Preparing for *Gaia* DR4: Detecting Long-Period Giant Planets with Astrometry

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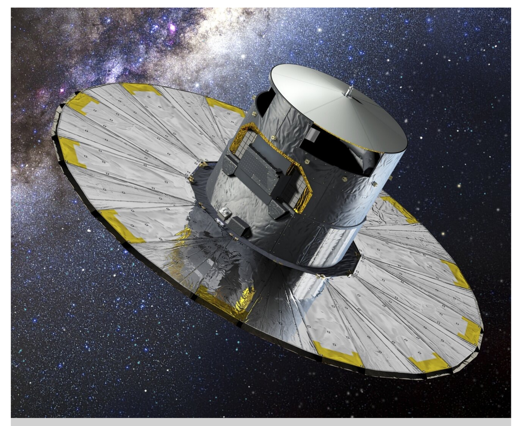
1. Background

Era of Astrometry: The *Gaia* Space Mission



Gaia telescope[1]

Lifetime: 2013-2025
Led by: European Space Agency (ESA)
Specialization: High-precision astrometry (positional measurements) of Milky Way stars
Status: Data Release 4 (DR4) expected December 2026 (4^{th} out of 5 total)

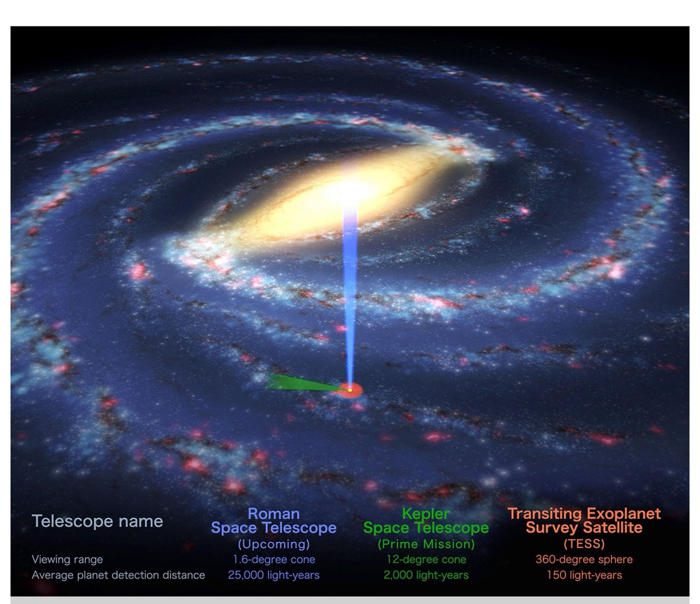
Primary Goal: Map entire 3D structure of the Milky Way

Detecting Stellar Companions

- Stars will "wobble" across the sky when in orbit with another massive object, which can be observed with astrometry
- **Long-period giant planets** (similar to Jupiter) in nearby low-mass star systems produce the biggest planet-induced wobble detectable by *Gaia*
- These planets are currently not well understood, making the *Gaia* mission significant for exoplanet demographics

Combined Demographics of *Gaia* and *Roman*

- The *Roman* space telescope will be able to probe planets with similarly long periods as *Gaia* for more distant stars using microlensing
- The combined yields from both surveys will provide the most complete census of long-period giant planets to date



Roman coverage of Milky Way[2]

2. Project Objective

Detection Sensitivity Limits of *Gaia*

- A metric called the **Renormalized Unit Weight Error (RUWE)** was used in DR3 data processing to filter out stars unlikely to have companions (RUWE < 1.4), which suggests the DR4 exoplanet catalog may be quite conservative
- **Our Objective:** We want to construct an exoplanet detection pipeline for DR4 that can recover more planets at low RUWE than the standard *Gaia* DR4 pipeline

3. Our Detection Pipeline

Simulating DR4 Data with `gaiamock`

- We simulate DR4 astrometry with the `gaiamock` code developed by El Badry et al. 2024[3]
- We test if a candidate would be rejected by DR3 standards by computing RUWE with `gaiamock`

