Using Gravity Darkening on Variable Stars to Constrain Planetary Formation Theories

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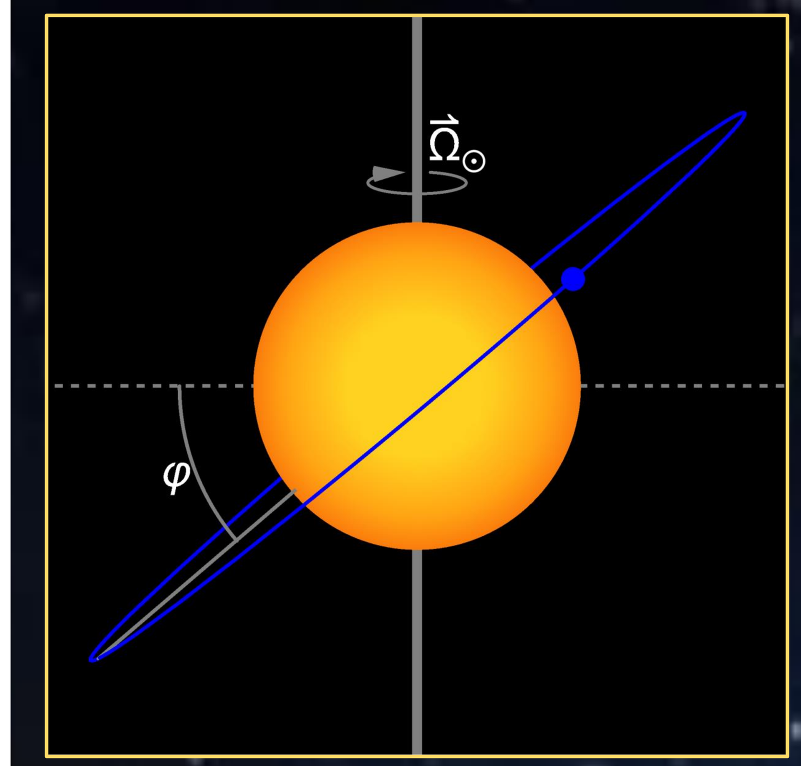
Introduction

Figure 1

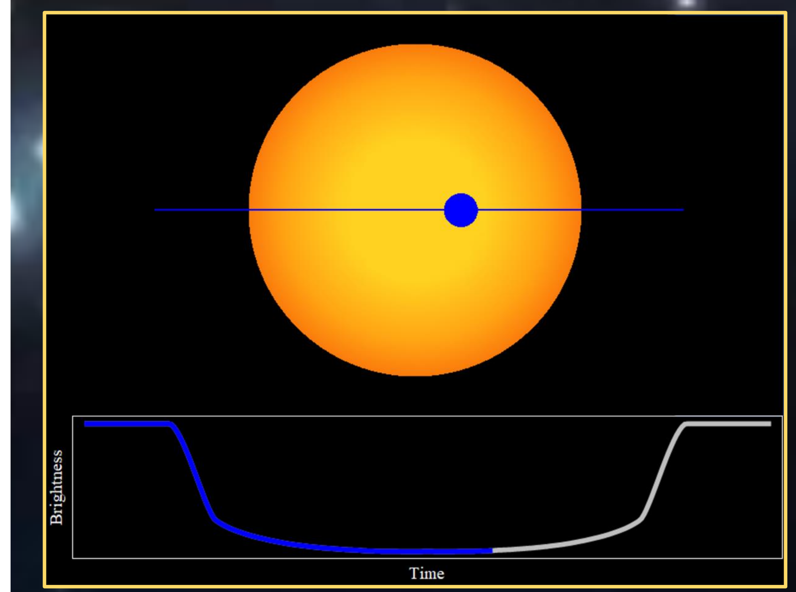


Above: Example of a planet, shown in blue, orbiting a star with rotation rate $\Omega_{\odot}$, in an orbit misaligned by angle φ.

