Limits on Planetary Companions from Doppler Surveys of Nearby Stars: **Methods and Data Products**

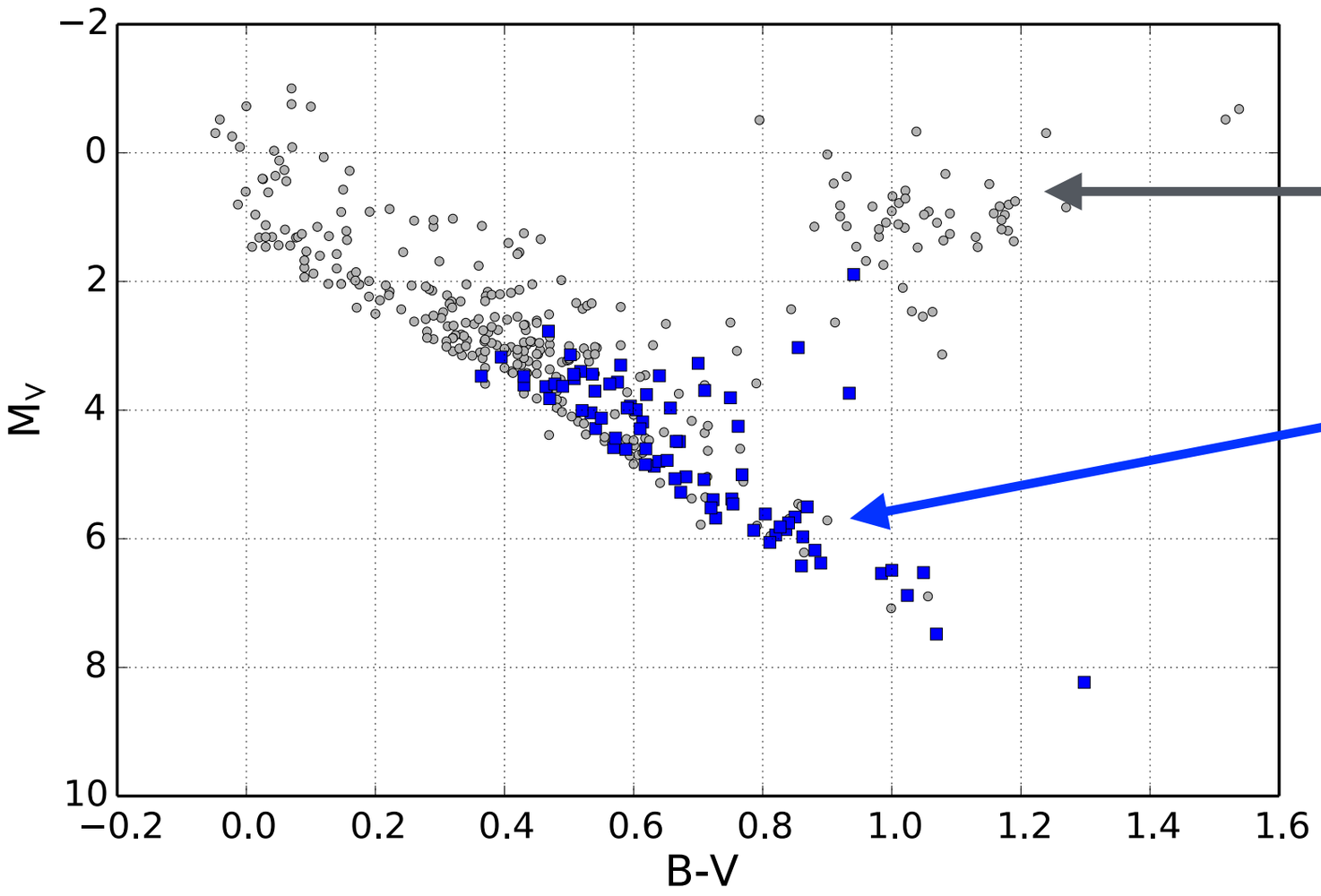
BJ Fulton & Andrew Howard
Institute for Astronomy, University of Hawaii

Lick Observatory

Keck Observatory

Star Lists and Data

Lick and Keck Observatory Star Lists



No Keck/Lick RVs
312 stars

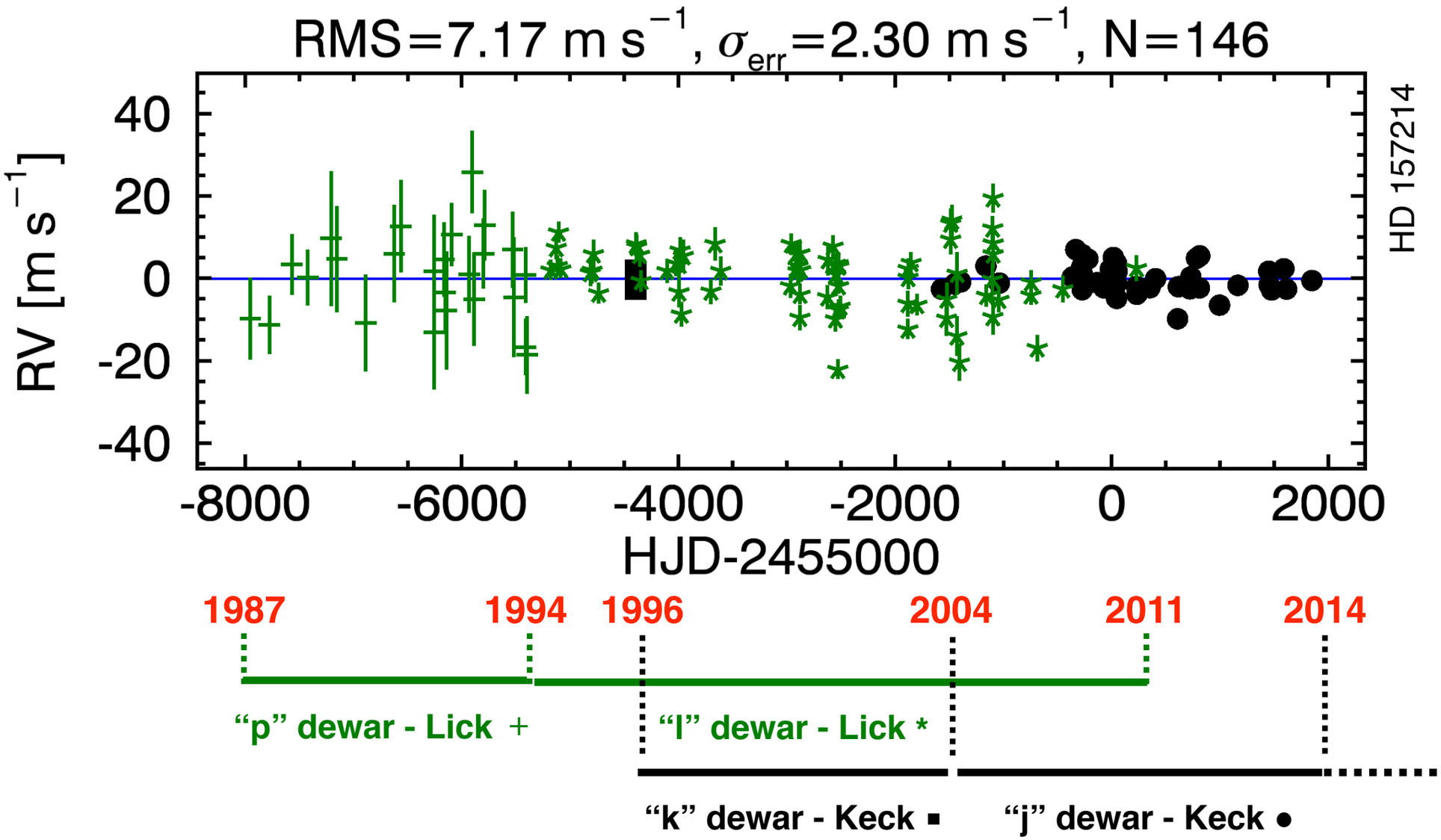
With Keck/Lick RVs
76 stars

Excluded from Lick/Keck Search:

1. Southern Hemisphere ($\delta \lessapprox$ -30-40°)
2. Early spectral type (< ~F8)
3. Evolved (subgiants & giants)
4. Young and active
5. Binaries (sep < 2")

