Near & Long Term Planet Searches (not a review)

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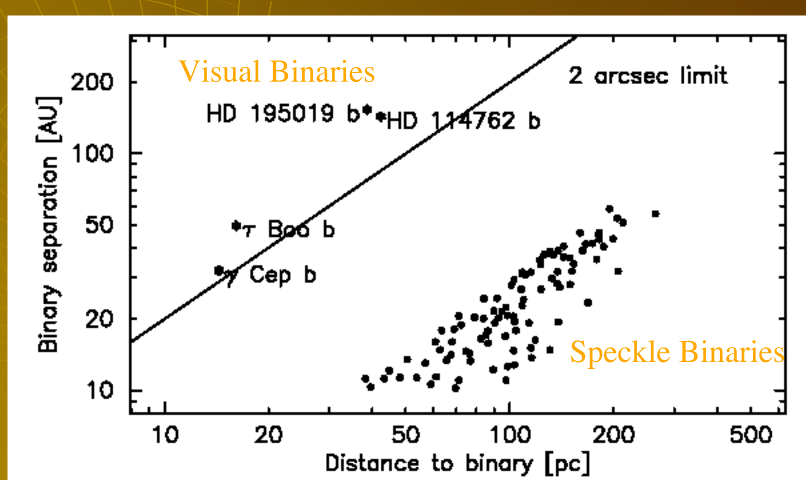
Programs at Caltech

- Searches for planets in binary stars using precision RV (Keck HIRES)
- Searches for planets in binary stars using astrometry (Palomar Interferometer)
- EPIcS (on SIM)

Planets via RV

- Geared towards single stars or >2 arcsec binaries
  - Precise Point Spread Function (PSF) modeling
  - Accurate velocity calibration
  - Two approaches
    - Iodine cell for both (e.g. California-Carnegie searches)
    - Stable spectrograph & synthetic spectra (e.g. Swiss)

Bias of Current RV surveys

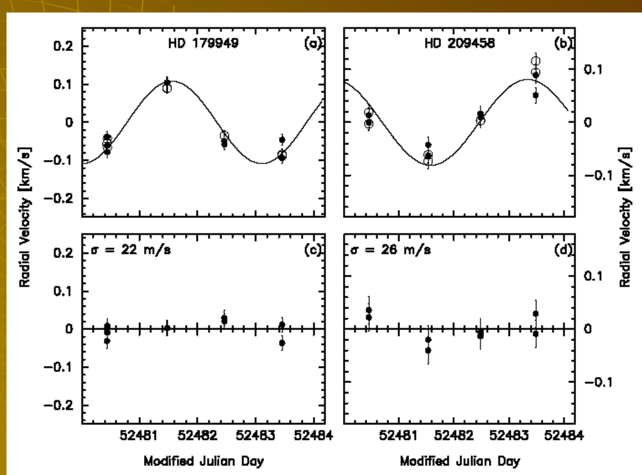


Difficulty observing speckle binaries

- Problem: Observed (without the iodine cell) stellar
spectra cannot be used as templates since the composite spectrum of a spectroscopic binary is time variable

- Solution: Use synthetic stellar spectra as templates

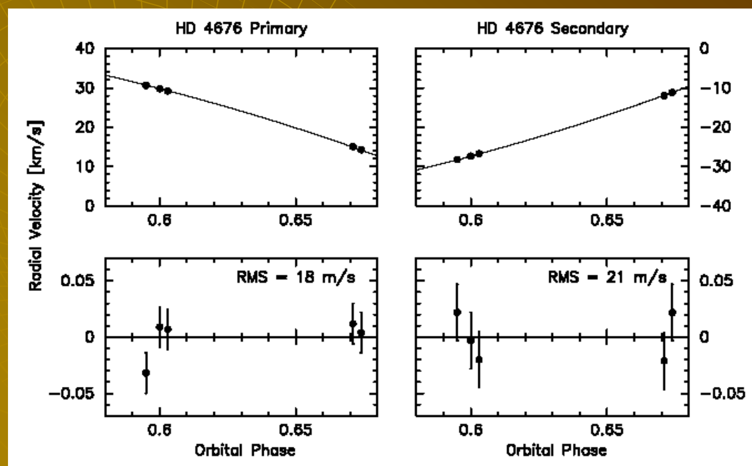
Results: HD 209458 & HD179949



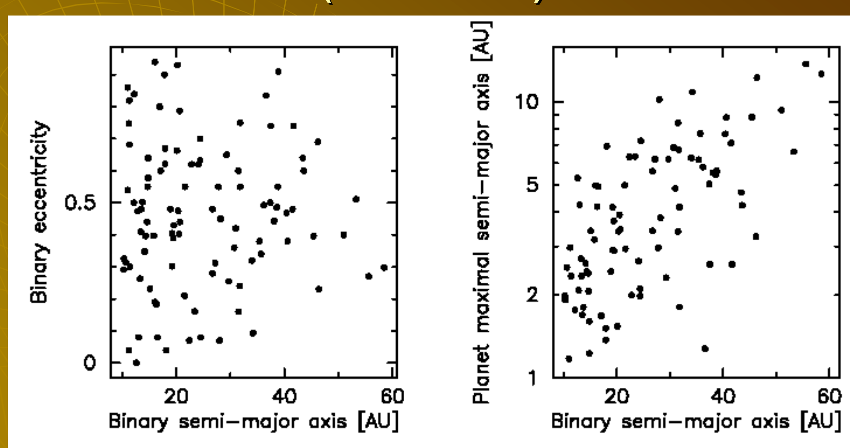
Precision RVs (filled circles) with synthetic spectra as templates

Results: SB2 HD 4676

F6V+F6V, orbital period of ~13 days, Keck/HIRES



Caltech Speckle RV program (Konacki)



100 speckle binaries with angular separation 0.3 arcsec or less

Status and Near Future

- Current approach demonstrably works but achieved precision is 20 m/s
- Next step: Combine best of both worlds
  - Observe with and without Iodine cell
  - Use Iodine observations to model PSF and wavelength calibration
  - Cross-correlate with synthetic spectra and derive both stellar velocities
  - Expected precision is 10 m/s (increased photon noise at the very least)

