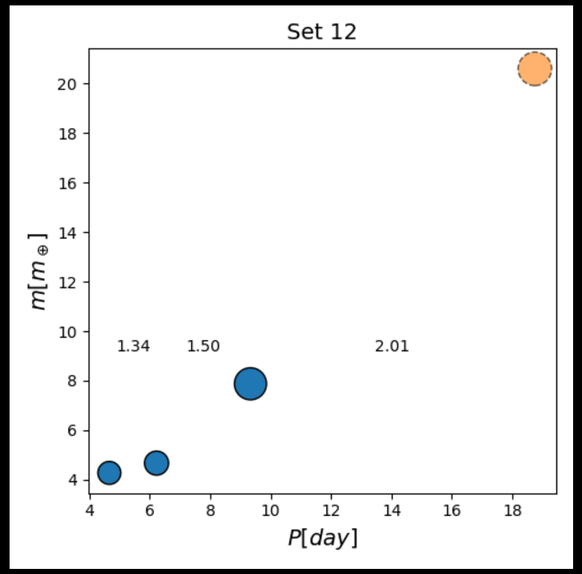
Chose 3-planet model that converged + most robust (+physically sound) masses

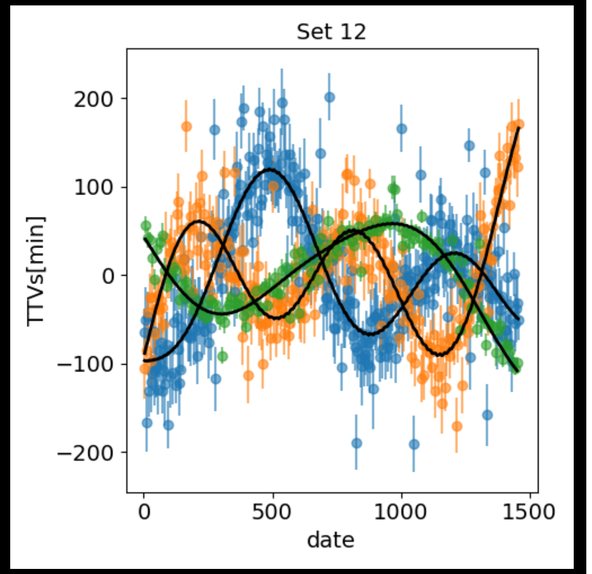


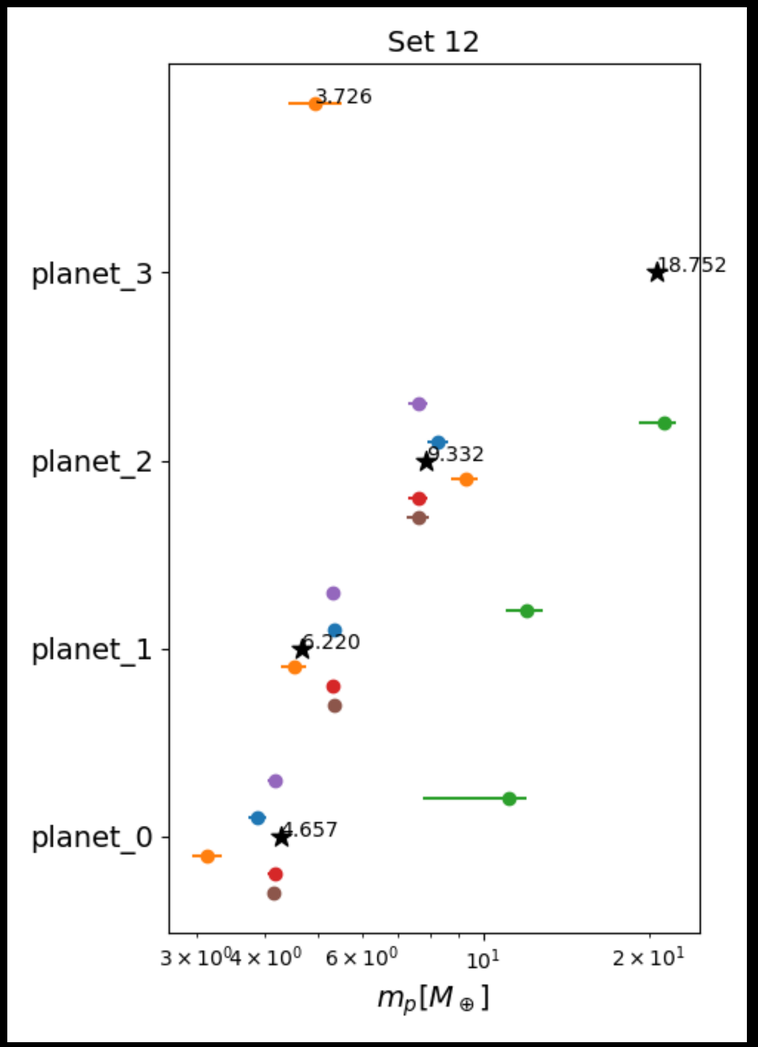