Star Lists and Data

Lick and Keck Observatory Data



Star Lists and Data

Sample RV Data

RV Measurements for HD 157214
filename = 157214_rv.csv

```
# star HD number, 157214
# Instrument codes:
#  p, Hamilton Spectrograph dewar 16
#  l, Hamilton Spectrograph all other dewars
#  k, pre-upgrade Keck HIRES (on or before August 19 2004)
#  j, post-upgrade Keck HIRES (after August 19 2004)
hjd-2440000,rv,rv_err,inst
7046.7095,-16.5,9.5299997,p
7224.01265281,-17.964094162,6.6331258,p
7431.6954,-3.33999991417,6.96,p
7578.04018203,-6.54584598541,6.3437233,p
7793.7143,2.95000004768,15.9200001,p
7846.6076,-2.03999996185,12.4399996,p
8113.74,-17.5100002289,11.3299999,p
8375.9723,-0.72000002861,11.3999996,p
8437.8988,5.90000009537,10.7799988,p
8744.93933414,-4.99877548218,13.3051147,p
8745.96034765,-19.8463840485,13.3721724,p
8834.75939096,-2.15345191956,8.669632,p
8846.682,-10.0799999237,9.1400003,p
```

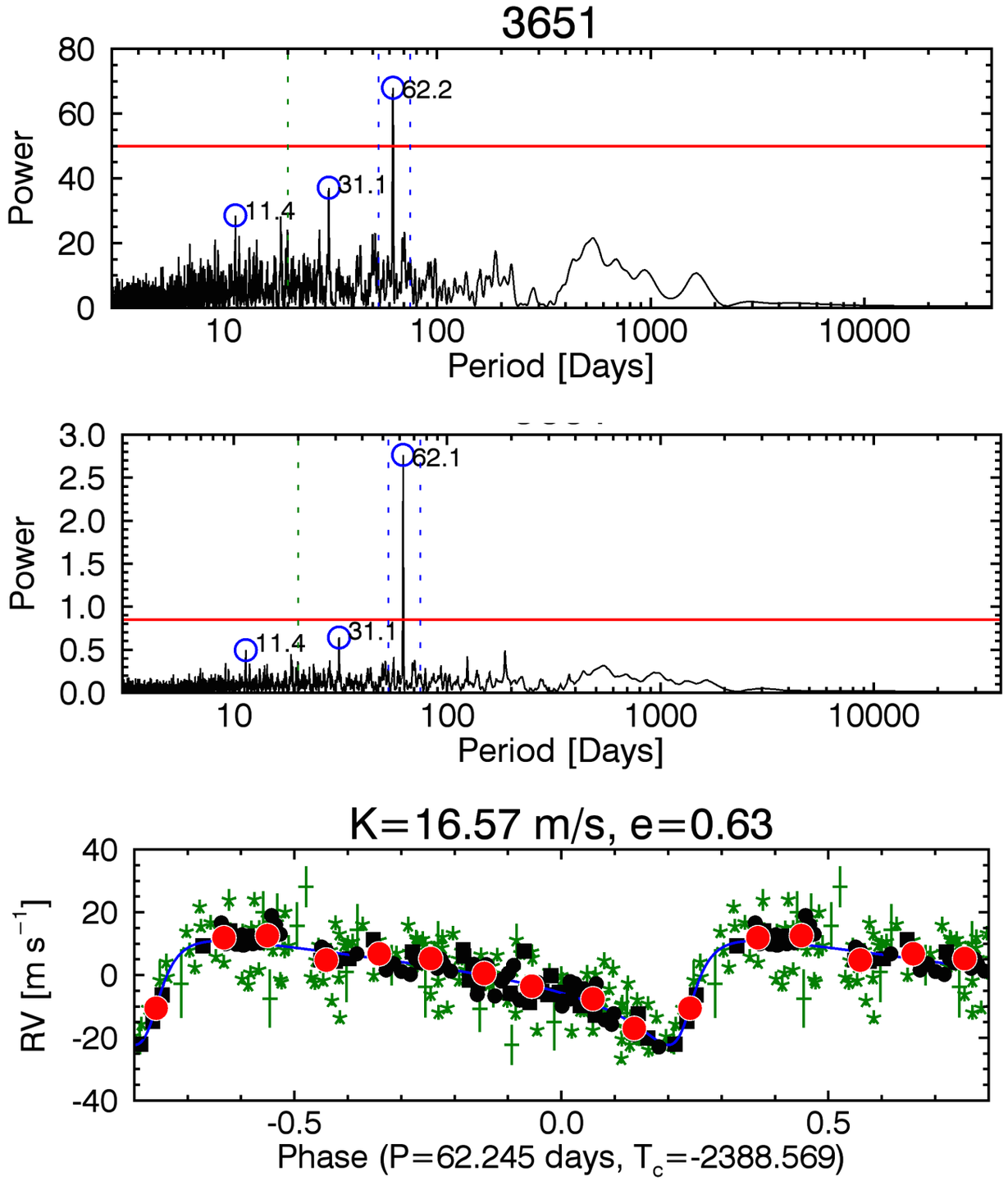
⋮

RVs provided for 76 Exo-C/Exo-S/AFTA targets with Keck/Lick Spectra

Automated Search

Search Algorithm

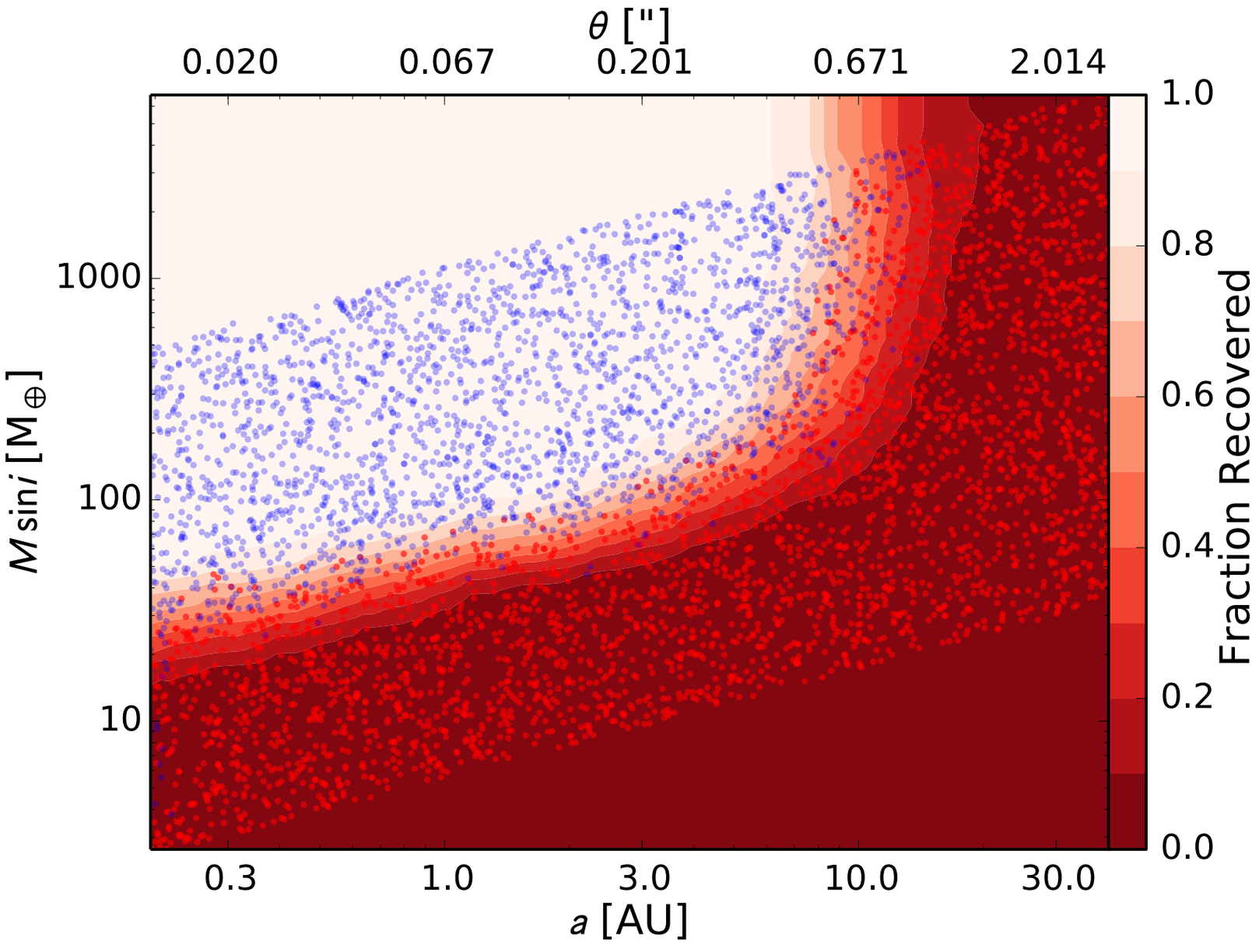
- 2DKLS periodogram (O'Toole+ 2009)
- Grid search over *P* and *e*
- Marginalize over T_p, ω, *K*
- Power, $Z = \frac{\chi^2_B - \chi^2}{\chi^2_B}$
- Incorporate measurement errors into fit
- Allow for offsets between datasets, and simultaneously fit for a linear trend
- single, or multi-planet