Ground Based Astrometry

- Phase difference between two points increases with length of baseline

  RMS phase $\sim (d/r_0)^{5/6}$
- As a result bigger telescopes (larger d) does not increase astrometric precision (though result in better photon SNR)
- Adaptive Optics and Interferometery (very narow angle astrometry) open up new regimes of ground based astrometry

Shao & Colavita

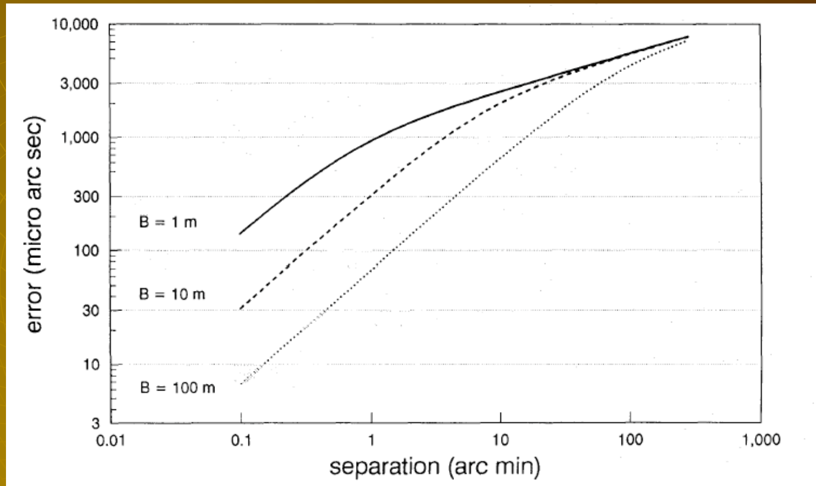
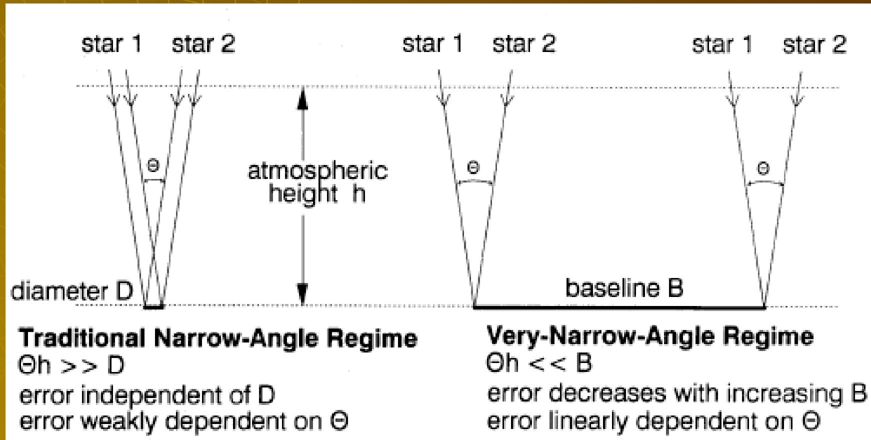
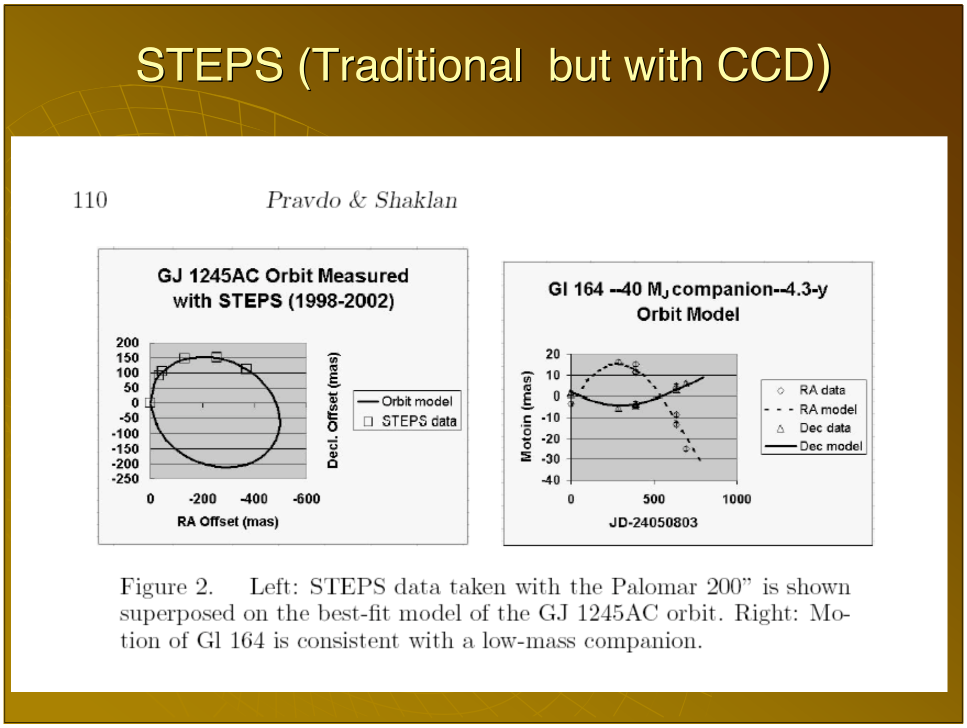


