The NEID Earth Twin Survey: Target Prioritization for Radial Velocity Exoplanet Searches

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The NEID Earth Twin Survey

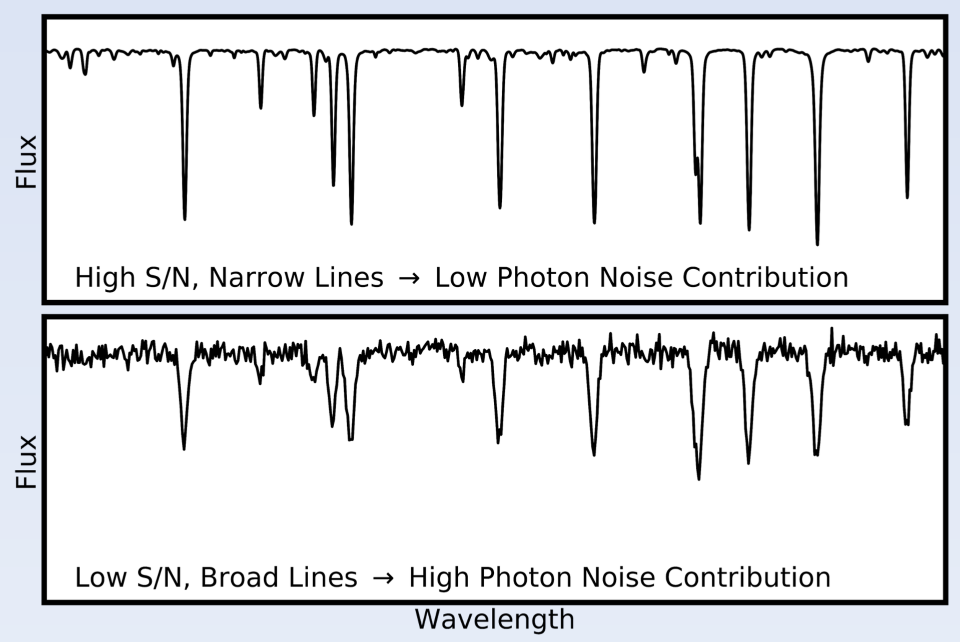
The NEID Earth Twin Survey (NETS) is a radial velocity search for low-mass, long-period exoplanets with the NEID spectrograph. With an instrumental precision of σ_{RV} = 27 cm/s and 30 nights of Guaranteed Time Observations (GTO) per year for 5 years, the survey has the potential to probe entirely unexplored exoplanet populations. But to accomplish this, we must **carefully account for all sources of uncertainty** and ensure that the **targets we observe are those most conducive to RV exoplanet detection**.

Target Selection Metrics

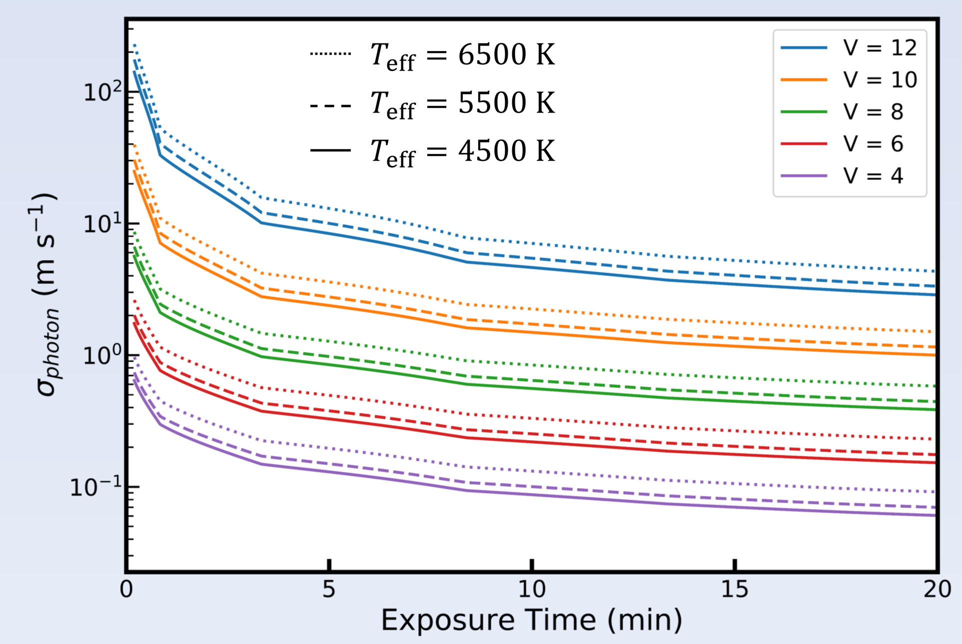
We consider three quantitative metrics when selecting targets for our survey: **Exposure Time**, **Empirical RV RMS**, and **Discovery Space**. These are described in detail below.

