

A giant planet transiting a 3 Myr protostar with a misaligned disk

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Astronomers have found more than a dozen planets transiting 10-40 million year old stars ¹, but younger transiting planets have remained elusive. The lack of such discoveries may be because planets have not fully formed at this age or that our view is blocked by the protoplanetary disk. However, we now know that many outer disks are warped/broken ²; provided the inner disk is depleted, transiting planets may thus be visible. Here we report the observations of the transiting planet IRAS 04125+2902 b orbiting a 3 Myr, $0.7 M_{\odot}$, pre-main sequence star in the Taurus Molecular Cloud. The host star harbors a nearly face-on ($i \simeq 30^{\circ}$) transitional disk ³ and a wide binary companion. The planet has a period of 8.83 days, a radius of $10.7 R_{\oplus}$ ($0.96 R_J$), and a 95%-confidence upper limit on its mass of $90 M_{\oplus}$ ($0.3 M_J$) from radial velocity measurements, making it a possible precursor of the super-Earths and sub-Neptunes commonly found around main-sequence stars. The rotational broadening of the star and the orbit of the wide ($4''$, 635 AU) companion are both consistent with edge-on orientations. Thus, all components of the system are consistent with alignment except the outer disk; the origin of this misalignment is unclear.

1 Main

IRAS 04125+2902 was first observed by NASA’s Transiting Exoplanet Survey Satellite (*TESS*) in November 2019, and since then, *TESS* has detected 17 transits of IRAS 04125+2902 b across six sectors (Figure 1). Follow-up observations using the Las Cumbres Observatory (LCO) 1-meter telescopes confirmed with higher angular resolution that the star is the source of the photometric variations seen by *TESS* and has a consistent depth at wavelengths $0.5 - 0.9\mu\text{m}$ (Figure 2). Our analysis of the light curve indicates that the planet orbits its star every 8.83 days and has a radius of $0.96 \pm 0.08 R_J$. The multi-color observations of transits, radial velocities (RVs), and multi-epoch high-resolution imaging combine to rule out all known false positive scenarios (see Methods).

IRAS 04125+2902 is a T-Tauri star inside the Taurus-Auriga star-forming region. Taurus-Auriga itself is made up of at least 17 distinct subpopulations ranging in age from 1.3 to 15 Myr. The star is a member of the D4-North subpopulation, with an estimated age of $2.49^{+0.35}_{-0.34}$ Myr⁴. By comparing the spectra, photometry, and *Gaia* parallax to a grid of evolutionary models⁵, we determined an age of $3.3^{+0.6}_{-0.5}$ Myr for the host star, consistent with the group age at 1.3σ .

This makes IRAS 04125+2902 b the youngest transiting planet discovered to date by a factor of $\simeq 3$. There are similar-age directly imaged systems^{6,7}, but they reside near the boundary between brown dwarfs and planets. Radial velocity surveys have also uncovered similar-aged non-transiting planet candidates^{8,9}, but those remain controversial^{10,11}. Even if confirmed, those planets are $> 1 M_J$, making them progenitors of brown dwarfs or hot Jupiters.

The analysis of archival and new RVs sets an upper limit of $< 0.3 M_J$ on the planet’s mass. Planets younger than ~ 100 Myr are expected to have inflated radii and will shrink over time¹². Gas-giant planet progenitors ($\gtrsim 1 M_J$) are expected to be $1.4\text{--}2 R_J$ for their first 20-30 Myr¹³. Observational data shows 10-700 Myr planets are larger and have a lower density than their older counterparts¹⁴. Further, small planets are intrinsically more common, particularly around lower-mass stars, so the likelihood of finding a hot Jupiter orbiting a $0.7 M_\odot$ star is small¹⁵. Thus the observational and statistical data indicate the planet is not a true giant, but instead a progenitor of a sub-Saturn ($4 - 7 R_\oplus$) or even a sub-Neptune ($\simeq 1.5 - 4 R_\oplus$).

Pebble accretion models can form and migrate a solid core of $\sim$ tens of Earth masses to $< 0.2\text{AU}$ within 2-3 Myr¹⁶. The existence of IRAS 04125+2902 b is not surprising in light of these models and provides observational evidence that planets can form and migrate on such a short timescale. It also demonstrates that a planet at this age can be a spherical object with a sharply defined photosphere (forming a trapezoid-like transit) rather than a cloud of dust and gas or a still-forming ring-like system¹⁷.

Protoplanetary disks dissipate from the inside out, creating large inner dust cavities, often tens of AU in diameter. Disks with such cavities are known as transition disks¹⁸. Stars with

transition disks have long been targeted by direct imaging planet searches, both because the cavity may have been cleared by a giant planet¹⁹ and because the region is optically thin enough to detect such a planet²⁰. The star shows clear evidence for a transition disk (Figure 3), based on its spectral energy distribution and on submillimeter observations of the outer disk³, but no directly-imaged planets inside the gap have been found to date²¹.

It was previously thought that the detection of a transiting planet in a disk-bearing system was improbable. A transiting planet must have a high orbital inclination (edge-on) and is assumed to have formed within the (sky-projected) plane of the disk, but an optically thick edge-on disk would also block observations of the host star at wavelengths of typical transit observations. However, the outer disk surrounding IRAS 04125+2902 is close to face-on when observed from Earth and has a depleted inner disk out to $\simeq 20$ AU³.

The stellar rotational axis is consistent with that of the planet’s orbital axis, but nearly perpendicular to the disk orientation (Figure 4, see Methods). The star has a 4'' binary companion, which could explain the disk misalignment. However, the orbit of the binary is also edge-on (see Methods), as has been seen in some other planetary systems with binary companions²². The lowest energy configuration is generally where system components are aligned^{23,24}, suggesting the companion-disk interactions should preferentially push the disk *into* alignment with the binary’s orbit.

The origin of the misaligned outer disk remains unclear. One possibility is that the inner and outer disk were initially aligned with each other and the orbital plane of the planet, but the planet became misaligned at a later phase (e.g., during migration). Current models for forming close-in sub-Neptunes tend to include migration of pebbles and/or planetesimals through the protoplanetary disk¹⁶, which produce planets aligned with their parent disk. Therefore, another massive object in the system likely would be required to move a planet into an orbit inclined from the disk that formed it, but there is no evidence of such an object in the system.

The alternative is that the outer disk became broken through a process distinct from interactions with the binary companion. Simulations of star-forming regions suggest outer disk warps could be common due to interactions between the early disk and the surrounding environment²⁵, such as infalling material from the surrounding cloud²⁶. Observational studies have also found increasing evidence of disk warps or breaks^{27,28}, although others have found general alignment²⁹. However, the frequency of outer disk misalignments at such young ages is not known. Thus, whether IRAS 04125+2902 is a special case or one of a larger population of systems with broken/warped disks³⁰ is still unclear.

Given its close proximity to Earth (160 pc) and rare configuration, the system is a powerful environment for understanding early formation and migration. Rossiter–McLaughlin measurements and future ALMA data can be used to further constrain the system alignment and disk

inclination. Due to the large radius and relatively low mass, we can conclude that the planet likely has a large extended atmosphere, ideal for follow-up with *JWST*. IRAS 04125+2902 b motivates further efforts to search the youngest stellar clusters for more of these infant planets.

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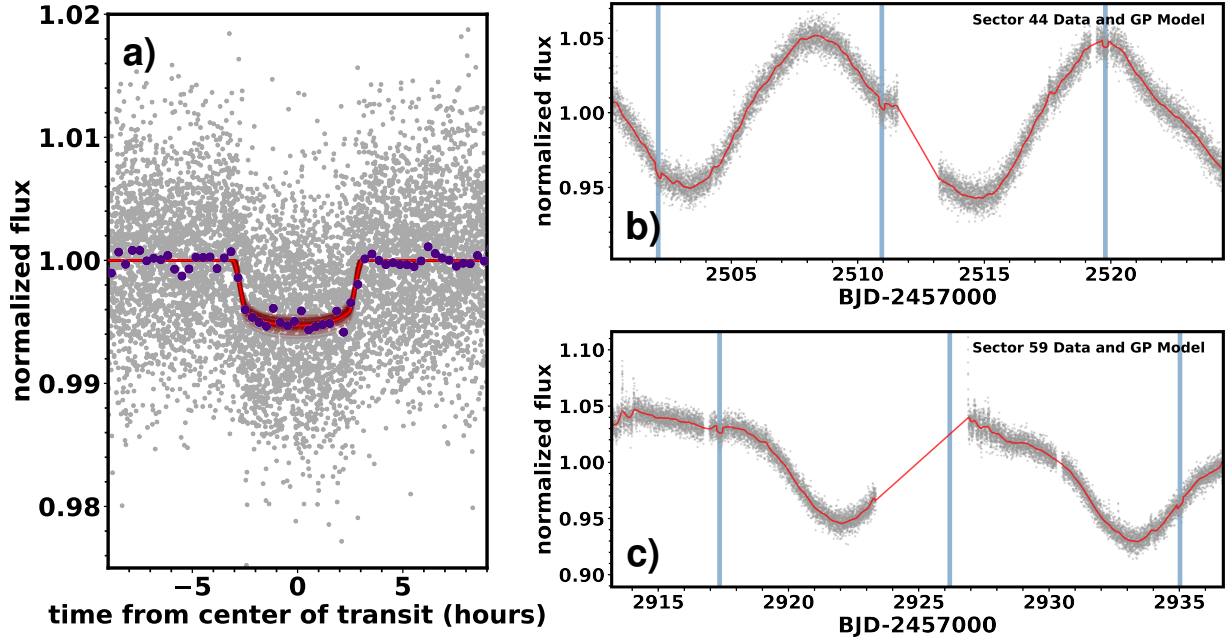


Figure 1: *TESS* light curve of IRAS 04125+2902

a) Phase-folded light curve from *TESS* (gray points) binned to 20-minute intervals (purple points). The uncertainty on the binned points are smaller than the size of the symbols. The best-fit transit model is shown as the bright, opaque red line with 100 model fits pulled from the posterior shown as the dark, translucent red lines. The best-fit GP model of the stellar variability was removed from the data and model. **b & c)** Representative sectors of the *TESS* light curve (gray points) with the best-fit GP model (red line). Blue regions indicate transits, which are visible by eye in most cases. In total, across the six sectors, *TESS* observed 17 transits.

