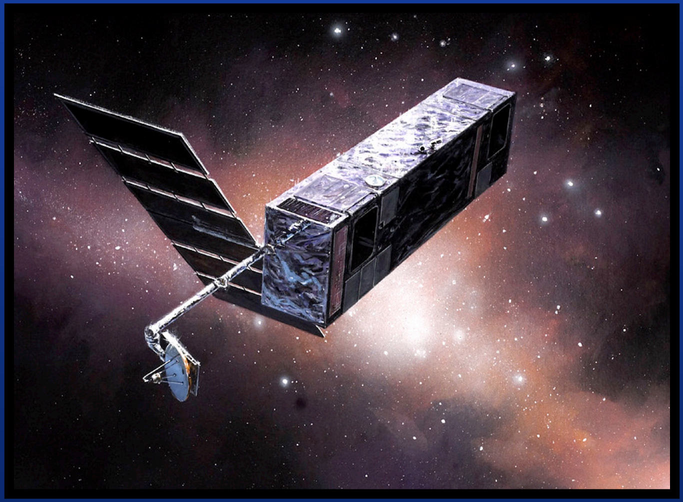
A SIM Key Project

Detecting Habitable Planets around Nearby Sun-Like Stars



Geoff Marcy, Mike Shao, Shri Kulkarni, Debra Fischer
Chas Beichman, Jim Marr
Renaud Goullioud, Raul Romero, Keith Warfield,
Charles Baker, Rebecca Wheeler,
Matthew Muterspaugh, Stuart Shaklan,

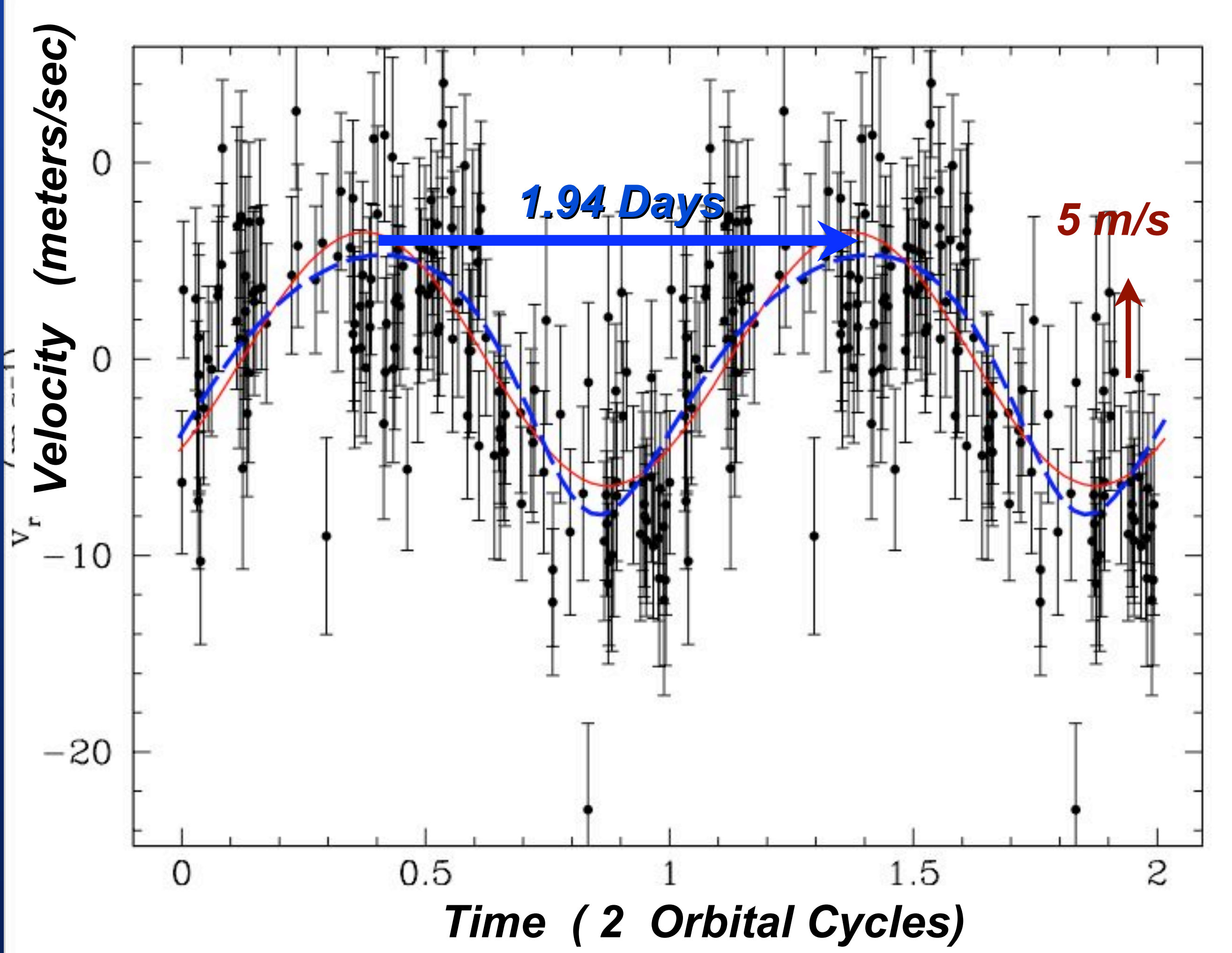
Outline

1. How known Exoplanets Inform SIM
2. SIM Search for Earth-like Planets:
3. Puzzles about other Earths

Gliese 876 d

$7.5 \ M_{Earth}$

Among Lowest Mass RV Exoplanet

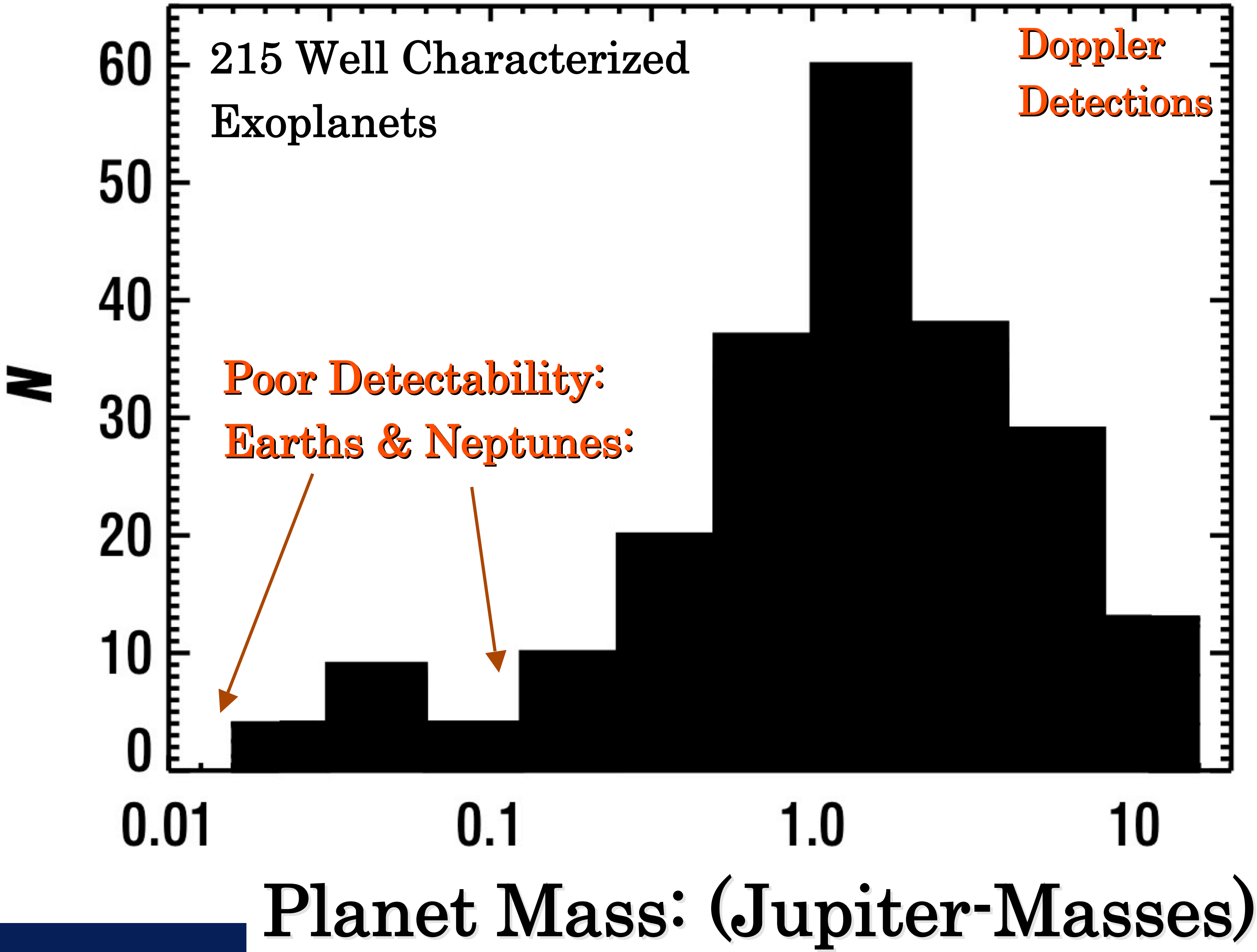


Messages:

Lower Planet Masses Detectable . . .

a) With difficulty
b) Within 0.1 AU

Exoplanet Mass Distribution



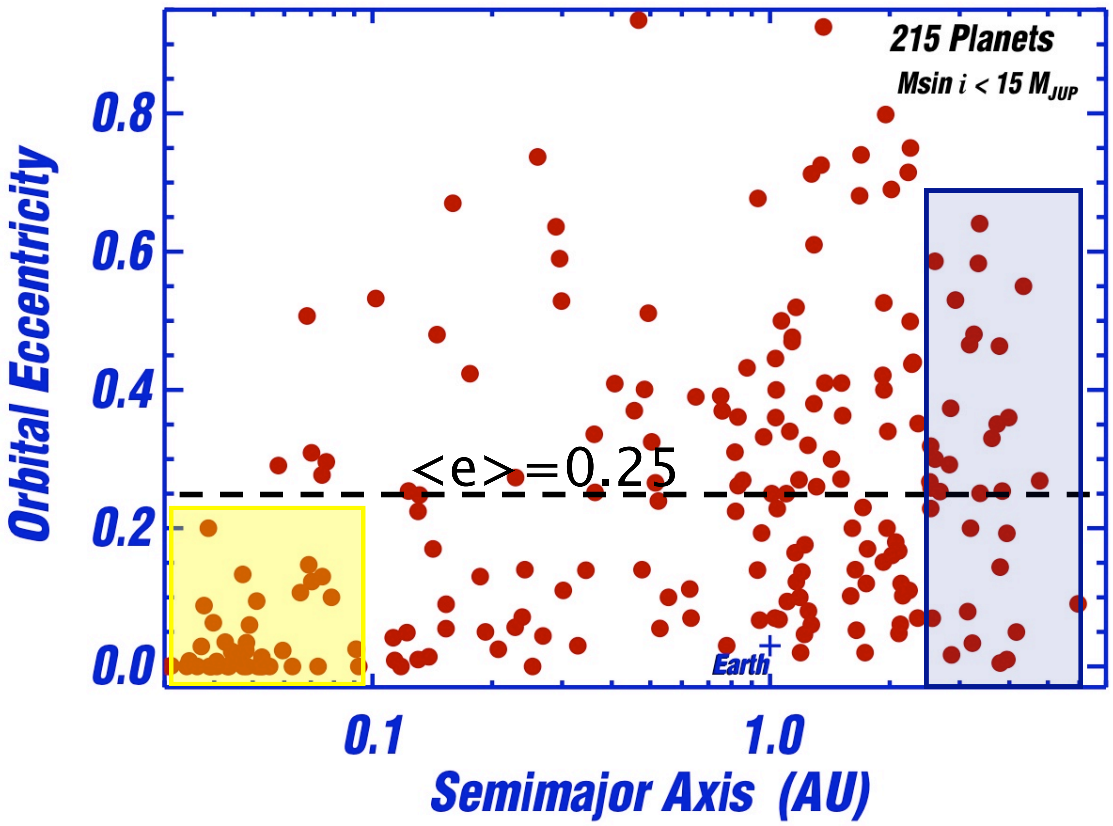
215 Well Characterized Exoplanets

Doppler Detections

Poor Detectability: Earths & Neptunes:

Planet Mass: (Jupiter-Masses)

Orbital Eccentricities



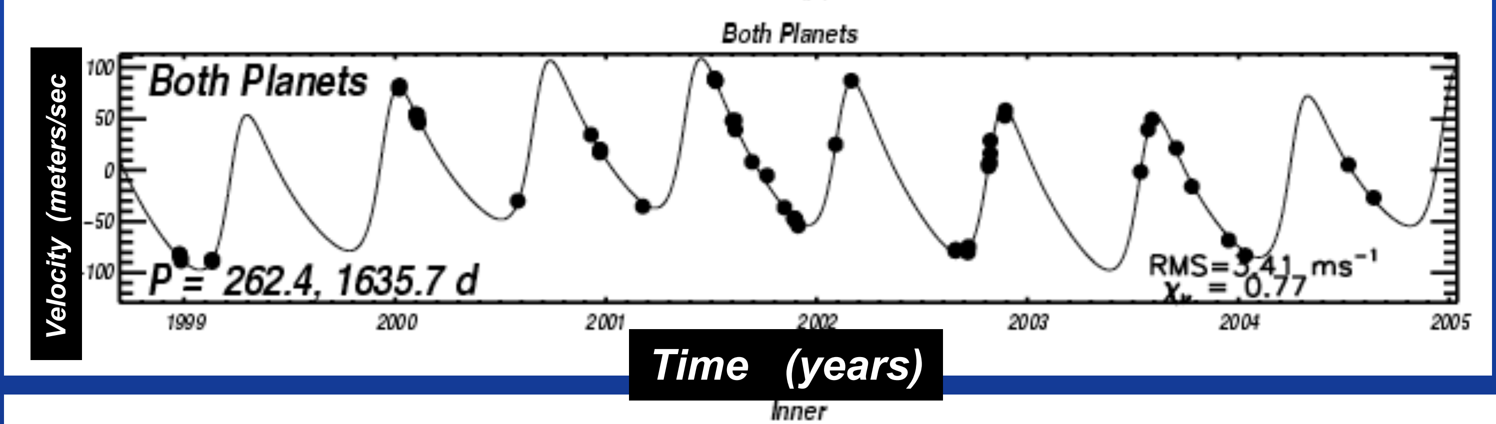
Tidal Circ.:

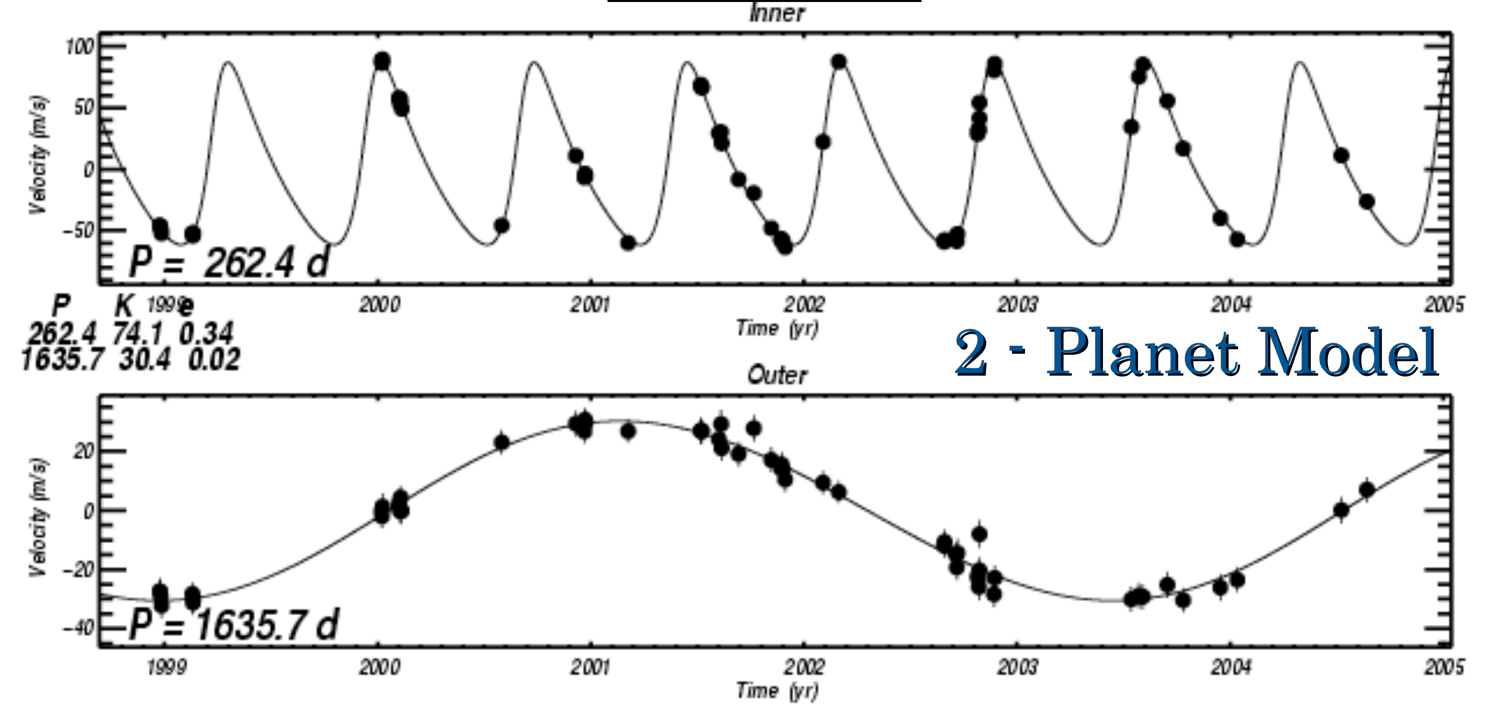
a < 0.1 AU

- <e> = 0.25
- Origin of ecc. *controversial .*

- *Ecc still high beyond 2.5 AU*

HD 12661: Two Jupiter System





2 - Planet Model

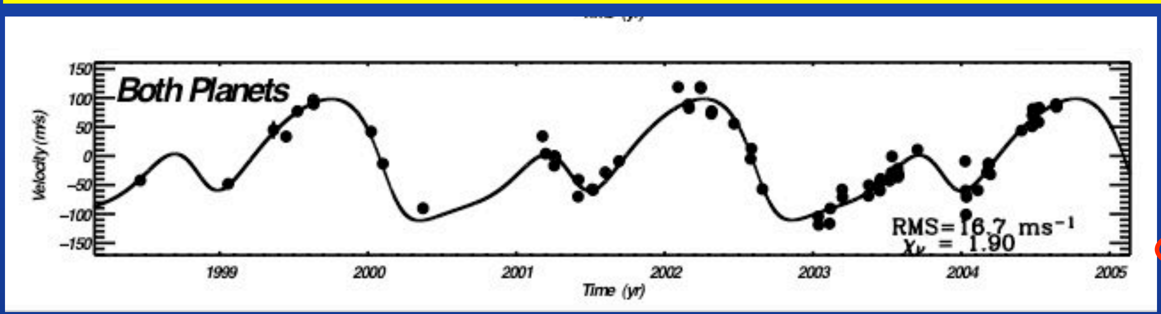
2.5 M_J

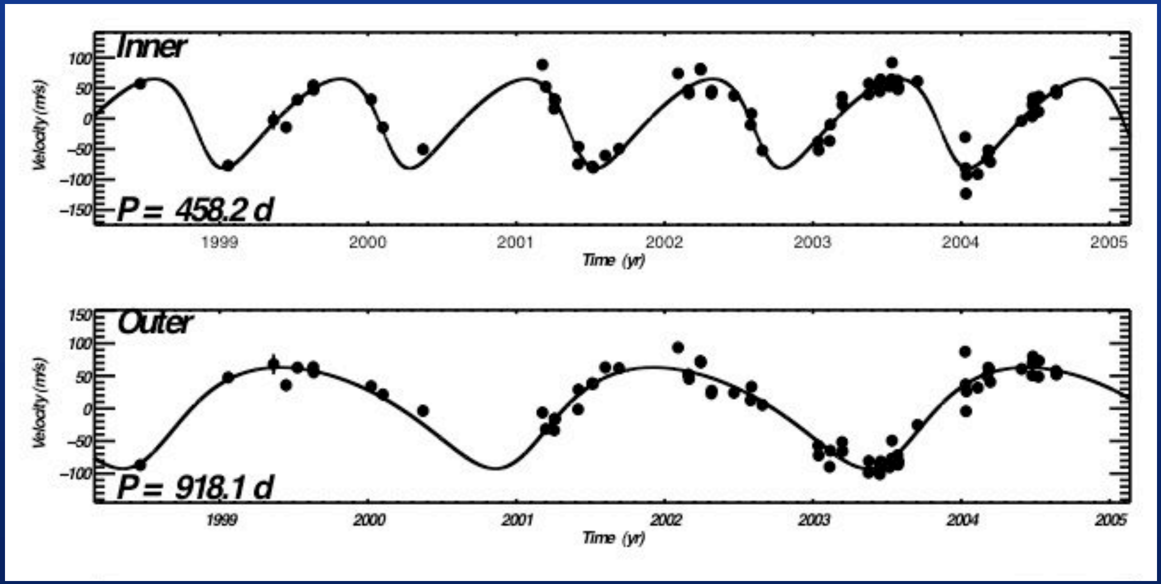
1.9 M_J

Weak Interactions

K0V, 1Gy, 16 pc

HD 128311
2:1 Resonance





	Inner	Outer
Per (d)	458	918
Msini	2.3	3.1
ecc	0.23	0.22
ω	119	212

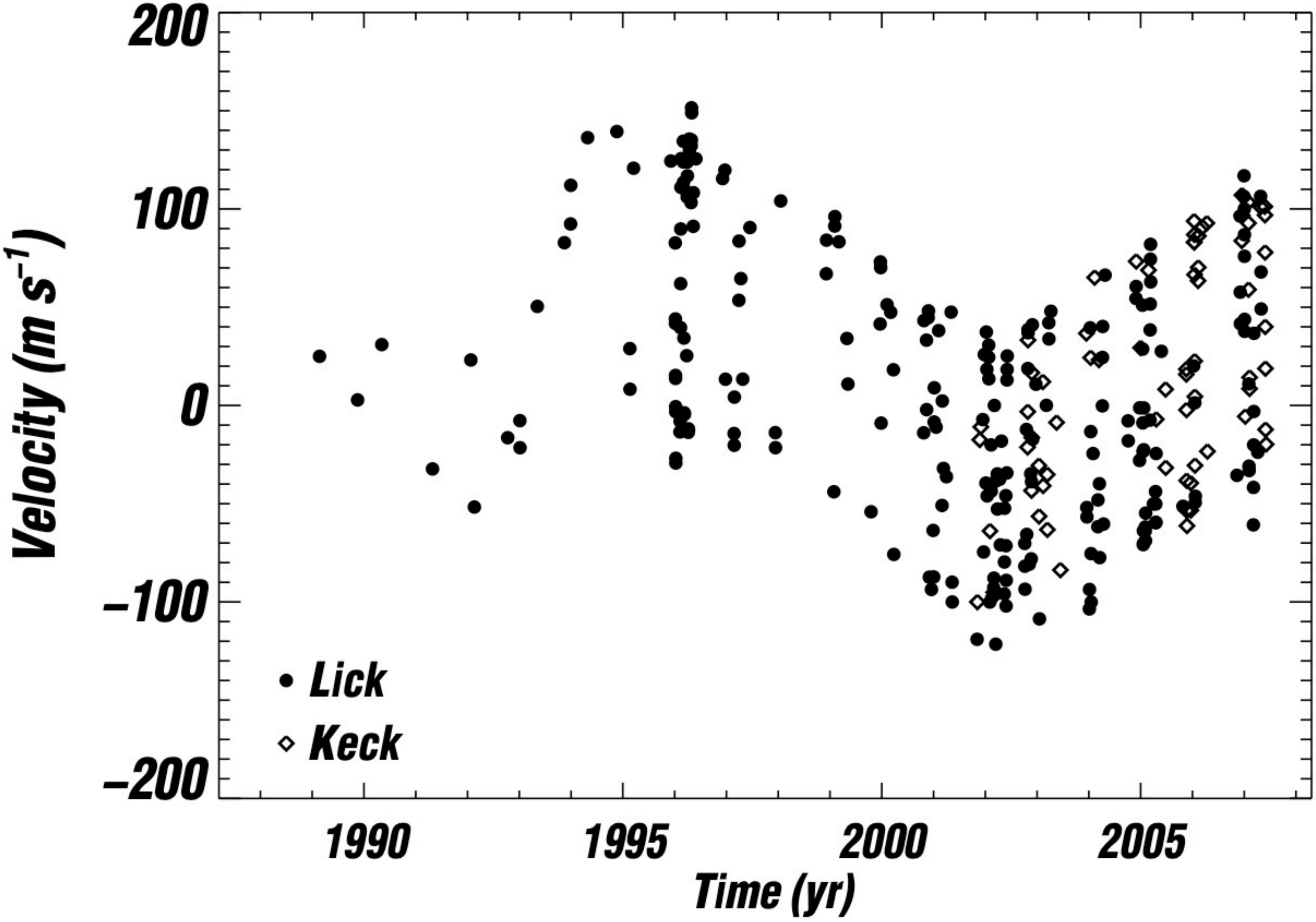
$P_c / P_b = 2.004$

Dynamical Resonance

(Laughlin)

