Limits on Planetary Companions from Doppler Surveys of Nearby Stars

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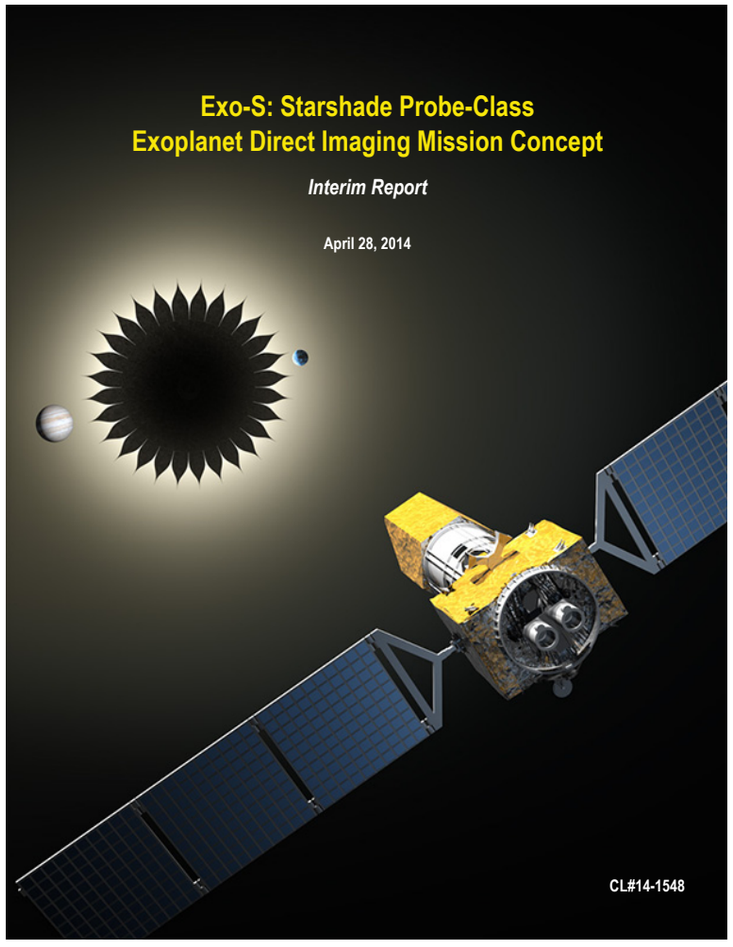
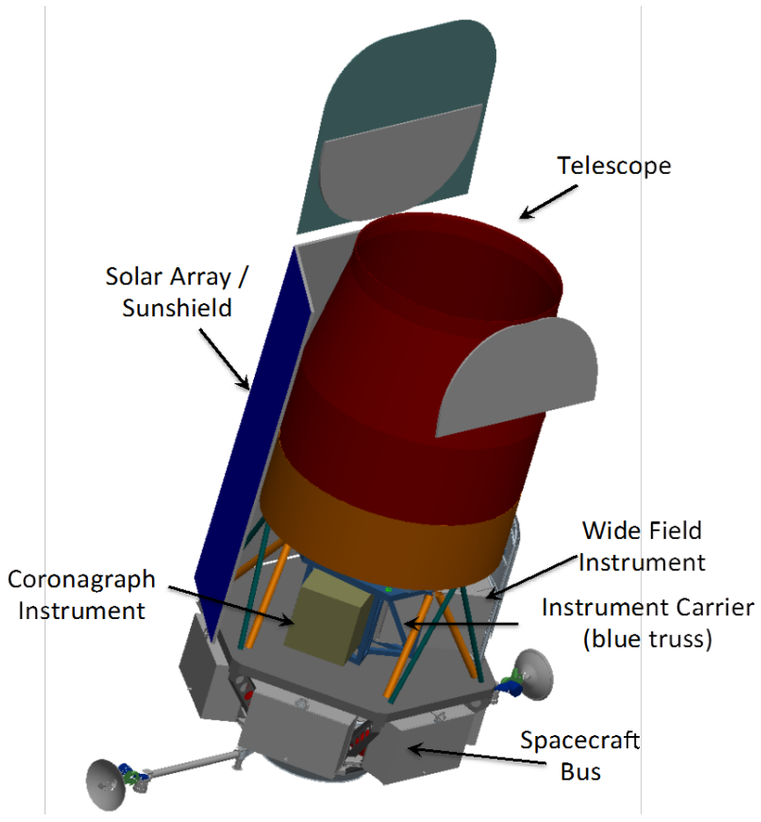
Lick Observatory

Keck Observatory

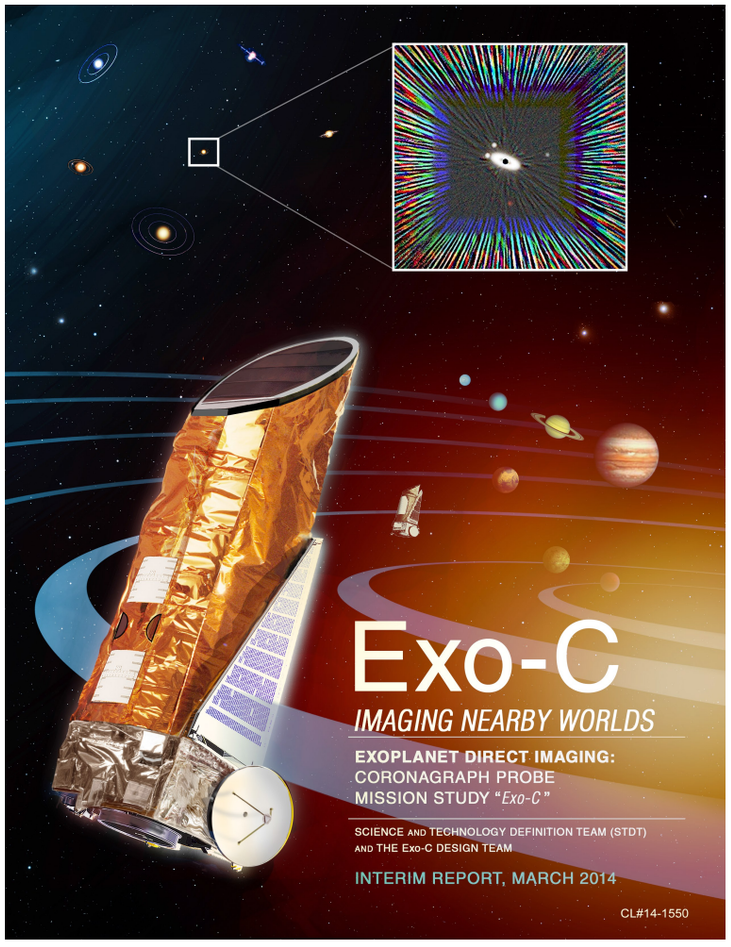
High-Contrast Imaging Mission Studies



Exo-S (Starshade)



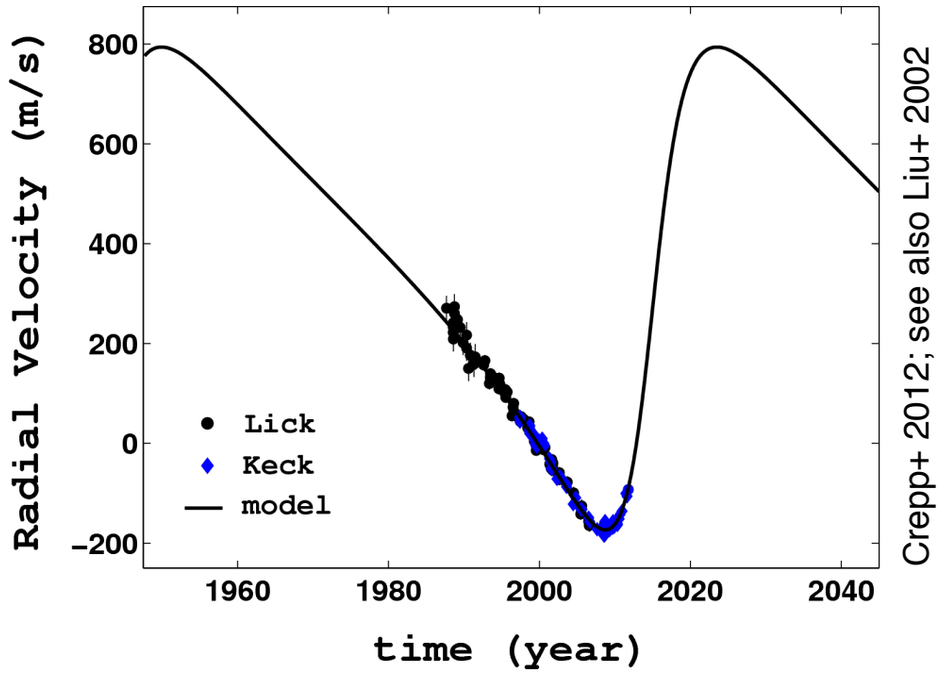
WFIRST/AFTA



Exo-C (Coronagraph)