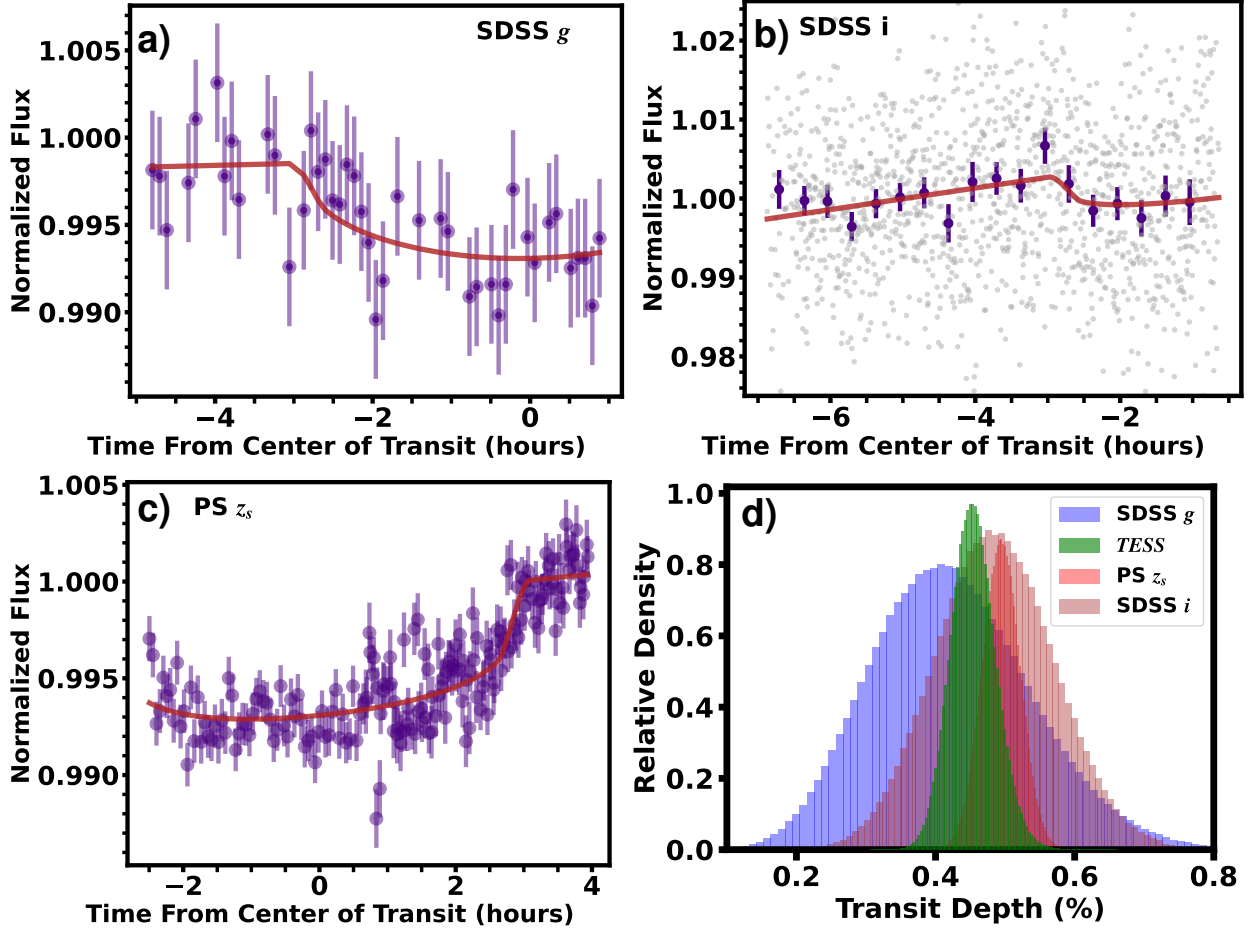


Figure 2: Ground-based transit observations of IRAS 04125+2902

a, b, & c) Ground-based follow-up transits observed by LCO. Light curves of the same filter have been combined (two PS z_s and two simultaneous SDSS i). Binned points are shown for SDSS i for clarity. Error bars are the 1σ uncertainties of the measurement for the SDSS g (**a**) and PS z_s (**c**) data and the standard error on the binned flux for SDSS i (**b**) data. The models (red lines) are the best-fit transit model with a linear trend. **d)** Transit depth posterior from each of the four wavelengths. All calculated transit depths shown in Extended Table 1.

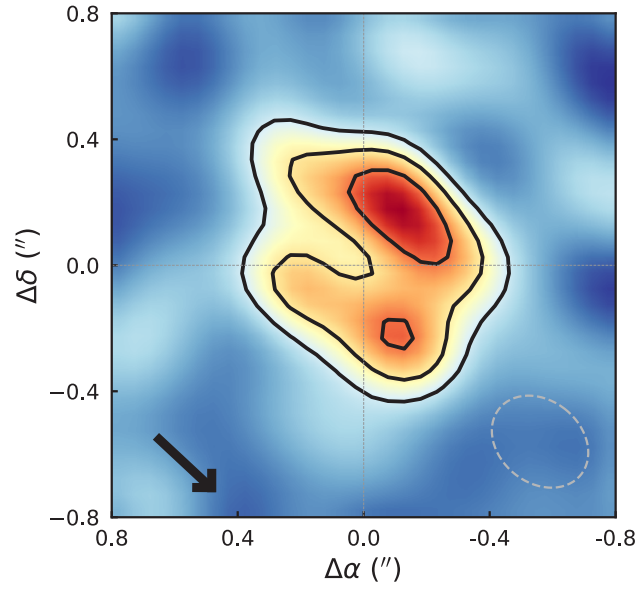


Figure 3: SMA observations of the protoplanetary disk

Archival SMA 880 μm continuum emission of IRAS 04125+2902³. The image is centered on the estimated disk center and is scaled so that reddest color is equal to the peak flux density. Contours at 2σ , 4σ , and 6σ (3.1, 5.3, and 8.0 mJy) are shown by the black solid lines. The synthesized beam is illustrated by the dashed gray ellipse drawn in the lower right corner. The black arrow points in the direction of the binary companion. The irregular shape is likely due to the resolution of the data rather than asymmetries of the disk.

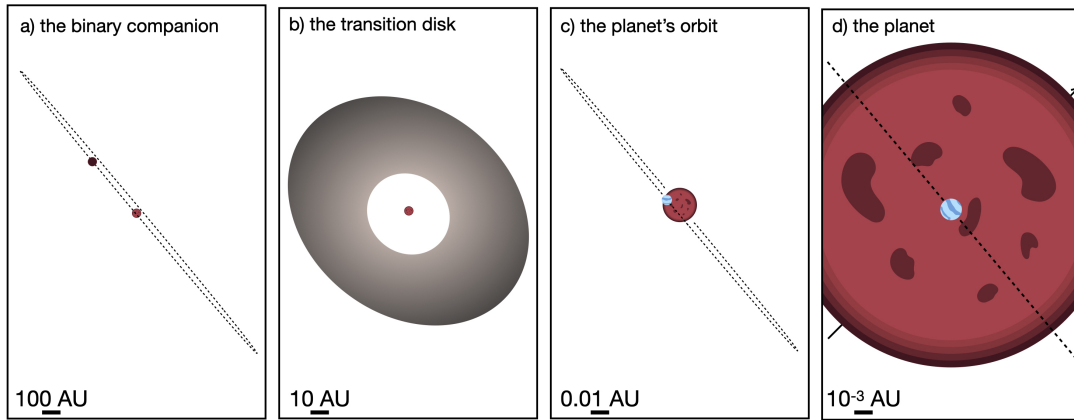


Figure 4: Illustration of the system configuration

Schematic of the system showing the stellar orbit (a), the disk (b), the planet orbit (c), and the planet (d). The scale is correct within each panel, and the inclination angle is preserved between panels. Note that the ascending node (Ω) is not known for the star or planet, but are drawn to match the binary.

Methods

***TESS* observation and identification of the planet:** IRAS 04125+2902 (TIC 56658270) was first observed by the Transiting Exoplanet Survey Satellite (*TESS*) in Sector 19, from 2019 Nov 28 to Dec 23. The target was re-observed by *TESS* in Sector 43 (2021 Sep 16 - Oct 11), Sector 44 (2021 Oct 12 - Nov 5), Sector 59 (2022 Nov 26 - Dec 23), Sector 70 (2023 Sep 20 - Oct 16) and Sector 71 (2023 Oct 17 - Nov 11). For Sectors 43, 44, 59, 70, and 71, the target was pre-selected for 2-minute cadence light curves produced by the Science Processing Operations Center (SPOC)³¹. Sector 19 was observed only in the 30-minute cadence Full Frame Images (FFIs).