Sources of Radial Velocity Uncertainty: Photon Noise and Stellar Variability

The precision with which the Doppler shift of a spectrum can be measured is limited by the S/N and the width of spectral lines. Following the photon noise calculations outlined by Bouchy et al. (2001), we use synthetic spectra (Husser et al., 2013) and lab measurements of the NEID system throughput to create an exposure time calculator. The calculator – as well as important caveats and assumptions – can be found at http://neid-etc.tuc.noao.edu/calc_shell/about.

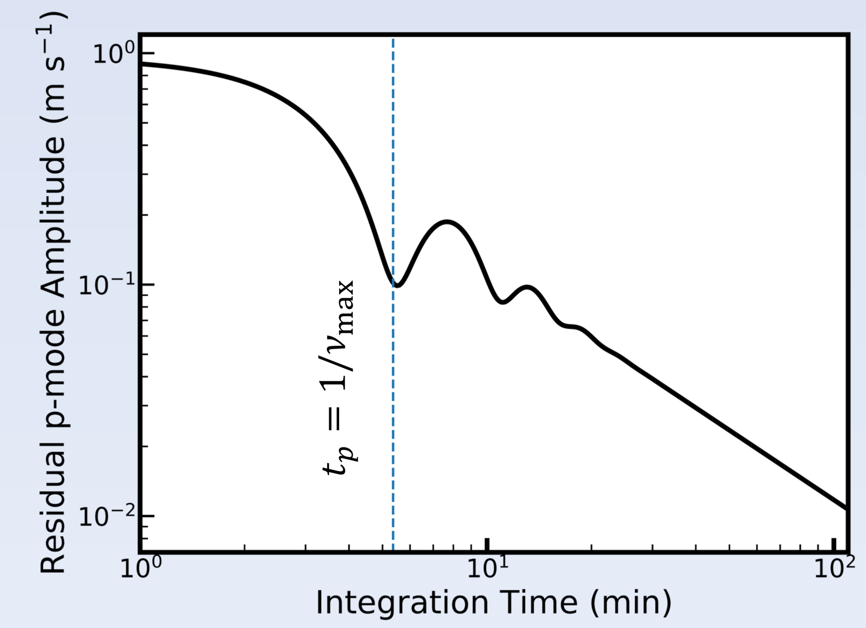


The radial velocity uncertainty due to photon noise depends on the S/N of an observed spectrum (exposure time and stellar brightness) and the width of spectral lines (rotational broadening).



Expected photon noise as a function of brightness, temperature, and exposure time for NEID observations.

Granulation, magnetic activity, and p-mode oscillations induce stellar RV variations, which lead to uncertainties significantly larger than the NEID instrumental precision. Oscillations can be filtered out over the course of an exposure, but contributions from granulation and activity manifest on longer timescales.