slide by Marylyn Rosenqvist

Sets 12







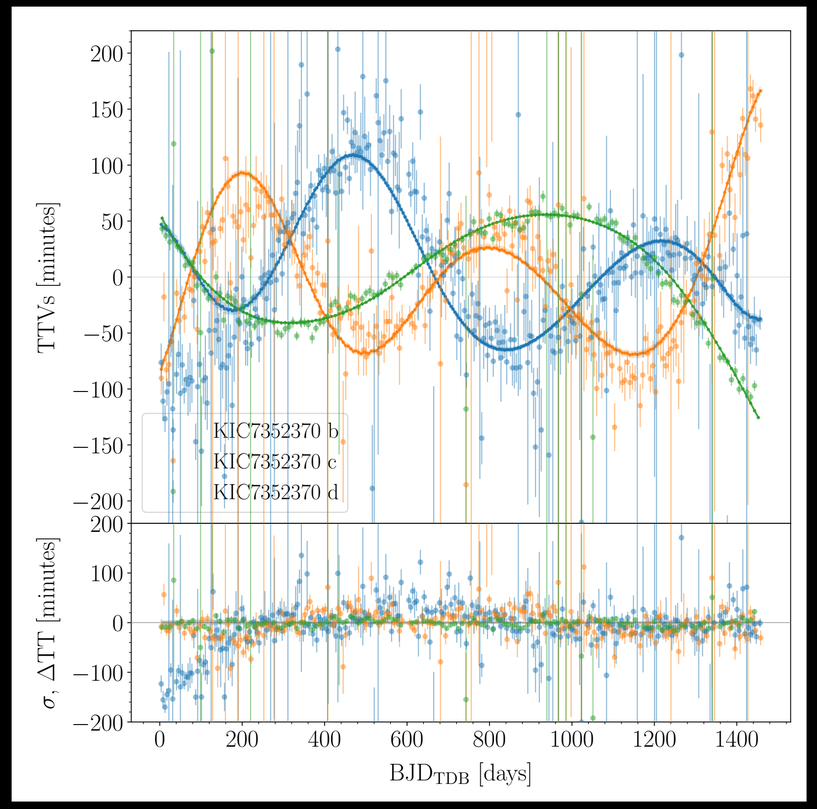


Same inner three planets, but set 12 has a 4th outer planet **continuing a resonant chain** based on the NGPPS 76 - 28 simulation