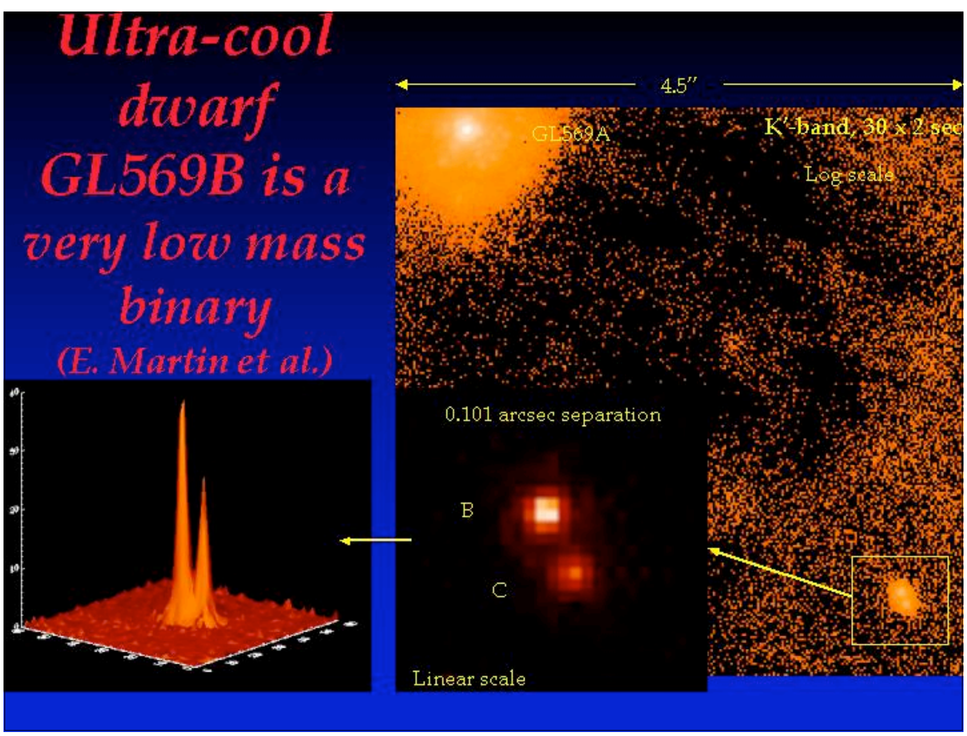
Fig. 2. Narrow- and very-narrow-angle astrometric error for several baseline lengths using measured Mauna Kea turbulence profiles and an integration time of 1 h

Very Narrow Angle Astrometry

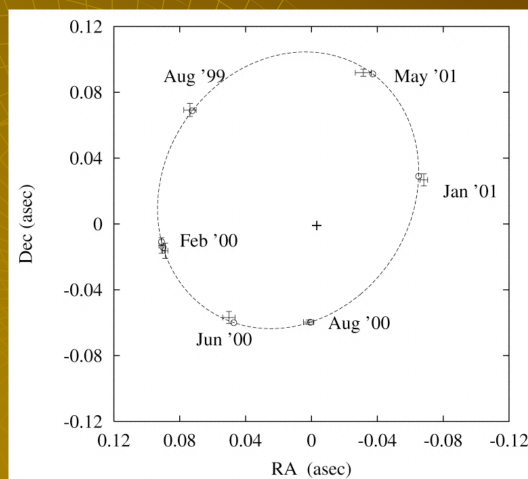


Shao & Colavita


STEPS (Traditional but with CCD)
110 Pravdo & Shaklan
GJ 1245AC Orbit Measured with STEPS (1998-2002)
RA Offset (mas)
Decl. Offset (mas)
Orbit model
STEPS data
Gl 164 --40 M$_J$ companion--4.3-y Orbit Model
JD-24050803
Motoin (mas)
RA data
RA model
Dec data
Dec model
Figure 2. Left: STEPS data taken with the Palomar 200" is shown superposed on the best-fit model of the GJ 1245AC orbit. Right: Motion of Gl 164 is consistent with a low-mass companion.


Ultra-cool dwarf GL569B is a very low mass binary
(E. Martin et al.)
4.5"
GL569A
K'-band, 30 x 2 sec
Log scale
0.101 arcsec separation
B
C
Linear scale