- Observations of exoplanets have revealed many systems to be misaligned (Figure 1)
  - This poses problems for our understanding of planetary formation theory[4]
- We set out to measure the spin-orbit misalignment of systems with orbit periods between 10 and 100 days
  - These systems have alignments that are likely preserved from initial formation
  - This will provide a wealth of statistical data with which to constrain new theories of planet formation

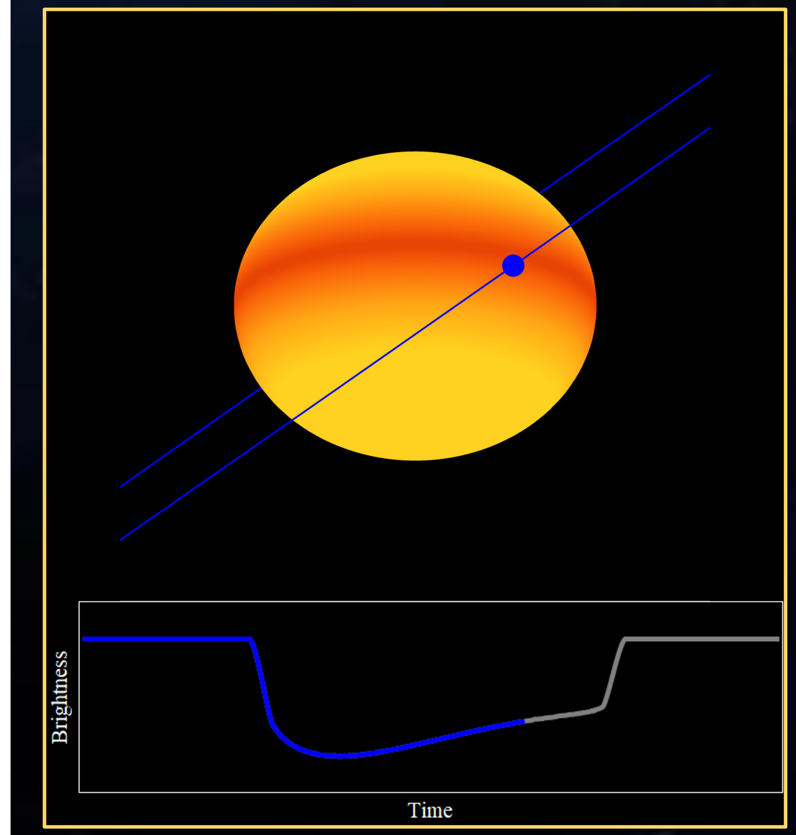
Methods

Figure 2



Above: Transit lightcurve of a non-gravity darkened, non-variable star.