As part of our survey for planets transiting stars in the youngest stellar associations, we searched the *TESS* light curves of all high-probability members of the Taurus-Auriga association⁴. We used a custom extraction pipeline starting from *TESS* FFIs and SPOC Simple Aperture Photometry (SAP)³². We extracted the light curves and applied our custom systematic corrections following the procedure in reference³³. To briefly summarize, we started with 30x30 pixel cutouts of *TESS* FFIs. Using the calibrated pixel files, we tested a range of circular and irregular aperture shapes, adopting the one that minimized the photometric scatter and nearby-star contamination. The resulting light curves were then corrected with a linear model including a regularly-spaced B-Spline, several moments of the distribution of the spacecraft quaternion time series measurements within each exposure, the robust mean of pixels in the background of the FFI cutouts, and seven co-trending basis vectors from the SPOC Presearch Data Conditioning^{34,35} single-band and band 3 (fast timescale) flux time series correction with the largest eigenvalues. The SPOC SAP curves were fit with a similar procedure, but with additional basis vectors and a high-pass filter on the background time series.

We searched for planets using the `Notch` pipeline³⁶. From the original code, we updated the box-least squares (BLS) search to the one implemented in `astropy`³⁷, and changed the period grid spacing used. The search recovered a signal at 8.8 days with a BLS SNR of 42. The resulting phase-folded transit showed a sharp ingress/egress with a flat bottom consistent with a planetary object.

We performed a suite of initial quality checks on the detection, including retrieval of the planet using multiple light curve pipelines³⁸, checking depth and duration consistency with varying aperture selection and across all six sectors. Passing these checks triggered our follow-up with a suite of high-resolution imaging, multiwavelength transits, and high-resolution spectroscopy, and checking for corresponding archival data which we detail below.

The *TESS* Science Office vetting team independently identified the signal and upgraded the system to TOI-6963 on April 3 2024.

High-Resolution Imaging: The target has archival high-resolution imaging spanning November 2009 to November 2016. This includes deep *H*-band imaging from the Strategic Exploration of Exoplanets and Disks with Subaru (SEEDS)³⁹, as well as *L_p*-band imaging⁴⁰, *K'*-band imaging,

and K' -band non-redundant aperture masking (NRM)²¹ with NIRC2 on Keck-II.

To provide a more recent epoch, we observed IRAS 04125+2902 on 2023 Dec 5 with K' -band adaptive optics imaging using NIRC2 on Keck-II. These observations were taken, reduced, and analyzed following prior strategies optimized for identifying stellar companions to *Kepler* planet hosts⁴¹.

We summarize the resulting contrast limits from the high-resolution data in Extended Figure 6a by band and time, alongside the location of the source at three epochs based on the *Gaia* proper motions in Figure 6bc.

Ground-based Transits: We observed four transits of the host star with the Las Cumbres Observatory telescope network (LCO)⁴². These were observed with Sinistro cameras, with a pixel scale of $0.389'' \text{ pixel}^{-1}$. On 2023 December 9 and 18, we observed egress using the Pan-STARRS z_s filter; on 2024 January 14, we observed an egress with the Sloan g' filter; and on 2024 Jan 22, we observed ingress simultaneously with two telescopes both using the SDSS i' filter (we extracted each light curve separately). The exposure times were 300, 150, and 3 s for g' , z_s , and i' observations, respectively. Due to the long transit duration, all were partial transits.

All images were initially reduced by the standard LCOGT BANZAI pipeline⁴³. We tested extracting photometry from BANZAI, AstroImageJ⁴⁴, and Photutils, varying sets of between 10 and 15 comparison stars, and varying aperture sizes (diameter of 1-6''). We recovered the transit with consistent depth across all methods.

Radial Velocities of IRAS 04125+2902: We retrieved two sets of spectra of the target taken with the Immersion Grating Infrared Spectrometer (IGRINS)⁴⁵ on 2015 Jan 27 and 2017 Dec 02. These observations were taken as part of a survey of young stellar objects in nearby star-forming regions⁷⁸. We reduced the IGRINS spectra with the publicly available IGRINS pipeline package⁴⁶ and extracted RVs using the IGRINS RV code⁴⁷. The RVs were consistent with no variation over a 3-year baseline.

We drew four additional RV measurements from the seventeenth APOGEE data release⁴⁸. The RVs span 2019 January 20 to 2020 January 6, and are consistent with no variation over this period.

We convert the absolute RVs from APOGEE and IGRINS into a comparable relative frame by subtracting the median value of the six measurements.

We obtained six new observations of the star with the Habitable-zone Planet Finder (HPF)^{49,50} on the 10-m Hobby-Eberly Telescope at McDonald Observatory. HPF is a high resolution ($R \sim 55000$), fiber-fed⁵¹, stabilized⁵² spectrograph covering $8100 - 12700 \text{ \AA}$. HPF has a laser frequency comb (LFC) to achieve extremely high quality wavelength calibration, exhibiting $\sim 20 \text{ cm s}^{-1}$ instrumental calibration precision⁵³.

Each HPF observation was composed of three sequential 600-s exposures to increase signal and average over high-frequency, oscillation-driven stellar RV variation. To minimize the effect of stellar activity-driven RV noise, we scheduled observations within one stellar rotation (11 days) while sampling at orbital phases of maximum velocity expected from the planet. We bracketed each observation with LFC exposures to monitor the instrumental velocity drift.

The HPF data were reduced using the HxRGproc toolbox^{54,55}. We corrected the derived wavelength solution for barycentric motion at the flux-weighted exposure midpoint using `barycorrpy`⁵⁶. We measured RVs using broadening functions⁵⁷ computed using the `saphires` Python package^{58,59}, which compares each individual spectrum to a template. We used an empirical template of the spectrum generated by stacking all HPF observations, and measured the RV by fitting a Gaussian to the combined broadening function for each HPF exposure and binned the three RVs comprising each observation. We repeated this procedure using a Phoenix model spectrum⁶⁰ to provide RVs on the same scale as the IGRINS and APOGEE RVs, because comparison to an empirical template offers more precise, but only relative RVs.

All RVs are summarized in Extended Table 3 and Extended Figure 1.

Host star properties: Star-forming regions near the Sun are generally Solar or slightly sub-Solar metallicity⁶¹. The Taurus-Auriga region is also consistent with Solar metallicity⁶², so we assume Solar metallicity for all analyses of the host-star properties.

We determined R_* , L_* , and T_{eff} by simultaneously fitting the available photometry and the archival optical spectrum⁶³. This approach has yielded radii accurate to 4-6% on extincted pre-main-sequence stars^{64,65}. To summarize, we compared a grid of flux-calibrated optical and near-infrared spectra^{66,67} to the available photometry and observed spectrum. The templates include young unreddened young stars from nearby moving groups⁶⁸. We used this grid because the flux-calibration is good to 2-4%⁶⁶ and the optical data uses the same instrument as the archival optical spectrum (SNIFS; ⁶⁹). We used BT-SETTL atmospheric models⁷⁰ to fill in gaps in the spectra (e.g., beyond $2.3\mu\text{m}$). In total we fit for five parameters; the choice of template, extinction (A_V), the model selection, and two nuisance parameters that capture imperfections in the flux calibration of SNIFS. We excluded photometry past $8\mu\text{m}$, which includes emission from the disk. Data blueward of this was consistent with the photosphere both in our analysis and prior fits of the SED including a disk model³. After accounting for stellar variability, the best-fit template reproduced the spectrum extremely well ($\chi^2_\nu = 1.1$, Extended Figure 2).

We estimated the bolometric flux (F_{bol}) from the integrated spectrum, the luminosity from F_{bol} and the *Gaia* parallax, and R_* from the Stefan-Boltzmann relation. The final fit yielded $T_{\text{eff}} = 3912 \pm 72 \text{ K}$, $L_* = 0.466 \pm 0.041 L_\odot$, $A_V = 2.71 \pm 0.20$, and $R_* = 1.48 \pm 0.07 R_\odot$. We obtain another estimate of R_* from the scale factor between the BT-SETTL model and the photometry (equal to $R_*^2/\text{distance}^2$), which yields a smaller but consistent $R_* = 1.39 \pm 0.08 R_\odot$.

We performed a similar SED fit to the companion and provide the resulting parameters in

Table 5.

The template grid is mostly main-sequence stars, while our target is pre-main-sequence. Prior work has found this has a weak impact on the final parameters⁶⁴. We further tested this by repeating our fit of the primary star using a grid of unreddened optical spectra of T-Tauri stars⁶³. This yielded fit parameters within 0.5σ of those above. The fit using T-Tauri stars was worse ($\chi^2_\nu = 1.6$) and the grid lacked empirical NIR spectra, so this fit was only used to confirm that gravity has a weak impact on our SED analysis.

The analysis above does not consider the impact of spots on the final stellar parameters, which may be significant for such a young star. We repeated the analysis above but replacing the templates with BT-SETTL models and using a two-temperature fit^{71,72}. This added two additional parameters: the spot coverage fraction (f_S) and the difference between the surface and spot temperature (ΔT). These parameters were limited to $0 < f_S < 1$ and $\Delta T < 1000$ K. The latter limit is set by the most extreme spot temperatures observed in similar T-Tauri stars^{73,74}. We restricted our models $\log g = 4.0$ based on our derived M_* and R_* , but adopting 3.5 or 4.5 had no impact on the result. The temperature difference was poorly constrained, but our fit ruled out large spot coverage fractions ($f_S > 0.4$) except when the spots are warm ($\Delta T < 250$ K). Cooler spots change the SED shape or imprint molecular lines that would be visible in the optical spectrum when f_S is large⁷⁵. As above, we calculate a radius from the scale factor, giving us similar radii to our prior analyses ($R_* = 1.45 \pm 0.10 R_\odot$) and a slightly warmer but consistent temperature ($T_{\text{eff}} = 4080 \pm 95$ K). We adopt this more conservative T_{eff} and R_* for further analyses of the host star.

