

## Asteroseismology of the Nearby K-Dwarf $\sigma$ Draconis using the Keck Planet Finder and TESS

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## ABSTRACT

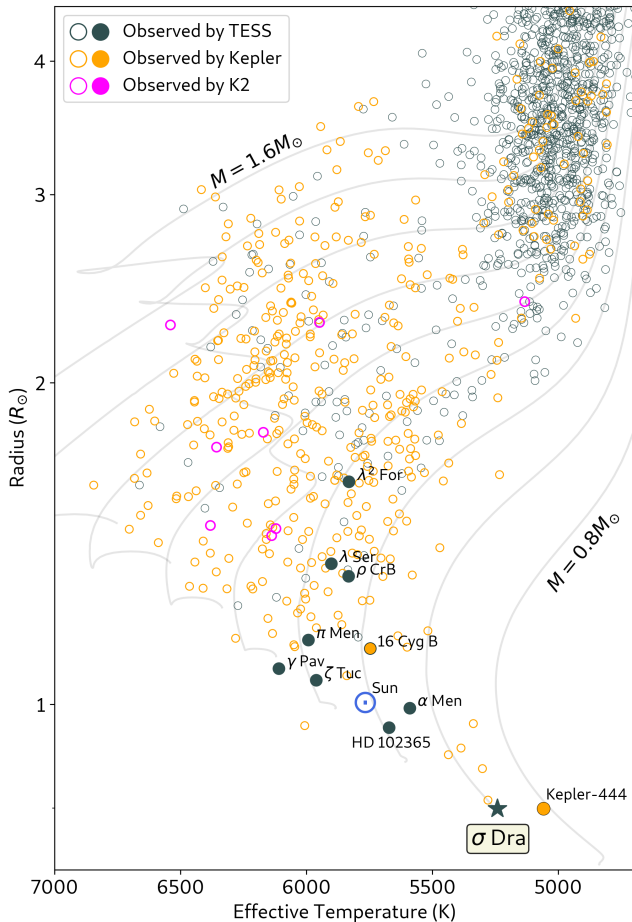
Asteroseismology of dwarf stars cooler than the Sun is very challenging due to the low amplitudes and rapid timescales of oscillations. Here, we present the asteroseismic detection of solar-like oscillations at 4-minute timescales ( $\nu_{\max} \sim 4300\mu\text{Hz}$ ) in the nearby K-dwarf  $\sigma$  Draconis using extreme precision Doppler velocity observations from the Keck Planet Finder and 20-second cadence photometry from NASA’s Transiting Exoplanet Survey Satellite. The star is the coolest dwarf star to date with both velocity and luminosity observations of solar-like oscillations, having amplitudes of  $5.9 \pm 0.8 \text{ cm s}^{-1}$  and  $0.8 \pm 0.2 \text{ ppm}$ , respectively. These measured values are in excellent agreement with established luminosity-velocity amplitude relations for oscillations and provide further evidence that mode amplitudes for stars with  $T_{\text{eff}} < 5500 \text{ K}$  diminish in scale following a  $(L/M)^{1.5}$  relation. By modeling the star’s oscillation frequencies from photometric data, we measure an asteroseismic age of  $4.5 \pm 0.9 \text{ (ran)} \pm 1.0 \text{ (sys)} \text{ Gyr}$ . The observations demonstrate the capability of next-generation spectrographs and precise space-based photometry to extend observational asteroseismology to nearby cool dwarfs, which are benchmarks for stellar astrophysics and prime targets for directly imaging planets using future space-based telescopes.

## 1. INTRODUCTION

Asteroseismology provides a powerful tool for measuring the fundamental properties of Sun-like stars, including masses and ages. However, the oscillation amplitudes of main-sequence stars cooler than the Sun are small, which makes detecting such oscillations difficult even with high-precision space-based photometry. A solution is to perform asteroseismology using radial velocities (RV), which are much less affected by stellar granulation noise than photometry (Harvey 1988; Grundahl et al. 2008; Kjeldsen & Bedding 2011) and permit a higher signal-to-noise detection of stellar oscillations. Indeed, the majority of asteroseismic detections before the era of space-based photometry were made using RVs (see reviews by Chaplin & Miglio 2013; Bedding 2014; García & Ballot 2019), including several Sun-like stars such as  $\alpha$  Cen A & B (Carrier & Eggenberger 2006; Kjeldsen et al. 2005), 18 Sco (Bazot et al. 2011),  $\tau$  Ceti (Teixeira et al. 2009), and  $\mu$  Ara (Bouchy & Carrier 2001). Even so, the primary targets were nearby stars with temperatures similar to or hotter than the Sun, as existing instruments required many nights of observation to detect Doppler variations at the  $\text{cm s}^{-1}$  level. Subsequently, NASA’s *Kepler* mission provided exquisite photometry of several main sequence stars cooler than the Sun (Campante et al. 2015; Lund et al. 2017), but their faintness is prohibitive for detailed ground-based follow-up.

Two recent developments have enabled a more systematic application of asteroseismology to nearby cool dwarfs. First, the introduction of 20-second cadence photometry in NASA’s Transiting Exoplanet Survey Satellite’s (TESS, Ricker et al. 2014) extended mission has greatly improved the photometric precision of bright stars (Huber et al. 2022). Second, next-generation RV spectrographs on 8 m class-telescopes like the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO, Pepe et al. 2021) aboard the Very Large Telescope (VLT) now have the efficiency to obtain high-cadence RVs with extreme precision. A prime example is the recent detection of oscillations in  $\epsilon$  Ind A with VLT/ESPRESSO, making it the coolest dwarf with detected oscillations to date (Campante et al. 2024; see also Lundkvist et al. 2024).

Here, we present the clear detection of solar-like oscillations in the nearby K-dwarf  $\sigma$  Dra (Alsafi; HIP 96100; HD 185144) from TESS 20-second cadence photometry and from radial velocity data by the Keck Planet Finder (KPF). Observations of  $\sigma$  Dra are the first asteroseismic observations with KPF, which is a newly-commissioned RV spectrograph at the W. M. Keck Observatory in Hawai’i. The dedicated fast-readout mode of KPF (readout time 15 seconds), combined with the 10-m aperture of the Keck telescope, makes KPF a highly efficient RV asteroseismology instrument.



**Figure 1.** Plot of radius versus effective temperature showing stars with solar-like oscillations detected via photometry.  $\sigma$  Dra is the coolest dwarf star to have solar-like oscillations detected using TESS photometry to date. Also shown are other dwarfs and subgiants with solar-like oscillations observed by TESS (Hatt et al. 2023), by the *Kepler* mission (Lund et al. 2017; Serenelli et al. 2017; Silva Aguirre et al. 2017), and by the *K2* mission (González-Cuesta et al. 2023). Highlighted are several dwarf stars for which solar-like oscillations have been detected and analyzed using space-based photometry —  $\alpha$  Men (Chontos et al. 2021), 16 Cyg A/B (Metcalf et al. 2012),  $\lambda^2$  For (Nielsen et al. 2020),  $\pi$  Men,  $\gamma$  Pav,  $\zeta$  Tuc (Huber et al. 2022),  $\rho$  CrB (Metcalf et al. 2021),  $\lambda$  Ser (Metcalf et al. 2023), HD 102365, and Kepler-444 (Campante et al. 2015). The radii and effective temperatures in this plot use measurements from the TESS Input Catalog (Stassun et al. 2019, DOI: 10.17909/fwdt-2x66), with MIST evolutionary tracks (Choi et al. 2016) displayed in the background.

To date,  $\sigma$  Dra is the coolest dwarf star that has oscillations detected by TESS (Fig. 1), which also makes it the coolest dwarf star for which both luminosity and velocity measurements of its oscillations has been obtained. Understanding the relationship between luminosity and velocity measurements of solar-like oscilla-

tions is useful for improving models of stellar convection (e.g., Houdek et al. 1999; Houdek 2010; Zhou et al. 2021) and for estimating activity levels of exoplanet hosts (Yu et al. 2018).  $\sigma$  Dra is a particularly valuable target for examining and calibrating this relationship, given the scarcity of measured solar-like oscillations in dwarf stars cooler than the Sun.

