Limits on Planetary Companions from Doppler Surveys of Nearby Stars

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Motivation

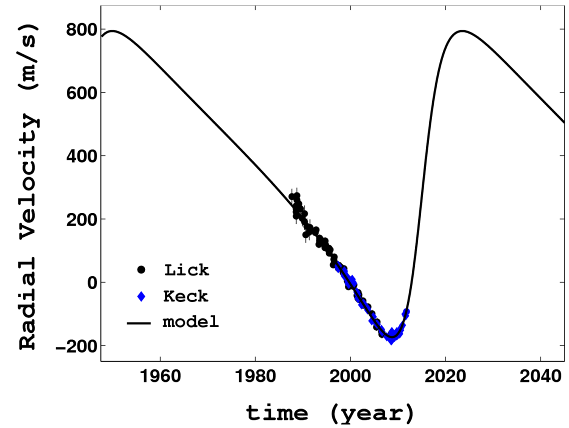
RV / Imaging Synergy

TRENDS Program:
Brown Dwarf discovery & characterization
e.g. HR 7672 - Crepp+ 2012; Liu+ 2002
RV trend → imaging → astrometry
→ mass/spectra

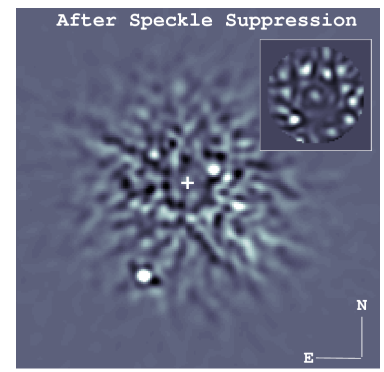
Doppler Measurements Provide:

Target Identification
Target Exclusion (non-detection limits)
Dynamical Masses

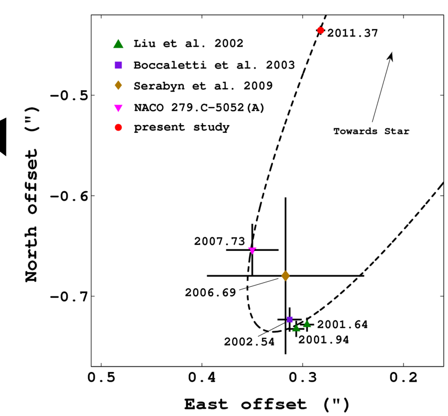
RV Detection



Direct Image



Astrometry



Outline

1. Scope of Study
2. Star Lists and Data
3. Automated Planet Search / Completeness
4. Results
5. Idealized Completeness
6. Sensitivity Improvements
7. Recommendations

Scope of Study

<u>Statement of Work</u>

1. Estimate completeness of RV observations for all Exo-C/Exo-S/AFTA stars with Keck/Lick data.

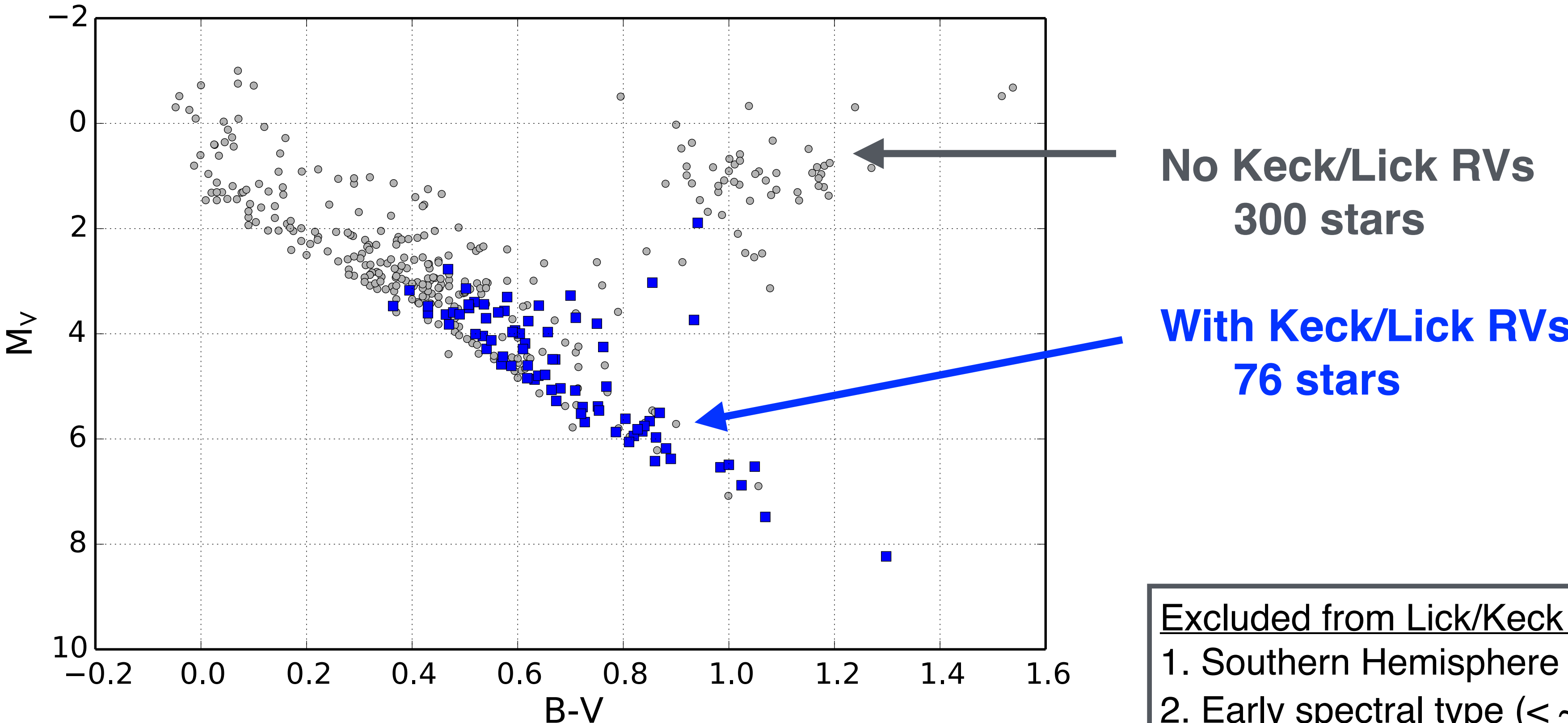
2. Estimate completeness for all Exo-C/Exo-S/AFTA stars *without* Keck/Lick data, for a nominal Doppler survey.

3. Provide a quantitative recommendations for RV data to maximize science yield.

4. Provide informal estimate of improvements in completeness from continuing RV observations for 10 years with no improvement.

Star Lists and Data

Lick and Keck Observatory Star Lists



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")