Figure 3



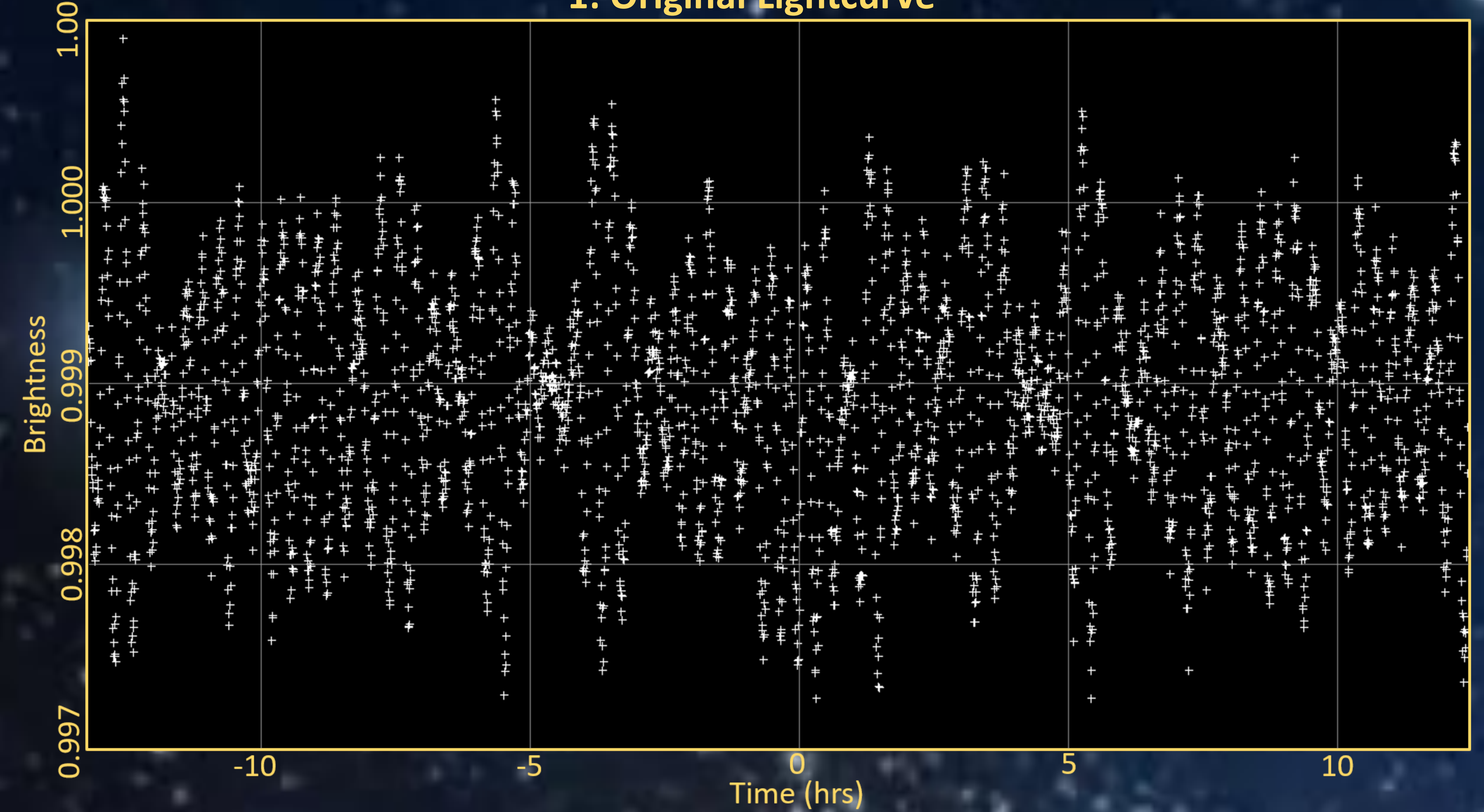
Above: A misaligned planet passes in front of a gravity darkened star. As it passes from the warmer south pole to the cooler equator it produces an asymmetric transit lightcurve.

- We measure spin-orbit misalignment using data from the *Kepler* Space Telescope
- We study early-type, fast-rotating stars that display gravity darkenening[3]
  - This produces asymmetric lightcurves (Figure 3) which can be fit with a χ^2-minimization technique to measure spin-orbit misalignment
- Gravity darkened stars are often variable stars
  - We can independently use oscillations to measure spin-orbit misalignment[2]
  - Oscillations can obscure the transit
- We employ a specialized technique to remove and analyze the variability
  - We remove each oscillation individually in frequency space using a least squares fitting algorithm

KOI-972

1. KOI-972.01 is a planetary candidate orbiting a star with an effective temperature of 7221 Kelvin and a projected rotational velocity of 120 km/s. KOI-972.01 orbits with a period of about 13 days making it an ideal candidate for our technique. Initial fits of the system proved problematic, resulting in large error bars, and further investigation revealed KOI-972 to be a variable star.