GJ 569Bb (Keck AO): An Example

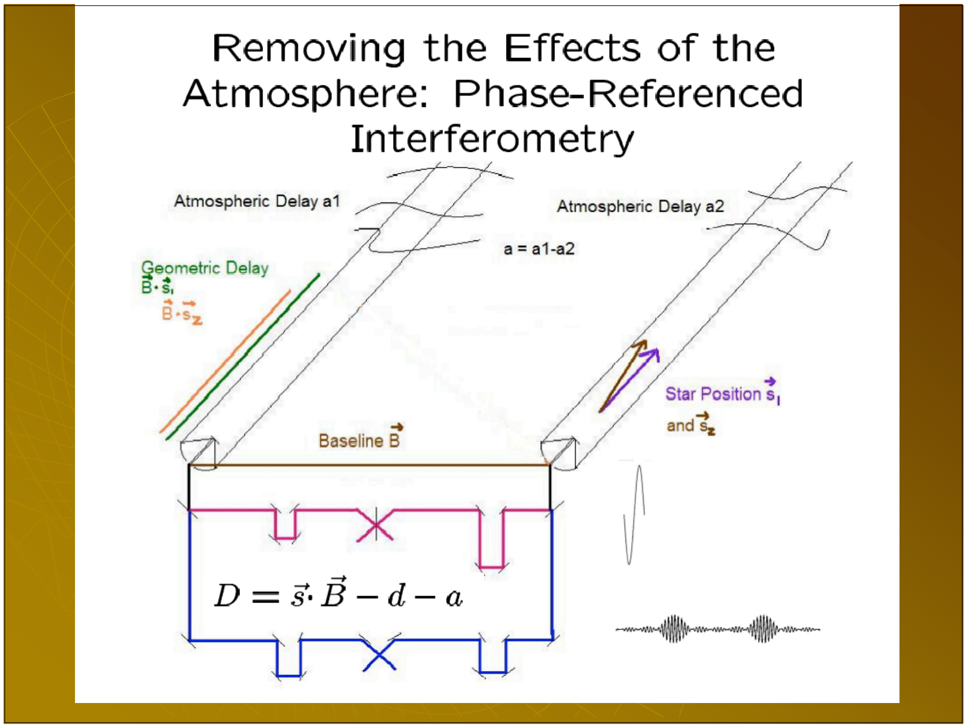


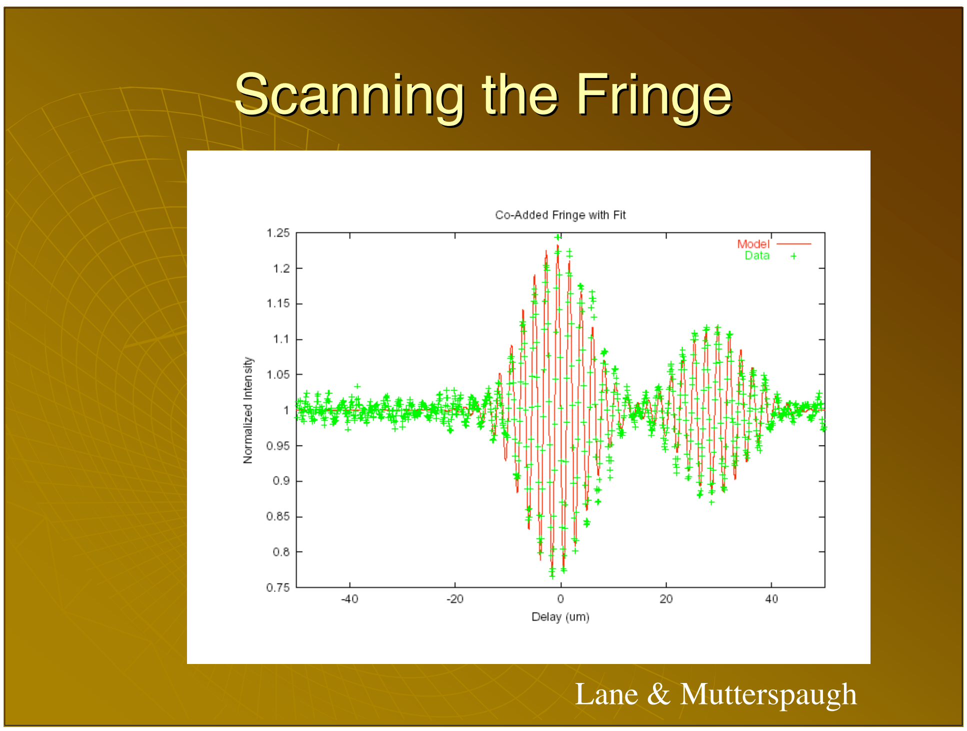
Lane et al.

PHASES:

Palomar High-precision
AStrometric Exoplanet Search

Caltech, MSC, JPL, MIT


Removing the Effects of the Atmosphere: Phase-Referenced Interferometry
Atmospheric Delay a1
Atmospheric Delay a2
a = a1-a2
Geometric Delay
Baseline B
Star Position
$D = \vec{s}\cdot\vec{B} - d - a$


Scanning the Fringe
Co-Added Fringe with Fit
Model
Data
Normalized Intensity
Delay (um)
Lane & Mutterspaugh

Shao & Colavita

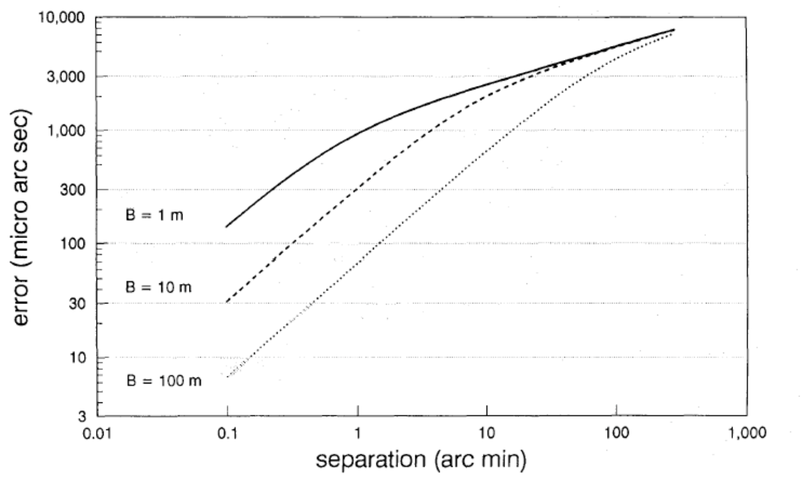
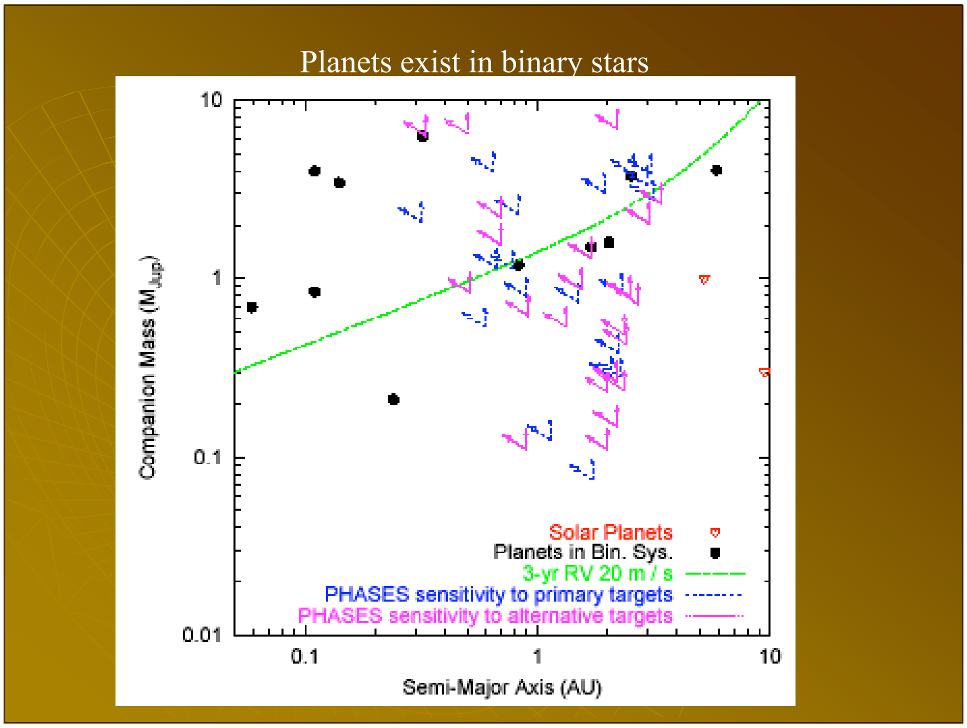
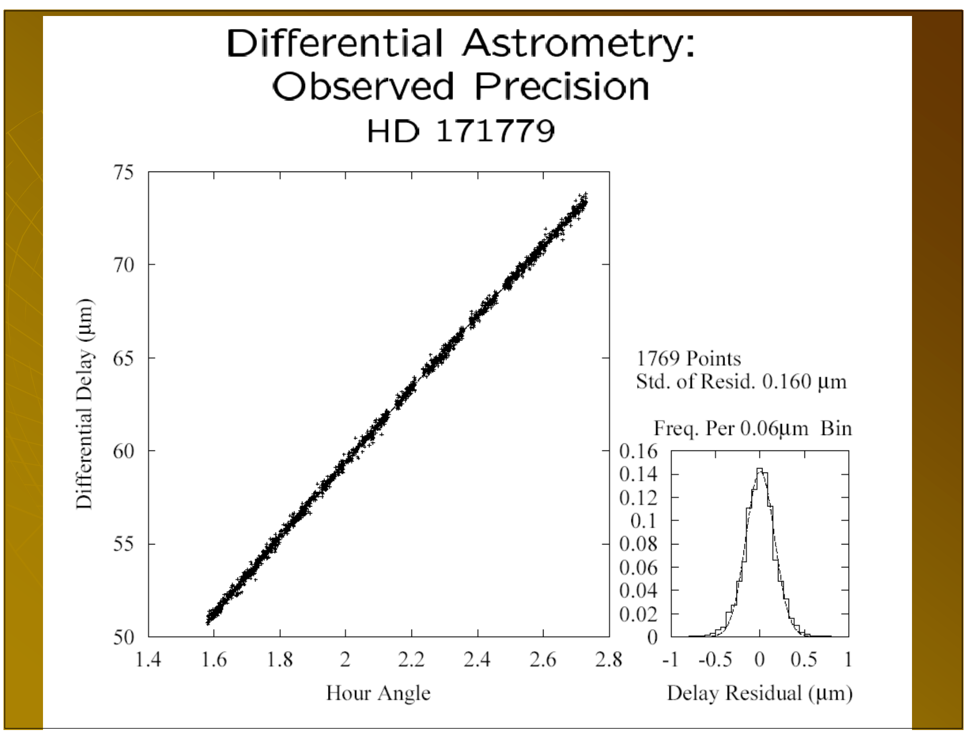