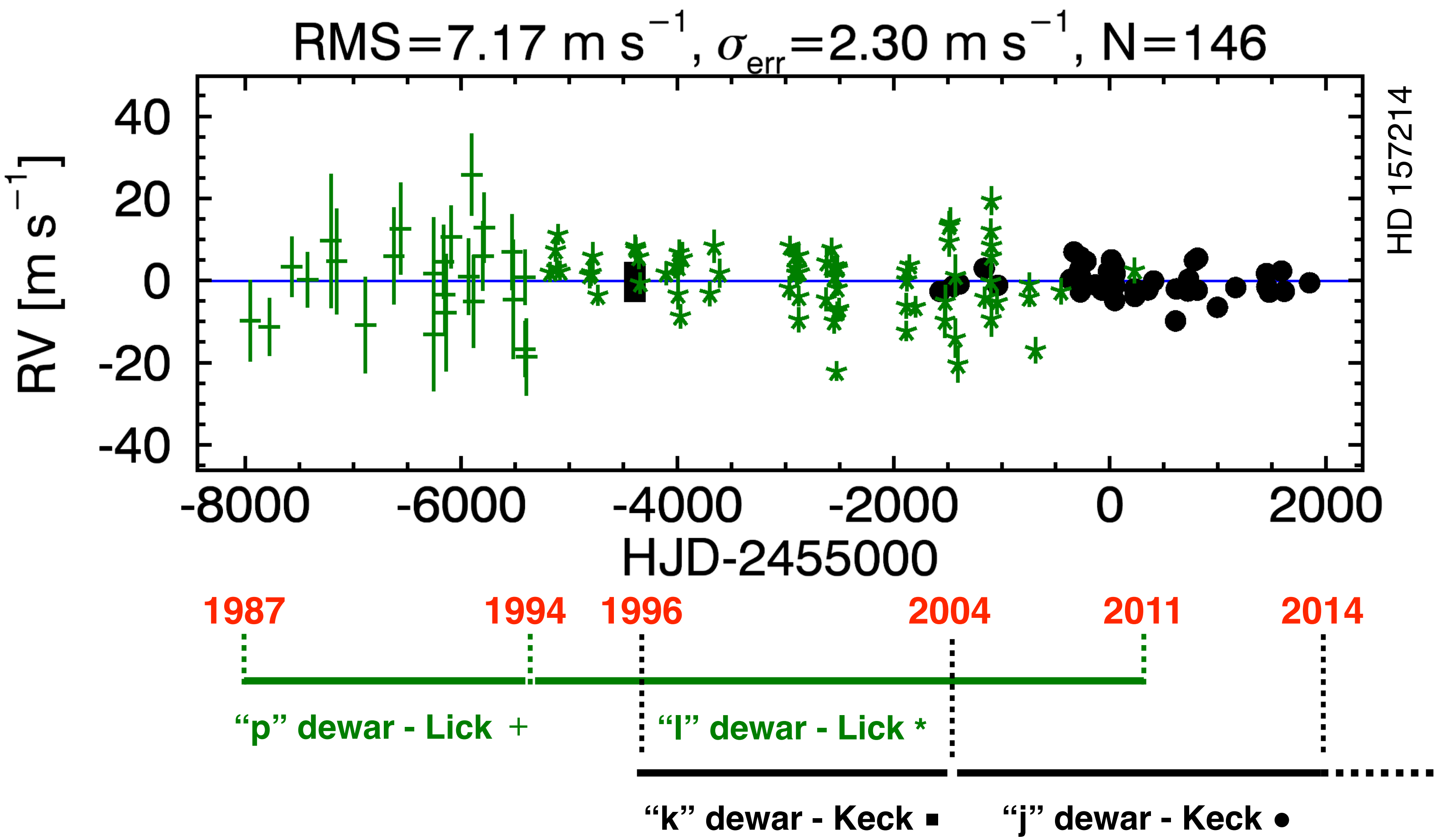
Star Lists and Data

Reasons for Lack of Keck/Lick RVs

Mission	Total Stars	Have RVs[b]	No RVs			
			Hot[c]	Southern[d]	Evolved[e]	Binary[f]
Exo-S (S)	127	57	19	24	3	22
Exo-C (C)	249	40	112	43	39	33
AFTA (A)	263	51	125	51	4	38
Total (S+C+A)	376	76	148	71	40	51