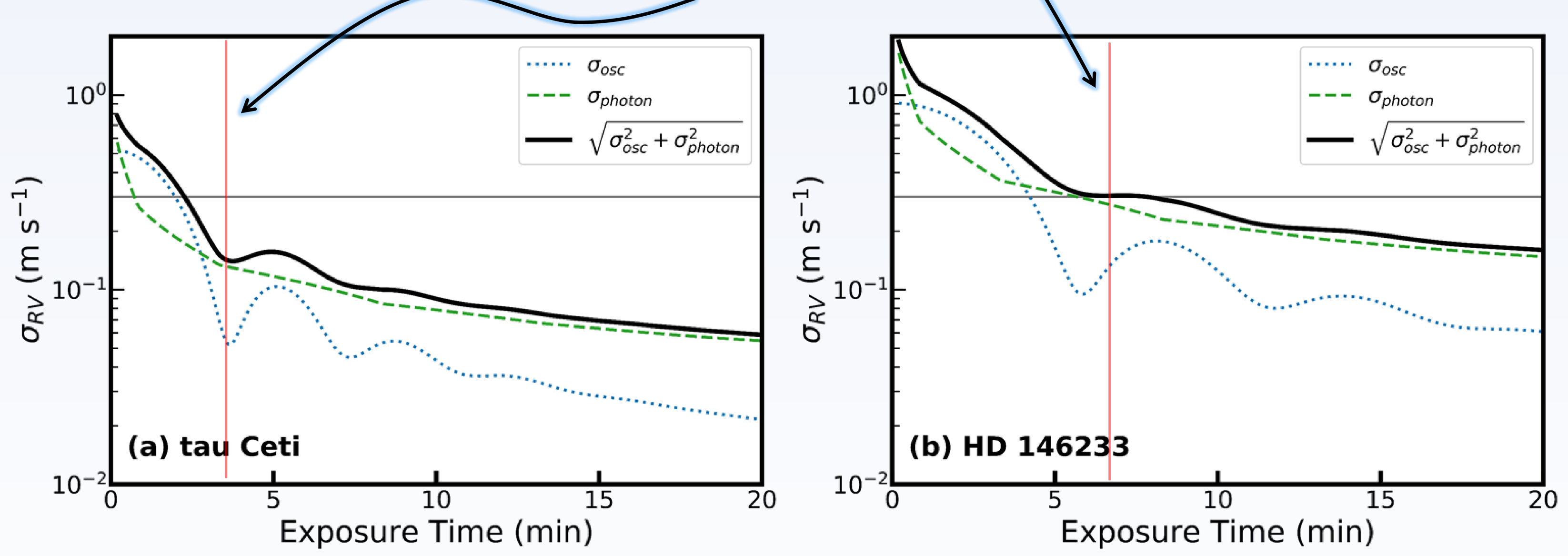
P-modes contribute to radial velocity uncertainties at the 1 m/s level for Sun-like stars. This contribution can be averaged out relatively rapidly, with a characteristic filtering timescale given by $\nu_{\max}$ (Chaplin et al., 2019).

Metric 1: Exposure Time

What is the observational cost of each star?

To calculate typical exposure times for each star, we consider p-mode oscillations and photon noise, two sources of uncertainty that can be mitigated on short timescales. We require that **(1)** the combined p-mode and photon noise contribution for a single observation is < 30 cm/s (t_{30}) and **(2)** the observation time meets or exceeds one p-mode period (t_p).

$$t_{\mathrm{exp}} = \begin{cases} t_{30}, & t_p \le t_{30} \\ t_p, & t_p > t_{30} \end{cases}$$

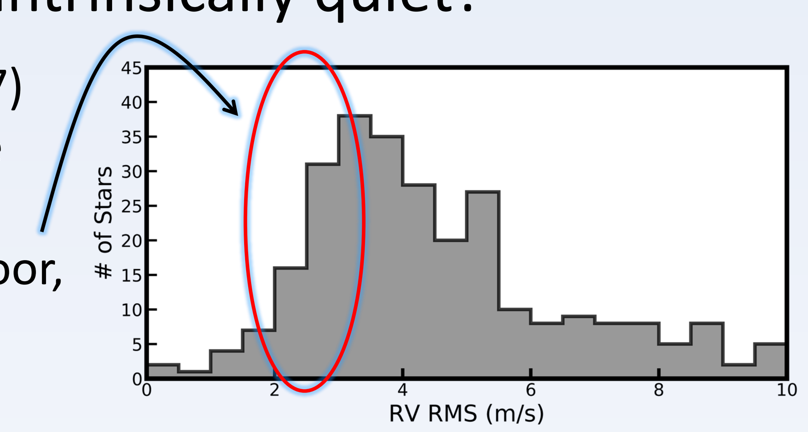


Exposure times for a star for which we achieve 30 cm/s precision before one p-mode period (left, tau Ceti) and for which we hit this precision after t_p (right, HD 146233). In the case of stars like tau Ceti, we return a significant gain in precision for relatively little extra cost by extending the exposure from to t_{30} to t_p.

Metric 2: Empirical RV RMS

Which stars are intrinsically quiet?

Archival HIRES data (Butler et al., 2017) can give us insight into which stars are RV-quiet. Although these data are limited by the 2-3 m/s instrumental floor, they allow us to weed out relatively active stars.



Radial velocity RMS values for a subset of stars observed with HIRES.