At a distance of 5.76 parsecs from the Sun,  $\sigma$  Dra is among the closest main-sequence stars to the Solar System (Reylé et al. 2021) and is an important benchmark target in stellar astrophysics. It serves as a standard star for radial velocity measurements (Soubiran et al. 2018) and for the calibration of photometric systems (e.g., Salsi et al. 2020; Huang et al. 2015; Bell et al. 1994). In addition, the star is a prime target for long-term stellar activity monitoring (e.g., Boro Saikia et al. 2018; Isaacson & Fischer 2010; Martínez-Arnáiz et al. 2010; Wilson 1963) and detailed chemical abundance surveys in the solar neighborhood (e.g., Ramírez et al. 2012; Tautvaišienė et al. 2020). Due to its proximity,  $\sigma$  Dra has also been a target of interest in searches for nearby exoplanets (e.g., Beichman et al. 1999; Wittenmyer et al. 2006; Fischer et al. 2014; Motalebi et al. 2015; Rosenthal et al. 2021). Despite the lack of confirmed planets orbiting  $\sigma$  Dra to date, it remains a promising candidate host star for exoplanet surveys using the latest radial velocity instruments (Gibson et al. 2016; Jurgenson et al. 2016) and direct imaging approaches (Bowens et al. 2021; Werber et al. 2023).

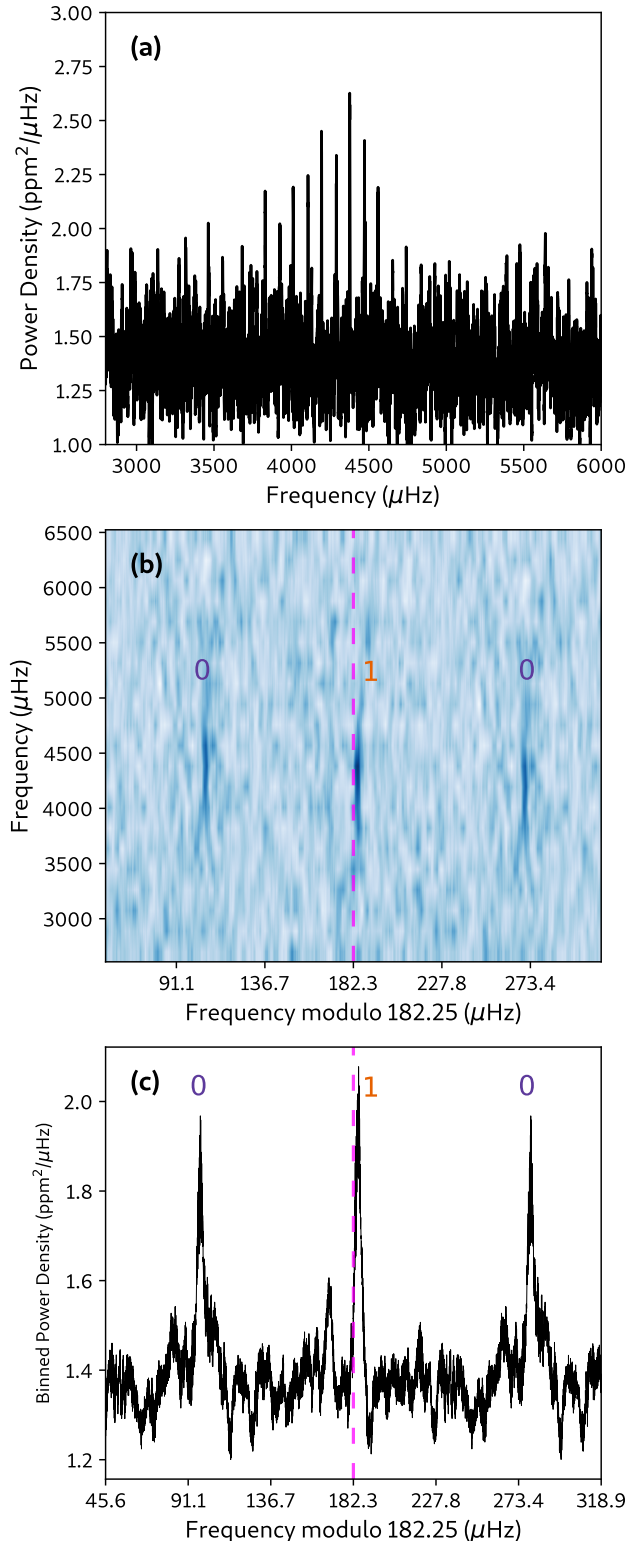
$\sigma$  Dra is identified as a target of high priority (Rank A) in the NASA ExEP Mission Star List for the Habitable Worlds Observatory (HWO, Mamajek & Karl 2023). Therefore, the detailed characterization of the star’s fundamental properties — such as its luminosity and age — is critical for pinpointing the extent of its habitable zone (e.g., Kopparapu et al. 2013; Rushby et al. 2013; Kane 2014, 2018), assessing the long-term dynamical stability of planetary orbits (Davies et al. 2014), and assessing the habitability timescales of planetary atmospheres (e.g., Lammer et al. 2018; Bixel & Apai 2020). With the detailed profiling of photometric, spectroscopic, and activity measurements for HWO targets well underway (Harada et al. 2024), asteroseismology from TESS and next-generation extreme-precision radial velocity (EPRV) instruments is uniquely positioned to contribute to the ambitious goal of studying  $\sim 25$  potentially habitable worlds, the goal envisioned by the Astro 2020 Decadal Survey (National Academies of Sciences & Medicine 2023).

## 2. TESS 20-SECOND CADENCE PHOTOMETRY

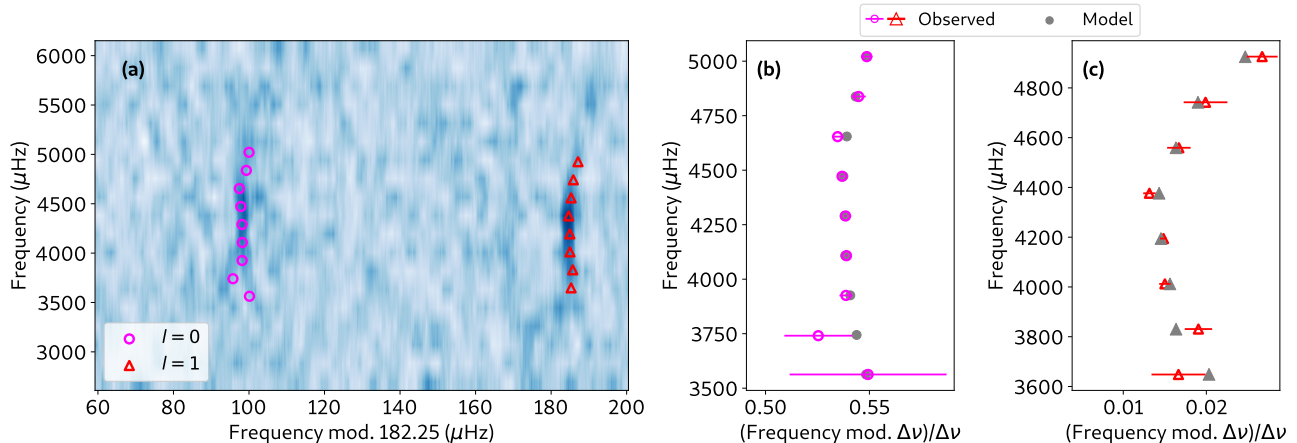
Located within TESS’s Northern Continuous Viewing Zone,  $\sigma$  Dra was observed at 20-second cadence during 14 sectors between July 2021 and January 2023, corresponding to Sectors 41-60. The use of 20-second cadence data places the high-frequency pulsations of the star well below the Nyquist frequency of 25 mHz and diminishes the attenuation of oscillation amplitudes due to averaging during the exposures. Importantly, TESS’s 20-second cadence data also mitigates the reduction in effective exposure time as a result of onboard cosmic ray mitigation, which significantly improves the photometric precision of observations for bright stars ( $V \lesssim 8$ ), subsequently increasing the detectability of oscillation modes (Huber et al. 2022). Here, we use PDCSAP light curves as reduced by the TESS Science Processing Operations Center (SPOC) pipeline (Jenkins et al. 2016), which are available on the Mikulski Archive for Space Telescopes (DOI: 10.17909/t9-st5g-3177).

