NASA Strategic Roadmap Committee
Tucson
11 January 2005

Exoplanets:
Known Properties and the Role of SIM/TPF

Geoff Marcy & Debra Fischer & Chris McCarthy
E. Ford, A. Quirrenbach, S. Reffert (Frink),
D. Monet, J. Scargle
w/ M.Shao, C.Beichman, S.Kulkarni

Disclaimer: ***Authors are on members of SIM Science Team***

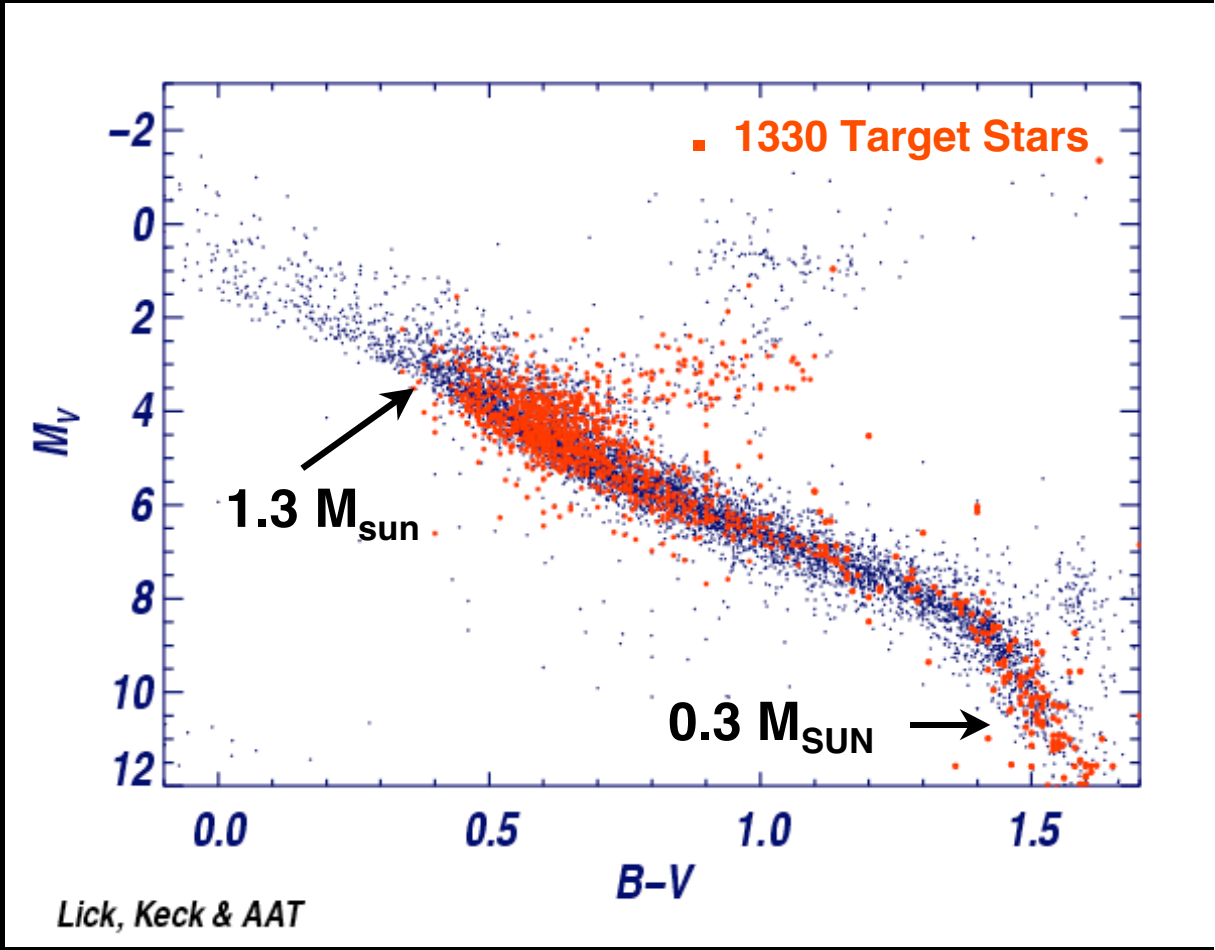
Doppler Planet Search

~2000 Nearby FGKM Stars

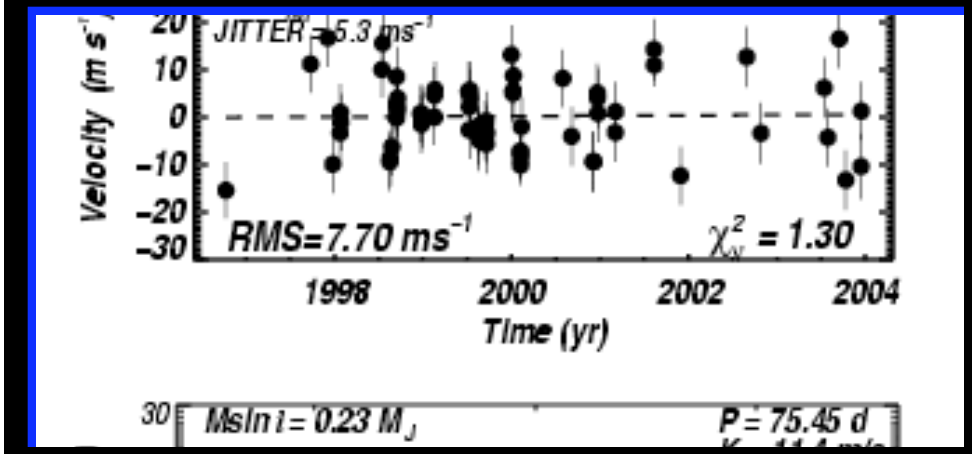
Masses: 0.3 - 1.3 M_{SUN}

Star Selection Criteria:

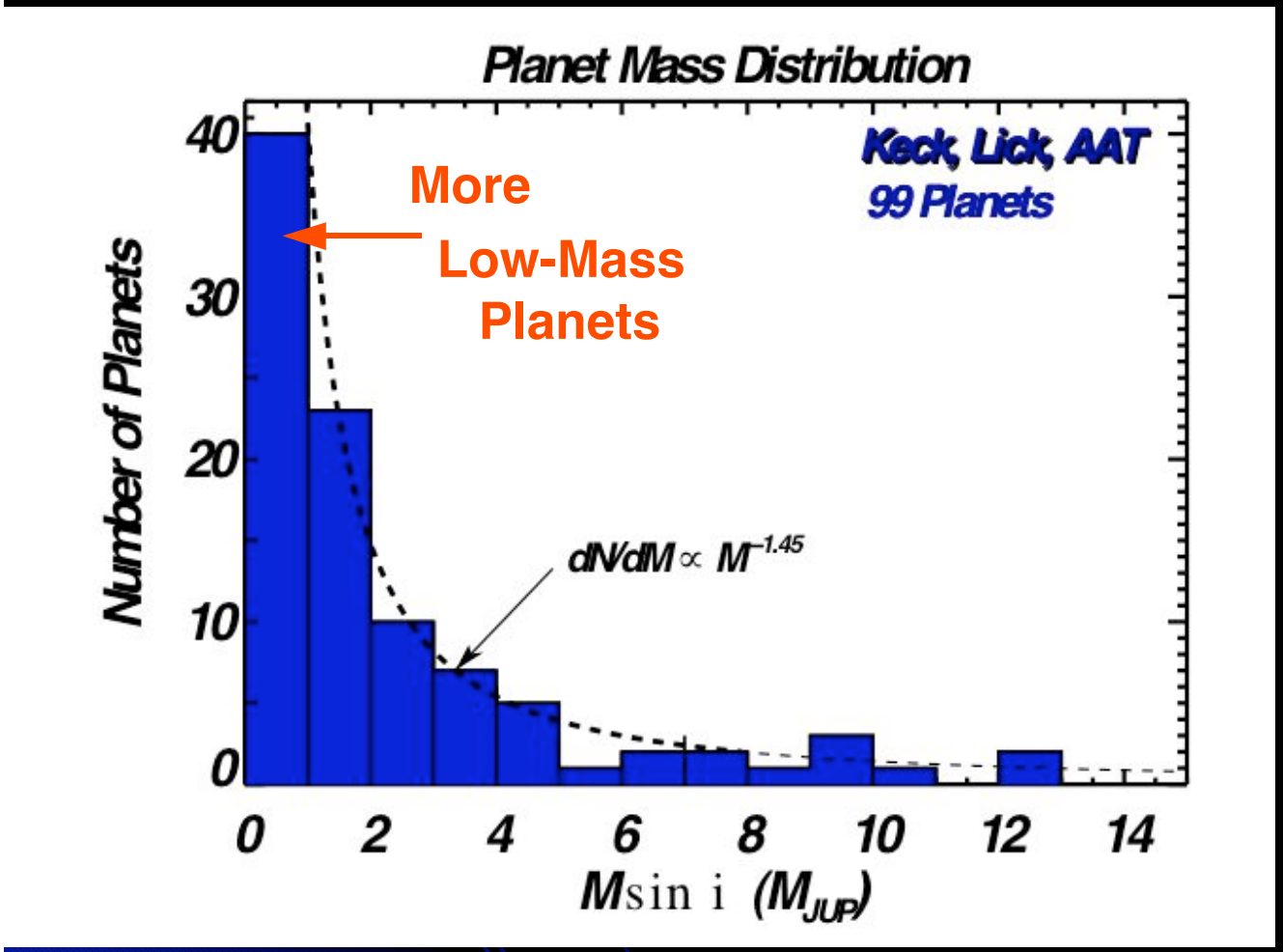
- Hipparcos Cat.
- V_{mag} < 10 mag
- No Close Binaries
- Age > 2 Gyr



HD 16141 1.0 M_{SUN}



Planet Mass Distribution



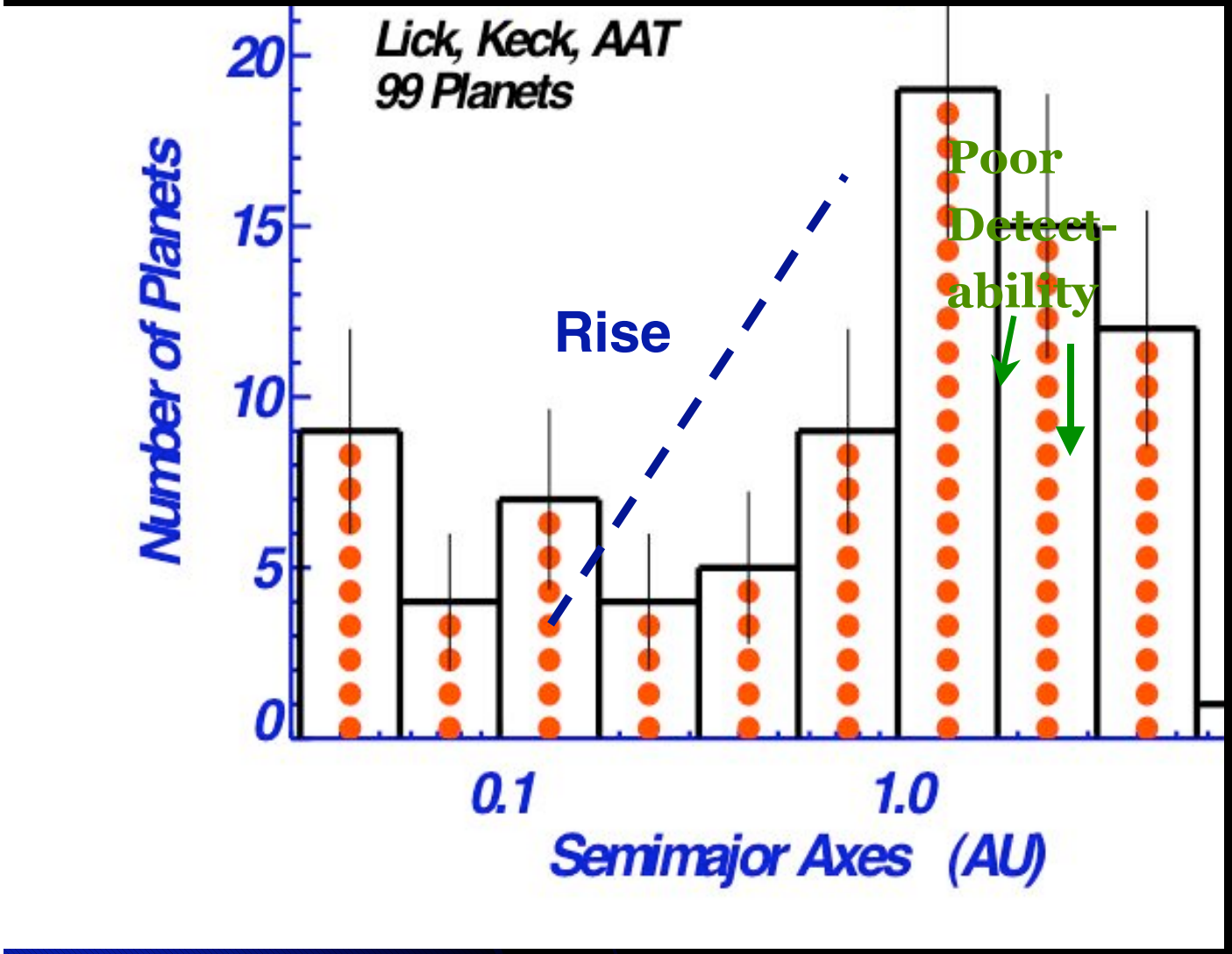
Three Neptunes:

- **Gl 436**
- **55 Cnc d**
- **μ Ara**

(Butler et al.
McArthur et al.
Santos et al.)

(Exclude 1st bin.)

