Michaelson Science Center
Summer School
July 28, 2005

Planetary Systems: Astrometric Detectability

Debra Fischer, SFSU

Overview

- Quick update on Doppler planet characteristics
- Space Interferometry Mission
- Monte Carlo modeling for testing detectability
  - Simulating Astrometric data
  - Simulating Doppler data
  - Periodograms

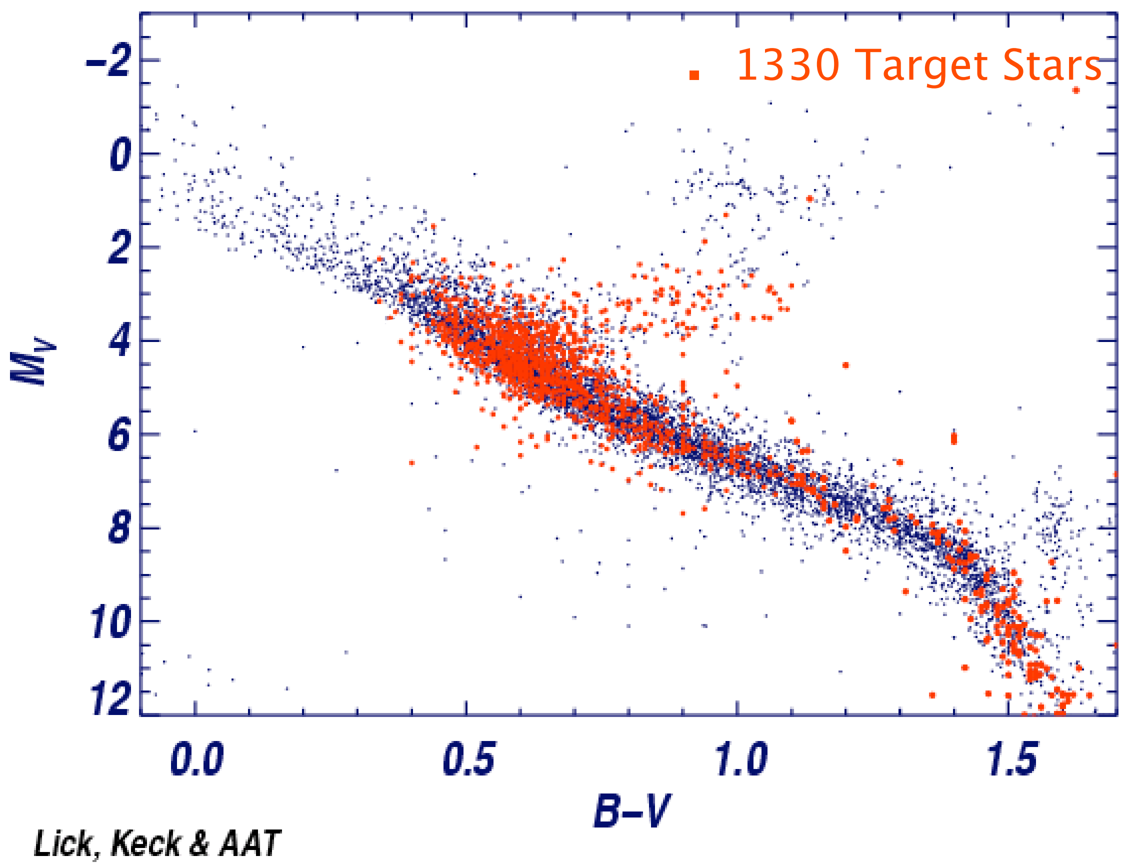
Stellar Sample –

1330 Nearby FGKM Stars

Masses: 0.3 – 1.3 M_{SUN}

Star Selection Criteria:

- Hipparcos Cat.
- V_{mag} < 10 mag
- No Close Binarie
- Age > 2 Gyr



Doppler Survey of 1330 Nearby Stars

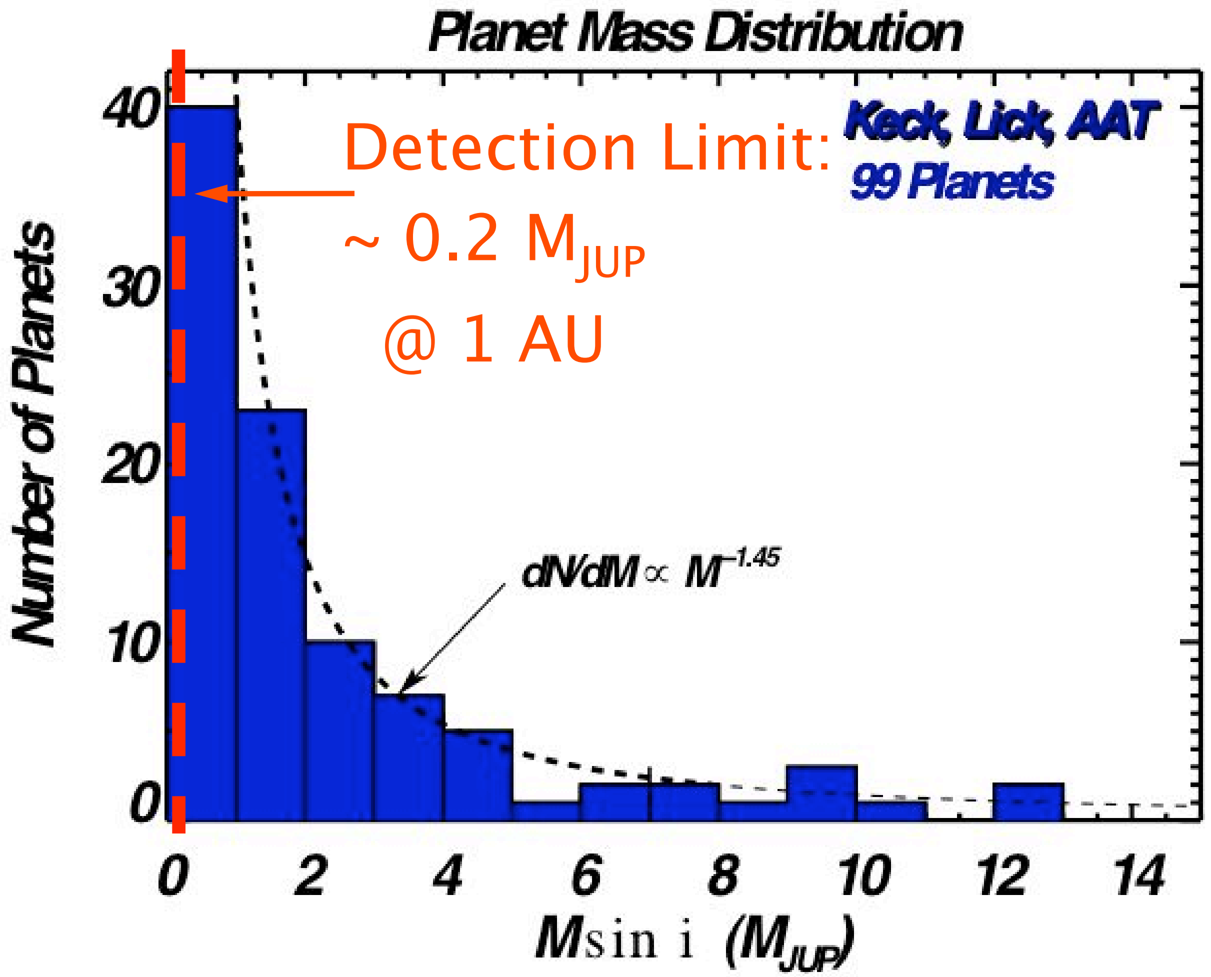
- 156 Planets Discovered
- 13+ Multiple-Planet Systems
- 131 Stars have known planets

- Occurrence of Planets: 131/1330 = 9.8 %

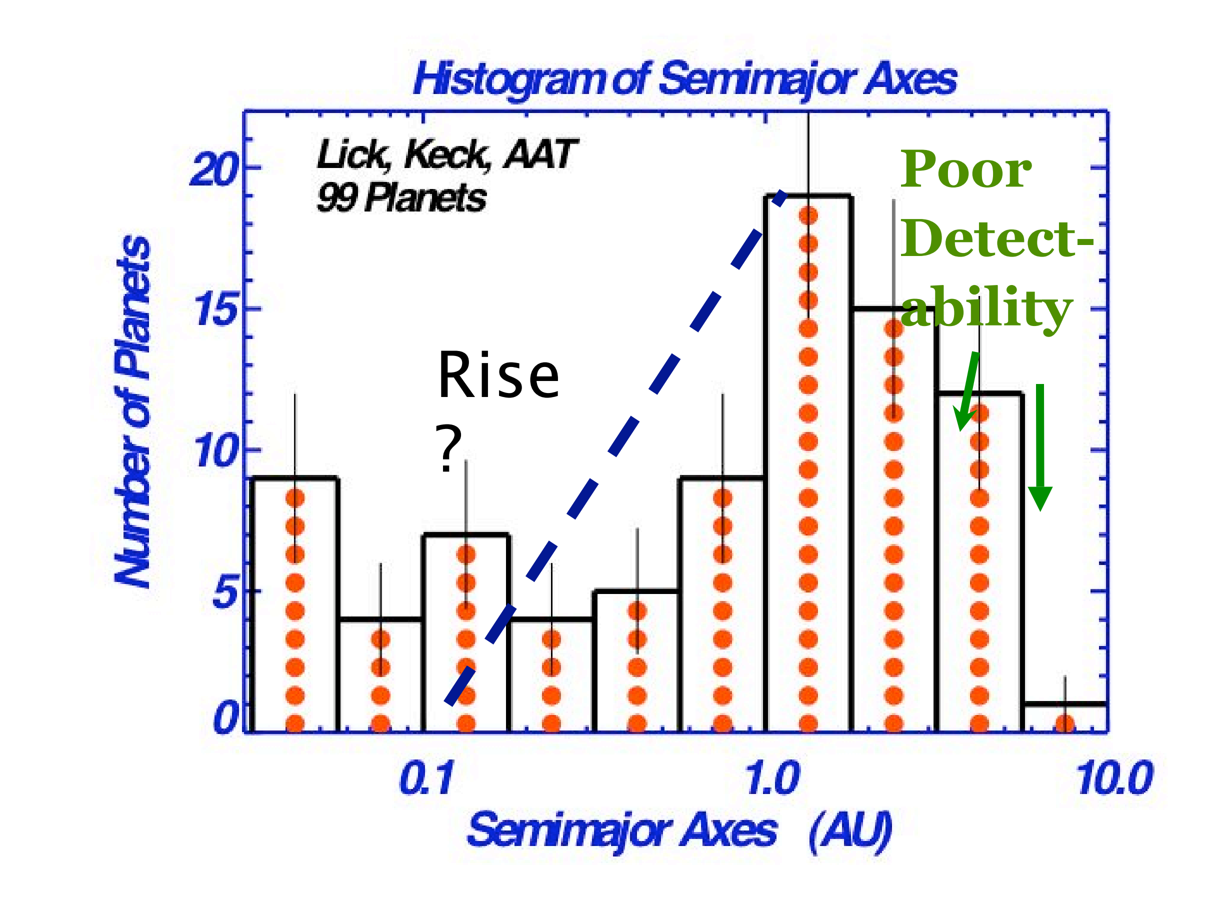
9.8 % of stars have a giant planet within 3 AU.