The power spectrum of  $\sigma$  Dra is shown in Fig. 2a-b, in which excess power corresponding to solar-like oscillations is observed at frequencies of 3500–5000  $\mu\text{Hz}$ . We note that this range of frequencies is commensurate with a predicted frequency at maximum power,  $\nu_{\text{max}} = 3762 \mu\text{Hz}$  from the revised Asteroseismic Target List (Hey et al. 2024), which also predicts a detection likelihood of 100%. Using the pySYD pipeline (Chontos et al. 2022), we estimate a  $\nu_{\text{max}}$  of  $4250 \pm 150 \mu\text{Hz}$  and a large frequency separation of  $\Delta\nu = 182.3 \pm 0.3 \mu\text{Hz}$ . The photometric data has a white noise level of 0.2 ppm based on the noise floor estimates at frequencies above 7000  $\mu\text{Hz}$  from the amplitude spectrum.

The frequency échelle diagram of the power spectrum (Fig. 2b) reveals oscillation modes forming two distinct ridges. We identified the left ridge with  $l = 0$  modes and the other with  $l = 1$  modes, by relying on established relations between  $\Delta\nu$  and the p-mode frequency offset ( $\epsilon$ , White et al. 2011; Ong & Basu 2019) and by comparing the mode pattern (e.g., Bedding & Kjeldsen 2010) with that from Kepler-444 (Campante et al. 2015), which is another K-type dwarf with a similar  $\Delta\nu$  value. To measure the frequencies of these oscillation modes, we adopted ‘peakbagging’ approaches using Lorentzian mode-profile fitting (Li et al. 2020; Breton et al. 2022) and iterative sine-wave fitting (Frandsen et al. 1995; Kjeldsen et al. 2005; Bedding et al. 2007). A final list is presented in Table 1, which comprises mode frequencies for which all peakbagging approaches agreed to within one standard deviation. The final list adopts values from a single Lorentzian mode-profile fitting method, with corrections based on the stellar line-of-sight Doppler velocity shift (Davies et al. 2014) applied assuming a radial



**Figure 2.** Solar-like oscillations of  $\sigma$  Dra as observed from 14 Sectors of TESS photometry (July 2021 to January 2023). (a) The power spectral density of the star smoothed with 3  $\mu\text{Hz}$ -wide boxcar filter. (b) The replicated échelle diagram of the smoothed power spectrum (Bedding 2012). (c) The collapsed replicated échelle diagram. The dashed line in panels (b) and (c) corresponds to  $\Delta\nu = 182.25 \mu\text{Hz}$  and the numbers identify the  $l = 0$  and  $l = 1$  mode sequences.



**Figure 3.** Mode identification of  $\sigma$  Dra’s oscillation spectrum from TESS photometry. (a) Extracted radial ( $l = 0$ ) and dipole ( $l = 1$ ) oscillation mode frequencies plotted on the échelle diagram of the smoothed power spectrum. (b,c) Comparison of observed mode frequencies with those predicted by the best-fitting stellar model by the TM2 modeling team (Section 4.1), which returned a reduced  $\chi^2$  value of 1.02.

velocity of  $v_r = 26.55 \pm 0.13 \text{ km s}^{-1}$  as reported by *Gaia* DR3 (Katz et al. 2023).

Figure 3a shows the extracted mode frequencies along with their identification as radial ( $l = 0$ ) and dipole ( $l = 1$ ) modes. The collapsed échelle diagram of the oscillation spectrum in Figure 2c. There is a hint of quadrupole ( $l = 2$ ) modes to the left of the  $l = 0$  peak but the presence of statistically significant modes could not be determined with confidence within the oscillation spectrum on a mode-by-mode basis.

### 3. RADIAL VELOCITIES

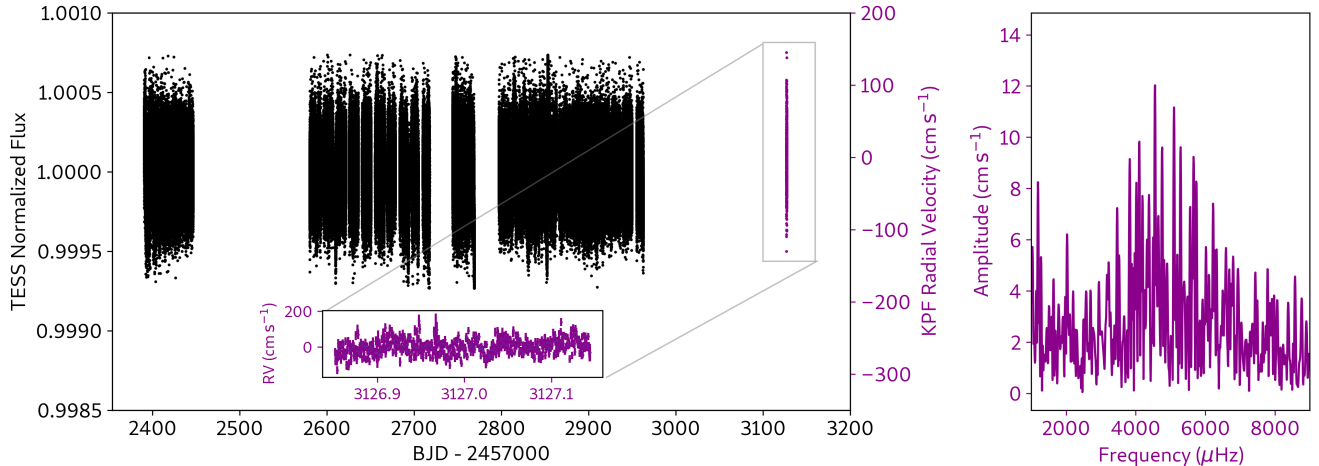
We obtained a radial velocity (RV) time series of  $\sigma$  Dra using the Keck Planet finder (KPF, Gibson et al. 2016, 2018, 2020). KPF is a fiber-fed echelle spectrometer that was commissioned at the W.M. Keck Observatory in April 2023, designed to achieve an instrumental Doppler measurement precision of  $30 \text{ cm s}^{-1}$  or better. The KPF main spectrometer spans 445–870 nm in two channels, each with three science slices, with a median resolving power of 97,000. Wavelength calibration is provided by a commercial laser frequency comb (LFC) from Menlo Systems, a broadband Fabry-Pérot etalon, and hollow cathode lamps (ThAr and UNE). KPF operates in “standard” and “fast” readout mode. The latter provides readout times of 15 seconds designed for asteroseismic observations and other rapid-cadence applications. This rapid readout speed, combined with the 10-m aperture of Keck, makes KPF a very efficient extreme-precision radial velocity instrument for asteroseismology. While KPF fast-readout solar observations have already demonstrated exquisite RV precision (Rubenzahl et al. 2023), the observations presented here are

**Table 1.** Peakbaggged oscillation frequencies of  $\sigma$  Dra from TESS photometry, corrected for stellar line-of-sight Doppler velocity shifts.

Frequency, $f$ ( $\mu\text{Hz}$ )	$\sigma_f$ ( $\mu\text{Hz}$ )	$l$	$n$
3563.0	6.9	0	18
3648.11	0.59	1	18
3740.8	3.0	0	19
3830.81	0.30	1	19
3925.52	0.56	0	20
4012.32	0.13	1	20
4107.82	0.15	0	21
4194.547	0.077	1	21
4289.99	0.14	0	22
4376.49	0.14	1	22
4471.93	0.16	0	23
4559.39	0.26	1	23
4653.80	0.50	0	24
4742.23	0.48	1	24
4837.90	0.62	0	25
4925.73	0.34	1	25
5020.87	0.50	0	26

the first KPF fast-readout observations of a star other than the Sun.