The Figure of Merit

We combine our selection metrics to construct a Figure of Merit by which potential targets are ranked. A 180 second correction is applied to the exposure time to account for overhead costs.

$$\mathbf{FOM = 0.5\log(\Delta) - \log(RMS) - \log(}t_{\mathbf{exp}}\mathbf{ + 180s)}$$

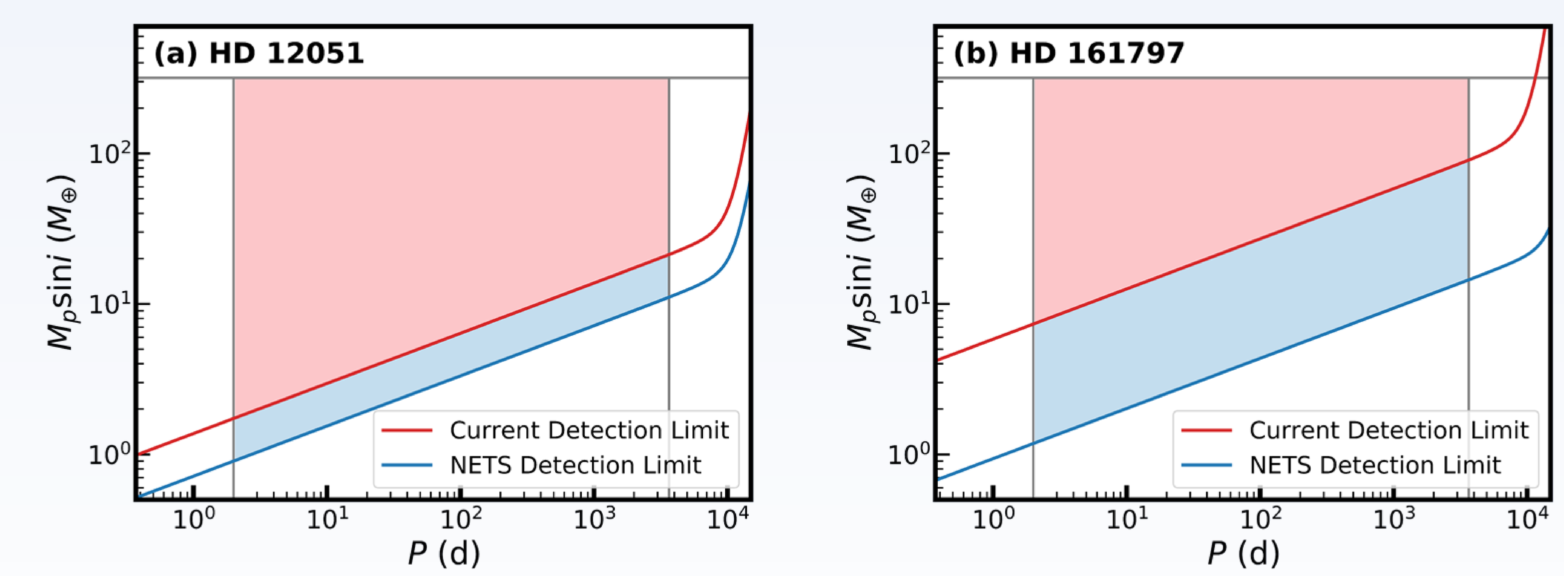
The Figure of Merit, along with considerations for observability and dynamical stability of the circumstellar habitable zone, will be used to construct the NETS target list. Given the time allocation of the NEID GTO, we expect to be able to observe 30 stars for the duration of the survey.

Metric 3: Discovery Space

Where can we find new exoplanets?

Most bright, RV-quiet stars have been heavily targeted by past exoplanet surveys. We calculate the detection limits of these past surveys as in Howard & Fulton (2016) and compare those to the limits that we expect to achieve with NETS, assuming 50 observations per star per year at 1.5 m/s single measurement precision. The Discovery Space metric, Δ, is calculated as:

$$\Delta = \int_{2\mathrm{d}}^{10\mathrm{yr}} \log\left(\frac{[M_p \sin i]_{\mathrm{Current}}}{[M_p \sin i]_{\mathrm{NETS}}}\right) d\log P$$



Discovery space for a star that has been thoroughly combed (left, HD 12051) and one that has relatively few past observations (right, HD 161797). Any exoplanets in the red shaded regions will have already been detected, whereas those in the blue regions may be discovered by NETS.

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References: **[1]** Bouchy, F., Pepe, F., & Queloz, D. 2001, A&A, 374, 733, **[2]** Butler, R. P., Vogt, S. S., Laughlin, G., et al. 2017, AJ,153, 208, **[3]** Chaplin, W. J., Cegla, H. M., Watson, C. A., Davies, G. R., & Ball, W. H. 2019, AJ, 157, 163, **[4]** Howard, A. W., & Fulton, B. J. 2016, PASP, 128, 114401, **[5]** Husser, T. O., Wende-von Berg, S., Dreizler, S., et al. 2013,A&A, 553, A6

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