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

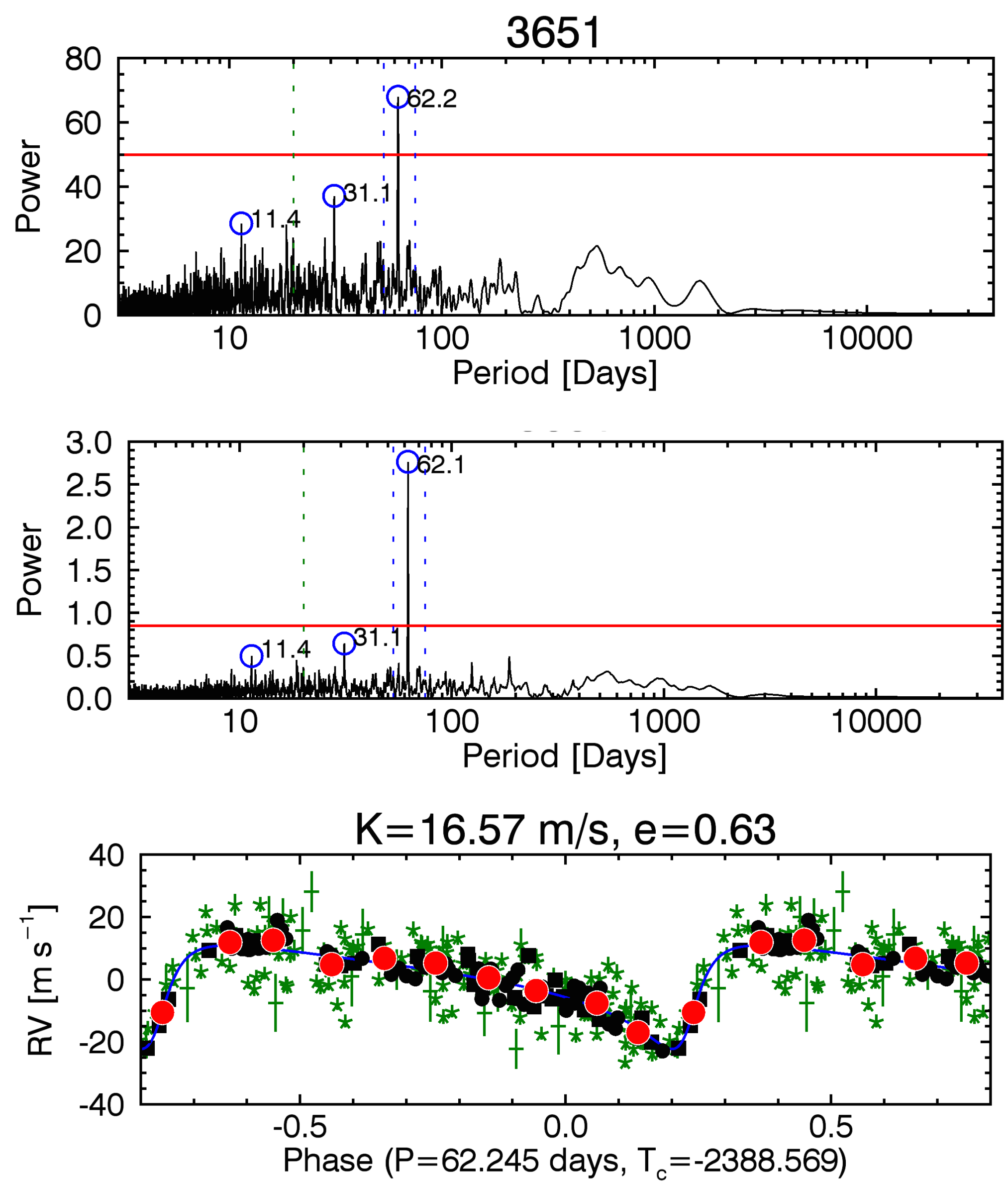
```
# star HD number, 157214
# Instrument codes:
#  p, Hamilton Spectrograph dewar 16
#  l, Hamilton Spectrograph all other dewars
#  k, pre-upgrade Keck HIRES (on or before August 19 2004)
#  j, post-upgrade Keck HIRES (after August 19 2004)
hjd-2440000,rv,rv_err,inst
7046.7095,-16.5,9.5299997,p
7224.01265281,-17.964094162,6.6331258,p
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

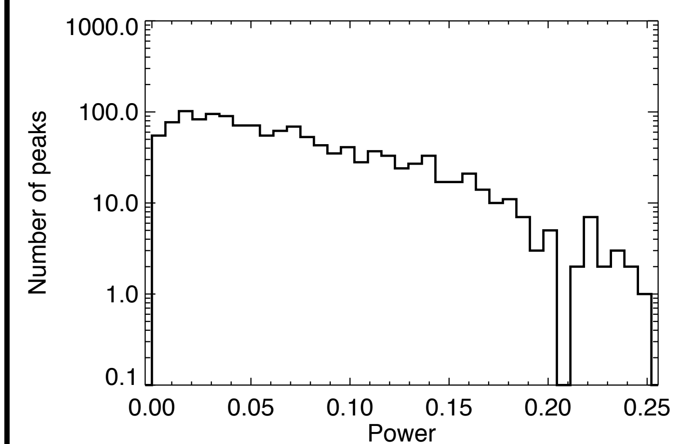
- 2DKLS periodogram (O'Toole+ 2009)
- Grid search over *P* and *e*
- Marginalize over T_p, ω, *K*
- Power, Z = $\frac{\chi_B^2 - \chi^2}{\chi_B^2}$
- Incorporate measurement errors into fit
- Allow for offsets between datasets, and simultaneously fit for a linear trend
- single, or multi-planet

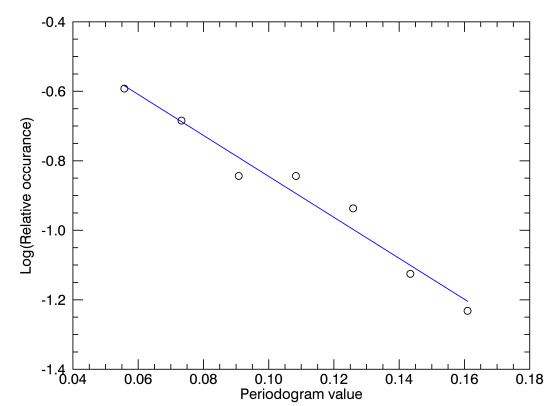


Automated Search

1% False Alarm Probability and Caveats

- Empirical false alarm probability (FAP)
- Fit distribution of periodogram peaks to predict the height of a peak that corresponds to a given FAP
- We adopt FAP<1% as a good detection