We obtained 7 hours of continuous observations of  $\sigma$  Dra with KPF on June 30, 2023, in excellent conditions. We used an exposure time of 30 seconds, yielding an average SNR of 640 at  $5500\text{\AA}$  (all three spectral slices combined), a median cadence of 45 seconds and a total of 560 RV datapoints with a median error of  $21 \text{ cm s}^{-1}$ . The spectra were reduced from 2D images to 1D spec-



**Figure 4.** (Left) Observations of  $\sigma$  Dra from TESS Sector 41-60 photometry in black and from Keck Planet Finder radial velocities (RVs) in purple. The inset is a zoom-in of the RV time series spanning 7 hours on June 20 2023. (Right) RV amplitude spectrum of  $\sigma$  Dra, in which a power excess corresponding to solar-like oscillations can be seen at frequencies  $\sim 4000 - 6000 \mu\text{Hz}$ .

tra with the KPF Data Reduction Pipeline (DRP)<sup>1</sup>. The KPF DRP performs quadrant stitching, flat-fielding, order tracing, optimal extraction, and wavelength calibration.

Stellar RVs are computed via a cross-correlation (CCF) mask approach. To measure the RVs, a Gaussian+top-hat function is used to fit an analytic mean of the CCF. A separate RV is computed for each KPF slice (3x) and camera (Green, Red). Slice RVs are combined using a weighted average, with the relative weights being proportional to photon-limited RV uncertainty in a given slice. The individual camera RVs are then median-subtracted and corrected for instrumental drift using the LFC spectra recorded before and after the stellar RV time series. The two drift-corrected stellar RV time series are then combined using a flux-weighted mean. The KPF fast read-mode data suffers from substantial charge transfer inefficiency (CTI) in one of the four readout amplifiers on both CCDs (Rubenzahl et al. 2023). To avoid adding significant systematic RV error from the contaminated spectra in these detector quadrants, spectral masks are applied to selectively mask out regions of the spectra that fell on the two bad amplifiers (one on the Green CCD, the other on the Red). A similar approach was applied to solar data by Rubenzahl et al. (2023). We note that the absolute RVs returned from the KPF CCF pipeline are consistent to within  $\sim 100 \text{ m s}^{-1}$  of the *Gaia* DR3 line-of-sight velocity.

Figure 4 shows the time series of our RV observations. The RMS of the time series is  $20.3 \text{ cm s}^{-1}$ , which includes the signal due to oscillations. The amplitude

spectrum shows a clear detection of oscillations. The average white noise level in the amplitude spectrum is  $1.89 \text{ cm s}^{-1}$ , as measured at frequencies above  $7000 \mu\text{Hz}$ .

## 4. ASTEROSEISMIC ANALYSIS

### 4.1. Stellar Modeling

Alongside mode frequencies in Table 1, we include measurements of effective temperature ( $T_{\text{eff}}$ ), metallicity ( $[M/H]$ ), and interferometric stellar radius ( $R$ ) as inputs for the modelling of  $\sigma$  Dra. The adopted values of  $T_{\text{eff}} = 5290 \pm 90 \text{ K}$  and  $[Fe/H] = -0.23 \pm 0.05 \text{ dex}$  are obtained as averaged measurements from the PASTEL catalogue<sup>2</sup> (Soubiran et al. 2016), with uncertainties derived as the dispersion across those measurements. For a radius constraint, we adopt the linear radius measurement of  $R = 0.778 \pm 0.008 R_{\odot}$  based on interferometric measurements by Boyajian et al. (2008). We note that the interferometrically-derived  $T_{\text{eff}}$  from that study,  $5299 \pm 32 \text{ K}$ , is consistent with our adopted value from the PASTEL catalog.

To derive stellar properties for  $\sigma$  Dra, modelling runs were conducted by four teams (TM1, TM2, JO, YL) using the ASTEC and MESA stellar evolution codes, with the ADIPLS or GYRE pulsation codes to simulate oscillations. Details of the input physics across each run are presented in Appendix A. We found a reasonable agreement for stellar mass and luminosity across modelling runs, with individual estimates spanning  $0.81 - 0.85 M_{\odot}$  and  $0.40 - 0.42 L_{\odot}$ . Inferred stellar ages were significantly more dispersed, with a range of  $3.2 - 6.1 \text{ Gyr}$  around a

<sup>1</sup> <https://github.com/Keck-DataReductionPipelines/KPF-Pipeline>

<sup>2</sup> An updated version of the catalog (Soubiran et al. 2022) give  $T_{\text{eff}} = 5298 \text{ K}$  and  $[Fe/H] = -0.21 \text{ dex}$ , which remain consistent with our adopted values.

median value of  $4.1 \pm 1.1$  Gyr across runs. In Table 2 we report the self-consistent set of stellar parameters from the TM2 team, which yields the smallest difference in age to the median across runs. We report random uncertainties from this adopted solution, as well as systematic uncertainties in the form of standard deviation of the solution across runs.

**Table 2.** Stellar Properties for  $\sigma$  Dra

General Properties	
HIP ID	96100
HD Number	185144
TIC Number	259237827
TESS Magnitude <sup>a</sup>	3.94
Distance <sup>b</sup> (pc)	$5.764 \pm 0.002$
Adopted Properties for Modelling	
$T_{\text{eff}}$ (K) <sup>c</sup>	$5290 \pm 90$
[M/H] (dex) <sup>c</sup>	$-0.23 \pm 0.05$
$R$ ( $R_{\odot}$ ) <sup>d</sup>	$0.778 \pm 0.008$
Derived Parameters	
Mass ( $M_{\odot}$ )	$0.84 \pm 0.01$ (ran) $\pm 0.02$ (sys)
Radius ( $R_{\odot}$ )	$0.772 \pm 0.005$ (ran) $\pm 0.006$ (sys)
Luminosity ( $L_{\odot}$ )	$0.42 \pm 0.04$ (ran) $\pm 0.01$ (sys)
$\log(g)$ (cgs)	$4.589 \pm 0.008$ (ran) $\pm 0.017$ (sys)
Age (Gyr)	$4.54 \pm 0.92$ (ran) $\pm 1.08$ (sys)

<sup>a</sup>Stassun et al. (2019)

<sup>b</sup>From Gaia DR3 (Gaia Collaboration et al. 2021)

<sup>c</sup>Soubiran et al. (2016)

<sup>d</sup>Boyajian et al. (2008)