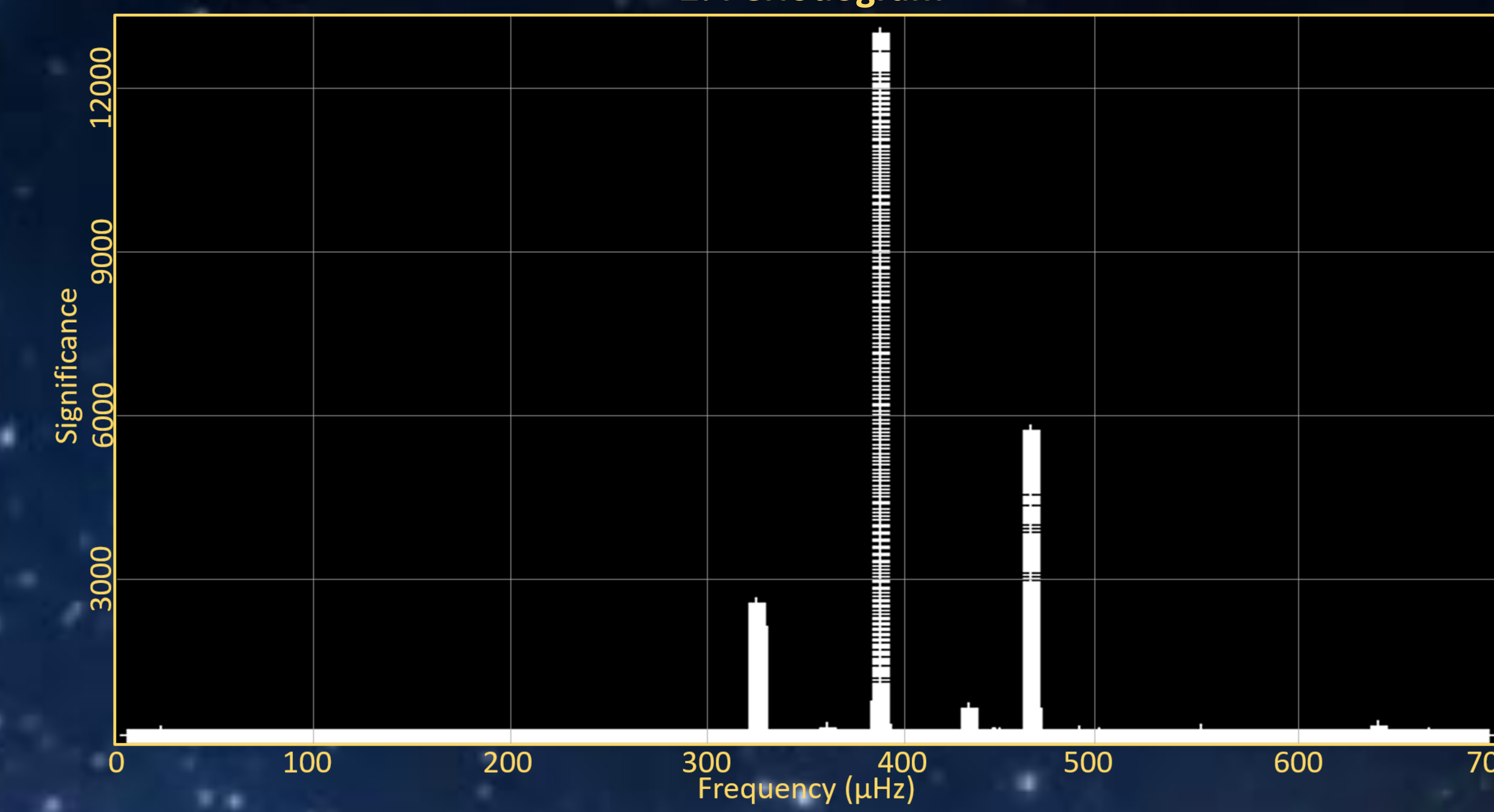
1: Original Lightcurve



Above: A small section of KOI-972 shortcadence lightcurve, centered around the location of an obscured transit.

2. In order to further analyze KOI-972, we remove stellar oscillations one at a time via the Linear Algorithm for Significance Reduction (LASR).[1] Selecting a portion of continuous shortcadence data spanning 30 days, we create a Lomb-Scargle periodogram to identify and fit for each individual frequency of stellar oscillation.