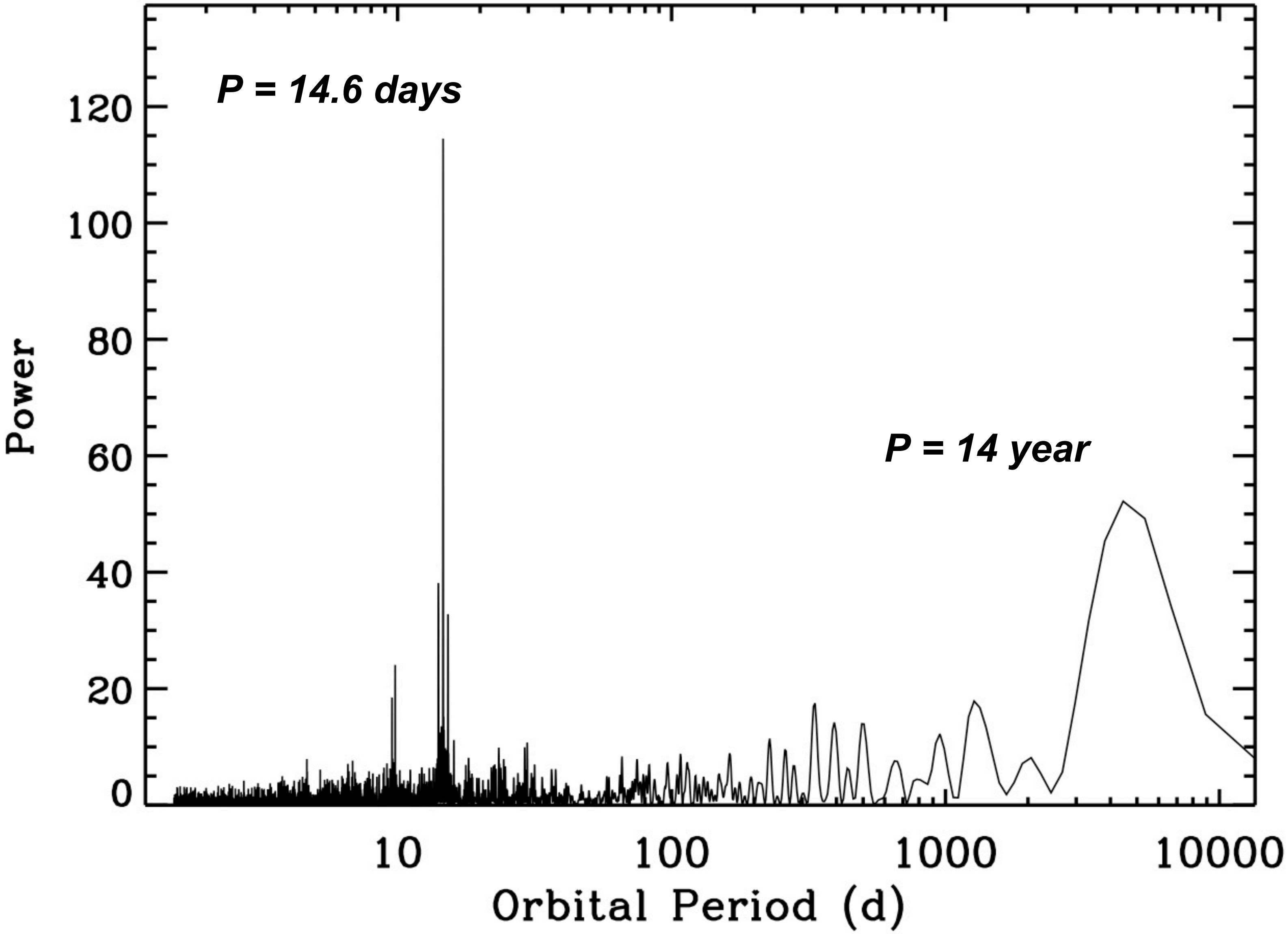
55 Cancri (G8V)

(Fischer et al. 2007)



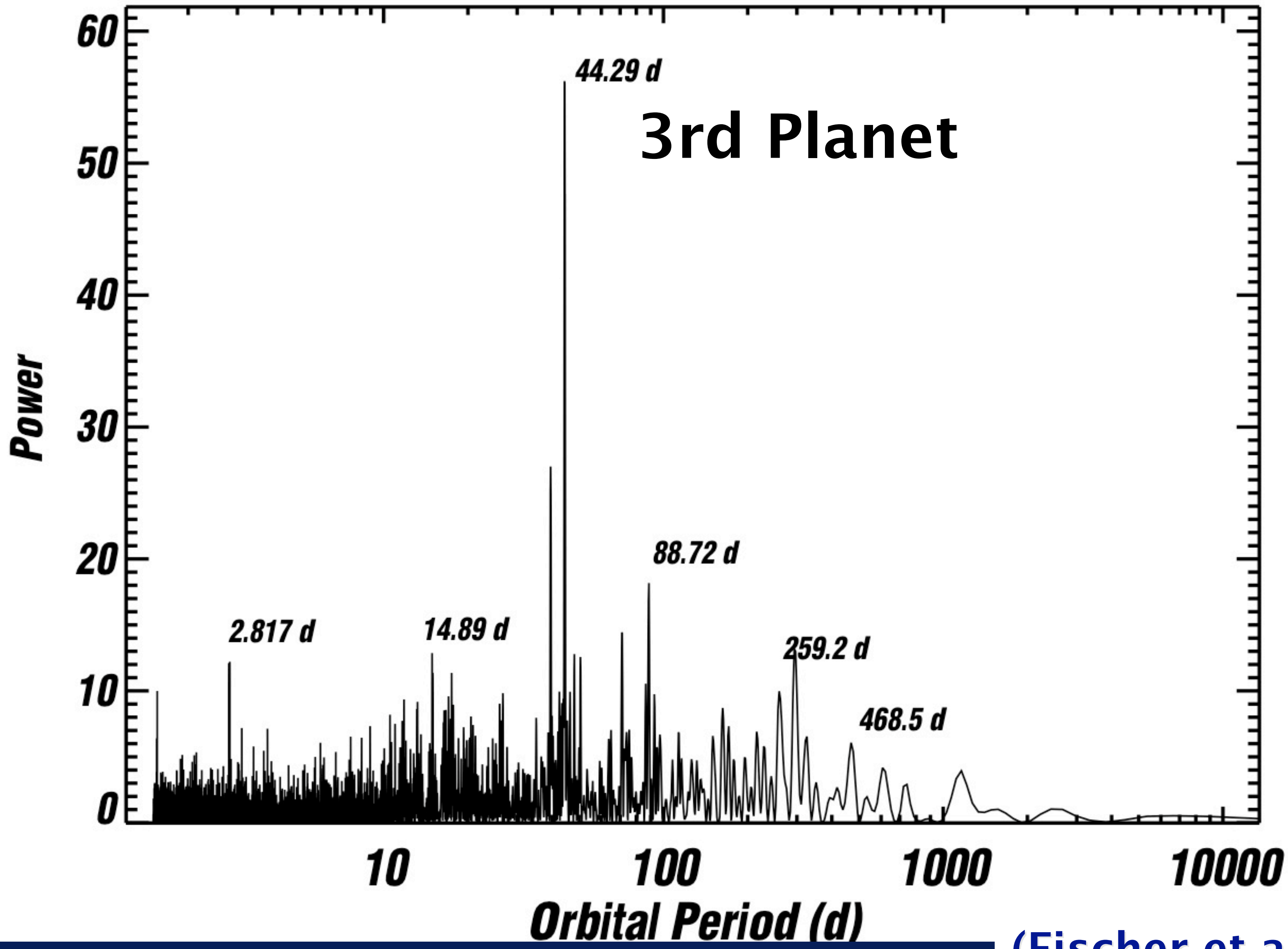
18 Years

55 Cancri Velocities: Fourier Power



55 Cancri

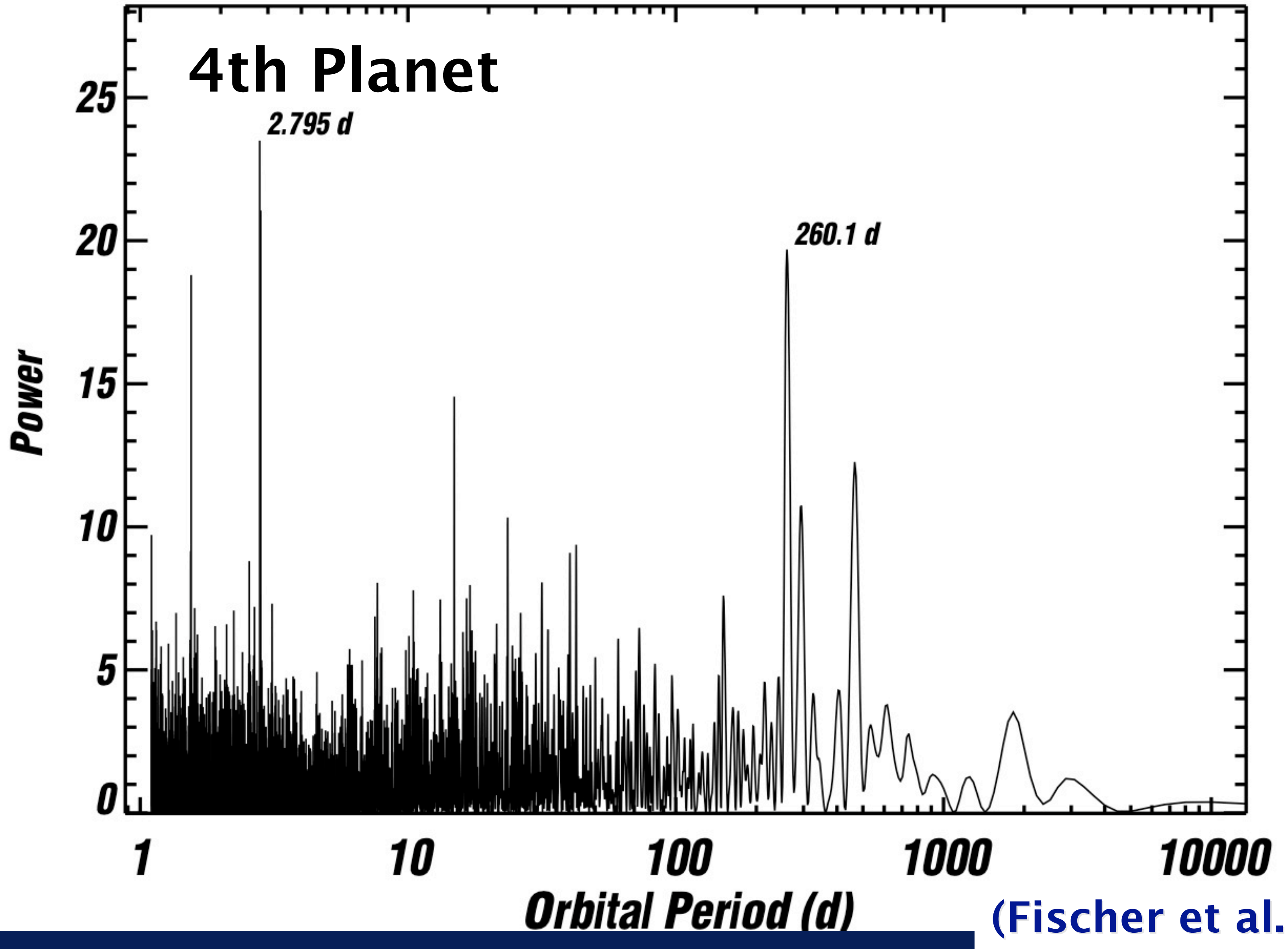
Fourier Power of Velocity Residuals



(Fischer et al. 2007)

55 Cancri

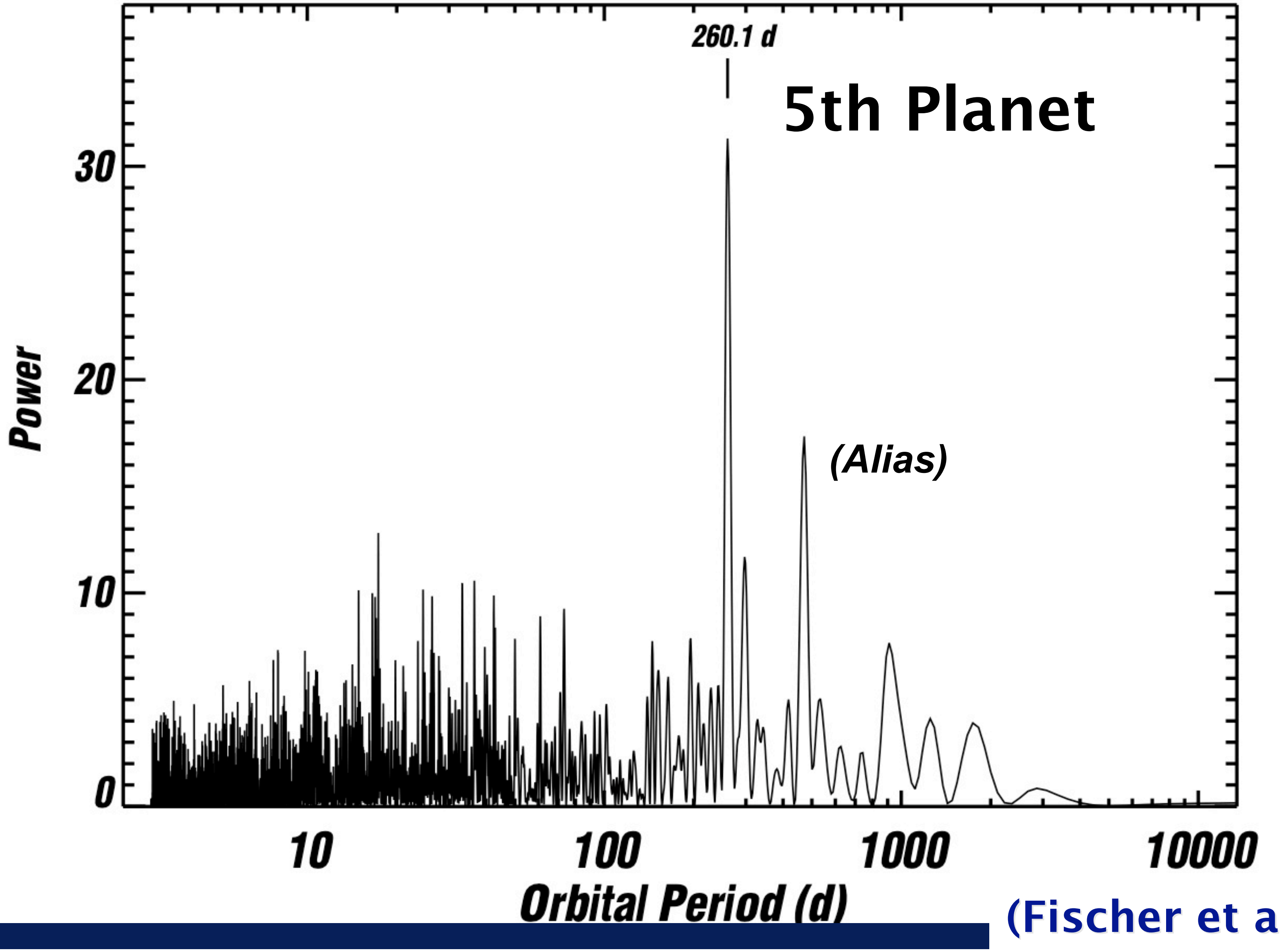
Fourier Power of Velocity Residuals



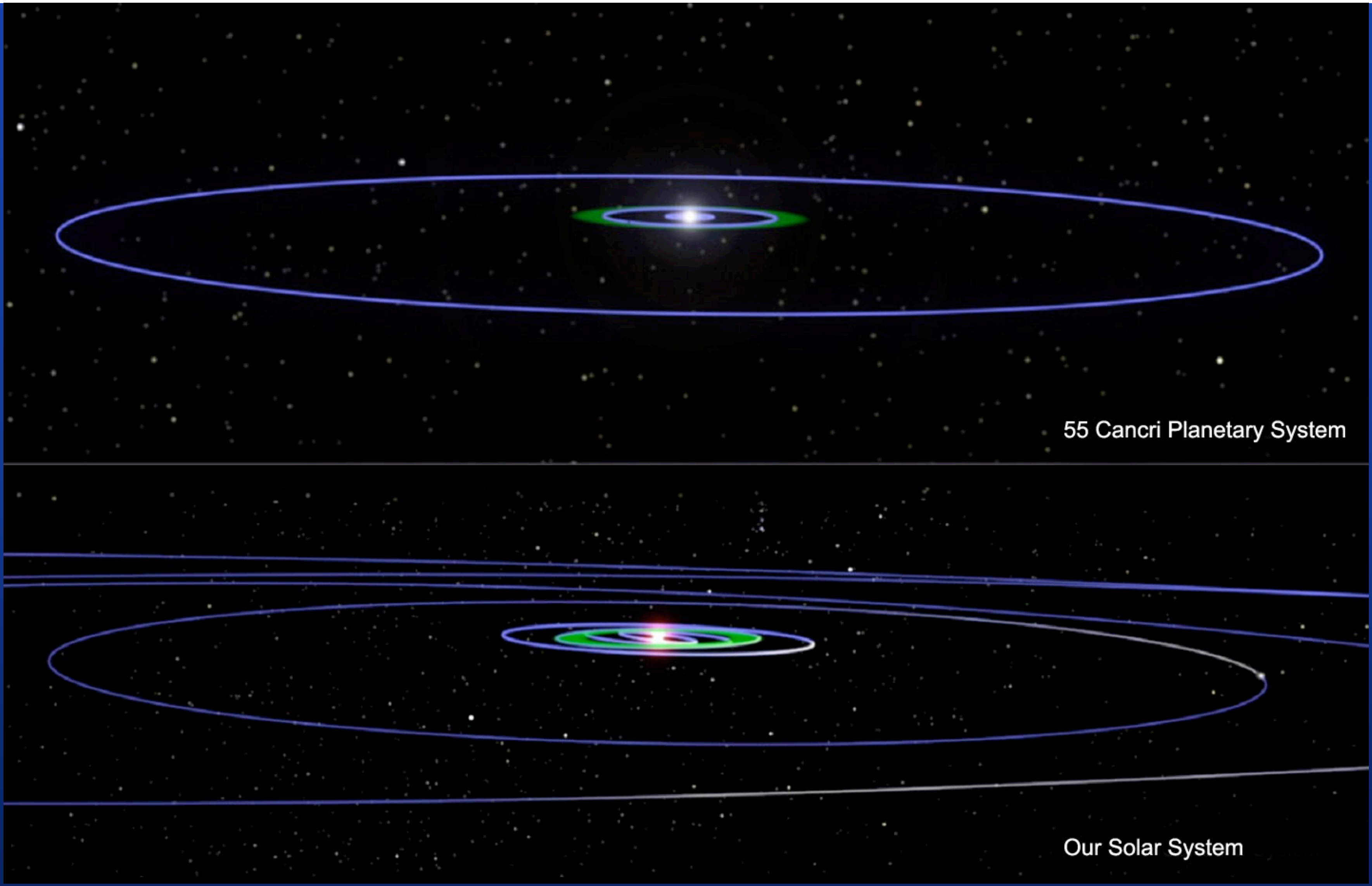
(Fischer et al. 2007)

55 Cancri

Fourier Power of Velocity Residuals



(Fischer et al. 2007)



55 Cancri vs Solar System

5 Planets & Gap

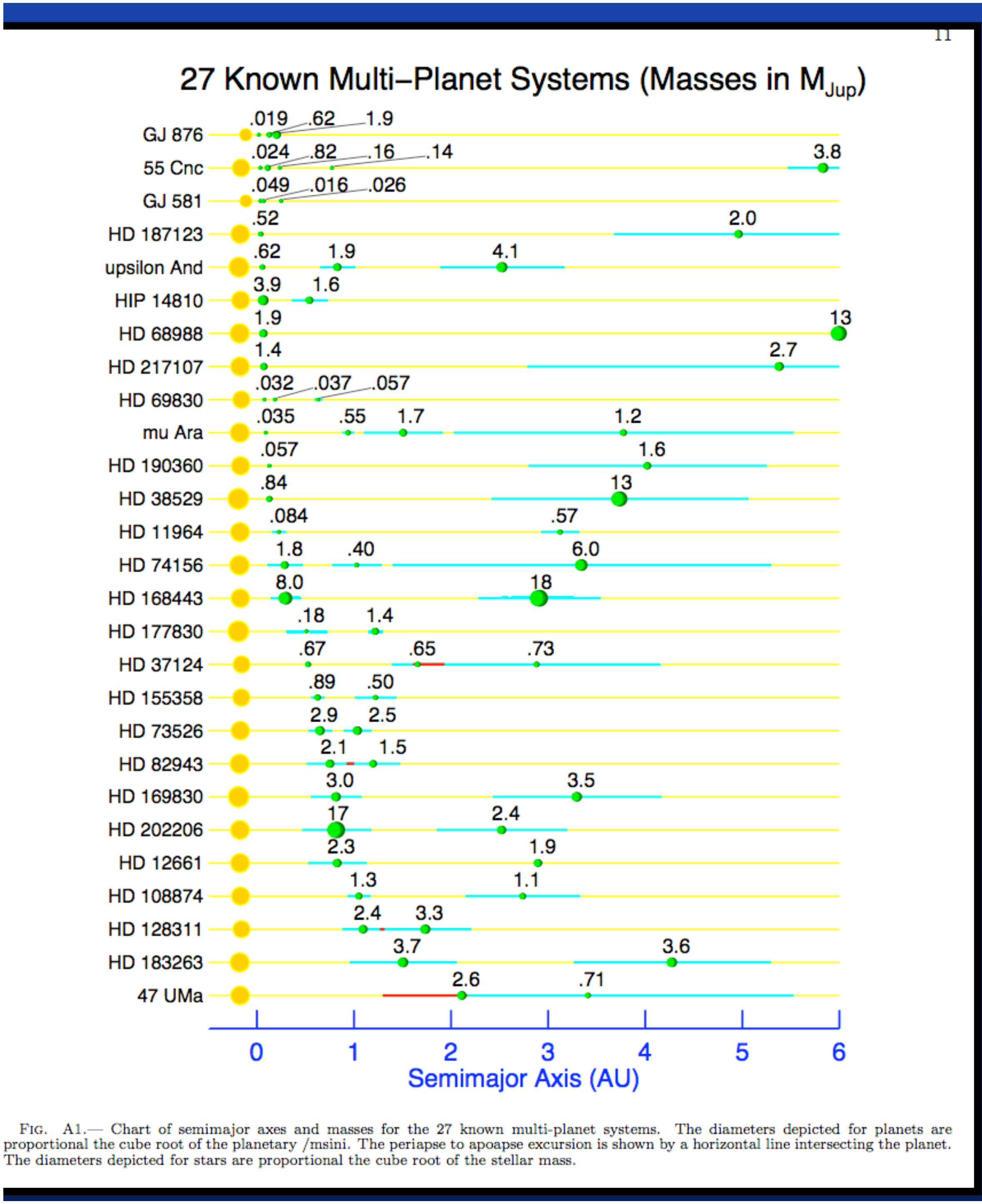


Fig. A1.— Chart of semimajor axes and masses for the 27 known multi-planet systems. The diameters depicted for planets are proportional the cube root of the planetary /msini. The periapse to apoapse excursion is shown by a horizontal line intersecting the planet. The diameters depicted for stars are proportional the cube root of the stellar mass.

Multi-Planets are common:

SIM must cope, and can . . .

Per Marr's talk.
SIM can detect rocky planets in HZ despite other planets.