Lower Limit

Planet Mass Distribution



Doppler Survey of 1330 Nearby Sun-like Stars



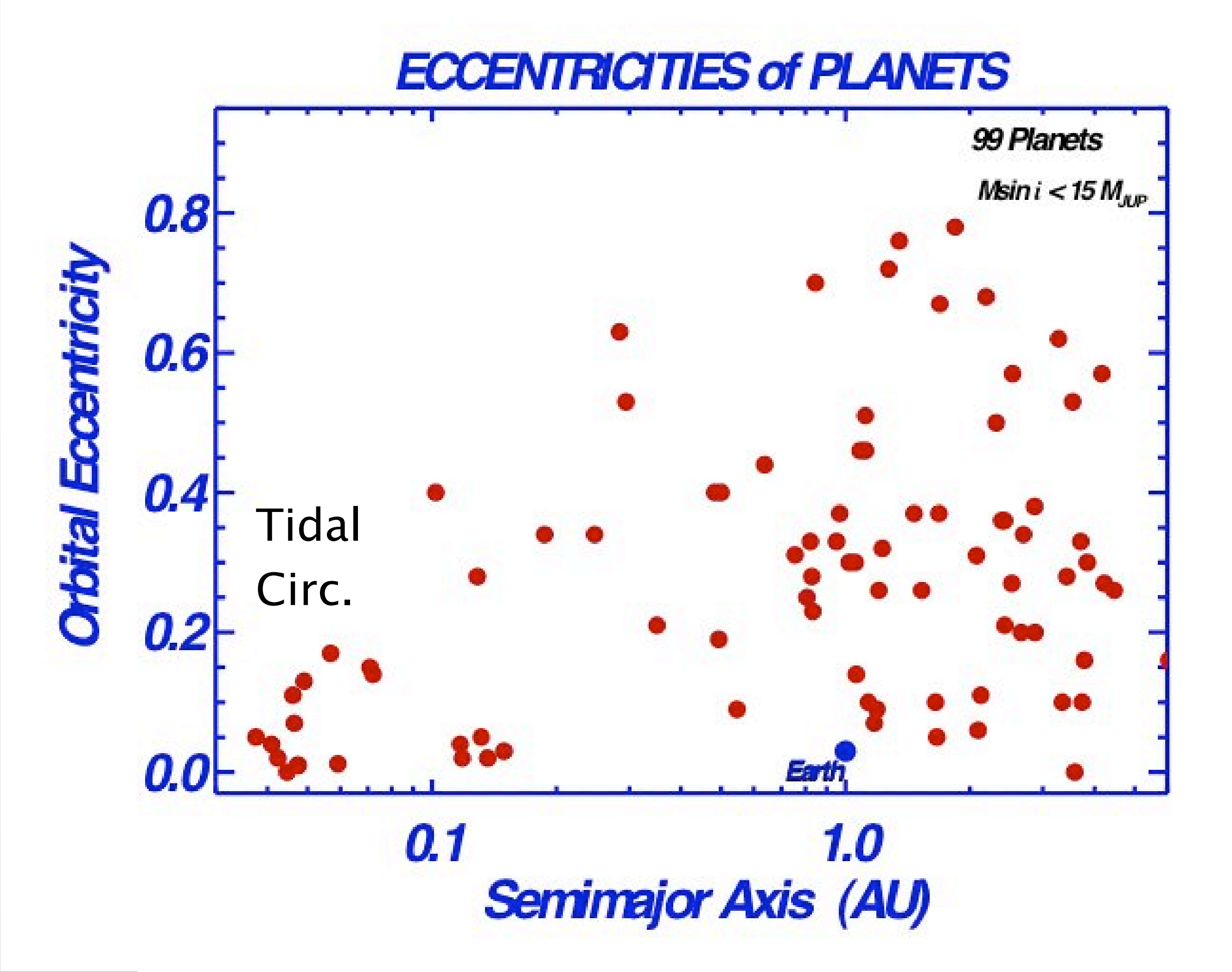
Extrapolation:

6% of stars have giant planets beyond 3 AU

6% + 10%:

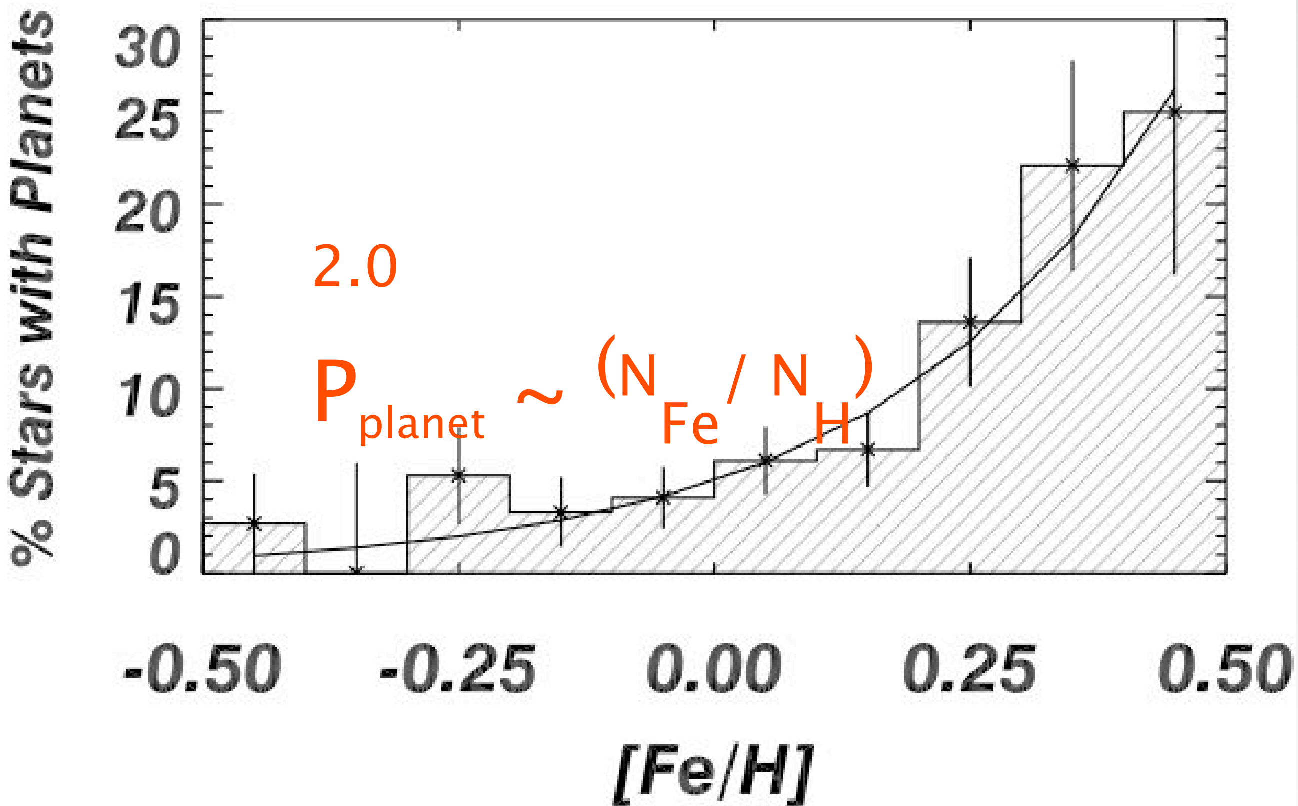
> 16% of stars have Doppler detectable planets