Doppler / High-contrast Imaging Synergy

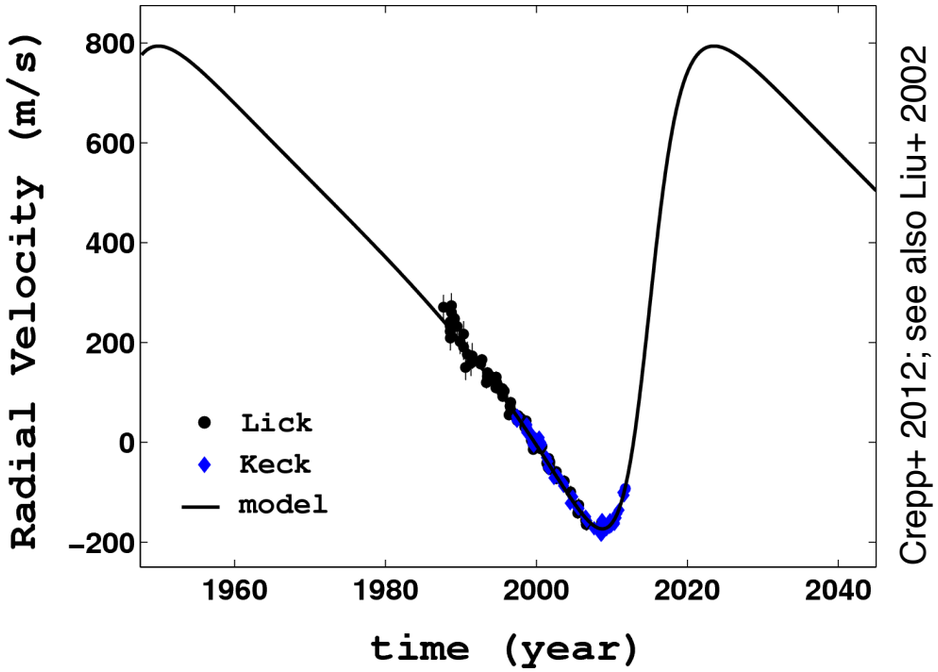
RV Detection



Crepp+ 2012; see also Liu+ 2002

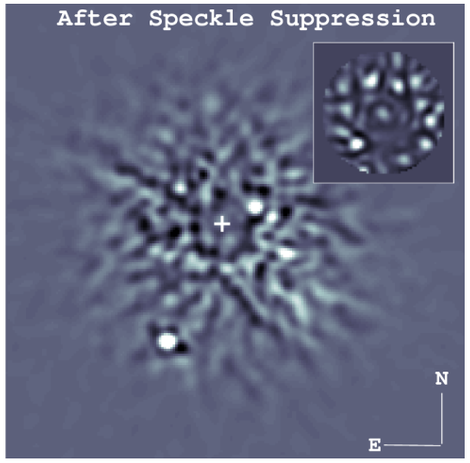
Doppler / High-contrast Imaging Synergy

RV Detection



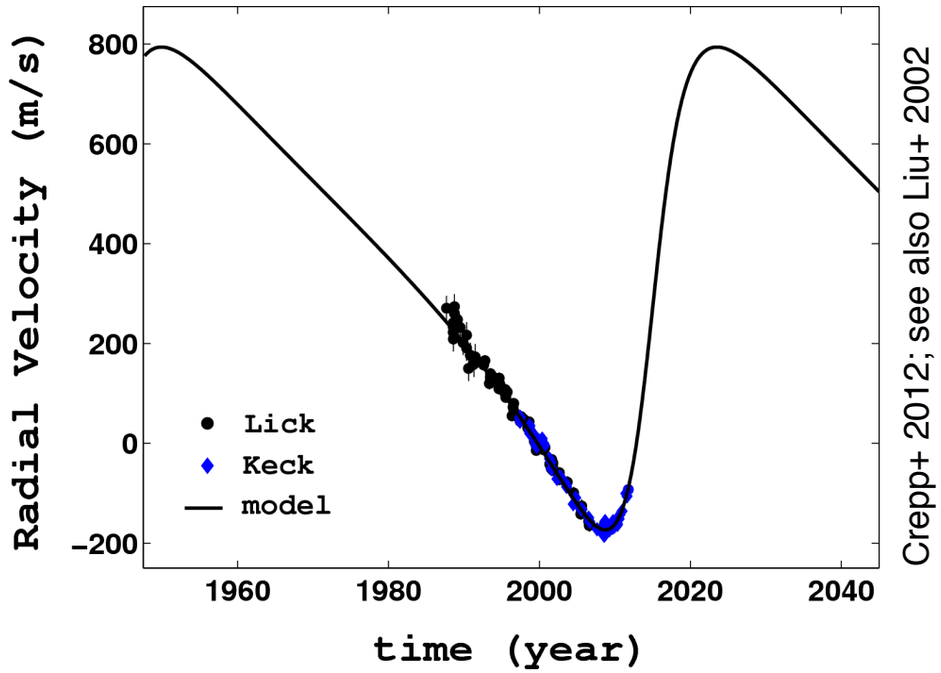
Crepp+ 2012; see also Liu+ 2002

Direct Image



Doppler / High-contrast Imaging Synergy

RV Detection



Crepp+ 2012; see also Liu+ 2002

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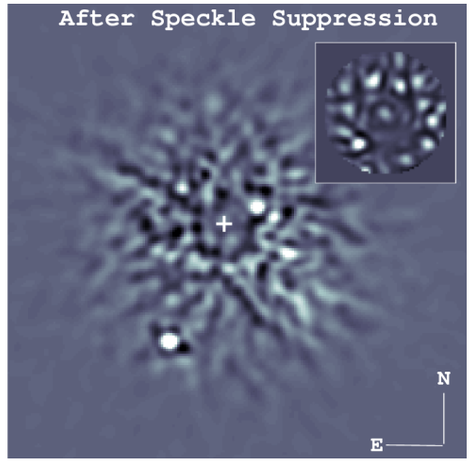
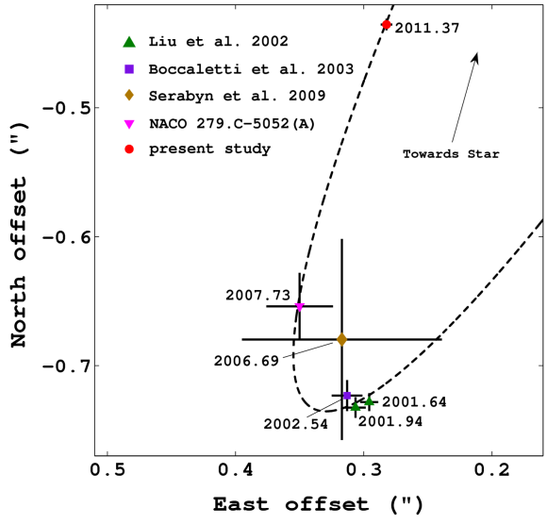
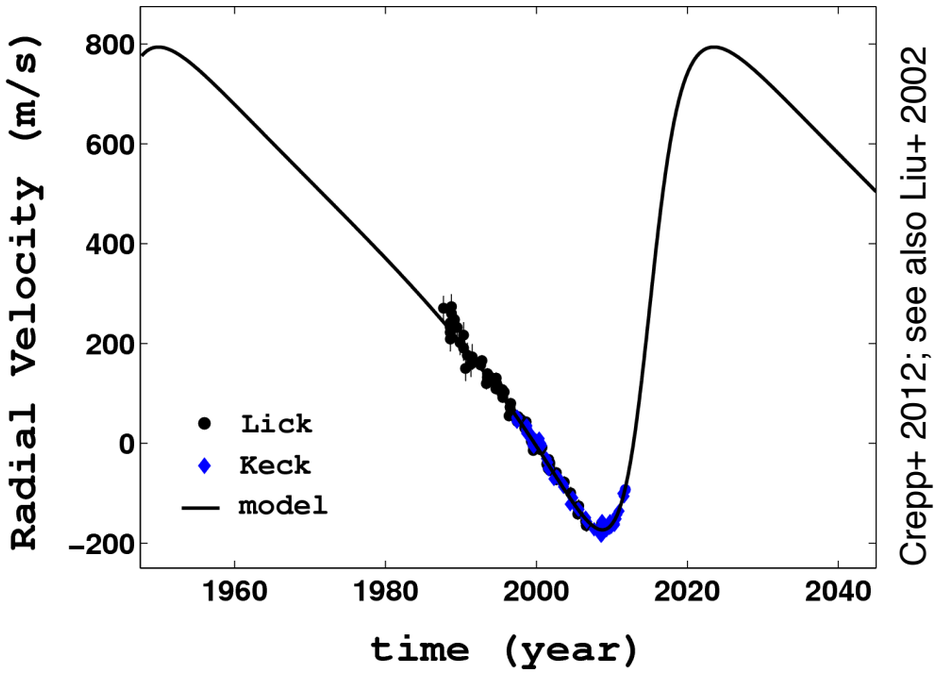


Astrometry

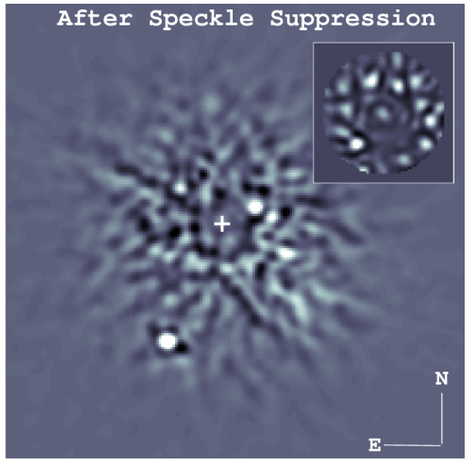


Doppler / High-contrast Imaging Synergy

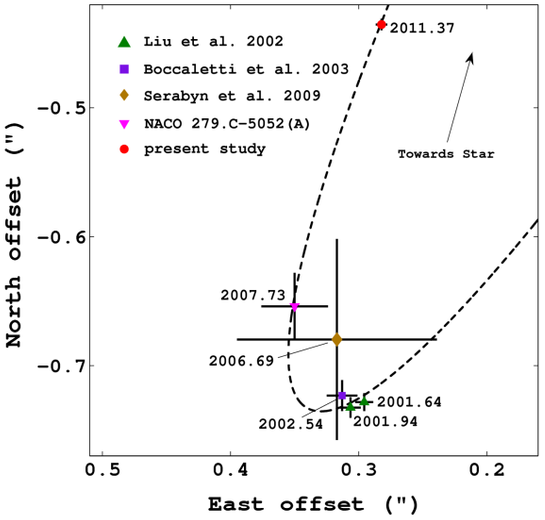
RV Detection



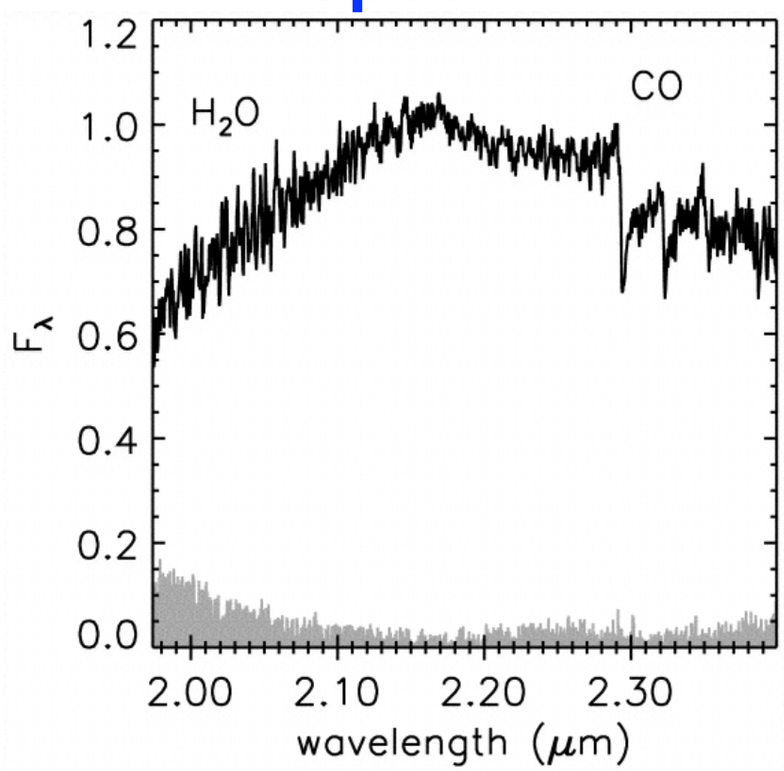
Direct Image



Astrometry



Spectrum

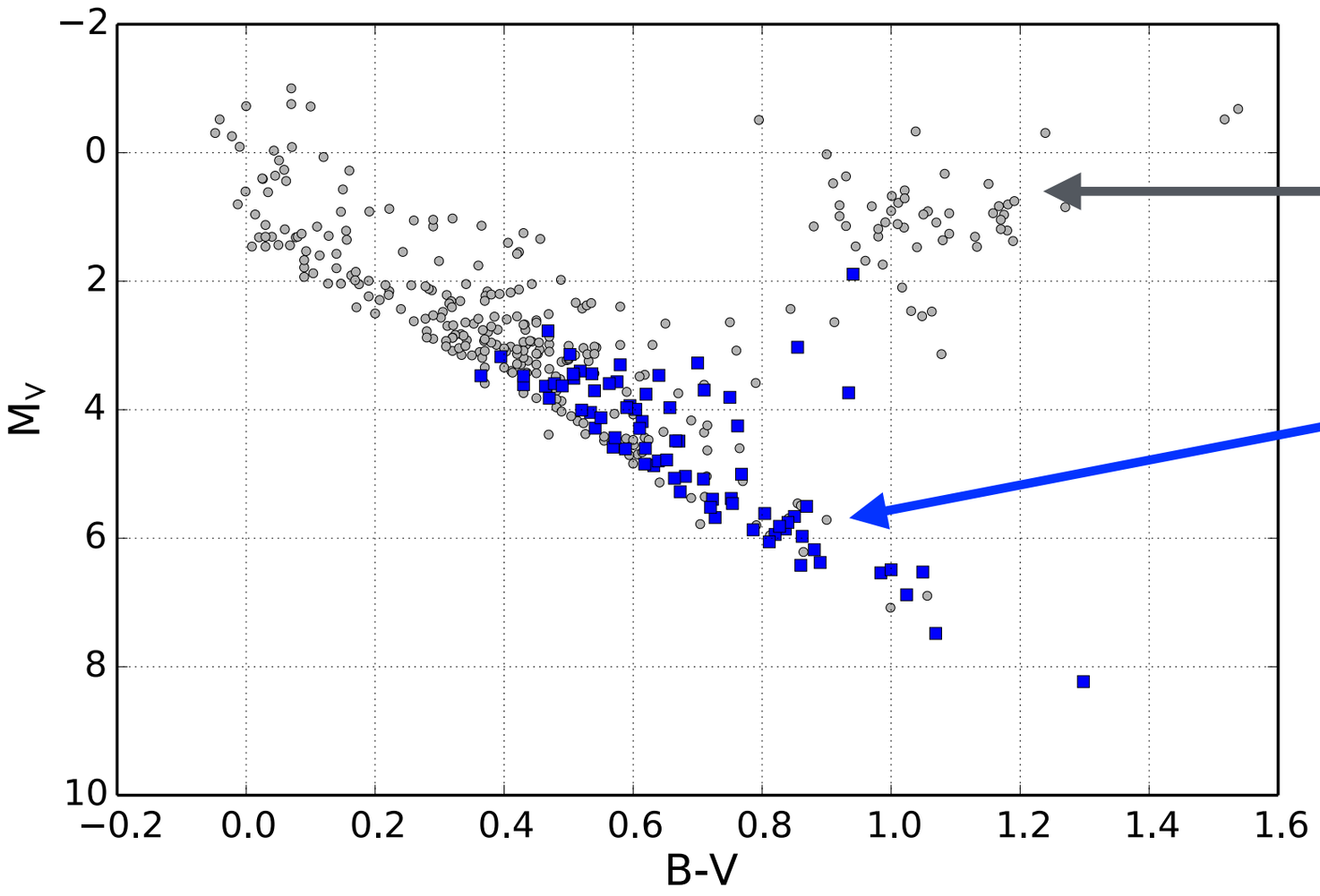


Doppler Measurements Provide:
Target Identification
Target Exclusion (non-detection limits)
Dynamical Masses