Detecting Earth-mass Planets by Doppler Measurements of Stars

Star’s Wobble Velocity:

$K = 0.1$ m/s $[M_{pl}/M^{1/2}_{star}\ 1/a_{AU}{}^{1/2}]$ (M_{pl} in M_E)

Benchmark Earth:

Induces 0.1 m/s (at 1 AU)

Photospheric Noise is ~1 m/s

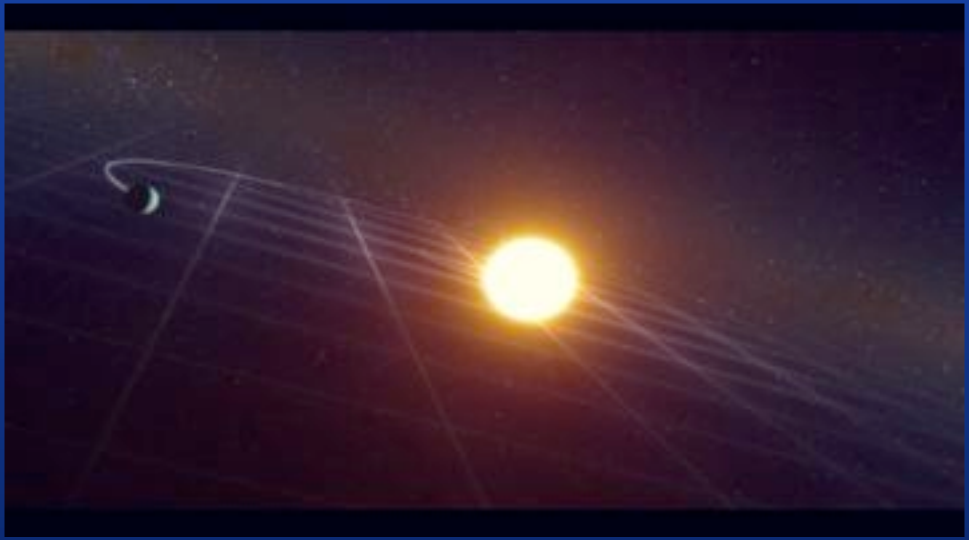
- Spots (on rotating star)
- Convection (granulation)
- Acoustic oscillations

Doppler Cannot Find Earths

Anywhere Near Habitable Zone

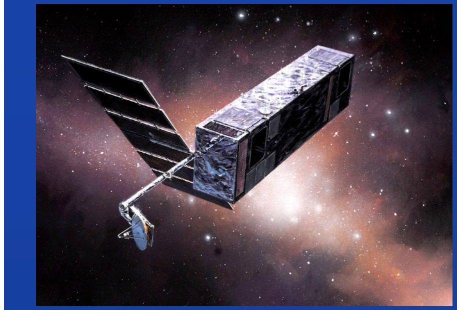
Around AFGK Stars

SIM: Detecting the Nearest Rocky Planets



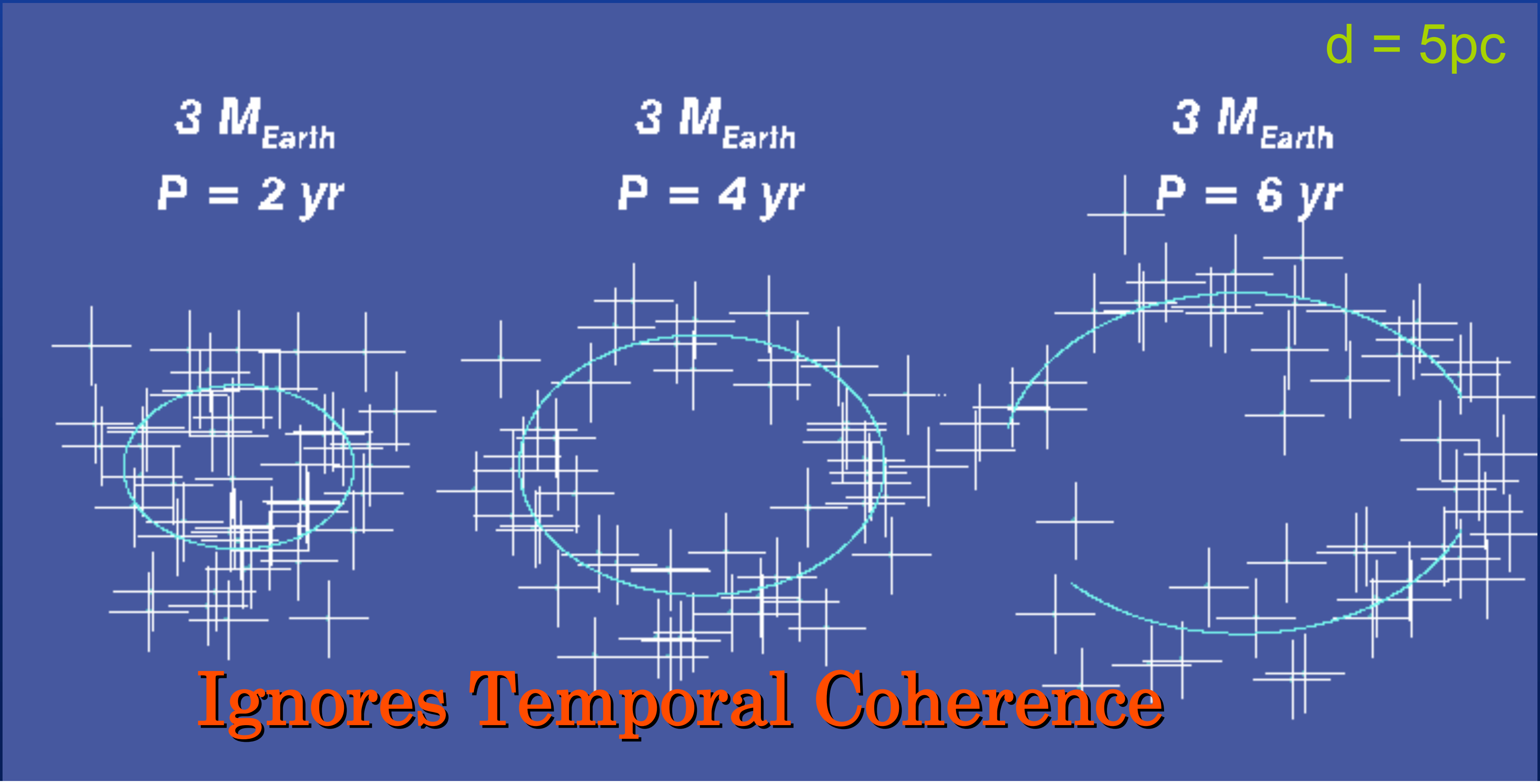
Detect Wobble of Star due to Gravitational pull by the planet.

- *Finds First Nearby Earths*
- *Determines Mass and Orbit*
- *Informs Direct Detection*



Simplisitic Detectability Threshold

Demand Wobble > σ = 1 μas



Ignores Temporal Coherence

Proper Detection Threshold, α_{TH} after N_{obs} Observations:

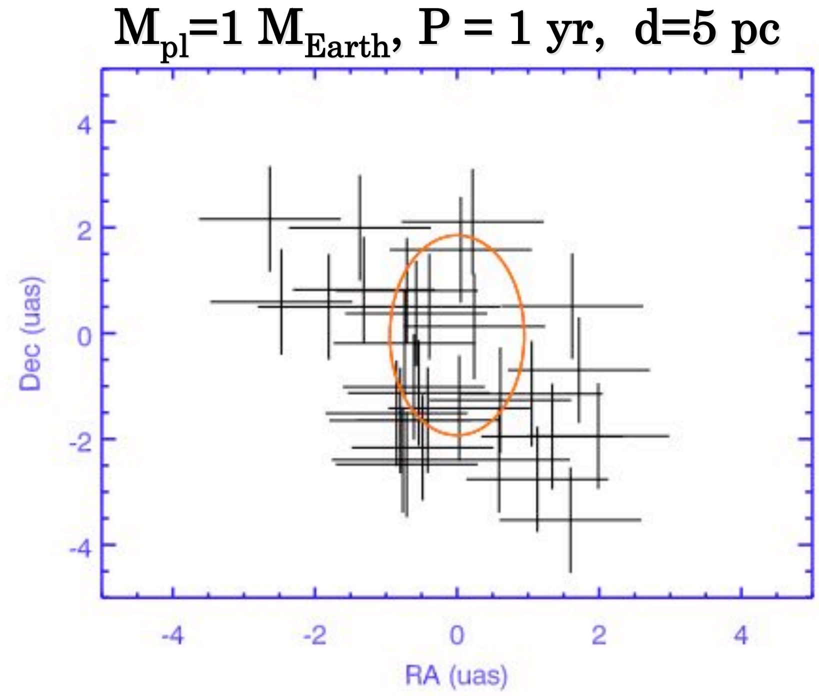
$$\alpha_{THRESH} = \sigma / N_{obs}^{1/2}$$

(SNR = 1)

For measurement uncertainty of σ = 0.82 μas, N = 250 measurements are needed to detect an Earth at 10 pc (0.3 *μas*) with SNR = 5.

SIMULATION: Near SIM Limit:

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

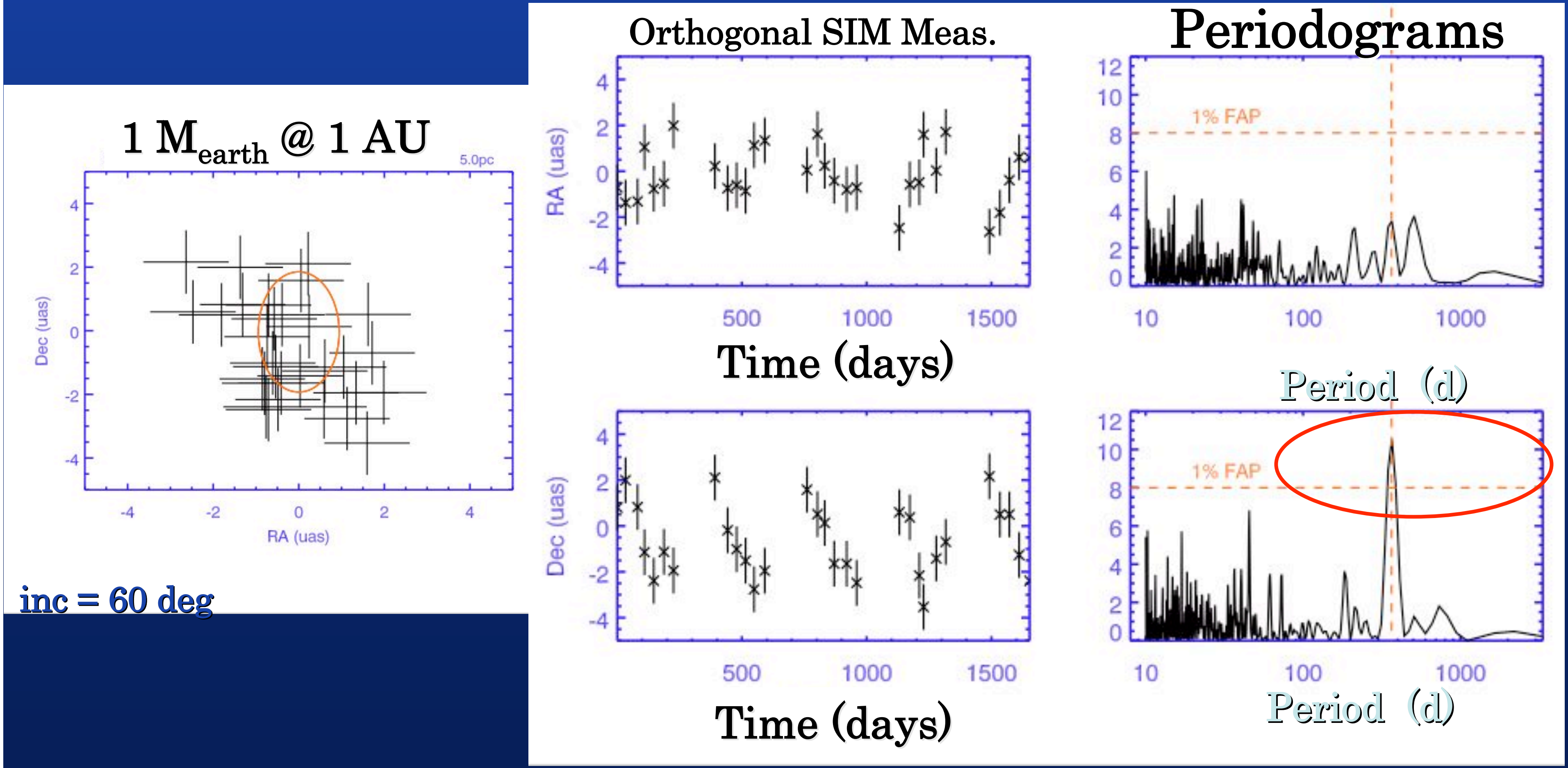


- Wobble ~ 1 μas
- Temporal Coherence

Proper FAP Assessment:

- Fit Orbit
- Chi-Square Analysis
- FAP Monte Carlo ==>
  Prob. of Chisq that low
  from noise fluctuations

False Alarm Probability Assessment:
Periodogram Analysis

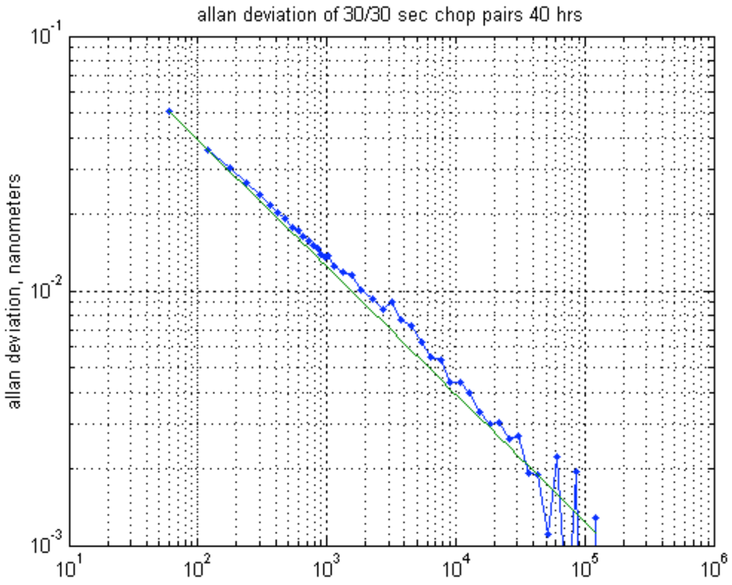


SIM Noise Floor

Instrument Errors

Noise Floor:
0.03 μas

- Thermal drift
  - Modeling predicts performance better than that of ground testbeds.
  - Ground testbed data (MAM & SCDU) show thermal noise to be white after chopping and averages to less than 1 pm with no floor based upon longest data sets taken to date.
- Field dependent (e.g., beamwalk)
  - Measurements all made within 1° of center of field.
- Color dependent
  - Spectral Calibration Development Unit showed how to correct for stellar color dependent errors when chopping.
    - See Proc SPIE Vol 7013, 70132H.



Integration Time (sec)

1 pm noise floor

Primary SIM Targets

- 60-100 A, F, G, K, M dwarfs within ~20 pc
  - Doppler Recon. @ 1 m s^{-1}

    → Jupiters & Saturns within 5 AU
  - SIM: 500 obs. during 5 yr (1 μas)

    → 1 M_{Earth} @ 0.5 - 1.5 AU 5 σ
- 4-6 K-giant reference stars @ 0.5 - 1 kpc
  - Located within 1 deg of each target
  - Doppler vetting for binaries and jupiters @ 25 m/s

Target List

Nearest A,F,G,K, M dwarfs

Criteria:

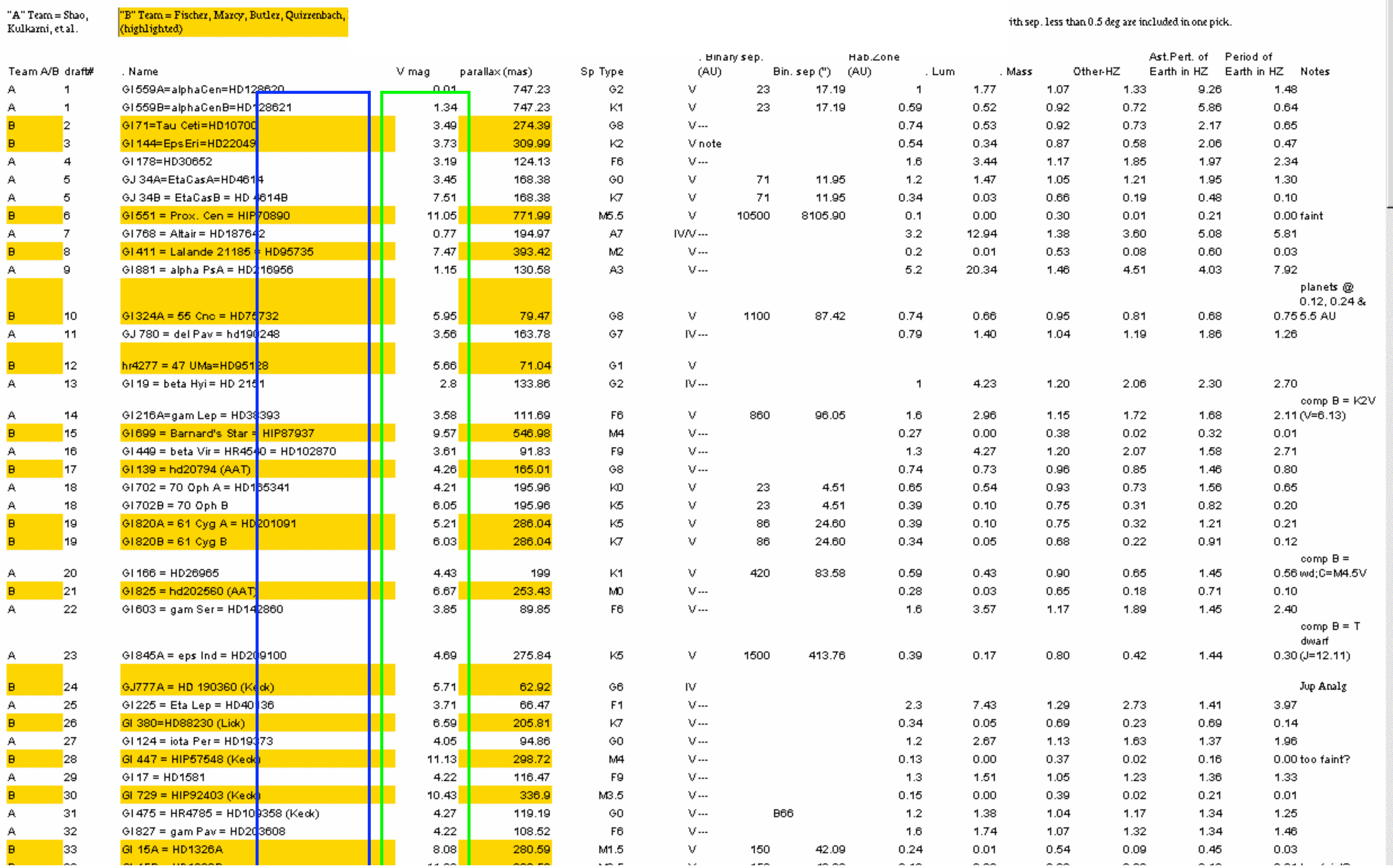
- Proximity
- Brightness V < 10
- Future TPF target (HZ ang. sep.)

- "Rocky" Search: Nearest 60-100 Stars
  - 0.20 µas wobble amplitude
  - 1% false alarm probability (FAP)
  - -- Match 0.22 µas of ExoPlanet Task Force
  - Number of visits, precision adjustable.
- Broad Survey:
  - ~1000 stars to 4 µas mission accuracy.
- Young Stars:
  - ~50 stars <100Myr to 5 µas mission acc.

#	HIP #	SIMBAD Name	SPEC	DIST pc	V mag	# of PH Visits in 5yrs	1Me/Hz AstSig [µas]
1	71683	alf Cen A	G2V	1.347	-0.01	200	2.37
2	71681	alf Cen B	K1V	1.347	1.35	200	1.70
3	37279	Procyon	F5IV-V	3.497	0.4	200	1.35
4	97649	Altair	A7IV-V	5.143	0.76	200	1.03
5	8102	LHS142	G8V	3.647	3.49	217	0.65
6	16537	V* eps Eri	K2V	3.218	3.72	224	0.64
7	2021	SV* ZI 21	G1IV	7.475	2.82	335	0.53
8	3821	V* eta Cas	G0VSB	5.953	3.46	347	0.52
9	99240	NSV 12790	G6/8IV	6.108	3.55	386	0.49
10	88601	V* V2391 Oph	K0V	5.086	4.03	409	0.48
11	22449	SV* ZI 311	F6V	8.026	3.19	414	0.47
12	108870	LHS 67	K4/5V	3.626	4.69	422	0.47
13	19849	V* DY Eri	K0/1V	5.044	4.43	475	0.44
14	89937	NSV 10749	F7Vvar	8.057	3.55	483	0.44
15	67927	NSV 19993	G0IV	11.342	2.68	484	0.44
16	81693	NSV 7915	F9IV	10.796	2.81	498	0.43
17	104214	V* V1803 Cyg	K5V	3.483	5.2	502	0.43
18	61941	LHS 2605	F1V	11.830	2.74	503	0.43
19	86974	LHS 3326	G5IV	8.400	3.42	513	0.42
20	15510	LHS 19	G8III	6.060	4.26	516	0.42
21	107556	V* del Cap	A5MF2(IV)	11.823	2.85	524	0.42
22	77952	NLTT 41426	F0III/IV	12.309	2.83	542	0.41
23	84405	CCDM J17155-2635	K(2)(III)	5.985	4.33	552	0.41
24	27072	NLTT 15560	F7V	8.969	3.59	554	0.41
25	96100	NSV 12176	K0V	5.767	4.67	601	0.39
26	17378	V* del Eri	K0IV	9.043	3.52	617	0.39
27	72659	SV* SVS 2491	G8V+K4V	6.700	4.54	666	0.37
28	57757	LHS 2465	F9V	10.900	3.59	688	0.37
29	61317	NSV 5725	G0V	8.371	4.24	696	0.36
30	46853	NSV 4519	F6IV	13.486	3.17	704	0.36
31	1599	LHS 5	G0V	8.593	4.23	711	0.36
32	44127	NSV 4329	A7IV	14.637	3.12	733	0.36
33	105858	NSV 13689	F7V	9.217	4.21	742	0.35
34	64394	LHS 348	G0V	9.155	4.23	757	0.35
35	27913	NLTT 15782	G0V	8.663	4.39	770	0.35
36	78072	NSV 7350	F6V	11.121	3.85	776	0.35
37	109176	NSV 14034	F5V	11.756	3.77	792	0.34
38	14632	LHS 166	G0V	10.534	4.05	820	0.34
39	71908	V* alf Cir	APSREU(C	16.402	3.18	853	0.33
40	104217	NSV 13546	K7V	3.504	6.05	860	0.33
41	99461	LHS 486	K2V	6.052	5.32	864	0.33
42	95501	SV* SVS 46	F2IV	15.373	3.36	866	0.33
43	12777	NSV 902	F7V	11.232	4.1	876	0.32
44	116727	NSV 14656	K1IV	13.793	3.21	885	0.32
45	64924	LHS 349	G5V	8.525	4.74	910	0.32
46	102422	LHS 3578	K0IV	14.341	3.41	943	0.31
47	14879	LHS 1515	F8V	14.112	3.8	948	0.31
48	5336	NSV 405	G5Vp	7.553	5.17	965	0.31
49	28103	* eta Lep	F1V	15.044	3.71	989	0.31
50	98036	NAME ALSHAIN	G8IVvar	13.708	3.71	1007	0.30
51	32362	SV* ZI 572	F5IV	17.538	3.35	1008	0.30
52	15457	V* kap01 Cet	G5V	9.159	4.84	1015	0.30
53	7981	NSV 600	K1V	7.468	5.24	1028	0.30
54	57443	LHS 311	G3/5V	9.240	4.89	1045	0.30
55	7513	NLTT 5367	F8V	13.468	4.1	1072	0.29
56	35550	HD 56986	F0IV...	18.034	3.5	1081	0.29
57	77257	SV* ZI 1157	G0Vvar	11.754	4.42	1085	0.29
58	114622	NSV 14458	K3Vvar	6.526	5.57	1105	0.29
59	116771	NSV 14657	F7V	13.791	4.13	1109	0.29
60	59199	* alf Crv	F0IV/V	14.769	4.02	1109	0.29
61	73184	V* KX Lib	K4V	5.906	5.72	1123	0.29
62	70497	SV* ZI 1068	F7V	14.571	4.04	1123	0.29
63	102485	* psi Cap	F5V	14.671	4.13	1165	0.28
64	10644	HD 13974	G0V	10.846	4.84	1177	0.28
65	8796	V* alf Tri	F6IV	19.658	3.42	1179	0.28

100 AFGKM Stars d < 20 pc

Selection by Proximity, Brightness, Habitable zone separation



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

"B" Team = Fischer, Marcy, Butler, Quirrenbach, (highlighted)

ith 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 ---	B66		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	8.08	280.59	M1.5	V	150	42.09	0.24	0.01	0.54	0.09	0.45	0.03	

Astrometric Planet Signal

The semiamplitude of the angular wobble, α, of a star of a given mass, M_*, and distance, D, due to planets of a given mass, is given by:

$$\frac{\alpha}{\mathrm{arcsec}} \equiv \frac{m_{\mathrm{pl}}}{M_*} \frac{a_{\mathrm{pl}}}{\mathrm{AU}} \frac{\mathrm{pc}}{D}$$

Benchmark: Earth-Mass orbiting 1 AU

from a Solar-mass star at 10 pc

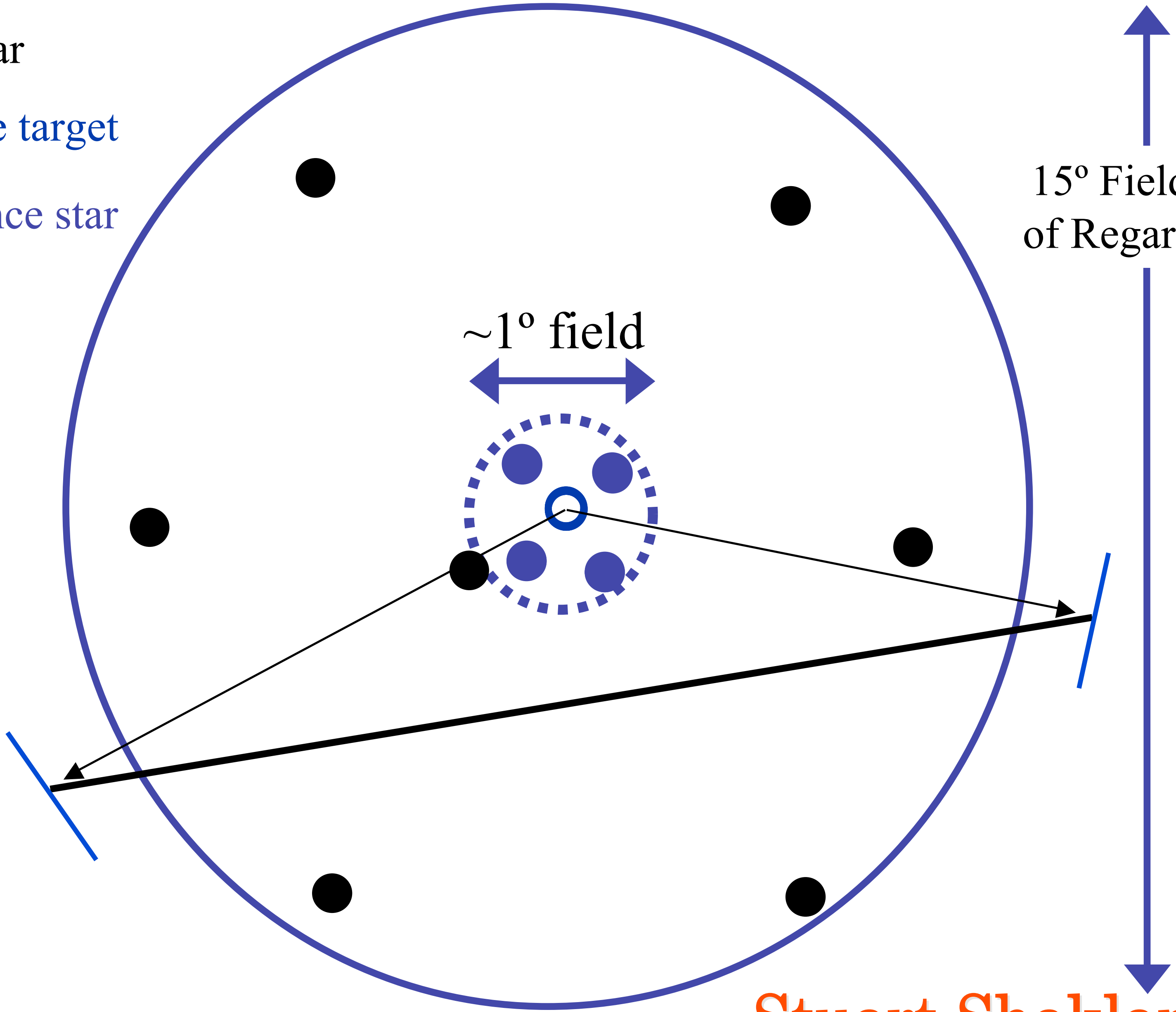
α = 0.3 μas .