Orbital Eccentricities



Jupiters
at 2-4 AU
Eccentric

Planet – Metallicity Correlation

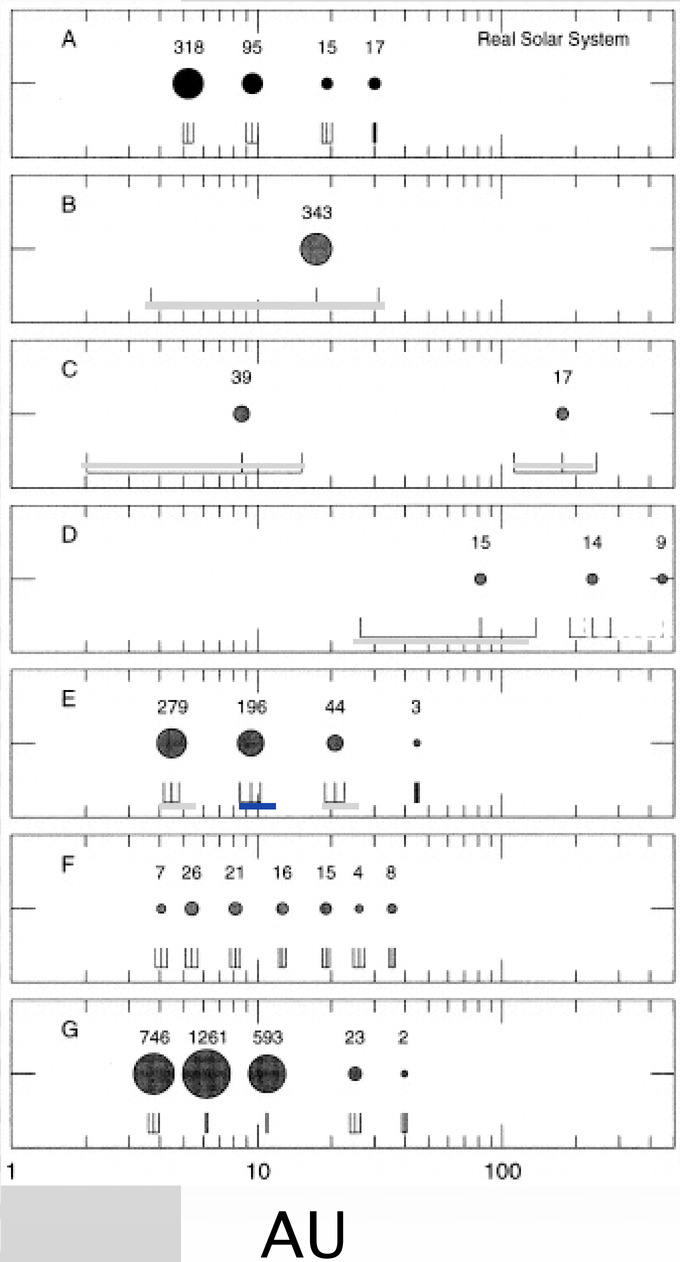


$$P_{planet} \sim (N_{Fe} / N_H)^{2.0}$$

Abundance
Analysis
of all
1000 stars:
Spectral
Synthesis

Fischer &Valenti 2005
Valenti & Fischer 2005
(catalog at http://tauceti.sfsu.edu/)

Monte Carlo Examples of Planetary Systems.



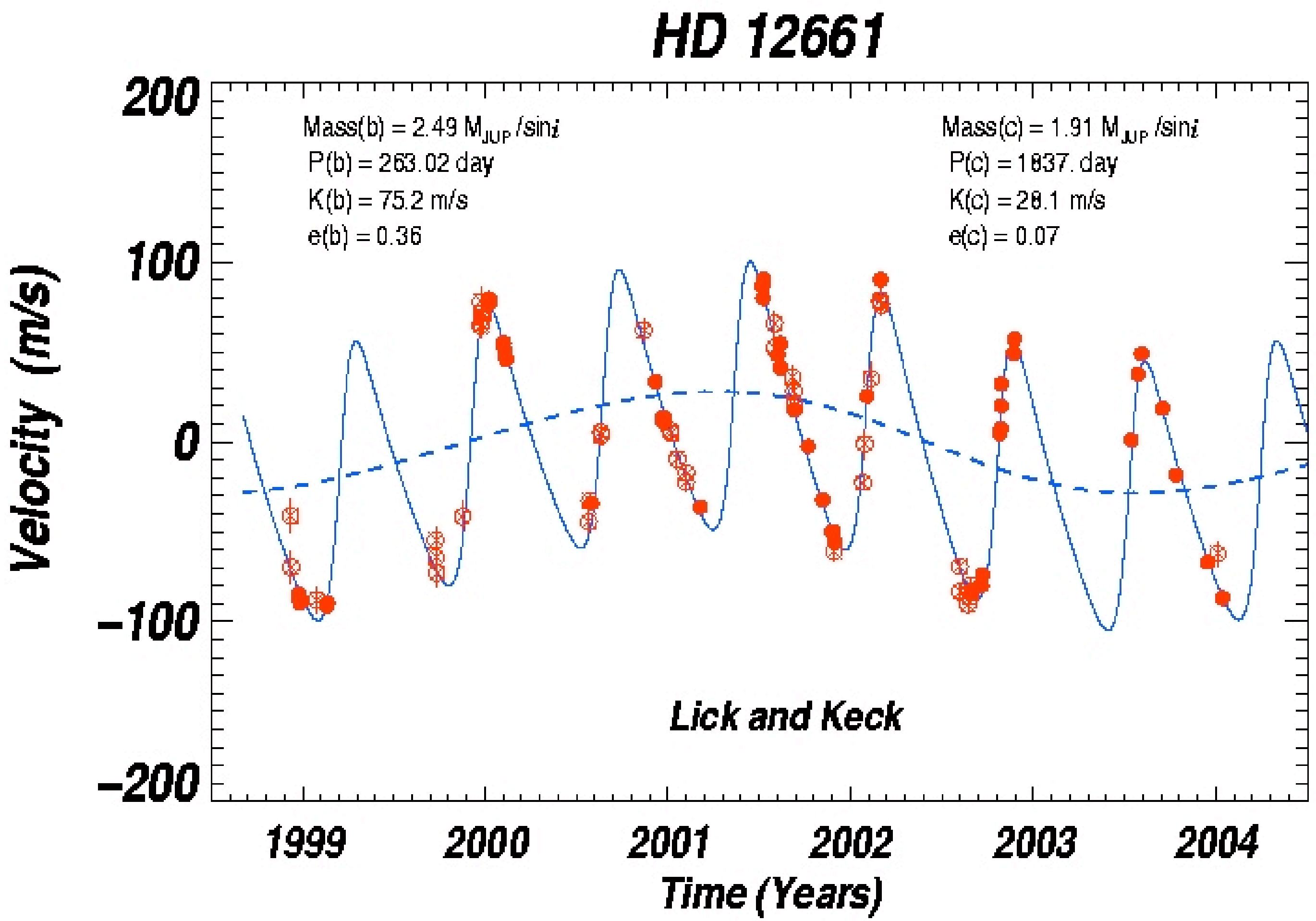
- Size ➔ Planet mass

  (in M $_{earth}$) above each planet.

Peri – Apo of orbit

Rocky Planets will Outnumber jupiters.