Doppler Survey of 1330 Nearby Sun-like Stars



Extrapolation:

6% of stars have giant planets beyond 3 AU

Model:

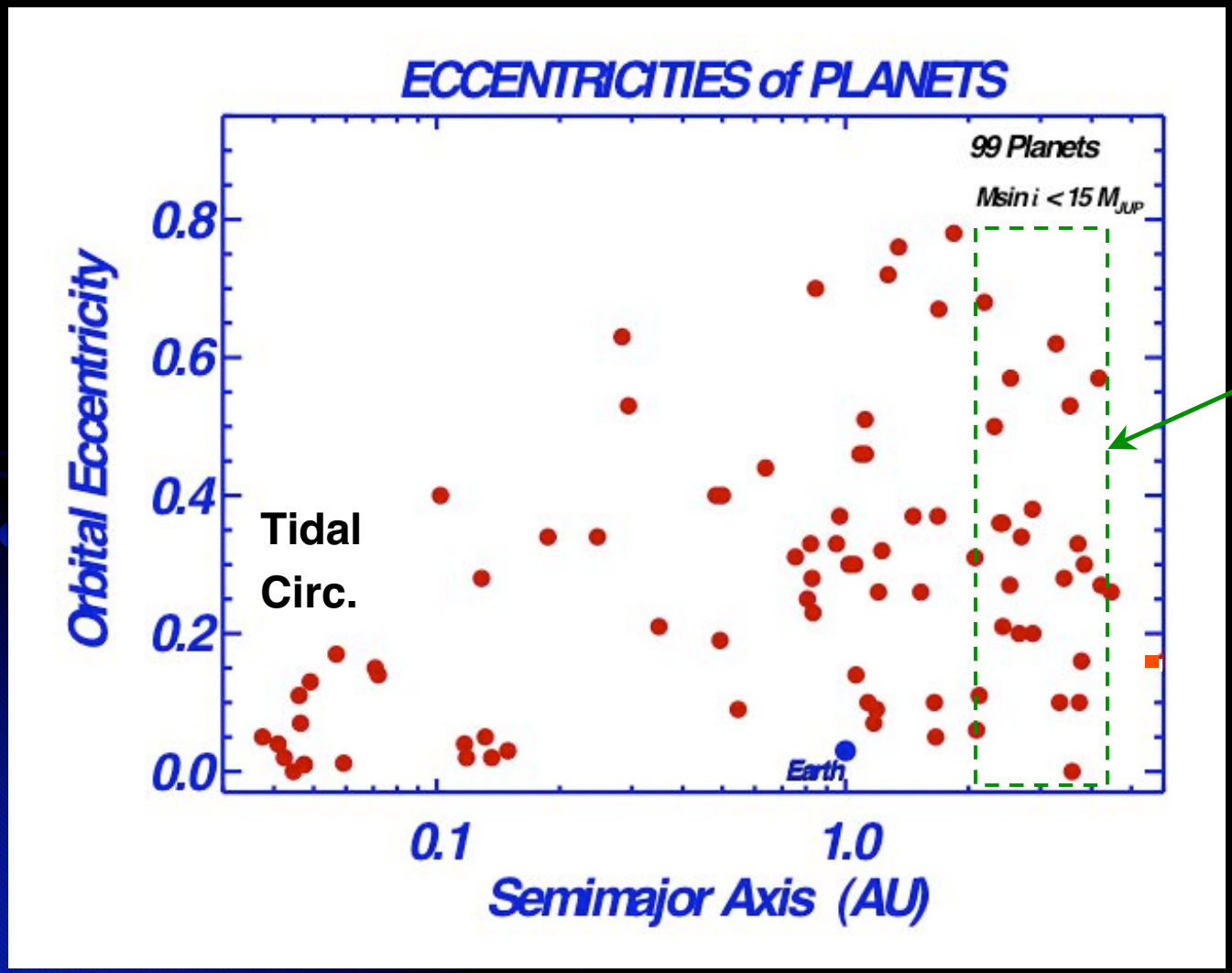
Inward Migration:

Planets in place as disk vanishes

Armitage, Livio, Lubow, Pringle et al. 2002

Trilling, Benz, Lunine 2002

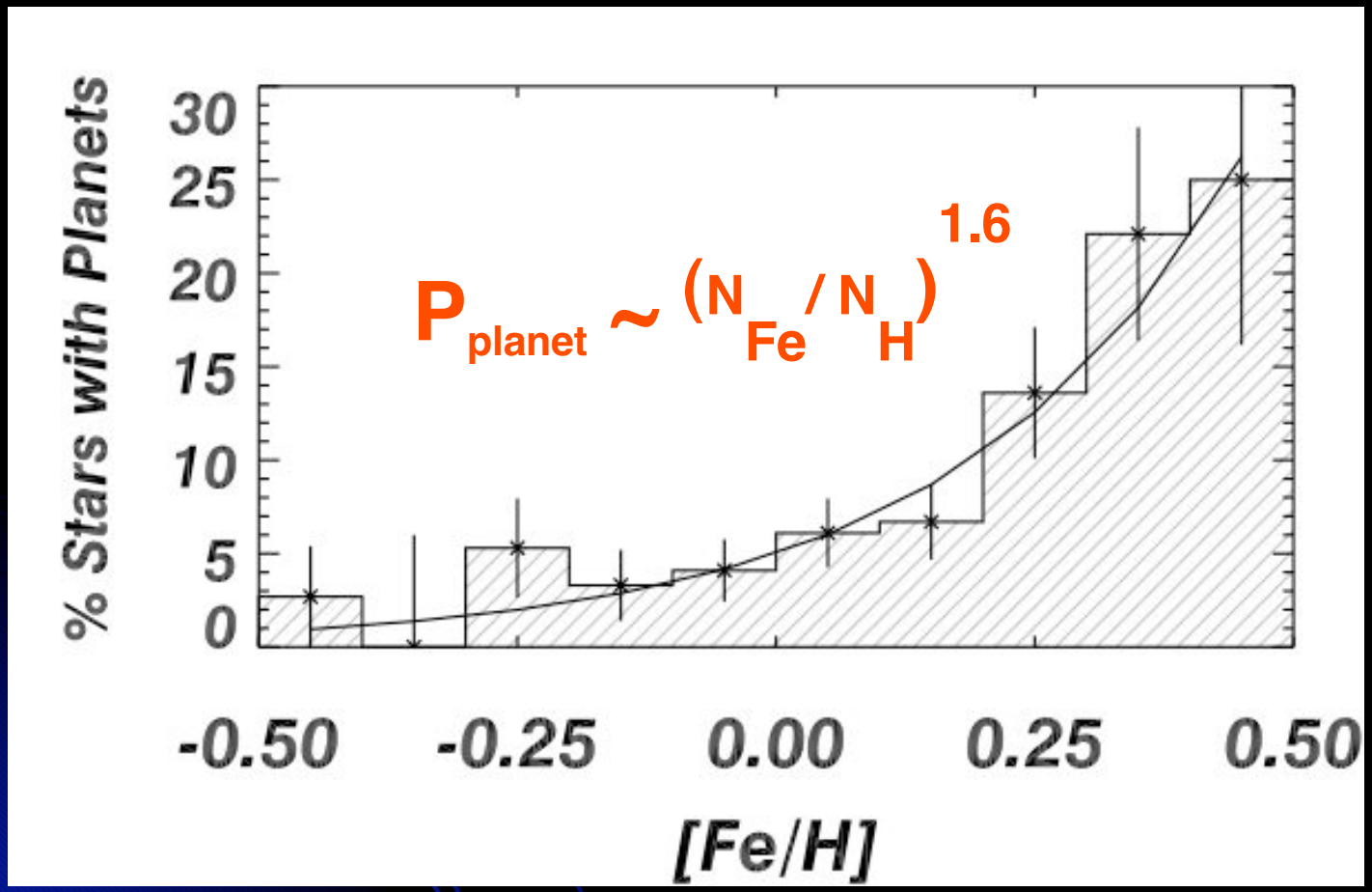
Orbital Eccentricities



Jupiters at 2-4 AU:

Still Eccentric

Planet – Metallicity Correlation



Abundance Analysis of *all* 1000 stars: *Spectral Synthesis*

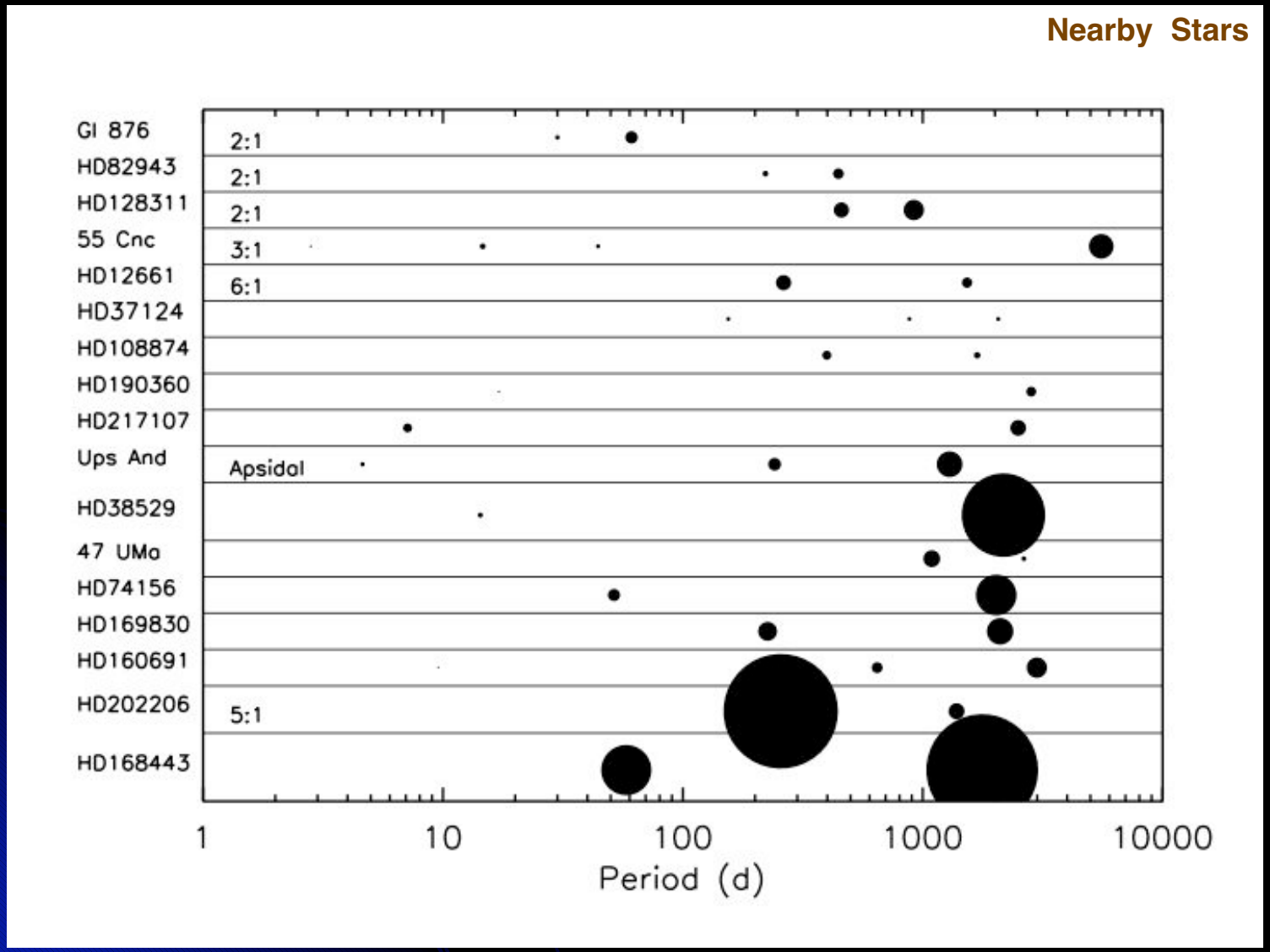
→ **Fe/H**

Valenti & Fischer 2005

Fischer & Valenti 2005

17 Known

*Multi - Planet Systems**



115 planet-host stars: 15% are multiple

*4 from Mayor et al.

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The Role of SIM toward Rocky, Habitable Planets

Geoff Marcy & Debra Fischer & Chris McCarthy
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Disclaimer: ***Authors are on member of SIM Science Team***

Is the SIM Planet Search:

- Scientifically Unique & Overwhelmingly Epochal ?
- Programmatically Viable & Worth the Cost ?

Outline of Talk

Rocky, Habitable Planets

Within 25 pc

- Goals: Occurrence, Masses, Orbits, Chem.Comp.

Primary SIM Targets

- 250 A, F, G, K, M dwarfs within ~15 pc
  - Doppler Recon. @ 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

5 σ

SIM: 250 AFGKM

Main Sequence Stars d < 15 pc

"A" Team = Shao, Kulkarni, et al. | "B" Team = Fischer, Marcy, Butler, Quirrenbach, Monet, Oppenheimer (highlighted) | to SIM allocation. | Binaries with sep. less than 0.5 deg are included in one pick.