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

Star Lists and Data

Lick and Keck Observatory Star Lists



No Keck/Lick RVs
300 stars

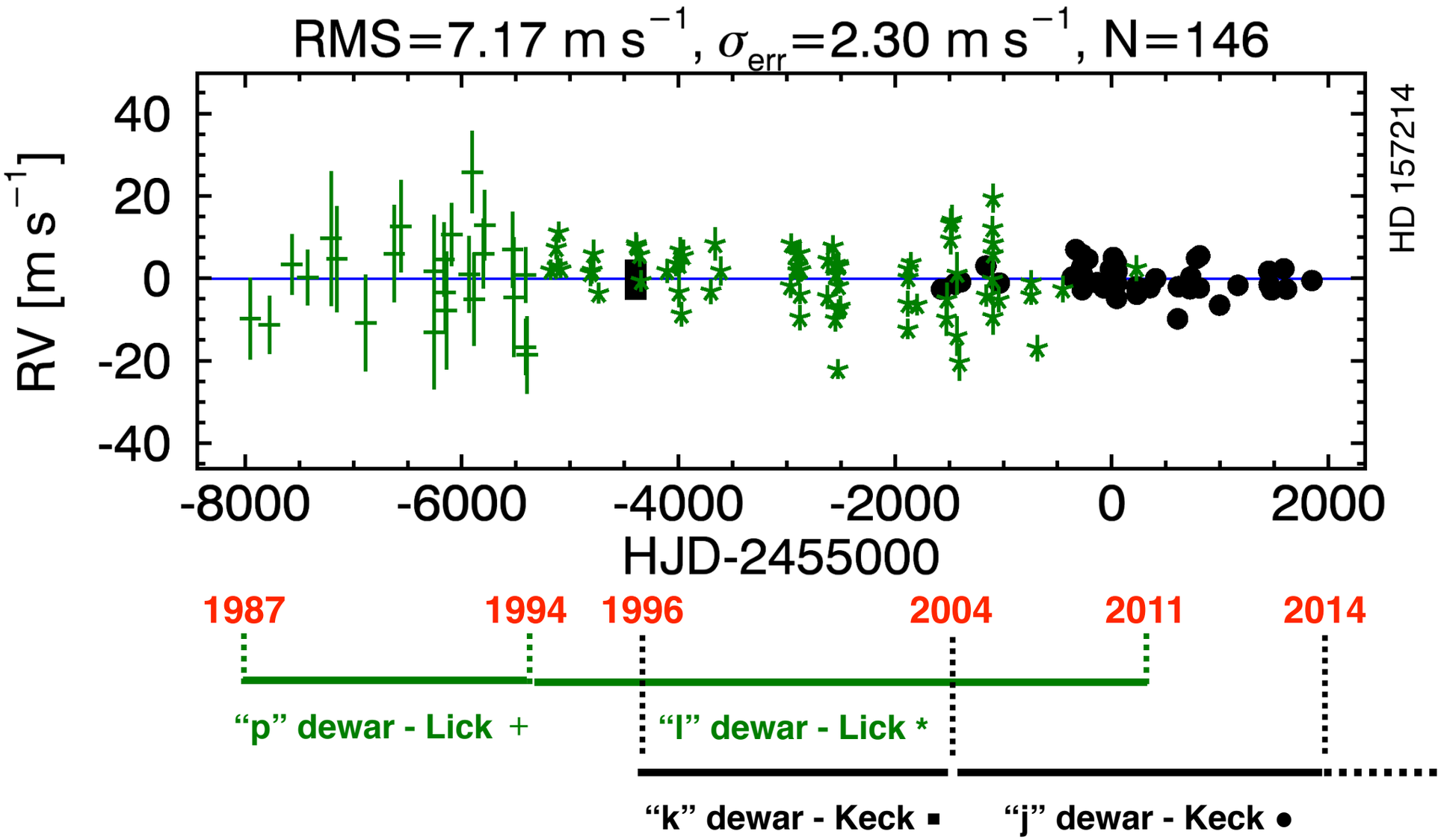
With Keck/Lick RVs
76 stars

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")