Planet Search Observing Scenario

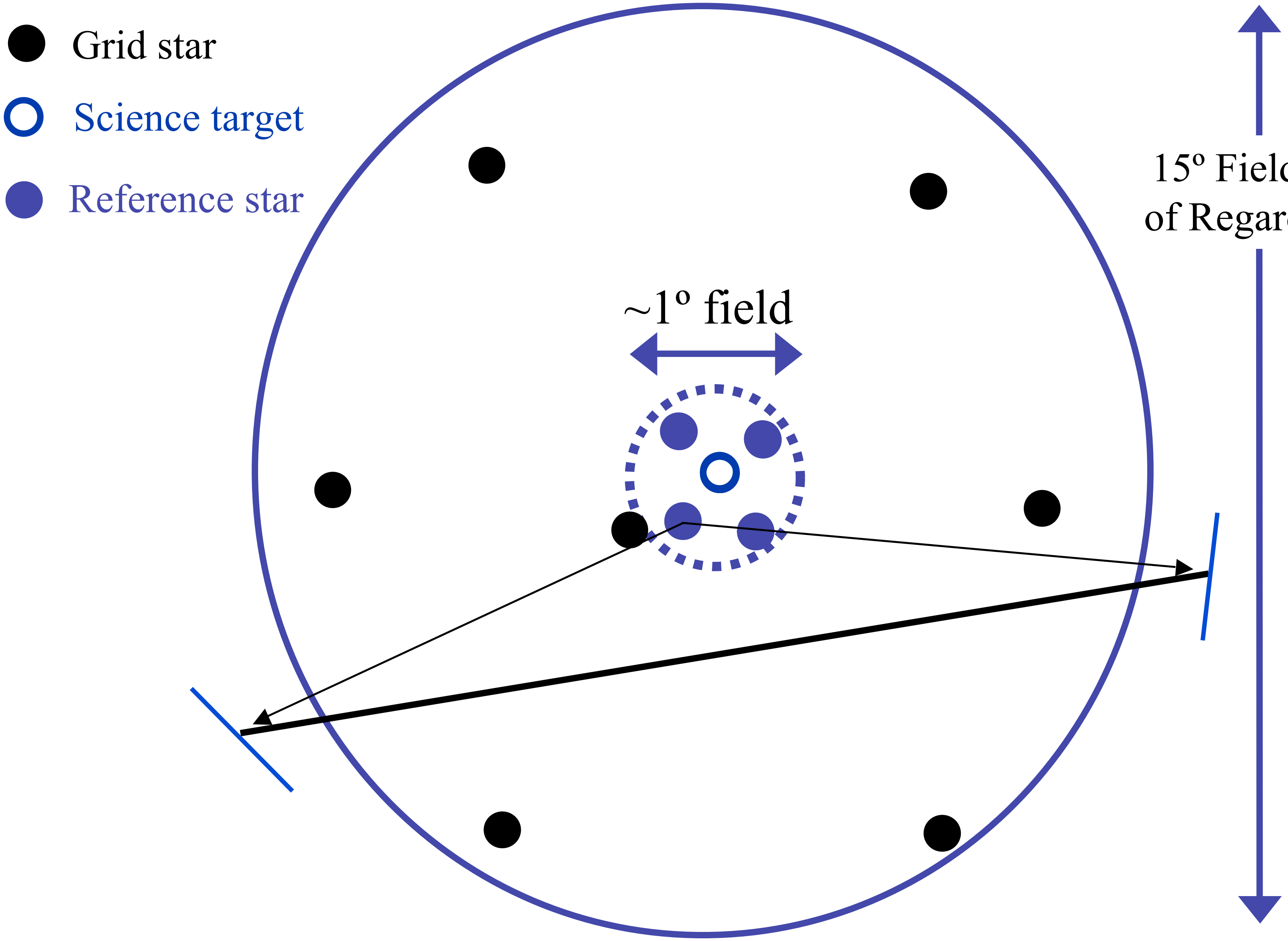
● Grid star

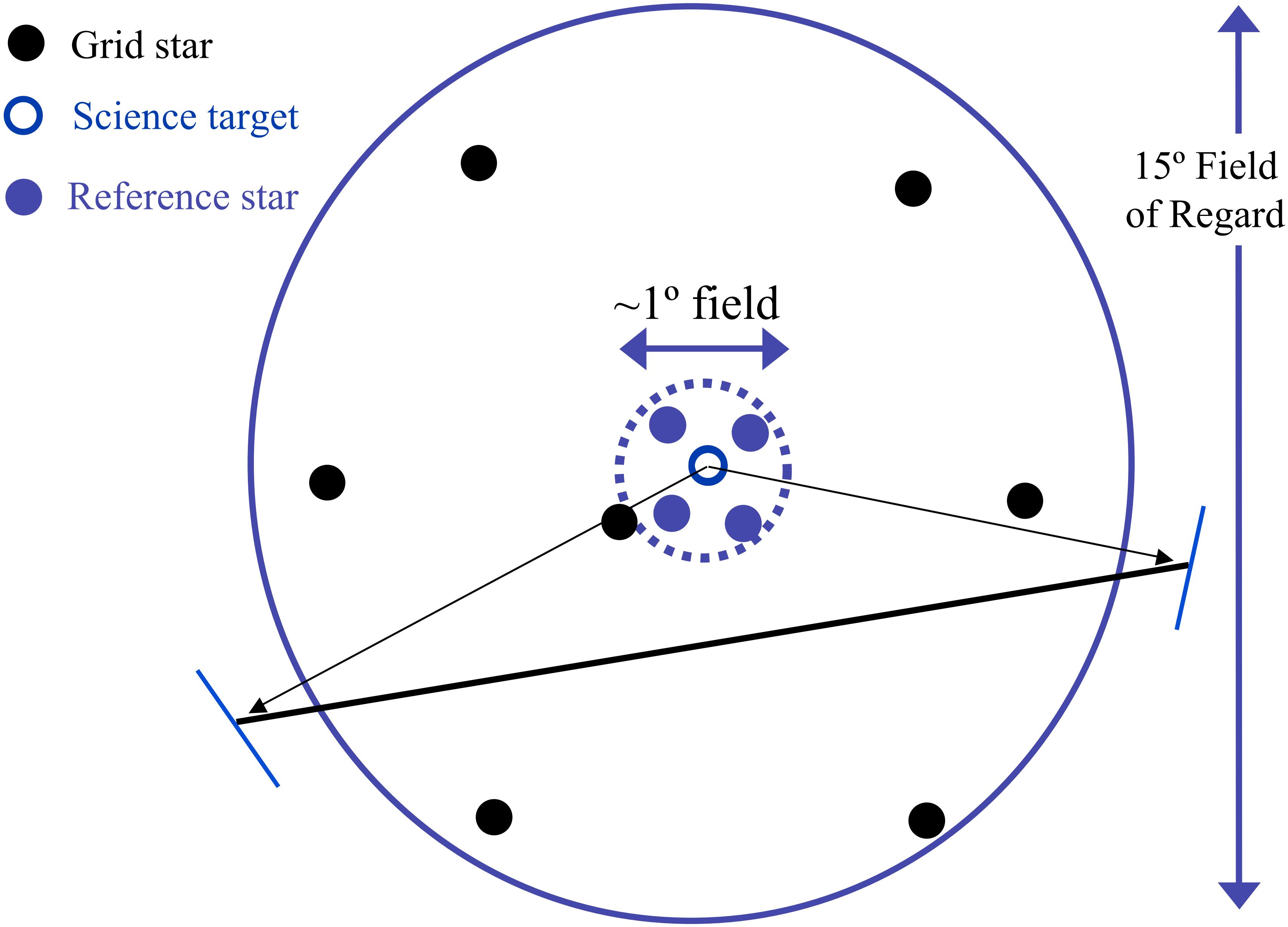
○ Science target

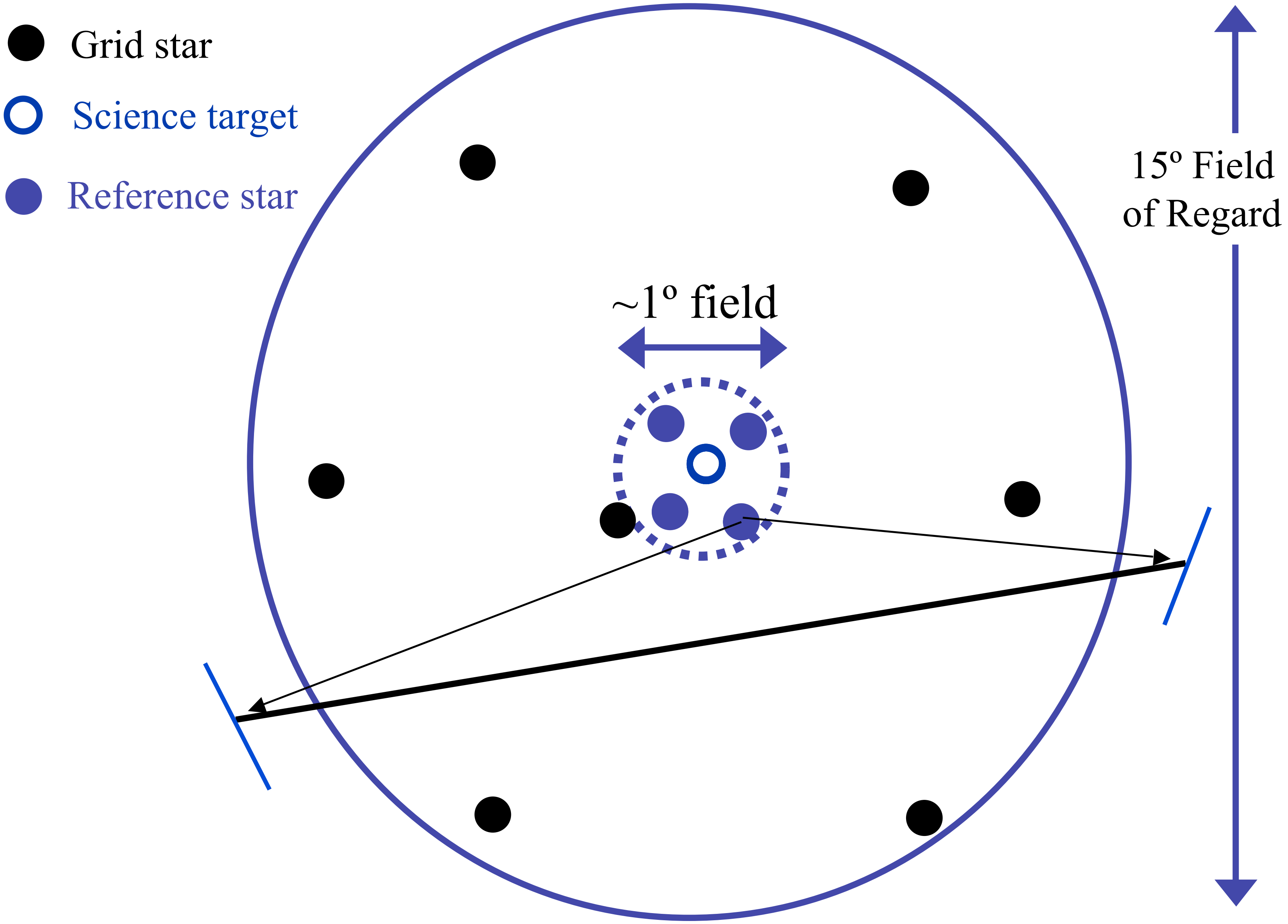
● Reference star

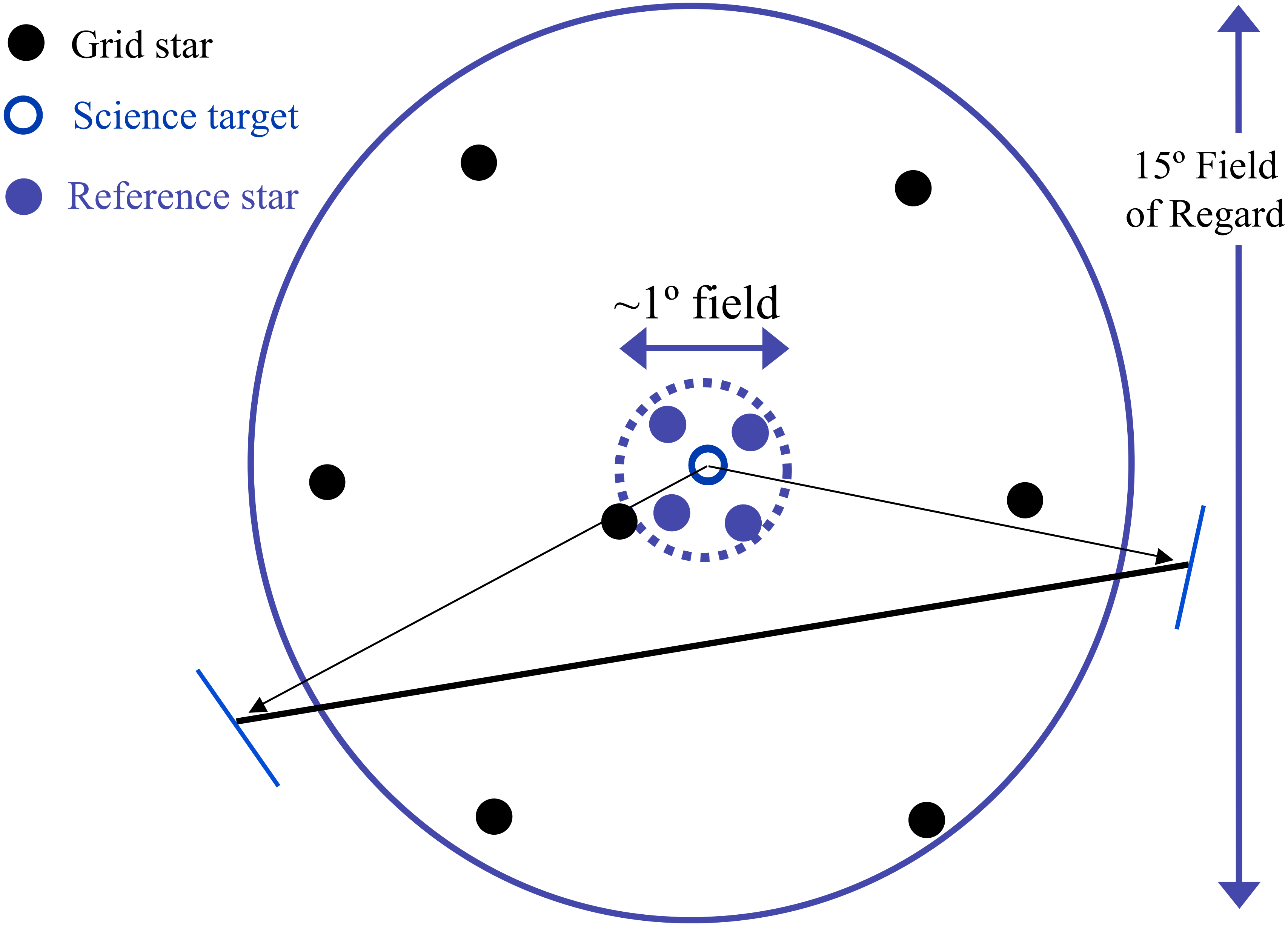


Stuart Shaklan

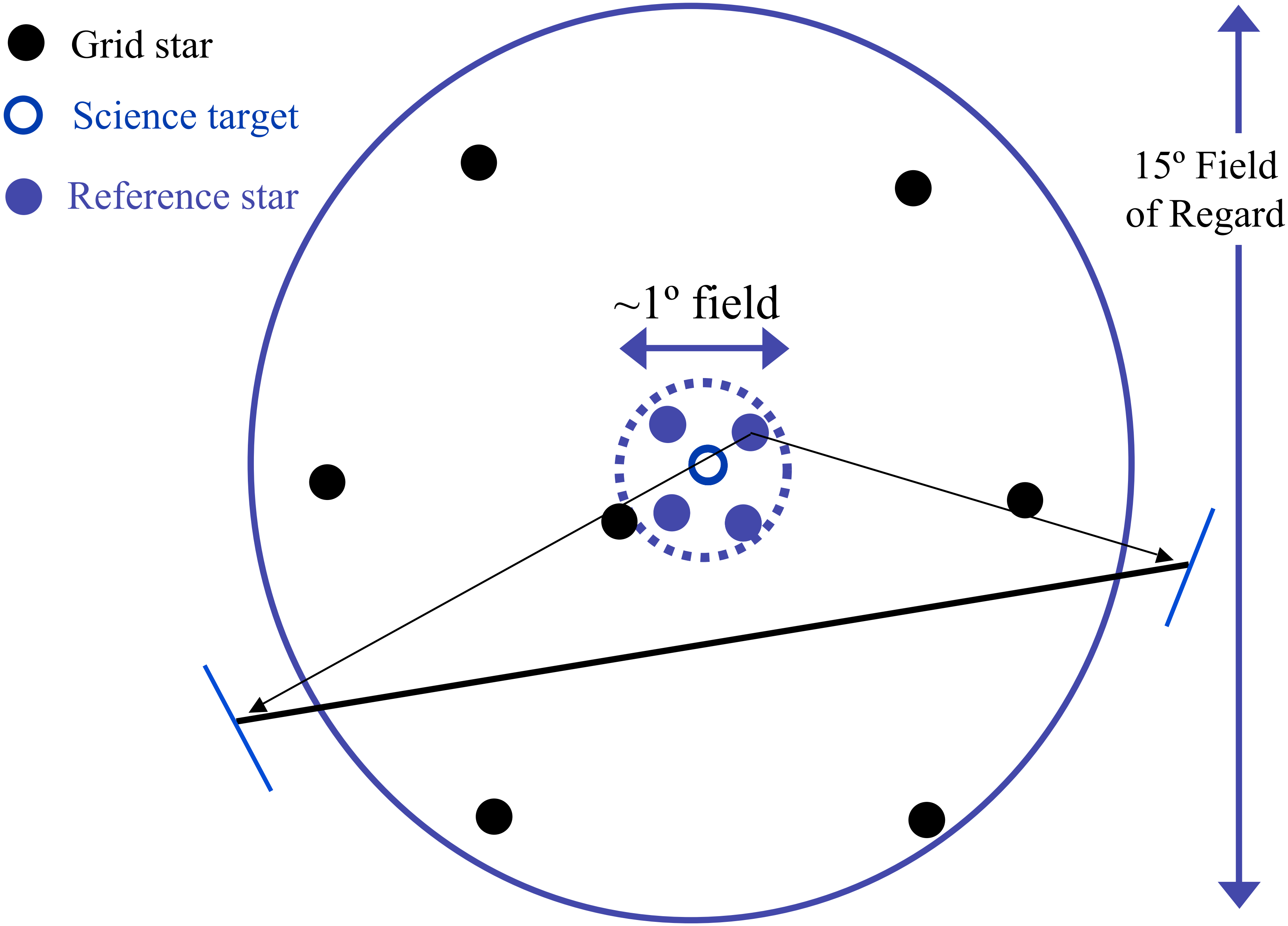

● Grid star
○ Science target
● Reference star
15º Field
of Regard
~1º field

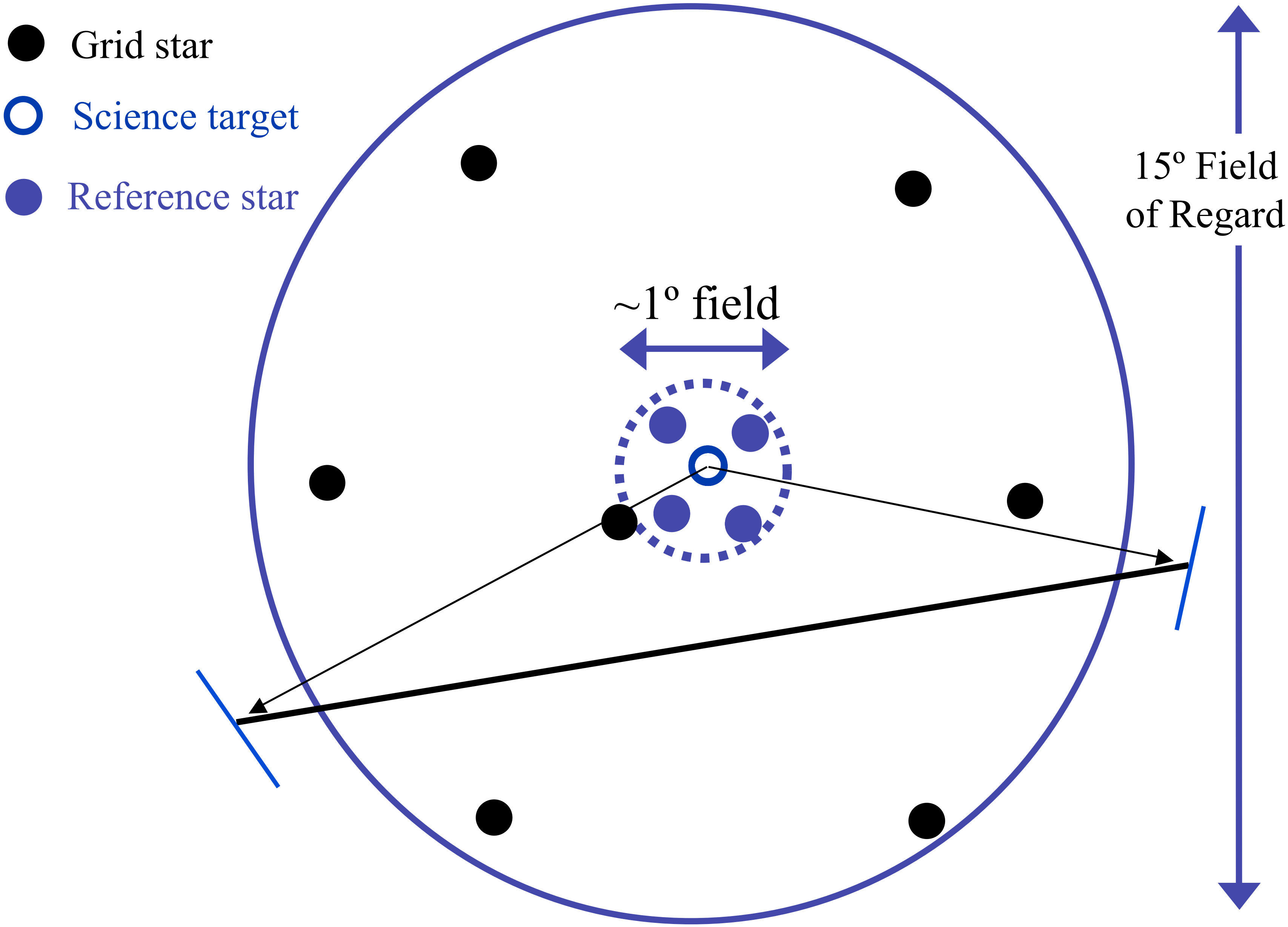

● Grid star
○ Science target
● Reference star
15º Field
of Regard
~1º field

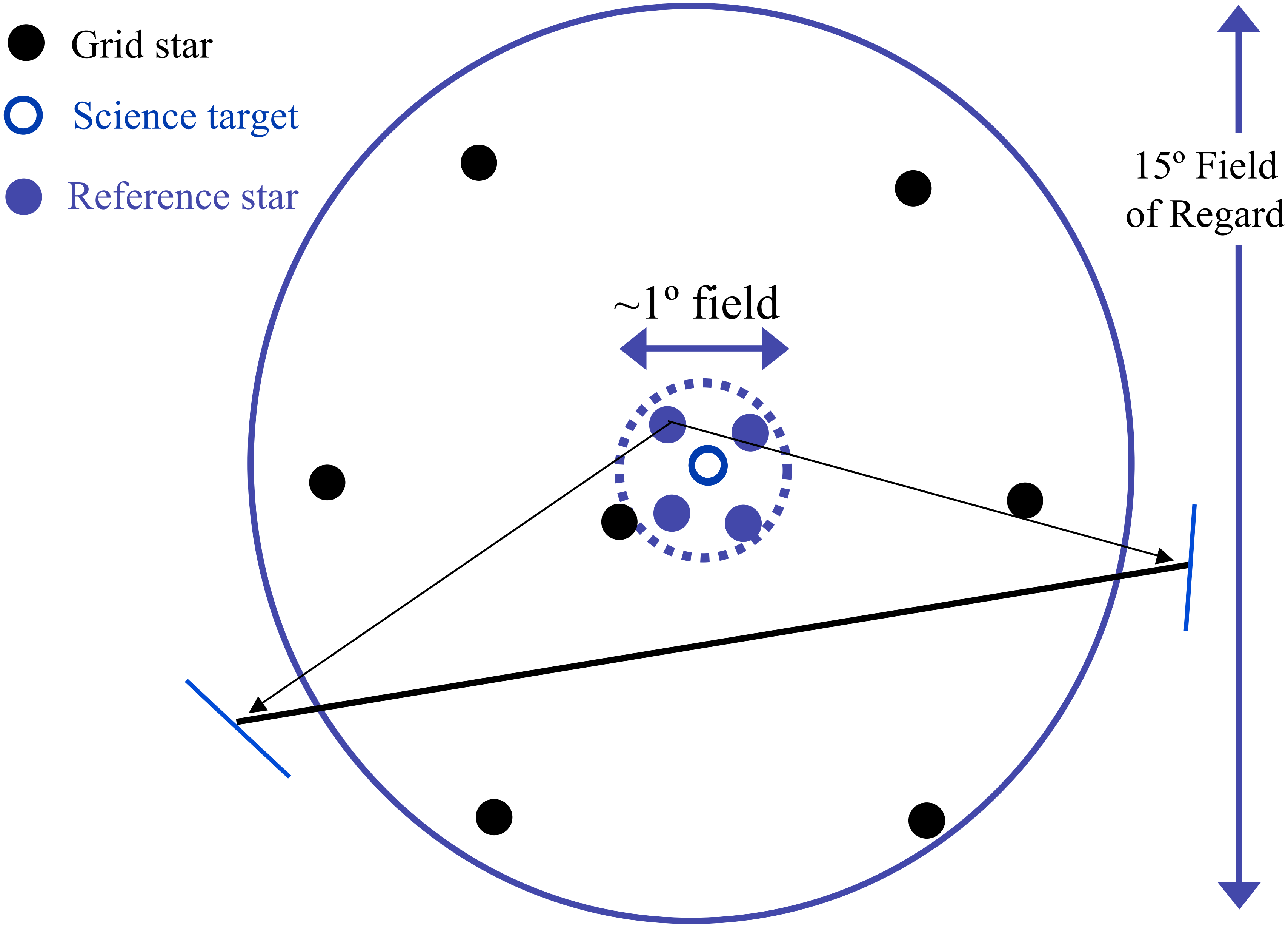

● Grid star
○ Science target
● Reference star
~1º field
15º Field of Regard



● Grid star
○ Science target
● Reference star
15° Field of Regard
~1° field


● Grid star
○ Science target
● Reference star
15° Field of Regard
~1° field


● Grid star
○ Science target
● Reference star
~1° field
15° Field of Regard

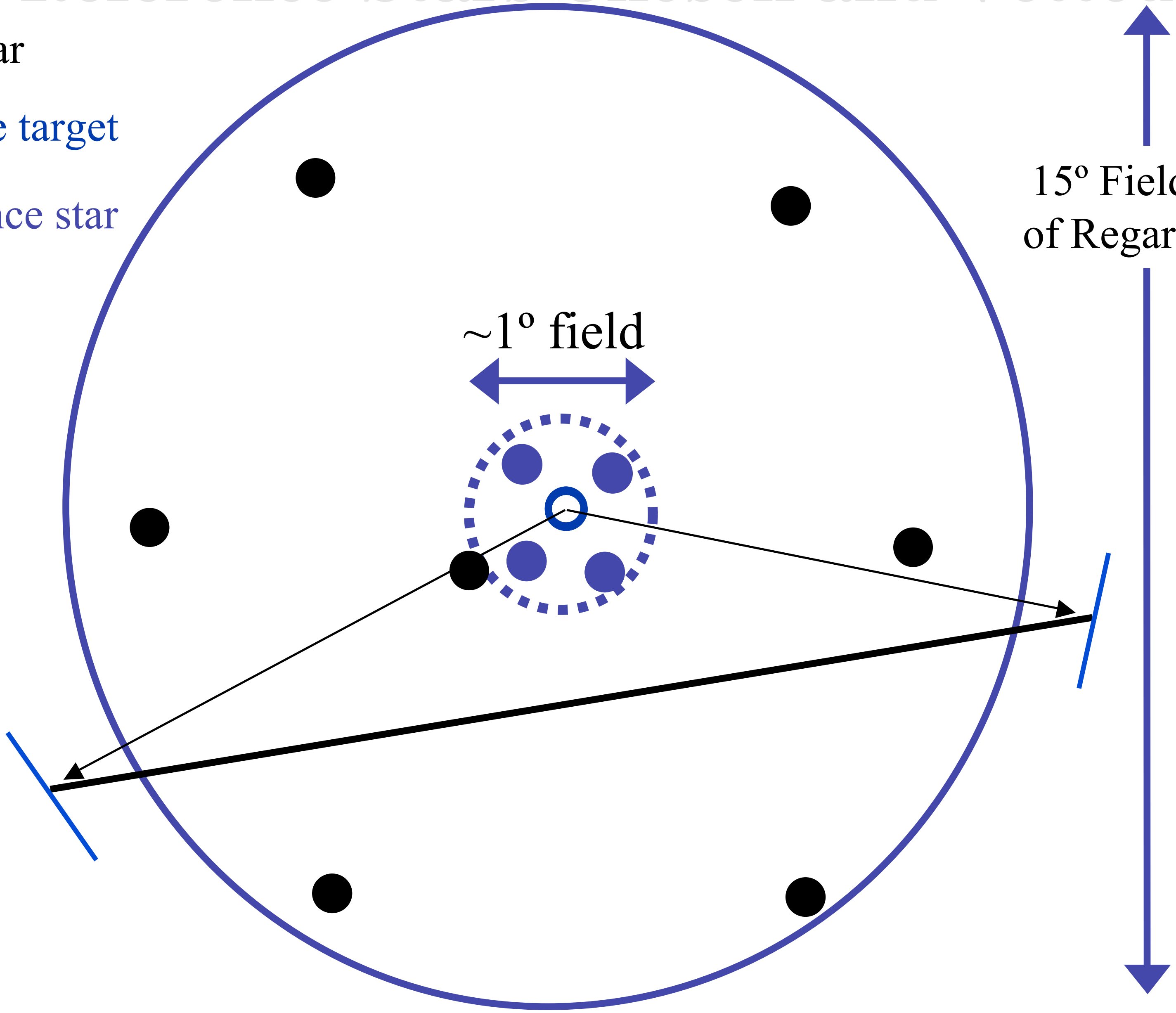

● Grid star
○ Science target
● Reference star
~1° field
15° Field of Regard

How are Reference Stars Chosen and Vetted?

● Grid star

○ Science target

● Reference star



~1° field

15° Field of Regard

Reference Stars

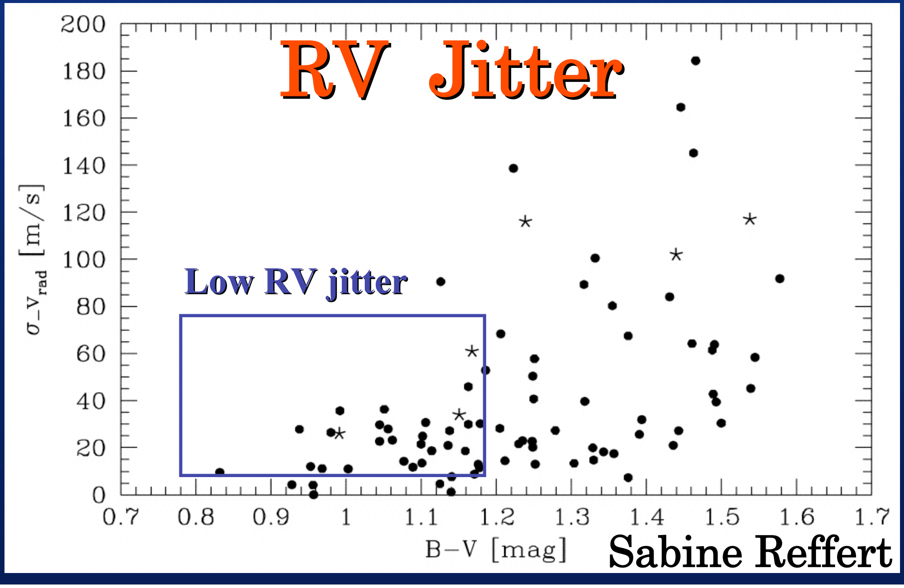
K Giants @ 0.5 - 1 kpc

- Distinguish Giants from Dwarfs: Reduced Proper Motion Diagram

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

  Select Giants

  90% Efficient (10% Dwarfs & Subgiants leak)



Sabine Reffert