Fitting Physical Models to the Data

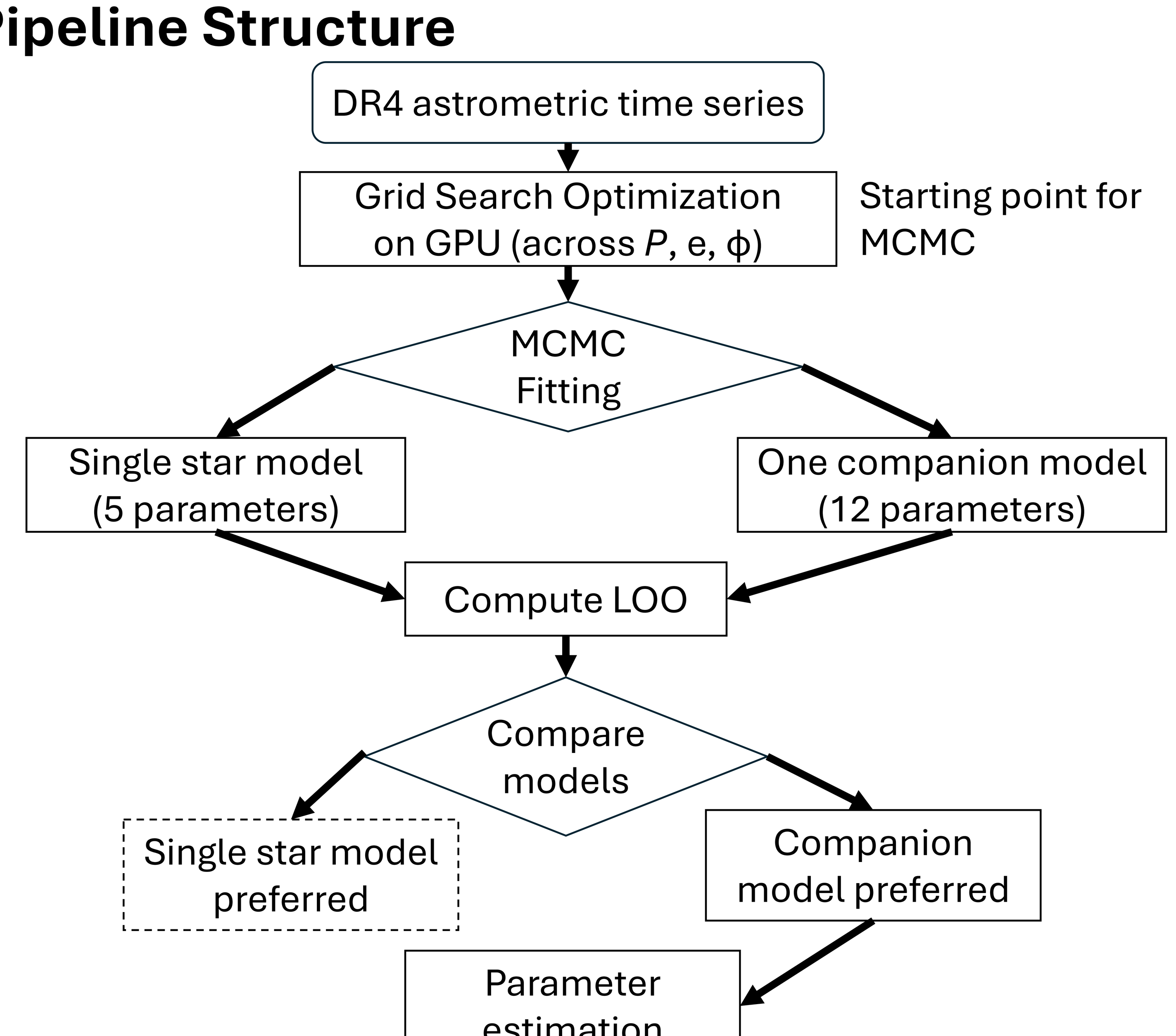
We use **Bayesian modeling** to fit two kinds of physical models to our simulated data using MCMC:

Single Star Model	Planet-Star (Orbital) Model
Parameters: • Proper motion (RA/Dec) • Stellar parallax • Coordinate offsets (RA/Dec) • Jitter (optional)	Parameters: • All single star parameters • Orbital period (*P*) • Eccentricity (*e*) • Phase of periastron (ϕ) • Astrometric amplitude (a_0) • Orbital orientation (i, Ω, ω)