To estimate M_* and age, we compared photometry and distance to the PARSECv1.2S⁵ and BHAC15⁷⁶ model grids within an MCMC framework⁷⁷. As with the SED fit, we excluded photometry past $8\mu\text{m}$. The free parameters were the stellar mass (M_*), age, extinction (A_V), and underestimated uncertainty (f). We placed a Gaussian prior on A_V based on a fit of the optical spectrum with a stellar template, but other parameters evolved under uniform priors. The PARSEC models yielded a $M_* = 0.70 \pm 0.04 M_\odot$ and an age of $3.3^{+0.6}_{-0.5}$ Myr, while BHAC15 gave $M = 0.67 \pm 0.05 M_\odot$ and an age of 3.1 ± 0.4 Myr. The model fits also provided estimates for T_{eff} and R_* of 3950 ± 60 K and $1.6 \pm 0.1 R_\odot$ from PARSEC and 4037 ± 90 K and $1.47 \pm 0.08 R_\odot$ from BHAC15. These parameters are consistent with our SED fit above, and the ages consistent with the parent Taurus-Auriga sub-group⁴. We adopted the PARSEC results because of a lower χ^2 in the comparison.

We tried fitting the primary and $4''$ companion simultaneously, assuming the same age. The fit was largely unchanged (3.6 ± 0.6 Myr) from the primary-only fit. This provided an mass estimate $M = 0.17 \pm 0.04 M_\odot$ for the companion we use in our binary orbit fit. We summarize the host and companion stellar properties in Extended Table 5.

Our stellar parameters are consistent to prior independent measurements^{3,63}, including T_{eff} from analyses of the APOGEE⁴⁸ spectra and both T_{eff} and $\log(g)$ from analyses of the IGRINS spectra⁷⁸. These analyses have also found the star to have little or no veiling in the optical or near-

infrared. Since these parameters were broadly consistent, we did not perform a new analysis of the IGRINS and APOGEE spectra.

Prior analysis of this target noted a U -band excess, suggestive of an accretion rate of $3_{-2}^{+6} \times 10^{-10} M_{\odot} \text{ yr}^{-1}$ ³, consistent with what is seen in other transitional disks⁷⁹. We detected a weak $\text{Pa}\gamma$ line in the HPF spectra, which we combine with $L_{\text{acc}} - L_{\text{line}}$ relations⁸⁰ to estimate an accretion rate of $\simeq 10^{-9} M_{\odot} \text{ yr}^{-1}$. We observe no significant Brackett or Paschen emission lines in the IGRINS data. Combined with the relatively low $\text{H}\alpha$ emission⁸¹, the star is likely undergoing variable and/or weak accretion.

Star-planet alignment: We estimated the inclination of the host star (i_*) using the combination of the stellar rotation period (P_{rot}), rotational broadening ($V \sin(i_*)$), and the stellar radius (R_*).

We measured P_{rot} by running a Generalized Lomb Scargle (GLS) periodogram on the *TESS* light curves. We used the simple-aperture photometry (SAP) fluxes, which we median-normalized to unity within a given sector, then stitched all sectors together. For the P_{rot} uncertainty, we used the standard deviation in P_{rot} determinations between sectors and the stitched curve. We find a final rotation period $P_{\text{rot}} = 11.31 \pm 0.06$ days.

To estimate rotational broadening ($V \sin(i_*)$) we cross-correlated the IGRINS spectra with artificially broadened IGRINS spectra of slowly-rotating stars with similar T_{eff} to the host star. The adopted $V \sin(i_*)$ was the broadening that gave the maximum cross-correlation. As with prior work⁸², we focused on spectral regions containing the CO bands because they are insensitive to the effect of magnetic fields⁸³. To estimate uncertainties, we repeated this process over multiple orders and with multiple templates, yielding a $V \sin(i_*)$ of $7.1 \pm 0.5 \text{ km s}^{-1}$. We also tested using PHOENIX atmosphere models, which let us explore the effect of lowering the surface gravity, and obtained a consistent 6.8 km s^{-1} . Our estimate was also consistent with earlier determinations which included direct modelling of small-scale magnetic fields⁷⁸.

Using the R_* and P_{rot} values above gave an equatorial velocity of $6.6 \pm 0.3 \text{ km s}^{-1}$, which we combined with our $V \sin(i_*)$ estimate to set limits on i_* . Our method for computing i_* accounts for statistical complications in estimating i_* laid out in prior studies⁸⁴, including corrections for the effective barrier at $\sin(i_*) = 1$. Our analysis yielded a lower limit on $i_* > 78^\circ$ at 1σ and $> 68^\circ$ at 2σ . The resulting inclination is consistent with that of the transiting planet. Despite the inclinations agreeing, the ascending nodes (Ω , the sky-projected angles) are unconstrained, and therefore the host star and planet are not necessarily truly aligned.

Star-binary alignment: *Gaia* detected a star $\simeq 4''$ away (TIC 56658273), corresponding to a sky-projected separation of 635 AU. To estimate the probability that this star is a random alignment versus a bound companion, we used the BinProb tool within Comove⁸⁵. To briefly summarize, BinProb compares the projected separation, *Gaia* contrast, relative proper motion, and parallax of a simulated binary population⁸⁶ orbiting IRAS 04125+2902 to the values of the empirical field population of nearby sources from *Gaia* (< 1 degree). It uses a kernel density estimator to smooth

both populations across phase space and then computes the probability from the relative amplitudes of their probability density functions. This gave a probability that TIC 56658273 is a bound binary companion of $P_{bin} > 99.99\%$.

We recovered TIC 56658273 in the three epochs from NIRC2/Keck. There are not enough stars in the field of view to establish an external reference frame. Instead, we measured the relative astrometry between the target and companion by fitting the PSFs with an empirical template built from other images taken in the same night⁴¹. We applied a -0.062 deg offset to the NIRC2 position angles to put them on the same scale as the *Gaia* astrometry. We summarize the resulting measurements in Extended Table 2.

A wide binary companion can explain the presence of a misaligned disk depending on the binary orbit⁸⁷. To investigate this, we fit the orbit of TIC 56658273 relative to the system using `lofti`⁸⁸. `lofti` uses the orbit fitting rejection sampling algorithm of `OFTI`⁸⁹ with relative *Gaia* proper motions and Keck astrometry as observational constraints.

Extended Figure 5b shows posterior distributions for the semi-major axis, period, and inclination resulting from our binary orbit fit. Due to the astrometric points covering only a small fraction of the orbit, the eccentricity is unconstrained⁹⁰. We find the companion’s orbital inclination (i_c) is $94.5^{+10.9}_{-4.7}$ degrees. This is consistent with the edge-on orbit of the star-planet system (within 1σ).

Both the *Gaia* and Keck astrometry are consistent with purely radial motion, although most of the orbital information came from the difference in *Gaia* proper motions. However, the *Gaia*-only fit yielded $i_c = 95 \pm 20$ degrees, highlighting the need for the NIRC2 astrometry to refine the fit.

Disk-star alignment and disk properties: IRAS 04125+2902 is known to harbor a transitional disk, as evident from the SED peak at $\simeq 100\mu\text{m}$ and a central hole seen in submm/mm imaging³.

To confirm a previous estimate of disk inclination (i_d)³, we reanalyzed the Submillimeter Array (SMA) data. We fit a simple elliptical Gaussian to the visibility data with the *uvmodelfit* task in CASA (version 6.5.6.22). Using CASA’s *importuvfits* task, we converted the SMA observations in UVFITS format to a CASA visibility data set. The *uvmodelfit* elliptical Gaussian model has six free parameters: integrated flux density (F_{cont}), FWHM along the major axis (a), aspect ratio of the axes (r), position angle (PA), right ascension offset from the phase center ($\Delta\alpha$), and declination offset from the phase center ($\Delta\delta$). We scaled the uncertainties on the fitted parameters by the square root of the reduced χ^2 value of the fit. We found $r = 0.856 \pm 0.077$, which implies an outer disk inclination $31 \pm 12^\circ$, consistent with the prior determination of $\lesssim 30^\circ$ ³. We show the image extracted from the visibilities in Figure 3. The disk inclination disagrees with the star-planet-binary system by $\sim 4\sigma$.

We calculate the disk gas mass from sub-mm/mm flux density under the assumption of optically thin and isothermal dust emission⁹¹. This method has been employed for large-scale ALMA

surveys of nearby disk populations⁹² by assuming a dust grain opacity (κ_ν) of $10 \text{ cm}^2 \text{ g}^{-1}$ at 1000 GHz and using an opacity power-law index of $\beta_d = 1.0$ ⁹³. Using the *Gaia* parallax, we find $M_{\text{dust}} = 10.6 \pm 0.3 M_\oplus$, or $M_{\text{gas}} = 0.00318 \pm 0.0009 M_\odot$ assuming a gas-to-dust mass ratio of 100. This is lower than previous analyses of the disk, which found a dust mass of $15.3 M_\oplus$ ($M_{\text{gas}} = 0.005 M_\odot$)⁹⁴ and $16.65 - 23.31 M_\oplus$ (from $M_{\text{gas}} = 0.005 - 0.007 M_\odot$)³. All three fits assumed the same gas-to-dust mass ratio but used different distances and wavelengths for converting from the continuum flux, causing discrepancies in the derived masses.