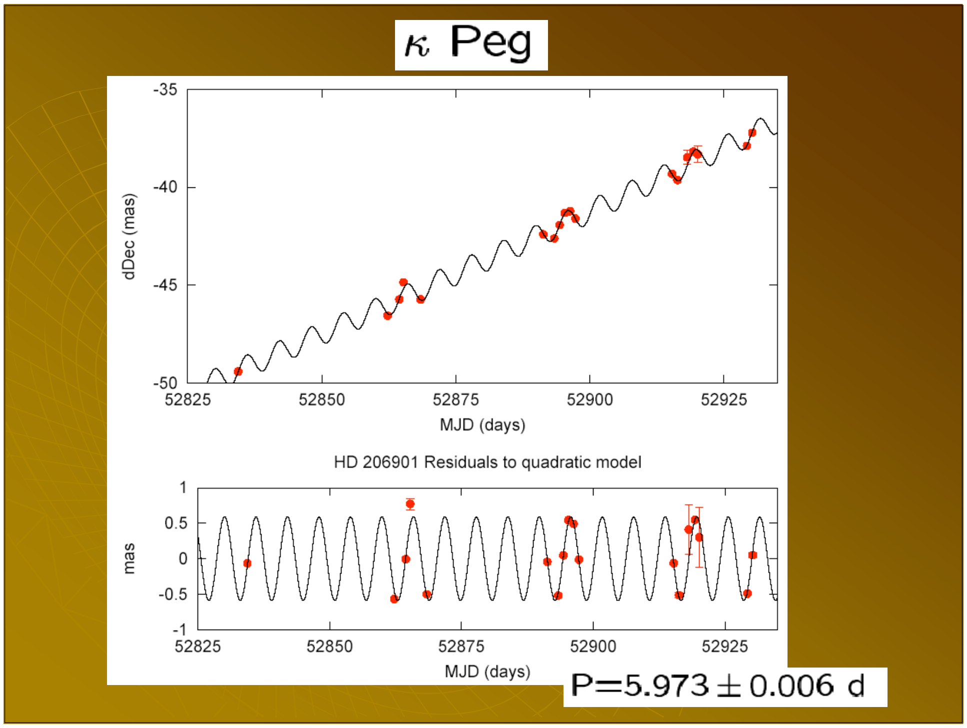
Fig. 2. Narrow- and very-narrow-angle astrometric error for several baseline lengths using measured Mauna Kea turbulence profiles and an integration time of 1 h

Planets in Binary Stars

- Starting an astrometric search for planets in binary stars
- Demonstrated precision is 20 microarcsecond and goal is 10 microarcsec
- The survey, if successful, will be a big boost to SIM and astrometry in general
- Planets thus found will motivate novel direct detection approaches


Planets exist in binary stars
Companion Mass (M_Jup)
Semi-Major Axis (AU)
10
1
0.1
0.01
0.1
1
10
Solar Planets
Planets in Bin. Sys.
3-yr RV 20 m / s
PHASES sensitivity to primary targets
PHASES sensitivity to alternative targets


Differential Astrometry:
Observed Precision
HD 171779
Differential Delay (μm)
Hour Angle
75
70
65
60
55
50
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
1769 Points
Std. of Resid. 0.160 μm
Freq. Per 0.06μm Bin
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-1
-0.5
0
0.5
1
Delay Residual (μm)



Phases Sample (I)