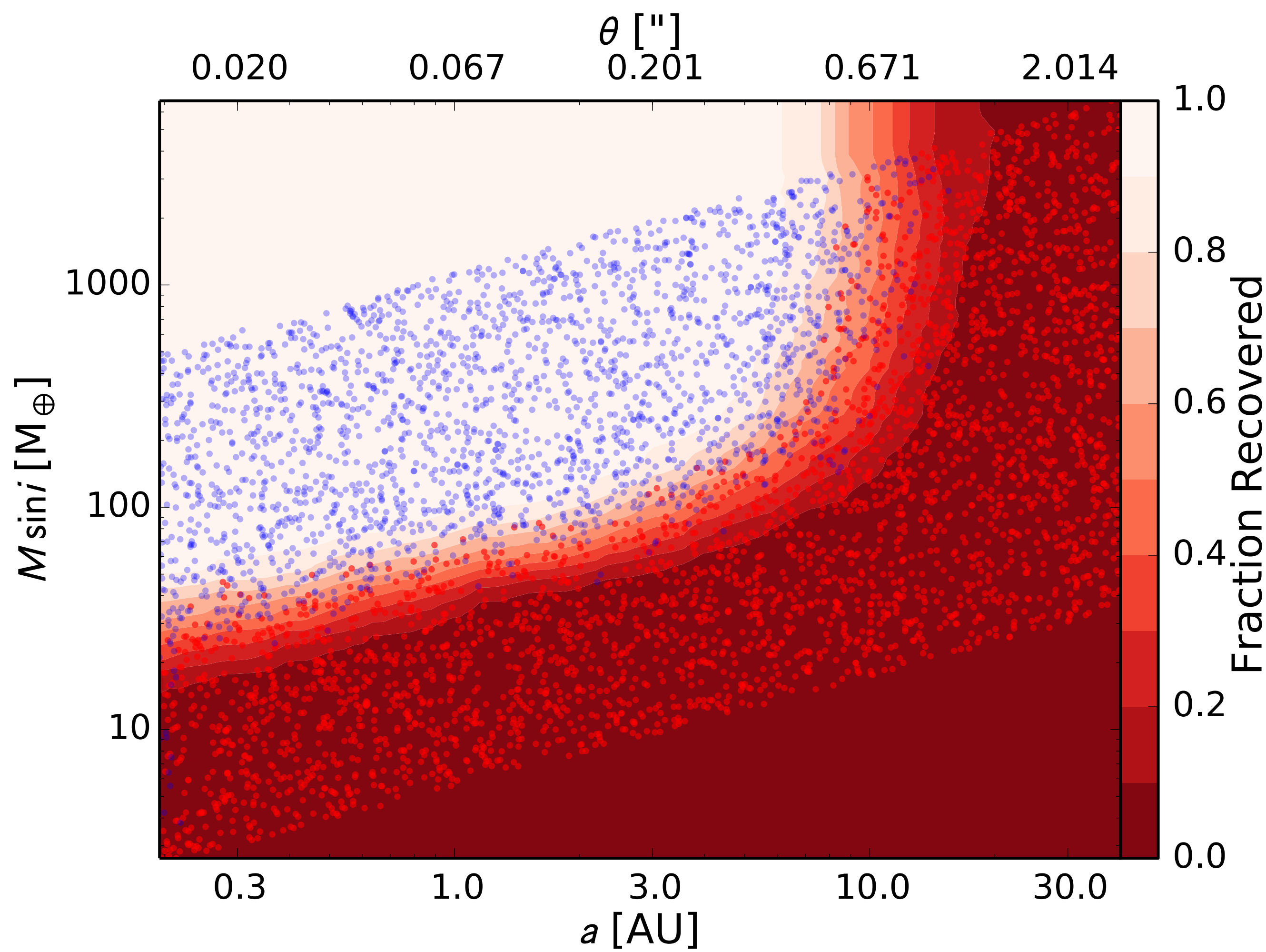
<u>Caveats</u>

- *<u>All</u>* significant signals are detected, whether planetary, astrophysical, or instrumental

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

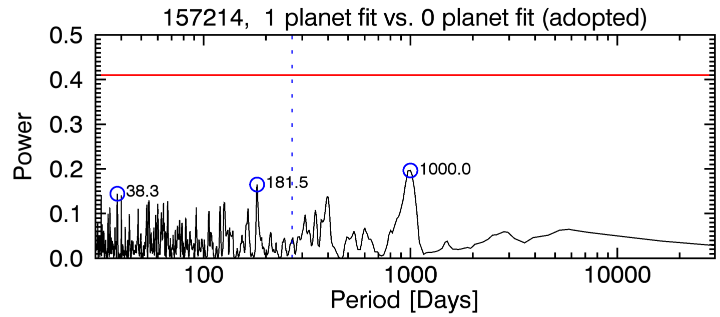
Completeness Contours for HD 157214
filename = 157214_contours.csv

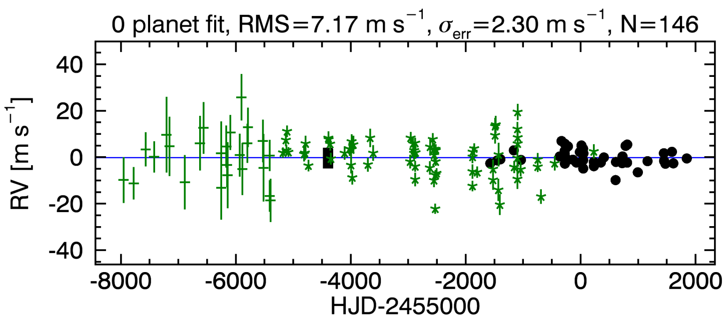
```
# star HD number, 157214
# Mstar, 0.871, Msun
# Dstar, 14.393, pc
period,a,theta,rec_16,rec_50,rec_84
30.061231691,0.180712767491,0.0125559234334,14.7425926001,22.3910787033,34.0076144745
32.5895618052,0.190708479539,0.0132504255257,14.7425926001,22.3910787033,34.0076144745
35.3305396654,0.201257081461,0.0139833424076,15.8060756552,22.3910787033,34.0076144745
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
    ⋮
```

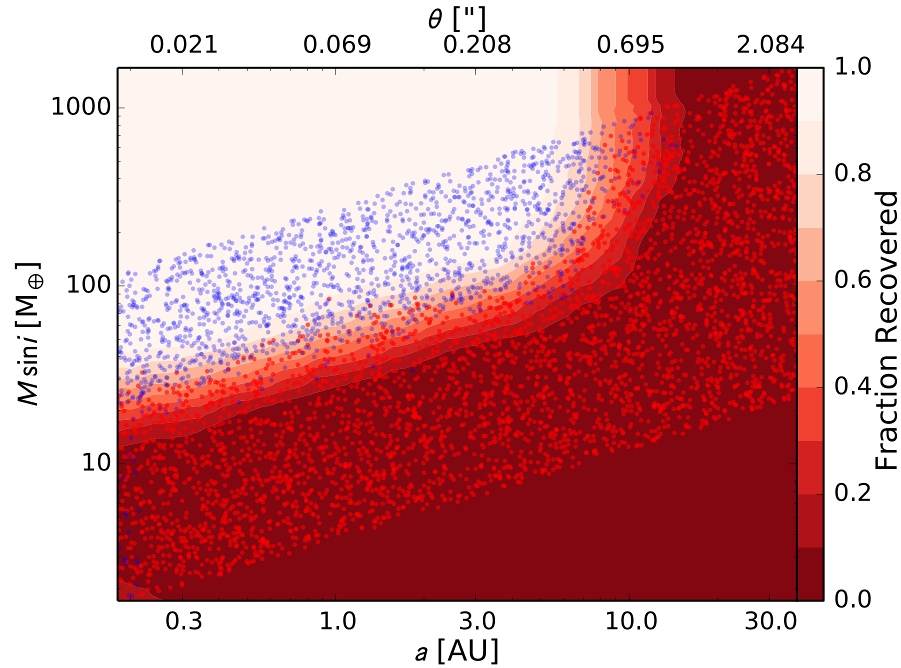
Completeness contours (16%, 50%, 84%) provided for 76 Exo-C/Exo-S/AFTA targets with Keck/Lick Spectra

Automated Search & Completeness

Example #1 - HD 157214

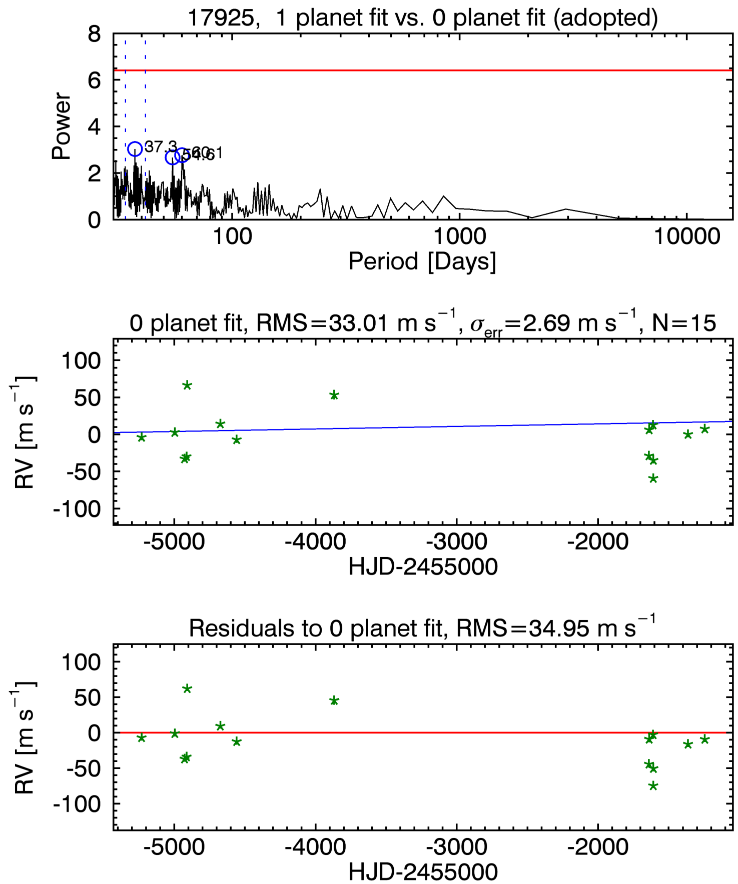


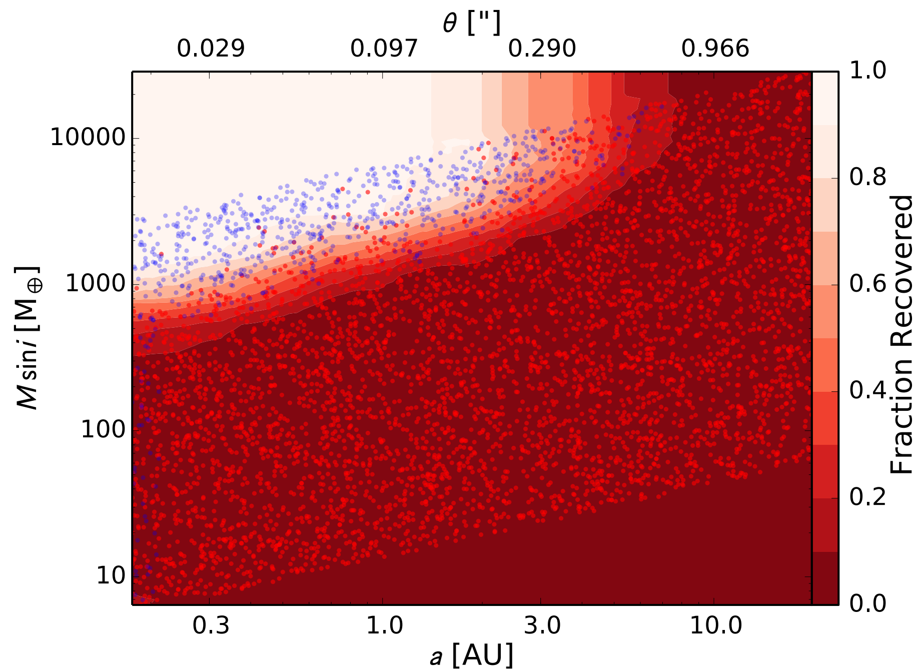




Automated Search & Completeness