Completeness

Injection/Recovery

- Inject synthetic planets (circular) and attempt to blindly recover signals using automated pipeline
- 5000 injections per star
- Inject/Recover in addition to any known planets



Completeness

Sample of Data Files

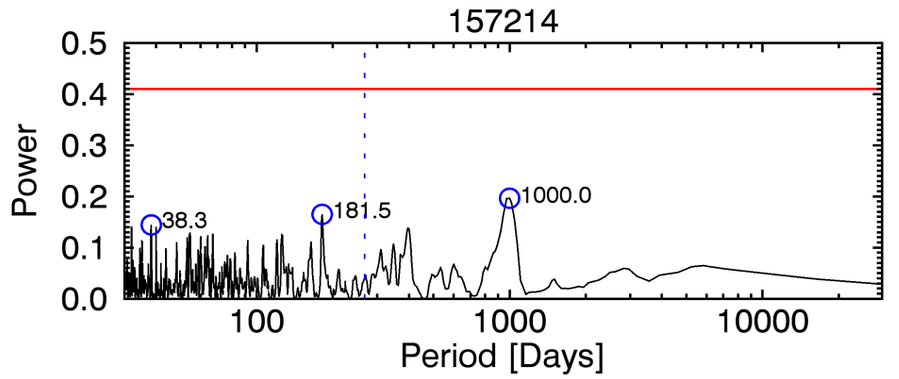
Completeness Contours for HD 157214
filename = 157214_contours.csv

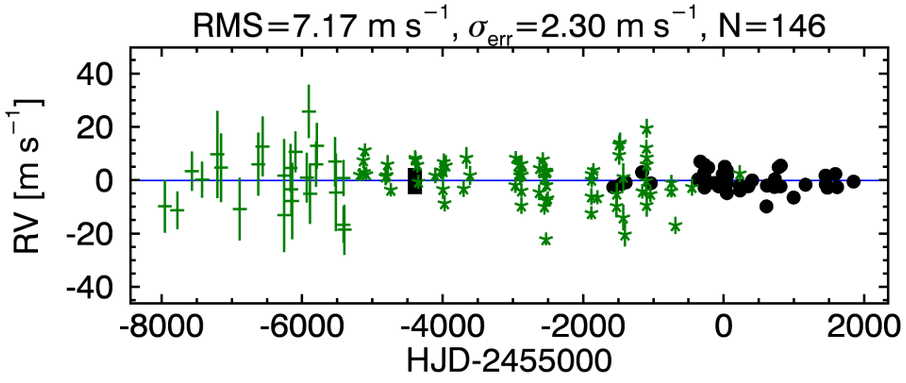
```
# star HD number, 157214
# Mstar, 0.871, Msun
# Dstar, 14.393, pc
period,a,theta,rec_16,rec_50,rec_84
30.061231691,0.180712767491,0.0125559234334,14.7425926001,22.3910787033,34.0076144745
32.5895618052,0.190708479539,0.0132504255257,14.7425926001,22.3910787033,34.0076144745
35.3305396654,0.201257081461,0.0139833424076,15.8060756552,22.3910787033,34.0076144745
38.3020502244,0.212389155093,0.014756798905,15.8060756552,22.3910787033,34.0076144745
41.5234826663,0.224136973832,0.0155730373736,15.8060756552,24.0062988639,36.4608140385
45.0158569226,0.236534596207,0.0164344242001,16.946274946,24.0062988639,36.4608140385
48.8019608268,0.249617964614,0.0173434566623,16.946274946,24.0062988639,36.4608140385
    ⋮
```

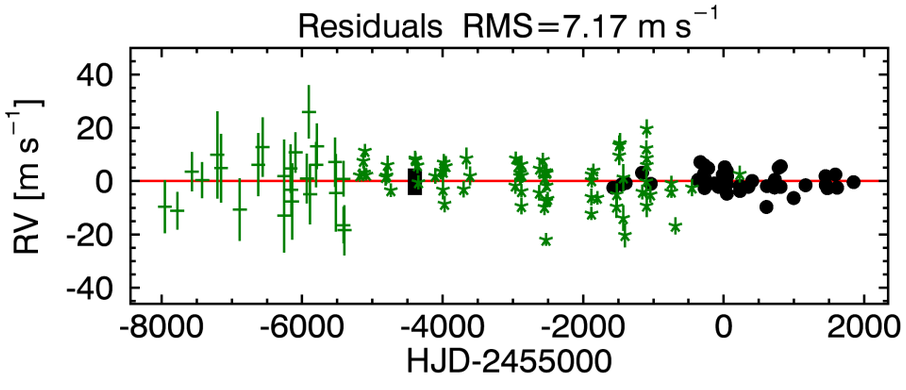
Completeness contours (16%, 50%, 84%) provided for 76 Exo-C/Exo-S/AFTA targets with Keck/Lick Spectra