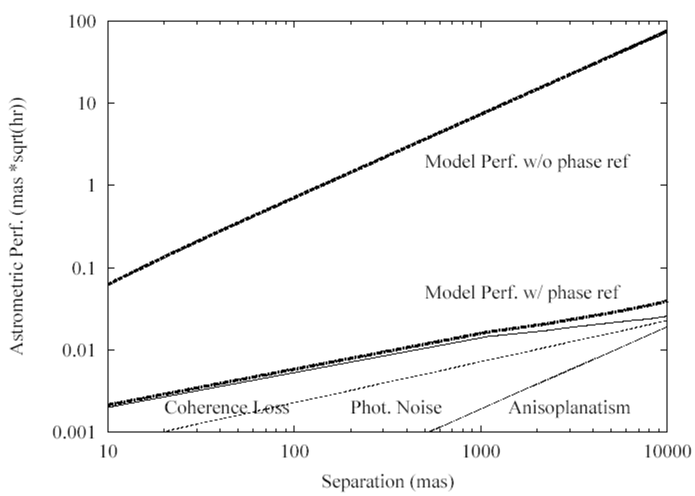
HD Number	Spectral Type	K	ΔV	P_{binary}	Maximum P_{planet} (years)	Maximum a_{planet} (AU)	Minimum Planet Mass (M_J)	Prior Data
206901	F5IV	2.97	0.3	11.6	1.3	1.4	0.73	28
176051	G0V	3.8	2.5	61.2	3.0	2.2	0.07	3
196524	F5IV	2.65	0.83	26.7	2.9	2.0	0.28	3
202275	F5V+...	3.27	0.3	5.7	0.4	0.6	0.53	10
114378	F5V	3.2	0	25.8	1.5	1.1	0.12	2
29140	A5m	3.82	2.9	18.1	3.0	2.0	0.38	3
19356	B8V	2.24	2.5	1.9	0.4	0.4	1.14	0
221673	K4III	1.76	0.1	246.2	3.0	3.2	2.76	26
171779	K0III	2.78	0.1	191.5	3.0	3.1	3.84	17
77327	A1Vn	3.53	0.39	35.6	1.8	2.4	3.85	4
58728	F5IV-V...	4.1	2	2.1	0.16	0.22	2.08	1
5286	K1IV	3.15	0.35	167.7	3.0	2.2	0.28	7
60318	K0III	3	0.4	213.1	3.0	2.4	0.82	6
13872	F6V	4.4	0.35	23.7	0.6	0.7	1.13	3
137909	F0p	3.3	1.5	10.3	0.7	0.7	0.79	1
17904	F4Vvar	4.3	0.9	31.5	0.6	0.7	2.30	10
215182	G2II-III..	0.93	?	2.2	0.3	0.6	3.96	0
6811	B7III	1.32	1	391.0	3.0	3.3	3.31	6
171745	G8III	3.4	0.15	210.9	1.7	1.9	3.03	0
44926	K1III	4.1	0.15	?	?	?	?	2
11636	A5V...	2.37	?	0.3	0.0	0.0	N/A	0

Phases Sample (II)

HD Number	Spectral Type	K	ΔV	P_{binary}	Maximum P_{planet} (years)	Maximum a_{planet} (AU)	Minimum Planet Mass (M_J)	Prior Data
137107	G2V	3.5	0.3	41.6	3.0	2.3	0.15	4?
68255	G0V	3.3	0.25	59.6	3.0	2.4	0.24	0
90537	G8III-IV	2.16	1.8	38.6	1.5	1.0	0.53	0
213973	A9III	4.2	0.25	224.0	3.0	2.6	0.79	0
140159	A1V	4.43	0.15	21.9	3.0	2.7	0.72	0
214850	G3V+...	4.2	0.65	20.8	0.4	0.5	0.83	0
16234	F7V	4.3	0.2	1.9	0.0	0.0	N/A	0
81858	F9V	4	0.65	118.2	3.0	2.1	0.23	0
76943	F5V	2.92	2	21.8	3.0	1.9	0.11	0
207652	F2III-IV	3.5	1	26.1	3.0	2.2	0.26	0
165908	F7V	3.7	2.06	56.4	1.3	0.6	0.11	0
49618	G4III...	3.2	0.9	290.5	3.0	3.3	2.04	0
85235	A3IV	4.4	0.2	105.4	3.0	3.5	2.61	0
18925	G8III+...	0.98	1.3	14.6	0.2	0.4	6.47	0
196867	B9V	3.9	1.8	17.0	1.6	1.2	1.30	0
40932	Am...	3.88	1.6	18.5	0.4	0.5	2.20	0
155763	B6III	3.49	1.04	6.6	1.1	1.8	6.89	0
157482	F9Vn...	4.1	?	5.5	0.13	0.33	6.29	0
41116	G7III	2	0.65	13.4	1.4	1.4	0.87	0
45542	B6III	2.3	1	13.0	0.0	0.0	N/A	0
50522	G5III-IV	2.33	1.05	262.0	3.0	2.6	0.49	0
140436	A1Vs	3.73	1.55	92.9	3.0	2.8	0.43	0
137391	F0V	3.6	?	3.8	0.4	0.7	1.54	0
26690	F3V...	4.4	1.1	7.2	0.9	0.7	0.62	5