Only stars observed by the California Planet Survey (CPS) shown

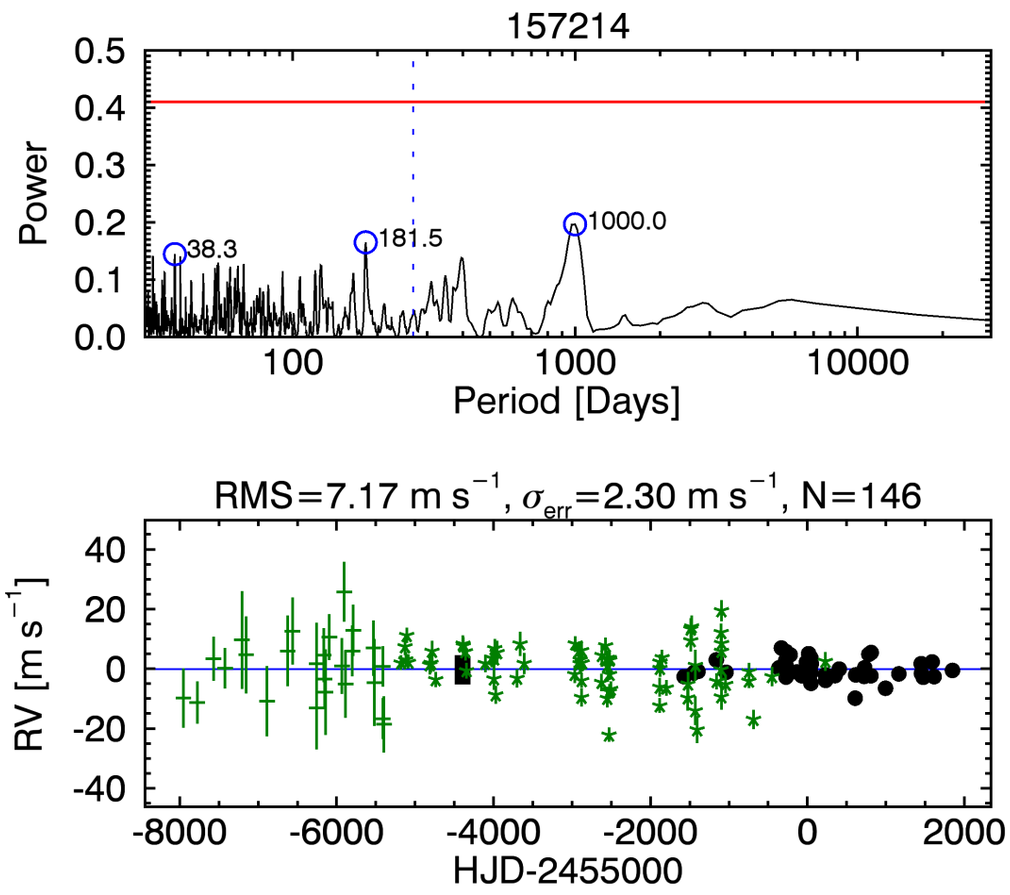
Star Lists and Data

Lick and Keck Observatory Data

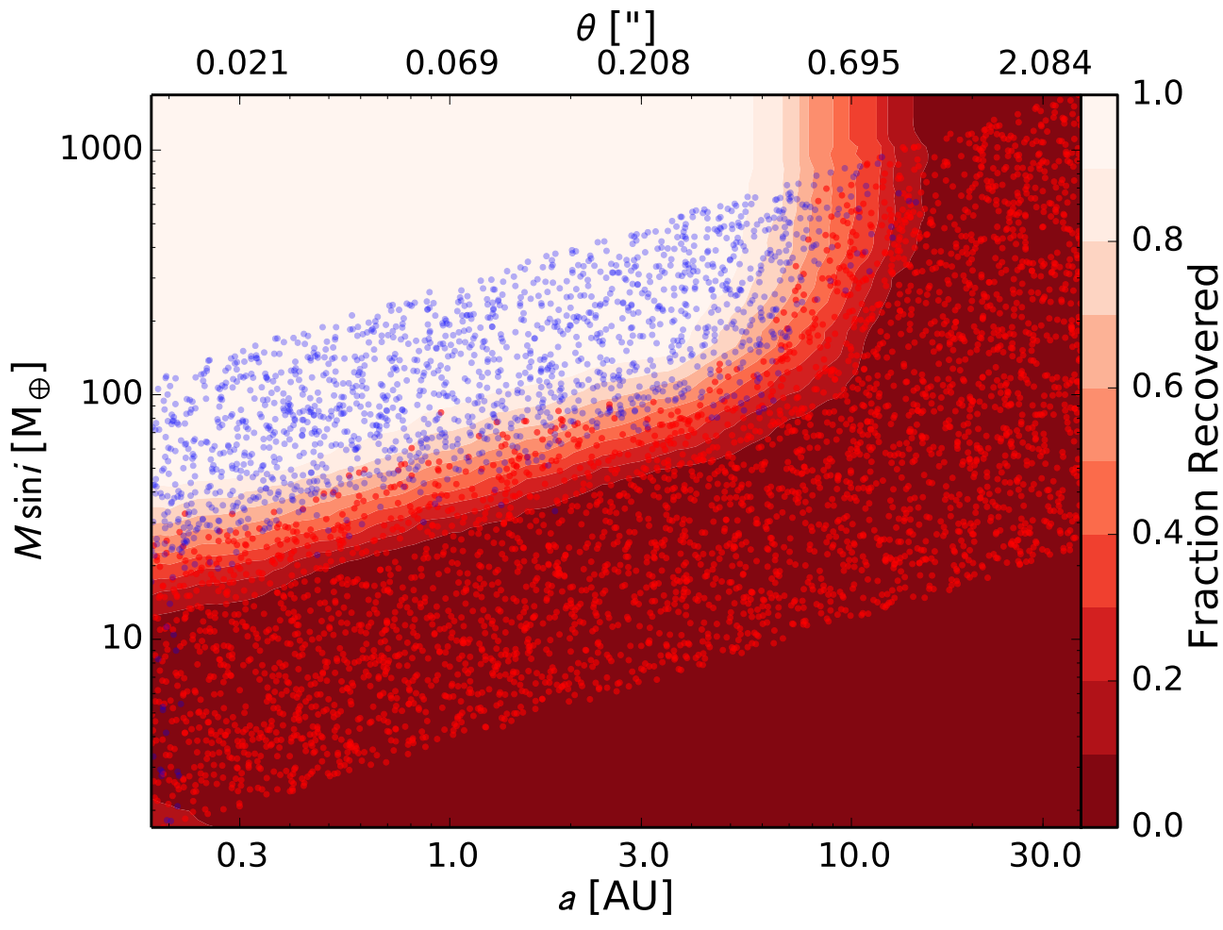


Automated Search & Completeness

HD 157214



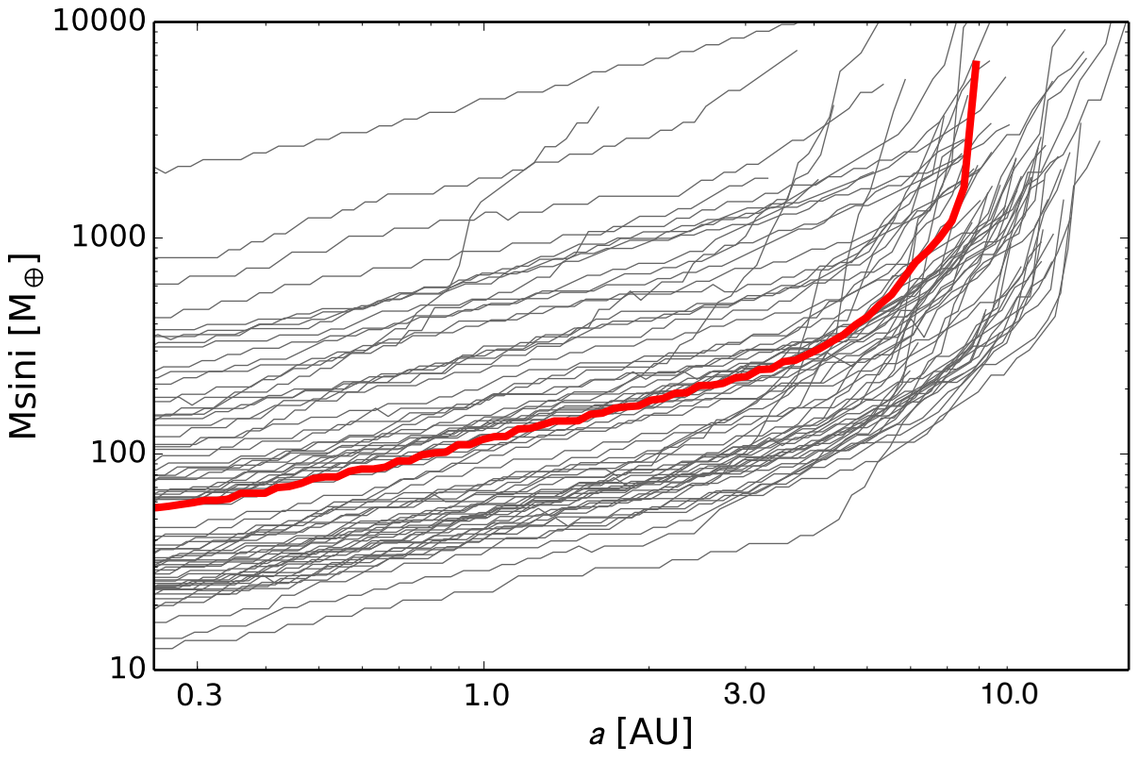
RV Time Series & Periodogram



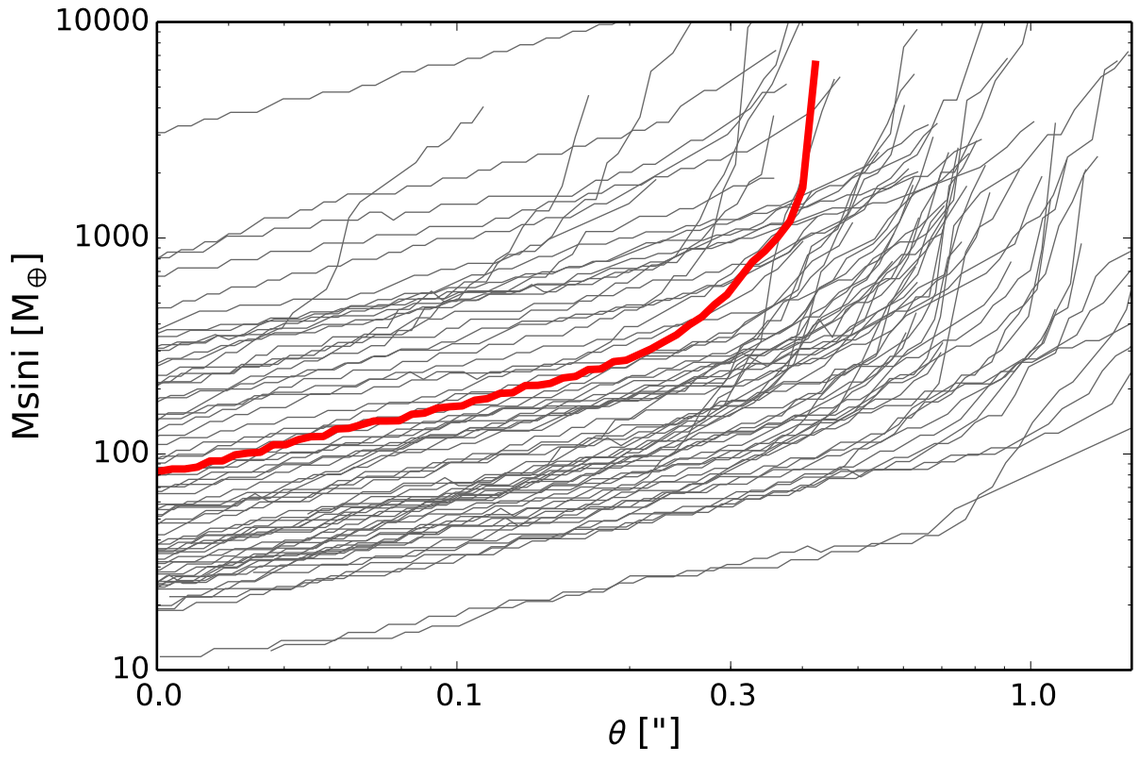
Completeness Limits

Survey Completeness

Completeness vs. Semi-major axis



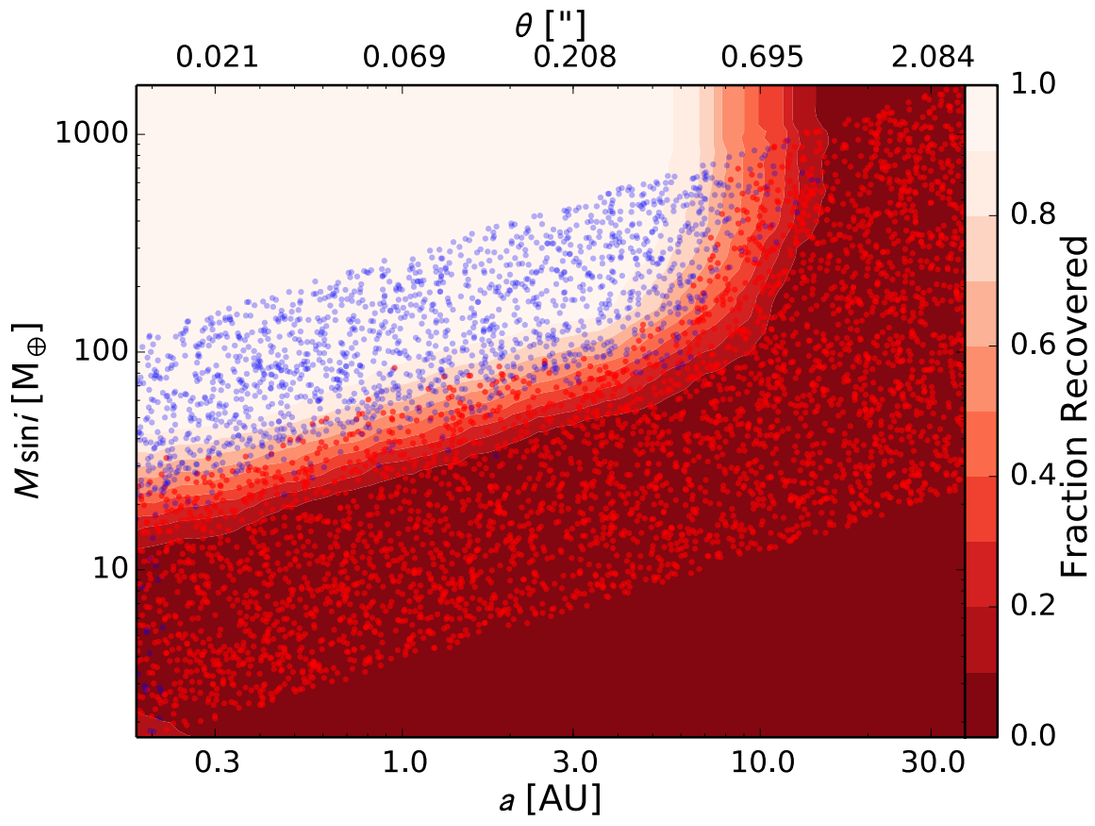
Completeness vs. Projected Separation



Completeness for all 76 Stars with RV Data

Idealized Completeness

Parameterize Sensitivity Curves



Idealized Completeness

Parameterize Sensitivity Curves

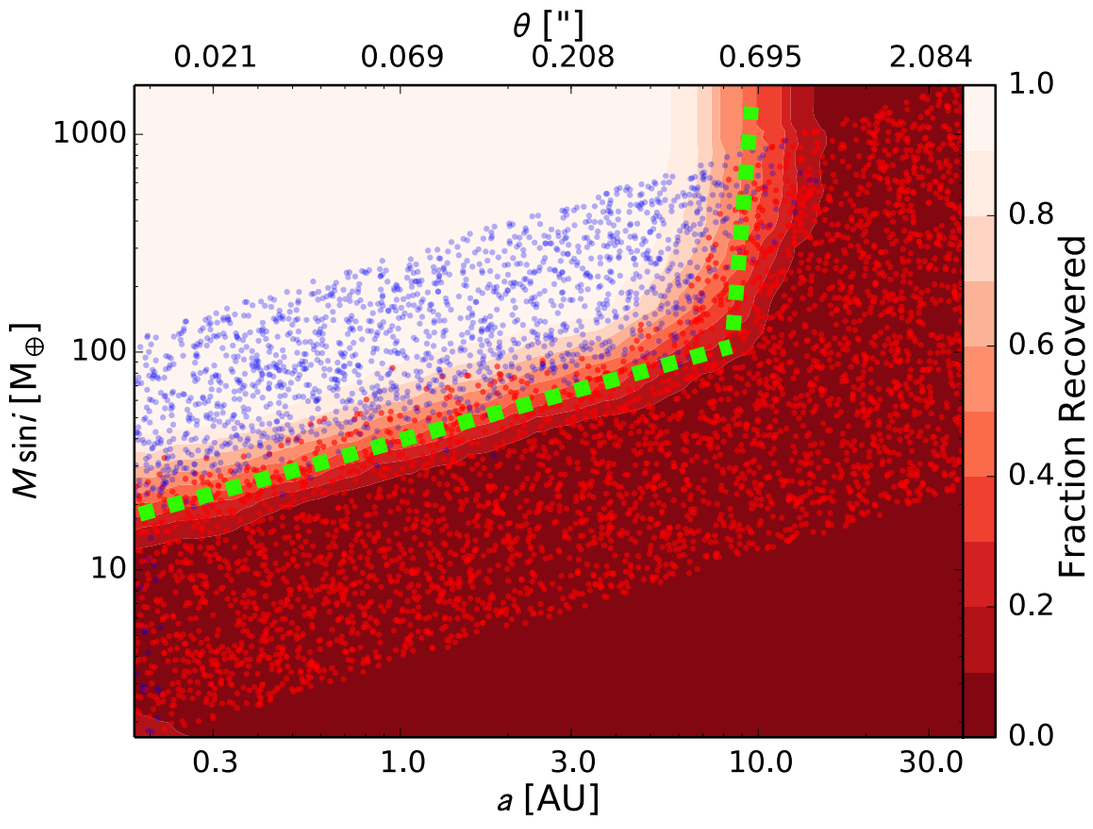
50% Detection Completeness

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

Parameterize Sensitivity Curves

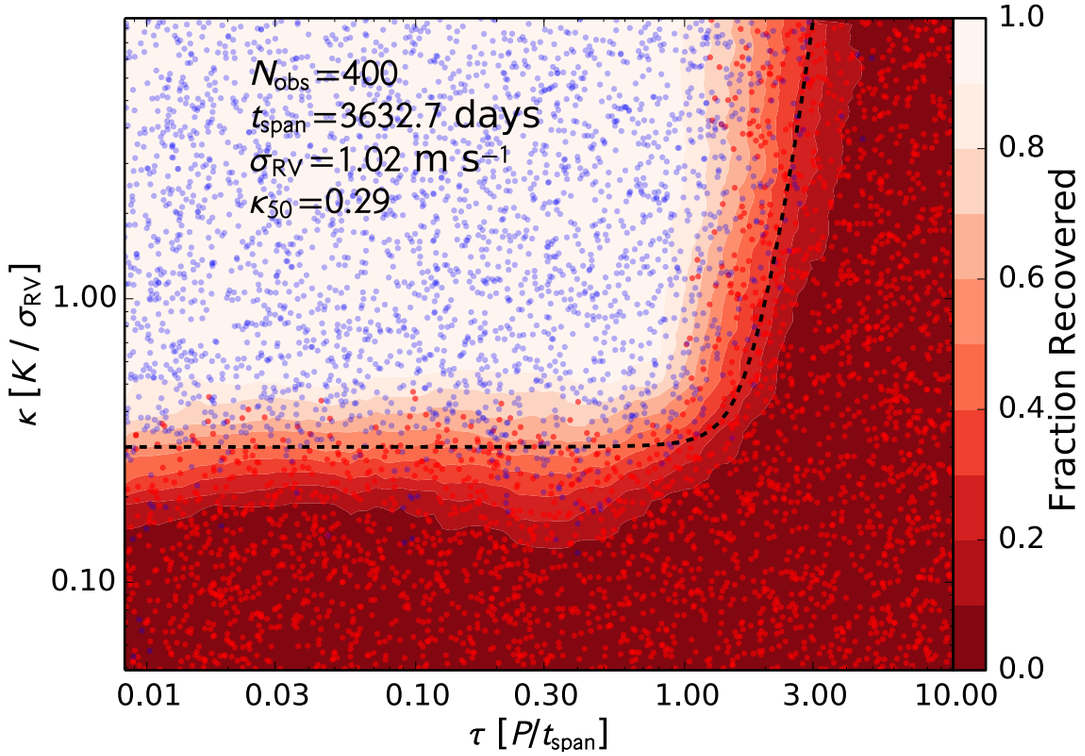
Make Problem Dimensionless

Dimensionless Doppler Amplitude:

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

Dimensionless Time:

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



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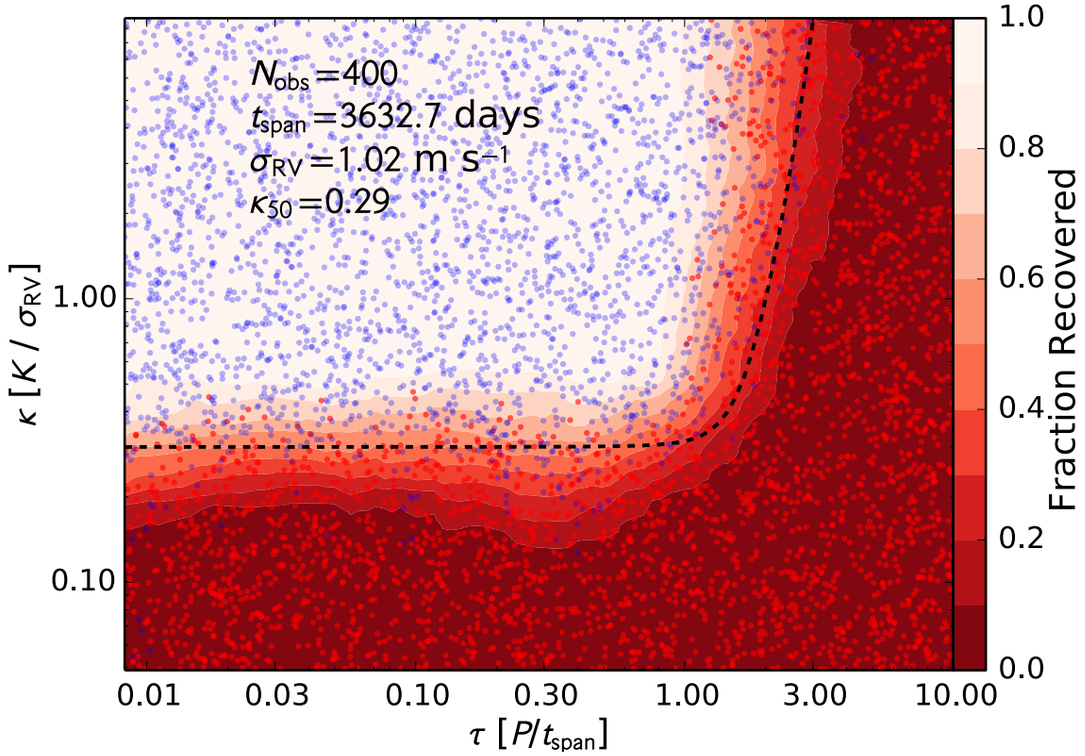

Threshold for Doppler Detection

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

Idealized Completeness

Parameterize Sensitivity Curves

Make Problem Dimensionless

Dimensionless Doppler Amplitude:

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

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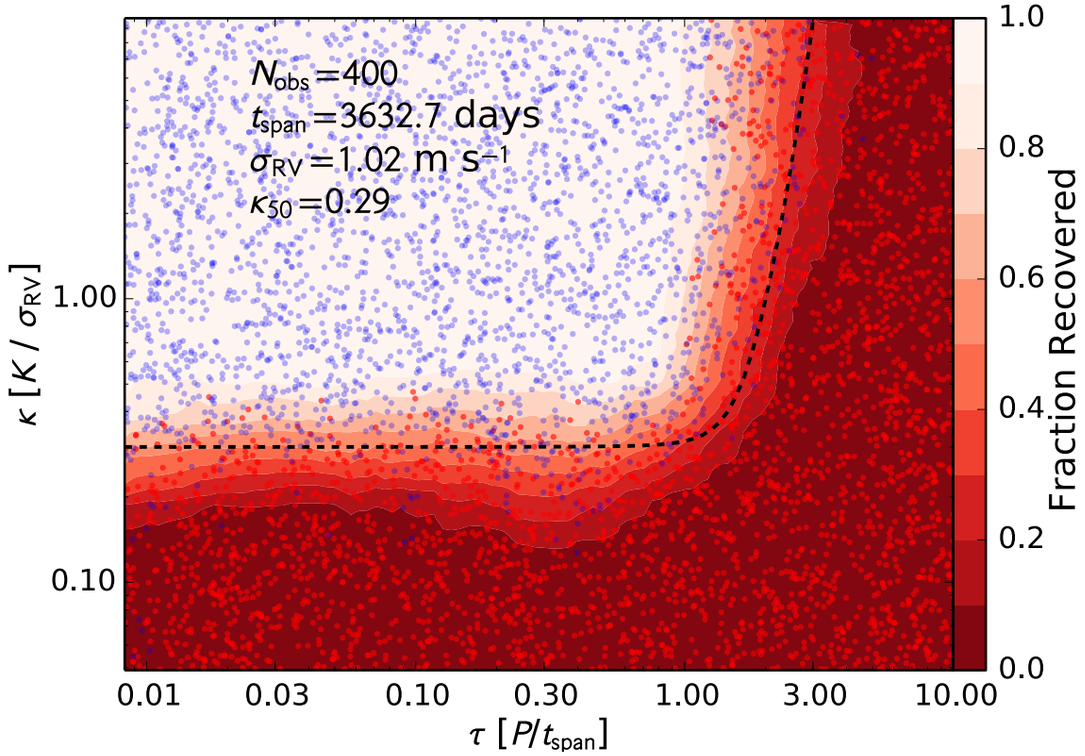


Threshold for Doppler Detection

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

Calibration from Simulations - How may "sigma" for detection?

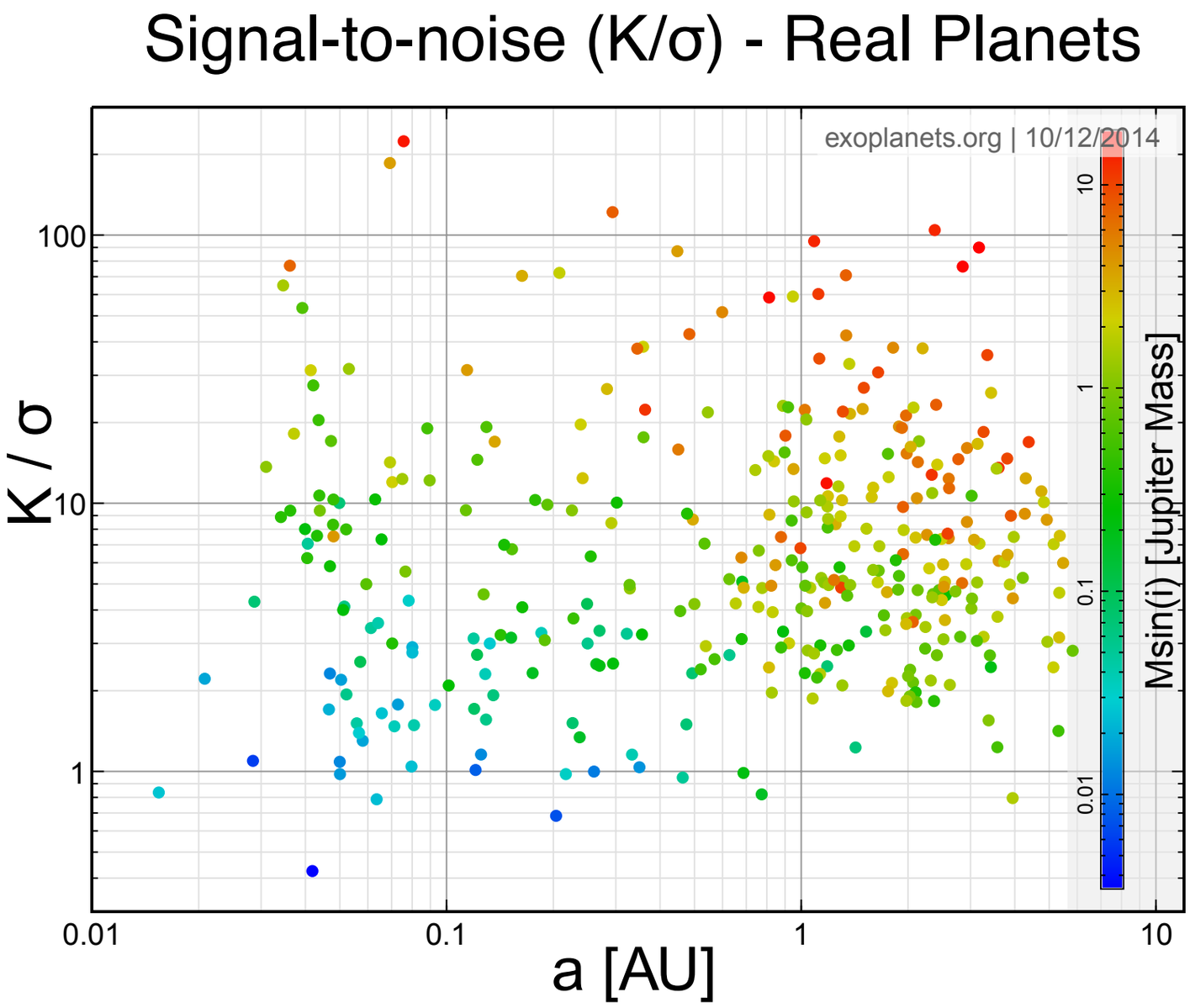
$$\alpha = \left(\frac{K_{50}}{\sigma_{\rm RV}}\right) \sqrt{N_{\rm obs}} \approx 6$$

Signal size

Observational effort

Real Planets

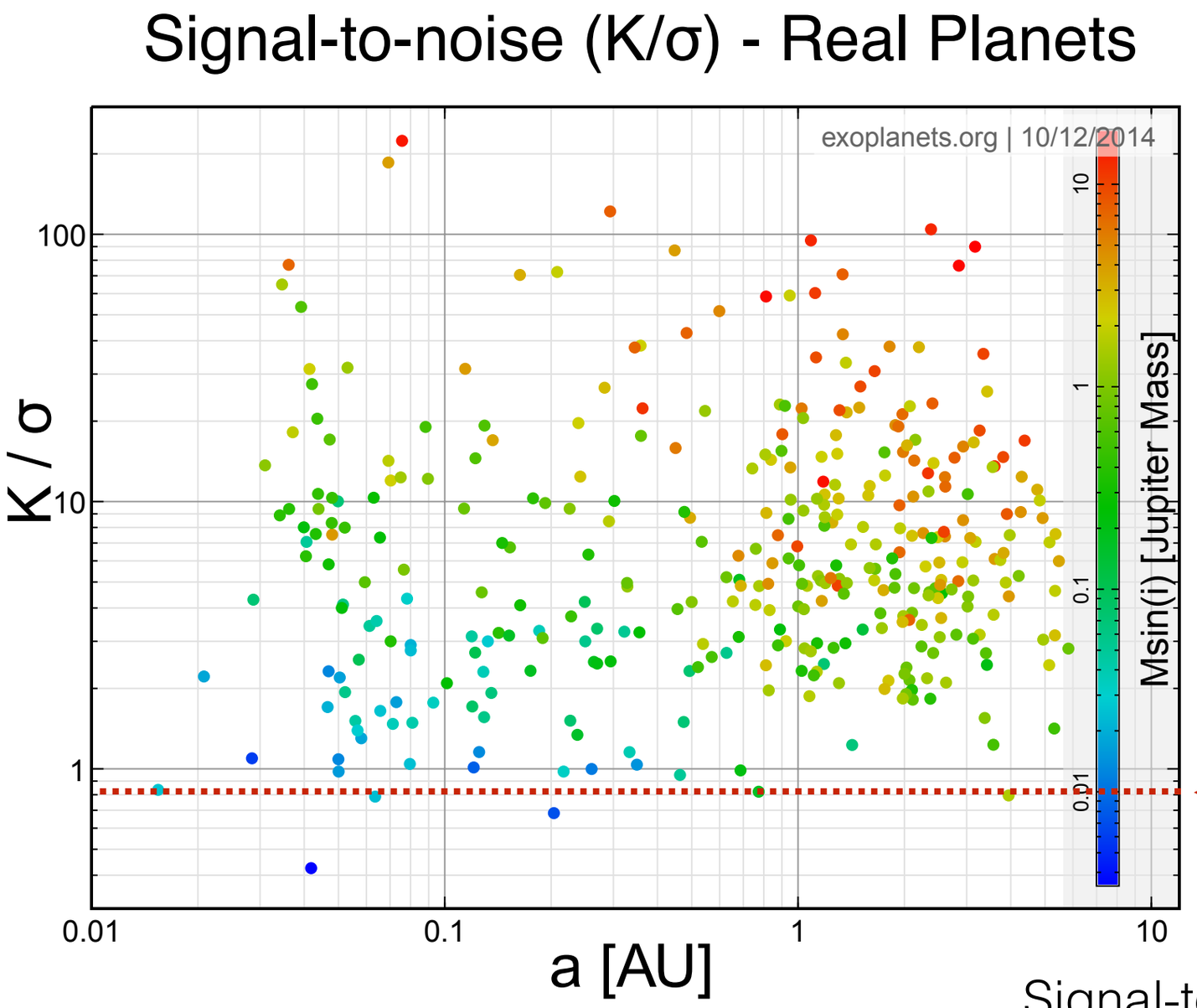
Signal-to-noise ratio needed for detection?



exoplanets.org

Real Planets

Signal-to-noise ratio needed for detection?