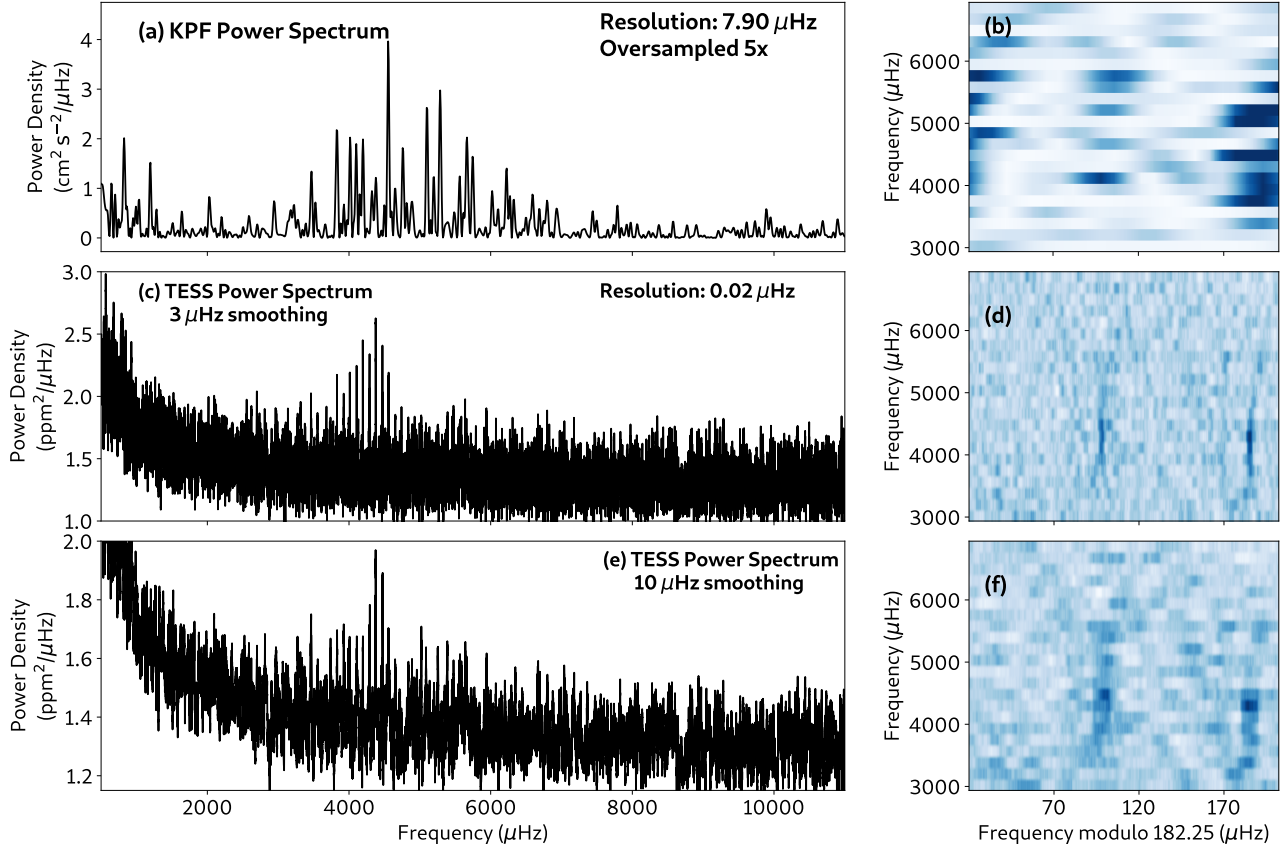
Adding random and systematic uncertainties in quadrature results in a total fractional age uncertainty of about 35%. The large uncertainty relative to cool dwarfs modeled by *Kepler* (e.g., *Kepler*-444,  $\sim 10\%$ , Campante et al. 2015) and warmer dwarfs observed by TESS ( $\sim 20\%$ , Huber et al. 2022) is likely a consequence of the absence of quadrupole ( $l = 2$ ) modes in the modeling process. We discuss the possibility of detecting quadrupole oscillation in Section 4.4, which could improve age estimates substantially. Nonetheless, our derived ages are consistent with the values of 3.0 – 5.7 Gyr estimated across literature using a broad range of measurements, including lithium abundances (Ramírez et al. 2012), activity measurements (Stanford-Moore et al. 2020), and gyrochronology (Barnes 2007; Mamajek & Hillenbrand 2008).

#### 4.2. Oscillations in Photometry versus Radial Velocities

A comparison of RV and photometric power spectra is presented in Figure 5. For low-amplitude oscillations in K-dwarfs, the lack of significant background power from granulation in the RV data is highly advantageous for increasing the S/N of the observed oscillations. As shown by the sloping background in Figs. 5c-d, the granulation background in photometry contributes a significant fraction of the total power in the spectrum. This becomes a factor in limiting the photometric detection of low-amplitude solar-like oscillations in TESS to the brightest stars — a limitation that will not be as severe for extreme-precision radial velocity measurements from KPF. Indeed, we find that the échelle diagram in Fig. 5b reveals structure resembling the vertical mode ridges seen in photometry (Fig. 5e), confirming that the observed power excess in the RV data corresponds to the star’s oscillation modes.

There is an unusual difference in the observed width of  $\sigma$  Dra’s power excess across the RV and TESS photometry. While both power excesses share a low frequency limit of about  $3600 \mu\text{Hz}$ , a pre-whitening analysis of the RV data (see Appendix B) identifies mode frequencies as high as  $6200 \mu\text{Hz}$ , whereas oscillation modes are undetectable in the TESS photometry at frequencies above  $5000 \mu\text{Hz}$  (see Figs. 6a-d). However, Figs. 6e-f show that further heavy smoothing of the TESS power spectrum reveals the marginal presence of p-modes spanning up to  $6000 \mu\text{Hz}$ . The likely reason why these modes are apparent only with heavy smoothing is the decrease of mode heights with frequency, which has been observed to occur drastically for dwarf stars cooler than the Sun (Appourchaux et al. 2014; Lund et al. 2017). Therefore, it is plausible that the heights of high-frequency modes for  $\sigma$  Dra are below the white noise level in the TESS power spectrum. This effect is prominent in the TESS data because the p-modes are well-resolved from the observations, unlike the p-modes in the KPF power spectrum that are based on a time series about 1,900 times shorter than the TESS observations.

Importantly, these differences result in a systematic offset of  $\sigma$  Dra’s frequency at maximum power,  $\nu_{\text{max}}$ , across KPF RVs and TESS photometry. We therefore caution against the use of  $\nu_{\text{max}}$  to characterize the asteroseismic properties of solar-like oscillations in dwarf stars. This caution is further warranted by other sources of offsets in  $\nu_{\text{max}}$  seen within the photometric and multi-wavelength Doppler datasets of the solar oscillation spectrum (Howe et al. 2020). The accurate characterization of solar-like oscillations is particularly relevant for RV searches of Earth-analogue planets. As detailed by Chaplin et al. (2019), the p-mode oscillation amplitudes of host stars can be effectively atten-



**Figure 5.** Oscillations of  $\sigma$  Dra as observed using Keck Planet Finder (KPF) radial velocity measurements (a-b) in comparison with observations using TESS photometry (c-f). The left column presents oscillation power spectra, whereas the right column presents their corresponding frequency échelle diagrams.

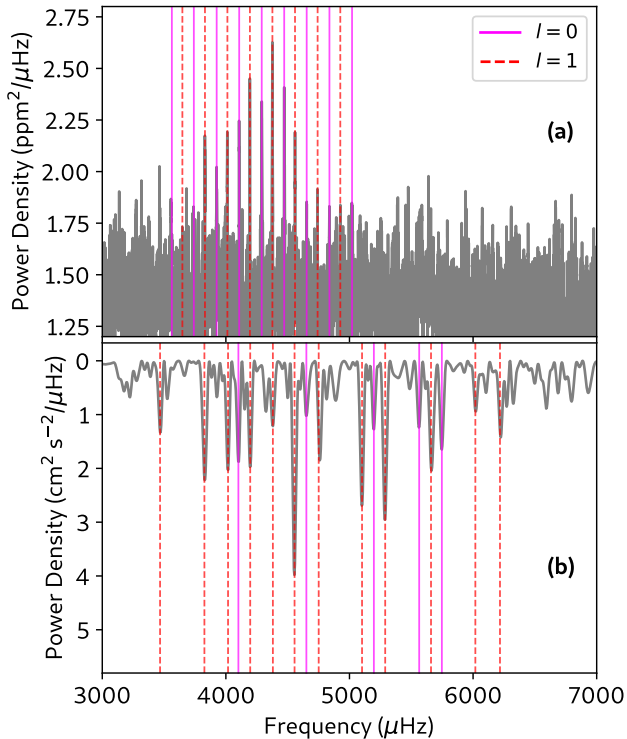
uated by setting exposure times to the stars’ typical oscillation timescales, identified as  $1/\nu_{\max}$ . Following this approach, an incorrect estimate of  $\nu_{\max}$  may lead to sub-optimal observing strategies in which p-mode oscillation amplitudes are not effectively averaged out, which can significantly hinder the identification of subtle signatures within the RV data.