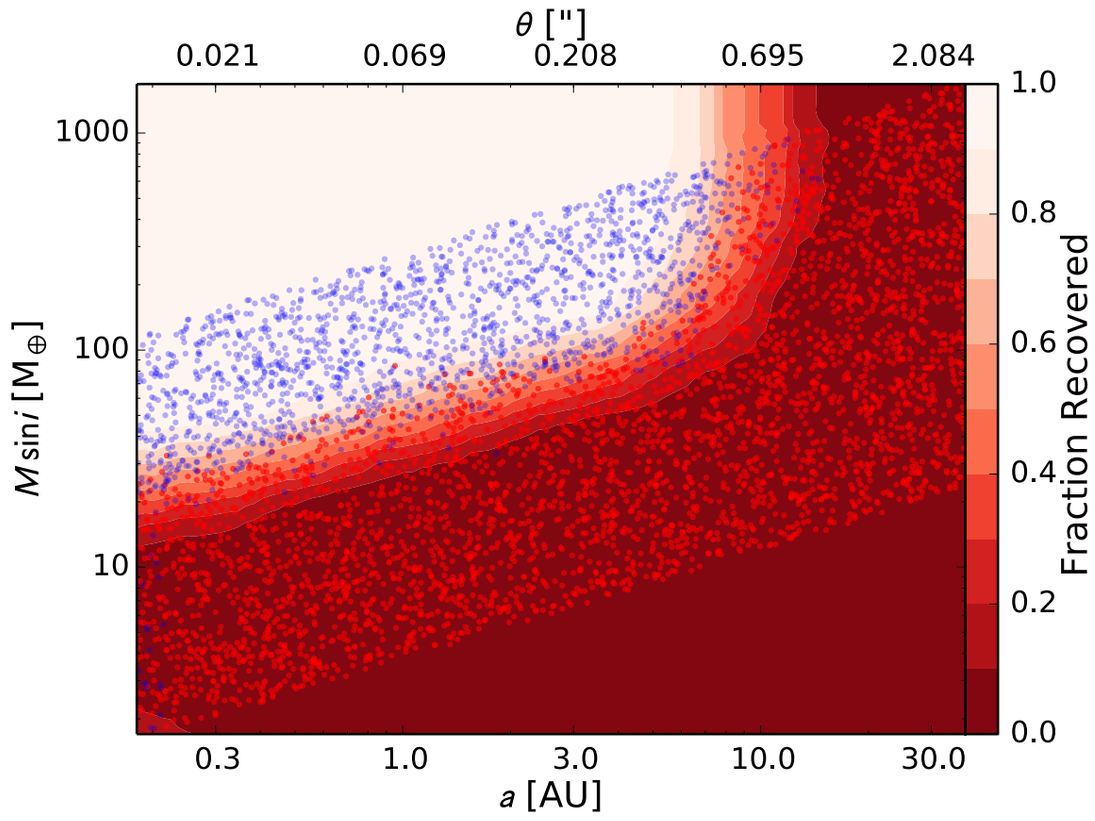
Automated Search & Completeness

Example #1 - HD 157214



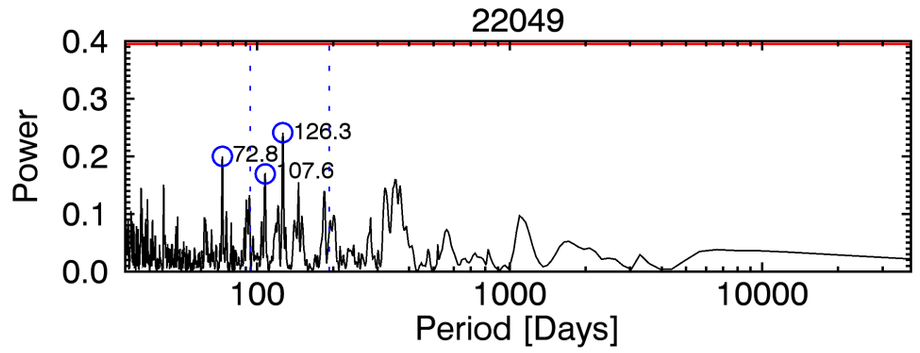


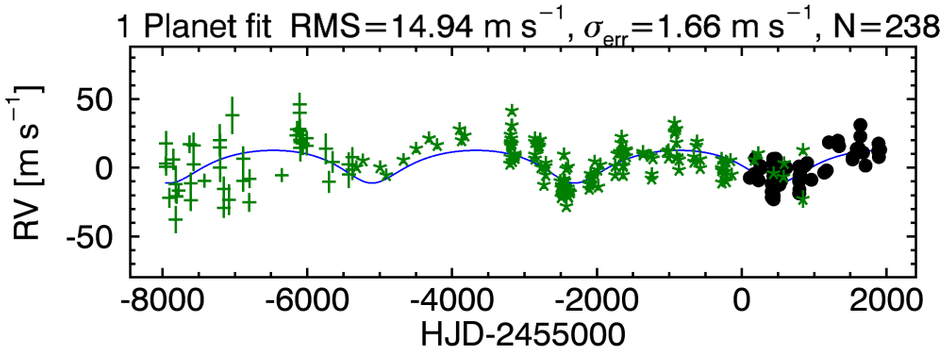


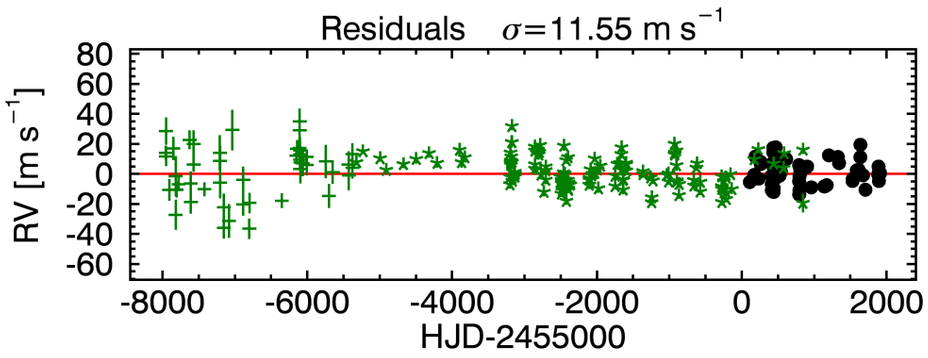


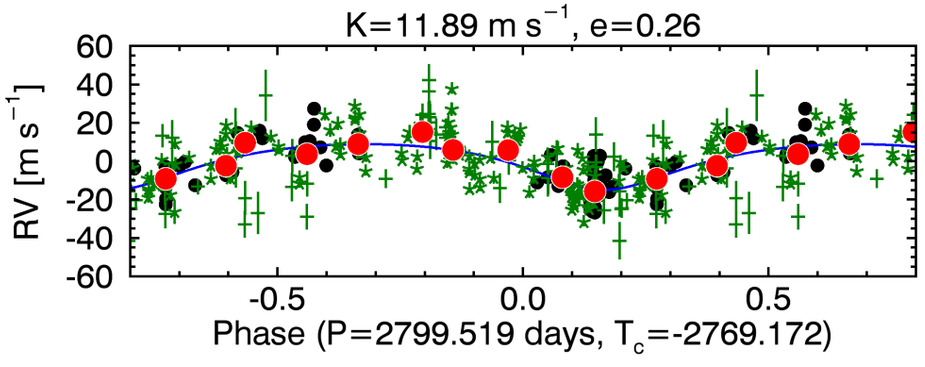
Automated Search & Completeness

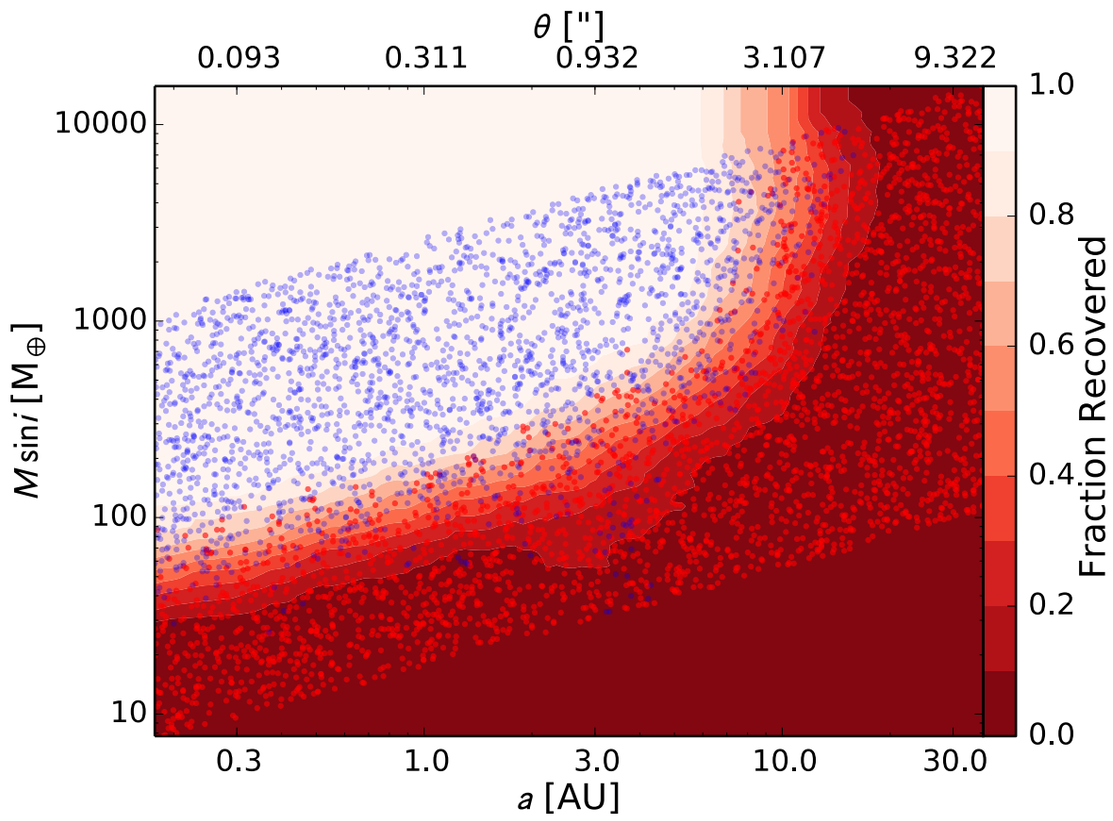
Example #5 - HD 22049 (ε Eridani)