- Select stars with B-V < 1.2

  (low RV jitter)

- RV vetting at 25 m/s

Selecting Reference Stars

- K Giants at d ~ 0.5 kpc

  (Elim. Astrometric Jitter from Earths, Neptunes)
- V < 10.5 mag (Exp. Time 30 sec, Low thermal drift)
- $\theta < 1$ deg (Angle Dep. Errors)
- RV Vetting: 25 m/s (Elim Binaries, BDs)

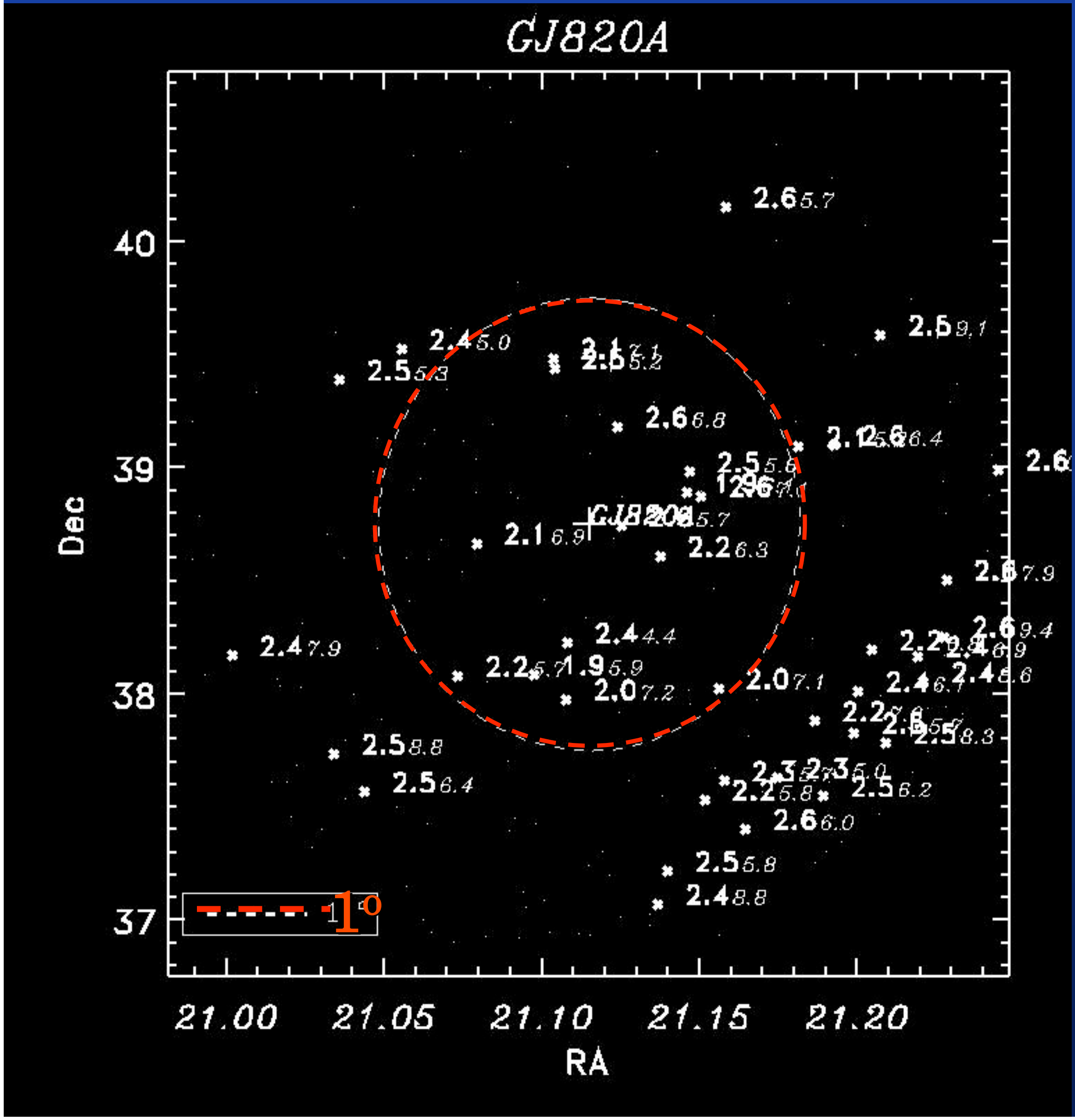
Two Types of Contamination:

- 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



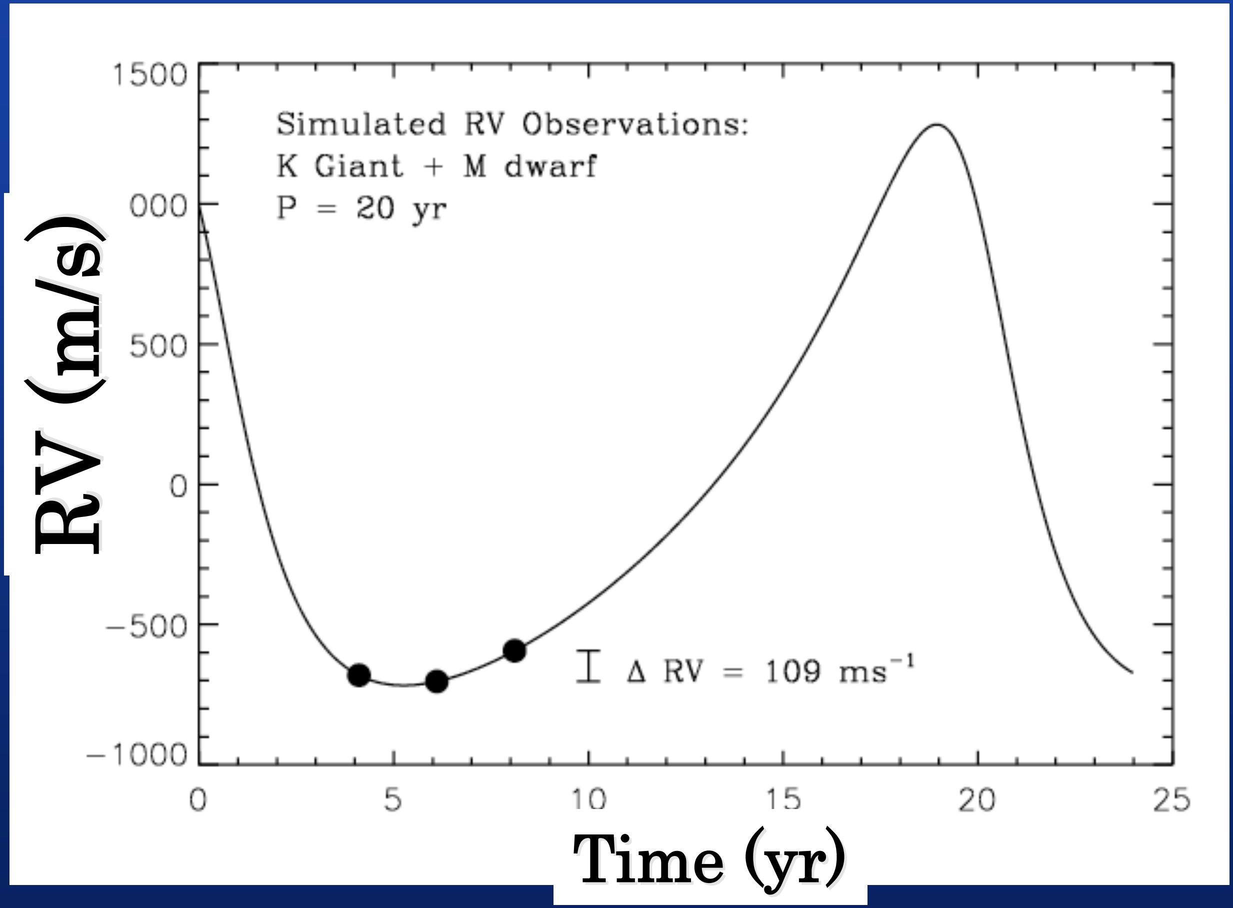
Exp. Error

- Photons
- Angle sep.
- Planet jitter

Failure Prob.

RV Vetting of Reference Stars:

Example: M Dwarf Companion

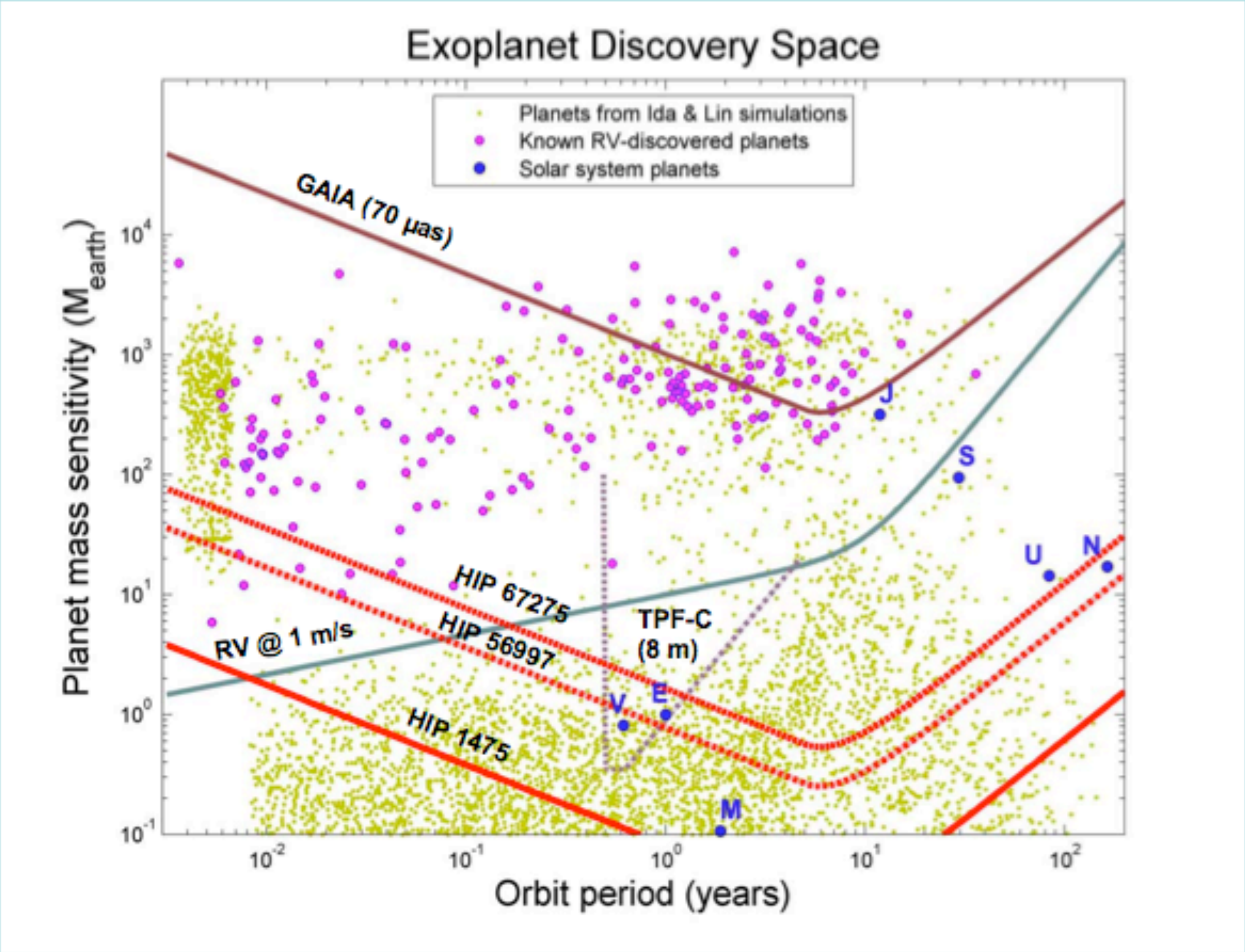


Elim. Companions:

25 m/s RV Precision

Planets
around K giants
get through

Earth Analog Survey



Science Goals of PlanetHunter:

Discovery and Characterization of Rocky Exoplanets

- Earth-like planets around Sun-like Stars in Habitable Zone
- Rocky Planets and super-Earths 0.5 - 3 AU.
- Planets around Massive Stars (A,F-type stars)
- Planets around young stars
- Planetary Masses and full Orbits
- Complementary Obs. Vis-à-vis RV Discoveries
- Architecture of Planetary Systems

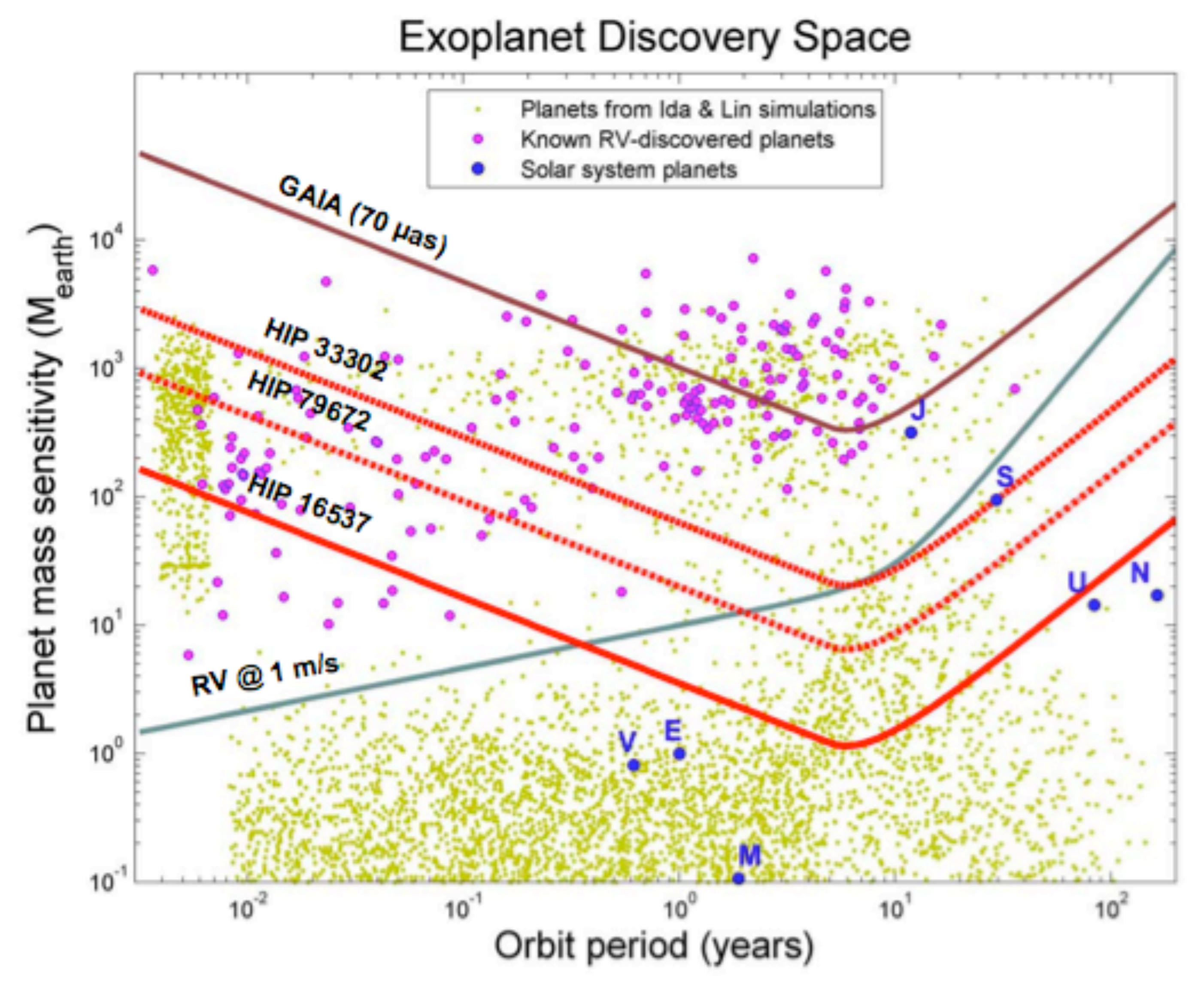
SIM Habitable Planet Survey

Mass sensitivity at mid-habitable zone	$1\ M_\oplus$
# of target stars that can be surveyed (1)	69
# of target stars that can be surveyed (2)	101

(1) Using 40% of SIM mission time (five years).