#### 4.3. Oscillation Amplitudes and Prospects for Detections in Cooler Stars

To measure the oscillation amplitudes from the KPF RV data, we follow the approach outlined in Kjeldsen et al. (2005, 2008). In particular, we smooth the RV power density spectrum heavily using a Gaussian window with a FWHM of  $4\Delta\nu$ , followed by the fitting and subtraction of background noise. The maximum power density value corresponding to the smoothed power excess is determined, which is then multiplied by  $\Delta\nu/c$  for its conversion into amplitude per radial mode. Here,  $c$  is taken to be 3.04, which represents the effective number of modes per radial order that is normalised to the amplitudes of radial modes for full-disk velocity observations (Kjeldsen et al. 2008). We measure an amplitude

of  $v_{\text{osc}} = 5.9 \pm 0.8 \text{ cm s}^{-1}$  for  $\sigma$  Dra, which is approximately 33% of that of the Sun’s solar cycle-averaged value of  $v_{\text{osc},\odot} = 18.7 \pm 0.7 \text{ cm s}^{-1}$  (Kjeldsen et al. 2008). We determine the uncertainties for  $v_{\text{osc}}$  by measuring the dispersion of  $v_{\text{osc}}$  calculated from 10,000 time series simulated to have  $\sigma$  Dra’s oscillations as observed with the KPF cadence and observation duration in this study. The simulations are generated using the asteroFLAG Artificial DataSet Generator (AADG3, Ball et al. 2018) using mode frequencies in Table 1 with amplitudes scaled by  $v_{\text{osc}}$ , and a mode linewidth of  $1.5 \mu\text{Hz}$ , a typical value based on observations of *Kepler* main-sequence stars at similar temperatures to  $\sigma$  Dra (Lund et al. 2017). We additionally inject a white noise component with a level identical to that observed in the KPF time series, and thus the noise in the simulations combine contributions from shot noise, realisation noise, and the stochastic behaviour of solar-like oscillations.

Observations of  $\sigma$  Dra’s oscillations in both photometry and radial velocities provides the opportunity to test the Kjeldsen & Bedding (1995) luminosity-velocity



**Figure 6.** A comparison of identified oscillation modes from (a) TESS photometric data (Table 1) with (b) Keck Planet Finder radial velocity data (Appendix B), highlighting the differences in the observed width of the oscillation power excess across the two datasets.

amplitude relation described by the following:

$$A_\lambda = \frac{v_{\text{osc}}/\text{cm s}^{-1}}{(\lambda/550 \text{ nm})(T_{\text{eff}}/5777 \text{ K})} 0.201 \text{ ppm}, \quad (1)$$

where  $A_\lambda$  is the fractional luminosity variation due to oscillations at a given wavelength  $\lambda$ . At the central wavelength  $\lambda = 786.5 \text{ nm}$  of the detector bandpass aboard TESS, we calculate  $A_{786.5} = 1.0 \pm 0.1 \text{ ppm}$  based on the KPF velocity amplitude. This value is in good agreement with the amplitude per radial mode of  $0.8 \pm 0.2 \text{ ppm}$  estimated from TESS photometry. While a more robust test of this relation requires simultaneous luminosity and velocity measurements,  $\sigma$  Dra is the solar-like oscillator with the lowest amplitude to date for which Equation 1 has been examined. The agreement shown here confirms the expected linearity of these low-amplitude oscillations for K-dwarfs and confirms the utility of the luminosity-velocity amplitude relation for predicting the asteroseismic detectability of cool dwarfs.

Another important relation related to asteroseismic detectability is the Doppler velocity p-mode oscillation amplitude scaling relation, which takes the form of  $v_{\text{osc}} \propto (L/M)^s$ . It was proposed by Kjeldsen & Bedding (1995) with  $s = 1$ , based on theoretical models

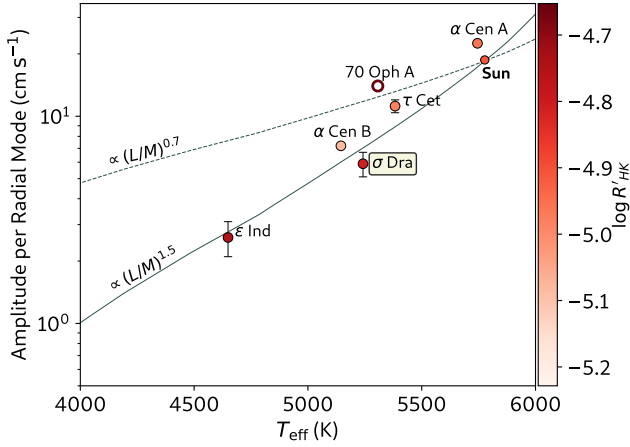
presented by Christensen-Dalsgaard & Frandsen (1983). Subsequently,  $s$  has been predicted theoretically to have a value between 0.7 and 1.5 (e.g., Houdek & Gough 2002; Samadi et al. 2007). However, observational measurements suggest a variation with temperature (Verner et al. 2011), for which the oscillation amplitudes of K-dwarfs diminish more rapidly than for hotter Sun-like stars with decreasing stellar luminosity. In their analysis of the K5 dwarf  $\epsilon$  Ind A, Campante et al. (2024) presented firm evidence of this relation for a K-dwarf with  $T_{\text{eff}} < 5000 \text{ K}$ , showing that its  $L/M$  scaling relation can be described with an exponent ( $s = 1.5$ ) larger than for hotter dwarf stars ( $s \sim 0.7 - 1.0$ ).

In Fig. 7, we present an update to the  $v_{\text{osc}} - T_{\text{eff}}$  plot presented in Fig. 5 of Campante et al. (2024), where we now include our measurements of  $\sigma$  Dra. Similar to  $\epsilon$  Ind A, the  $v_{\text{osc}}$  for  $\sigma$  Dra favors an amplitude scaling relation with an exponent  $s$  of approximately 1.5, which has been suggested by Campante et al. (2024) to be caused by the fact that cooler stars are more likely to have higher surface magnetic activity, which suppresses observed oscillation amplitudes. Given that  $\sigma$  Dra has moderate levels of chromospheric activity ( $\log \mathcal{R}'_{HK} = -4.808 \text{ dex}$ , Boro Saikia et al. 2018), these results corroborate the hypothesis that increased magnetic activity among cooler stars skews the scaling relation's exponent to larger values. This would suggest that the oscillations of old, metal-rich K-dwarfs are more likely to be detected, given their observed decrease of activity with age and metallicity (Fig. 8).

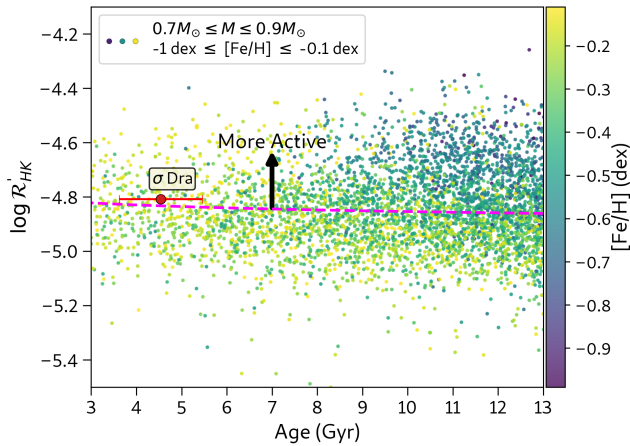
#### 4.4. Quadrupole Oscillation Modes

Our approaches for measuring individual mode frequencies in this study did not identify any significant quadrupole ( $l = 2$ ) p-modes in  $\sigma$  Dra's TESS oscillation spectrum, nor can they be observed clearly in the échelle diagram in Fig. 2b. Such modes greatly improve the age precision obtainable from asteroseismology because their frequencies relative to radial modes provide a measurement of central hydrogen abundance in dwarf stars, which is an indicator of stellar age along the main sequence. Thus, we seek to identify whether any quadrupole modes can be detected in  $\sigma$  Dra's oscillation spectrum.