Planet Properties

Transit analysis: For the transit, we use our FFI-extracted light curve for Sector 19 and the 2-minute systematic-corrected SPOC PDCSAP light curves for Sectors 43, 44, 59, 70, and 71. We remove one transit in Sector 43 (expected $T_0 \simeq 2459484.5 \text{ BJD_TBD}$) as the transit occurs close to the *TESS* data edge. We remove a flare at $\sim 2459519.95 \text{ BJD_TBD}$, which marginally interrupts the egress of a transit in Sector 44 (expected $T_0 \simeq 2459519.8 \text{ BJD_TBD}$).

We fit the systematics-corrected *TESS* photometry using MISTTBORN (MCMC Interface for Synthesis of Transits, Tomography, Binaries, and Others of a Relevant Nature) code^{95,96}. MISTTBORN utilizes BATMAN⁹⁷ to generate the light curve models, emcee⁷⁷ to explore the parameter space, and celerite⁹⁸ to model the stellar variability with a Gaussian Process (GP).

We fit 10 parameters in total. Five are the common transit parameters: time of periastron (T_0), planet orbital period (P), planet-to-star radius ratio (R_p/R_*), impact parameter (b), and stellar density (ρ_*). We also fit two quadratic limb darkening coefficients (q_1 and q_2) following the triangular sampling prescription⁹⁹.

The last three parameters were used to model the GP in the celerite code. We used a stochastically-driven damped simple harmonic oscillator (SHO) to model the stellar variability. SHOs have been proposed as ideal for stellar variability modeling⁹⁸, and have been used widely for *TESS* photometry of young stars^{65,100}. The GP consisted of three parameters: the natural logarithm of the GP period ($\ln(P)$), the natural logarithm of the GP amplitude ($\ln(amp)$), and a quality factor ($\ln(Q)$).

We show the best-fit parameters with uncertainties in Extended Table 4. We also show the phase-folded light curve with the best-fit and sample-fit model transits and representative sectors with the GP fit in Figure 1 and representative transits in Extended Figure 3. We show how the planet compares in period and radius space to the set of known, young ($< 700 \text{ Myr}$) transiting planets in Extended Figure 4.

While we did not explicitly fit for eccentricity, we can gain some constraints by comparing the transit-fit stellar density to the estimated stellar density from our SED fit. The transit-fit ρ_* is sensitive to the transit duration, so any disagreement between the two values would suggest an eccentric planet¹⁰². The transit fit yielded a density of $\rho_* = 0.26^{+0.05}_{-0.09} \rho_\odot$ and SED/model fit yielded $\rho_* = 0.23 \pm 0.05 \rho_\odot$, in agreement with our assumed circular-orbit transit-fit. Alternatively, if we

assume the orbit is circular, this provides additional confirmation of our stellar parameters.

We fit the ground-based transits using the *BATMAN* model as above, but replaced the GP with a linear model to handle out-of-transit variations, updated the limb-darkening values to the relevant wavelength, and locked other parameters to the fit of the *TESS* data excluding R_P/R_* and T_0 . The variability model coefficients, a and b , were fit by removing a correction of the form $f(t) = a + b \times (t - \min(t))$. We simultaneously fit transits observed in the same filter. The resulting transit fits are shown in Figure 2, and the inferred transit parameters are shown in Extended Table 1. The estimated transit depth was consistent across all observed wavelengths, and all agreed with the *TESS* depth to $< 1\sigma$.

TTV analysis: Using the same light curves as above, we searched for transit timing variations (TTVs) of the system. TTVs may suggest the presence of another planet and large TTVs can bias the inferred transit properties. To this end, we fit each transit separately using the *BATMAN* model, with the exception of the transit near the *TESS* data edge, locking all parameters to the *TESS* fit, except the transit midpoint. For stellar variability, we model the region around each transit with a Gaussian process (GP) from *celerite*, utilizing the simple harmonic oscillator (SHO) kernel as above. We ran the MCMC using 30 walkers for 10,000 steps including a burn-in of 2,000 steps (for each transit). Transit variations were calculated by comparing observed with calculated (O-C) transit midpoints. We find that fourteen of the sixteen (88%) transits in the analysis agreed with the predicted period (O-C of zero) within 1σ , with the remaining two transits being 1.9σ (27.0 minutes) and 2.3σ (20.6 minutes) off, suggesting no significant TTVs are present and our parameters are not biased by assuming a linear ephemeris.

RV analysis: We fit the relative RVs from HPF. Fitting just the HPF data allowed us to minimize the effects of long-term variations in the stellar signal. We fit only three parameters; the planet’s semi-amplitude (K), a velocity offset (γ), and the jitter (σ_J). All parameters evolved under uniform priors with only physical limits. The jitter term is added in quadrature with the measurement uncertainties. Other parameters were locked to the results from the transit and we assumed zero eccentricity. Using K , we fit for the mass and find an upper limit on the mass of IRAS 04125+2902 b of $0.3M_J$ (95%) with a jitter of 60 m s^{-1} . The fitted mass posterior agrees with the distribution of planets of similar radii. However, the best-fit mass suggests the planet is low density compared to other large planets with mass measurements, and models predict young super-Earths and mini-Neptunes should be similar in radius to IRAS 04125+2902 b¹⁰³.

The APOGEE and IGRINS data agree with the fitted signal using just HPF, despite the long baseline between observations. This holds even using the (less precise) absolute velocities, confirming that our signal has no long-term trend and is planetary-mass. We do not include the archival velocities in our mass limit since there are too few points to model any zero-point offsets between the instruments. Allowing for more parameters to float (eg, eccentricity) or allowing for more complex jitter terms increased the mass limit, but under any condition we find $M_p < 2M_J$ (95%).

False positive analysis: We consider each false-positive scenario individually below.

Transit signal originates from instrumental artifacts: The transit is recovered in both *TESS* and ground-based data across different sites, filters, and instruments.

Transit signal originates from stellar variability: While the stellar variability amplitude is large (1-10%; Figure 1), the signal is spread over $\simeq 11.3$ days; in some sectors, the stellar signal is weaker than the planet signal over the 6-hour transit duration. The stellar variability profile evolves between *TESS* sectors (Figure 1), yet the transit signal remains constant. Despite some stellar variability signals mimicking transit-like depths and durations, these signals are not periodic. Finally, the transit is recovered from ground-based data at multiple wavelengths, while stellar signals will depend on wavelength.

Transit signal is from a background or foreground star: Based on the proper motions from *Gaia*, the host star has moved by ~ 305 mas (in the *Gaia* frame) over the 14 years spanned by the high-resolution data. This is more than the inner working angle of the Keck/NIRC2 image (~ 100 mas). As a result, a background/foreground star that was undetected in one set of Keck/NIRC2 observations because it happen to be behind or in front of the target would be visible in later observations. We show the locations of IRAS 04125+2902 at each of the imaging epochs in Extended Figure 6. This rules out any background/foreground source with $\Delta K < 5$ mag.

We can use the transit depth and shape to set limits on the brightness of sources that can reproduce the transit by considering the depth and duration of the largest possible companion. From this, the ratio of the ingress or egress duration to the duration from first to third contact (start of ingress to start of egress) limits the radius ratio of the transit source regardless of any diluting flux³³. This calculation suggests if the transit signal comes from another star, it must be $\Delta T \leq 1.7$ mag fainter ($T \leq 14.5$ mag) at 99% confidence. This is far brighter than the limits set by the imaging.

IRAS 04125+2902 b is an eclipsing binary or brown dwarf: A basic fit to the RVs rules out anything with mass $> 0.3M_J$. Even under pessimistic assumptions about the eccentricity and stellar variability, all brown dwarf masses ($> 13M_J$) are easily rejected. Further, the Sonora Bobcat models¹⁰⁴ predict an object with a brown-dwarf mass ($\sim 13 M_J$) at this age would be $\sim 2.0 R_J$, inconsistent with our fitted radius ($\simeq 1 R_J$).

Transit signal is from an eclipsing binary bound to IRAS 04125+2902: To set additional limits on bound companions, we combine the high resolution images, RVs, and *Gaia* imaging using MOLUSC (Multi-Observational Limits on Unseen Stellar Companions)¹⁰⁵. MOLUSC generates synthetic companions and compares them to the observational data. Since we are only interested in companions that could reproduce the transit, we reject any companion that would not land within the photometric aperture used to recover the ground-based transits ($2.7''$). This also rules out the bound companion ($4''$) and any nearby sources detected in *Gaia*. MOLUSC generated 1,000,000 sample stars and $\sim 98.4\%$ were rejected.

The remaining companions consistent with the observational data generally have small mass ratios ($q < 0.06$) with long orbital periods ($\log_{10}(P/\text{days}) = 6.31^{+1.46}_{-1.91}$). Applying the brightness constraints above removes all but 800 companions (0.08%). The remaining binaries are all $\Delta J < 1.5$; such systems would appear as a second set of lines in our IGRINS or HPF spectra ($\text{SNR} > 100$ per epoch) and as an elevated position on the color-magnitude diagram, neither of which were detected.

We can set additional limits using the multi-wavelength ground-based follow-up. If the transit signal were from another star, the depth would vary between bands due to changes in the relative flux contribution with wavelength⁸⁵. Taking the 95th percentile of depths, we set limits on color combinations from g to z . The strongest are in $g - T$, which limit the true host to, at most, 0.67 mag redder than the target. As with the depth and duration constraints, allowed companions would all be detected in our suite of other follow up.