Differential Astrometry: Theoretical Precision

$$\delta D = \delta \vec{s} \cdot \vec{B} - \delta d - \delta a$$

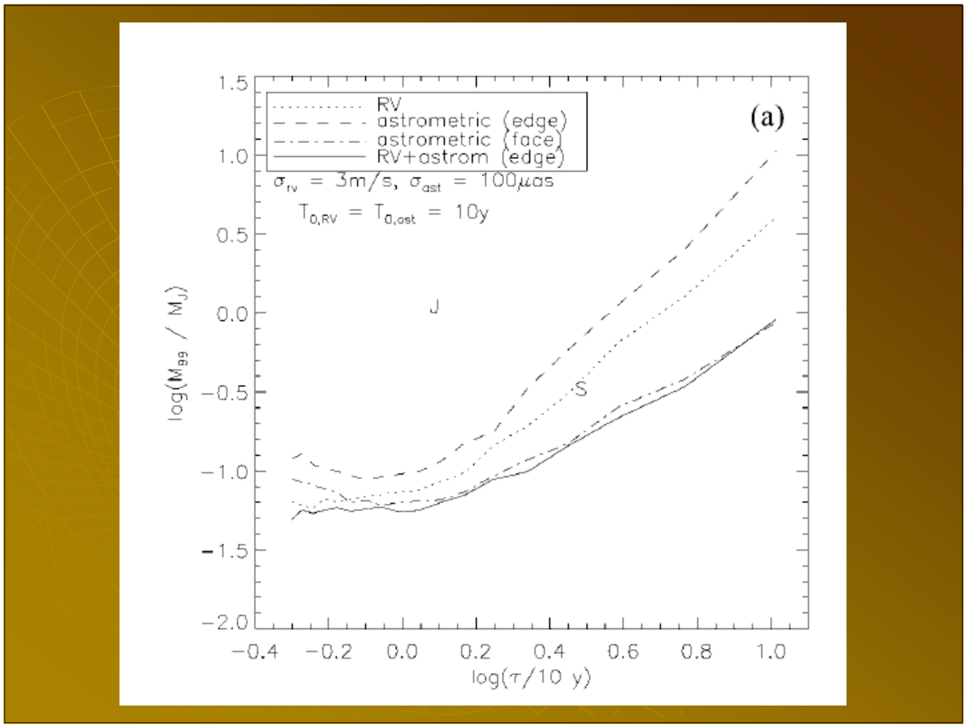


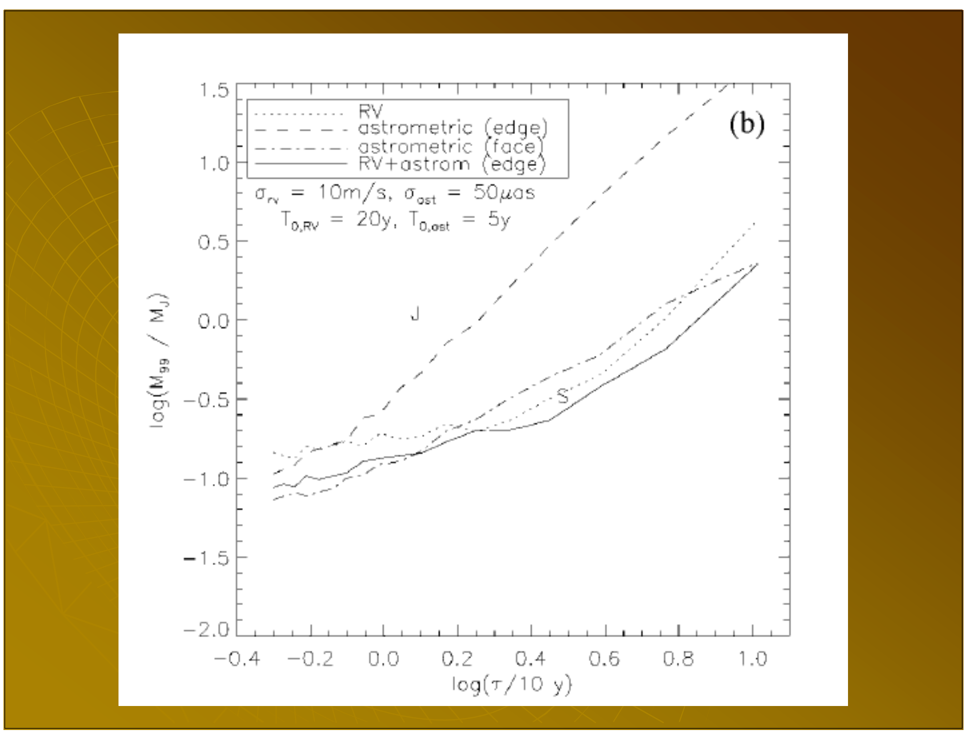
Keck Outrigger Array

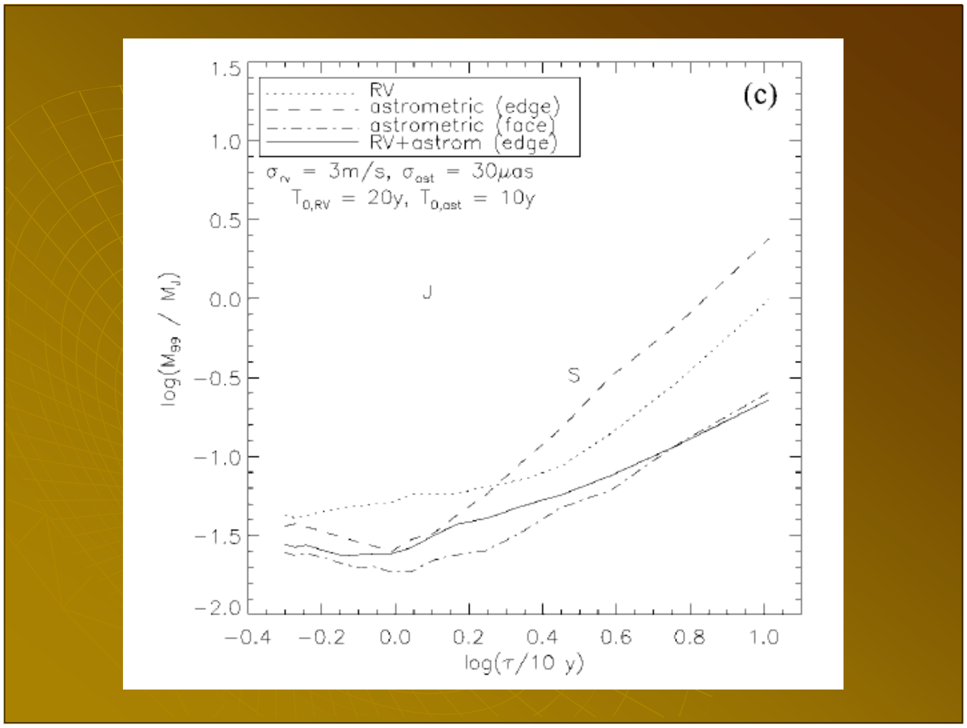
- Very Narrow Angle is the basis of Keck Outrigger Array
  - Main concern: need to find multiple reference stars.
- Why not focus Outrigger on binary star?
  - Achieves SIM like precision ahead of SIM
  - No reference star problem!