Detection Threshold

$$\left(\frac{K}{\sigma}\right) \approx 0.8\text{-}1.0$$

Signal-to-noise

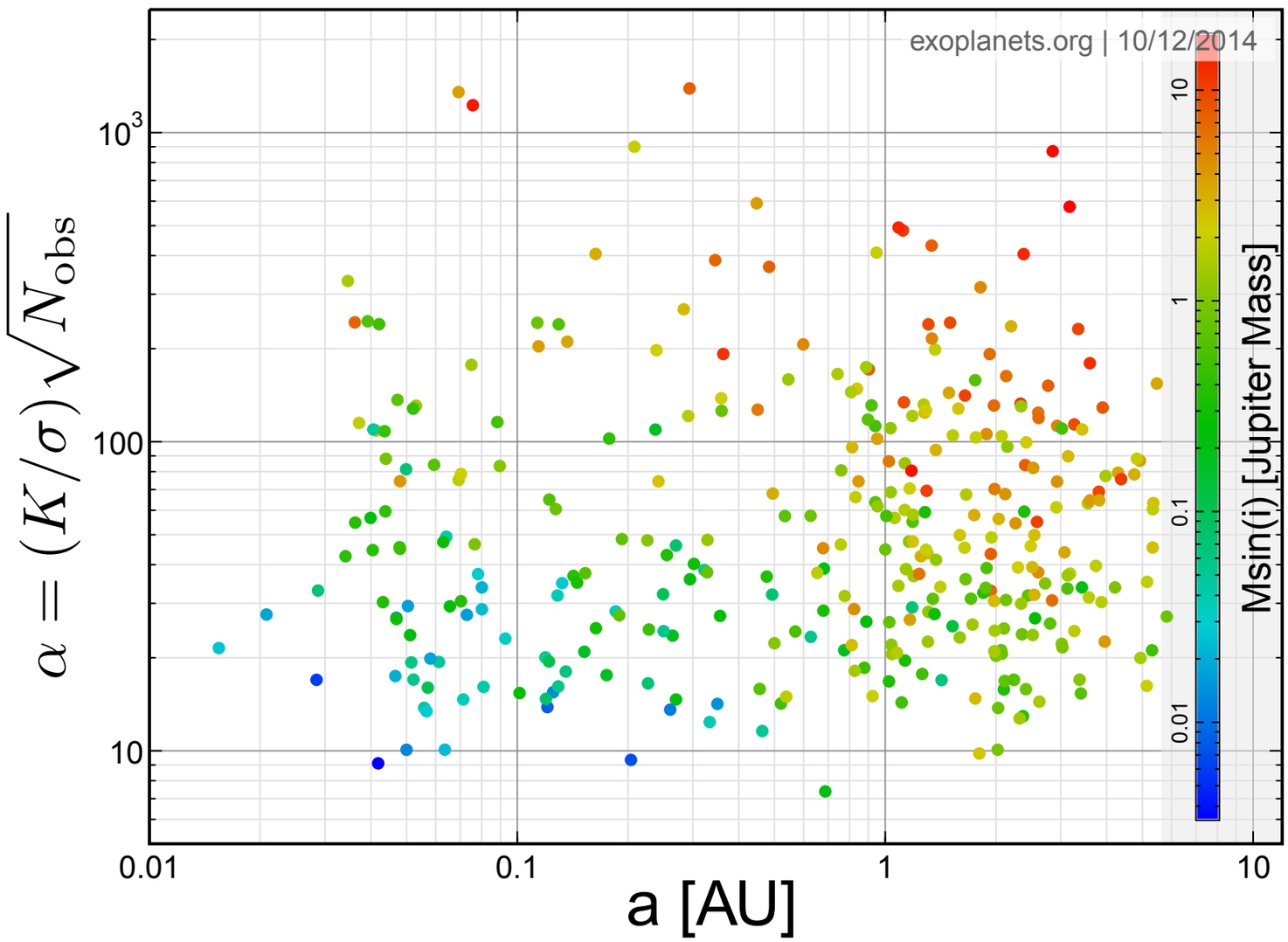
(σ = RV uncertainty)

exoplanets.org

Real Planets

How many “sigma” needed for detection?

$(K/\sigma)\sqrt{N_{\rm obs}}$ - Real Planets



$$\alpha = \left(\frac{K}{\sigma}\right)\sqrt{N_{\rm obs}}$$

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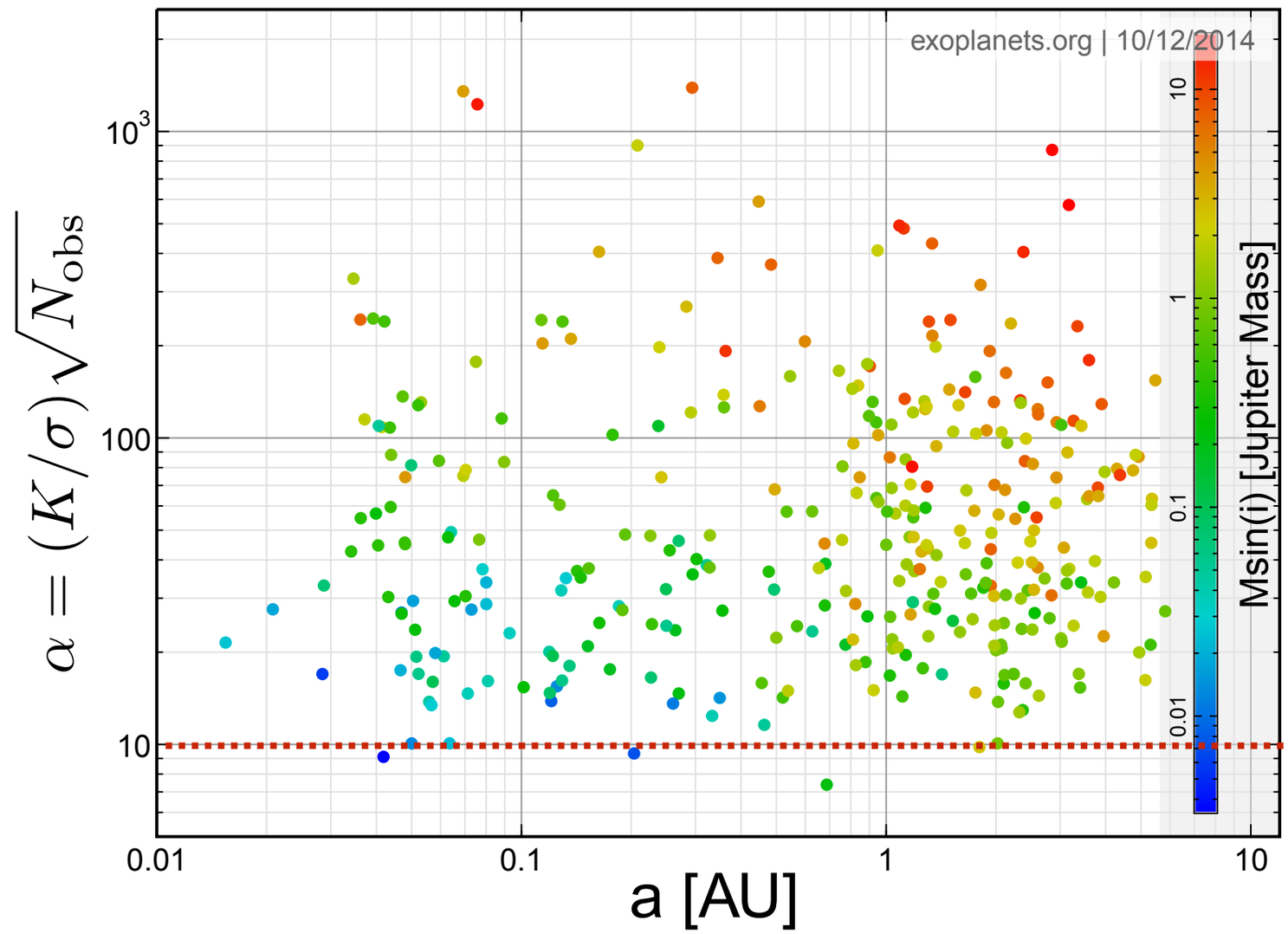
Real Planets

How many “sigma” needed for detection?

$(K/\sigma)\sqrt{N_{\rm obs}}$ - Real Planets



How many “sigma” for detection?

$$\alpha = \left(\frac{K}{\sigma}\right)\sqrt{N_{\rm obs}} \approx 10$$

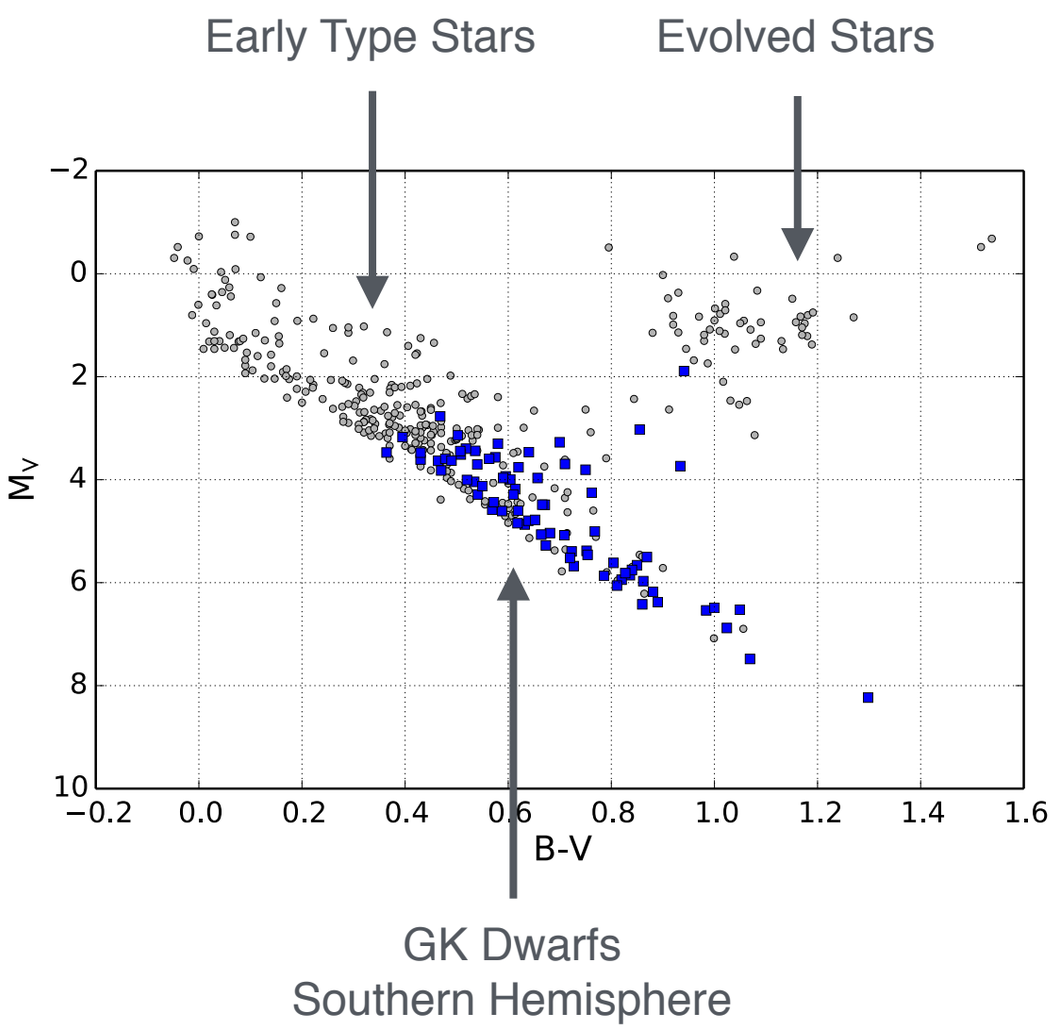
Signal-to-noise

Observational effort

exoplanets.org

What about the Missed Stars?