The transit signal is a persistent flux dip or transient dipper: Many disk-bearing young stellar objects show ‘dips’ in their light curves, commonly attributed to dust or gas near the co-rotation radius¹⁰⁶. The overwhelming majority of these objects exhibit light curve morphology and quasi-periodicity inconsistent with a planet on a Keplerian orbit. However, PTFO 8-8695 exhibits light curve dips that were originally attributed to a planet¹⁰⁷ before it was found to be a transient dipper¹⁰⁸. At least five other systems exhibit similar behavior¹⁰⁹.

We can reject this scenario by comparing the light curve behavior. PTFO 8-8695 and its brethren are not truly periodic, showing both long-term variations in the dip timing and many events not happening at all¹¹⁰. Depths and durations from dippers (including PTFO 8-8695) vary by a factor of 2-3 over 1-2 month windows^{111,112}. None of these systems show a flat bottom and sharp ingress/egress, the hallmarks of non-grazing planetary transits.

To test for consistency in depth and transit shape, we fit individual transits of IRAS 04125+2902 b, locking P , T_0 , and limb-darkening parameters, but allowing R_P/R_* and a/R_* to vary alongside a Matern GP kernel to handle the stellar variability. Overall, 94% of the R_P/R_* results and 100% of the a/R_* are within 2σ of one another, suggesting a consistent transit shape across four years of data.

Data Availability We provide all reduced light curves and spectra as source data products to the manuscript and in a GitHub repository: https://github.com/madysonb/discovery_resources.

Code availability We provide access to a GitHub repository including all code created for the analysis of this project that is not already publicly available. https://github.com/madysonb/discovery_resources

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Author Contributions M.G.B. identified the planet candidate, performed the transit and false positive analysis, helped organize further analysis and observations, made most figures for the paper, and wrote large portions of the manuscript. A.W.M. estimated parameters of the host star and companion, organized LCO follow-up, helped with analysis of the ground-based photometry, and wrote large portions of the manuscript. A.V. wrote the light curve extraction pipeline to help identify the target and consulted on the pipeline's outputs. D.K. analyzed the radial velocity from HPF and wrote the portion of the manuscript describing the analysis. A.K. helped organize the HPF observations, contributed to the LCO observation time, contributed NIRC2 observation time, analyzed the AO images, and contributed to the binary analysis. M.A. analyzed the disk and wrote the portion of the manuscript describing the analysis. L.P. analyzed the binary's orbit and wrote the portion of the manuscript describing the analysis. G.M. fit the IGRINS data and extracted the radial velocities. G.M., D.J., and E.S. provided the IGRINS data. S.A. and C.E. provided the SMA data. A.B. calculated the rotation period and wrote the portion of the manuscript that describes the analysis. K.C., R.P.S., F.M., E.P. and C.N.W. contributed LCO observation time and reduced the data. M.D.F. aided in the Keck/NIRC2 observations. D.D. provided funding for the project during the planet discovery and characterization. A.F. created the schematic representation of the system. M.F. analyzed the $V \sin(i_*)$. A.I.L.M. analyzed the TTVs. E.R.N. aided in organizing follow-up observations. B.M.T. contributed to the LCO observation time, contributed NIRC2 observation time. P.C.T. contributed code to make the planet demographics plots. J.J. leads the SPOC which provided the calibrated FFI data and PDC and SAP light curves used in the analysis. J.J., D.L., G.R., S.S., R.V., and J.N.W. are TESS mission architects. D.C., Z.E., D.R.R., A.S., J.D.T., and J.N.V. are TESS mission contributors.

Competing Interests The authors declare that they have no competing financial interests.

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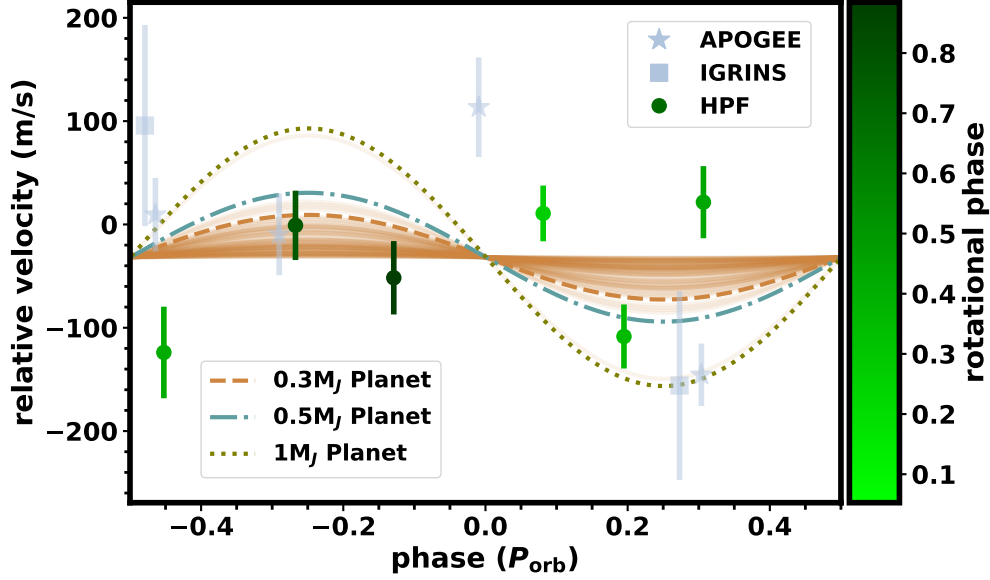
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Description	Parameter	Value		
		SDSS g	SDSS i	PS z_s
Planet-to-star radius ratio	R_p/R_*	$0.0647^{+0.0088}_{-0.009}$	$0.0696^{+0.006}_{-0.0063}$	0.0703 ± 0.0019
Transit timing variation	$T_{0,O} - T_{0,C}$	0.002 ± 0.005	0.004 ± 0.003	0.0 ± 0.002
Constant coefficient	a	-0.0014 ± 0.0011	-0.0027 ± 0.0007	-0.0019 ± 0.0004
Linear coefficient	b	$0.0018^{+0.0116}_{-0.0110}$	$0.033^{+0.0062}_{-0.0061}$	0.0085 ± 0.0017

Extended Data Table 1: Ground-based transit and variability fit parameters.
Fit parameters of the simultaneous transit and variability models of the ground-based transits.

Epoch [BJD]	Separation [mas]	Position Angle [deg]
2455157.03	4012.94 ± 1.45	198.148 ± 0.020
2456881.12	4009.26 ± 1.44	198.158 ± 0.021
2460283.78	3998.46 ± 1.51	198.148 ± 0.022
2460283.78	3997.12 ± 1.42	198.148 ± 0.020

Extended Data Table 2: Keck/NIRC2 Astrometry
Astrometry values for TIC 56658273 measured with Keck/NIRC2. A -0.062 deg offset has been applied to position angle to convert from Keck/NIRC2 frame into Gaia DR3 frame.



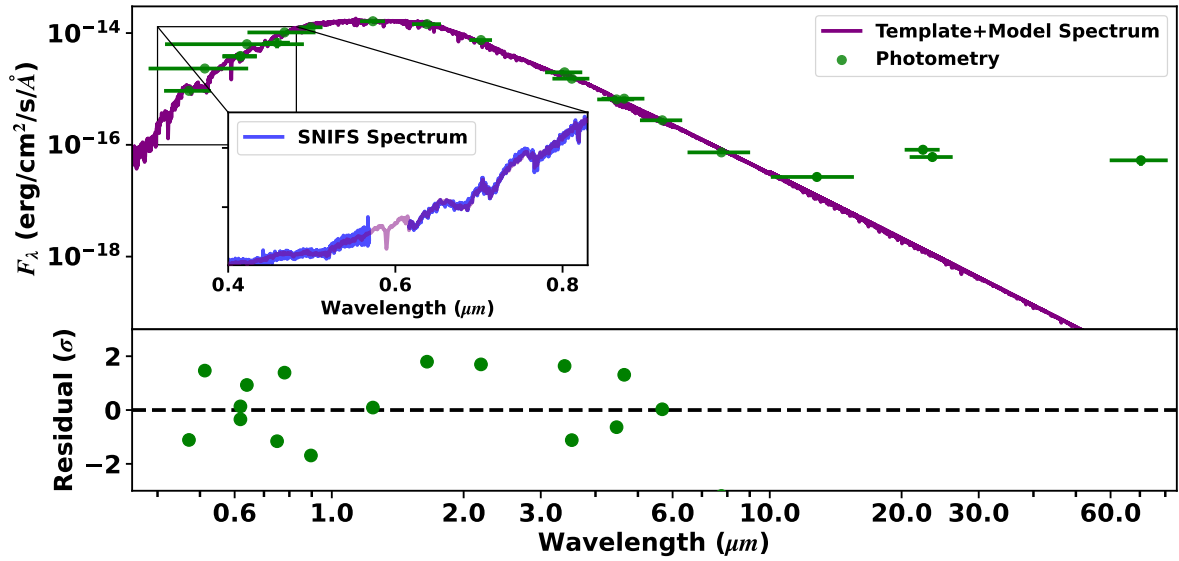
Extended Data Figure 1: Radial velocities and signal fit models

Radial velocities of IRAS 04125+2902 phased to the period of the planet. RVs from APOGEE are shown as stars, those from IGRINS are shown as squares, and those from HPF are shown as circles colored by the stellar rotation phase (with an arbitrary zero point). Error bars represent the 1σ uncertainties. We show the expected signals from a 0.5 and 1 M_J companion, as well as the 95% upper-mass limit (0.3 M_J) and 100 random draws from the fit posterior. The long term RVs rule out any companion of stellar mass, and the best-fit of the HPF measurements constrains the planet's upper mass limit.