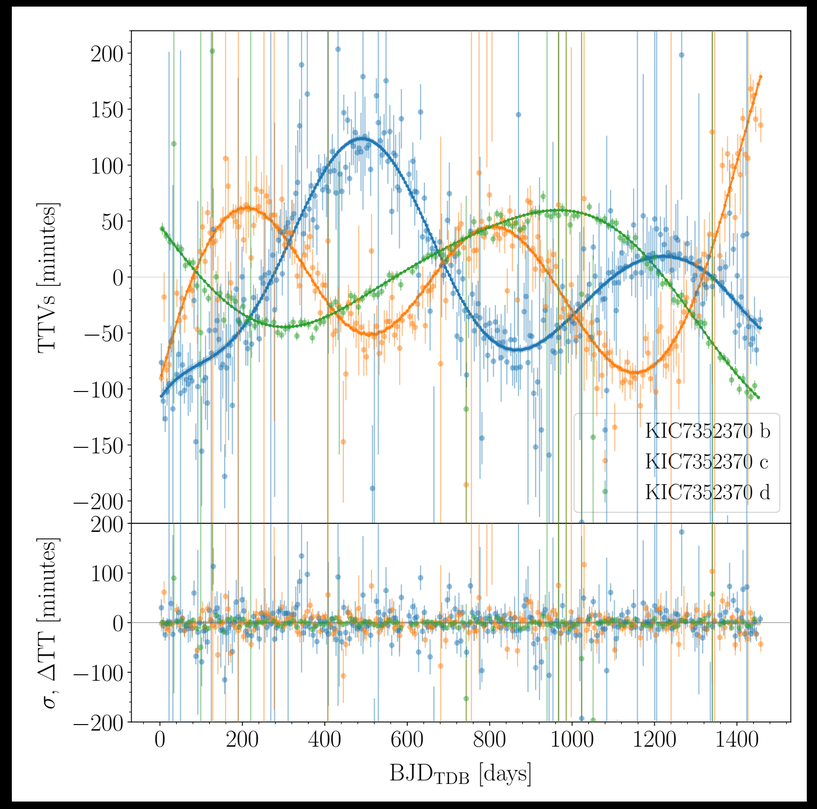
-3 participants out of 4 considered a 4-planet model for set 12 based on residuals
-one solution was submitted adding a planet on the inside, biasing the retrieved masses