Jitter Estimates - σ_{RV}



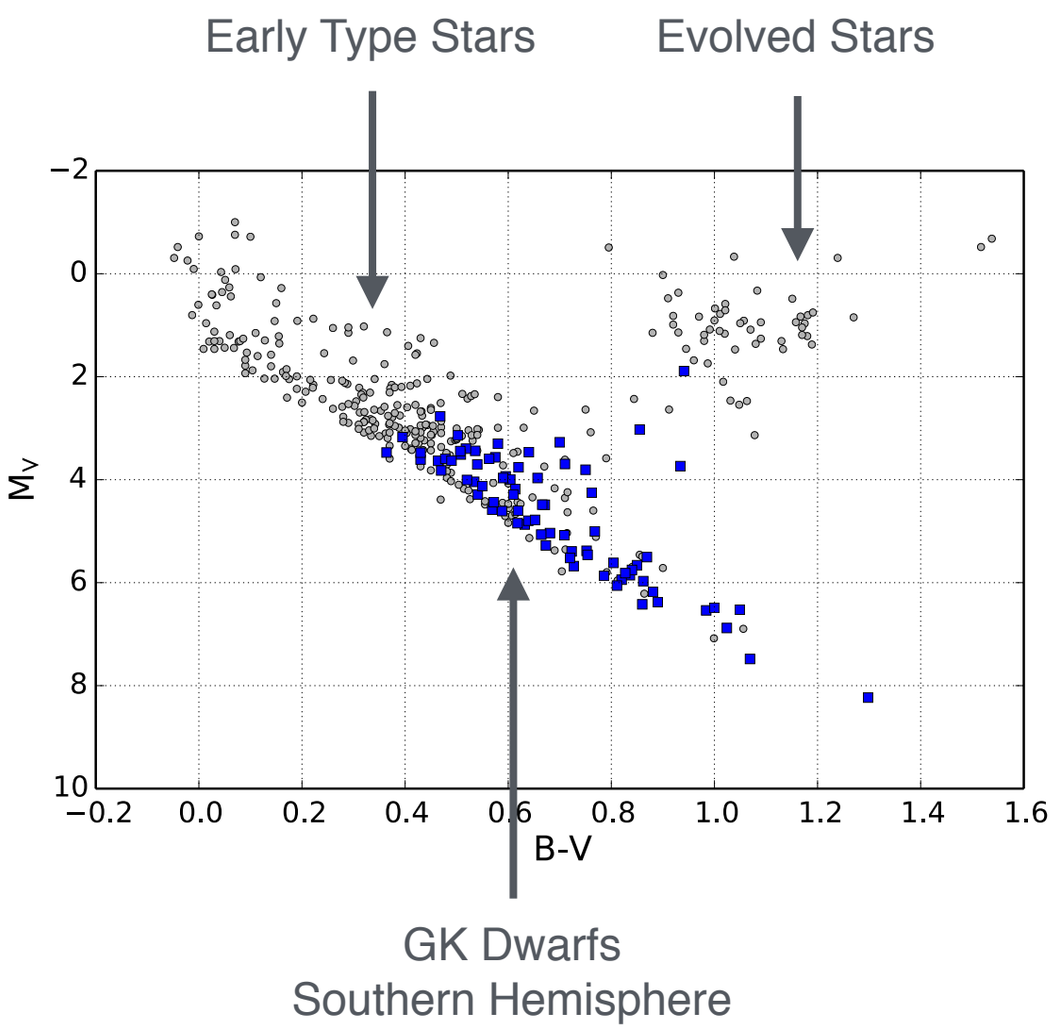
Apply Idealized Completeness:

Which planets are detectable around the nearby stars that were not observed?

What is σ_{RV}?

What about the Missed Stars?

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 $\log R'_{HK}$)

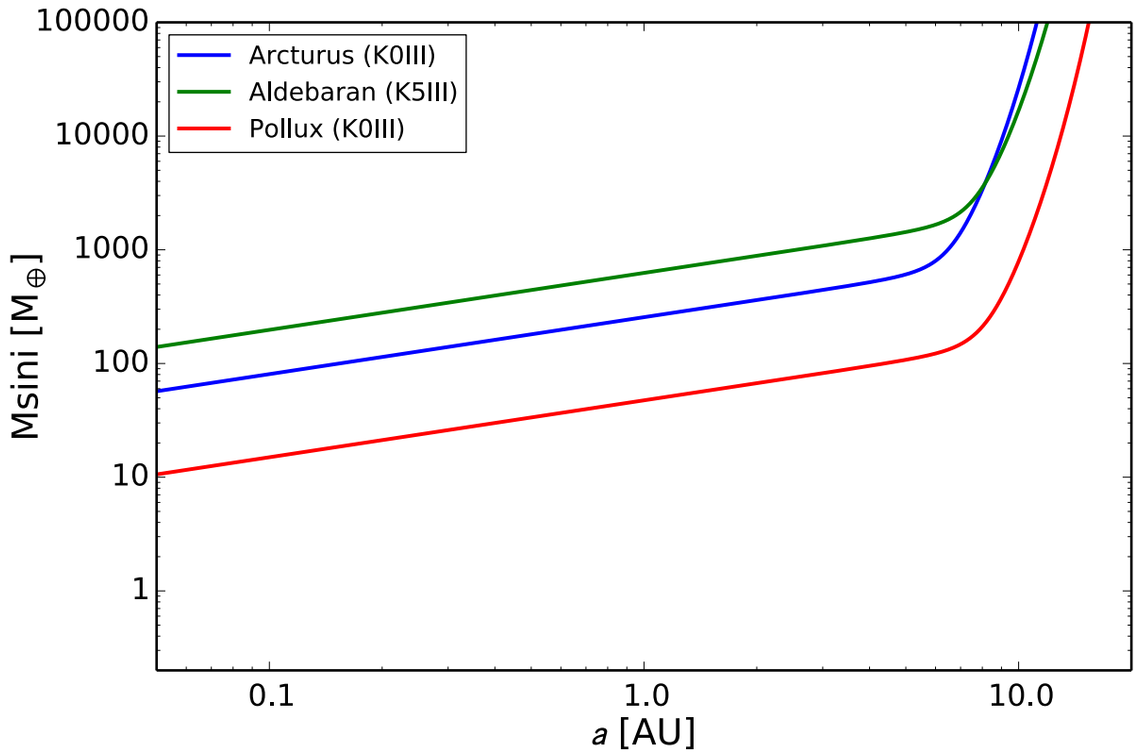
Binaries:

too hard, not recommended

Projected Sensitivity:
A Dedicated RV Campaign for the Missed Stars

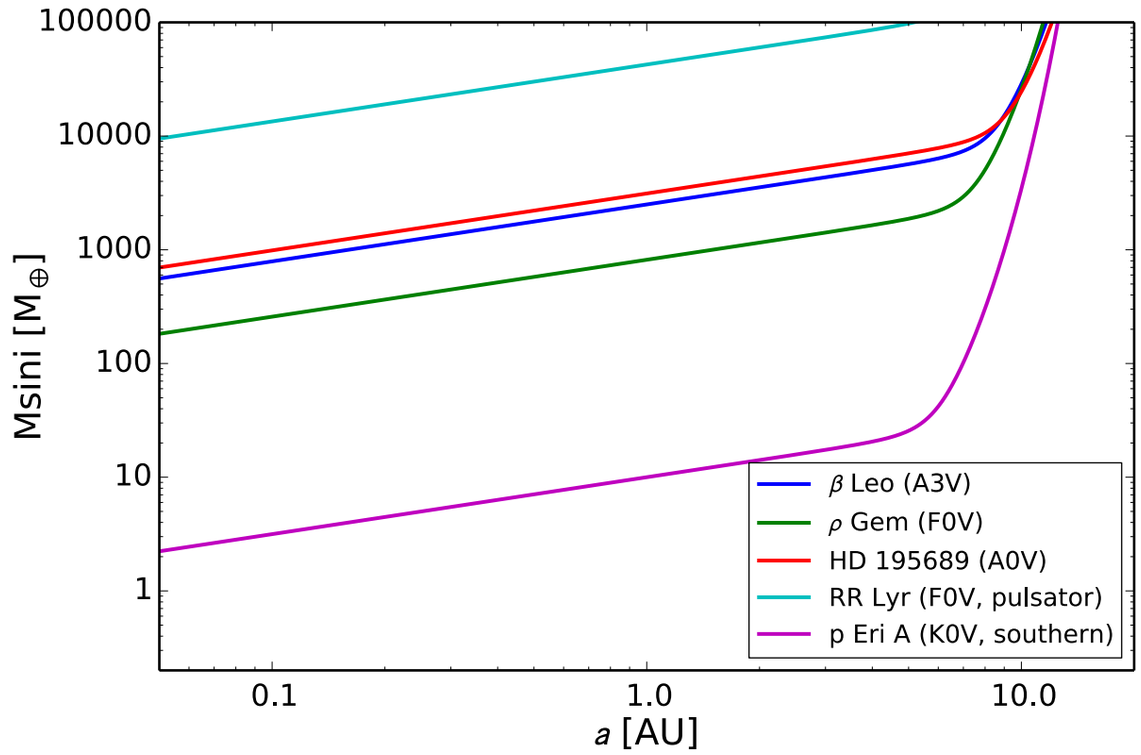
Giant Stars

Sensitivity: Jupiters/Saturns at ~1-5 AU



Hot Stars

Sensitivity: super-Jupiters/BDs at ~1-5 AU



Survey Parameters:

σ_{RV} estimated for each star

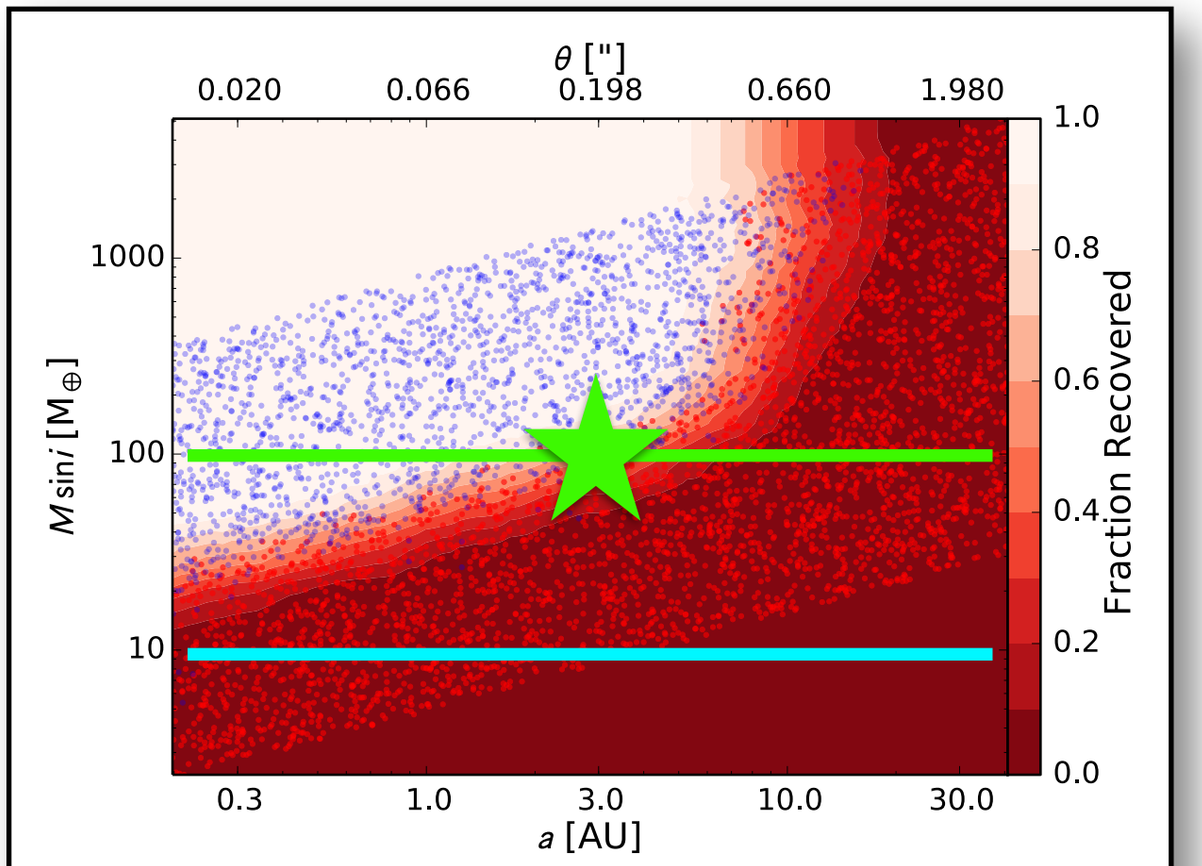
N_{obs} = 100 RVs

T_{span} = 10 yr

α = 6

Sensitivity Gain

HD 182572 (G8 dwarf, 15 pc)