Epoch (BJD)	Absolute RV (km s^{-1})	$\sigma_{Abs. RV}$ (km s^{-1})	Relative RV (m s^{-1})	$\sigma_{Rel. RV}$ (m s^{-1})	Source
2457050.603	17.174	0.097	95.7	97.3	IGRINS
2458090.937	16.923	0.091	-155.9	91.4	IGRINS
2458499.666	17.088	0.036	9.5	35.6	APOGEE
2458503.684	17.192	0.048	113.5	48.3	APOGEE
2458744.995	16.933	0.030	-145.5	30.2	APOGEE
2458854.603	17.069	0.040	-9.5	39.5	APOGEE
2460306.817	16.91	0.10	10.7	27.0	HPF
2460307.821	16.87	0.11	-108.4	31.0	HPF
2460308.808	17.00	0.12	21.6	34.9	HPF
2460312.574	16.93	0.11	-0.9	33.6	HPF
2460313.795	16.98	0.13	-51.6	35.5	HPF
2460319.773	16.80	0.16	-123.9	44.3	HPF

Extended Data Table 3: Radial velocity measurements of IRAS 04125+2902

For IGRINS and APOGEE, the relative RVs are normalized to each other. For HPF, the relative RVs are the extracted values using the empirical template, as described in text. Times in in Barycentric Dynamical Time, although epochs are not measured with sufficient precision to distinguish.



Extended Data Figure 2: SED fit of IRAS 04125+2902

Example fit to the SED and residuals (in σ), showing a combination of a template and atmospheric model (purple) compared to the observed photometry (green). The vertical errors are the photometric uncertainties (in almost all cases, smaller than the size of the symbol), while the horizontal error bars indicate the width of the filter. The inset shows the template compared to the observed SNIFS spectrum of IRAS 04125+2902.

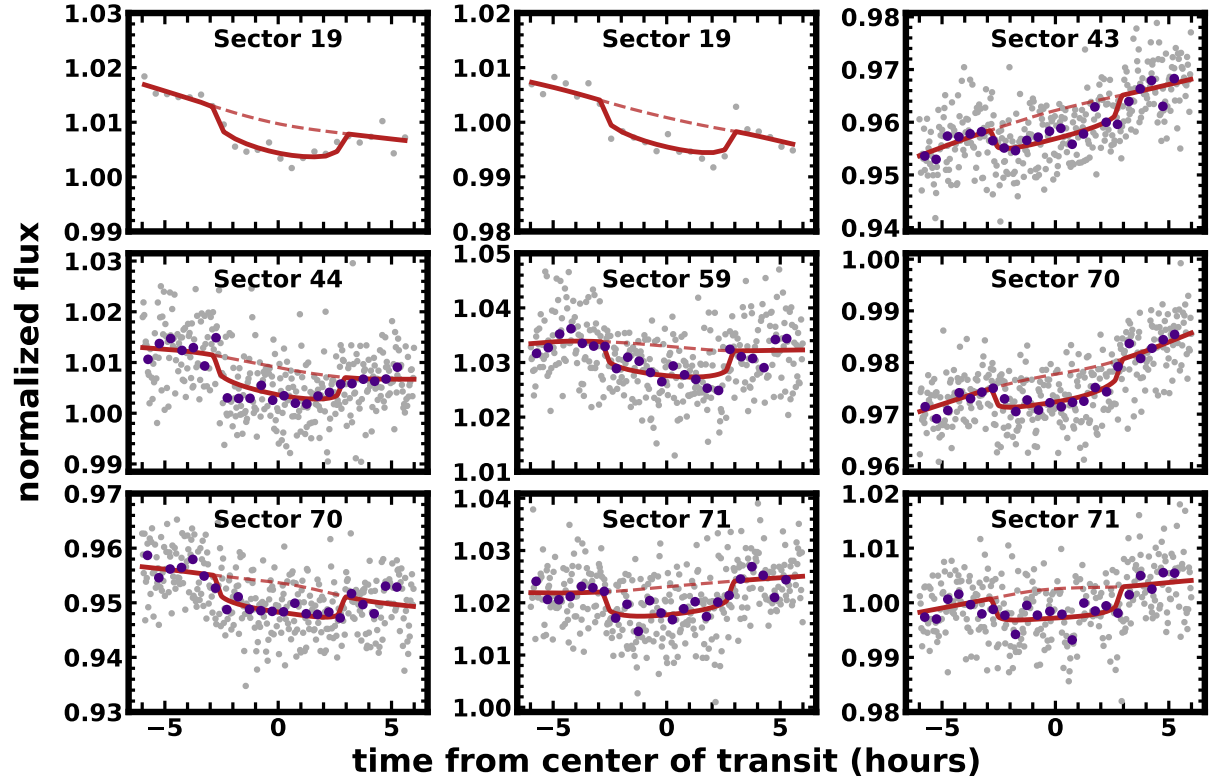
Description	Parameter	Value
Measured Parameters		
Initial transit mid-point	T_0 (BJD-TBD)	2458821.8251 ± 0.0033
Orbital Period	P (days)	$8.834978 \pm 2.8 \times 10^{-5}$
Planet-to-star radius ratio	$R_P/R_\star$	$0.0679^{+0.0028}_{-0.0025}$
Impact parameter	b	$0.34^{+0.24}_{-0.23}$
Stellar density	$\rho_\star$ ($\rho_\odot$)	$0.256^{+0.047}_{-0.087}$
<i>TESS</i> limb-darkening coefficient	$q_{1,1}$	$0.29^{+0.17}_{-0.14}$
<i>TESS</i> limb-darkening coefficient	$q_{2,1}$	$0.321^{+0.098}_{-0.1}$
GP Parameters		
Natural logarithm of period	$\ln(P)$	$2.52^{+0.16}_{-0.15}$
Natural logarithm of amplitude	$\ln(\text{amp})$	$-5.82^{+0.18}_{-0.2}$
Quality factor	$\ln(Q)$	$0.564^{+0.031}_{-0.021}$
Derived Parameters		
Semi-major axis to stellar radius ratio	$a/R_\star$	$11.42^{+0.66}_{-1.0}$
Orbital inclination	i ($^\circ$)	$88.3^{+1.2}_{-1.6}$
Transit duration (first to fourth contact)	T_{14} (days)	$0.2498^{+0.007}_{-0.0054}$
Planet radius	R_P (R_J)	$0.958^{+0.077}_{-0.075}$
Semi-major axis	a (AU)	$0.077^{+0.0069}_{-0.01}$
Equilibrium temperature [†]	T_{eq} (K)	$854.0^{+59.0}_{-32.0}$

[†] assuming zero albedo

Extended Data Table 4: Properties of IRAS 04125+2902 b
Planet and orbital parameters derived from the *TESS* light curve transit analysis