(2) Using 75% of SIM mission time (maximum available for science investigations, five years).

“Tier 2” Survey @ 4 μas: No Chopping

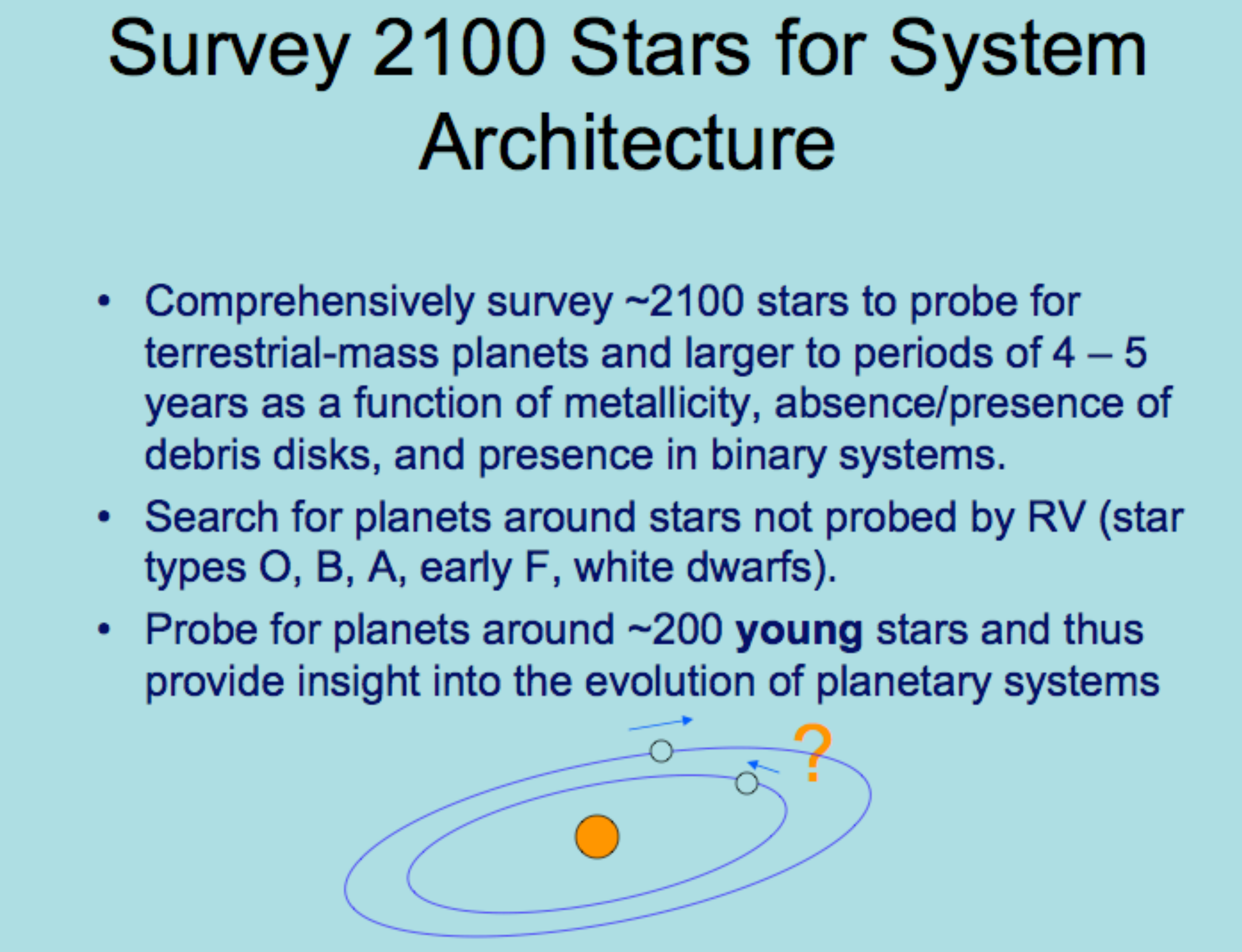


Neptunes:

Takes
only ~3%
of SIM

-Fewer visits
-Lower Prec.

Tier-2 Survey at 4 μas



Survey 2100 Stars for System Architecture

- Comprehensively survey ~2100 stars to probe for terrestrial-mass planets and larger to periods of 4 – 5 years as a function of metallicity, absence/presence of debris disks, and presence in binary systems.
- Search for planets around stars not probed by RV (star types O, B, A, early F, white dwarfs).
- Probe for planets around ~200 **young** stars and thus provide insight into the evolution of planetary systems

What About Kepler?

- Kepler is a transit mission that looks at ~100,000 stars in a 12° solid angle of sky in the direction of Cygnus/Lyra.
  - Stars at average distance of ~1 kpc.
    - Difficult to follow up by direct detection.

  - Transit requires alignment of the planetary plane with line of sight.
    - 0.5% to 1% will be so aligned.

  - Transit methods can give size, if stellar distance is accurately known, but not mass.

- Kepler will measure the frequency of habitable terrestrials.
  - That will be useful in selecting the PH depth of search.

What About Gaia?

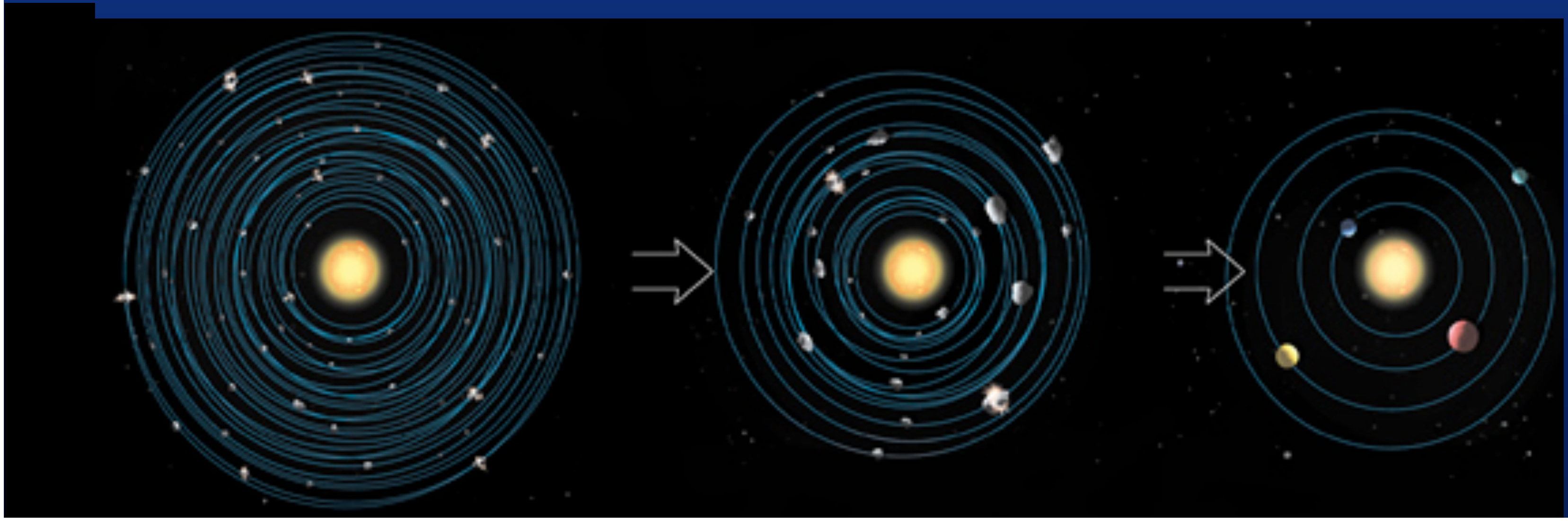
- Gaia is a scanning astrometry mission like Hipparcos.
  - Will achieve a mission accuracy of ~6 μas for stars between ~V7 and ~V12.
- All PH target stars are too bright for Gaia (≤ V7).
- Gaia's precision of 6 μas is not sufficient to detect HZ terrestrial planets.

Theory of Rocky Planet Formation Inward of 2 AU

Assume **Planetesimals** (km-sized comets & asteroids)

- Orderly growth by collisions.
- Dynamical Friction circularizes orbits of large “oligarchs”
- They stir small ones: excite eccentricities and inclinations
- Mergers, growth to 1 M_{earth}

Lithwick, Goldreich, Sari



Ida & Lin 2008 (last month)

Toward a Deterministic Model of Planetary Formation V.

Accumulation Near the Ice Line and Emergence of Short-Period Earths

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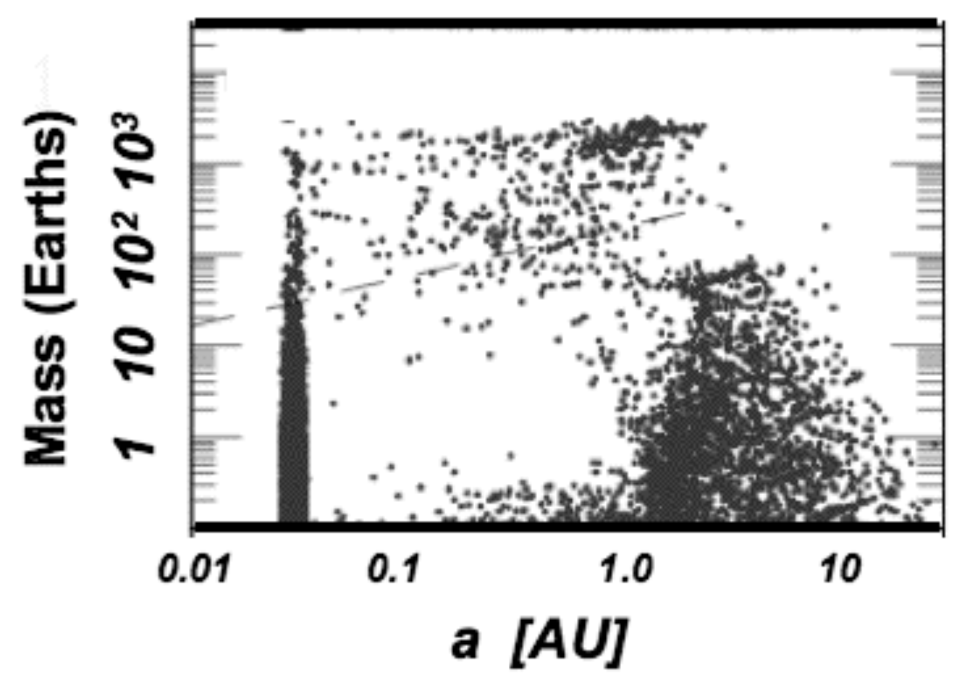
ABSTRACT

We address two outstanding issues in the sequential accretion scenario for gas giant planet formation, the retention of dust grains in the presence of gas drag and that of cores despite type I migration. The efficiency of these processes is determined by the disk structure. Theoretical models suggest that planets form in protostellar disk regions with an inactive neutral "dead zone" near the mid plane, sandwiched together by partially ionized surface layers where magnetorotational instability is active. Due to a transition in the abundance of dust grains, the active layer's thickness decreases abruptly near the ice line. Over a range of modest accretion rates ($\sim 10^{-9} - 10^{-8} M_{\odot}$ yr^{-1}), the change in the angular momentum transfer rate leads to local surface density and pressure distribution maxima near the ice line. The azimuthal velocity becomes super Keplerian and the grains accumulate in this transition zone. This barrier locally retains protoplanetary cores and enhances the heavy element surface density to the critical value needed to initiate efficient gas accretion. It leads to a preferred location and epoch of gas giant formation. We simulate and reproduce the observed frequency and mass-period distribution of gas giants around solar type stars without having to greatly reduce the type I migration strength. We also predict slightly smaller populations of Earth-mass planets in the habitable zone and close to their host stars. The mass function of the short-period planets can be utilized to calibrate the efficiency of type I migration and to extrapolate the fraction of stars with habitable terrestrial planets.

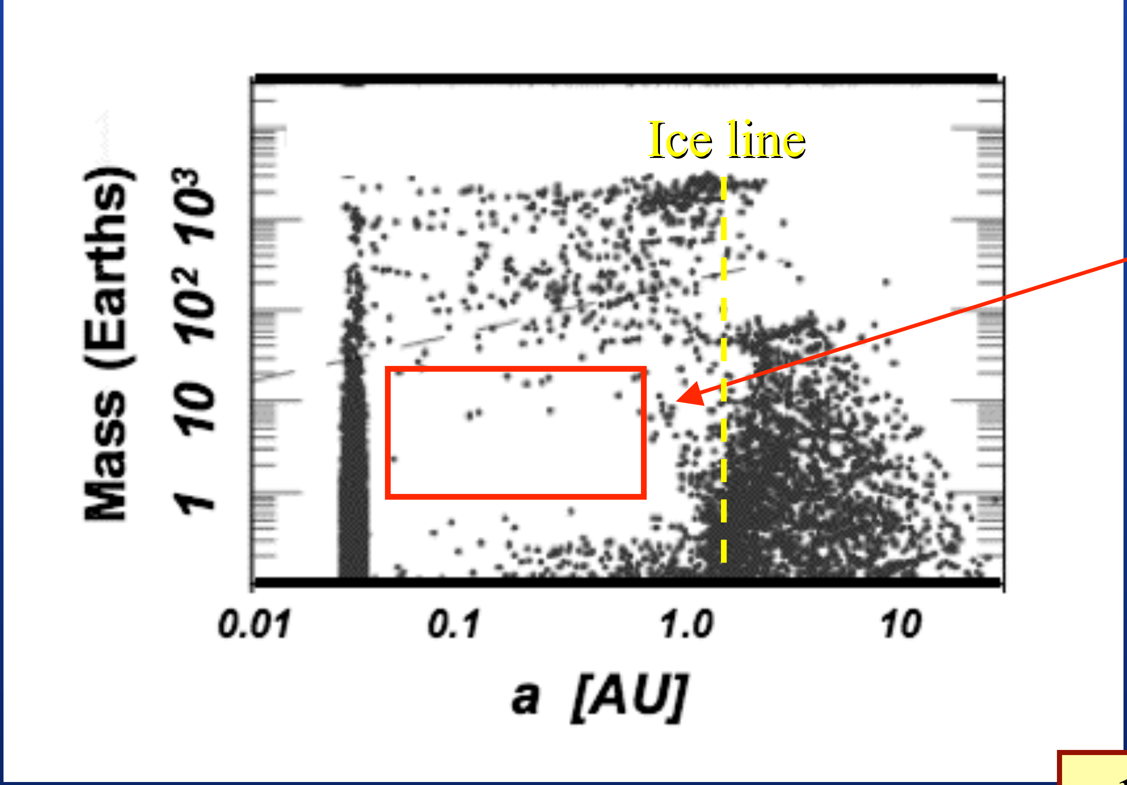
Predicted Distribution of
Mass-Semimajor Axis
(Ida & Lin 2008)



C1=0.3,
Both σ_gas and σ_dust
enhanced at ice line

Predicted Distribution of Mass-Semimajor Axis

(Ida & Lin 2008)



Planet Desert:
a = 0.05 - 1.0 AU
$M = 1 - 30\ M_{Earth}$

Migration fast through desert.

- H_2O and (H & He) makes super-Earths
- But causes migration.

After 10 Myr:

Gas Gone, No Migration

- *Ida & Lin don't include t > 10 Myr :*

- $1\ M_{Earth}$: Largest rocky planet?
- Formation of $M > 1M_{Earth}$ decoupled from $M < 1M_{Earth}$
- Super-Earths: don't inform us of Earths

Summary

Planet Search

- Detects Rocky Planets at ~1 AU around Nearby Stars
- Survey 100 AFGKM Stars (within 20 pc)
- Rocky Planets: Occurrence, Masses, Orbits
- Theory of rocky planets: Not well constrained
- Mass Desert: 1 - 30 M_{Earth} ?

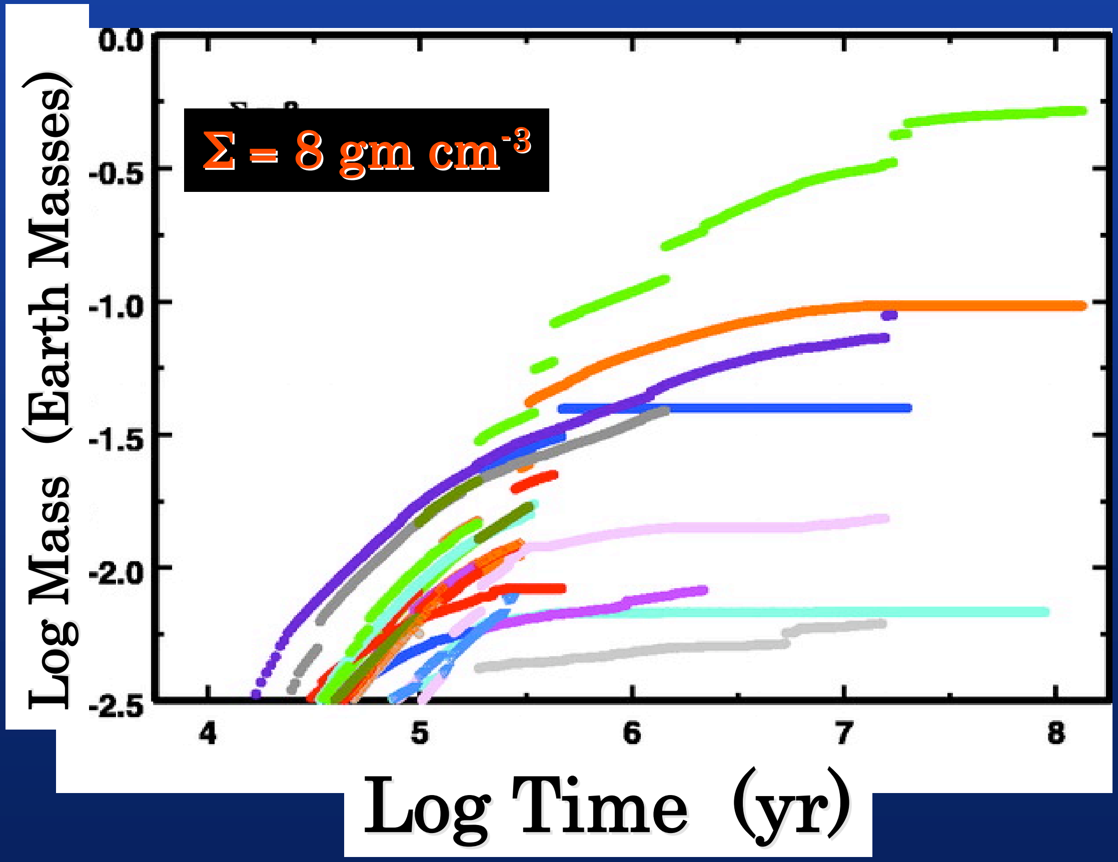
Detects Earths @ FAP < 1 %

Keys for Terrestrial Planet Finder (TPF):

- SIM Identifies Stars with Earths
- SIM Sets Time of Maximum Angular Sep.

Kenyon & Bromley (2006)

Rocky Planet Mass Growth Rate



Evolution of masses for oligarchs in a full planet-formation calculation at 0.86–1.14 AU.

Each colored track shows the mass evolution for one oligarch. Discontinuities or terminations in the tracks indicate mergers of large objects.

$\tau = 10^7$ years

$M > 1\ M_{earth}$ are rare !?

Water Content of Rocky Planets

N-Body Planet Growth with Water Delivery
Raymond, Quinn, Lunine 2004

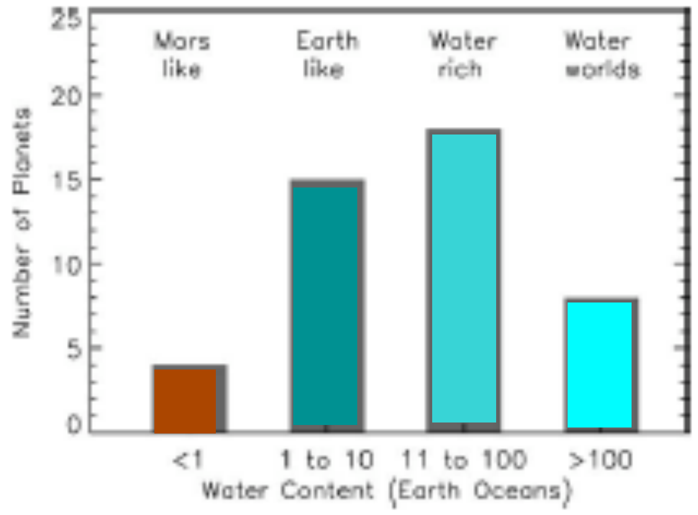


Fig. 9. Histogram of the water content of 45 planets with 0.8 AU < a < 1.5 AU which formed in 44 simulations. See text for discussion.

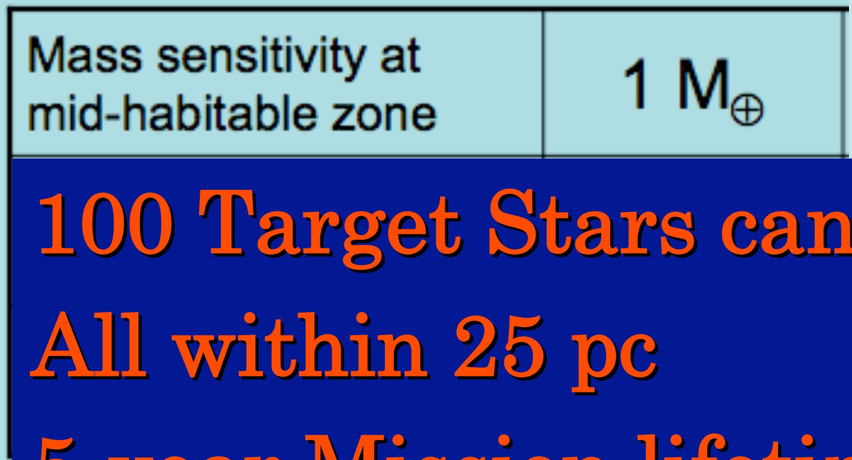
- Water Delivery: Comets & hydrated asteroids
- H_2O content vs r_{orb} from meteorites
- N-body: collisions deliver H_2O
- Jupiter ejects asteroids, preventing their delivery of water to the terrestrial planets at 1 AU.

- Continuous H_2O delivery
- Loss of H_2O by impacts ? ? ?

