How many radial velocity observations are required to mass-characterise exoplanets?

Introducing Ravest, a new package to answer this question

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Abstract

Mass characterisation of exoplanets from radial velocity (RV) measurements is difficult due to the small RV signal compared to the instrumental precision and stellar activity.

We introduce **Ravest**, a new Python package that can simulate and fit realistic RV data.

Ravest can estimate **how many observations are required** to reach a target precision or estimate **what precision can be achieved** for a fixed observing schedule.

Fitting models to data

Planet model
Number of planets, parameterisation

↓

Noise model
White noise or **Gaussian Process**

↓

Priors
Normal or **Uniform**

↓

Maximum a Posteriori fitting
Find initial parameters

↓

Markov Chain Monte Carlo
Uncertainty estimation

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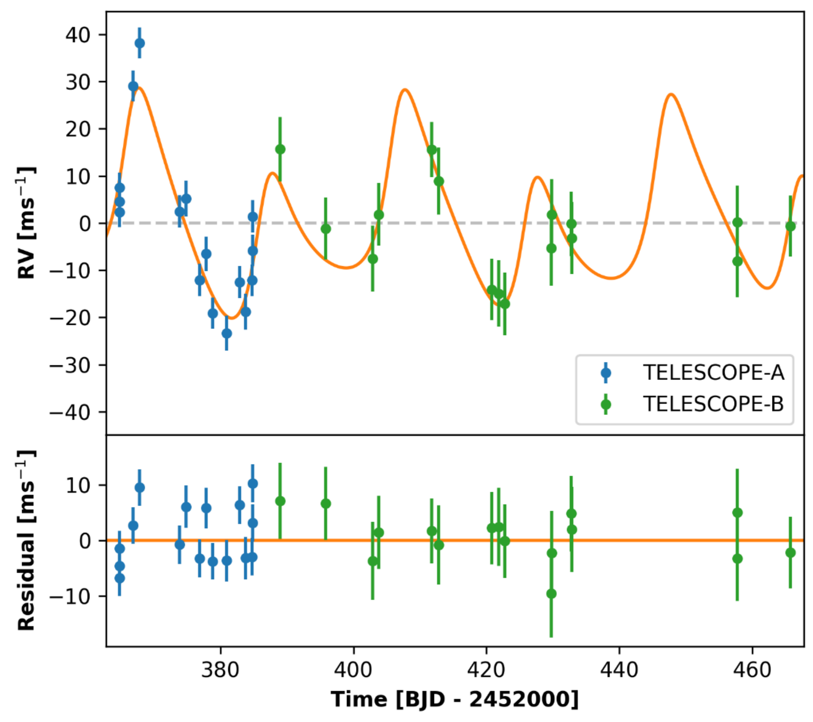
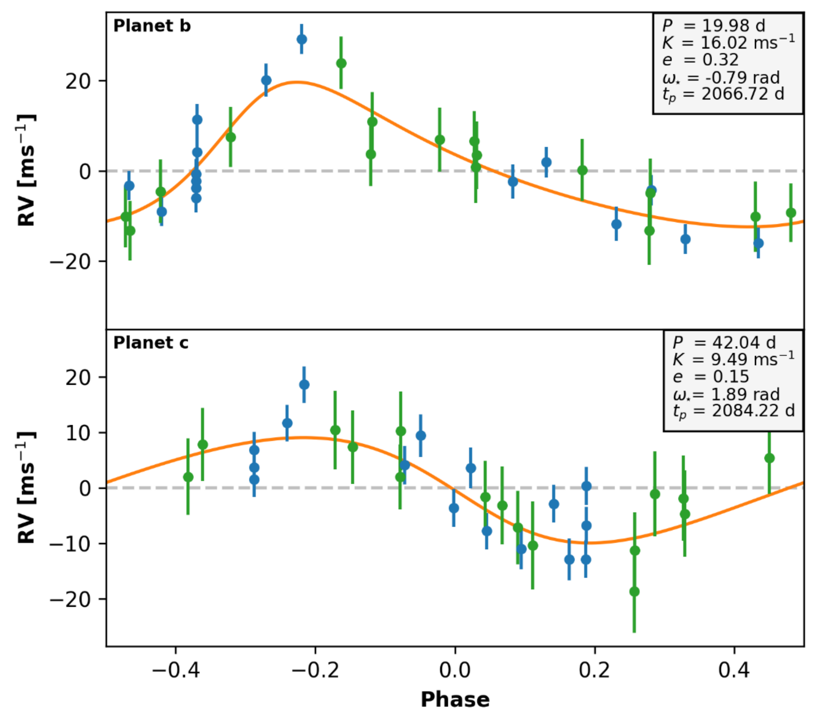
Bayesian model comparison
Learned harmonic mean estimator