Determining Preferred Model

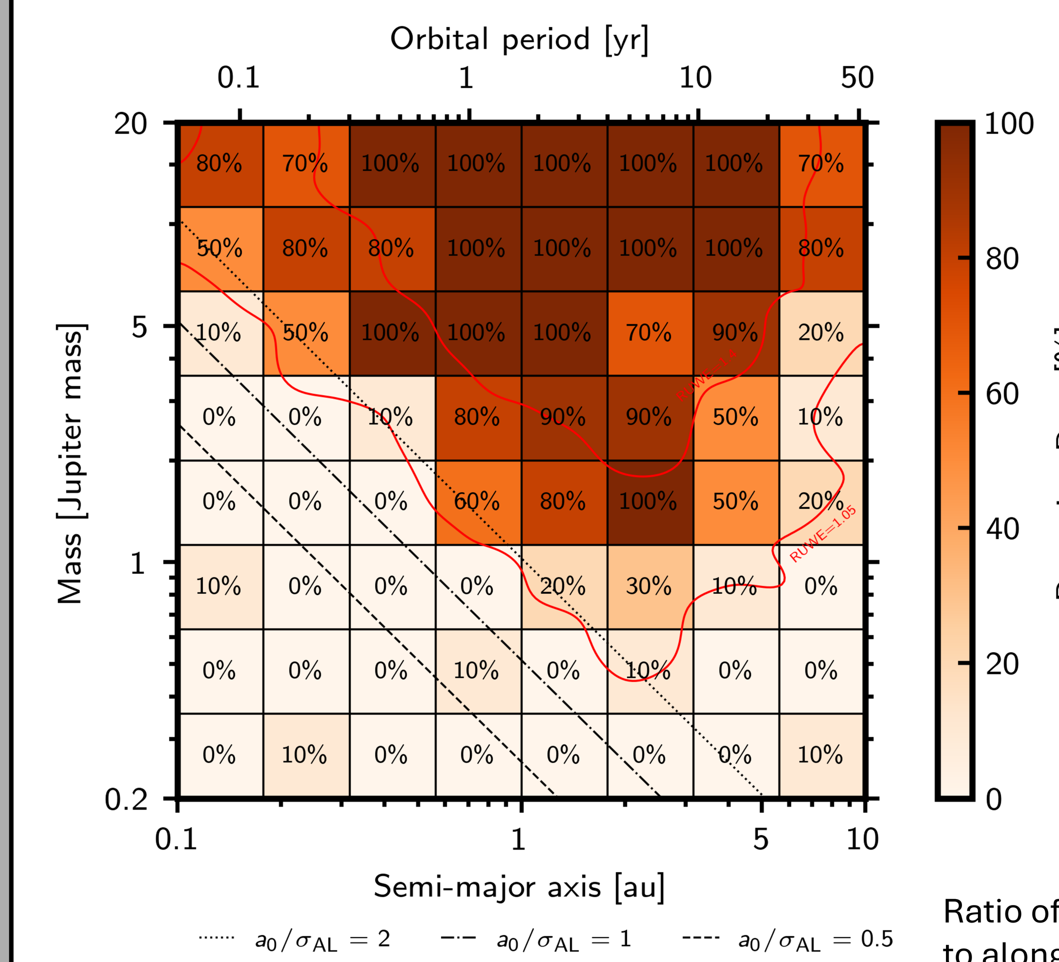
- We use the **leave-one-out (LOO)** cross-validation metric to select the preferred model
- The LOO metric is useful because it penalizes overfitting and works well on low S/N data
- For model comparison, we compute the LOO difference signal-to-noise ratio (SNR): $(LOO_{binary} - LOO_{single})/SE_{difference}$