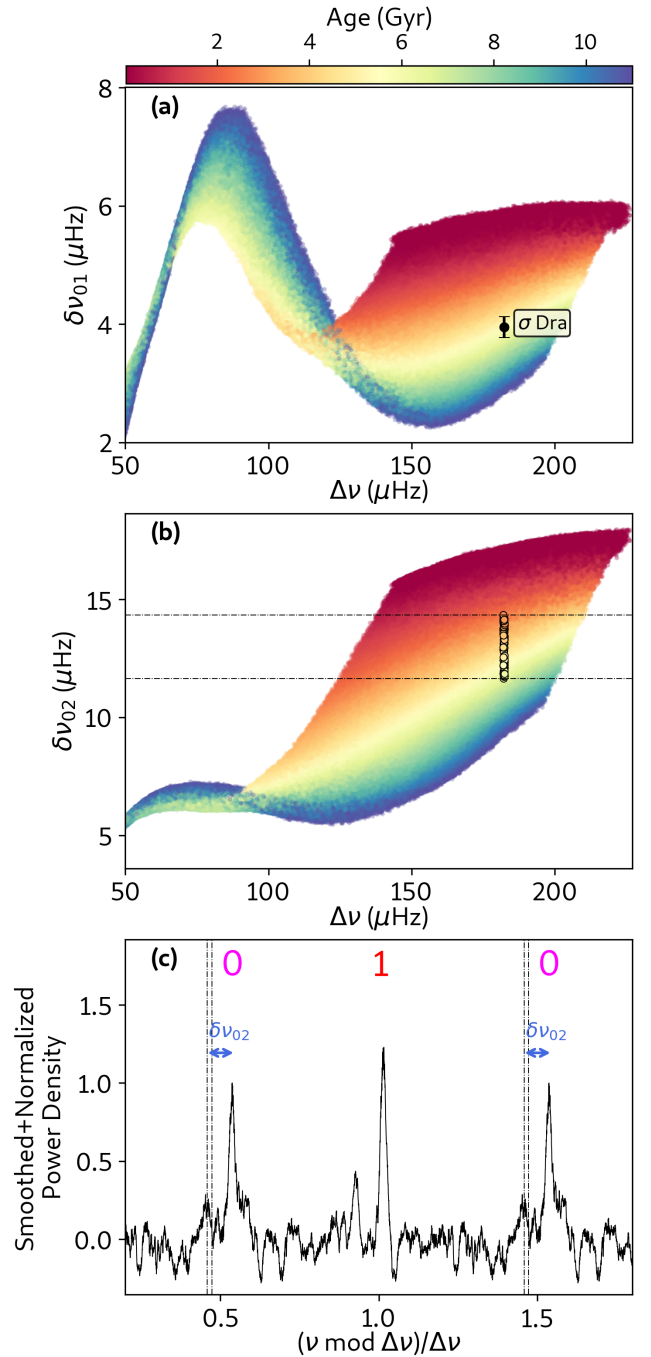
To determine the expected small frequency spacing ( $\delta\nu_{02}$ ) of the star using a grid of models, we first measure the frequency separation between  $l = 0$  and  $l = 1$  frequencies,  $\delta\nu_{01} = \frac{1}{2}(\nu_{n,l=0} + \nu_{n+1,l=0}) - \nu_{n,l=1}$ , averaged across radial orders ( $n$ ). The averaging weight across orders are determined by fitting a Gaussian enve-



**Figure 7.** Comparison of the amplitude of radial mode of  $\sigma$  Dra with those from other cool dwarfs with published measurements. Two scalings of the mode amplitudes are shown, differing in terms of the exponent ( $s = 0.7$ , dotted curve;  $s = 1.5$ , solid curve). The  $L/M$  relations are shown using a 4.57 Gyr, solar-metallicity isochrone computed with the PAdova and TRieste Stellar Evolution Code (PARSEC, Bressan et al. 2012). The value of  $\log \mathcal{R}'_{HK}$  for all other stars besides  $\epsilon$  Ind A (Mamajek & Hillenbrand 2008) are adopted from Gomes da Silva et al. (2021). For  $T_{\text{eff}}$ , values for  $\epsilon$  Ind A and 70 Oph A are from Rains et al. (2020), while those for other stars are from Bruntt et al. (2010).



**Figure 8.** Age and activity of  $\sigma$  Dra relative to a sample of 5,497 K-dwarfs with sub-solar metallicities from the Ye et al. (2024) *Kepler*-LAMOST catalog of FGK-dwarfs with isochrone-derived ages. The dashed line represents the adopted relation  $\log \mathcal{R}'_{HK} = -0.061 \log \frac{\text{Age}}{\text{Gyr}} - 4.244$  that describes the age-activity relation for stars within this mass and metallicity bin. The value of  $\log \mathcal{R}'_{HK}$  for  $\sigma$  Dra is adopted from Boro Saikia et al. (2018), while its age is derived from this study.



**Figure 9.** (a–b) Location of  $\sigma$  Dra on asteroseismic diagrams relative to  $M = 0.7\text{--}1.0 M_{\odot}$  models with a metallicity within 2 standard deviations of  $\sigma$  Dra’s  $[\text{Fe}/\text{H}]$ . The grid of models are emulated using *modelflows* (Hon et al., in review). Panel (a) shows the position of  $\sigma$  Dra on the  $\delta\nu_{01} - \Delta\nu$  diagram. Given  $\sigma$  Dra’s age of  $4.54 \pm 0.92$  Gyr, the highlighted points in panel (b) show models with  $\delta\nu_{02}$  within 2 standard deviations from the star’s age and  $\Delta\nu$ . The  $\delta\nu_{02}$  interval spanned by such models is indicated by horizontal lines. This range of predicted  $\delta\nu_{02}$  is shown in  $\sigma$  Dra’s observed collapsed échelle diagram in panel (c), which is annotated with mode spherical degrees. The spectrum used to construct this diagram is smoothed using a  $3 \mu\text{Hz}$  boxcar filter, while the collapsed échelle diagram is background-subtracted and normalized by dividing by the height of the collapsed  $l = 0$  mode profile.

lope<sup>3</sup> centered about a fiducial frequency value of 4250  $\mu\text{Hz}$ . We measure a value of  $\delta\nu_{01} = 3.95 \pm 0.18 \mu\text{Hz}$ , which is shown in Fig. 9a to be consistent with an age of approximately 5 Gyr from a grid of stellar models.

Next, we query the same grid for all models within 2 standard deviations of  $\sigma$  Dra’s derived age in Table 2 at the same  $\Delta\nu$  and  $[\text{Fe}/\text{H}]$ , which yields models with  $11.6 \mu\text{Hz} \leq \delta\nu_{02} \leq 14.3 \mu\text{Hz}$  as shown in Fig. 9b. This range of  $\delta\nu_{02}$  predicts  $l=2$  modes at  $(\nu \bmod \Delta\nu)/\Delta\nu \sim 0.45$ , which is observed to correspond to a slight excess in power as seen in Fig. 9c. If we assume that the collapsed échelle peak height,  $\mathcal{H}$ , is a proxy for mode visibility, we measure  $\mathcal{H}_{l=1}/\mathcal{H}_{l=0} \sim 1.15$  and  $\mathcal{H}_{l=2}/\mathcal{H}_{l=0} \sim 0.2$ . These correspond approximately to the expected values as seen in the *Kepler* mission for dwarf stars similar in evolution to  $\sigma$  Dra, which are about 1.1 and 0.3 for the relative dipole and quadrupole mode visibility, respectively (c.f. KIC 7970740, Lund et al. 2017). It is thus plausible that the highlighted regions in Fig. 9c do indeed correspond to the quadrupole oscillation modes of  $\sigma$  Dra.

An important caveat for this identification is that it is based on a smoothed spectrum that is averaged (i.e., collapsed) across radial orders. With an estimated amplitude per radial order of  $0.8 \pm 0.2$  ppm (Section 4.3) and a white noise level of 0.2 ppm as estimated at frequencies above 7000  $\mu\text{Hz}$  from the amplitude spectrum, it is likely that individual, low-amplitude quadrupole modes are at the detection limit of the TESS photometry. Meanwhile, EPRV observations can extend beyond this limit to easily detect and measure such modes. As shown for  $\epsilon$  Indi A (Campante et al. 2024), EPRV observations collected over multiple nights provide sufficient frequency resolution to resolve  $\delta\nu_{02}$ , allowing for precise asteroseismic age estimates.