- Water-rich worlds common ?:
10 - 100 “Earth-Oceans”

Most are Water Worlds

PlanetHunter Survey for Earths



Mass sensitivity at mid-habitable zone	1 $M_\oplus$

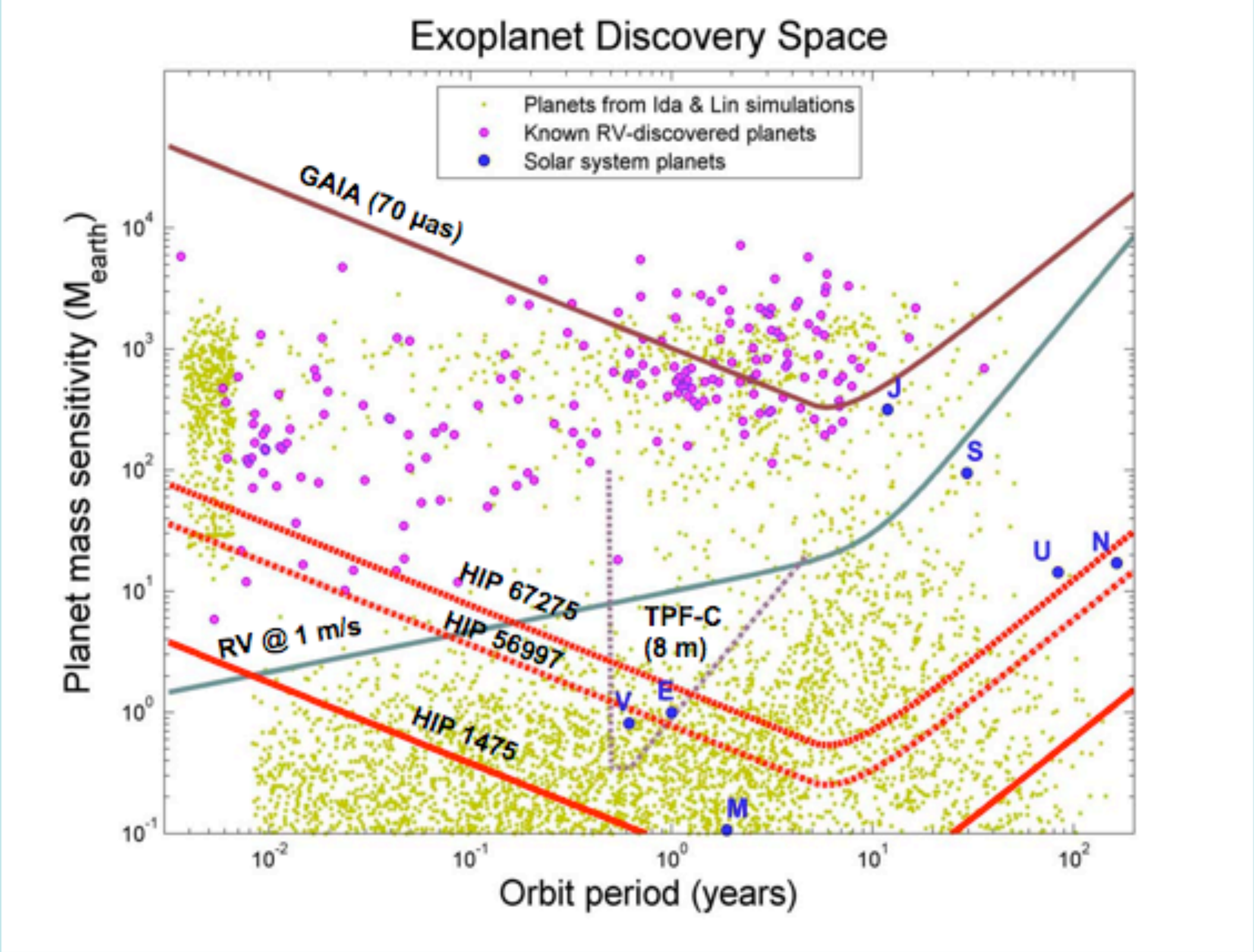
100 Target Stars can be surveyed

All within 25 pc

5-year Mission lifetime

Primary Goal

PlanetHunter will find Earth-Analogs Around nearest Solar-Type Stars



PlanetHunter Characterizes Rocky Planets

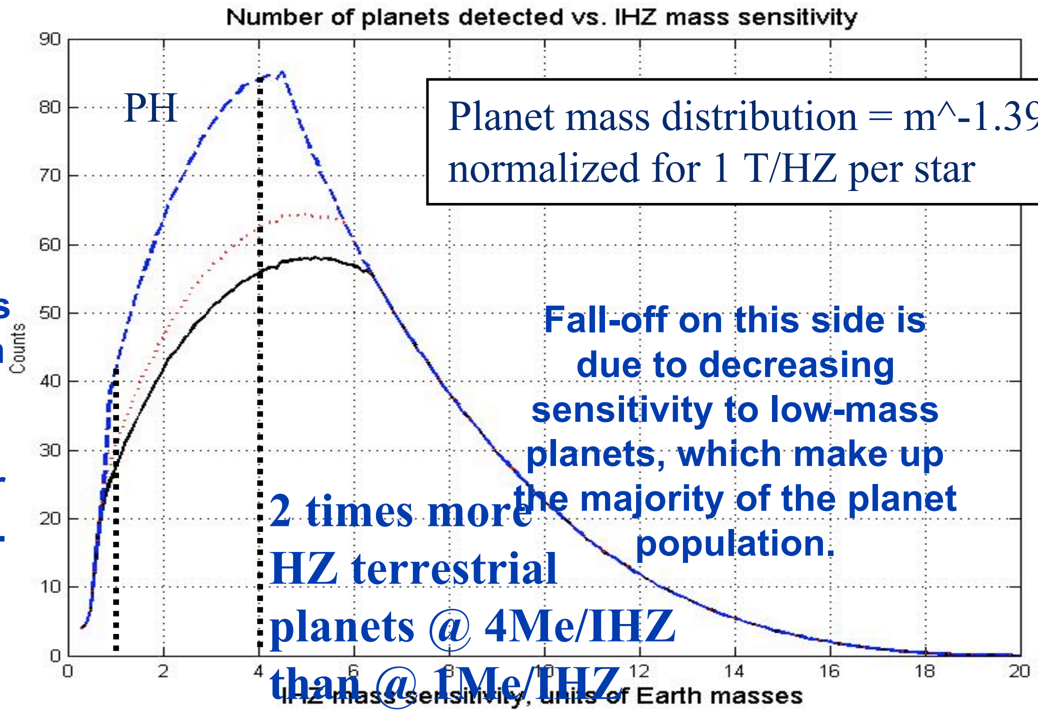
Measures:

- Planet Masses
- Orbital Parameters (all 7)
- Occurrence Rate of Earths
- Other giant planets in system
- Infer Temperature (modulo greenhouse)

Expected Yield of Habitable Planets

ExoPTF recommendation does not yield the maximum number of HZ terrestrials.
What *is* the best objective?

Fall-off on this side is due to lack of available targets that can be probed to lower masses.



Planet mass distribution = m^-1.39
normalized for 1 T/HZ per star

Fall-off on this side is due to decreasing sensitivity to low-mass planets, which make up the majority of the planet population.

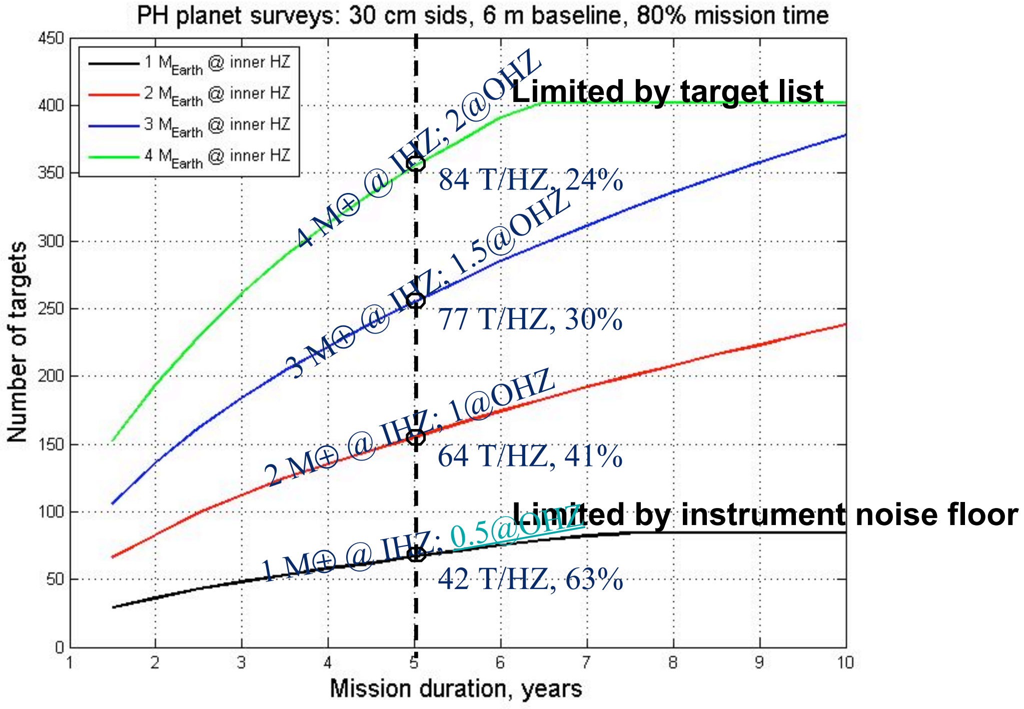
2 times more HZ terrestrial planets @ 4Me/IHZ than @ 1Me/IHZ

Maximum yield of HZ terrestrial planets	
PH30 with 80% of mission time	85

Curves assume 1 HZ terrestrial per star. More likely will by ~0.1 to 0.2 HZ terrestrial per star.

Preliminary

PH: number of survey targets



Search depth, M_{Earth}@ IHZ	# targets
1	67
2	155
3	255
4	355

T/HZ planet counts assume that each star has one T/HZ planet drawn from a mass Distribution of m^-1.39 normalized for one T/HZ planet per star.

What About Doppler?

- Doppler shift in stellar spectrum gives star’s motion about the star-planet barycenter.
  - Currently limited to ~1 m/s precision. Possibly improving to high fractions of a m/s in coming decade.
  - Can find HZ terrestrials only around coolest M-dwarfs.
    - Can’t reach FGK dwarfs in reasonable observation time (would take many 10’s of yrs to accomplish PH mission).

PlanetHunter: Conclusions

- PH is the next logical step in the search for *nearby* habitable terrestrial planets around Sun-like stars.
  - Provides unambiguous mass.
  - Provides orbital parameters for direct detection follow-up.
  - Recommended by ExoPlanet Task Force.
- Performance verified by a rigorous double-blind planet finding capability stu
  - Finds HZ terrestrials even in complex planetary systems.
- PH is technically ready to go now.
  - Technology completed in 2005.
  - Designs mature: based on SIM designs developed over last 12 years.

Term	Description	Value
Interferometer Baseline (BL)	The distance between two collecting mirrors.	6 m
Single Measurement Accuracy (SMA)	The uncertainty associated with measuring the angle between the baseline vector and target star.	1.0 µas, 1-sigma RMS
One-Dimensional (1D) Measurement Accuracy or Differential Measurement Accuracy (DMA)	During a typical ~1100 s measurement, the angle between the target star and baseline vector is measured to the SMA. Similarly, the angle between the baseline vector and a reference star (or the average of a group of reference stars) is determined to the SMA. Both angles are measured from one interferometer baseline orientation in inertial space. The angle between the target star and the reference is the difference between these two angles with a resulting accuracy given by the root-sum-square (RSS) of these two measurement accuracies.	1.4 µas, 1-sigma RMS
Two-Dimensional (2D) Measurement Accuracy	Two one-dimensional (1D) measurements made with roughly orthogonal interferometer baseline orientations and made relatively close together in time.	2-axis, 1.4 µas on each axis, 1-sigma RMS.
External Delay Uncertainty Noise Floor (EDUNF)	Uncertainty in measuring the difference in external delays resulting from all instrument errors (see the Astrometric Error Budget (AEB)) as validated by testbed measurements.	1 picometer, 1-sigma RMS
Instrument Noise Floor (INF)	Noise floor for measuring the angular distance between two stars, determined from the fringe position uncertainty noise floor and the interferometer baseline (EDUNF/BL*asec/radian).	0.035 µas
N_Obs_Max, or N_lim (2D)	The number of 2D differential measurments that can be made on a single target star that results in net noise reaching the Instrument Noise Floor. Equals (DMA/INF)^2.	1,600
Minimum Detectable Astrometric Signature (MDAS)	Instrument Noise Floor times desired SNR. For 1% false alarm probability (FAP), want SNR=~6. INF*SNR=0.035µas*6= 0.21µas.	0.21 µas
Minimum Detectable Earth-like Planet Mass	This is dependent upon the MDAS, star distance, stellar mass, and the planet's orbit. For a one Solar mass star at 10 pc, the minimum detectable habitable-zone planet mass depends upon where the planet is in the habitable-zone as shown below.	See below
	At the outer edge of habitable zone (1.6 AU)	0.44 Mearth
	Mid habitable zone (1.0 AU)	0.70 Mearth
	At the inner edge of the habitable zone (0.82 AU)	0.85 Mearth

Ida Lin Models:

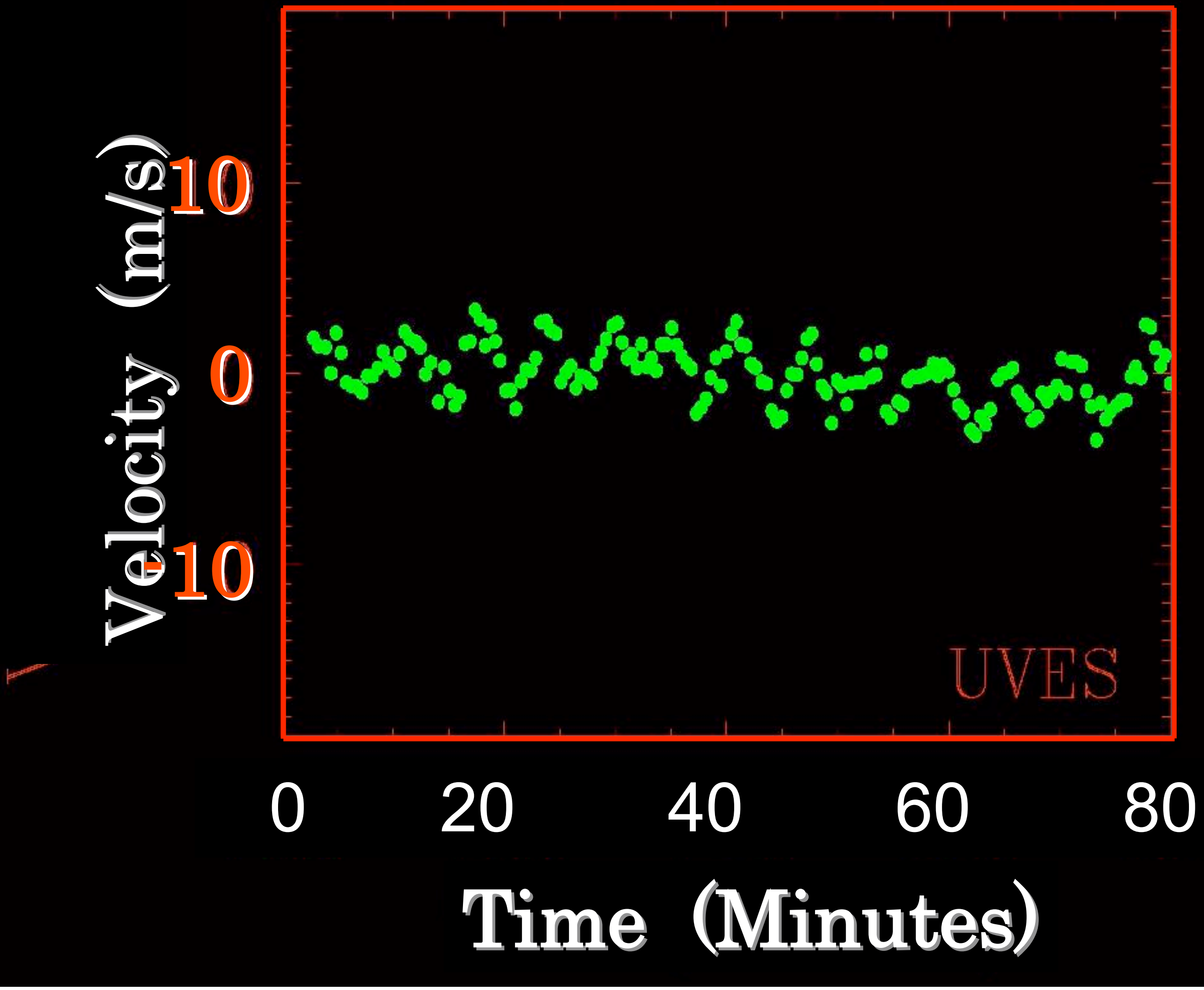
- Dust and Gas: $\sigma \sim a^{-3/2}$
- Growth to Mars-size ("embryos")
- Type I Migration: Tidal Interaction with disk *gas*.
- Migration too fast (~100 yr): requires suppression
- Past: Migration Fudge factor, $C_1 \ll 1$
- Determines dN/da (distrib. of planet orbital radii)

Idea: At ice line (~2.5 AU) icy dust removes electrons,
suppressing ionization and hence suppresses
magneto-rotational instability, lowering viscosity.

- Low accretion rate --> ***build-up material at ice line***

Acoustic p-modes in Solar-Type Stars

Alpha Cen A (G2 V)



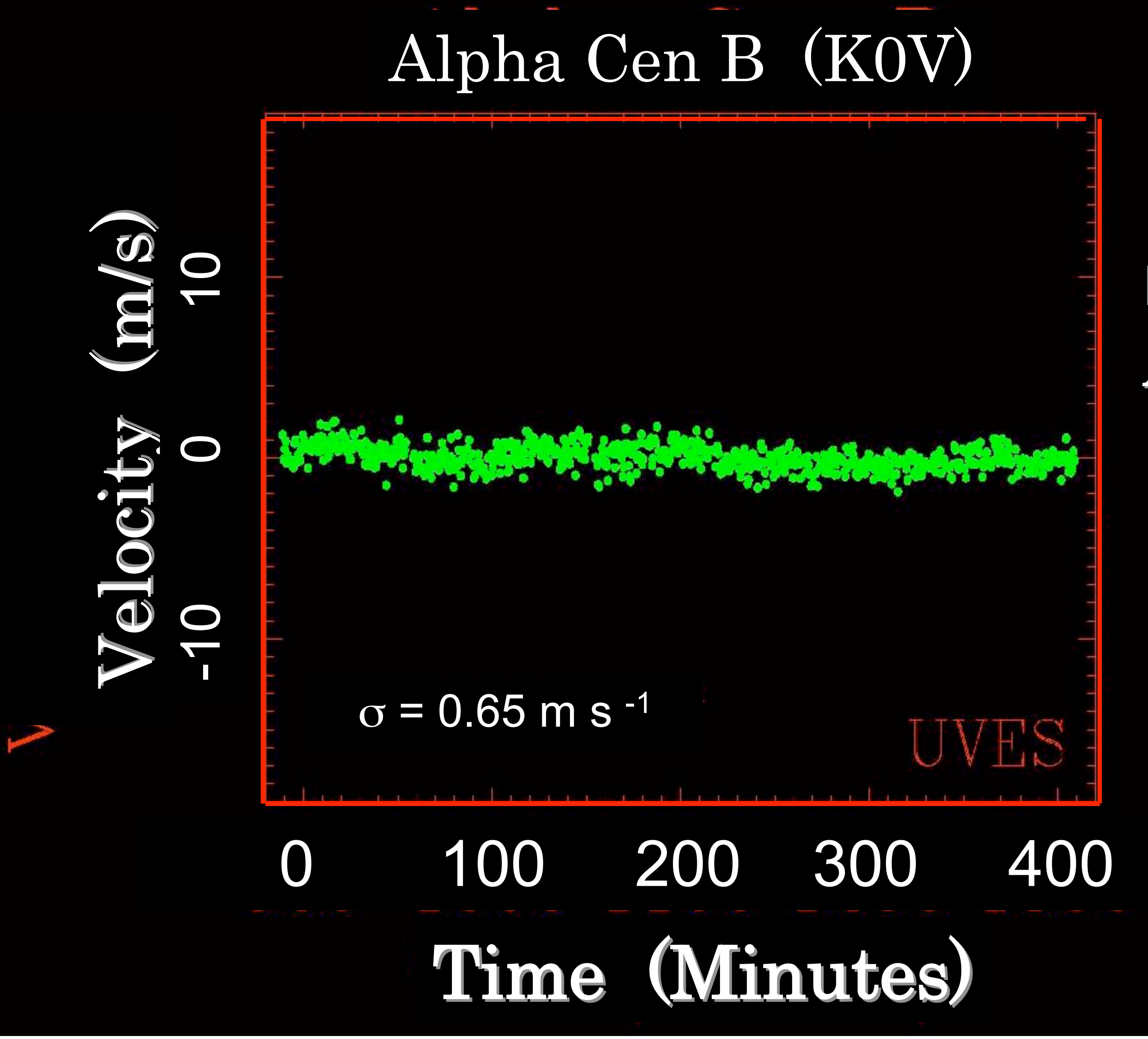
Amp ~ 1.5 m/s
Period = 5 min

“Noise”

Avg over
P-modes !?

o: Coherence
times hours-days

Acoustic P-modes in K dwarfs



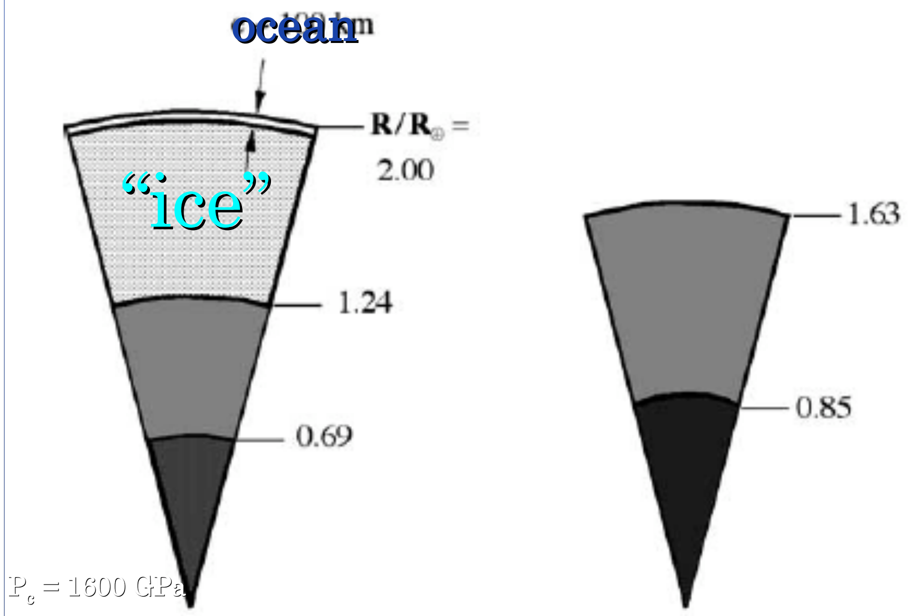
K dwarfs Quieter:

Amp ~ 0.5 m/s

Earth Formation *beyond* 2 AU:
10 - 50% H_2O

$6\ M_{Earth}$ Planets:

$50\%\ H_2O$ **No H_2O**



6 M⊕ Ocean-Planet
(3 M⊕ metals & silicates
+ 3 M⊕ H_2O)

6 M⊕ Rocky Planet
(6 M⊕ metals & silicates)

$\rho = 4.3\ g\ cm^{-3}$ $\rho = 7.7\ g\ cm^{-3}$

- H_2O Atmosphere +
- H_2O Ocean +
- Ice Envelope (ala Neptune)

- Lower Density than rocky planets

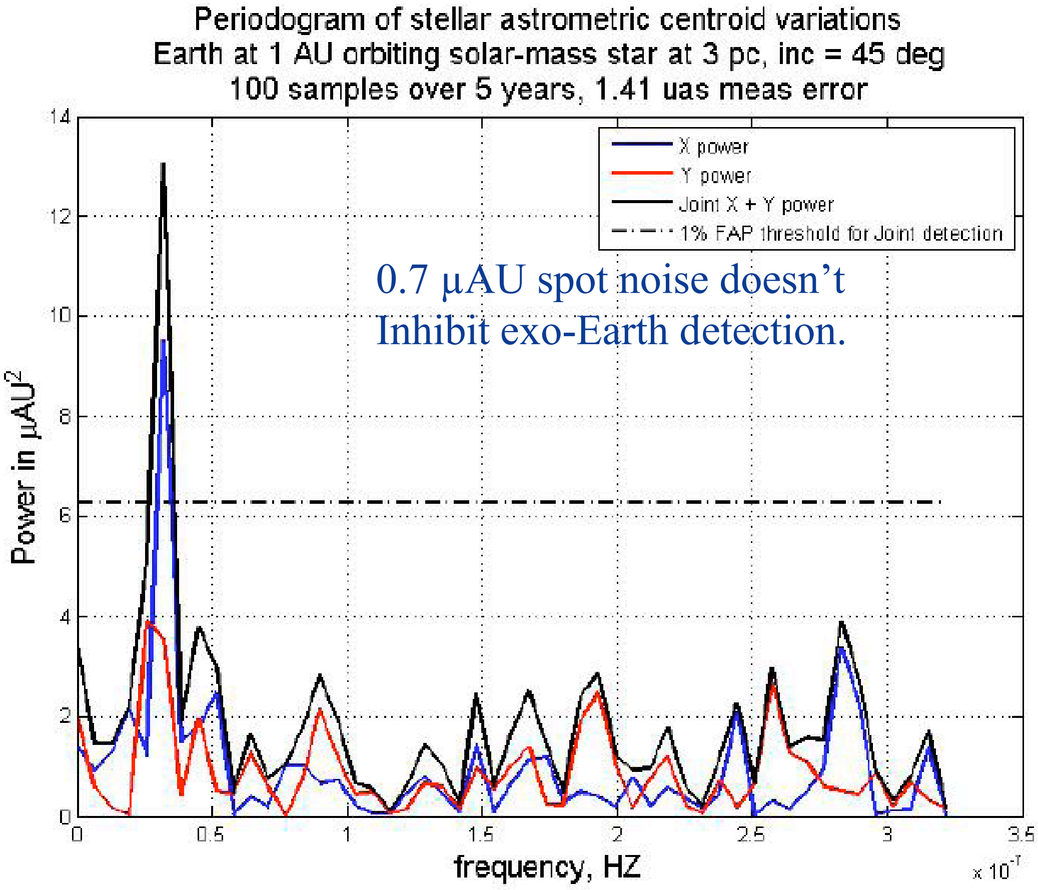
- Distinguish water worlds from rocky worlds:

Need SIM and transit →
Mass & Radius .