Some Obvious Points that are worth remembering

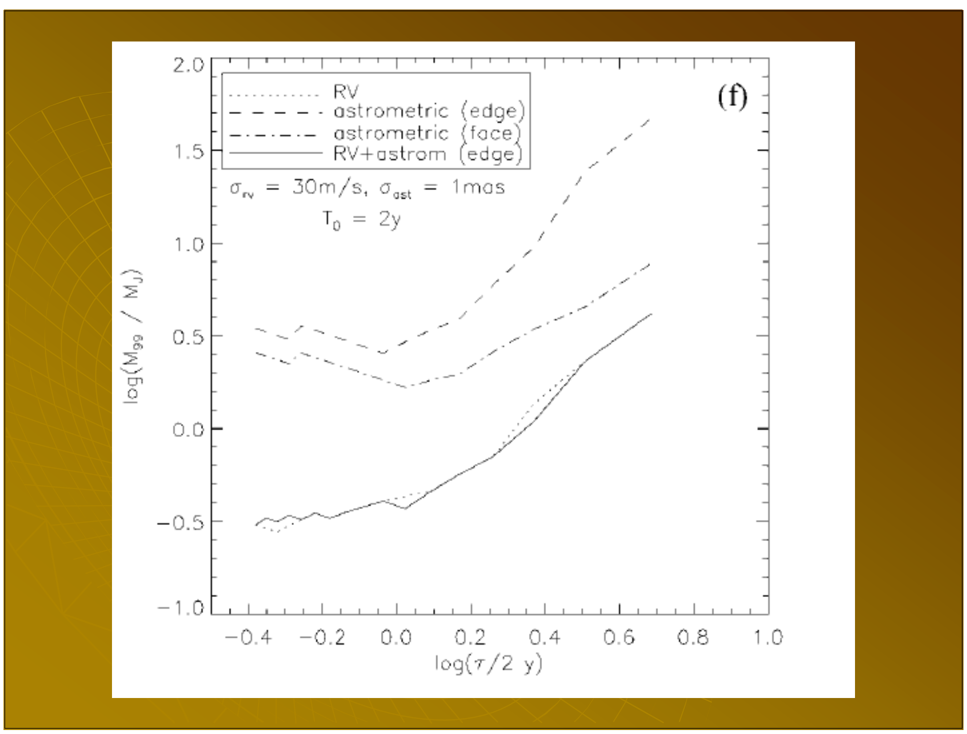
- RV + Astrometry is better than either
- RV + Astrometry is sensitive to all inclination angles
- Full orbit determinations


RV
astrometric (edge)
astrometric (face)
RV+astrom (edge)
(a)
σrv = 3m/s, σast = 100μas
T0,RV = T0,ast = 10y
J
S
log(M99 / MJ)
log(τ/10 y)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0


RV
astrometric (edge)
astrometric (face)
RV+astrom (edge)
(b)
σrv = 10m/s, σast = 50μas
T0,RV = 20y, T0,ast = 5y
J
S
log(M99 / MJ)
log(τ/10 y)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
1.0



RV
astrometric (edge)
astrometric (face)
RV+astrom (edge)
(c)
σrv = 3m/s, σast = 30μas
T0,RV = 20y, T0,ast = 10y
J
S
log(M99 / MJ)
log(τ/10 y)
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0



RV
astrometric (edge)
astrometric (face)
RV+astrom (edge)
(f)
σrv = 30m/s, σast = 1mas
T0 = 2y
log(M99 / MJ)
log(τ/2 y)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0

SIM: A Michelson Interferometer

Three Colinear Fixed Baseline Interferometers

Baseline: 10 m
Wavelength: 0.4-1 micron (CCD)
Aperture: 0.3 m
Field of View: 0.3 arcsecond
Resolution: 10 milliarcsecond

Orbit: Earth Trailing (SIRTF)
Launch: 2009
Lifetime: 5 yr (10 yr?)

How does SIM work?

Principal Observable is Delay:

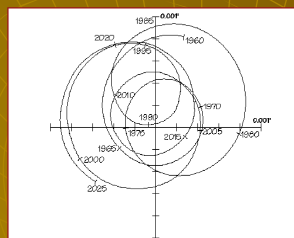
Delay = B . s + C

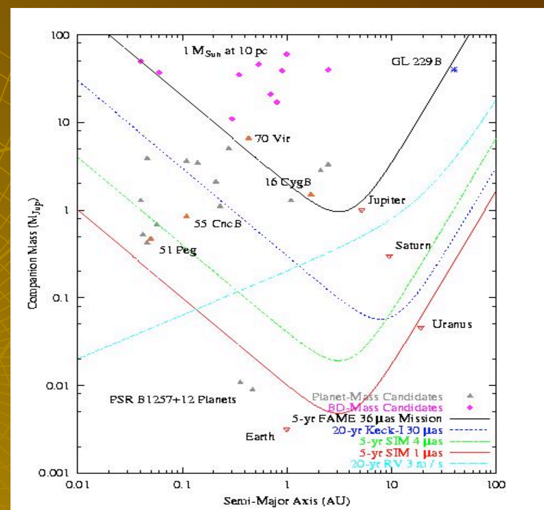
B = baseline
s = source direction
C = instrumental constant

Stabilize with 2 grid stars observed with "guide" interferometers
Derive B from observations of the grid stars (known s)
Keep track of C from internal metrology
Measure Delay with "science" interferometer

http://planetquest.jpl.nasa.gov/simcraft/sim_frames.html

Planet Detection: Comparison





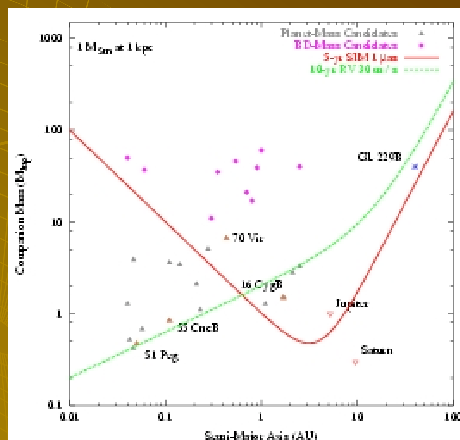
Detection Limits
SIM: 1 μas over 5 years (mission lifetime)
Keck Interferometer: 20 μas over 10 years

Reference Stars: Requirements

Reference stars should not have planets!

→ Moderate distance K giants (mini-grid)
or
→ Eccentric Binaries

Reference Star: K giants



Considerable Preparatory Work: Identification & Stability

Reference Stars: Eccentric G star binaries

Eccentric binaries do not possess planets over a range of orbital separation.

Risk: Uneasy Feeling

Extrasolar Planets InterferometriC Survey: EPIcs, a two-pronged search

Known extra-solar system planets (7%) are different (orbital period and eccentricity distribution)

Two possibilities:

- Solar System is unique.
- Planetary Systems are ubiquitous BUT diverse

→Tier 1-Tier Program

100 nearby stars at 1.5 microarcsec
1000 nearby stars at 4 microarcsec

Extra-solar Planet Interferometric Survey (EPIcS)

M. Shao & S. R. Kulkarni (Co-PI)

S. Baliunas	C. Beichman
A. Boden	D. Kirkpatrick
D. Lin	D. Stevenson
T. Loredo	S. Unwin
D. Queloz	
S. Shaklan	C. Gelino →
S. Tremaine	
A. Wolszczan	

http://www.astro.caltech.edu/~srk