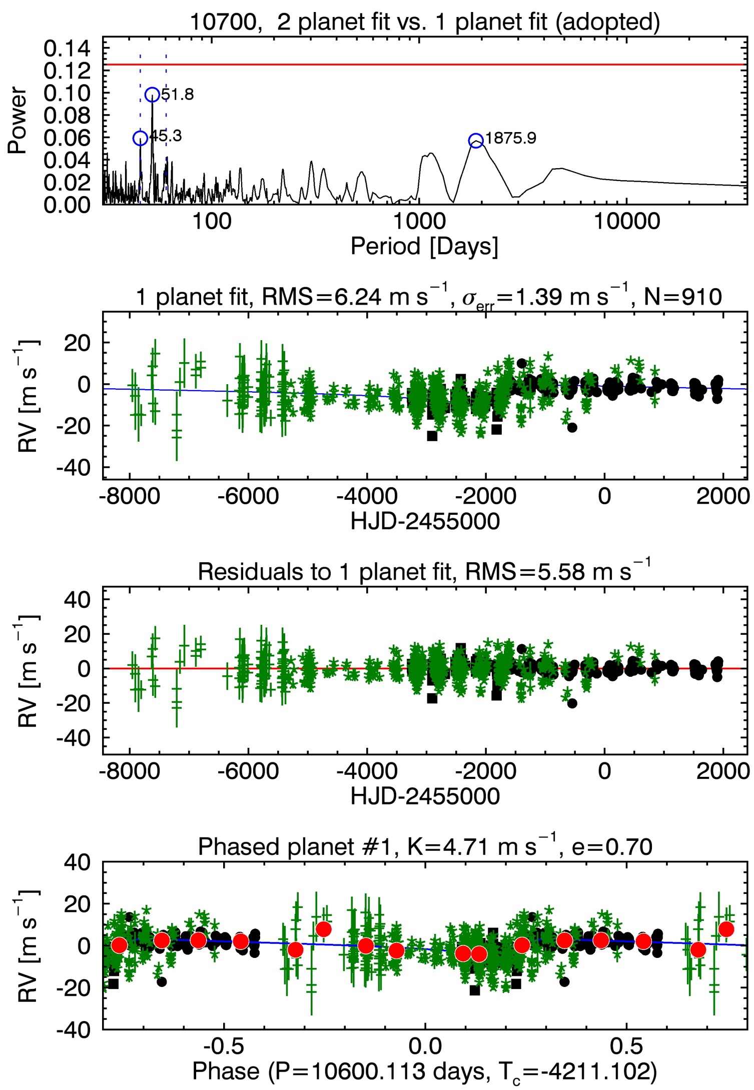
Example #2 - HD 17925

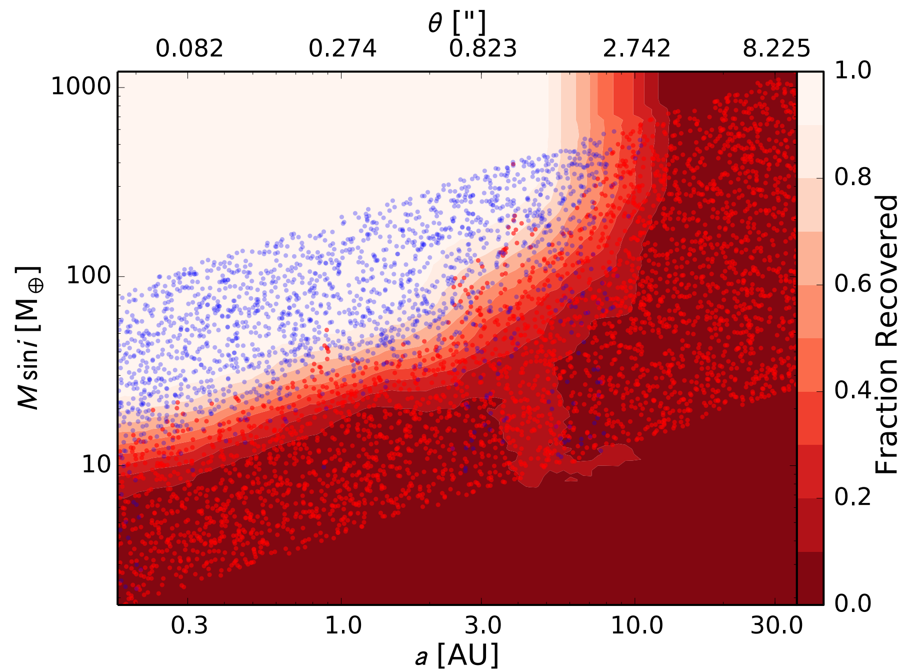




Automated Search & Completeness

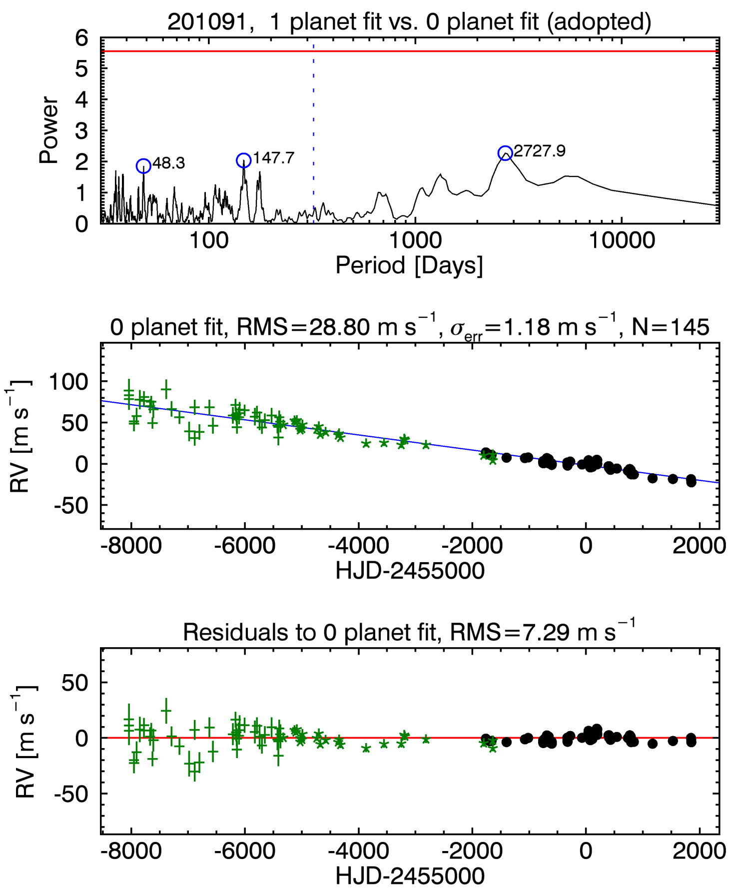
Example #3 - HD 10700 (τ Ceti)

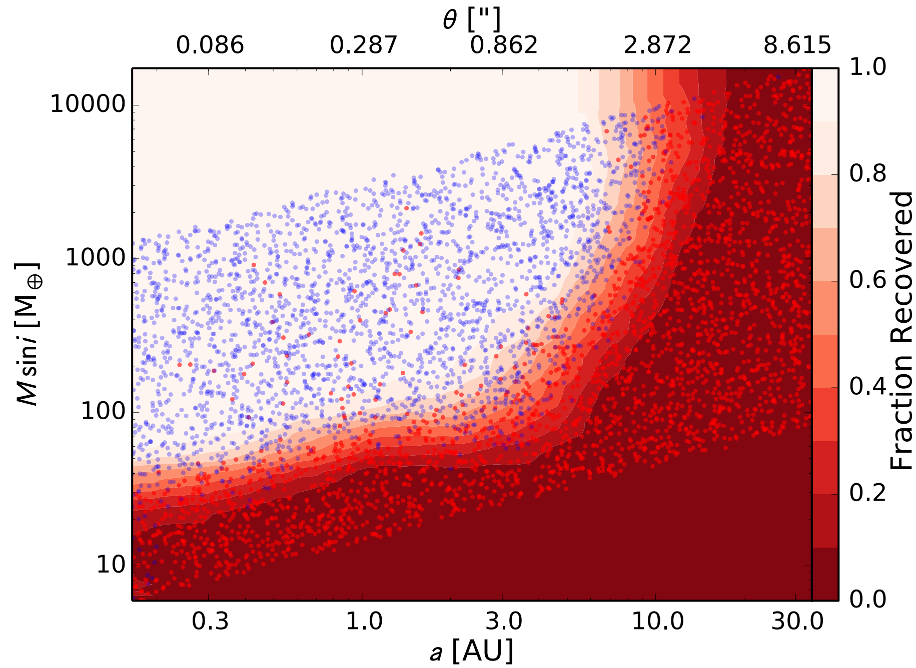




Automated Search & Completeness

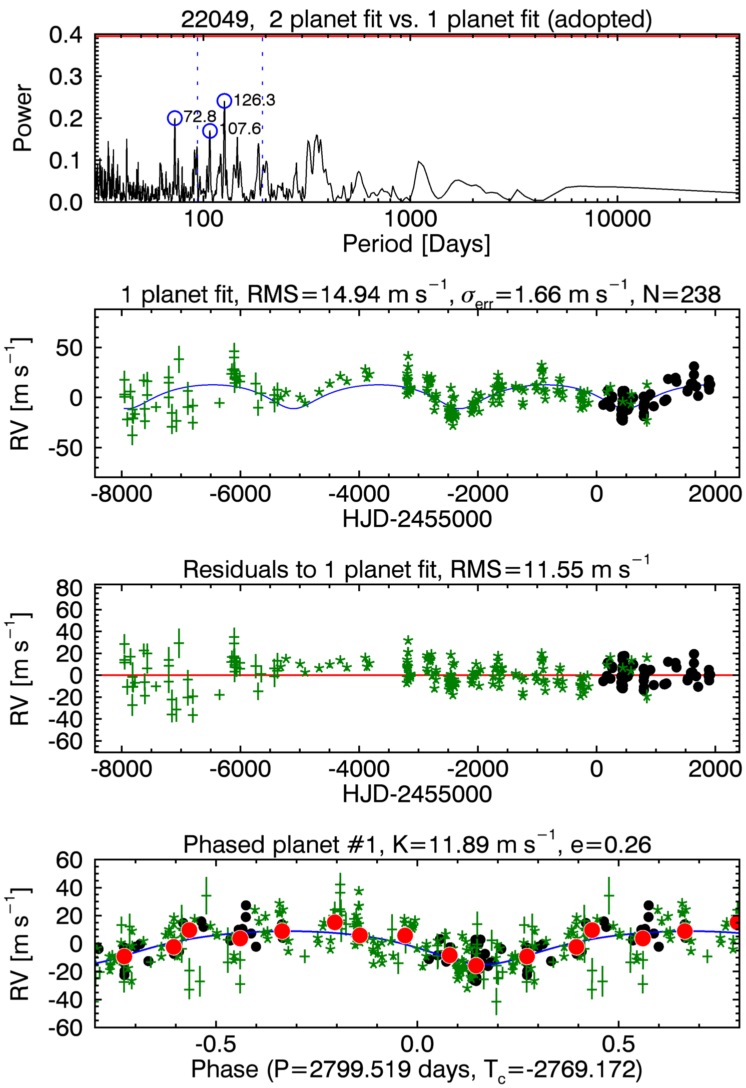
Example #4 - HD 201091 (wide binary)

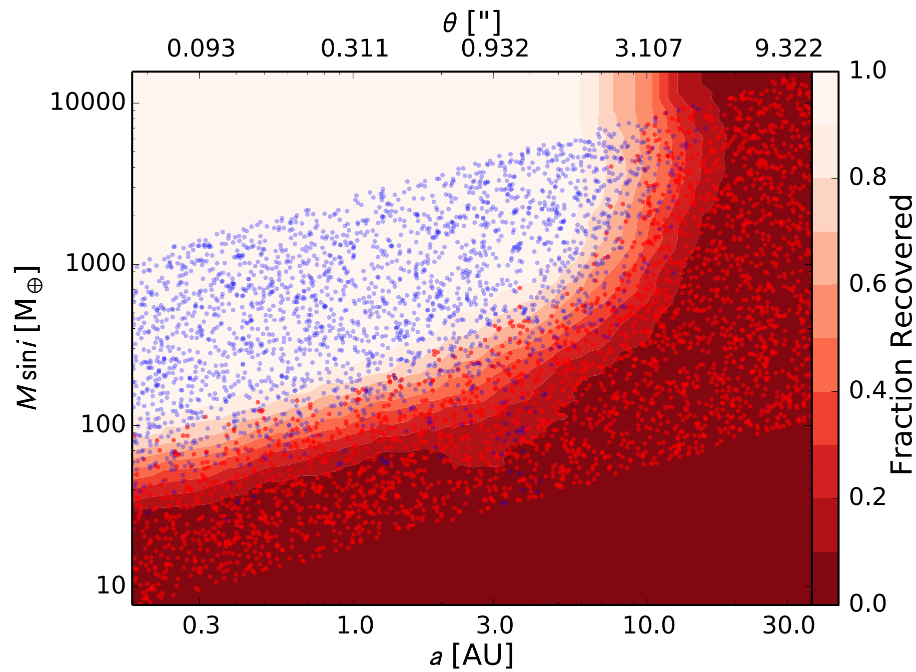




Automated Search & Completeness

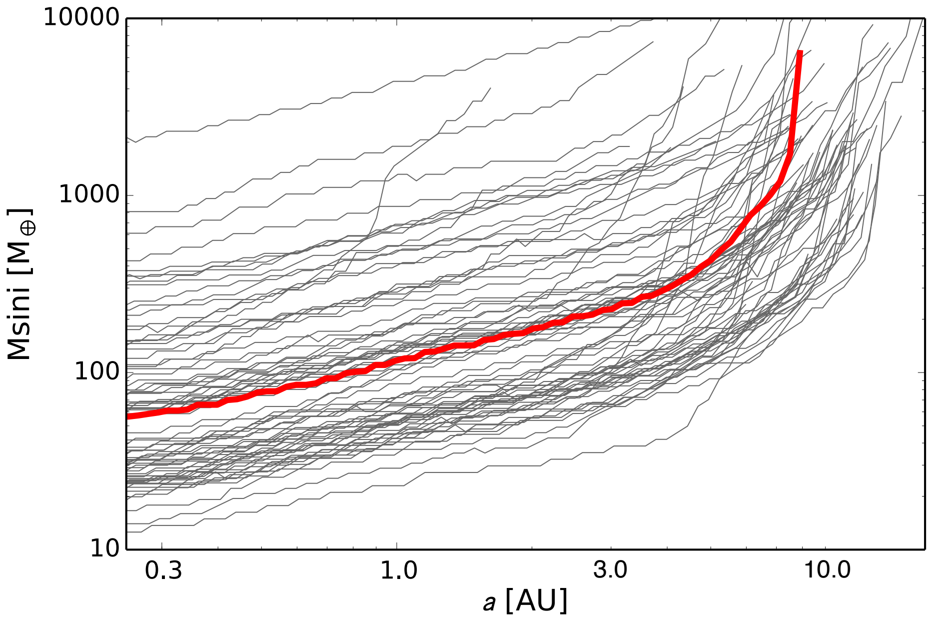
Example #5 - HD 22049 (ε Eridani)



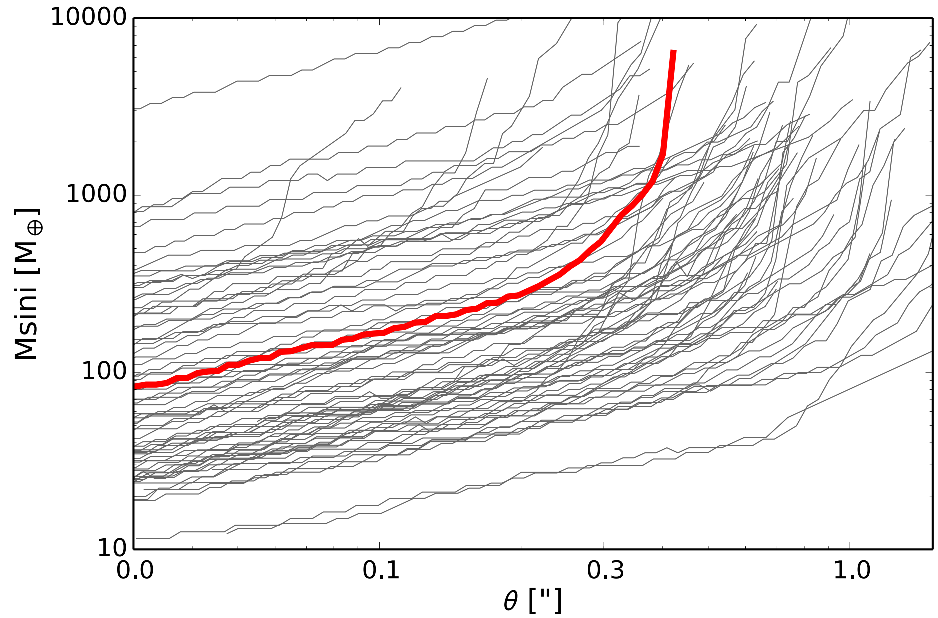


Survey Completeness

Completeness vs. Semi-major axis



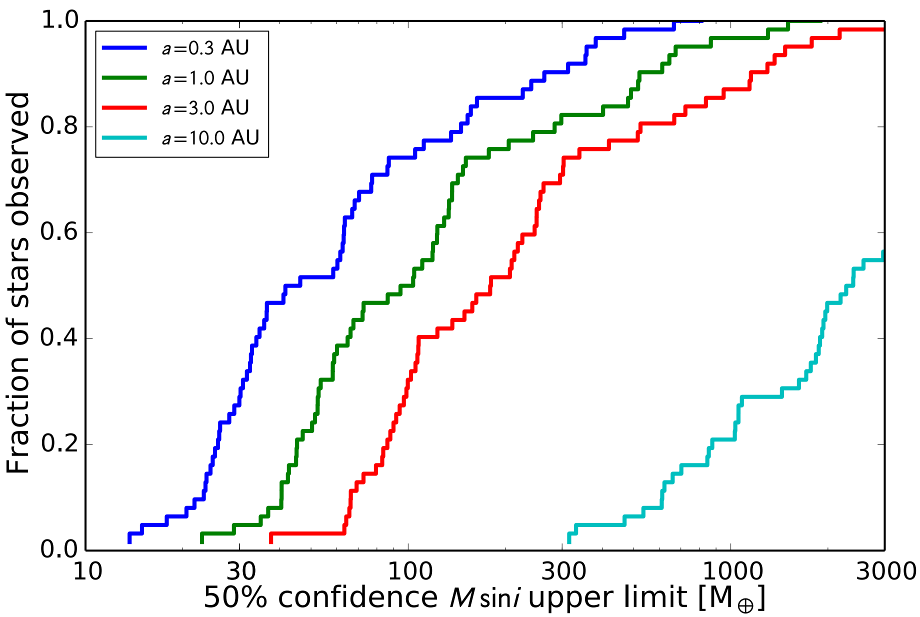
Completeness vs. Projected Separation



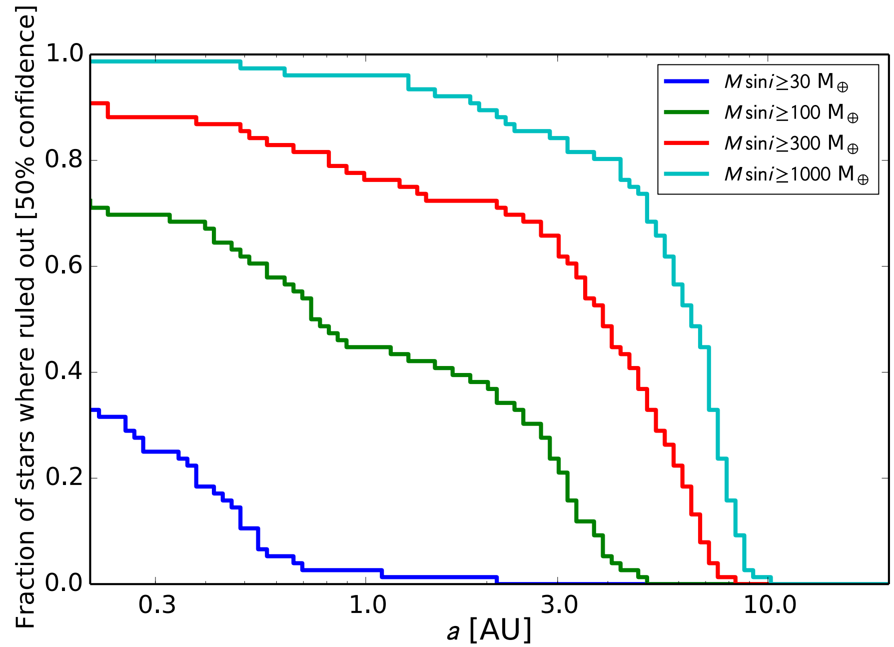
Completeness for all 76 Stars

Survey Completeness

Completeness Limits vs. Mass



Completeness Limits vs. Semi-major Axis



Completeness for all 76 Stars

Idealized Completeness

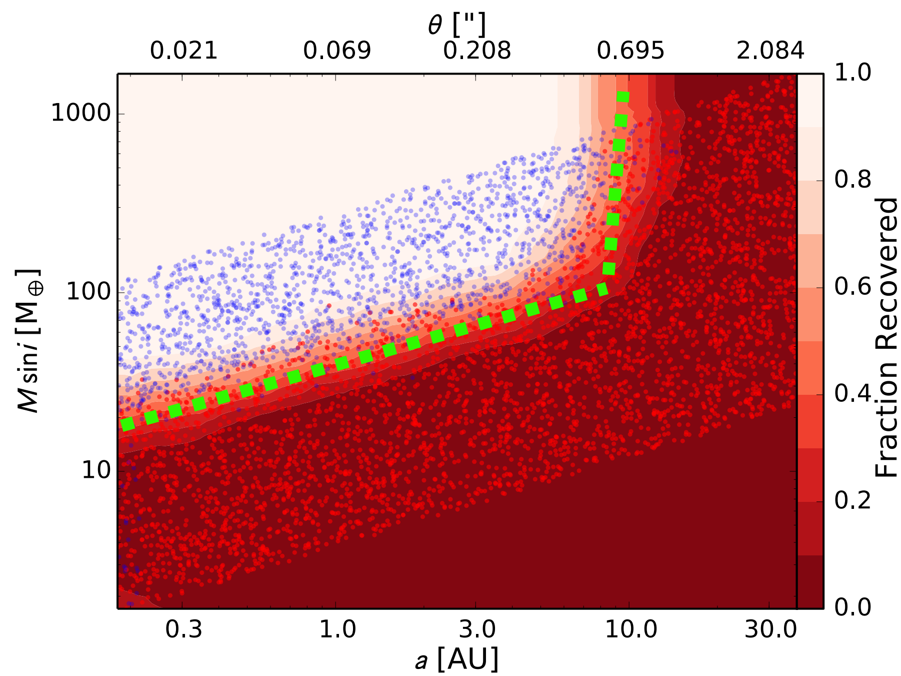
50% Detection Completeness

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

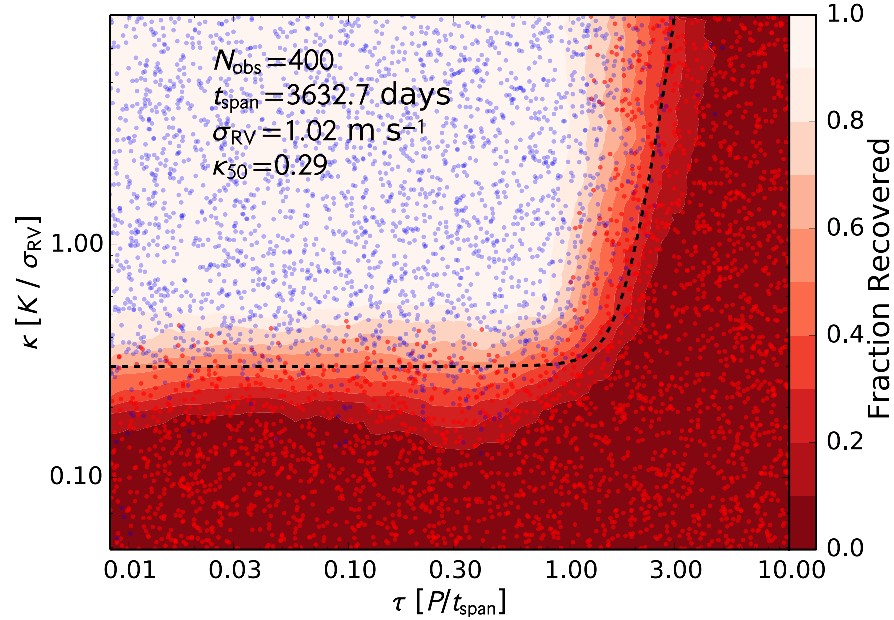
Make Problem Dimensionless

Dimensionless Doppler Amplitude:

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

Dimensionless Time:

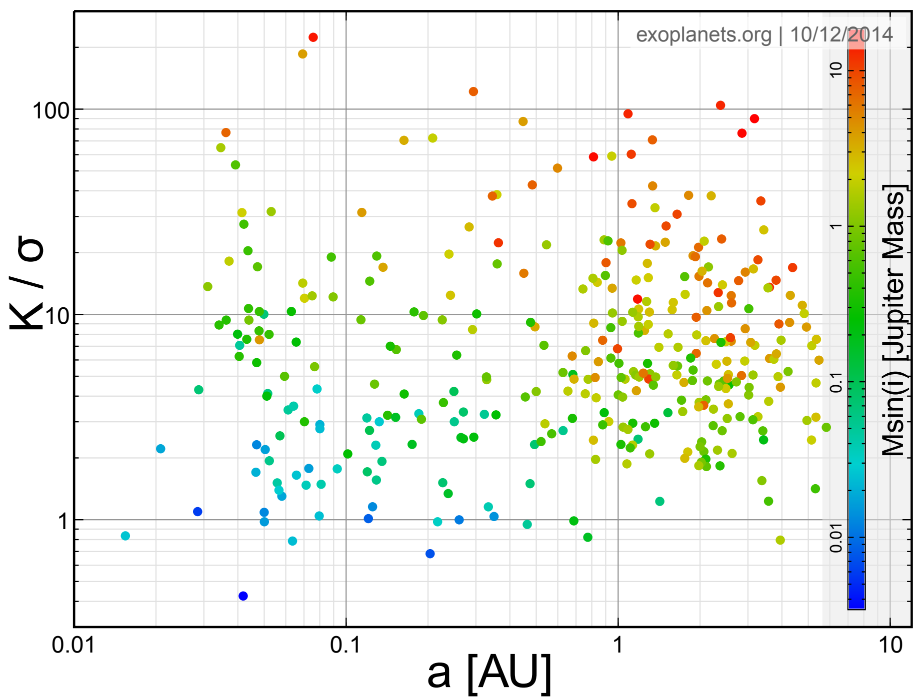
$$\tau = P/t_{\rm span}$$

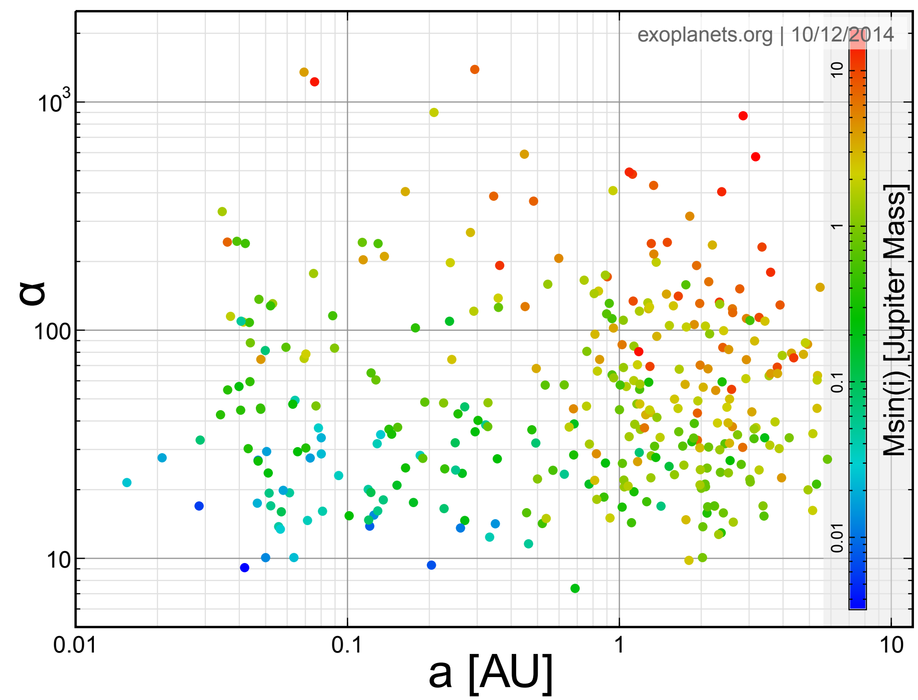


$$K_{50}(\tau) = \frac{\sigma_{\rm RV}\,\alpha}{\sqrt{N_{\rm obs}}} \cdot \sqrt{1 + (10^{\tau - 1.5})^2}$$

$\alpha \approx 6$ — Injection/recovery Simulations

Idealized Completeness





α ≈ 10 — Real Planets on exoplanets.org

Idealized Completeness

Prescription for Computing Completeness for Hypothetical Observing Campaign

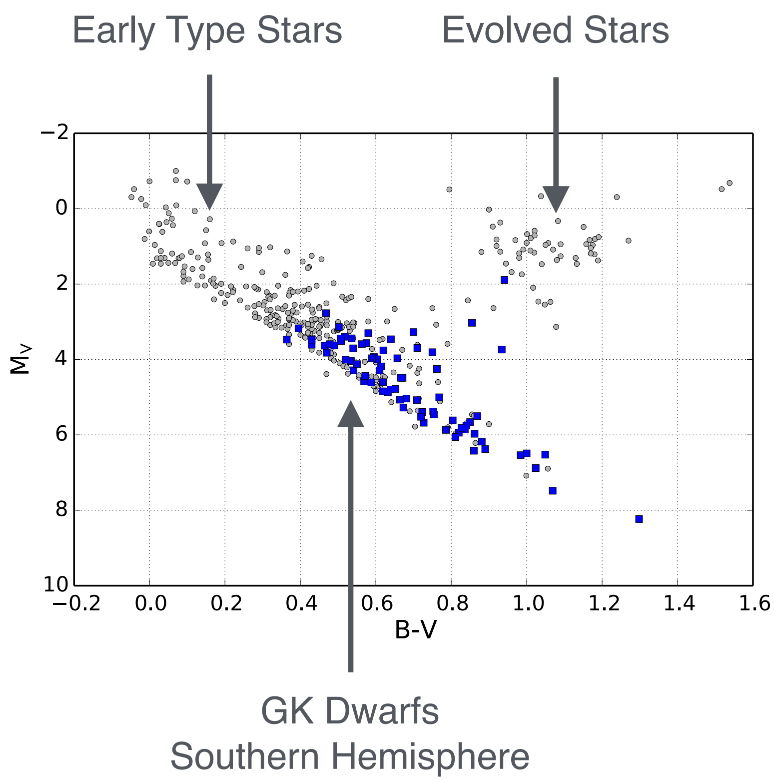
1. Choose N_{obs} and T_{span} for survey and $M_\star$ and σ_{RV} for stars.
2. Compute $K_{50}(P)$
3. Convert $K_{50}(P)$ to $Msini_{50}(P)$
4. Convert $Msini_{50}(P)$ to $Msini_{50}(a)$

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

What is σ_{RV} for Exo-C/Exo-S/AFTA Target Stars?

Idealized Completeness

Jitter Estimates - σ_{RV}



Early Spectral Type (hot, < ~F8):

few and broad lines

$\sigma_{RV} \approx 0.16 * V\sin i^{1.5}$

Evolved Stars (subgiants, giants):

oscillations

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