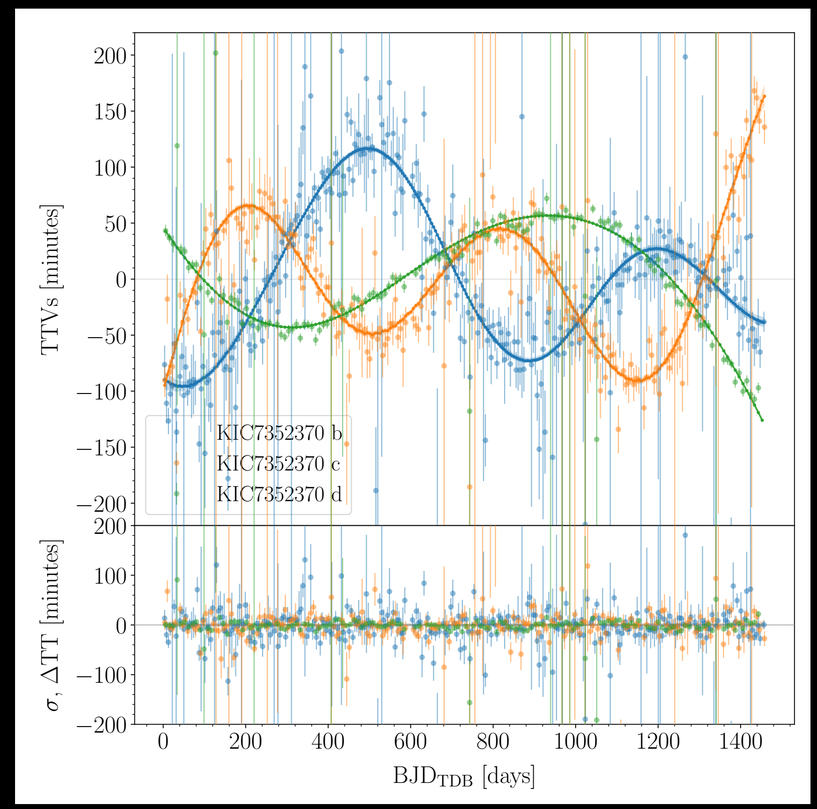
Set 12 - adding a planet inside

3 planets model



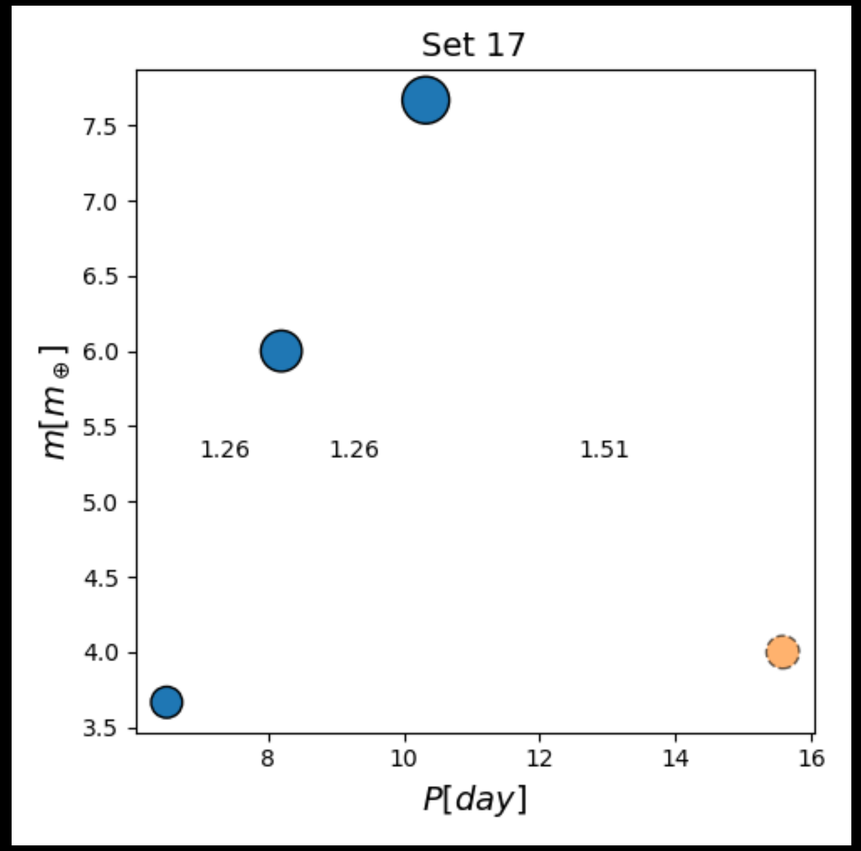
4 planets models

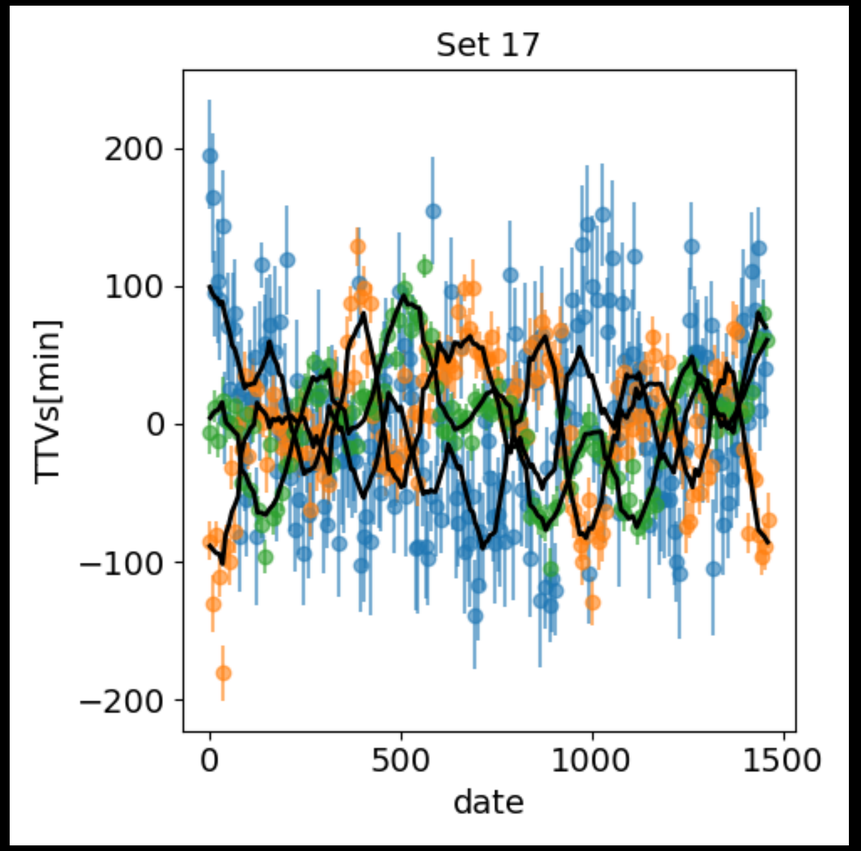


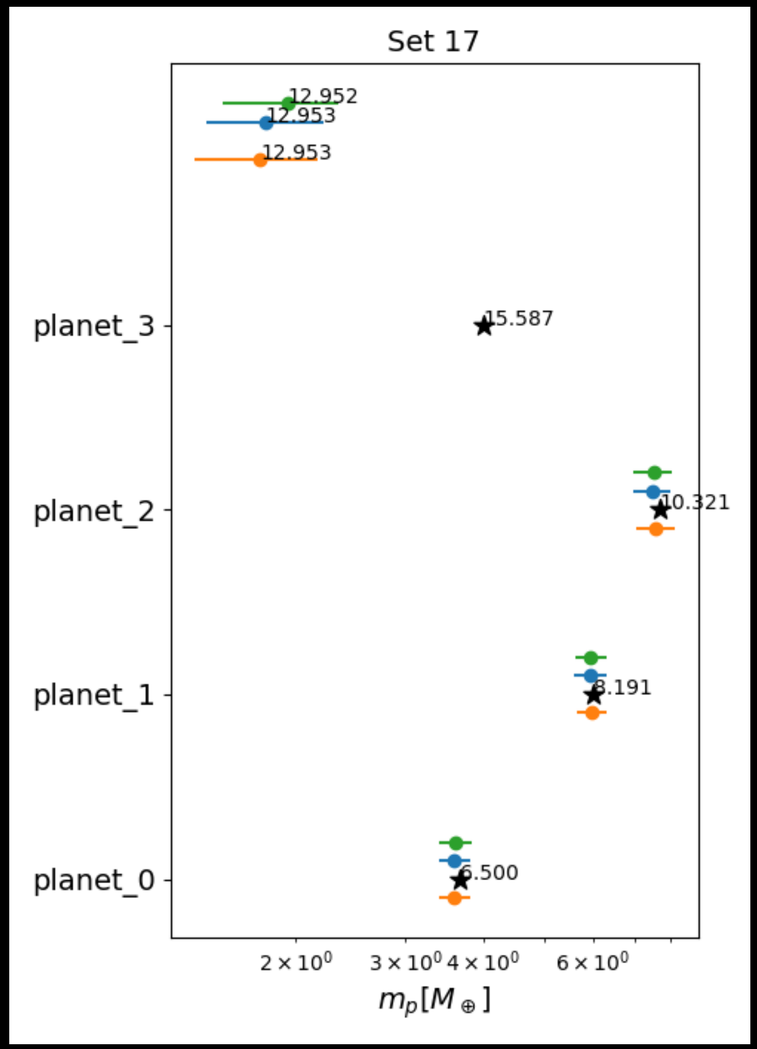


plots by José Almenara

Set 17







A 3-planet model is not able to achieve this, even when started at the correct solution.

solution by Marylyn Rosenqvist

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The distribution for a given planet in a given dataset can be found by injection-recovery.