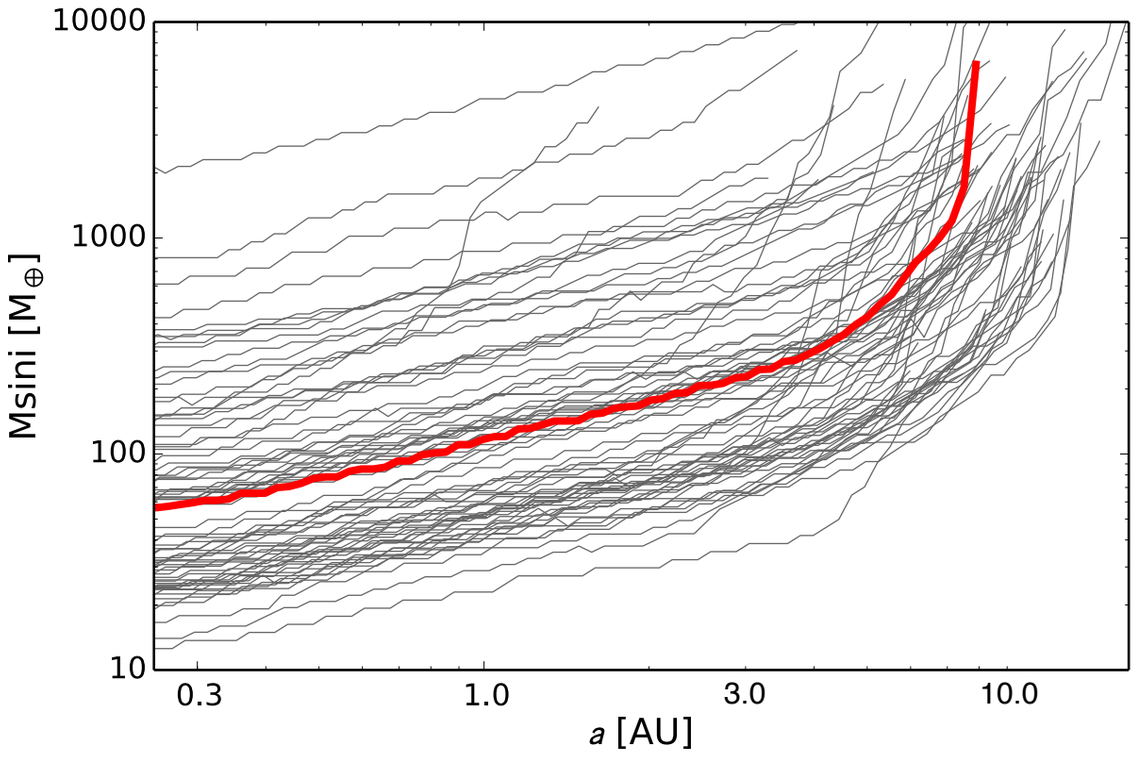




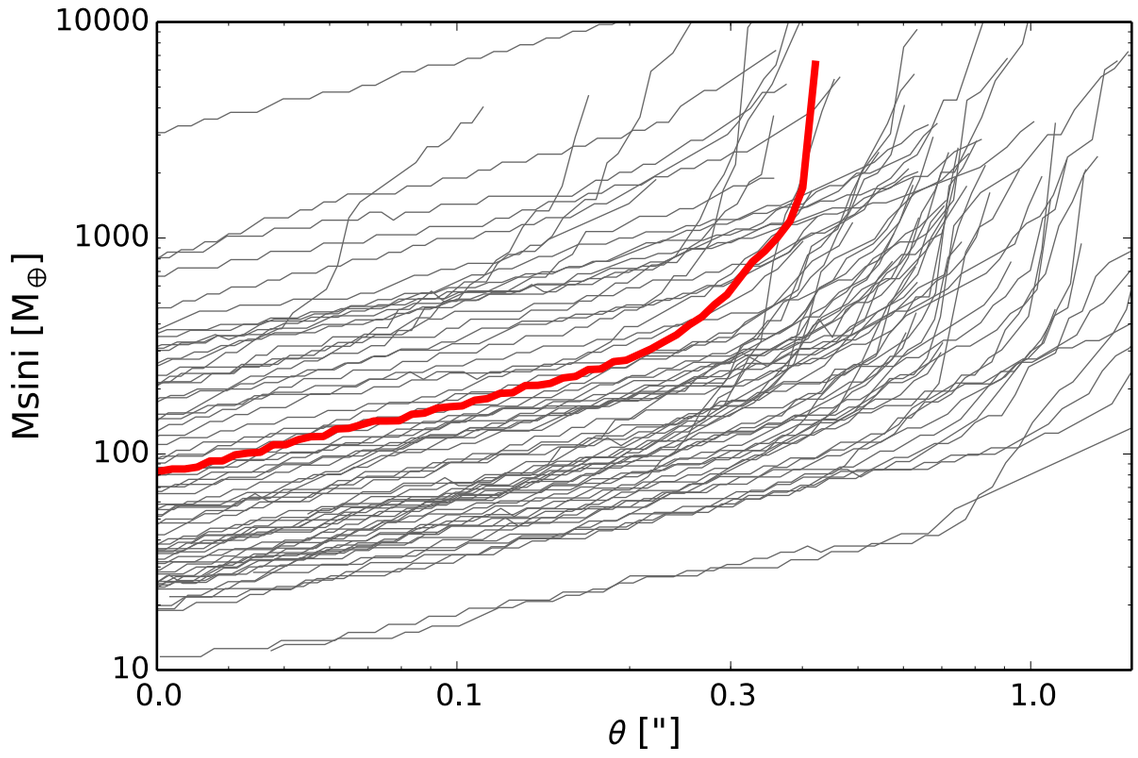


Survey Completeness

Completeness vs. Semi-major axis

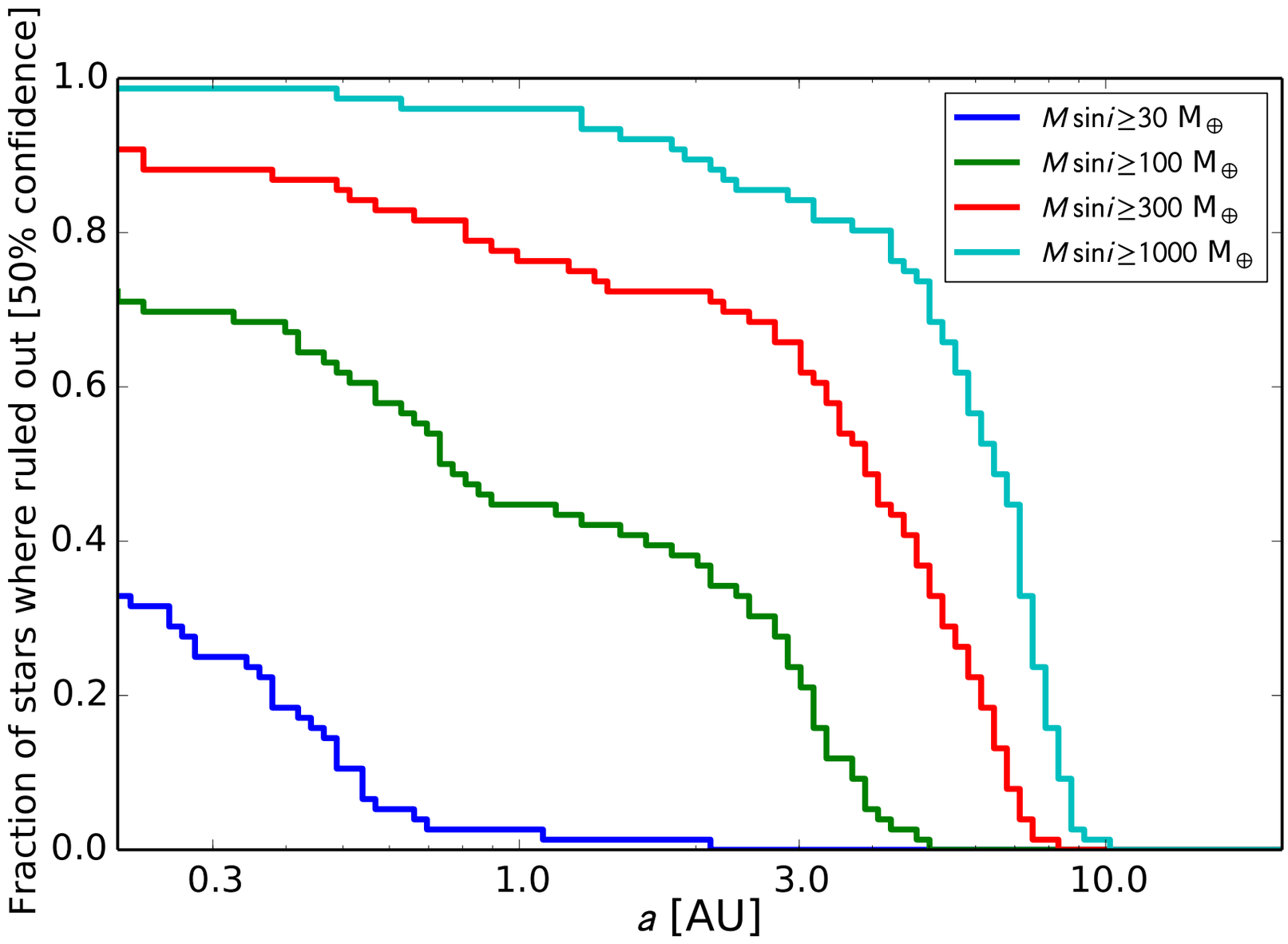


Completeness vs. Projected Separation



Completeness for all 76 Stars

Survey Completeness



Idealized Completeness

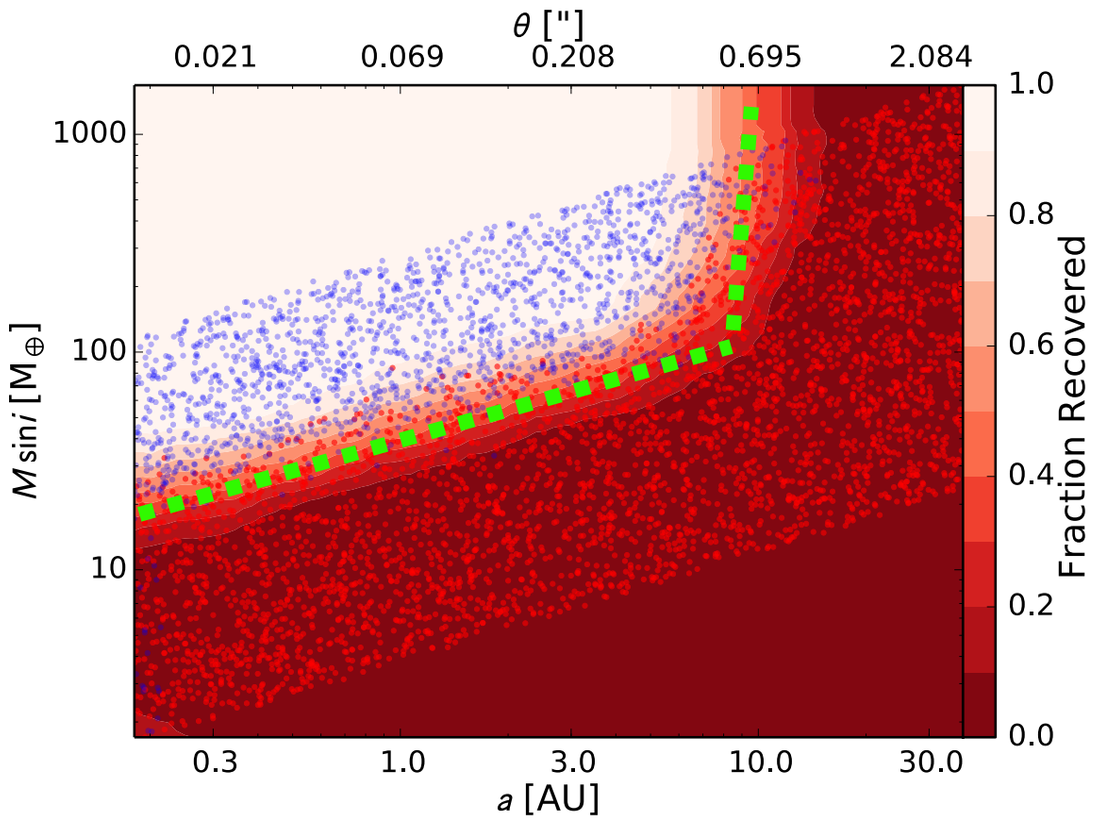
50% Detection Completeness