Selection:

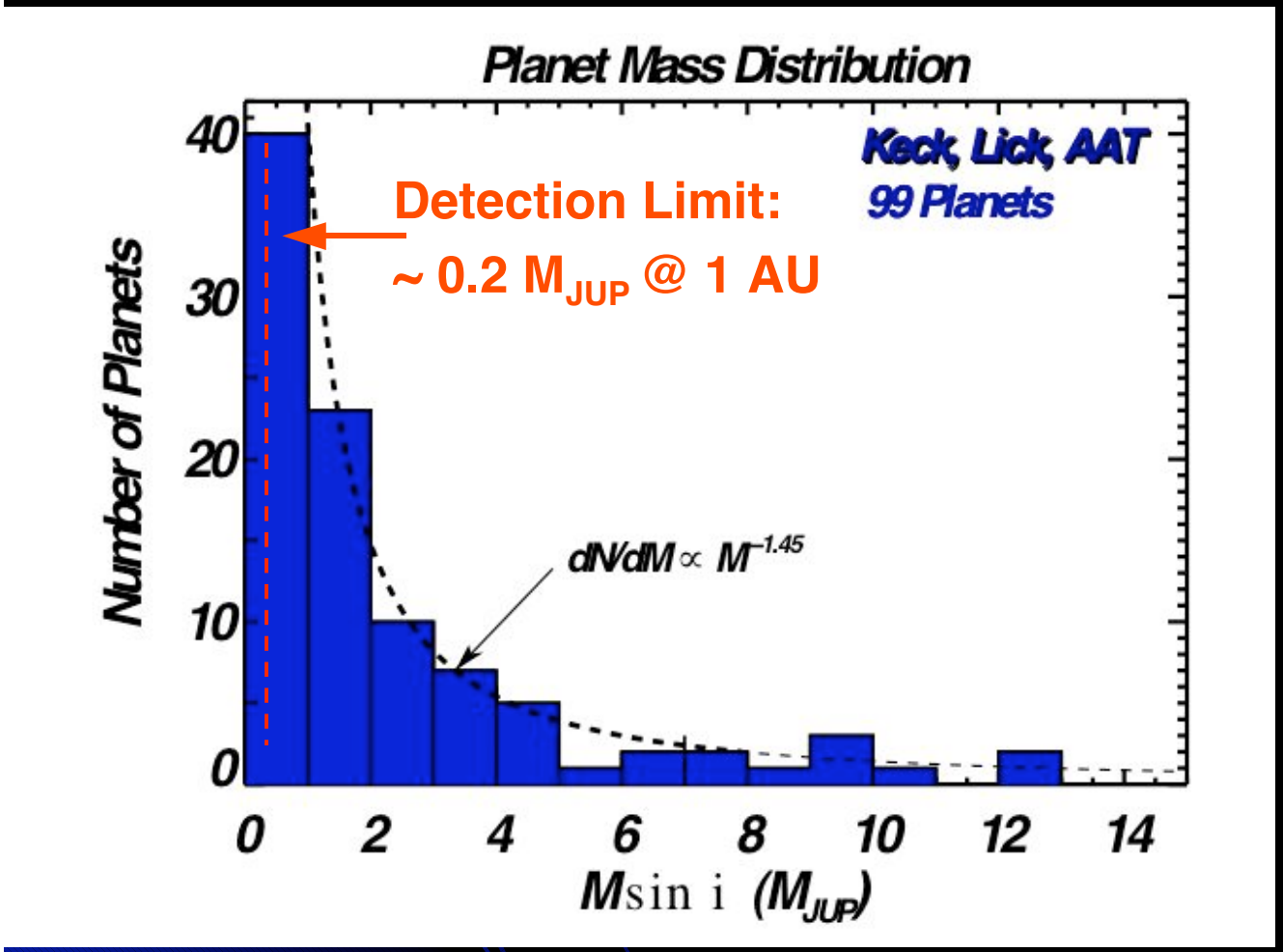
- **Proximity**
- **Hab. Zone**

Star Name | **Parallax** | **Sp-Type**

Team A/B	draft#	. Name	V mag	Parallax	Sp-Type				(")	Hab.Zone (AU)	. Lum	. Mass	Other-HZ	Ast.Pert. of Earth in HZ	Period of Earth in HZ
A	1	GI559A=alphaCen=HD128620	0.						17.19	1	1.77	1.07	1.33	9.26	1.4
									17.19	0.59	0.52	0.92	0.72	5.86	0.6
										0.74	0.53	0.92	0.73	2.17	0.6
														2.06	0.4
						F6	V---			1.6	3.44	1.17	1.85	1.97	2.3
		514				G0	V	71	11.95	1.2	1.47	1.05	1.21	1.95	1.3
		4614B				K7	V	71	11.95	0.34	0.03	0.66	0.19	0.48	0.1
B	6	GI551 = Prox. Cen = HIP70890	11.05		771.99	M5.5	V	10500	8105.90	0.1	0.00	0.30	0.01	0.21	0.0
A	7	GI768 = Altair = HD187642	0.77		194.97	A7	IV/V---			3.2	12.94	1.38	3.60	5.08	5.8
B	8	GI411 = Lalande 21185 = HD95735	7.47		393.42	M2	V---			0.2	0.01	0.53	0.08	0.60	0.0
A	9	GI881 = alpha PsA = HD216956	1.15		130.53	A3	V---			5.2	20.34	1.46	4.51	4.03	7.9
B	10	GI324A = 55 Cnc = HD75732	5.95		79.47	G8	V	1100	87.42	0.74	0.66	0.95	0.81	0.68	0.7
A	11	GJ 780 = del Pav = hd190248	3.56		163.73	G7	IV---			0.79	1.40	1.04	1.19	1.86	1.2
B	12	hr4277 = 47 UMa=HD95128	5.66		71.04	G1	V								
A	13	GI 19 = beta Hyi = HD 2151	2.8		133.86	G2	IV---			1	4.23	1.20	2.06	2.30	2.7
A	14	GI216A=gam Lep = HD38393	3.58		111.69	F6	V	860	96.05	1.6	2.96	1.15	1.72	1.68	2.1
B	15	GI699 = Barnard's Star = HIP87937	9.57		546.98	M4	V---			0.27	0.00	0.38	0.02	0.32	0.0
A	16	GI449 = beta Vir = HR4540 = HD102870	3.61		91.83	F9	V---			1.3	4.27	1.20	2.07	1.58	2.7
B	17	GI139 = hd20794 (AAT)	4.26		165.01	G8	V---			0.74	0.73	0.96	0.85	1.46	0.8
A	18	GI702 = 70 Oph A = HD165341	4.21		195.96	K0	V	23	4.51	0.65	0.54	0.93	0.73	1.56	0.6
A	18	GI702B = 70 Oph B	6.05		195.96	K5	V	23	4.51	0.39	0.10	0.75	0.31	0.82	0.2
B	19	GI820A = 61 Cyg A = HD201091	5.21		286.04	K5	V	86	24.60	0.39	0.10	0.75	0.32	1.21	0.2
B	19	GI820B = 61 Cyg B	6.03		286.04	K7	V	86	24.60	0.34	0.05	0.68	0.22	0.91	0.1
A	20	GI 166 = HD26965	4.43		199	K1	V	420	83.58	0.59	0.43	0.90	0.65	1.45	0.5
B	21	GI825 = hd202560 (AAT)	6.67		253.43	M0	V---			0.28	0.03	0.65	0.18	0.71	0.1
A	22	GI603 = gam Ser = HD142860	3.85		89.85	F6	V---			1.6	3.57	1.17	1.89	1.45	2.4
A	23	GI845A = eps Ind = HD209100	4.69		275.84	K5	V	1500	413.76	0.39	0.17	0.80	0.42	1.44	0.3
B	24	GJ777A = HD 190360 (Keck)	5.71		62.92	G6	IV								
A	25	GI225 = Eta Lep = HD40136	3.71		66.47	F1	V---			2.3	7.43	1.29	2.73	1.41	3.9
B	26	GI 380=HD88230 (Lick)	6.59		205.81	K7	V---			0.34	0.05	0.69	0.23	0.69	0.1
A	27	GI124 = iota Per = HD19373	4.05		94.86	G0	V---			1.2	2.67	1.13	1.63	1.37	1.9
B	28	GI 447 = HIP57548 (Keck)	11.13		298.72	M4	V---			0.13	0.00	0.37	0.02	0.16	0.0
A	29	GI17 = HD1581	4.22		116.47	F9	V---			1.3	1.51	1.05	1.23	1.36	1.3
B	30	GI 729 = HIP92403 (Keck)	10.43		336.9	M3.5	V---			0.15	0.00	0.39	0.02	0.21	0.0
A	31	GI475 = HR4785 = HD109358 (Keck)	4.27		119.19	G0	V---	B66		1.2	1.38	1.04	1.17	1.34	1.2
A	32	GI827 = gam Pav = HD203608	4.22		108.52	F6	V---			1.6	1.74	1.07	1.32	1.34	1.4
B	33	GI 15A = HD1326A	8.08		280.59	M1.5	V	150	42.09	0.24	0.01	0.54	0.09	0.45	0.0
B	33	GI 15B = HD1326B	11.06		280.59	M3.5	V	150	42.09	0.13	0.00	0.38	0.02	0.16	0.0
A	34	GI107A = HD 16895	4.13		88.85	F7	V	250	22.21	1.5	2.82	1.14	1.68	1.31	2.0

Done

Radial Velocity Planet Searches



15 - 20 M_{earth}

- **Gl 436**
- **55 Cnc d**
- **μ Ara**

RV Limitations:

- **Only a < 0.1 AU**
- **M > 10 M_{earth}**

(Butler et al. McArthur et al., Santos et al.)

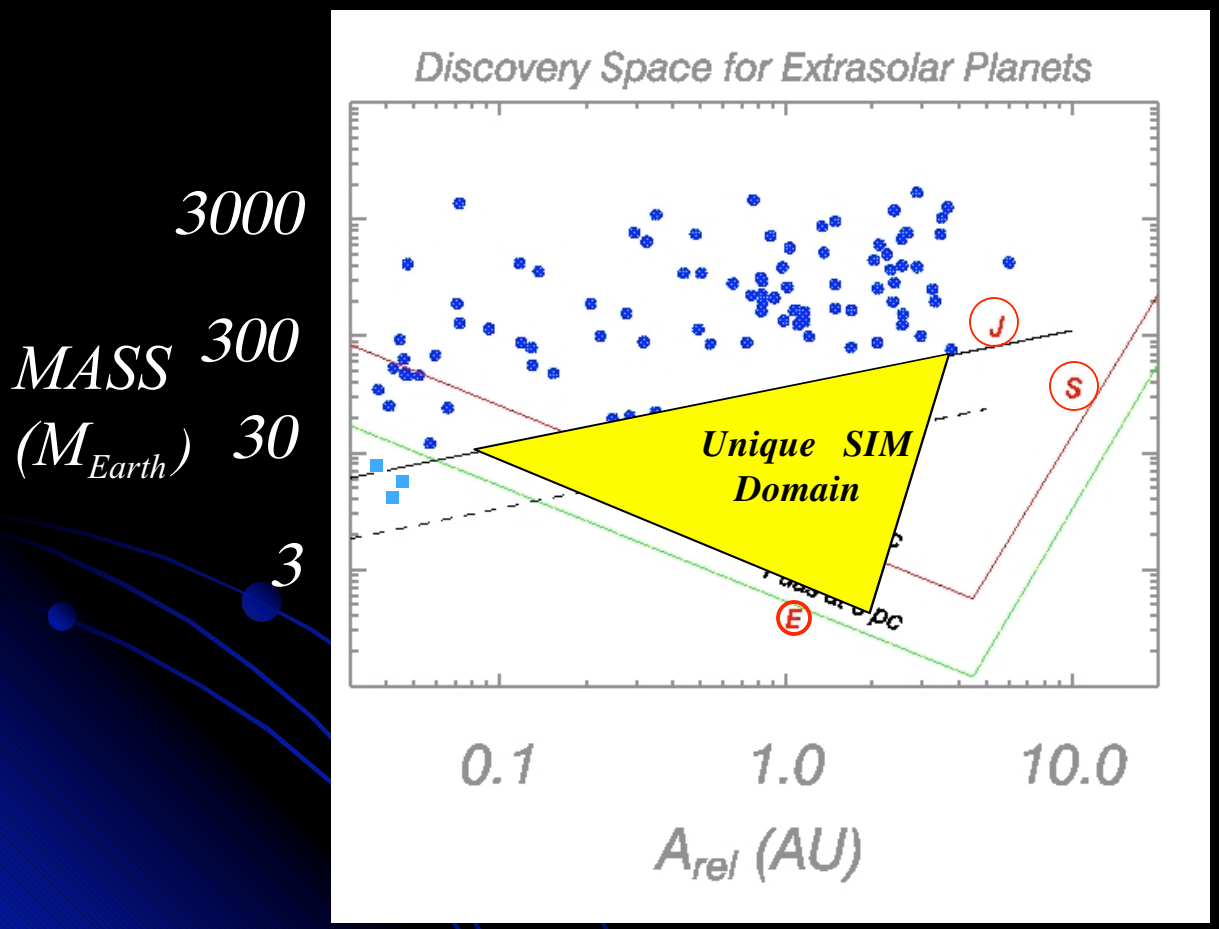
Can RV Detect
Rocky Planets at 1 AU ?

Benchmark: 1 Earth Mass at 1 AU.

RV Amplitude: K = 0.09 m/s
RV Errors: σ = 1.0 m/s

$$S/N \sim K / \sigma \sim 0.1$$

Nominal SIM Discovery Space:



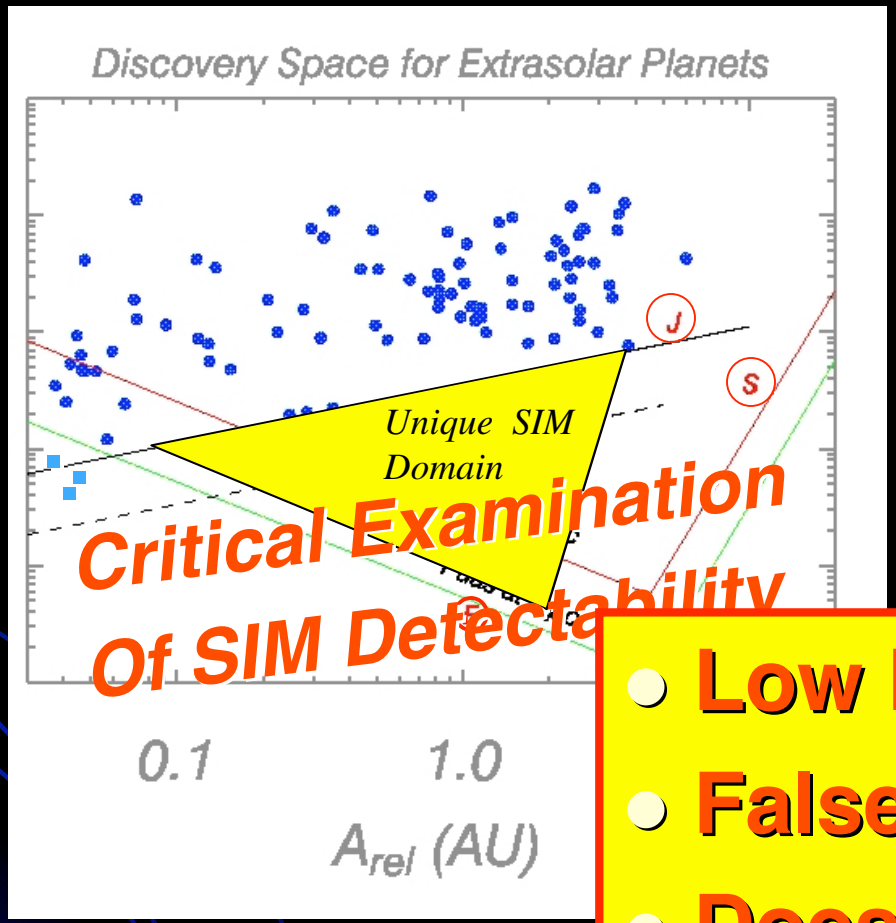
Unique SIM Domain:

3 - 30 M_{EARTH}

Near Habitable Zones

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

Nominal SIM Discovery Space:



Unique SIM Domain:

3 - 30 M_{EARTH}

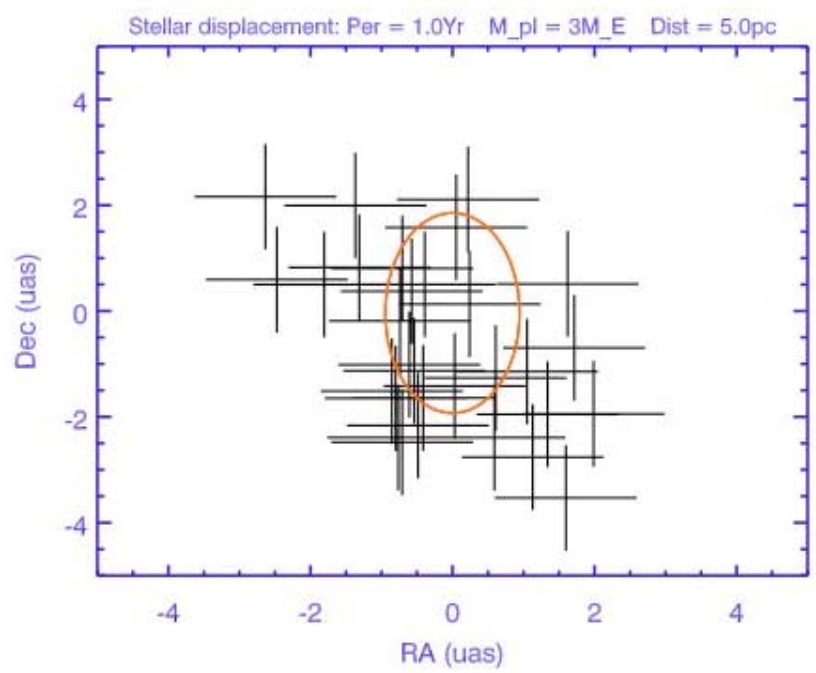
Near Habitable Zones

Critical Examination Of SIM Detectability

- **Low Mass Thresh ?**
- **False Alarms ?**
- **Does SIM Help TPF ?**

SIMULATION: Nominal SIM Limit:

3 M_{earth} @ 1 AU (d = 5 pc)



- Wobble > 1 μas
- Overkill:
  Temporal Coherence

Proper FAP Assessment:

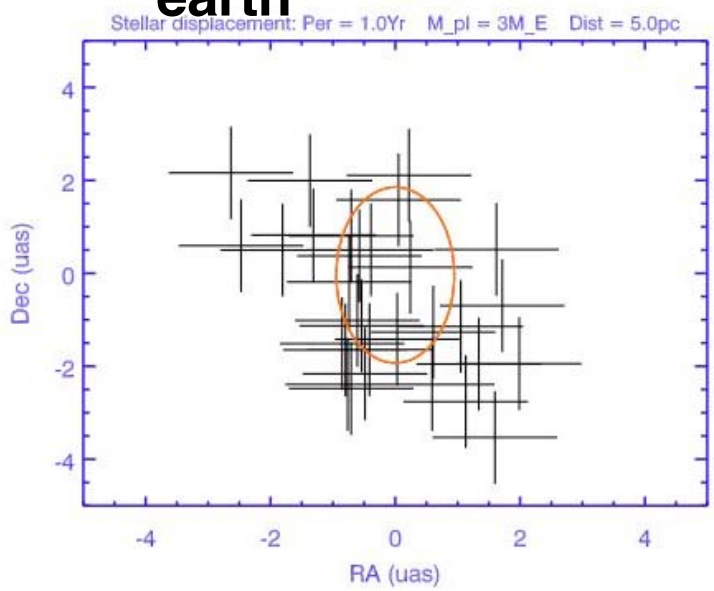
- Fit Orbit
- Chi-Square
- F-Test or Monte Carlo
  (Prob. of Chisq that low
  from noise fluctuations)

FAP Assessment:

Periodogram Surrogate

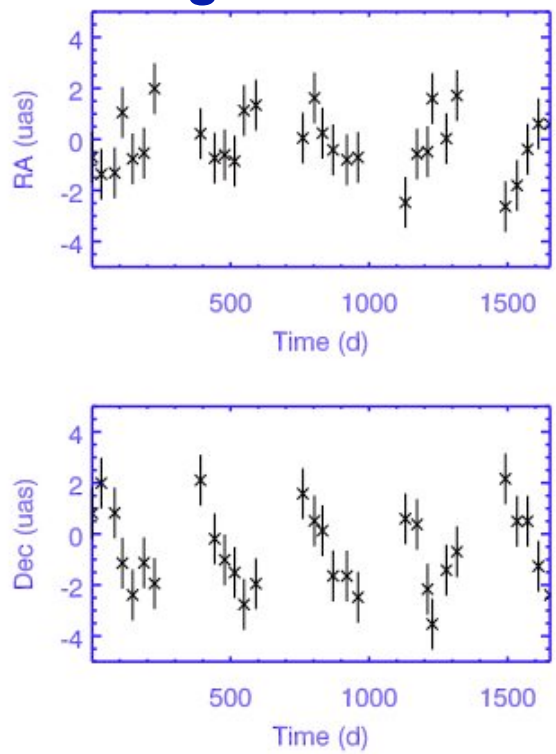
(for $P < T_{TimeSeries}$)

3 M_{earth} @ 1 AU

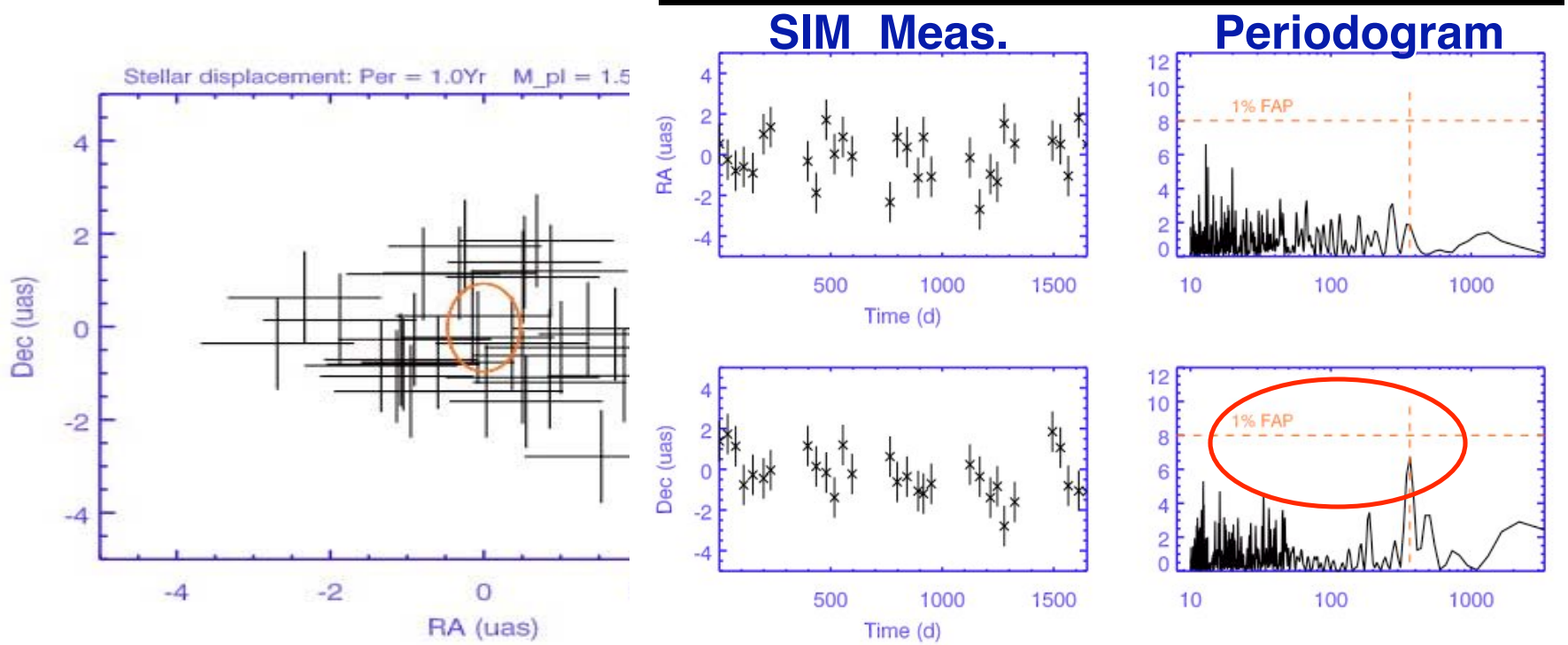


I = 60 deg

Orthogonal SIM Meas.



1.5 Mearth @ 1 AU (d = 5 pc)

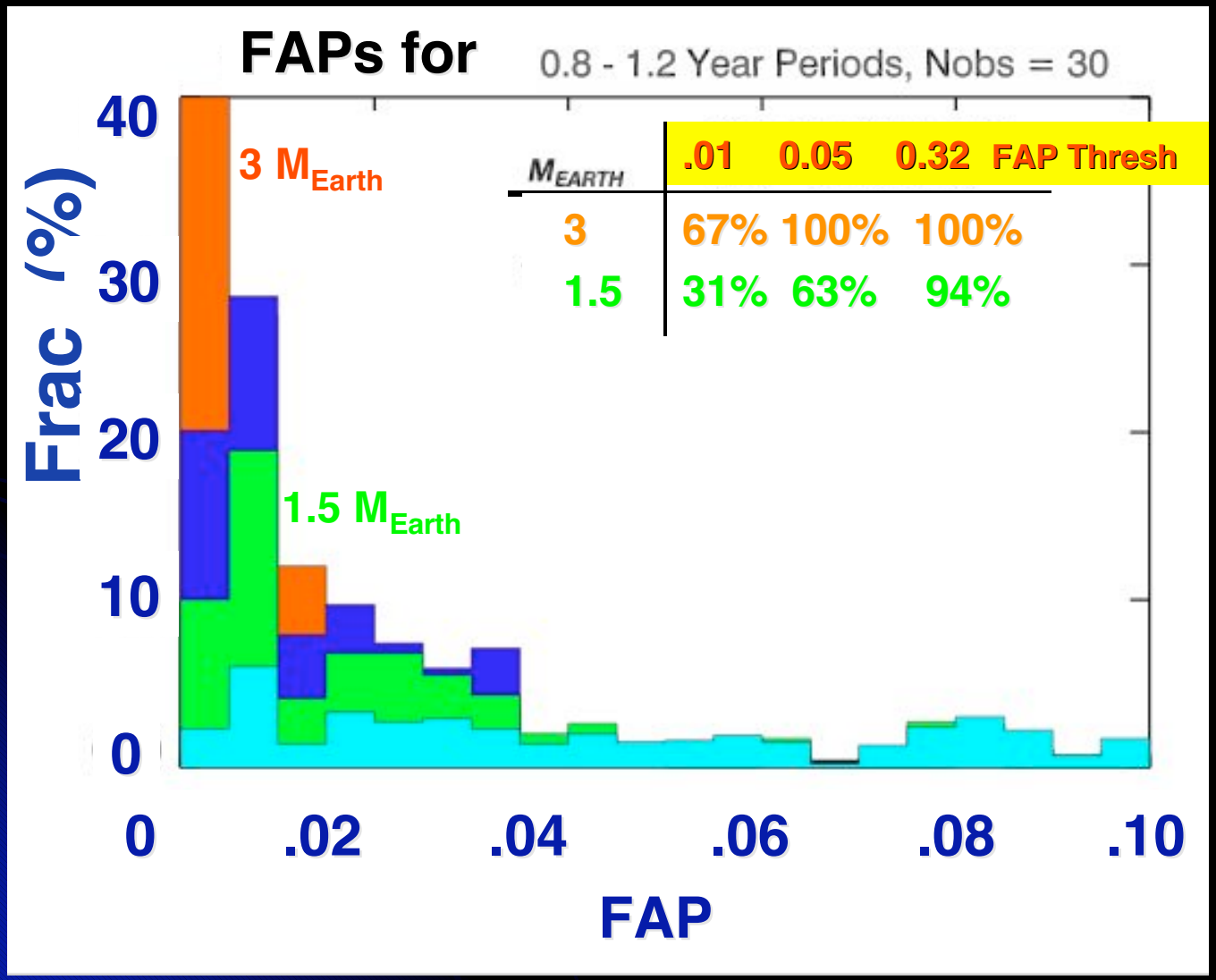


Marginal Detection: FAP = 3%

Fraction Meeting FAP Thresh

for Different Planet Masses

(a =1 AU, d = 5 pc)