Levison, Lissauer, Duncan 1998



2.5 M_J

1.9 M_J

"Hierarchical" Double Planet

Weak Interactions

Possible 6:1 Resonance

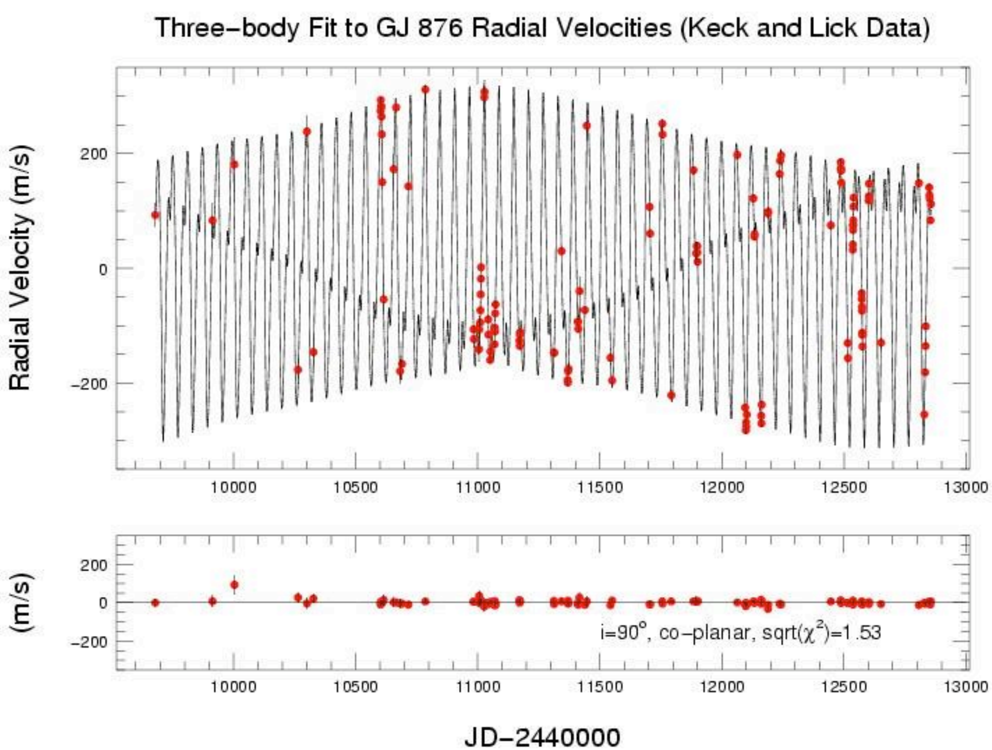
Gozdziewski & Maciejewski,

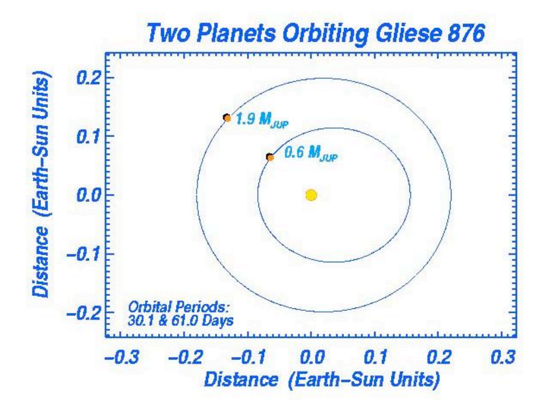
Lee & Peale

GL 876

2:1 Mean-Motion Resonance & Apsidal Lock

	Inner	Outer
P(d)	30.1	61.0
Msin*i*	0.56	1.89 M_J
e	0.27	0.10
ω	330	333°





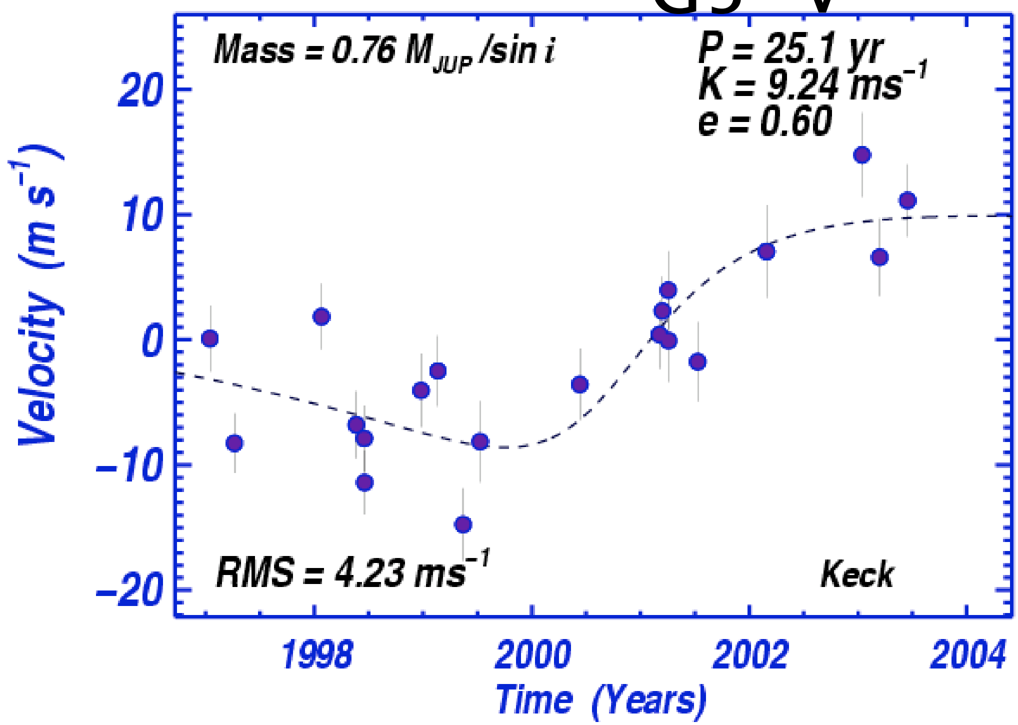
Resonance Theory:

- Laughlin & Chambers
- Lissauer & Rivera
- Man Hoi Lee & S.Peale

I = 84 +- 6° (Benedict et. al. 2002)

Planets Beyond 5 AU

G5 V



Astrometry:

Need 25 yr

Proper motion

Absorption.

Current Astrometric Contribution to Exoplanets:

Determining Orbital Inclination of Known Planets

- Upper Limits for Planet Masses
  47 UMa and 70 Vir (Perryman, Lindegren, et al. 1997)
- Orb. Inclination to GL 876 (Benedict et al. 2002)
- Orb. Inclination to 55 Cancri (McArthur et al. 2004)

Two SIM Planet Searches for
Rocky Planets

G. Marcy & D. Fischer

C. McCarthy, R.P. Butler, B.R.Oppenheimer,
D.G.Monet, J.Scargle, A.Quirrenbach,

S.Reffert (Frink)

Mike Shao

Shri Kulkarni, Chris Gelino

Andy Boden, Stuart Shaklan, Didier Queloz

Scott Tremaine, Sallie Baliunas, Alex Wolszczan

Tom Loredo, Doug Lin

Primary SIM Targets
& Reference Stars

- **250 A, F, G, K, M dwarfs within 15 pc**
  - Doppler Reconnaisance @ 1 m s^{-1}
    Jupiters & Saturns within 5 AU
  - SIM: 30 obs. during 5 yr (1 μas)
    ==> 3 M_{Earth} @ 0.5 - 1.5 AU

- Need 6 K-giant reference stars @ 0.5 - 1 kpc
  - Located within 2 deg of each target
  - Doppler vetting for binaries @ 25 m/s

Lower-Precision SIM Planet Search

- **400 AFGKM stars at 10-30 pc**
  - SIM precision: 4 μas
  - Use "SIM GRID"
    (not narrow angle Ref Stars)

4 μas @ 30 pc reveals:
30 M_{earth} at 1 AU

DRAFT of SIM TARGET STARS

Held at JPL on 27 March 2003

SIM Target List:
www.exoplanets.org

Selection:

- Proximity
- Sp = A-M type

Meeting Participants (left to right): G.Marcy, S.Kulkarni, Chris Gelino, M.Shao, D.Fischer

"A" Team = Shao, Kulkarni, et al.

"B" Team = Fischer, Marcy, Butler, Quirrenbach, Monet, Oppenheimer, Frink, Scargle (highlighted)

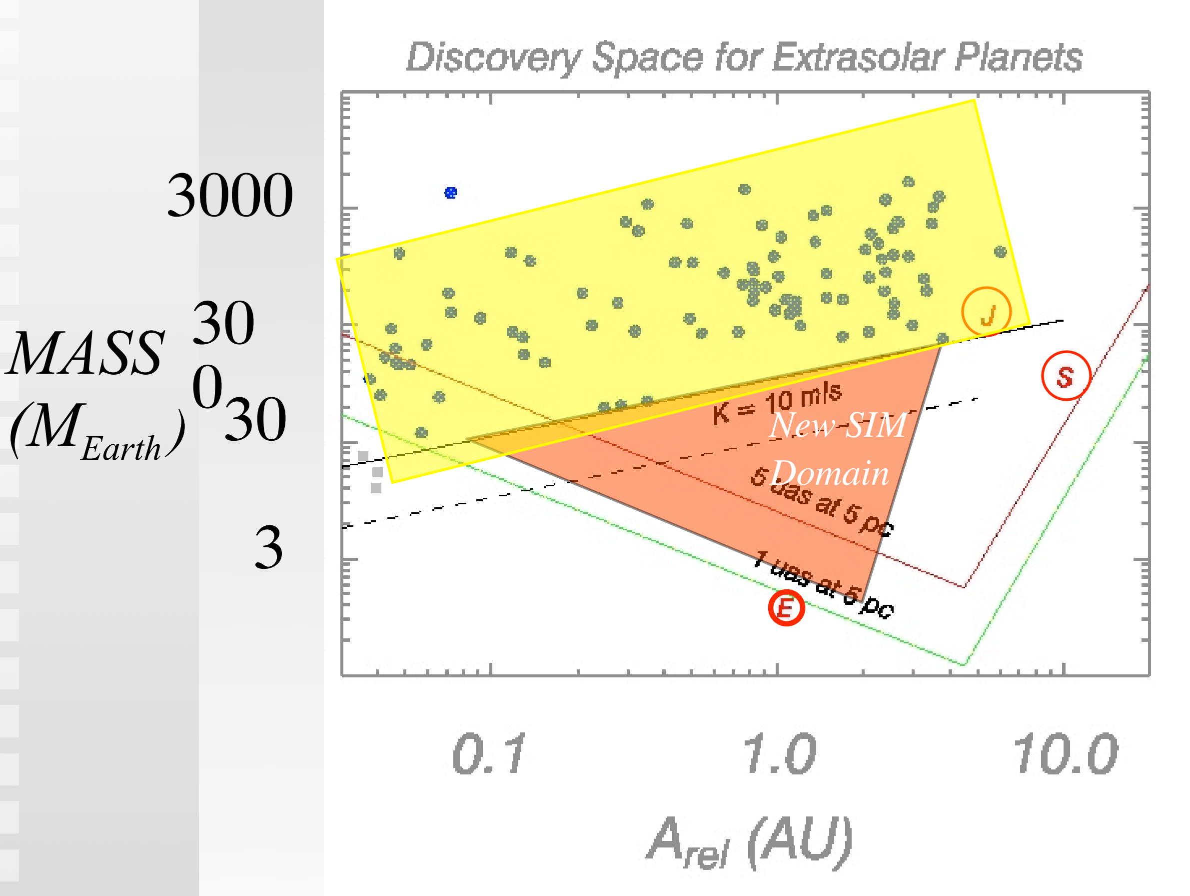
"A" team gets 5 draft picks for every 4 the "B" team gets, due to SIM allocation.

Binaries with sep. less than 0.5 deg are included in one pick.