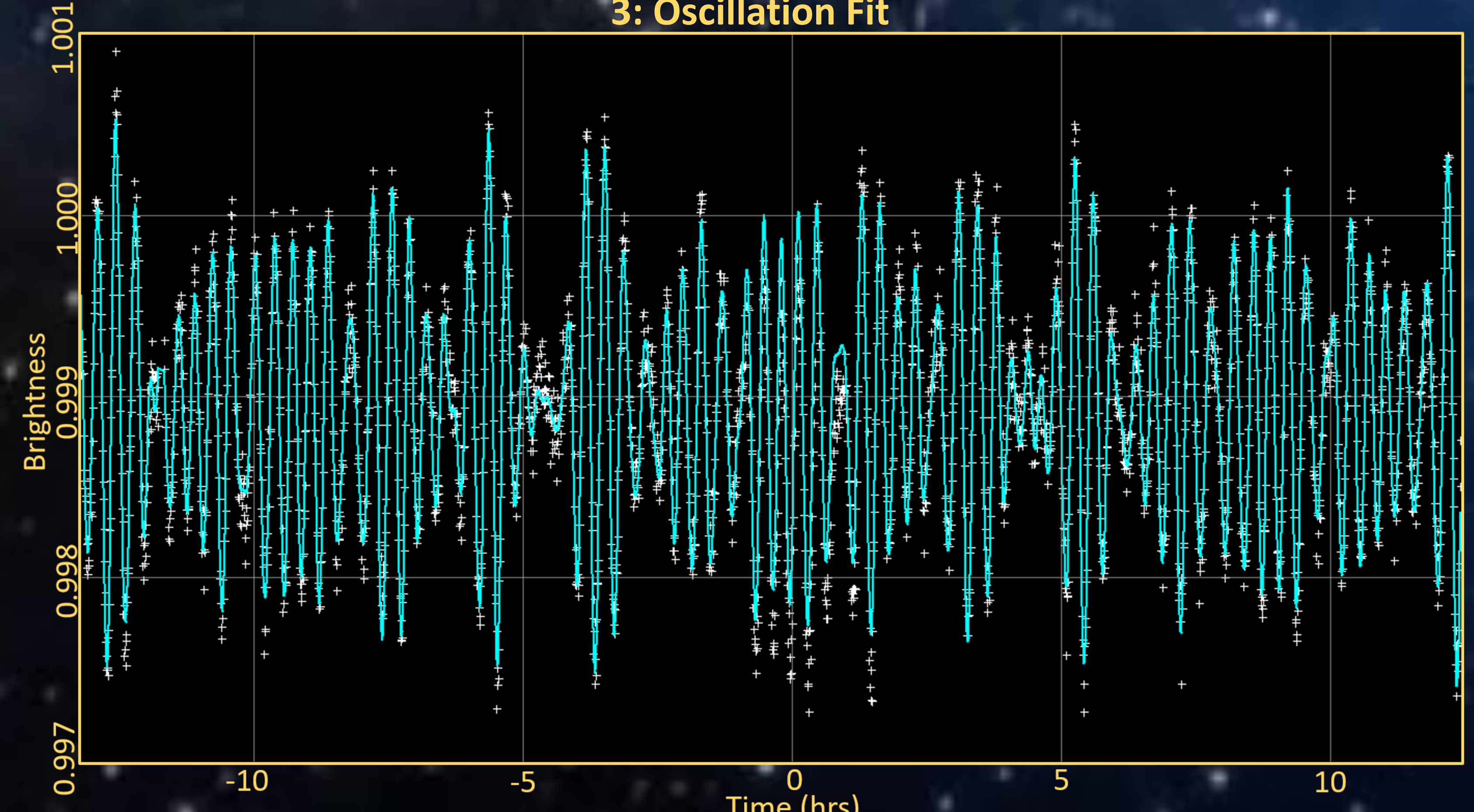
2: Periodogram



Above: The initial Lomb-Scargle periodogram of KOI-972 with frequency along the x-axis and significance along the y-axis. Higher significance denotes a higher prominence oscillation.

3. LASR analysis reveals 54 different stellar oscillation frequencies. We combine each fit to create a complete mathematical description of the system's stellar variability.