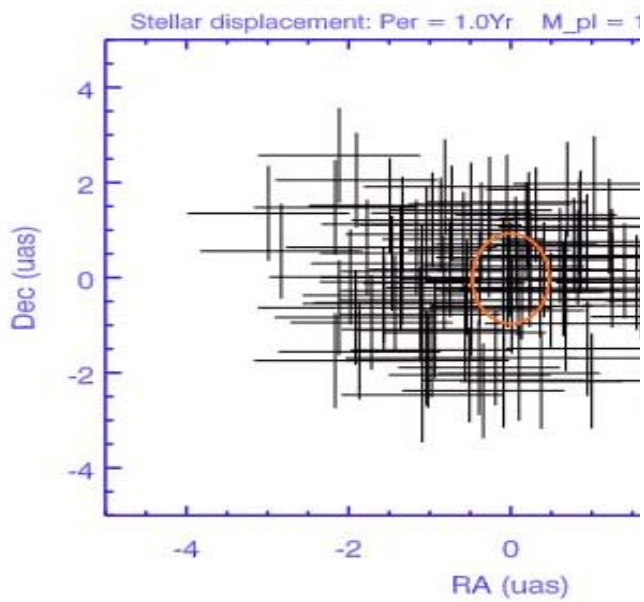


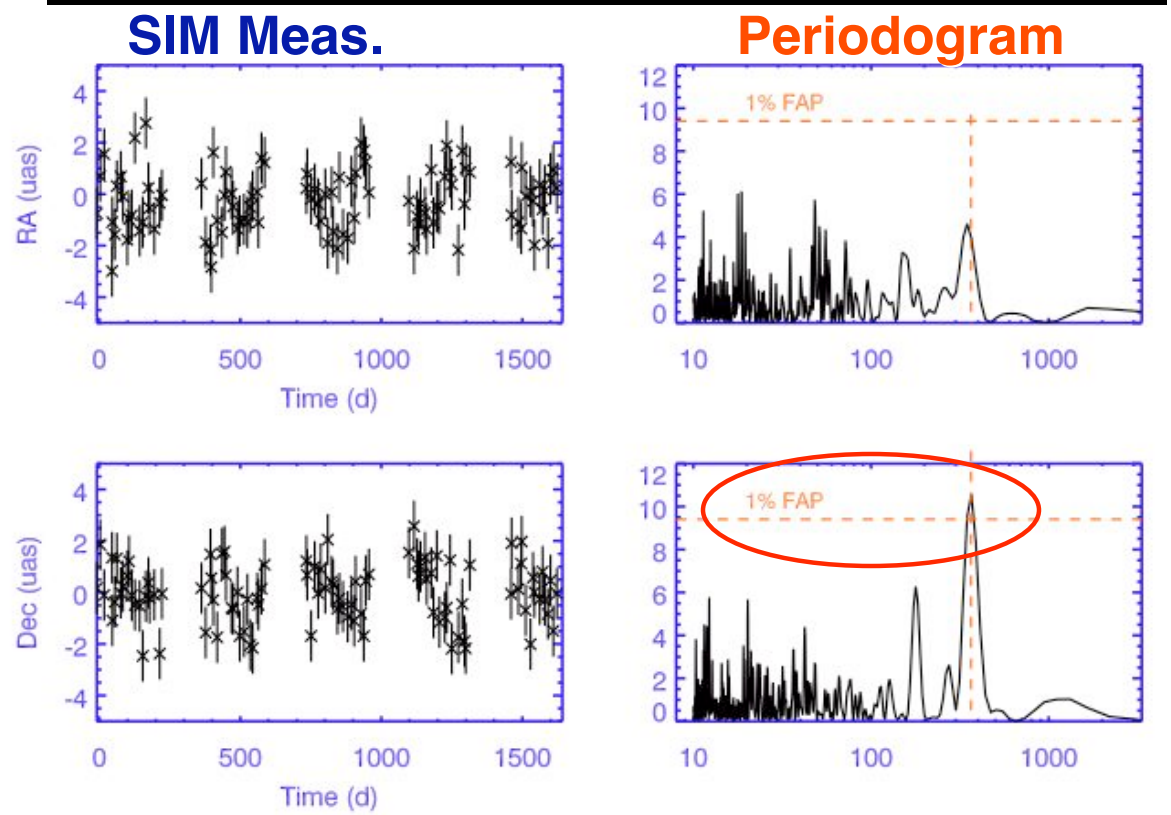
M_{EARTH}	.01	0.05	0.32 FAP Thresh
3	67%	100%	100%
1.5	31%	63%	94%

Highest Priority Stars

1.5 M_{earth} @ 1 AU

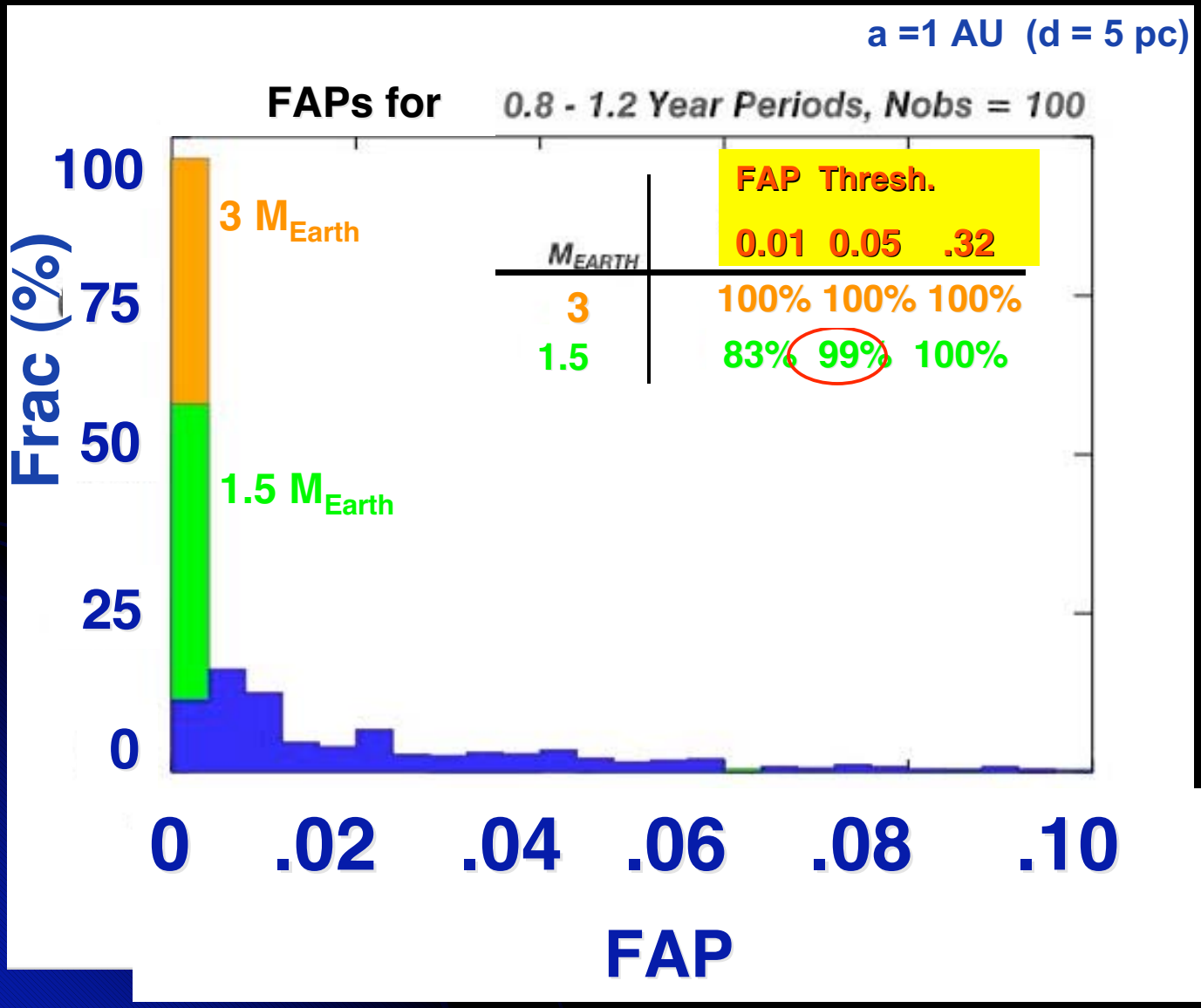
100 SIM Observations





Fraction Meeting FAP Threshold

100 SIM Observations



M_{EARTH}	FAP Thresh. 0.01	0.05	.32
3	100%	100%	100%
1.5	83%	99%	100%

Fraction Meeting FAP Thresh.

N = 30 2-D SIM Obs.

FAP Thresh.	0.01	0.05	0.32
3 M_{Earth}	99	100	100
1.5 M_{earth}	31	63	94
1 M_{earth}	9	27	71

N = 100 2-D SIM Obs.

FAP Thresh.	0.01	0.05	0.32
3 M_{Earth}	100	100	100
1.5 M_{earth}	83	99	100
1 M_{earth}	49	85	98

1 AU,
5 pc

Enhancing TPF Stellar Sample

- $\text{Eta}_{\text{Earth}}$ = Fraction of Stars with Earth-mass in HZ
- Enrichment Factor:

$$\frac{\text{Frac}_{\text{FAP}}}{(1\text{-Eta})\ \text{Thresh}_{\text{FAP}} + \text{Eta}\ \ \text{Frac}_{\text{FAP}}}$$

Frac_{FAP} is Frac FAP < $\text{Thresh}_{\text{FAP}}$

For Eta ~ 0.1, Enrichment Factor = 3

Instead of 10% of TPF sample, 30% of sample has earths.

Eta_{Earth}: TPF vs SIM

Two Eta_{Earth} Cases:

- $Eta_{Earth} < 0.1$: "SIM won't find many 5-σ planets"

  Reply: If so, TPF-C with ~30 targets won't either!
  TPF needs SIM to enrich stellar sample with earths.

- $Eta_{Earth} > 0.2$: then TPF doesn't "need" SIM.

  Reply: SIM will find many rocky planets.
  Bonanza of information on rocky planets.
  - dN/dM, Relation to star mass & Metallicity
  - Orbital radius, eccentricity

SIM is *the* Terrestrial Planet Finder.

TPF *characterizes* planets.

Conclude:

SIM Offers

- Astrophysics of rocky planets as valuable as TPF:
  - Masses & Mass Distribution
  - Orbital radii
  - Eccentricities
  - Correlation with Stellar Mass & Metallicity

- Enhancement and Security to TPF:
  If SIM doesn't fly, TPF is vulnerable to criticism of inadequate reconnaissance and possible failure.

- Require:
  - $N_{OBS} \sim 30$ -100 to detect 1 M_{EARTH}
  - 8 Ref. Stars per Target: Ensure 1 μas

The End

Extra Slides follow . . .

Culling K Giants @ 0.5 - 1 kpc

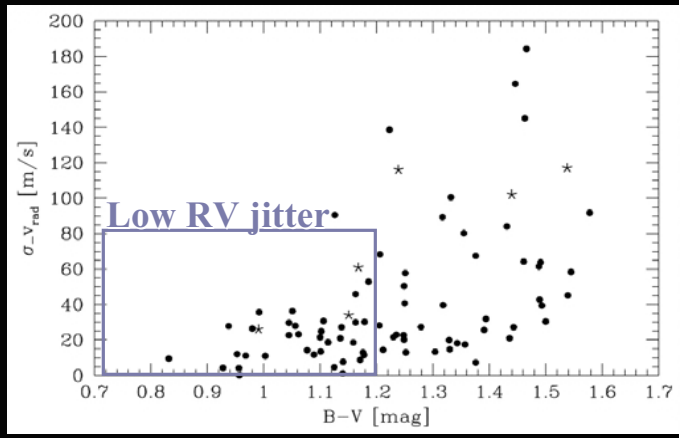
- Distinguish Giants from Dwarfs: Reduced Proper Motion Diagram

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)

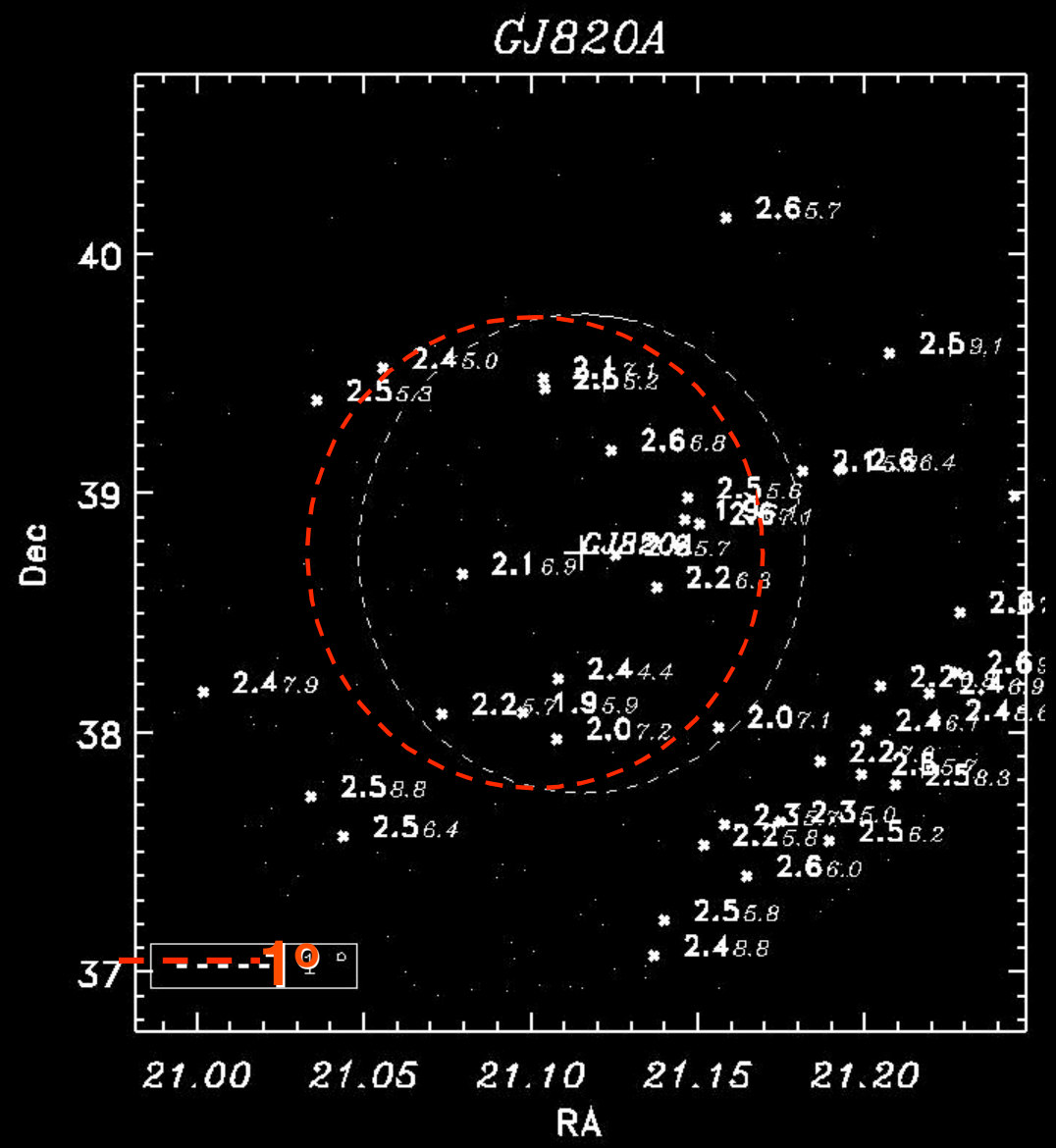
Two Types of Contamination:

- 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



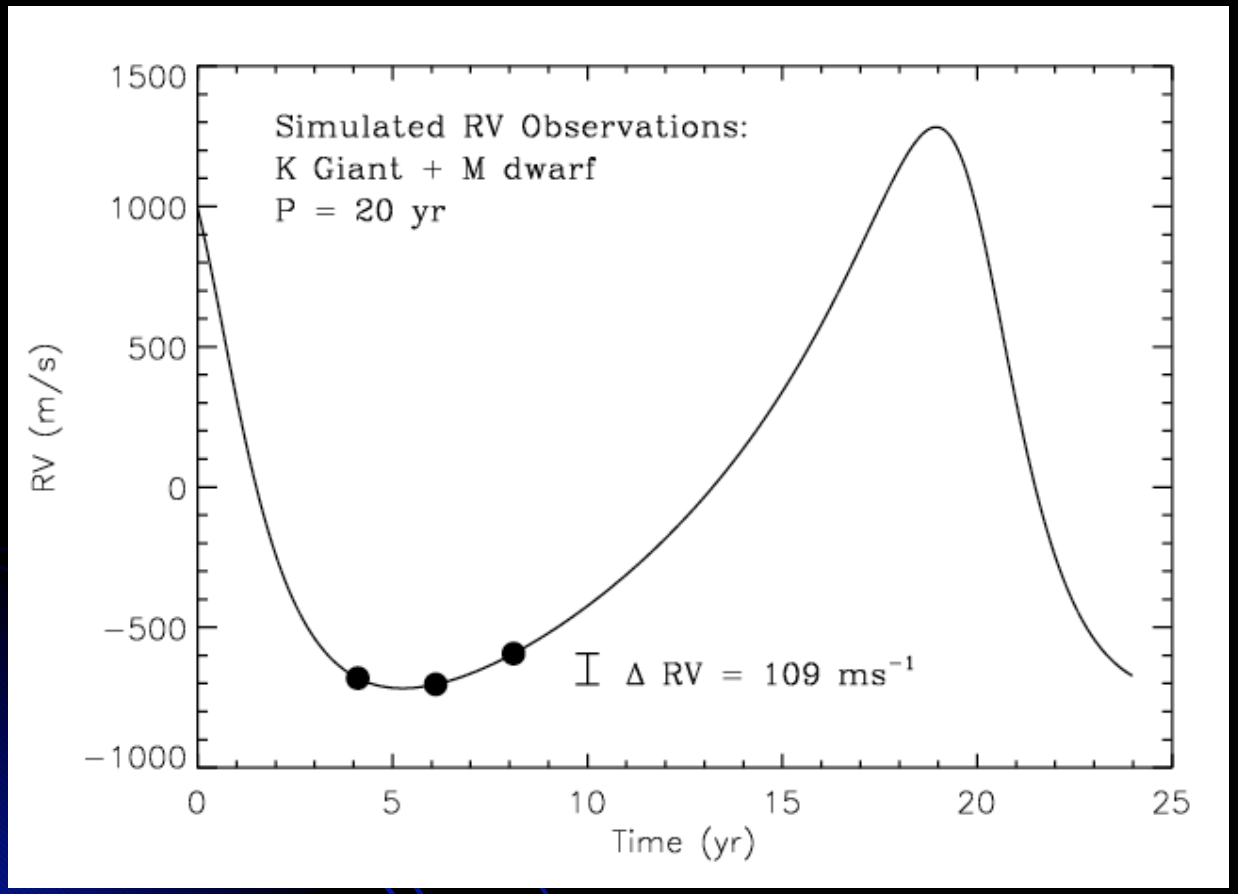
Exp. Error

- Photons
- Angle sep.
- Planet jitter

Failure Prob.

RV Vetting of Reference Stars:

Typical M Dwarf Companion

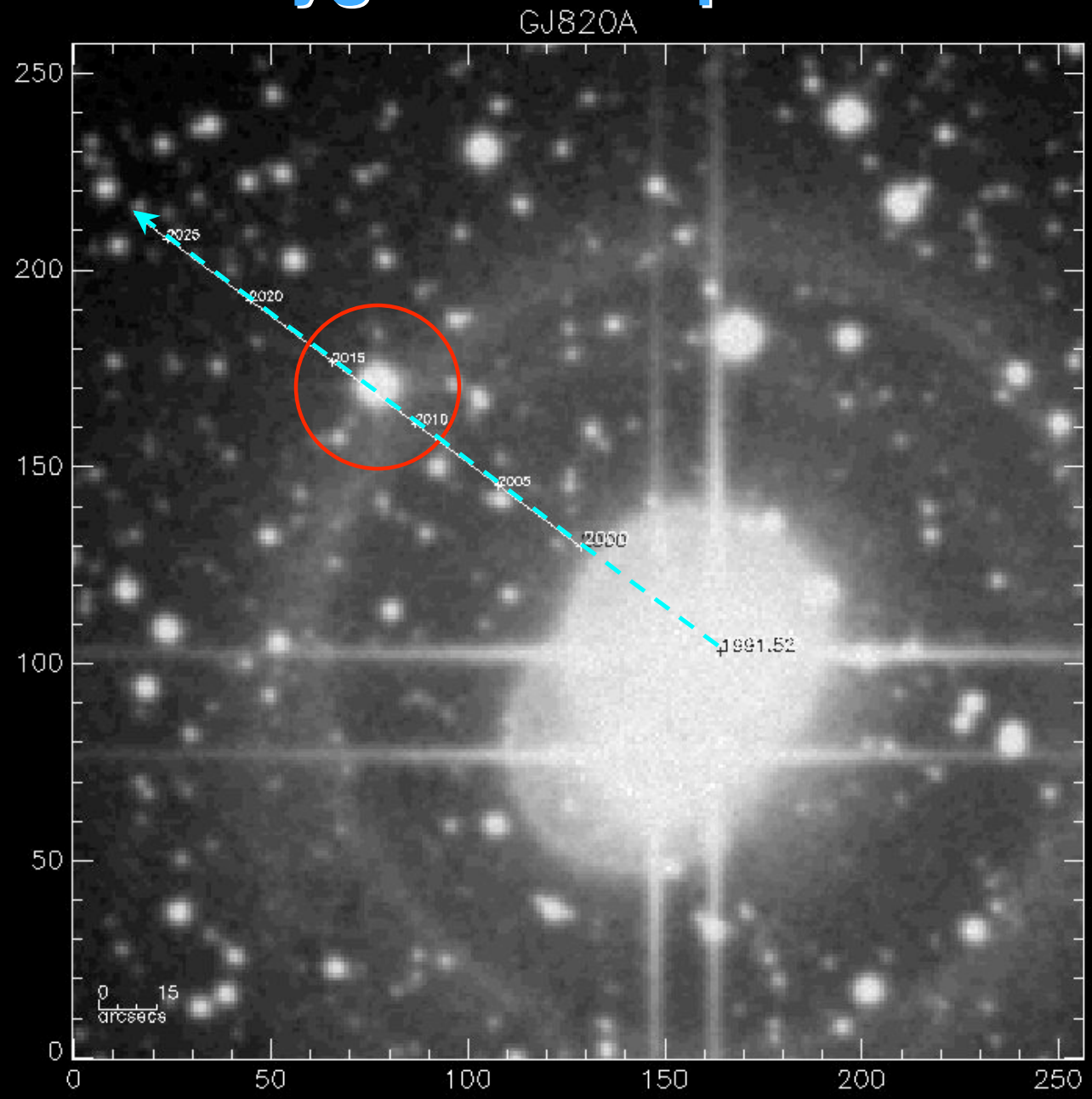


Elim. Companions:

25 m/s RV Precision

Planets around K giants get through

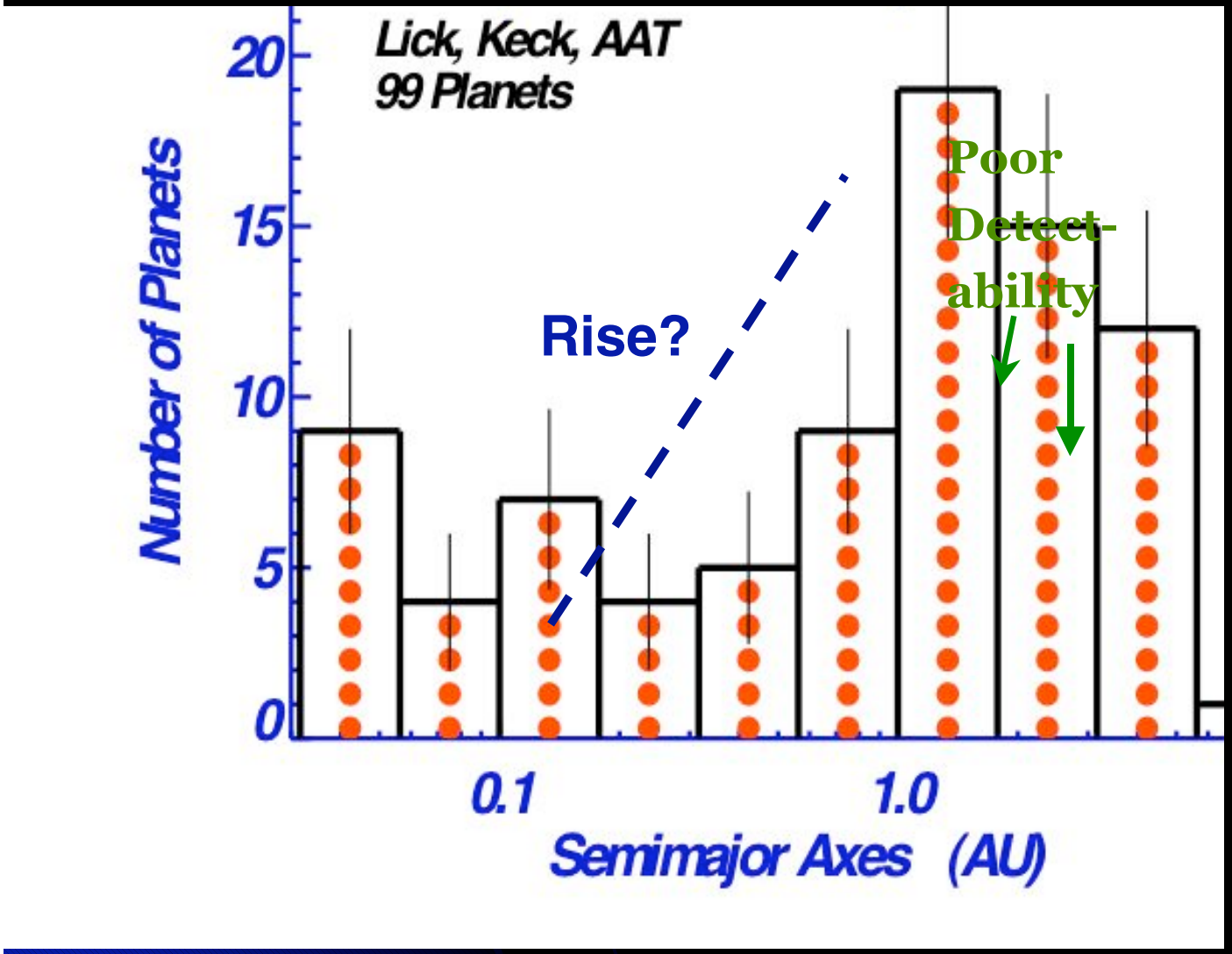
61 Cygni A: Proper Motion



Nuisance Stars

Fringe Contamination if within 2 arcsec

Doppler Survey of 1330 Nearby Sun-like Stars



Extrapolation:

6% of stars have giant planets beyond 3 AU

Model:

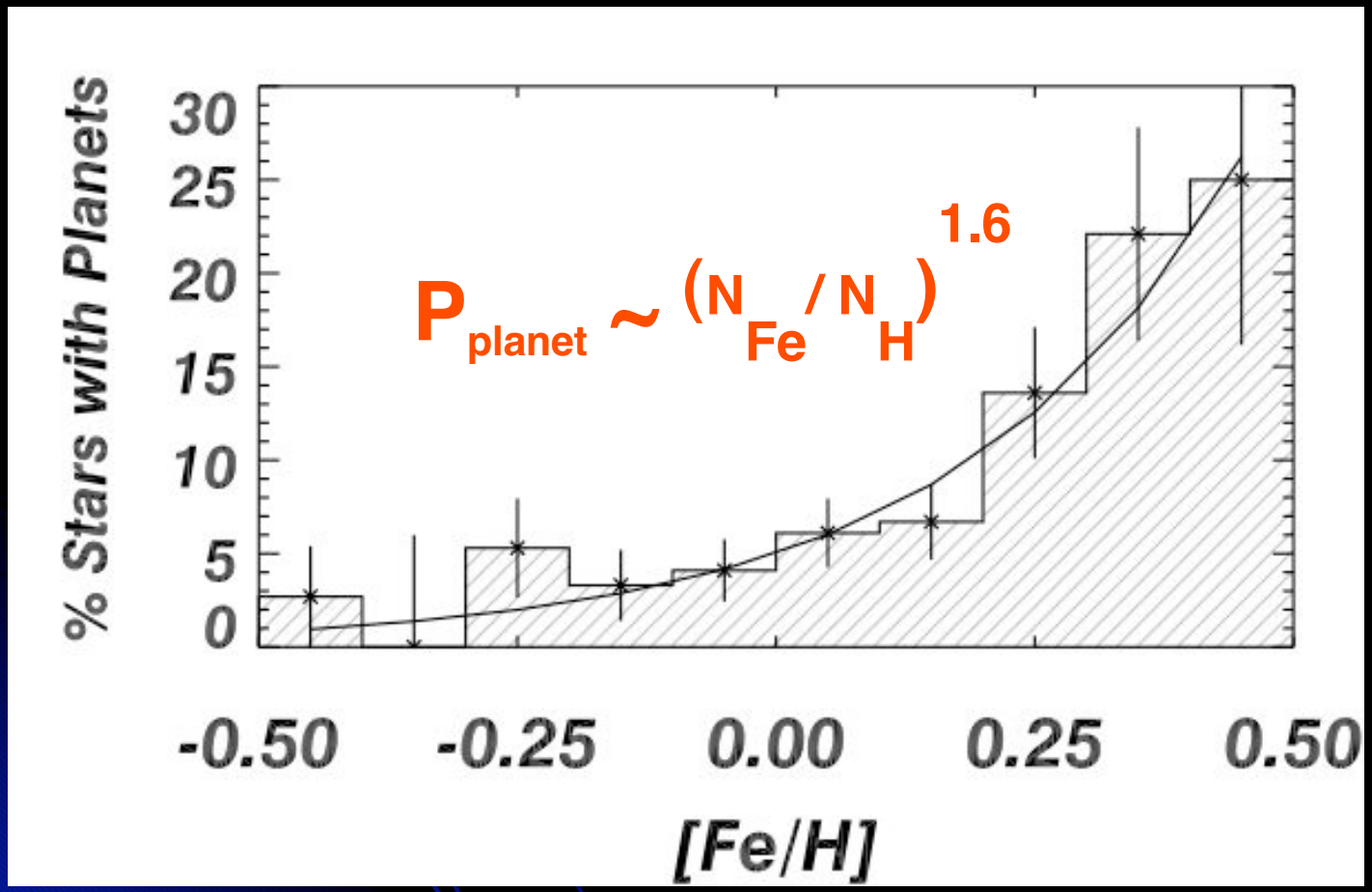
Inward Migration:

Planets left behind as disk vanishes

Armitage, Livio, Lubow, Pringle et al. 2002

Trilling, Benz, Lunine 2002

Planet – Metallicity Correlation



Abundance Analysis of *all* 1000 stars: *Spectral Synthesis*

→ **Fe/H**

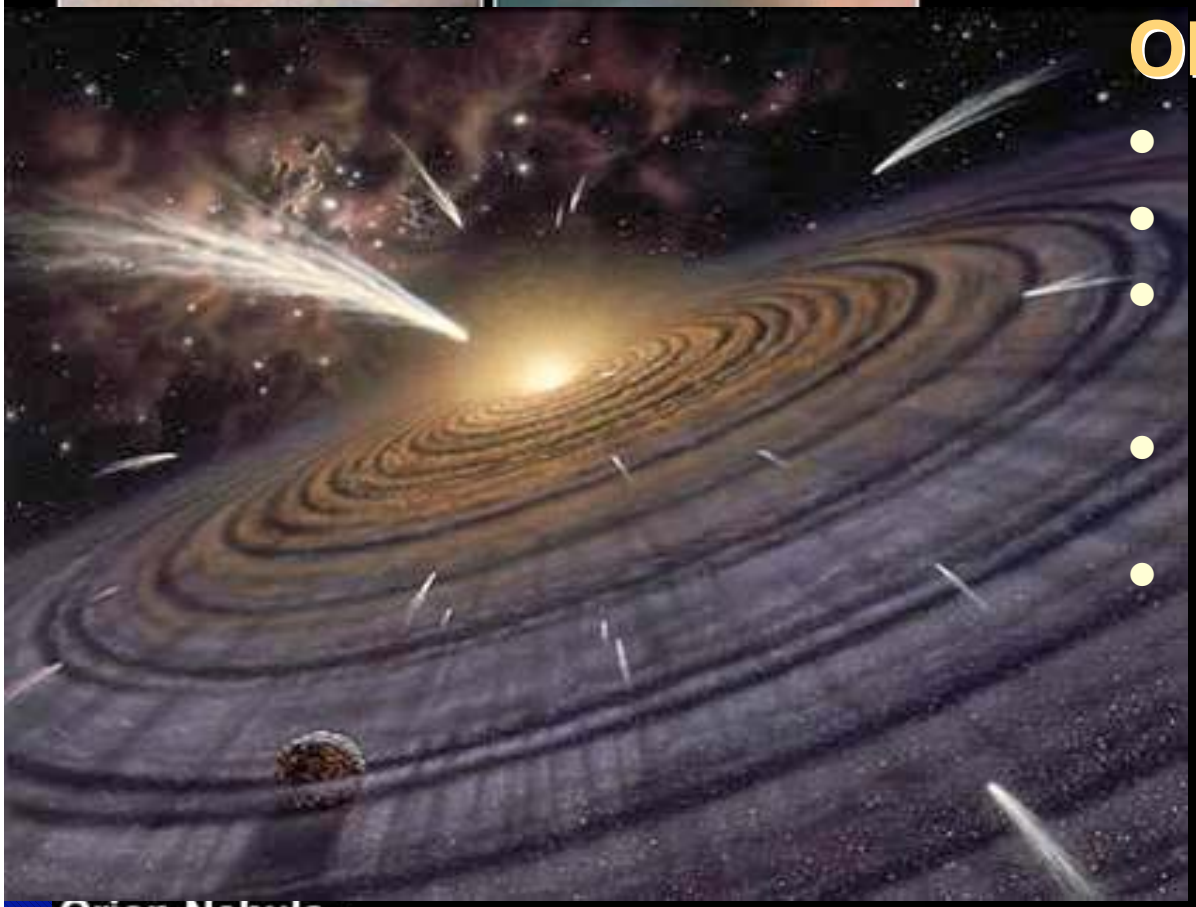
Valenti & Fischer 2005

Fischer & Valenti 2005

Formation of Planetary Systems:

The Solar System Paradigm

Models of
Protoplanetary Disks of Gas & Dust



Orion Nebula

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

Observations

- mm-wave dust emission
- IR Excess/Spectra & SEDs
- HST Imaging
- ➔ $M_{DISK} = 10\text{-}100\ M_{JUP}$ ➔
- Disk Lifetime ~ 3 Myr

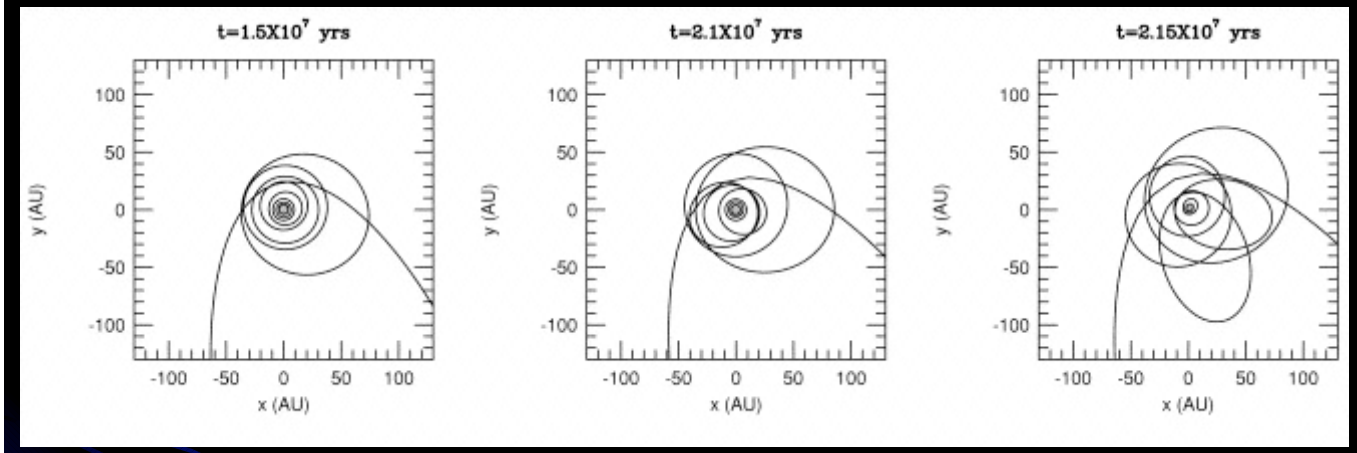
Theoretical Planet Formation:

- Dust Growth
  - pebbles/rocks
- Grav. Runaway
- Gas Accretion

Migration & Interactions

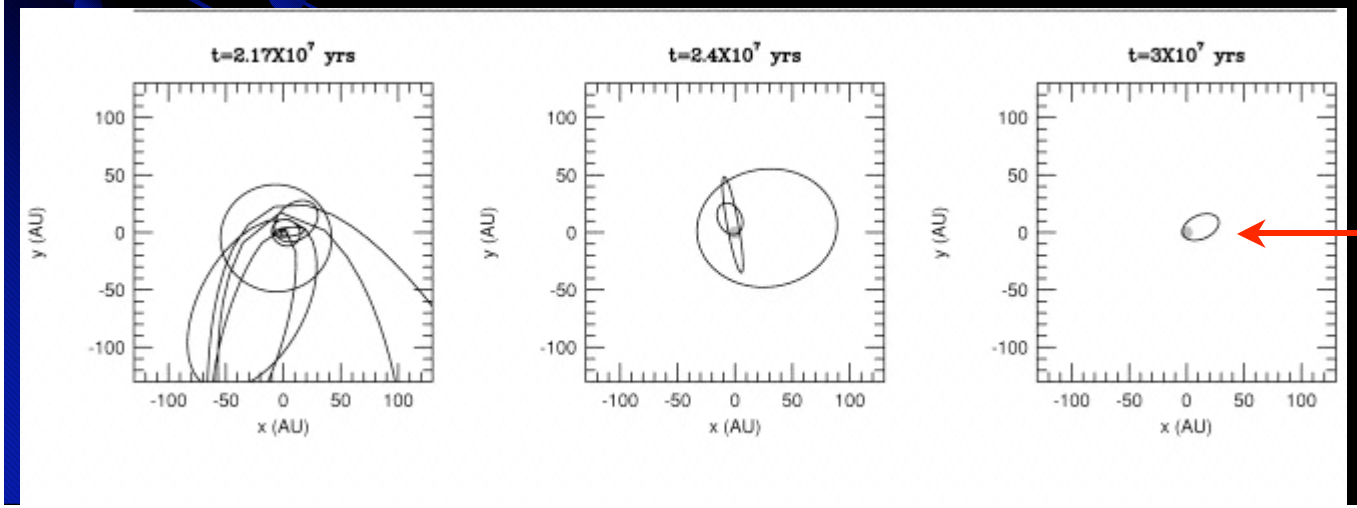
Multi-Planet Interactions (Levison, Lissauer, Duncan1998)

- 100 Planet "Embryos" (~M_{Earth})
- Scatter, Collide, Stick,
- Accrete Gas



After 21.5 Myr

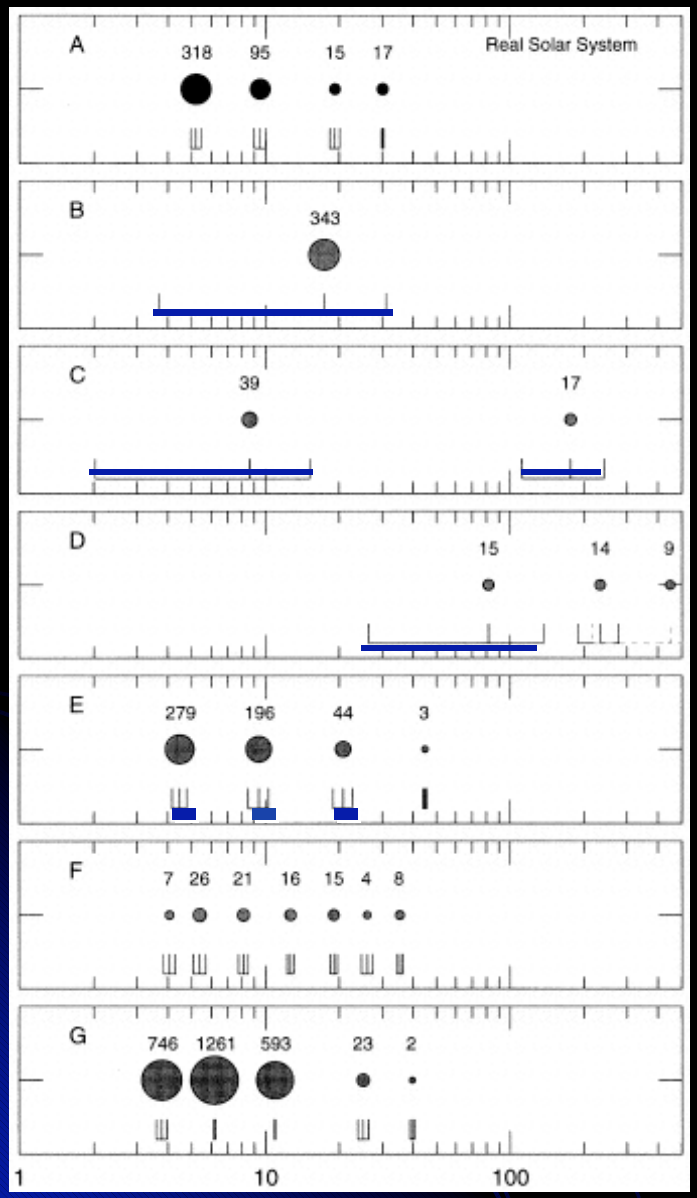
Chaos



After 30 Myr

Lone Close-in, Jupiter in Eccentric Orbit.

Monte Carlo Examples of Planetary Systems.



AU

- **Size → Planet mass**

  (in M_{earth}) above each planet.

Peri - Apo of orbit

Rocky Planets will Outnumber jupiters.