Team A/B	draft#	. Name	V mag	parallax (mas)	Sp Type		. Binary sep. (AU)	Bin. sep (")	Hab.Zone (AU)	. Lum	. Mass	Other-HZ	Ast.Pert. of Earth in HZ	Period of Earth in HZ	Notes
A	1	Gl559A=alphaCen=HD128620	0.01	747.23	G2	V	23	17.19	1	1.77	1.07	1.33	9.26	1.48	
A	1	Gl559B=alphaCenB=HD128621	1.34	747.23	K1	V	23	17.19	0.59	0.52	0.92	0.72	5.86	0.64	
B	2	Gl71=Tau Ceti=HD10700	3.49	274.39	G8	V ---			0.74	0.53	0.92	0.73	2.17	0.65	
B	3	Gl144=EpsEri=HD22049	3.73	309.99	K2	V note			0.54	0.34	0.87	0.58	2.06	0.47	
A	4	Gl178=HD30652	3.19	124.13	F6	V ---			1.6	3.44	1.17	1.85	1.97	2.34	
A	5	GJ 34A=EtaCasA=HD4614	3.45	168.38	G0	V	71	11.95	1.2	1.47	1.05	1.21	1.95	1.30	
A	5	GJ 34B = EtaCasB = HD 4614B	7.51	168.38	K7	V	71	11.95	0.34	0.03	0.66	0.19	0.48	0.10	
B	6	Gl551 = Prox. Cen = HIP70890	11.05	771.99	M5.5	V	10500	8105.90	0.1	0.00	0.30	0.01	0.21	0.00	faint
A	7	Gl768 = Altair = HD187642	0.77	194.97	A7	IV/V ---			3.2	12.94	1.38	3.60	5.08	5.81	
B	8	Gl411 = Lalande 21185 = HD95735	7.47	393.42	M2	V ---			0.2	0.01	0.53	0.08	0.60	0.03	
A	9	Gl881 = alpha PsA = HD216956	1.15	130.58	A3	V ---			5.2	20.34	1.46	4.51	4.03	7.92	
B	10	Gl324A = 55 Cnc = HD75732	5.95	79.47	G8	V	1100	87.42	0.74	0.66	0.95	0.81	0.68	0.75	planets @ 0.12, 0.24 & 5.5 AU
A	11	GJ 780 = del Pav = hd190248	3.56	163.78	G7	IV ---			0.79	1.40	1.04	1.19	1.86	1.26	
B	12	hr4277 = 47 UMa=HD95128	5.66	71.04	G1	V									
A	13	Gl19 = beta Hyi = HD 2151	2.8	133.86	G2	IV ---			1	4.23	1.20	2.06	2.30	2.70	
A	14	Gl216A=gam Lep = HD38393	3.58	111.69	F6	V	860	96.05	1.6	2.96	1.15	1.72	1.68	2.11	comp B = K2V (V=6.13)
B	15	Gl699 = Barnard's Star = HIP87937	9.57	546.98	M4	V ---			0.27	0.00	0.38	0.02	0.32	0.01	
A	16	Gl449 = beta Vir = HR4540 = HD102870	3.61	91.83	F9	V ---			1.3	4.27	1.20	2.07	1.58	2.71	
B	17	Gl139 = hd20794 (AAT)	4.26	165.01	G8	V ---			0.74	0.73	0.96	0.85	1.46	0.80	
A	18	Gl702 = 70 Oph A = HD165341	4.21	195.96	K0	V	23	4.51	0.65	0.54	0.93	0.73	1.56	0.65	
A	18	Gl702B = 70 Oph B	6.05	195.96	K5	V	23	4.51	0.39	0.10	0.75	0.31	0.82	0.20	
B	19	Gl820A = 61 Cyg A = HD201091	5.21	286.04	K5	V	86	24.60	0.39	0.10	0.75	0.32	1.21	0.21	
B	19	Gl820B = 61 Cyg B	6.03	286.04	K7	V	86	24.60	0.34	0.05	0.68	0.22	0.91	0.12	
A	20	Gl166 = HD26965	4.43	199	K1	V	420	83.58	0.59	0.43	0.90	0.65	1.45	0.56	comp B = wd;C=M4.5V
B	21	Gl825 = hd202560 (AAT)	6.67	253.43	M0	V ---			0.28	0.03	0.65	0.18	0.71	0.10	
A	22	Gl603 = gam Ser = HD142860	3.85	89.85	F6	V ---			1.6	3.57	1.17	1.89	1.45	2.40	
A	23	Gl845A = eps Ind = HD209100	4.69	275.84	K5	V	1500	413.76	0.39	0.17	0.80	0.42	1.44	0.30	comp B = T dwarf (J=12.11)
B	24	GJ777A = HD 190360 (Keck)	5.71	62.92	G6	IV									Jup Analg
A	25	Gl225 = Eta Lep = HD40136	3.71	66.47	F1	V ---			2.3	7.43	1.29	2.73	1.41	3.97	
B	26	Gl 380=HD88230 (Lick)	6.59	205.81	K7	V ---			0.34	0.05	0.69	0.23	0.69	0.14	
A	27	Gl124 = iota Per = HD19373	4.05	94.86	G0	V ---			1.2	2.67	1.13	1.63	1.37	1.96	
B	28	Gl 447 = HIP57548 (Keck)	11.13	298.72	M4	V ---			0.13	0.00	0.37	0.02	0.16	0.00	too faint?
A	29	Gl17 = HD1581	4.22	116.47	F9	V ---			1.3	1.51	1.05	1.23	1.36	1.33	
B	30	Gl 729 = HIP92403 (Keck)	10.43	336.9	M3.5	V ---			0.15	0.00	0.39	0.02	0.21	0.01	
A	31	Gl475 = HR4785 = HD109358 (Keck)	4.27	119.19	G0	V ---	866		1.2	1.38	1.04	1.17	1.34	1.25	
A	32	Gl827 = gam Pav = HD203608	4.22	108.52	F6	V ---			1.6	1.74	1.07	1.32	1.34	1.46	
B	33	Gl 15A = HD1326A	8.09	280.59	M1.5	V	150	42.09	0.24	0.01	0.54	0.09	0.45	0.03	
B	33	Gl 15B = HD1326B	11.06	280.59	M3.5	V	150	42.09	0.13	0.00	0.38	0.02	0.16	0.01	too faint?
															comp B =

SIM: Planet Discovery Space:

1 M_{earth} @ 1 AU for d= 1 pc ==> 3 microarcsec



SIM Planet Domain:

3 - 30 M_{EARTH}

Near Habitable Zones

- **Unambiguous Mass**
- **Co-planarity of orbits in multi-planet systems**
- **Orbital: a, P, e**

Do 3 - 10 M_{Earth} Planets Exist?

Reference Stars

Culling K Giants @ 0.5 - 1 kpc

- Distinguish Giants from Dwarfs: Reduced Proper Motion Diagram

  Tycho 2 Cat. + 2MASS JHK + Tycho BV + proper motion

  RPM = K + 5 * log (mu)   RPM & Color ==> Giants

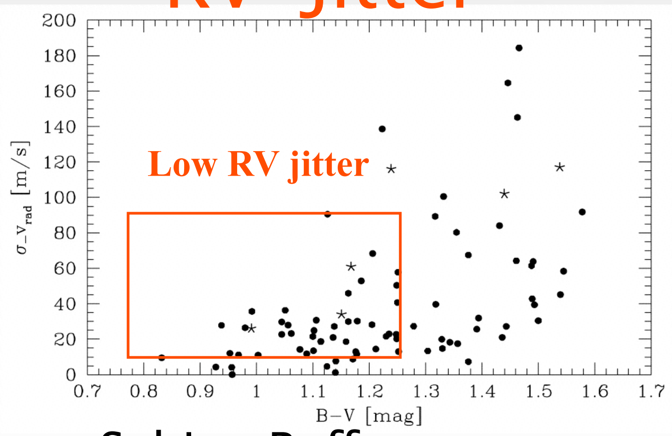
  90% Efficient (10% Dwarfs & Subgiants leak)

RV Jitter

- Select stars with B-V < 1.2

  (low RV jitter)

- RV vetting at 25 m/s



Sabine Reffert

Selecting Reference Stars

- K Giants at d > 500 pc
  (Elim. Astrometric Jitter from Earths, Neptunes)
- V < 10.5 mag (Exp. Time 30 sec, Low thermal drift)
- θ < 2 deg (Angle Dep. Errors)
- RV Vetting: 25 m/s (Elim Binaries, BDs)

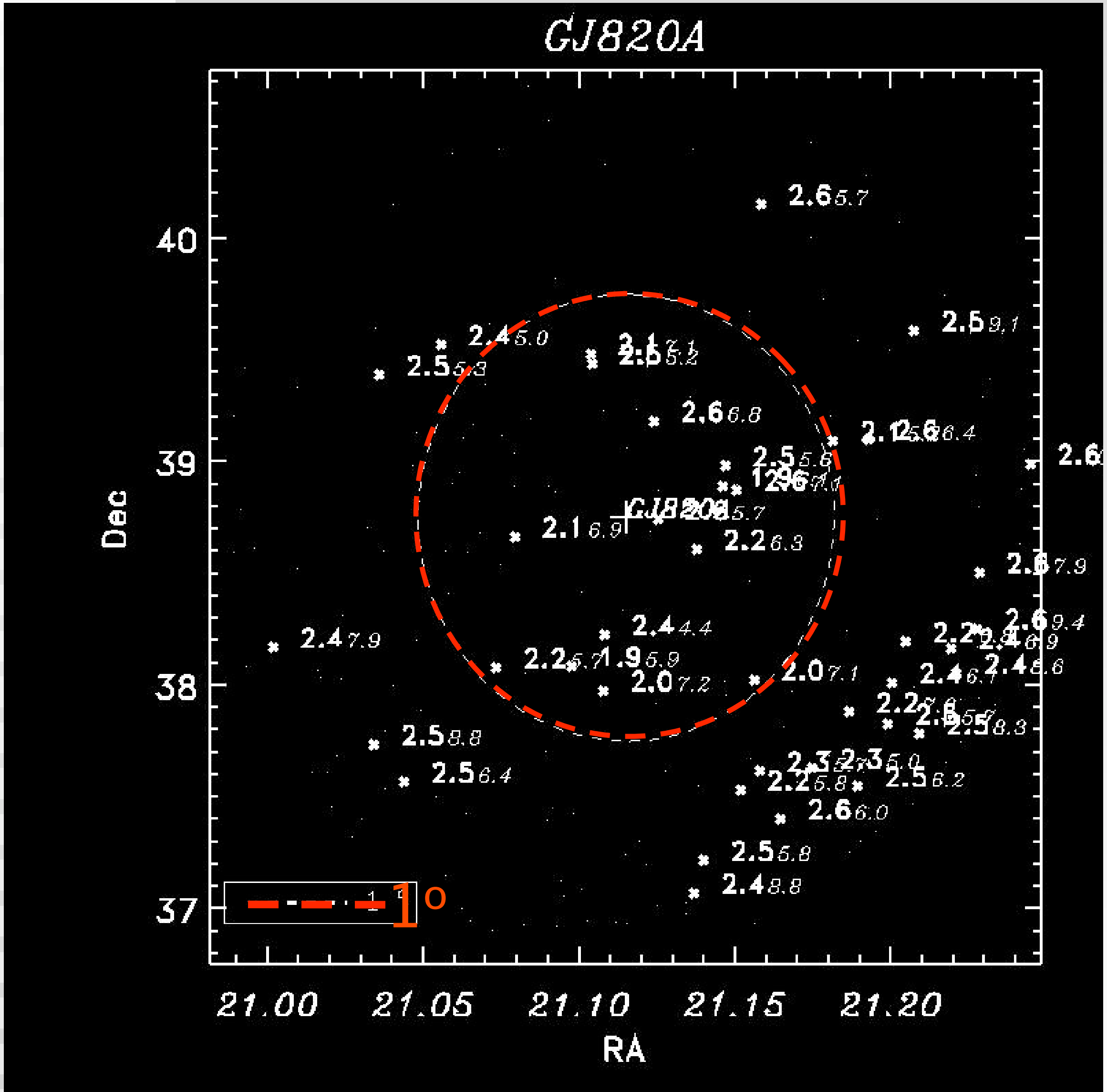
Two Types of Contamination:

- Giant Planets M < 5 Mjup within 5 AU (10 % occurrence)
- Wide Binaries: a = 10 - 100 AU

Unresolved at 1 kpc, Contaminate Fringes

10% have delta mag < 7 → Error > 4 uas.