Southern Hemishere (GK dwarfs):

< 3 m/s; limited by spectrometer?

Young Stars:

line distortions; rotational spot modulation

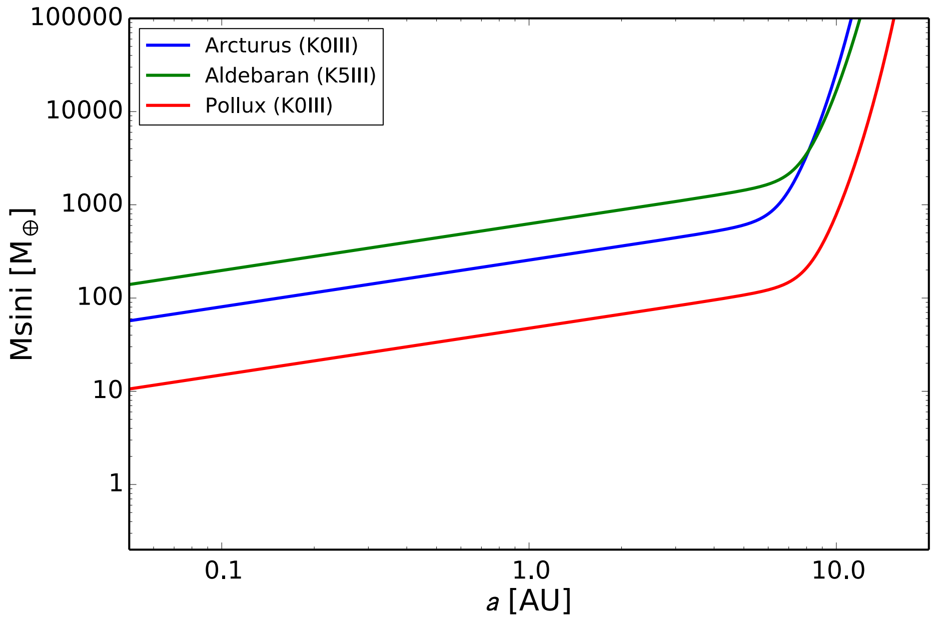
100 m/s → < 3 m/s (function of $\log R'_{HK}$)

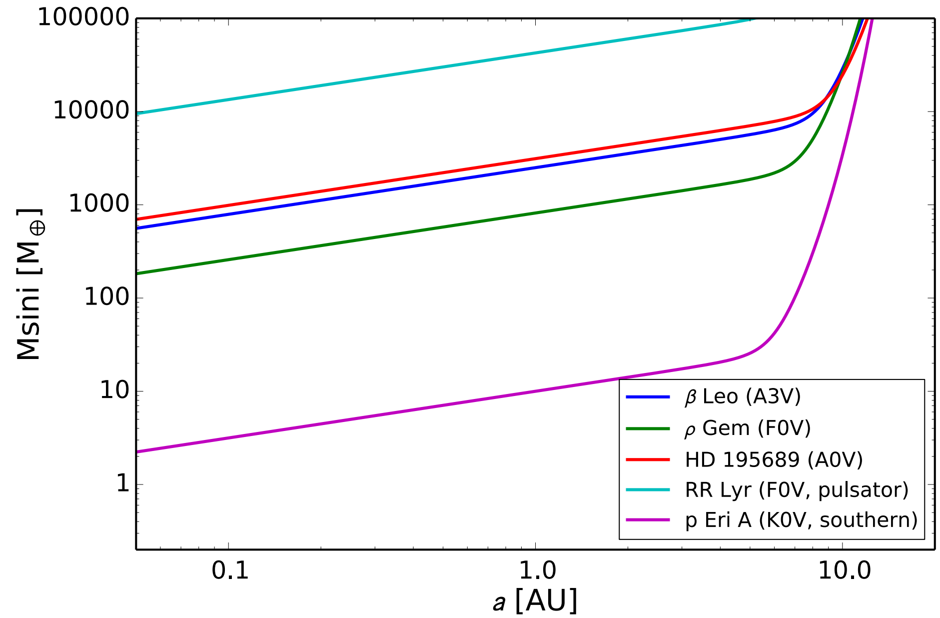
Binaries:

too hard, not recommended

Idealized Completeness

Dedicated RV Campaign





Survey Parameters:

σ_{RV} estimated for each star

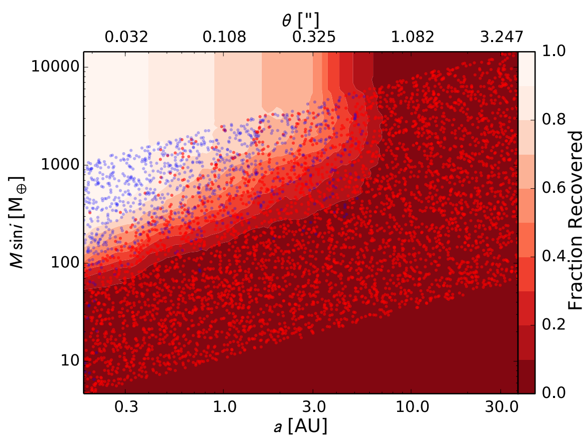
N_{obs} = 100 RVs

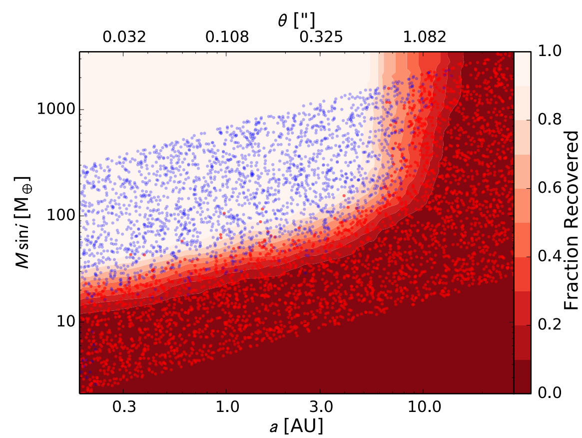
T_{span} = 10 yr

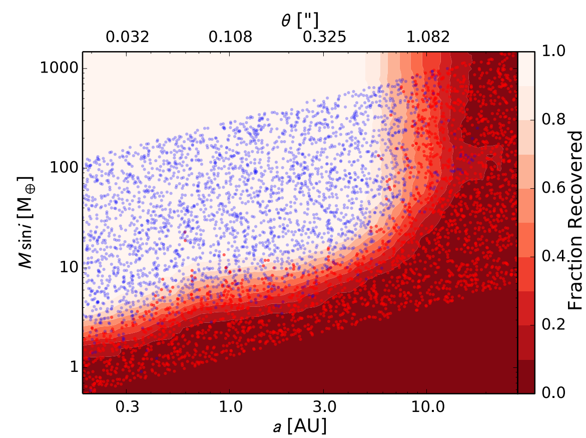
α = 6

Sensitivity Gain

HD 102365







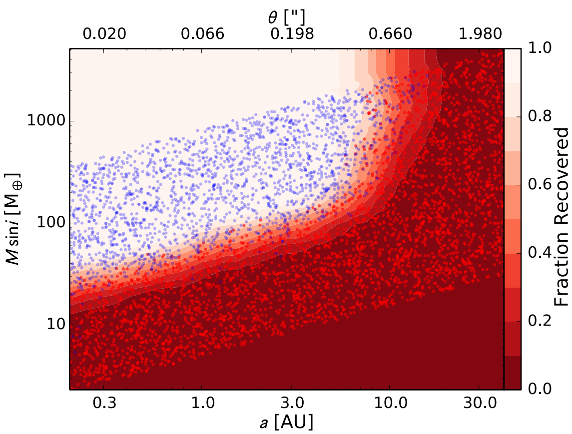
<u>Current RVs:</u>
N_{obs} = 16 RVs
T_{span} = 6.6 yr
σ_{RV} = 2.5 m/s

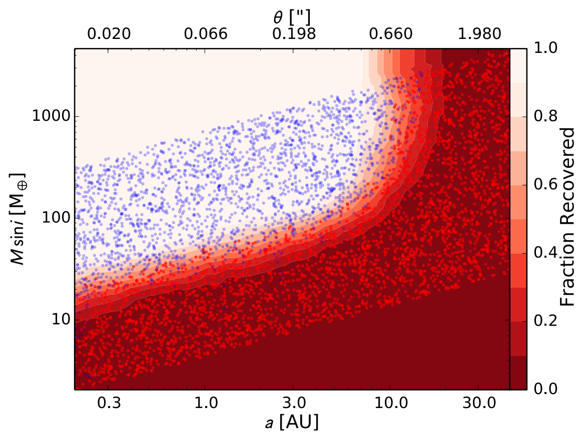
<u>Continued RVs:</u>
N_{obs} = 16 **+ 30 RVs**
T_{span} = 6.6 yr + 10 yr
σ_{RV} = 2.5 m/s

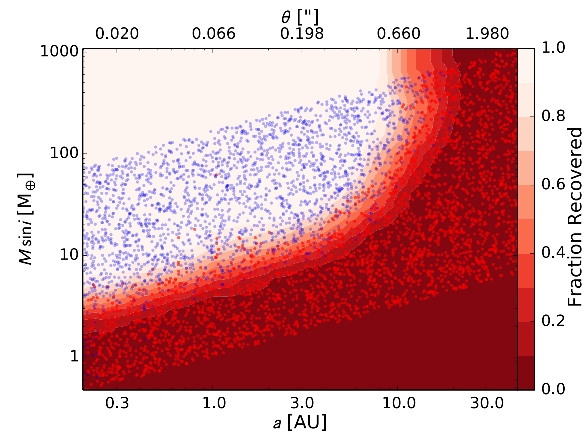
<u>Ideal Survey:</u>
N_{obs} = 16 **+ 100 RVs**
T_{span} = 6.6 yr + 10 yr
σ_{RV} = 0.5 m/s (new RVs)

Sensitivity Gain

HD 182572







<u>Current RVs:</u>
N_{obs} = 82 RVs
T_{span} = 17.8 yr
σ_{RV} = 4.0 m/s

<u>Continued RVs:</u>
N_{obs} = 82 **+ 30 RVs**
T_{span} = 17.8 yr + 10 yr
σ_{RV} = 3.6 m/s (new RVs)

<u>Ideal Survey:</u>
N_{obs} = 82 **+ 100 RVs**
T_{span} = 17.8 yr + 10 yr
σ_{RV} = 0.5 m/s (new RVs)

Recommendations

1. Needed RV measurements should be written into mission requirements. Current Doppler surveys cannot observe (TACs won't support observations of) imaging targets without justification.

2. Invest in a dedicated facility with the time baseline and RV precision to prepare for 10+ yr for the imaging missions.

3. Start dedicated RV campaigns to measure the jitter (σ_{RV}) of every plausible direct imaging target.

Recommendations (2)

4. We recommend that all target G and K dwarfs (in the North and South) be observed at least 10 times per year with as high of a precision as possible ($\leq$ 2 m/s) to detect or place limits on super-Earths and Neptune-mass planets in few AU orbits.

5. For stars showing low enough jitter to enable completeness encompassing giant planets in few AU orbits, we recommend 10 RV epochs per year for 10 yr, with a short-term observing cadence designed to average over photospheric jitter.