Pipeline Structure



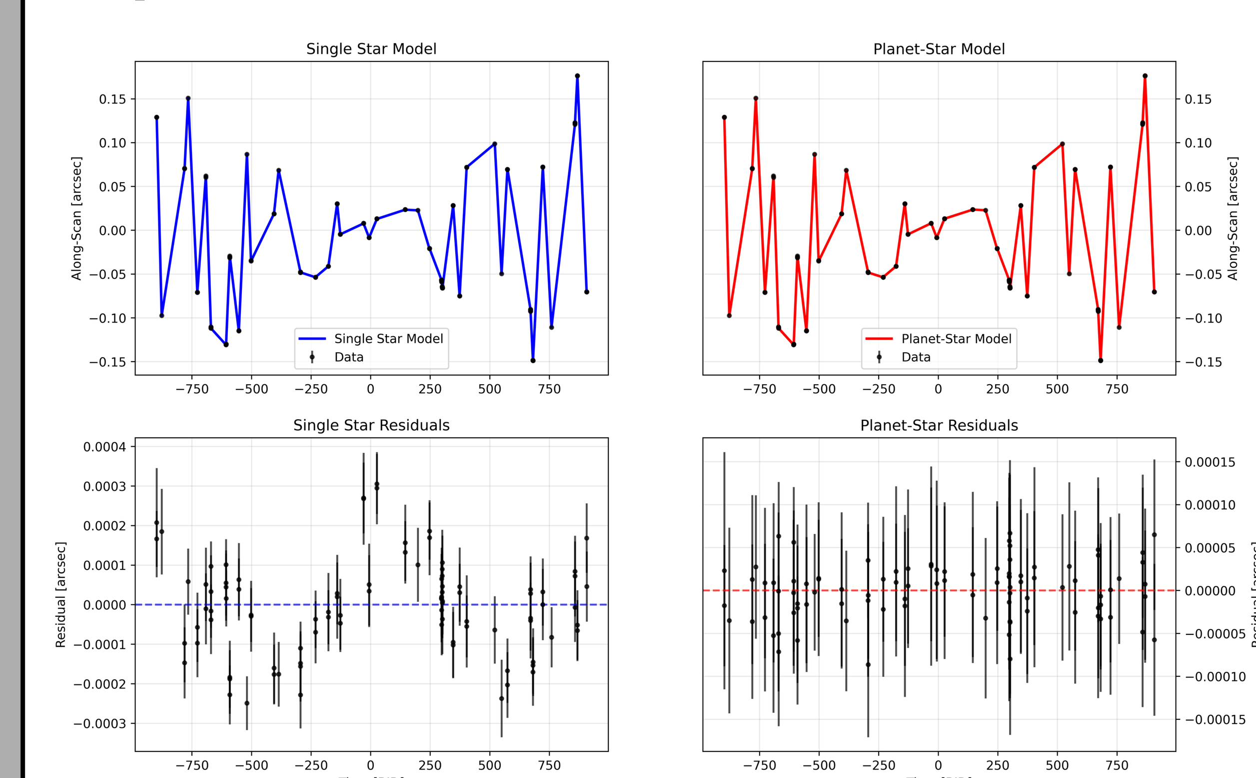
4. Results

Injected Planets around a 0.35 $M_\odot$ star at 30 pc



- Threshold for detection set to LOO SNR of 3.92 (1% False Alarm Probability)
- Detection coverage extends 1-2 bins lower than RUWE of 1.4

Pipeline Performance on DR4 Prerelease Data



Gaia-4b[4]

- 0.644 $M_\odot$ star, 73.7 pc
- 11.8 ± 0.7 M_{Jup} planet
- 1.56 ± 0.004 yr orbital period

Our Fit

- 10.54 ± 1.02 M_{Jup} planet
- 1.58 ± 0.024 yr orbital period
- LOO SNR: 5.96 (companion model strongly preferred)

Conclusions & Future Work

- Our pipeline shows promise for constraining the orbits of Jupiter-mass planets in low RUWE DR4 data that would not have met the *Gaia* DR3 RUWE cutoff
- Impact of detection threshold on false positive rate requires further evaluation
- Need to test pipeline on more DR4 prerelease targets to better understand real DR4 observations

Acknowledgements

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References

1. *Gaia* Image Credit: European Space Agency
2. *Roman* Image Credit: NASA Goddard Space Flight Center
3. El-Badry et al. 2024, *The Open Journal of Astrophysics*, 7,100
4. Stefánsson et al. 2025, *The Astronomical Journal*, 169,107