Simulating RV data

Upload observing schedule
or
Generate random or evenly-spaced times

↓

Specify planet parameters for Keplerian model

Observed RV Parameters K, P, e, ω_*, t_p or **Physical Parameters** $M_*, M_p, i, P, e, \omega_*, t_p$

↓

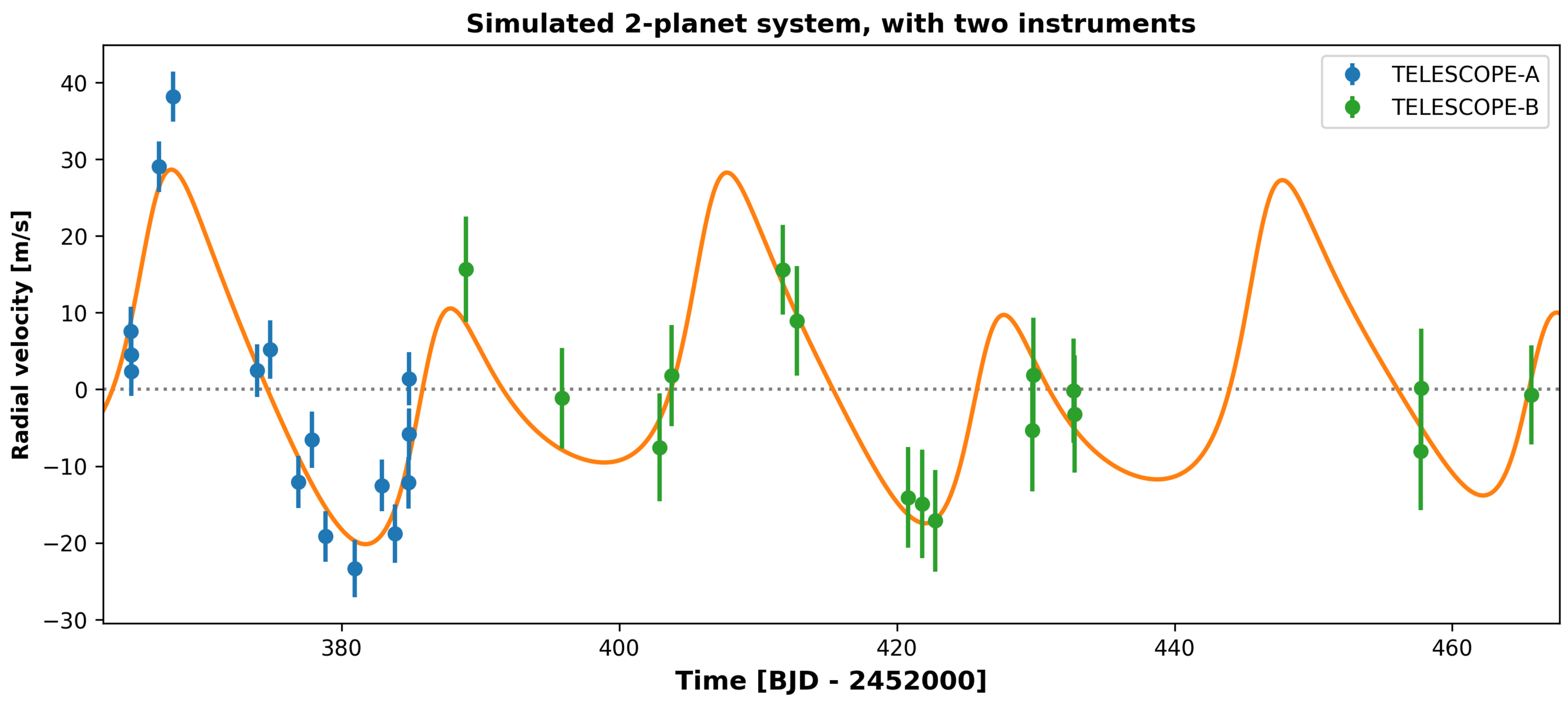
Add noise

White noise $\sim N(0, \sigma_w^2)$

Trend $\gamma + \dot{\gamma}(t) + \ddot{\gamma}(t)^2$

Correlated noise $A \sin(Bt + C)$

Multiple instruments can be simulated, each with different noise models



Model comparison

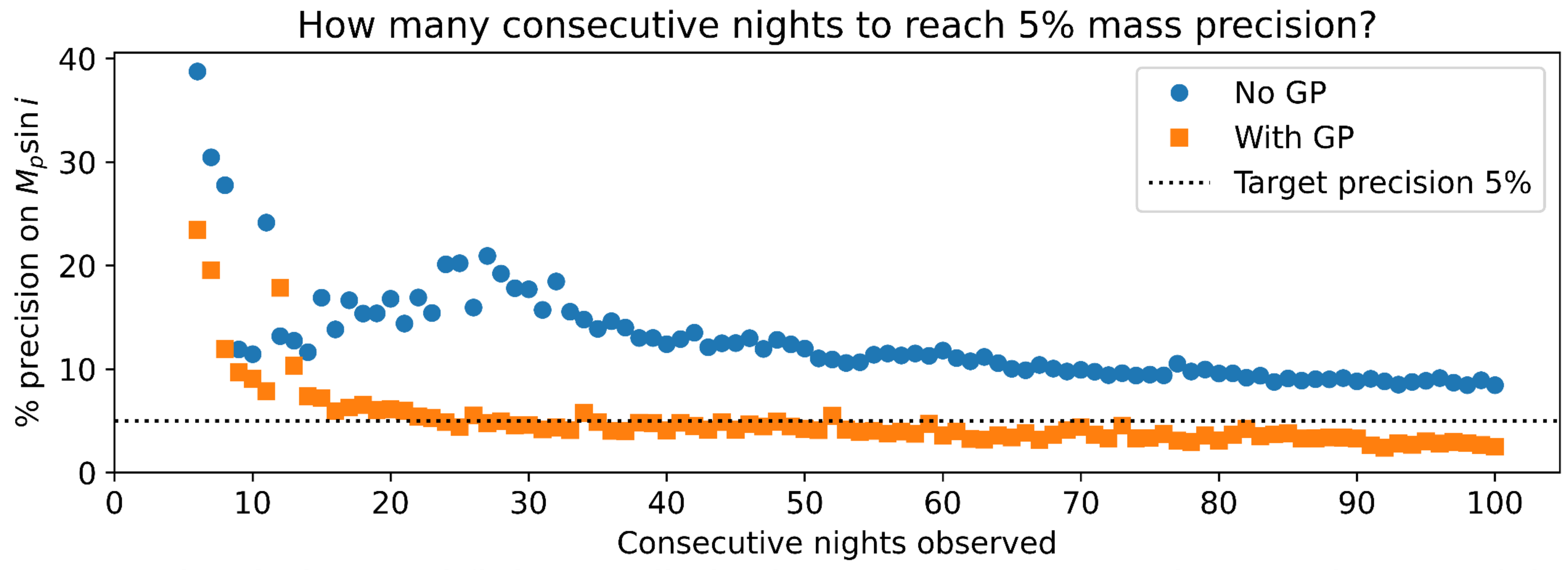
- We need to be able to compare RV models (e.g. eccentric vs circular orbits, or choice of Gaussian Process kernel function) in the light of data by evaluating the Bayes factor. However, this requires the Bayesian evidence, which is very challenging to compute.
- We implement the **learned harmonic mean estimator** [1] available in the harmonic python package. Normalising flows [2] are used to train an importance sampling target density on the MCMC posterior samples, which allows estimation of the Bayesian evidence and its variance.
- Comparing and selecting the most appropriate model ensures more reliable estimates of the true planetary mass.