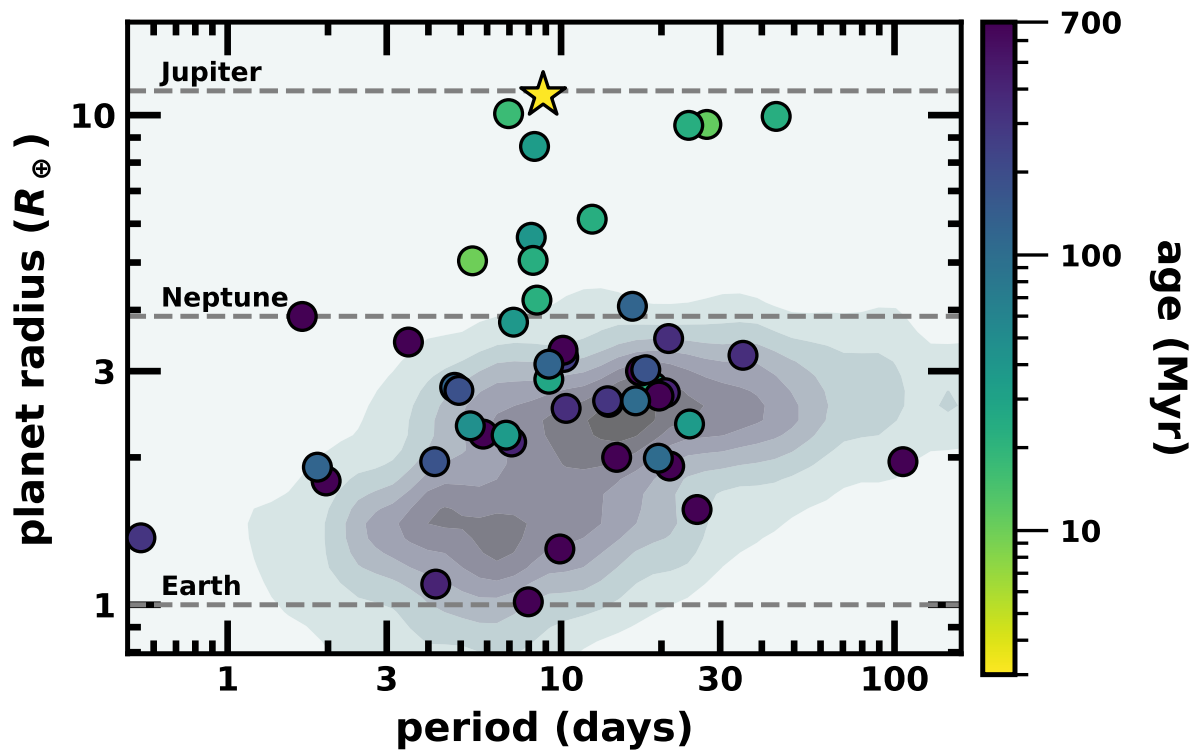
Parameter	Host	Companion	Source
Identifiers			
IRAS	04125+2902	...	IRAS
Gaia	164800235906366976	164800235906367232	<i>Gaia</i> DR3
TIC	56658270	56658273	<i>TESS</i>
TOI	6963	...	<i>TESS</i>
2MASS	J04154278+2909597	J04154269+2909558	2MASS
ALLWISE	J041542.77+290959.5	...	ALLWISE
Astrometry			
α	63.928341	63.927944	<i>Gaia</i> DR3
δ	29.166539	29.165482	<i>Gaia</i> DR3
μ_α (mas yr ⁻¹)	12.104 ± 0.035	12.56 ± 0.16	<i>Gaia</i> DR3
μ_δ (mas yr ⁻¹)	-18.145 ± 0.023	-17.19 ± 0.11	<i>Gaia</i> DR3
π (mas)	6.247 ± 0.027	6.26 ± 0.12	<i>Gaia</i> DR3
Photometry			
<i>TESS</i> (mag)	12.8131 ± 0.0068	15.619 ± 0.013	<i>TESS</i>
G_{Gaia} (mag)	13.9814 ± 0.0017	17.4450 ± 0.0015	<i>Gaia</i> DR3
BP_{Gaia} (mag)	15.595 ± 0.007	20.64 ± 0.13	<i>Gaia</i> DR3
RP_{Gaia} (mag)	12.738 ± 0.004	15.832 ± 0.007	<i>Gaia</i> DR3
u' (mag)	19.718 ± 0.003	23.371 ± 0.441	SDSS DR16
g' (mag)	16.811 ± 0.004	22.986 ± 0.154	SDSS DR16
r' (mag)	14.652 ± 0.003	20.128 ± 0.028	SDSS DR16
i' (mag)	13.648 ± 0.001	16.805 ± 0.005	SDSS DR16
z' (mag)	12.568 ± 0.003	15.259 ± 0.005	SDSS DR16
J (mag)	10.709 ± 0.029	12.726 ± 0.034	2MASS
H (mag)	9.756 ± 0.030	11.807 ± 0.041	2MASS
K_s (mag)	9.376 ± 0.028	11.288 ± 0.028	2MASS
$W1$ (mag)	9.192 ± 0.030	...	ALLWISE
$W2$ (mag)	9.096 ± 0.032	...	ALLWISE
$W3$ (mag)	8.714 ± 0.037	...	ALLWISE
$W3$ (mag)	4.739 ± 0.026	...	ALLWISE
Physical Properties			
P_{rot} (days)	11.31 ± 0.06	...	This work
$v \sin i_\star$ (km s ⁻¹)	7.1 ± 0.5	...	This work
$i_\star$ (°)	> 78	...	This work
F_{bol} (erg cm ⁻² s ⁻¹)	(5.8 ± 0.5) × 10 ⁻¹⁰	(6.6 ± 0.5) × 10 ⁻¹¹	This work
T_{eff} (K)	4080 ± 95	2830 ± 90	This work
A_V (mag)	2.71 ± 0.20	2.85 ± 0.25	This work
$R_\star$ ($R_\odot$)	1.45 ± 0.10	0.96 ± 0.12	This work
$L_\star$ ($L_\odot$)	0.466 ± 0.041	0.050 ± 0.004	This work
$M_\star$ ($M_\odot$)	0.70 ± 0.04	0.17 ± 0.04	This work
Age (Myr)		3.3 ^{+0.6} _{-0.5}	This work

Extended Data Table 5: Parameters of the host star and companion
Properties of the host star IRAS 04125+2902 and wide binary companion TIC 56658273



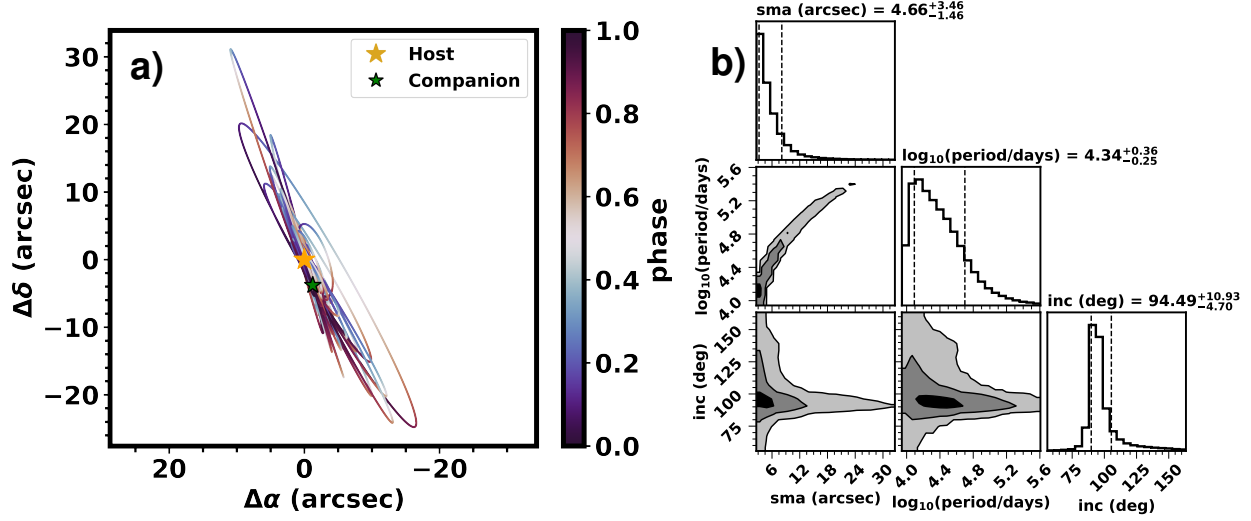
Extended Data Figure 3: Individual transits of IRAS 04125+2902 b from *TESS*

Representative transits from each *TESS* sector (gray points). SPOC data in sectors 43, 44, 59, 70, and 71 are binned to 30 minute intervals (purple points) for a fair comparison to sector 19 (30-minute FFI only). The combined GP and transit model is shown as the solid red line with a dashed line showing the GP fit without the transit.



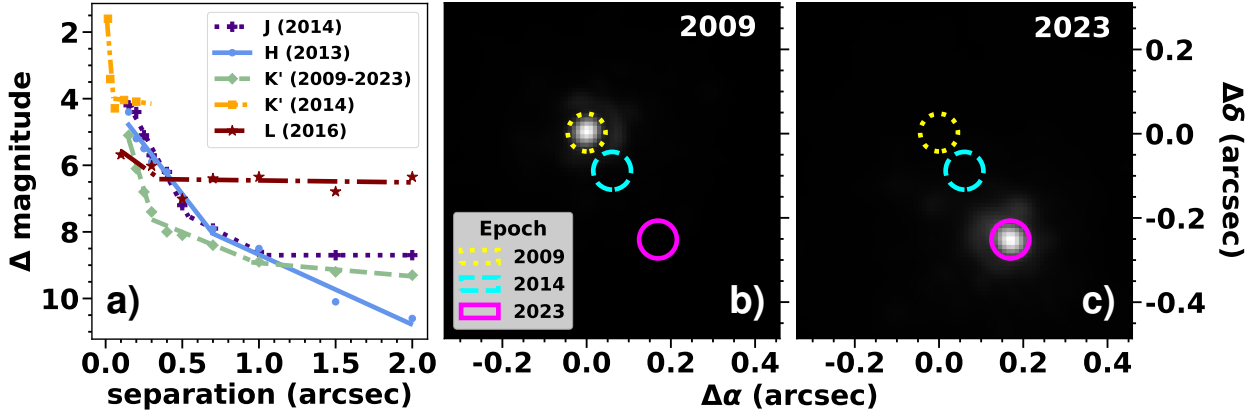
Extended Data Figure 4: IRAS 04125+2902 b in comparison to other transiting systems

The contour distribution of (primarily older) planets discovered by *Kepler* and *K2* ¹¹³ overlapped with the young (< 700 Myr) transiting systems discovered in a cluster or association. The young planets are colored by their approximate age in log space. IRAS 04125+2902 b is marked with a star and sits high in radius compared to older systems. Planet properties from ¹¹⁴.



Extended Data Figure 5: Orbital properties of the binary companion

a) 100 random fits of the orbit of TIC 56658273 colored by the orbital phase. The orange star represents the location of the host star, IRAS 04125+2902, and the green stars represent the measured relative locations of TIC 56658273. The 1σ uncertainties of the locations of TIC 56658273 are smaller than the data points, and the individual locations are indistinguishable at this scale. **b)** Corner plot of the parameters of the wide binary companion. The dashed lines represent the 16th and 84th percentile of the distribution. 99% of points are shown for clarity. The inclination of the orbit is highly consistent with edge-on.



Extended Data Figure 6: Imaging data of IRAS 04125+2902

a) Contrasts from high-resolution data. We show the deepest data for each band, but additionally separating K -band imaging (green) and K -band NRM (yellow) as they cover different angular separations. A simple break-point linear fit for each band is shown for clarity. **b) & c)** AO images from Keck/NIRC2 of IRAS 04125+2902 across 2 epochs with circles representing the previous/future locations: 2009 (dotted yellow), 2014 (dashed blue), and 2023 (solid pink). Based on the *Gaia* proper motions, the star has moved ~ 305 mas ($6 \lambda/D$) over the 14 year period spanned by the Keck/NIRC2 data, which is greater than the PSF width of the star. We can see there are no stars coming in or out of view that could be causing the observed transit signal.