61 Cyg A



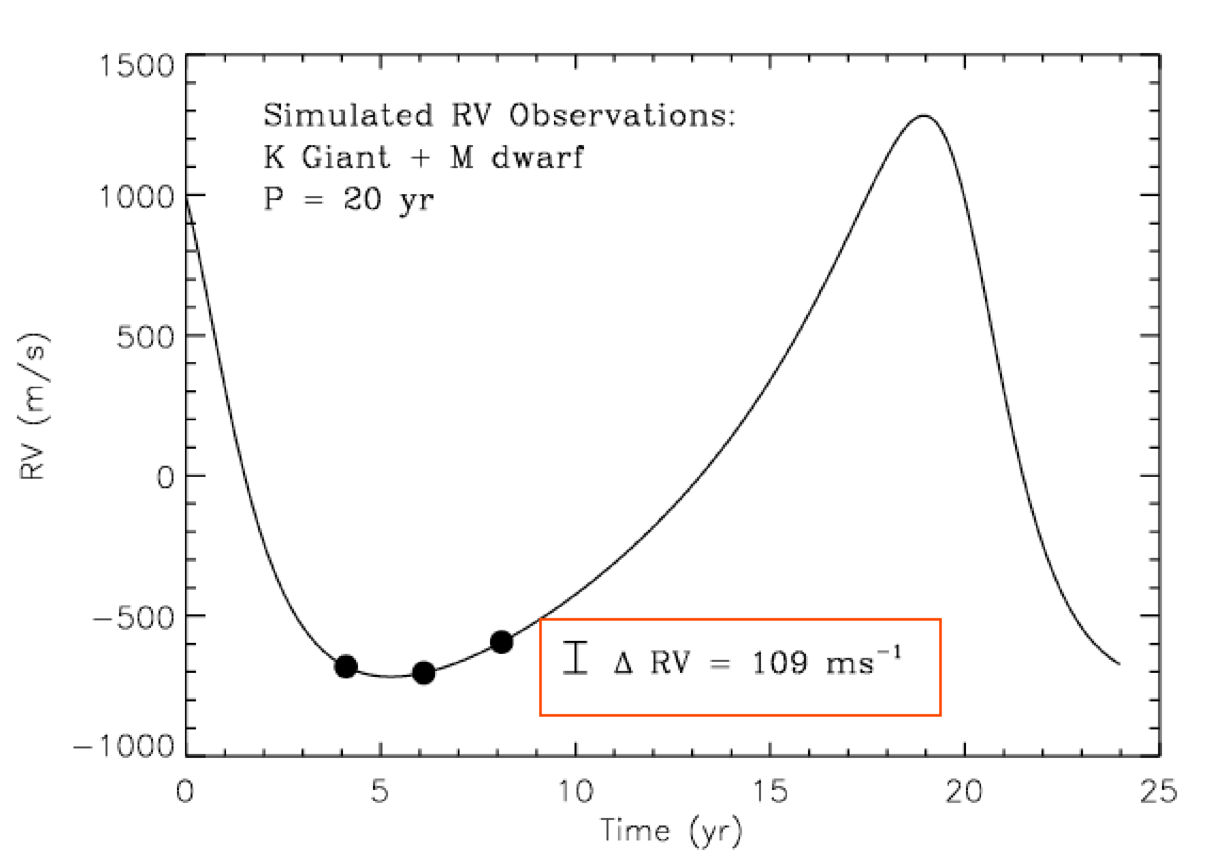
Reference Star

Merit Function
(Chris McCarthy)

Exp. Error

- Photons
- Angle sep.
- Planet jitter

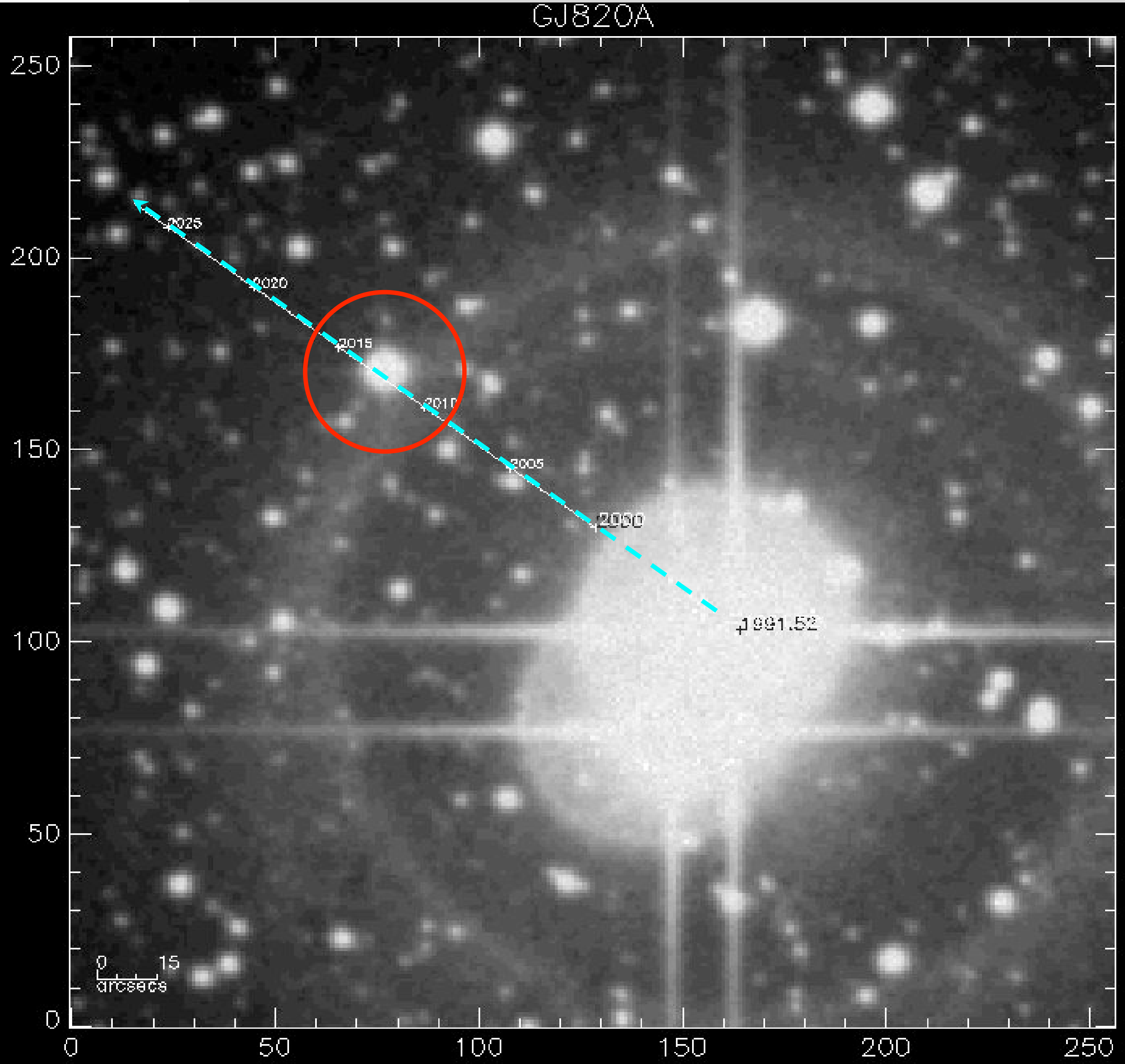
RV Vetting of Reference Stars: Typical M Dwarf Companion



Eliminate Companions: need 25 m/s RV Precision

Planets around K giants get through.

61 Cygni A: Proper Motion



Proper Motion tracking KL Tah (SFSU)

Crowded Fields

Fringe Contamination if within 2

SIM Complements *Darwin & TPF-C*

- ***SIM ~250*** closest ***stars:***
  Identify targets for Darwin & TPF

Definite targets: SIM finds rocky planet in the habitable zone

Potential targets: 3-σ SIM earths

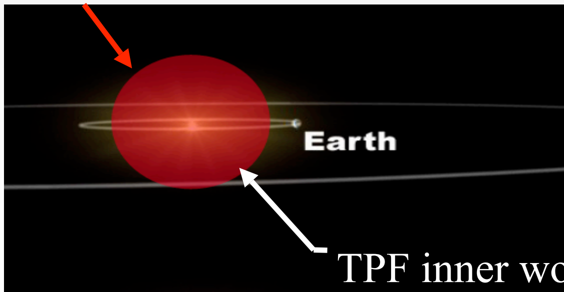
Avoid targets: SIM finds a <u>giant planet in the habitable zone</u>

SIM is the only mission that can measure masses and set upper limits on masses.

Darwin/TPF Timing:

Catch planets when they are 4 λ/d from star.

Inner Working Distance



Monte Carlo simulations

•Construct a keplerian orbit and rotate into space

•Add astrometric noise to change "clean" theoretical values to realistically simulated observational data

•Construct the radial velocity curve with a different observational sampling

•Add gaussian noise to change "clean" theoretical rv values to realistically simulated observational data

* input parameters:
  inclination (*i*), omega (ω) and big omega (Ω)
  Parallax, M_{STAR}, M_{PLANET}
  Orbital period, eccentricity