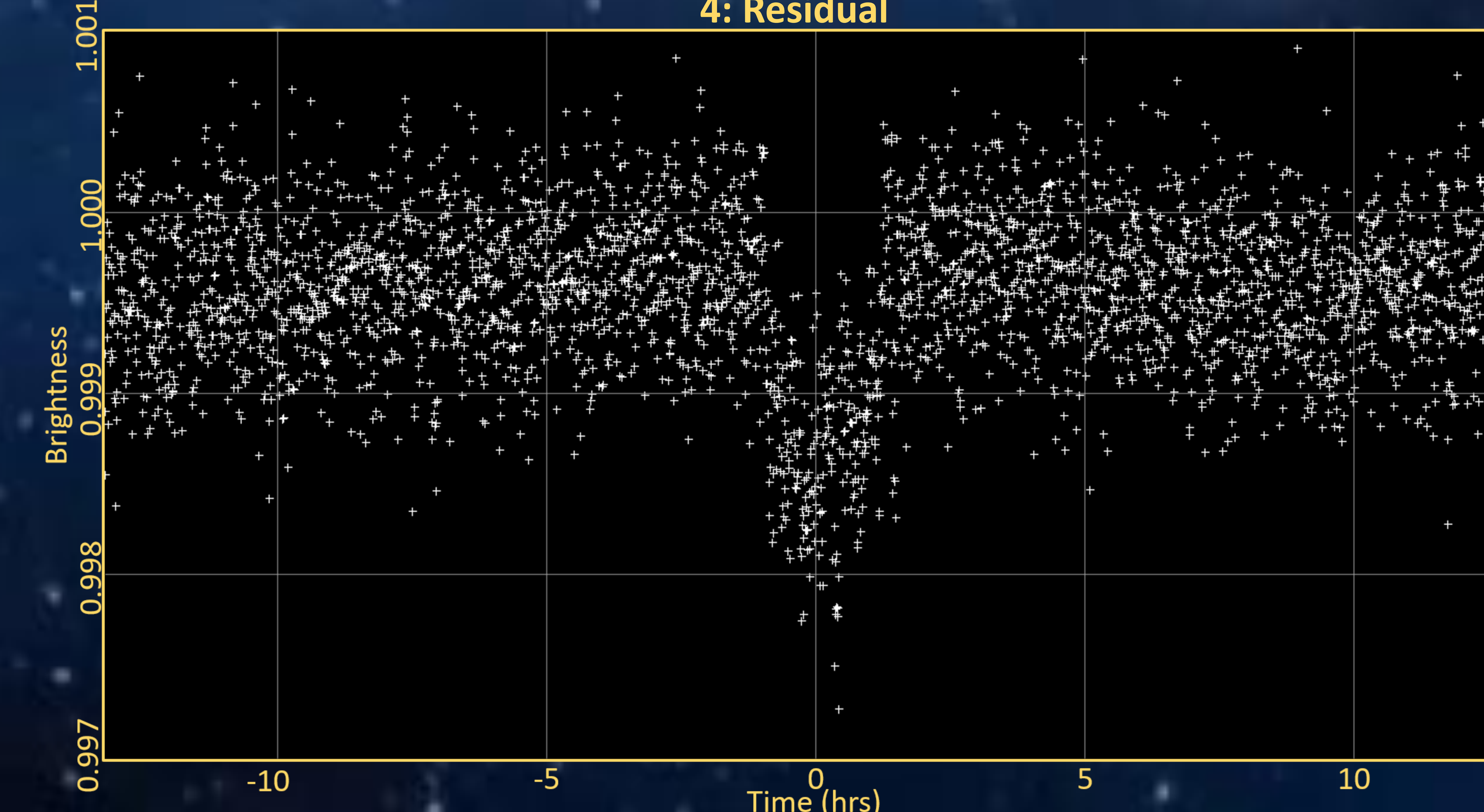
3: Oscillation Fit



Above: The same section of KOI-972 shortcadence lightcurve with fit of 54 stellar oscillation frequencies superimposed on top. The linear combination of the frequencies clearly closely matches the stellar variability.

4. We subtract the complete stellar oscillation fit from the original baseline. The residual clearly reveals the transit and allows us to apply our gravity-darkening technique in order to constrain the stellar variability.

4: Residual



Above: The same section of KOI-972 shortcadence lightcurve after stellar variability has been subtracted. The transit is now clearly visible.

Expected Results

Our combined stellar oscillation-gravity darkening technique allows for the characterization of planets orbiting most high-mass, fast-rotating stars. In the future we expect to further constrain parameters for KOI-972 and measure the spin-orbit misalignment of systems KOI-1932 and KOI-2577. Preliminary fits and stellar oscillation removal has already been performed on these systems. Additionally, we expect to be able to apply our technique to dozens of other high-mass, fast-rotating KOI's. Compiling a list of spin-orbit misalignments for these systems will then allow us to use the data to put constraints on theories of planetary formation and evolution.

References

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2. Goupil, M-J, et. al. (2000). Rotational Splitting of delta Scuti Stars. Delta Scuti and Related Stars, Vol 210.
3. von Ziepel, H. (1924). The Radiative Equilibrium of a Rotating System of Gaseous Masses. Monthly Notices of the Royal Astronomical Society, Vol. 84, p.665-683.
4. Woolfson, M. M. (1993). The Solar System-its Origin and Evolution. Quarterly Journal of the Royal Astronomical Society, 24, 1-20.