Levison, Lissauer, Duncan 1998

Low-Precision Planet Search

- 400 AFGKM stars at 10-30 pc
  - SIM precision: 4 μas
  - Use "SIM GRID" (not nearby Ref Stars)
  - Doppler Recon. at 1 m/s

    ==> Jupiters and Saturns within 5 AU

4 μas @ 30 pc reveals:

30 M_{earth} at 1 AU

SIM Synergy with *TPF*

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

Definite targets: SIM finds rocky planets
- in the habitable zone

Potential targets: 2-σ SIM earths
Enrich TPF targets

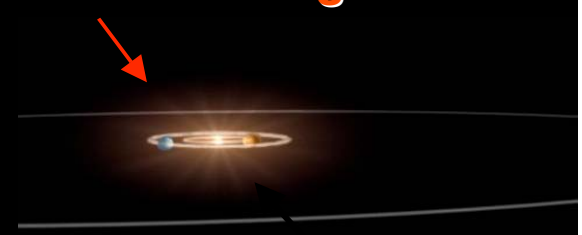
Avoid targets: SIM finds a giant planet in
- the habitable zone

TPF Timing:

Catch planets when they are 4 λ/d = 65 mas

from star.

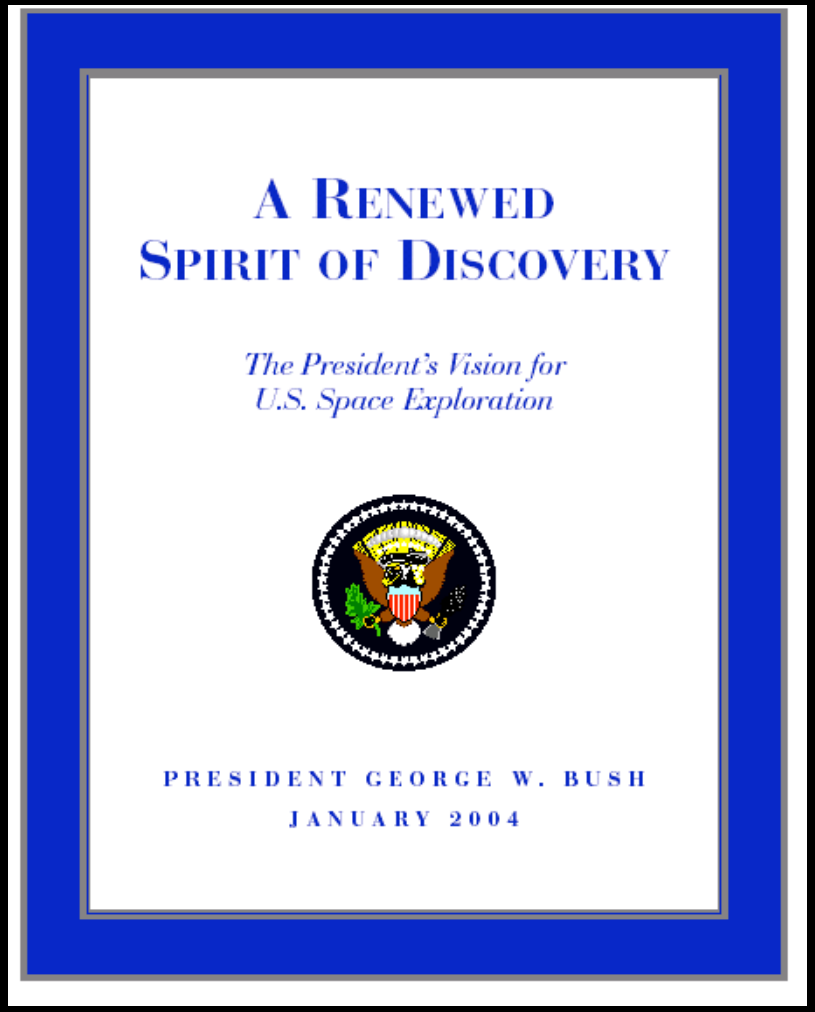
Inner Working Distance



- Focus on manned mission to Moon and Mars, robotic exploration of solar system, and search for life around other stars

- Among 20 goals the President set for NASA is the following:
  - *"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"*

- International participation --- *"This is not a race ..."*


A RENEWED SPIRIT OF DISCOVERY

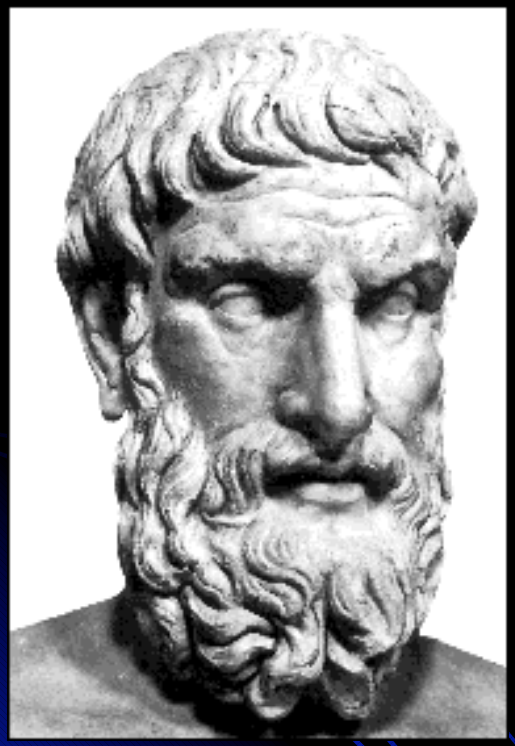
The President's Vision for U.S. Space Exploration

PRESIDENT GEORGE W. BUSH

JANUARY 2004

Epicurus (341-270 B.C.)

Greek philosopher in Athens where he opened a school of philosophy



"There are infinite worlds both like and unlike this world of ours ... we must believe that in all worlds there are living creatures and plants and other things we see in this world..."

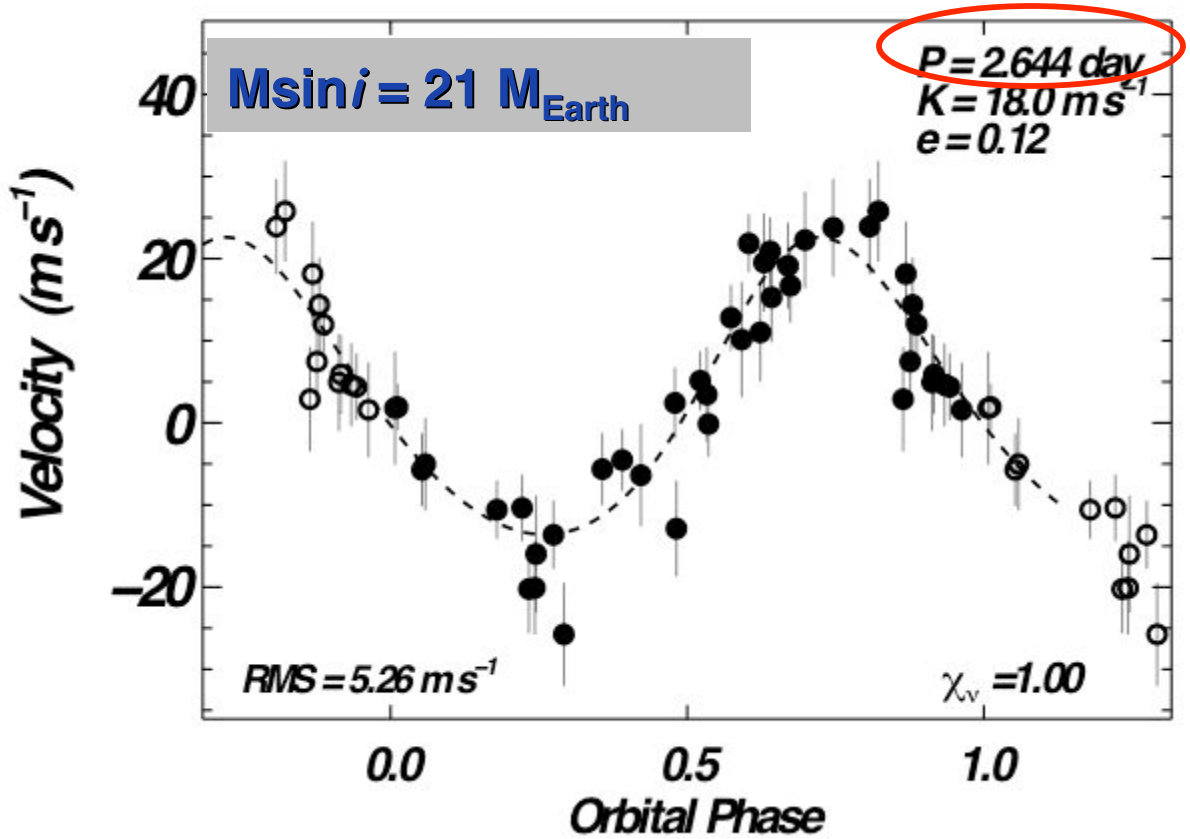
Democritus:

Pre-Socratic Greek philosopher

(460 - 370 BC).

" *There are innumerable worlds of different sizes.* These worlds are at irregular distances, more in one direction and less in another, and some are flourishing, others declining. Here they come into being, there they die, and they are destroyed by collision with one another. Some of the worlds have no animal or vegetable life nor any water. "

Gliese 436:
Velocity vs. Phase



M ~ 21 M_{Earth}

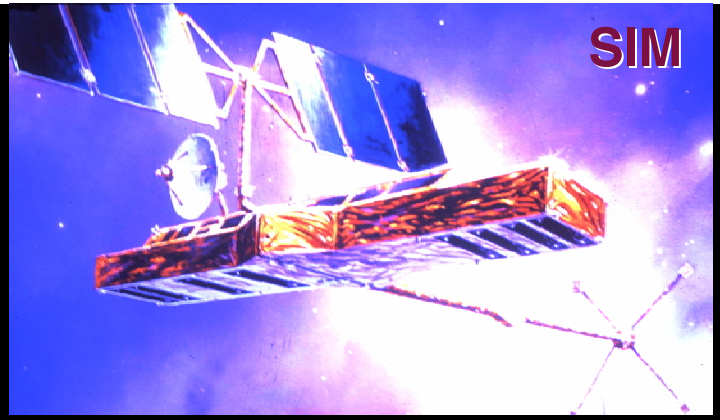
a = 0.03 AU

K ~ M_{pl} / $a^{1/2}$

3 Mearth at 1 AU

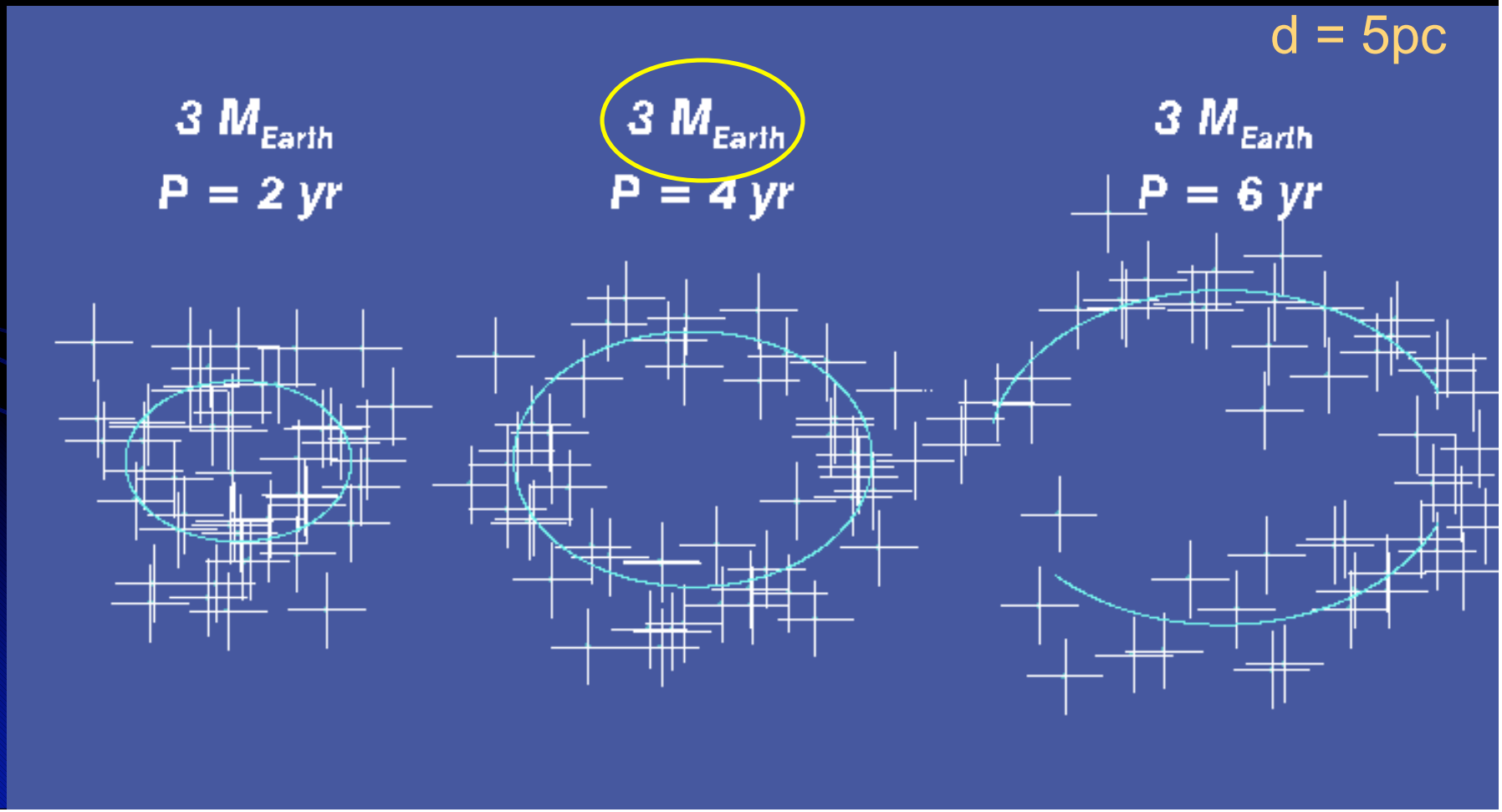
K = 10 cm/s

At 1 AU, RV can detect



SIM: 3 Earth-Mass Planets

precision 1 μas



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