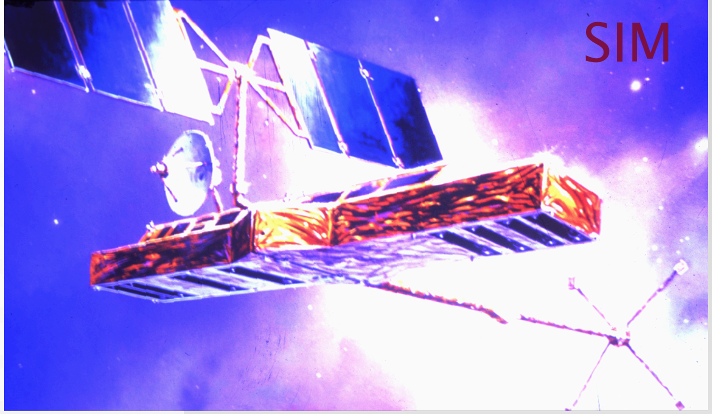
Monte Carlo programs

http://www.physics.sfsu.edu/~fischer/MSC_school.html

orbsim_earths.pro
euler_rotd.pro
simrv.pro

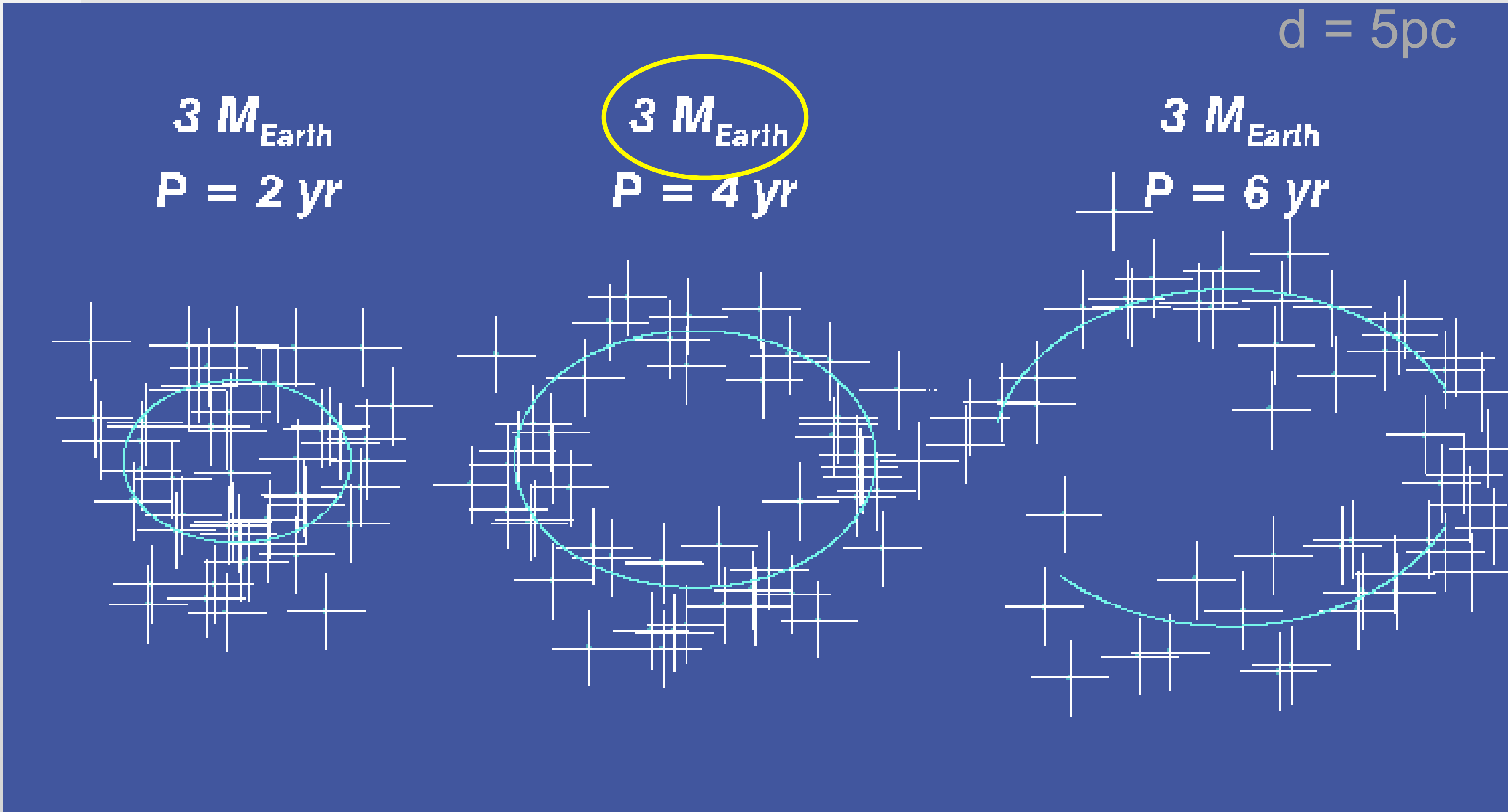
Download and run these idl programs to create synthetic astrometric and Doppler data, useful for detectability simulations, observing proposals, etc.