Current RVs:

N_{obs} = 82 RVs

T_{span} = 17.8 yr

σ_{RV} = 4.0 m/s

Sensitivity Gain

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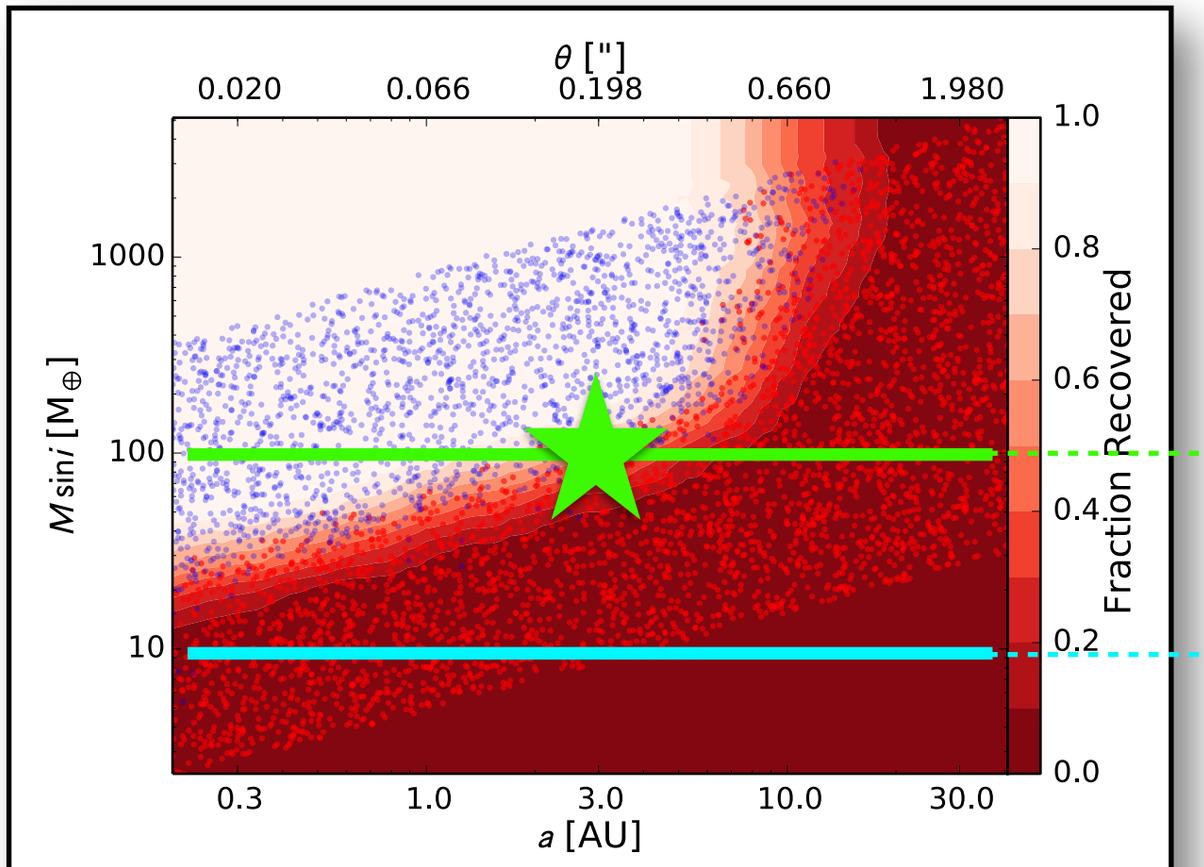

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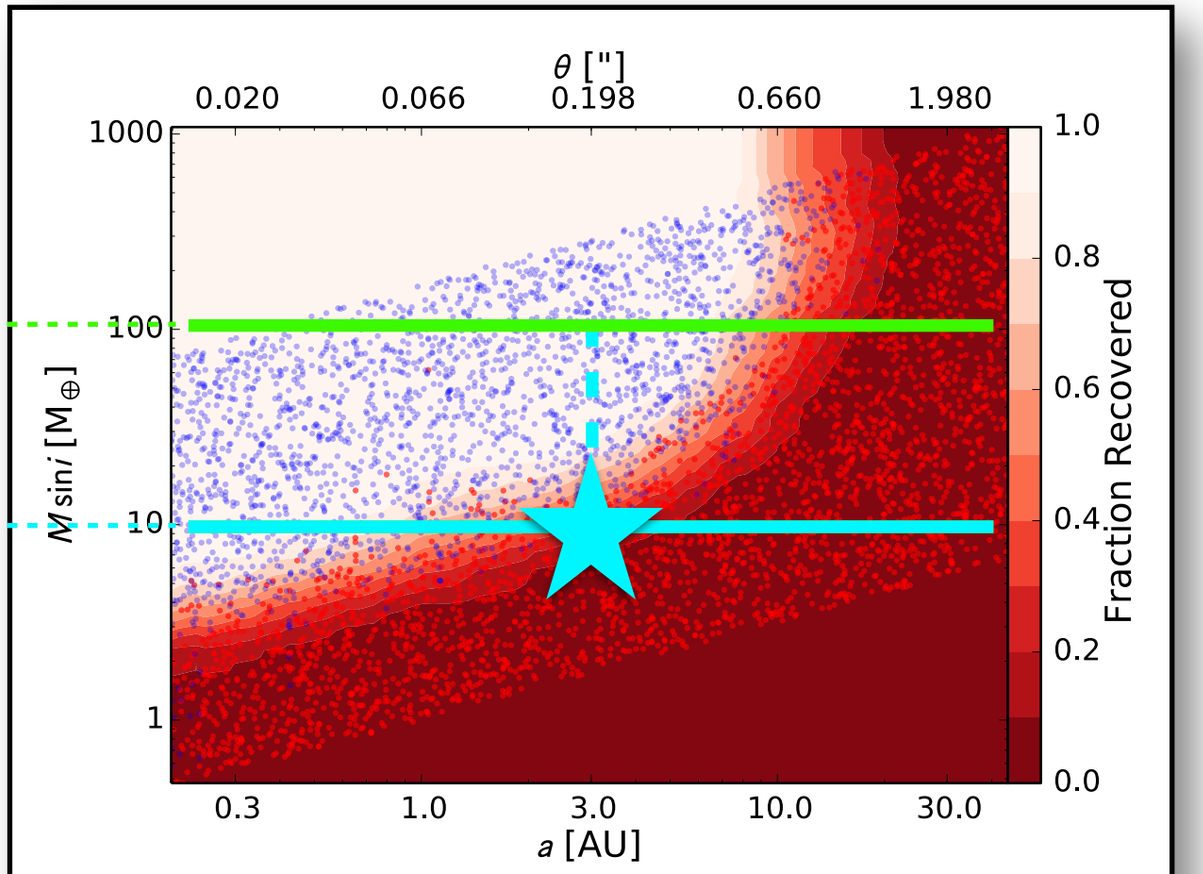


Ideal Survey:

N_{obs} = 82 + 100 RVs

T_{span} = 17.8 yr + 10 yr

σ_{RV} = 0.5 m/s (new RVs)

Recommendations

Long-term RV Surveys - Fading!

Difficult to get telescope time & funding

1. Include Doppler Measurements in Mission Requirements

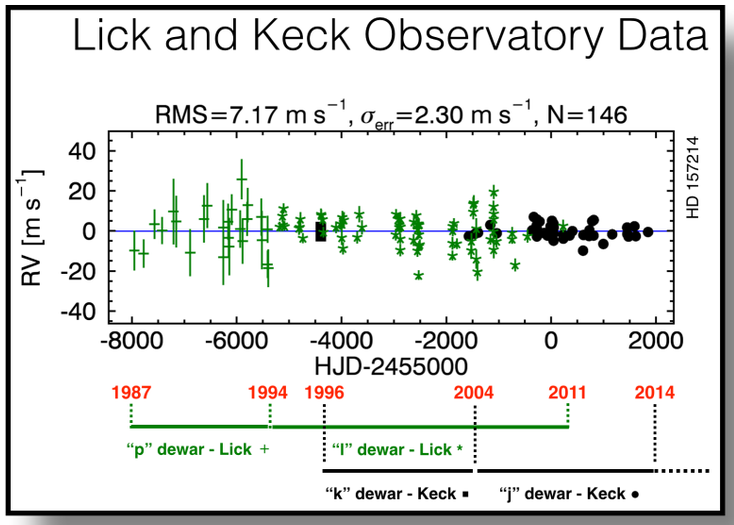
2. Invest in a Dedicated RV Facility and for pre-imaging survey

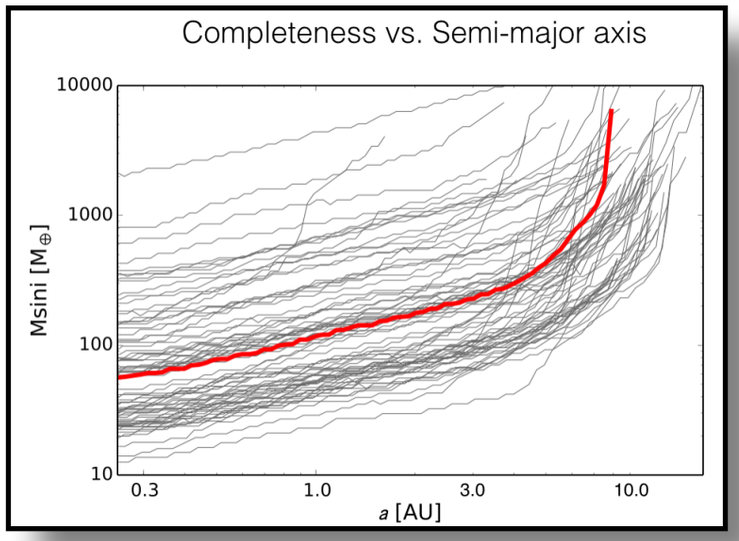
3. Measure the Jitter (σ_{RV}) of every plausible direct imaging target.

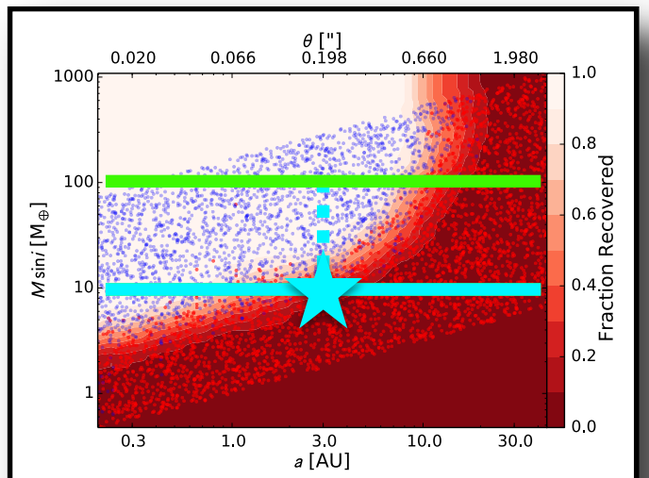

Photo: Laurie Hatch


Photo: Ethan Tweedie

Summary







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

<u>Recommendation</u>: Include Doppler Measurements in Mission Requirements


Photo: Laurie Hatch


Photo: Ethan Tweedie

Extra Slides

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 (≤ 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.