## 5. CONCLUSIONS AND OUTLOOK

We have detected solar-like oscillations in  $\sigma$  Dra using TESS photometry and also with Keck Planet Finder (KPF) in radial velocity (RV).  $\sigma$  Dra represents the coolest dwarf star to date for which oscillations are detected in both photometry and radial velocity data. This discovery consolidates the potential of extreme-precision radial velocity (EPRV) instruments for cool-dwarf asteroseismology, while also highlighting the synergy between TESS and ground-based observatories for precisely characterizing the properties of the most promising candi-

dates of future surveys for habitable zone exoplanets from the Habitable Worlds Observatory.

By modelling oscillation frequencies extracted from TESS photometry, we found an age of 4.54 Gyr for  $\sigma$  Dra with an age uncertainty of 35%. The relatively large uncertainty is due to the lack of clear detectability of quadrupole oscillation modes from the TESS data. The oscillations from TESS also show a lack of detectability for high-frequency modes, whereas such modes are clearly visible from the KPF data. However, smoothing and averaging the oscillation spectrum revealed that information regarding  $\sigma$  Dra’s quadrupole and high-frequency modes may still be recoverable from photometry. Because it is evident that  $\sigma$  Dra’s oscillation amplitudes are at the limit of detectability in TESS, the KPF data has a clear advantage in unambiguously detecting  $\sigma$  Dra’s oscillation modes. Thus, additional nights of EPRV observations are expected to yield a more precise age estimate ( $\sim 10\%$ ) for this star.

With the asteroseismic age estimate having significant potential for improvement, the detailed examination of age-activity relations for  $\sigma$  Dra, which is the subject of a follow-up study (Metcalf et al. in prep), will provide unique insight into the potential habitability of cool, moderately active dwarfs about the same age as the Sun. In relation to  $\sigma$  Dra’s activity levels, we identified that its measured mode amplitudes favor a  $(L/M)^{1.5}$  scaling relation, similar to the Campante et al. (2024) result for  $\epsilon$  Ind A. This further supports the recommendation by Campante et al. (2024) for a calibration of the relation for cool, moderately active dwarfs with  $T_{\text{eff}} < 5500$  K.

With non-contemporaneous photometric and RV measurements, we found that Kjeldsen & Bedding (1995) luminosity-velocity amplitude relation predicts values consistent with those observed from  $\sigma$  Dra, providing direct evidence that the relation holds for cool dwarfs with  $T_{\text{eff}} < 5500$  K. Simultaneous ground- and space-observations of  $\sigma$  Dra will allow a detailed study of differences in the properties of solar-like oscillations as seen by photometric and spectroscopic measurements, which have only been permitted for a few stars to date. Such observations are valuable for enhancing our understanding of the dynamics of turbulent convection at the near-surface layers of cool stars (e.g., Houdek et al. 1999), which in turn improves our modelling of mode pulsation properties and predictions of amplitudes in photometry (Chaplin et al. 2005; Zhou et al. 2021). Because  $\sigma$  Dra is fortuitously located in TESS’s Northern Continuous Viewing Zone, opportunities for simultaneous observations for  $\sigma$  Dra will be abundant, which when combined with a long baseline coverage in the coming years will

<sup>3</sup> The width of the envelope is determined as  $W = \nu_{\text{max}}^k \cdot e^b$ , where  $k = 0.9638$ ,  $b = -1.7145$  based on parametric fits to the widths of *Kepler* asteroseismic targets (Li et al. 2020).

establish the star as a benchmark target in asteroseismology.

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*Facilities:* Keck:I (Keck Planet Finder), TESS

## APPENDIX

### A. DETAILS OF STELLAR MODELLING APPROACHES

Table 3 lists details of the input physics adopted by each team for the stellar modelling described in Section 4.1 of the main text.

### B. MODE FREQUENCIES FROM RADIAL VELOCITY DATA

We extract mode frequencies from the radial velocity data using iterative sine-wave fitting, which is also known as pre-whitening. We first estimate the values of the large frequency separation ( $\Delta\nu$ ) and p-mode phase offset ( $\epsilon$ ) using mode frequencies extracted from TESS photometry (Table 1). We determine the asymptotic p-mode frequencies for each radial order  $n$  using  $\nu = \Delta\nu(n + \epsilon + l/2)$ , where  $l$  is the mode’s spherical degree. We search within a  $\pm 10 \mu\text{Hz}$  range of each asymptotic mode frequency value for radial and dipole modes, identifying the frequency at which highest power can be found. A sine wave with this frequency is fitted to and subtracted from the residual time series, where their amplitudes and phases are treated as free parameters. The uncertainties are estimated based on Equation 3.4 of Kjeldsen & Bedding (2012). The signal-to-noise (S/N) of each mode is calculated by dividing the mode’s power the white noise level, which is estimated as median power in the spectrum at frequencies above  $7000 \mu\text{Hz}$ . We provide the list of extracted mode frequencies in Table 4, where only modes with power higher than the high-frequency noise ( $0.1 \text{ cm}^2 \text{ s}^{-2} / \mu\text{Hz}$ ) in the radial velocity power spectrum are reported.

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**Table 3.** Input physics used for the stellar modelling task for  $\sigma$  Dra.

Team	TM1 (AMP 1.3)	TM2 (AMP 2.0)	JO	YL
Models	ASTECC	MESA r12778	MESA r12778	MESA r15140
Oscillations	ADIPLS	GYRE	GYRE	GYRE
Opacities	OPAL <sup>0</sup>	OPAL <sup>0</sup>	OPAL <sup>0</sup>	OPAL <sup>0</sup>
Equation of State	OPAL 2005 <sup>a</sup>	MESA/OPAL <sup>aa</sup>	MESA/OPAL <sup>aa</sup>	MESA/OPAL <sup>aa</sup>
Atmosphere	Eddington	Eddington	Eddington	Eddington
Solar mixture	Grevesse & Sauval (1998)	Grevesse & Sauval (1998)	Grevesse & Sauval (1998)	Asplund et al. (2009)
Nuclear reaction rates	NACRE <sup>c</sup>	NACRE <sup>c</sup>	JINA REACLIB <sup>e</sup>	JINA REACLIB <sup>e</sup>
Mixing length formalism	Böhm-Vitense (1958)	Cox & Giuli (1968)	Heney et al. (1965)	Heney et al. (1965)
Overshooting	None	None	$f_{ov} = 0.008$	None
Chemical diffusion	Helium only <sup>d</sup>	Heavy elements and helium	Heavy elements and helium	None
Surface correction	Kjeldsen et al. (2008)	Ball & Gizon (2014)	Ball & Gizon (2014); Roxburgh (2016)	Ball & Gizon (2014)

<sup>0</sup> Iglesias & Rogers (1996); Ferguson et al. (2005)

<sup>a</sup> Rogers & Nayfonov (2002)

<sup>aa</sup> Saumon et al. (1995)

<sup>c</sup> Angulo et al. (1999)

<sup>d</sup> Michaud & Proffitt (1993)

<sup>e</sup> Cyburt et al. (2010)

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$f$ ( $\mu\text{Hz}$ )	$l$	S/N	$\sigma_f$ ( $\mu\text{Hz}$ )
3467.56	1	17.75	3.94
3826.28	1	24.83	3.33
4017.59	1	21.49	3.58
4101.29	0	25.09	3.32
4196.95	1	21.46	3.59
4380.29	1	20.25	3.69
4555.66	1	45.07	2.47
4651.32	0	15.04	4.28
4750.96	1	24.45	3.36
5101.70	1	30.43	3.01
5197.36	0	14.93	4.30
5289.03	1	28.19	3.13
5564.04	0	17.56	3.96
5659.70	1	24.50	3.36
5747.39	0	20.17	3.70
6018.41	1	10.04	5.24
6217.70	1	16.03	4.15

**Table 4.** Mode frequencies extracted from the Keck Planet Finder radial velocity data. Definitions of each columns are provided in the text of Appendix B

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