RV Precision

$$K_{50} = \alpha \frac{\sigma_{\mathrm{RV}}}{\sqrt{N_{\mathrm{obs}}}}$$

What is α?

Number of RVs



α = SNR of a successful detection

Idealized Completeness

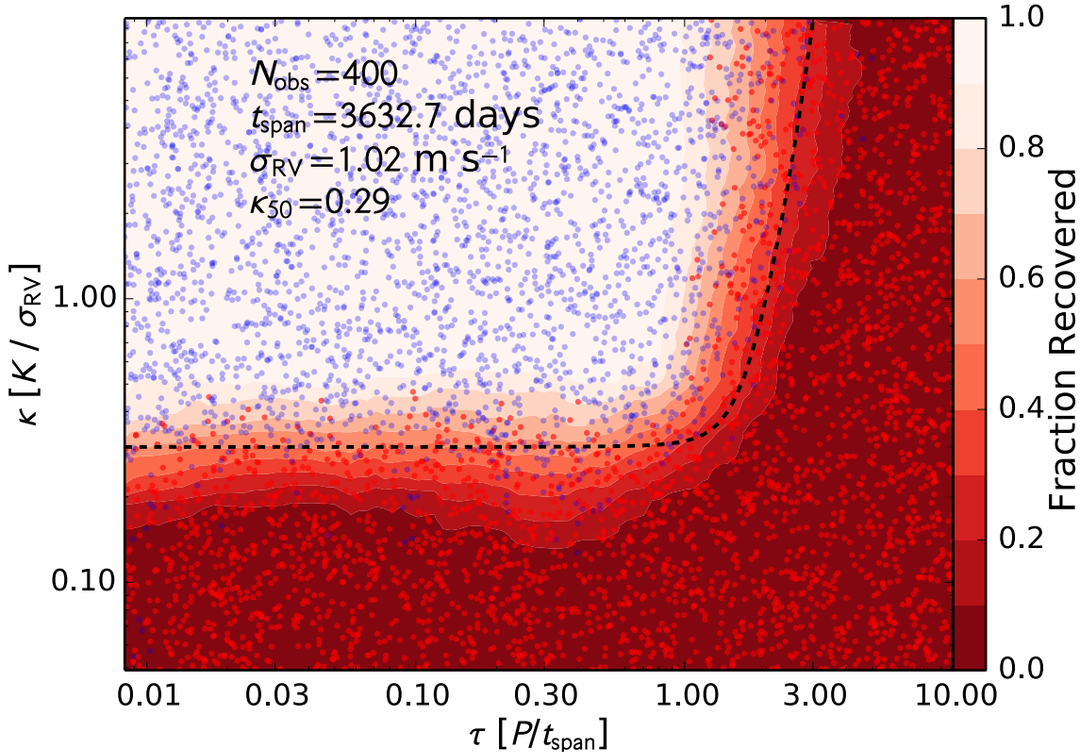
Make Problem Dimensionless

Dimensionless Doppler Amplitude:

$$\kappa_{50} = \frac{K_{50}}{\sigma_{\rm RV}} = \frac{\alpha}{\sqrt{N_{\rm obs}}}$$

Dimensionless Time:

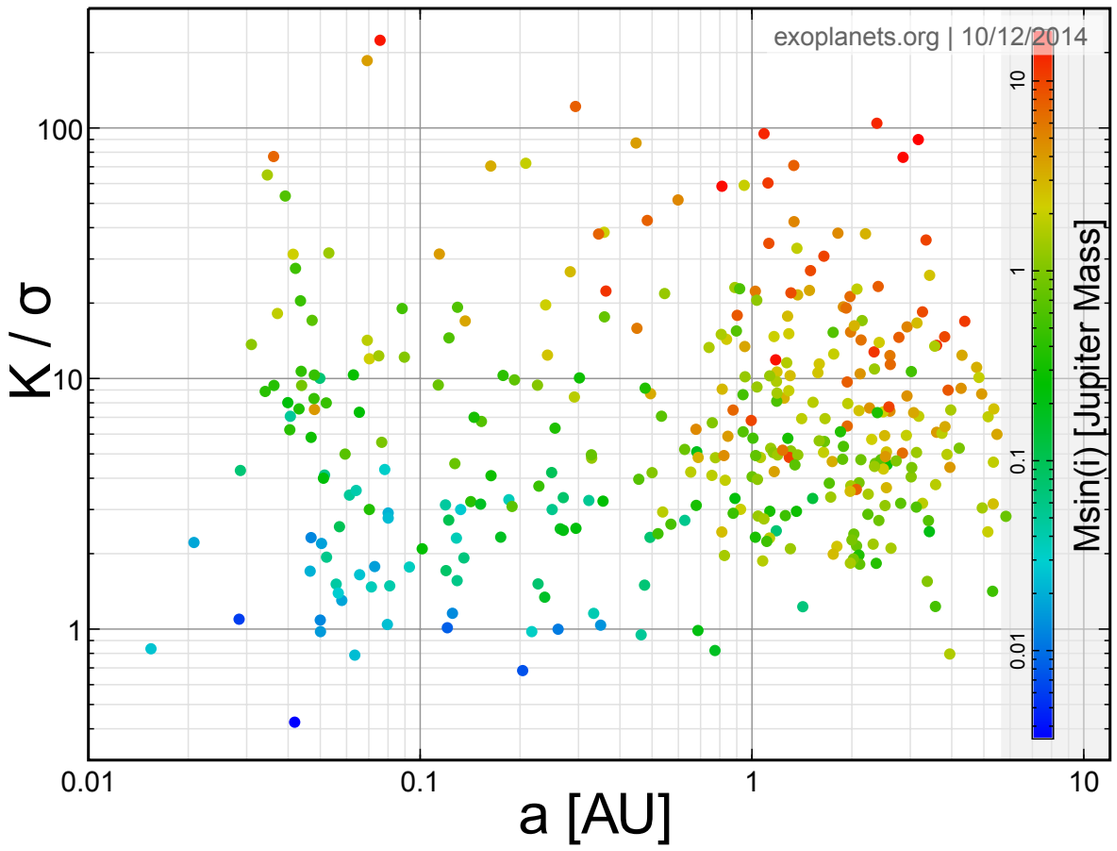
$$\tau = P/t_{\rm span}$$

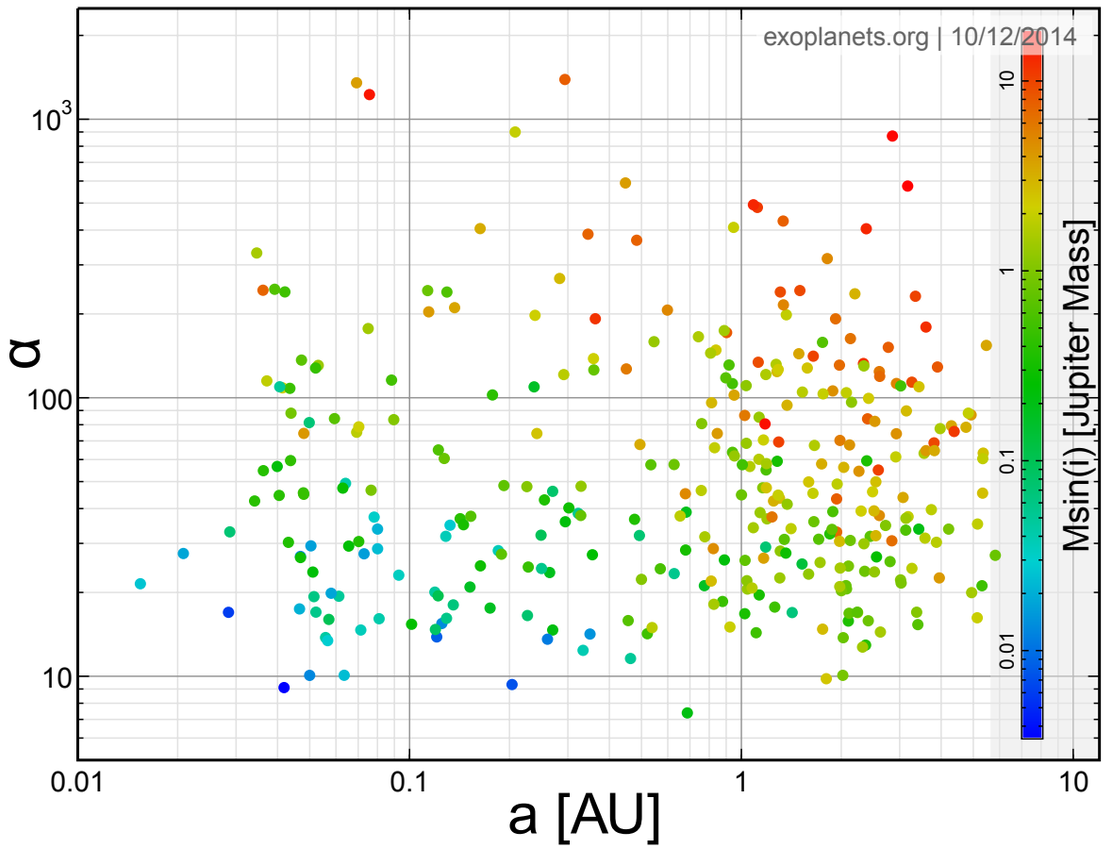


$$K_{50}(\tau) = \frac{\sigma_{\rm RV}\,\alpha}{\sqrt{N_{\rm obs}}} \cdot \sqrt{1 + (10^{\tau - 1.5})^2}$$

α ≈ 6 — Injection/recovery Simulations

Idealized Completeness

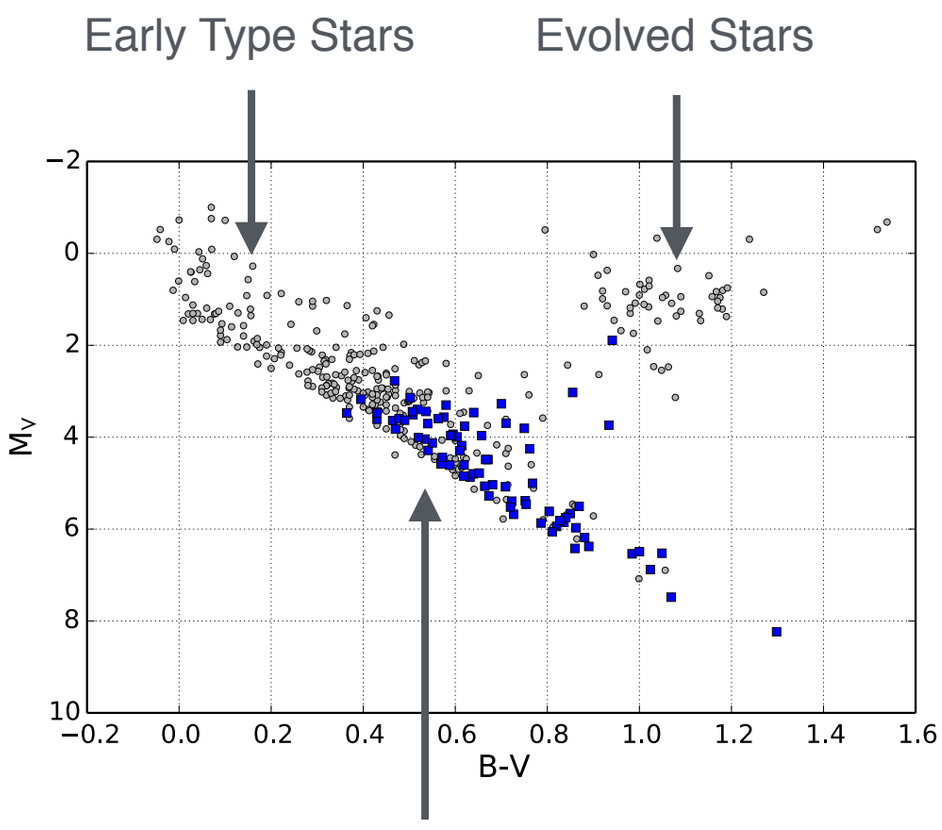




α ≈ 10 — Real Planets on exoplanets.org

Idealized Completeness

Jitter Estimates - σ_{RV}



Early Spectral Type (hot, < ~F8):

few and broad lines

$\sigma_{RV} \approx 0.16 * V\sin i^{1.5}$ (Galland et al. 2005)

Evolved Stars (subgiants, giants):

oscillations

$\sigma_{RV} \approx v_{osc} = 0.234(L_\star/M_\star)$ m/s (Kjeldsen & Bedding 1995)

Southern Hemishere (GK dwarfs):

< 3 m/s; limited by spectrometer?

Young Stars:

line distortions; rotational spot modulation

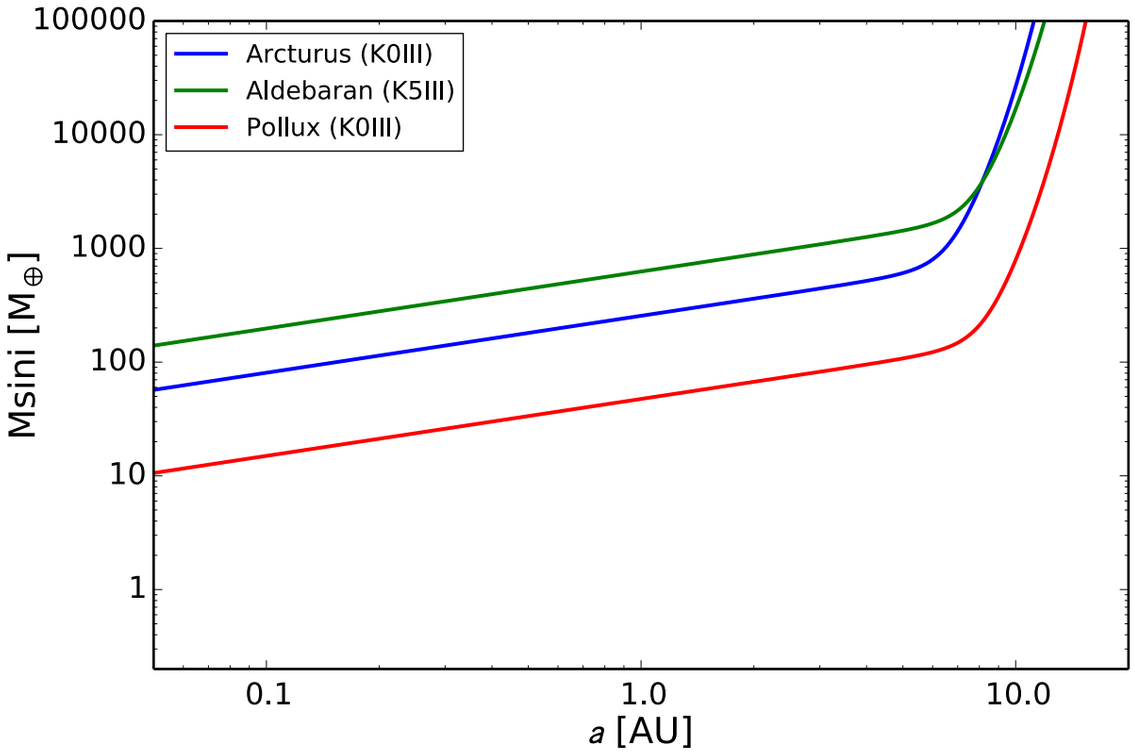
100 m/s → < 3 m/s (function of $\log R'_{HK}$)

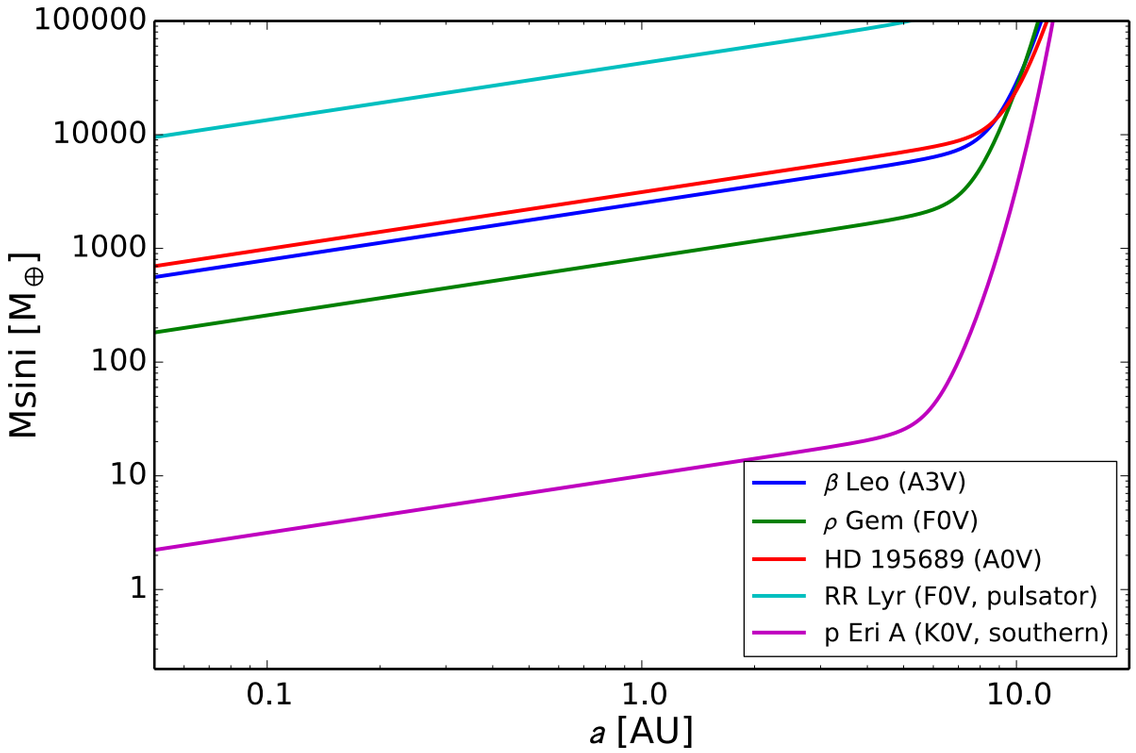
Binaries:

too hard, not recommended

Idealized Completeness

Dedicated RV Campaign





<u>Survey Parameters:</u>

σ_{RV} estimated for each star

N_{obs} = 100 RVs

T_{span} = 10 yr

α = 6

EXOPLANET EXPLORATION PROGRAM

PLANETQUEST
public outreach site

Documents

Recent Papers on Exoplanet Instruments, Mission Concepts, and Studies

SAO/NASA Astrophysics Data System - ADS is a valuable source for published papers on Exoplanet science, Instruments, and Mission Concepts. To search by topic, enter one or more terms, like the following, into the keyword box: starshade, coronagraph, "debris disk", exoplanet.

ArXiv.org (astro-ph) - Many of the most recent preprints are available from arXiv. Use the 'Advanced search' to narrow your search with more than one criterion

Papers on instruments for space-based exoplanet imaging and spectroscopy - A list of recent instrument papers and reports on high-contrast imaging with starshades and coronagraphs, compiled by Peter Lawson.

Key Documents

***Quick Studies* of science capabilities of exoplanet imaging missions** (2014)

Completeness of Precision Radial Velocity Surveys of Nearby Stars for Planetary Companions (2014)

Study on Applications of Large Space Optics (SALSO, 2013)

Exoplanet Exploration Program Technology Plan Appendix: 2013

New Worlds, New Horizons in Astronomy and Astrophysics (2010)

A European Roadmap for Exoplanets (2010)

Blue Dots Report (2010)

Exoplanet Community Report (2009)

ExoPTF Report (2008)

Earth-like Exoplanets (2006)

Exoplanet Program Analysis Group (ExoPAG)

EXOPLANET EXPLORATION PROGRAM

PLANETQUEST
public outreach site

A study of the completeness of precision radial velocity surveys of nearby stars for planetary companions

In June 2014 the Exoplanet Program contracted with Andrew Howard (U Hawaii) to perform an analysis of the completeness of the planet searches for target stars in the California Planet Search team's archives. The objective was to provide completeness statistics for use by three NASA-selected imaging studies currently underway (the **Exo-C** and **Exo-S** probes, and the **AFTA coronagraph**).

Limits on Planetary Companions from Doppler Surveys of Nearby Stars - Presentation, Oct 22, 2014

Limits on Planetary Companions from Doppler Surveys of Nearby Stars - Final Report, Oct 24, 2014
Andrew W. Howard & Benjamin J. Fulton (U Hawaii)

Final Report Appendices

For each star in one or more of the candidate target star lists for the 3 studies, the following data are provided, by Hipparcos Catalog number:

- RV data (CSV)
- Completeness fraction vs mass and semi-major axis (plot data)
- Completeness fraction vs mass and semi-major axis (PDF)
- Completeness contours vs period or semi-major axis (CSV)
- RV Power spectra and residuals from planet-search fits (where detected)

166, **3651**, **4614**, **4628**, **9826**, **10476**, **10700**, **10780**, **16160**, **17925**, **19373**, **19994**, **20630**, **22049**, **22484**, **23249**, **25457**, **26965**, **30495**, **30652**, **32147**, **32923**, **34411**, **37394**, **43042**, **48682**, **67228**, **69830**, **69897**, **72905**, **75732**, **84117**, **84737**, **86728**, **90839**, **95128**, **100623**, **101501**, **102365**, **102870**, **104304**, **109358**, **114613**, **114710**, **115383**, **115617**, **117176**, **120136**, **128167**, **131156**, **131977**, **134083**, **136352**, **141004**, **142373**, **142860**, **146233**, **149661**, **157214**, **161797**, **168723**, **172051**, **173667**, **182572**, **185144**, **185395**, **187691**, **188512**, **191408**, **201091**, **201092**, **210302**, **215648**, **217014**, **219134**, **222368**

Summary

Methods

- Analyzed Lick+Keck RVs that make good targets for space-based direct imaging missions
- Automated detection algorithm and injection recovery tests
- Developed a technique to estimate sensitivity to planets for stars without any RVs to date

Products

- Relative RVs for 76 nearby stars spanning nearly 30 years
- Identified stars with long-term RV trends or partial orbits
- Sensitivity contours
- $K_{50}(\tau) = \frac{\sigma_{\rm RV}\,\alpha}{\sqrt{N_{\rm obs}}} \cdot \sqrt{1 + (10^{\tau - 1.5})^2}$
- Recommendations for future/ongoing RV surveys