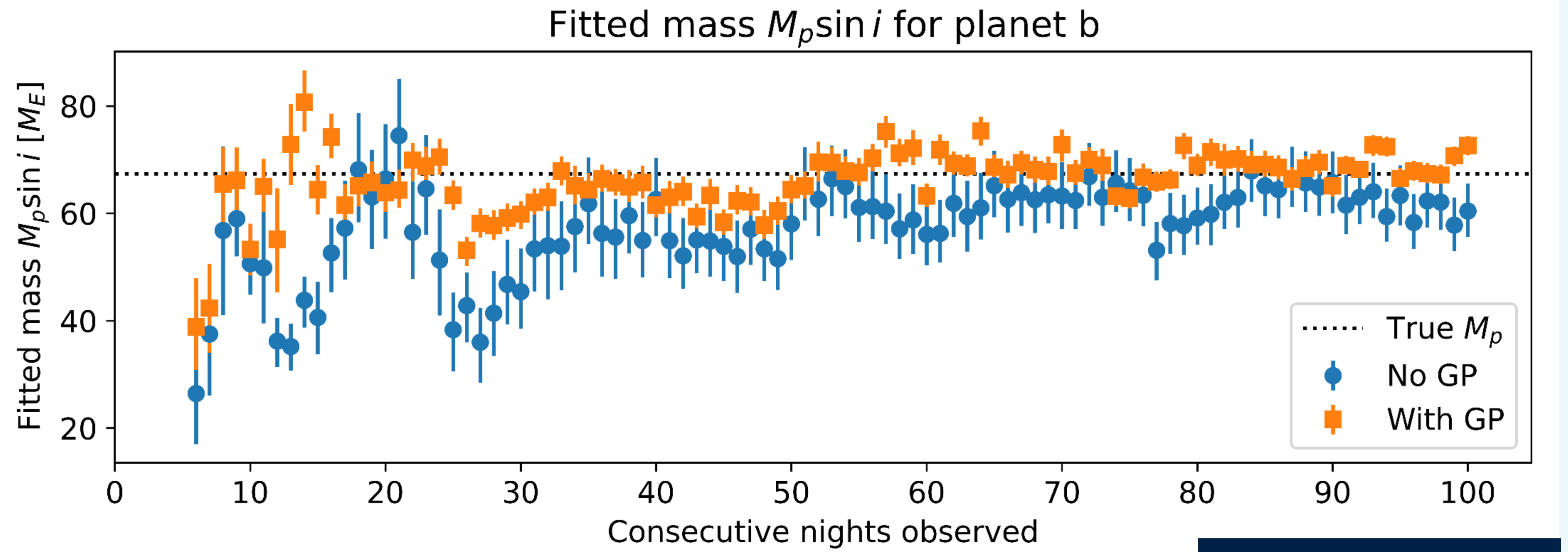
HARMONIC

astro-informatic / harmonic

Precision estimation

Mass precision prediction: Planetary parameters $P = 20$ d, $M_P = 67\ M_E$, $e = 0.32$, $\omega_* = -0.79$ rad, $M_* = 1.07\ M_\odot$ with correlated noise (period = 54 d, amplitude = 20 ms^{-1}).





- By simulating and fitting realistic data, Ravest can estimate what precision can be reached on the minimum mass estimate $M_P \sin i$.
- Can simulate RV data for specific dates (e.g. upcoming observation schedule) and see what precision will be reached, or can set a target precision and find the minimum number of RV observations needed to reach it.
- Ravest can also load existing RV data alongside simulated future data when fitting – helpful for justifying time in observing proposals.
- The ability to simulate and fit for stellar activity using Gaussian Processes aids precision estimation for low-mass planets.

Ravest website

[1] McEwen, J.D., Wallis, C.G., Price, M.A. and Mancini, A.S., 2021. "Machine learning assisted Bayesian model comparison: learnt harmonic mean estimator". arXiv preprint arXiv:2111.12720

[2] Polanska, A., Price, M.A., Piras, D., Mancini, A.S. and McEwen, J.D., 2024. "Learned harmonic mean estimation of the Bayesian evidence with normalizing flows". arXiv preprint arXiv:2405.05969

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