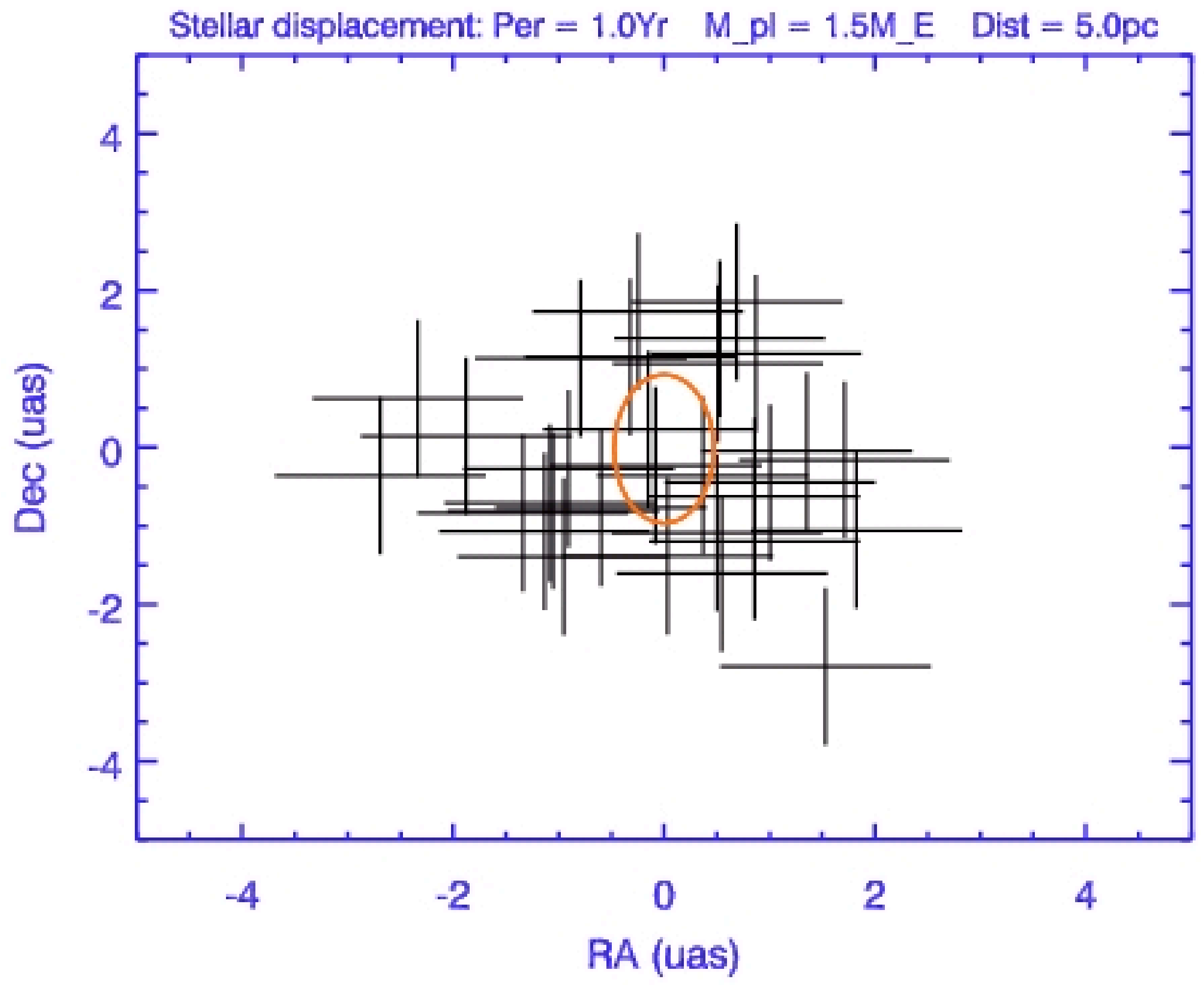
Demo…

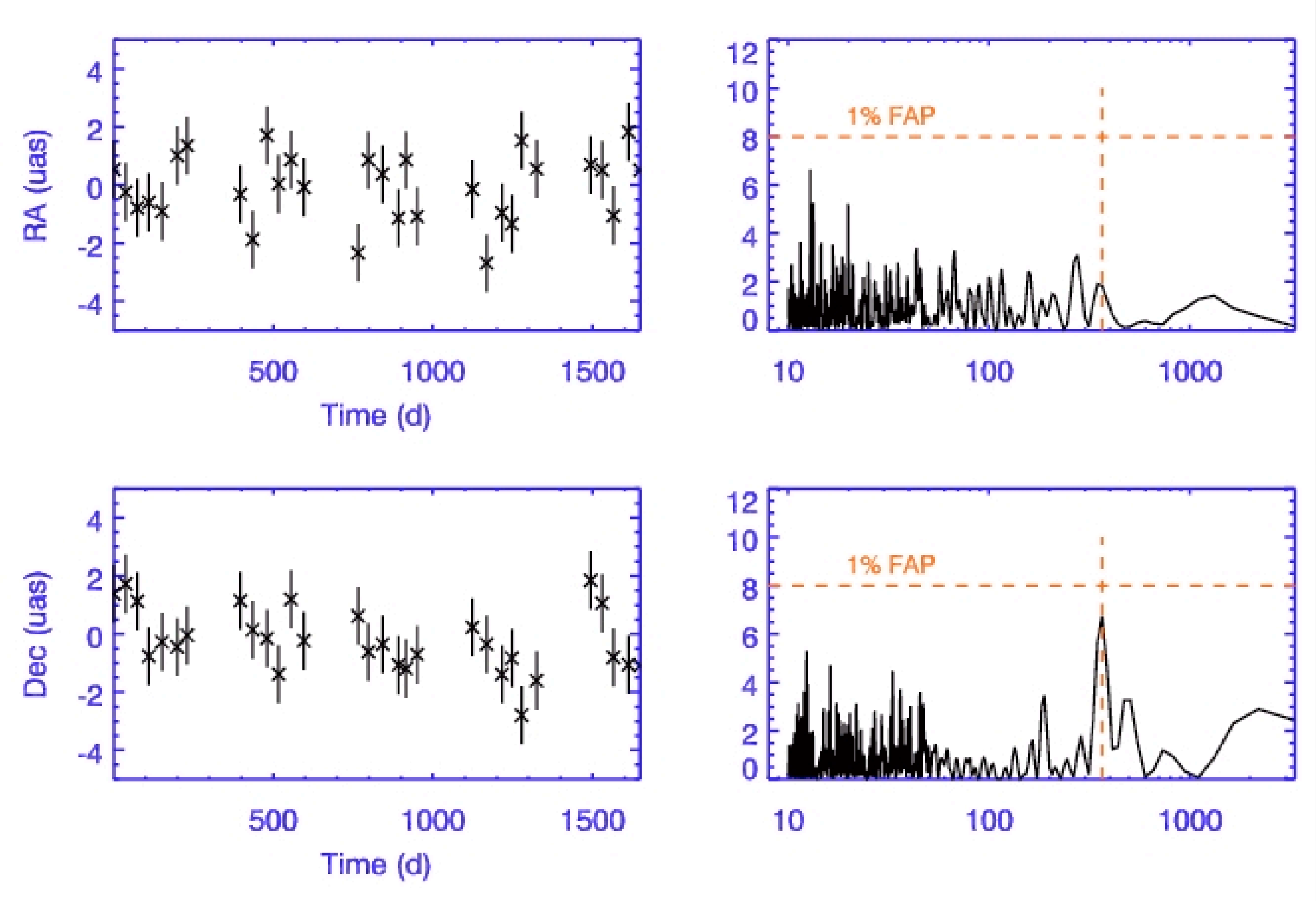


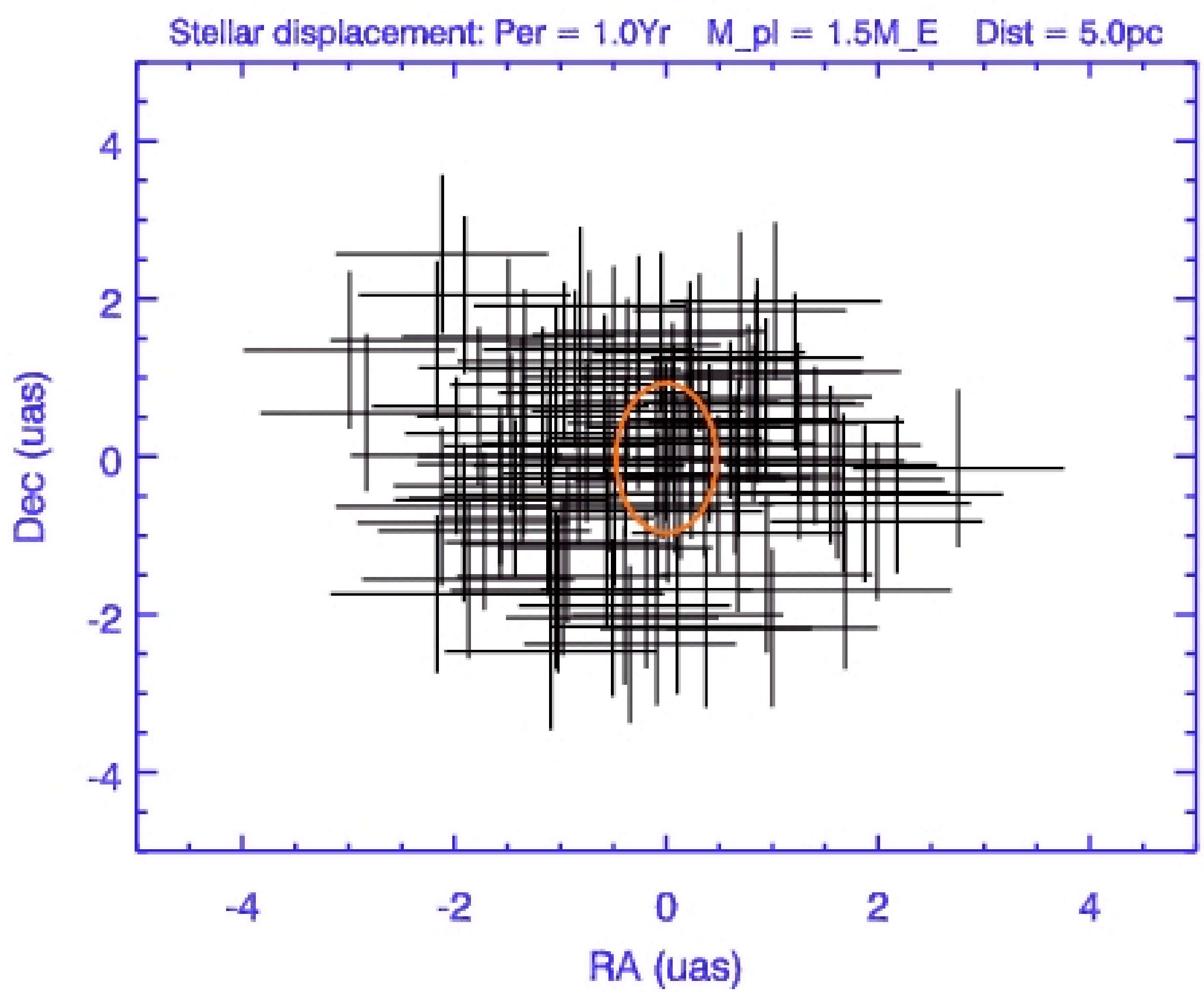
SIM: 3 Earth-Mass Planets

precision 1 μas

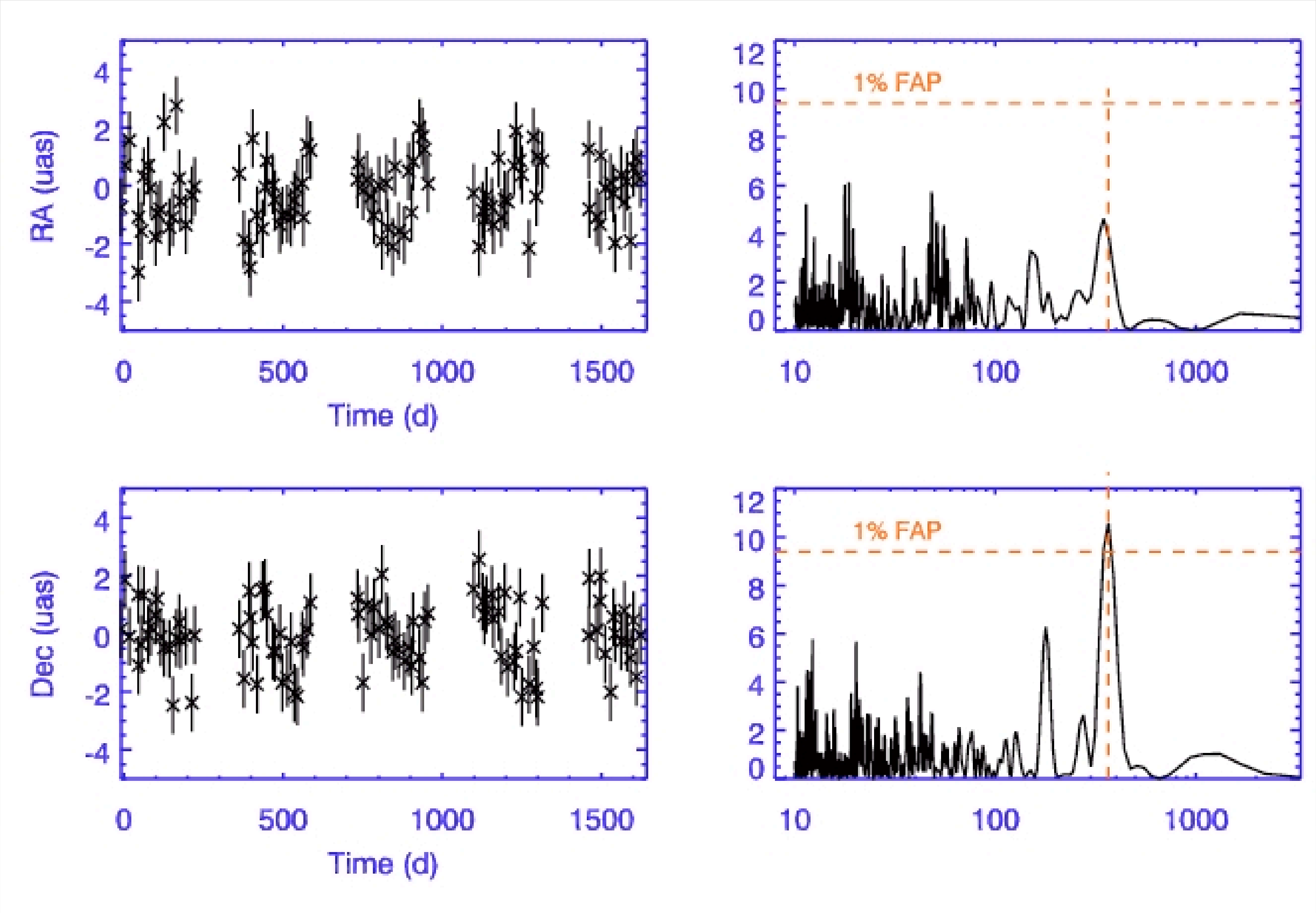



Stellar displacement: Per = 1.0Yr M_pl = 1.5M_E Dist = 5.0pc
Dec (uas)
RA (uas)
4
2
0
-2
-4
-4
-2
0
2
4


RA (uas)
Dec (uas)
Time (d)
500
1000
1500
1% FAP
10
100
1000
4
2
0
-2
-4
12
10
8
6



Stellar displacement: Per = 1.0Yr M_pl = 1.5M_E Dist = 5.0pc
4
2
0
-2
-4
Dec (uas)
-4
-2
0
2
4
RA (uas)



RA (uas)
Time (d)
1% FAP
Dec (uas)
Time (d)
1% FAP

Lessons from Doppler work

1. You always want higher precision and more data than you think you'll need (more than DOF + 1).
2. Planetary architectures can be complicated (see above)
   - Multiple planets, including resonance systems
   - High eccentricities
3. Need more than 1 full orbit to properly characterize unseen companions
4. Difficult trade-offs between number of targets observed and the achieved precision. High precision always takes more telescope time.