Kuchner (2003), Sotin et al. (2007),
Valencia, Sasselov, O'Connell (2006)
Leger 2004, Raymond 2005

PH Astrophysical Errors

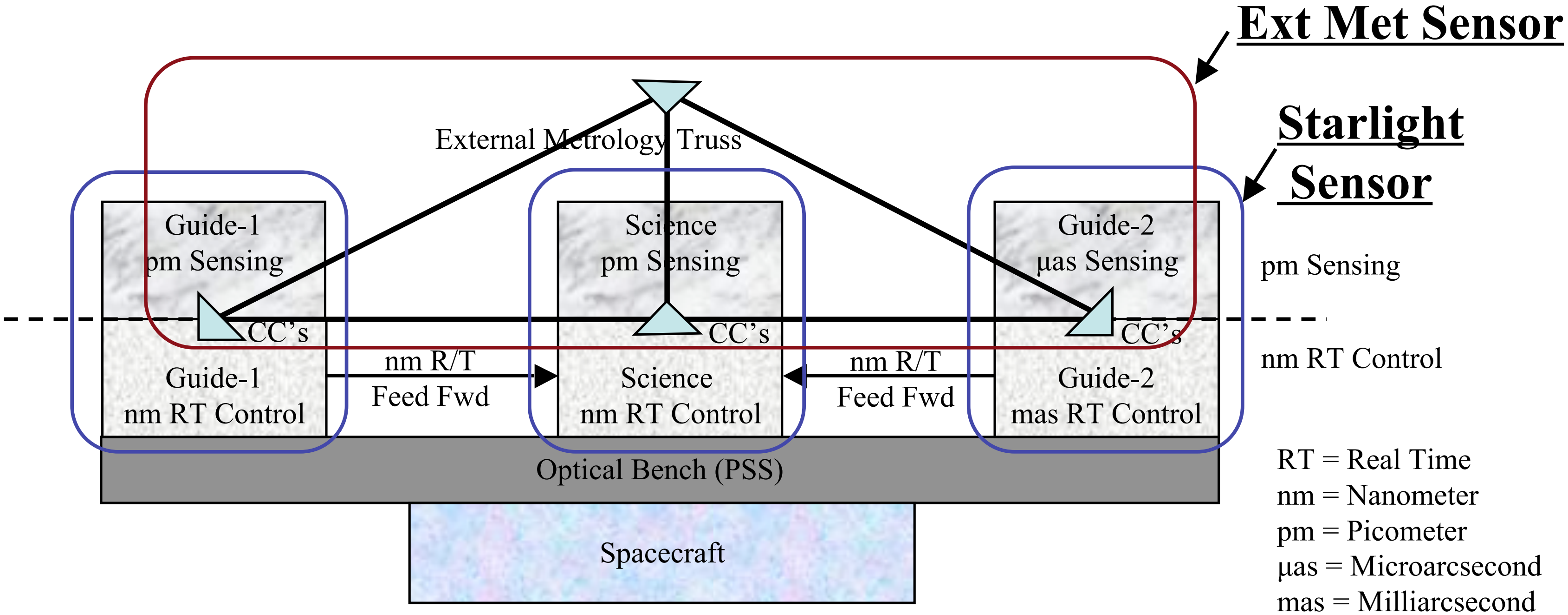
- Reference star companions
  - Three cases:
    - (1) Large, so pre-screened by RV;
    - (2) Too small (ignore);
    - (3) Solved for along with target star companions.
- Star Spots impact on detection of habitable exo-Earths:
  - Astrometry: Spot noise significantly below exo-Earth signature and instrument noise.
  - RV: Sport noise larger than exo-Earth signature.
  - See Proc SPIE Vol. 7013, 70132K



0.7 µAU spot noise doesn't Inhibit exo-Earth detection.

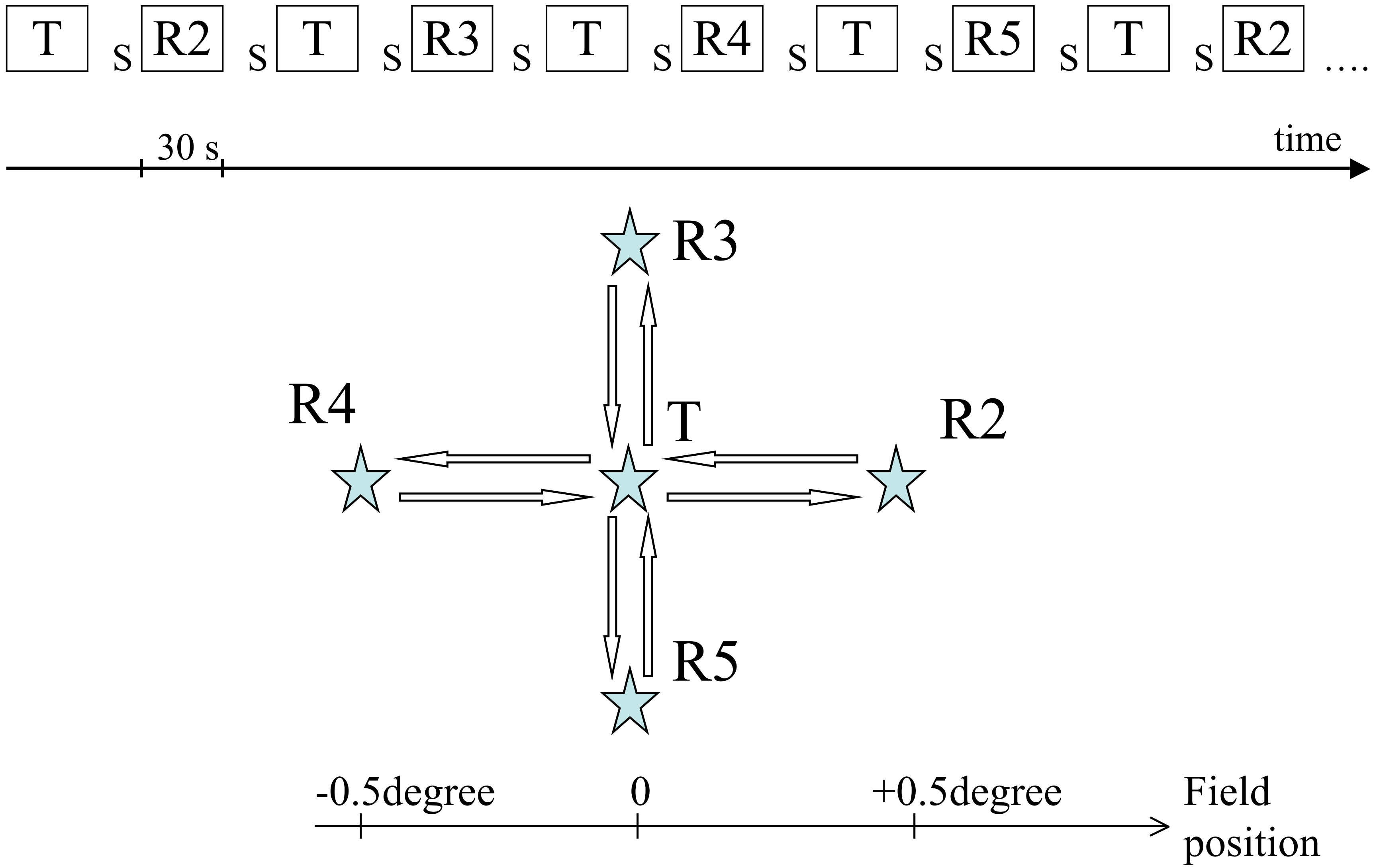
PH Building Blocks

- PH operates in two distinct regimes: (1) real-time nanometer control and (2) picometer sensing
  - Real-time nanometer control is system-wide and does not depend upon picometer sensing (nm-level external metrology information is used in real-time control)
  - Picometer sensing runs on top of real-time nanometer control (i.e., picometer measurements are taken while the system is operating in the real-time nanometer control), with all data being sent to the ground for mission processing
- Interferometer and external-metrology picometer-sensors are separable and intersect only at fiducials.



RT = Real Time
nm = Nanometer
pm = Picometer
µas = Microarcsecond
mas = Milliarcsecond

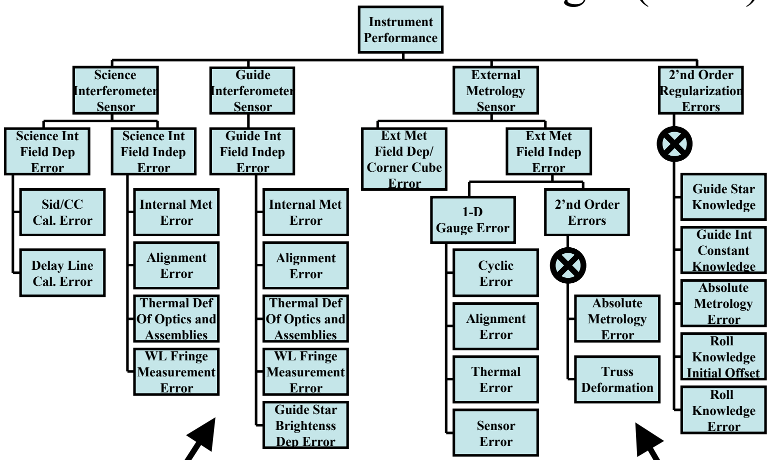
Five-star Narrow Angle observation sequence



Performance Prediction & Validation

AEB, testbeds, model predictions & integrating analytical models used to verify overall system performance (for both Technology Development and Flight)

Astrometric Error Budget (AEB)



- Instrument Performance
  - Science Interferometer Sensor
    - Science Int Field Dep Error
      - Sid/CC Cal. Error
      - Delay Line Cal. Error
    - Science Int Field Indep Error
      - Internal Met Error
      - Alignment Error
      - Thermal Def Of Optics and Assemblies
      - WL Fringe Measurement Error
  - Guide Interferometer Sensor
    - Guide Int Field Indep Error
      - Internal Met Error
      - Alignment Error
      - Thermal Def Of Optics and Assemblies
      - WL Fringe Measurement Error
      - Guide Star Brightenss Dep Error
  - External Metrology Sensor
    - Ext Met Field Dep/ Corner Cube Error
    - Ext Met Field Indep Error
      - 1-D Gauge Error
        - Cyclic Error
        - Alignment Error
        - Thermal Error
        - Sensor Error
      - 2'nd Order Errors
        - ⊗
          - Absolute Metrology Error
          - Truss Deformation
  - 2'nd Order Regularization Errors
    - ⊗
      - Guide Star Knowledge
      - Guide Int Constant Knowledge
      - Absolute Metrology Error
      - Roll Knowledge Initial Offset
      - Roll Knowledge Error

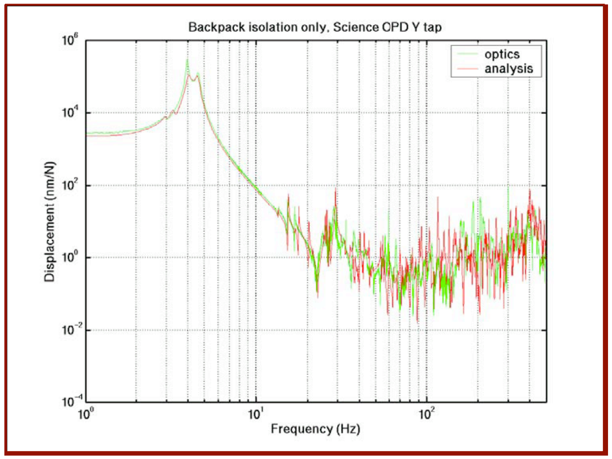
AEB top-level summary.

Verify Physics

Independent Review & Assessment

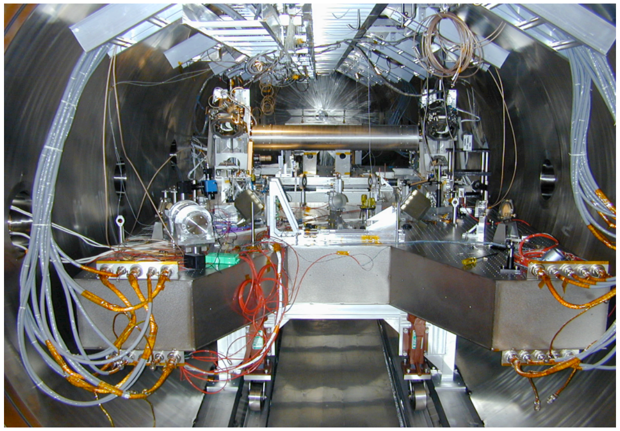
-Allocation/Capability

-Verify no missing terms



Model Predictions

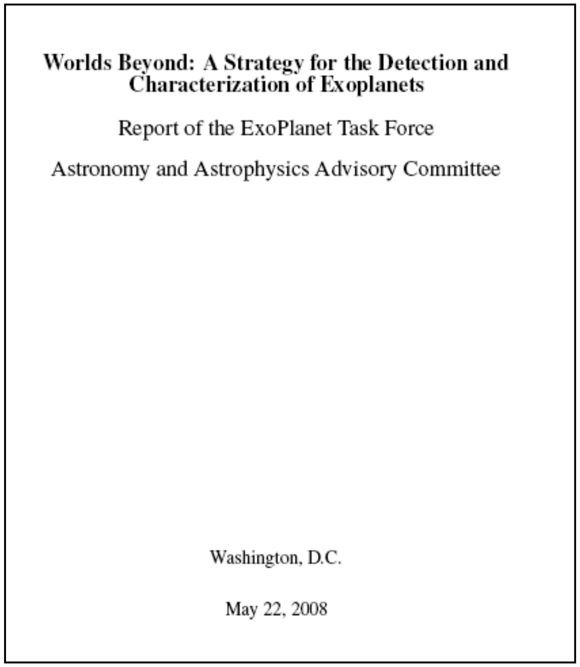
Confirm physics-based predict match actual?



Testbed Demonstrations

Who Wants This? & Why?

- ExoPTF Final Report
  - "The only technique appropriate to survey the nearest hundred or so bright sun-like stars in the mid-term is space-based astrometry, and this is one cornerstone of the Task Force recommendations."
- "0.1.4 B. Recommendations for 6–10 Years"
  - "B. I. a.: What are the physical characteristics of planets in the habitable zones around bright, nearby F, G, K stars?"
    - "Recommendation B. I. a. 1: Launch and operate a space based astrometric mission capable of detecting planets down to the mass of the Earth around 60–100 nearby stars, with due consideration to minimizing the width of any blind spot associated with Earth's parallax motion. (This requires a mission precision, over many visits to a given star, as small as 0.2 microarcseconds.)"



Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets

Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee

Washington, D.C.

May 22, 2008

- Why?
  - Uniquely provides planet mass to ~25%
  - Provides orbital parameters
    - Helps direct detection missions know when/where to look.

PlanetHunter Mission

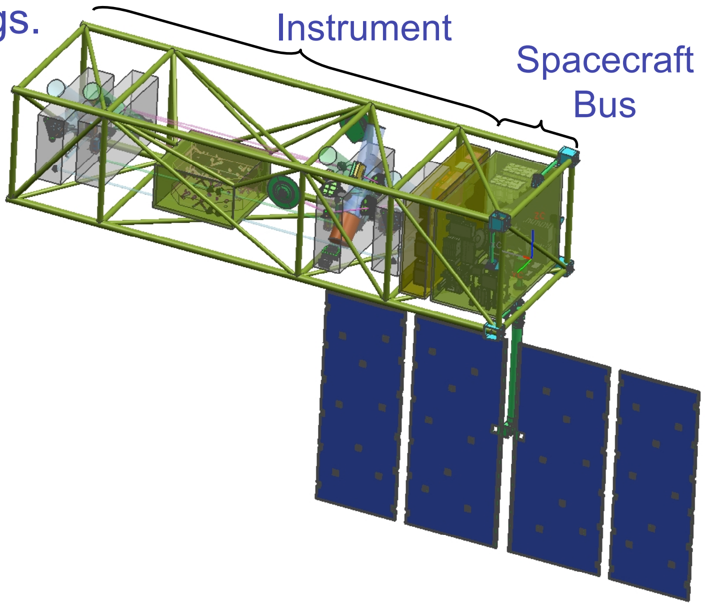
PI: Geoff Marcy, U.C. Berkeley

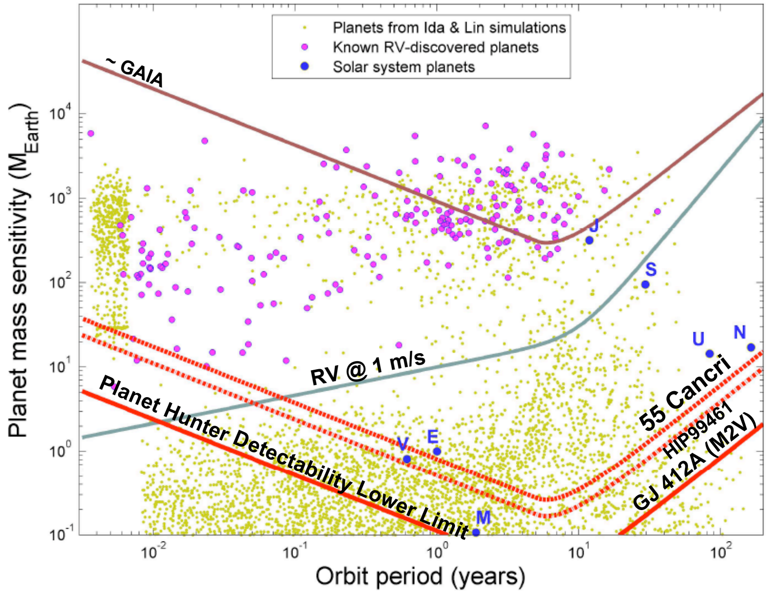
Partnering with JPL

Deep Search:
60-100 nearby FGK stars for Earth-analogs.

Broad Survey:
Planetary systems around 1000 nearby stars.

Young Planet Search:
50 nearby young stars.





6m astrometric interferometer using mature technology (from SIM).

Outline

Rocky, Habitable Planets

Within 25 pc

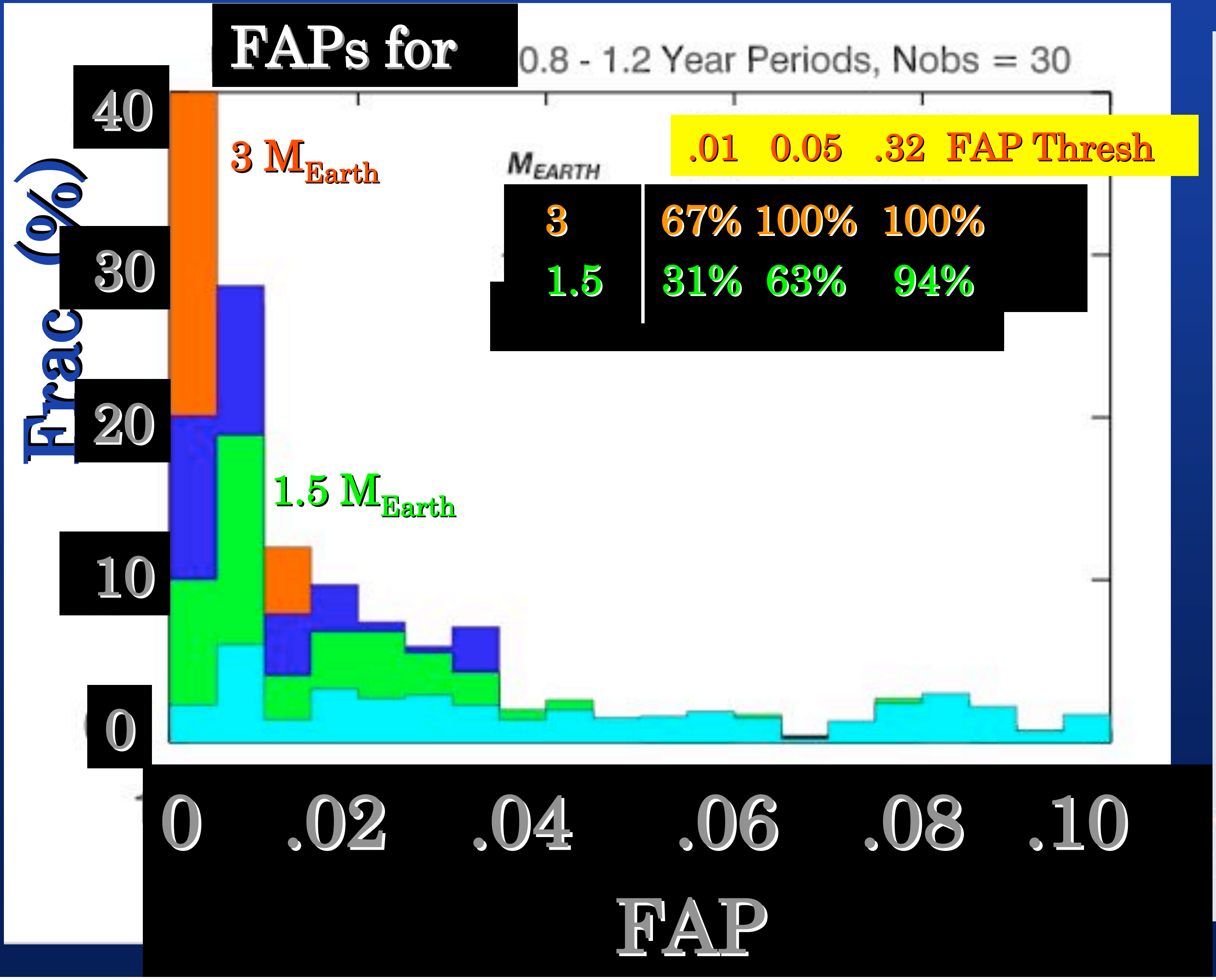
- Goals: Occurrence, Masses, Orbits, Chem.Comp.
- SIM & TPF : Only hope Except Darwin (not RV, Kepler)
- Theory: Can't predict Occurrence (or any property)
- SIM will survey 250 AFGKM Stars (15 pc):
  - Finds 3 M_{earth} @ 5 σ … *Direct Science*
  - Finds 1 M_{earth} @ 1 σ … *Feed to TPF*

1. Earth-enriched TPF stellar sample
2. Orbital phase of TPF observations:
   When planet outside 4 λ/d (0.06 arcsec).

Fraction Meeting FAP Thresh

for Different Planet Masses

(a =1 AU, d = 5 pc)



M_{EARTH}	.01	0.05	.32 FAP Thresh
3	67%	100%	100%
1.5	31%	63%	94%

For 3 M_{earth}:

100 % have

FAP < 5%

For 1.5 M_{earth}:

63% have

FAP < 5%

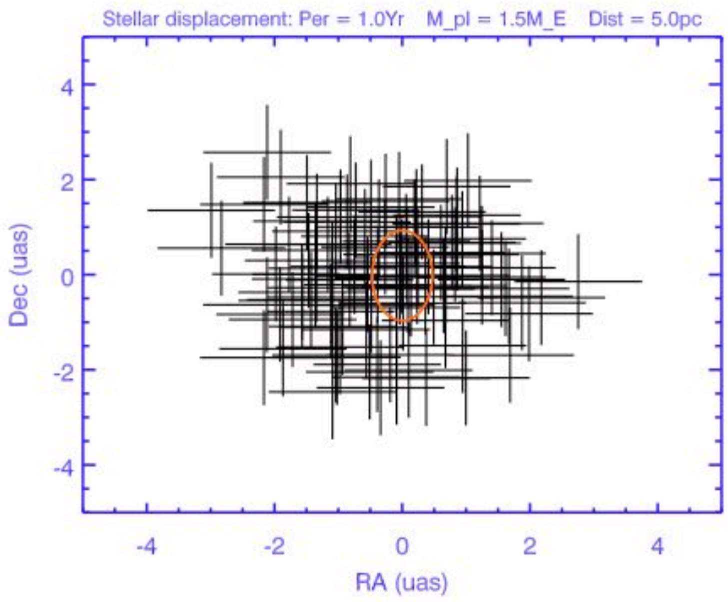
Find 63% of earths.

ncur 5% false postives

Highest Priority Stars

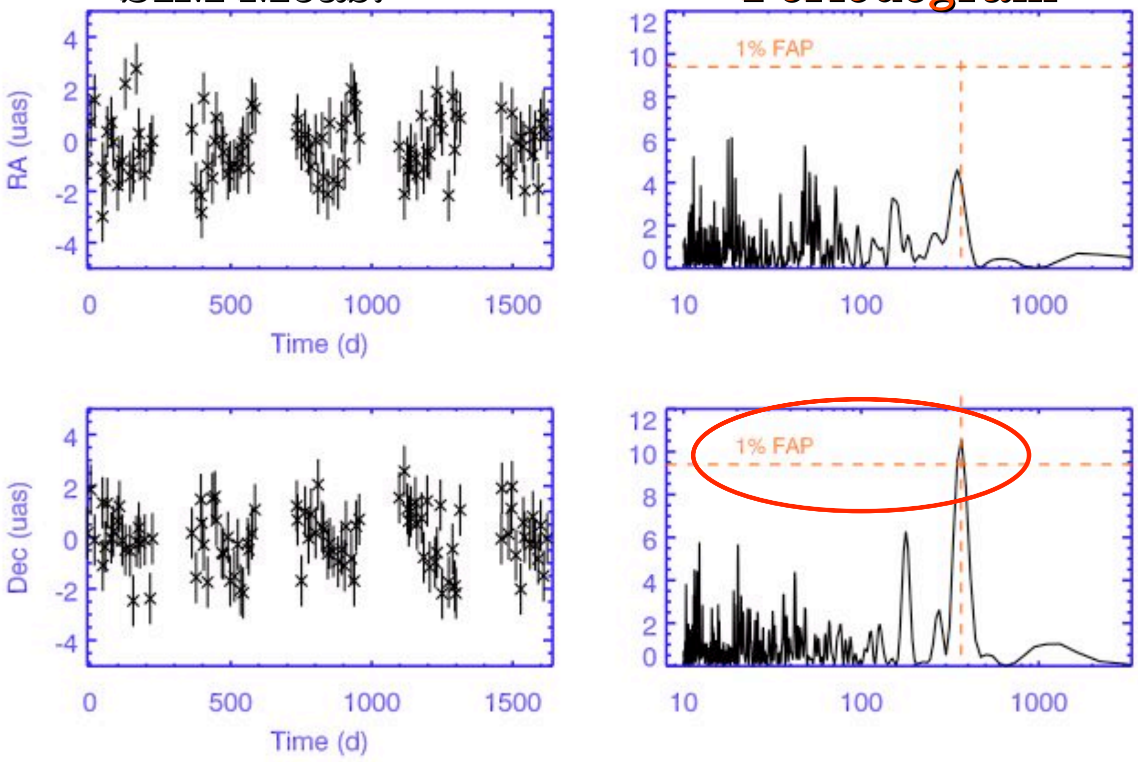
1.5 M_{earth} @ 1 AU

100 SIM Observations



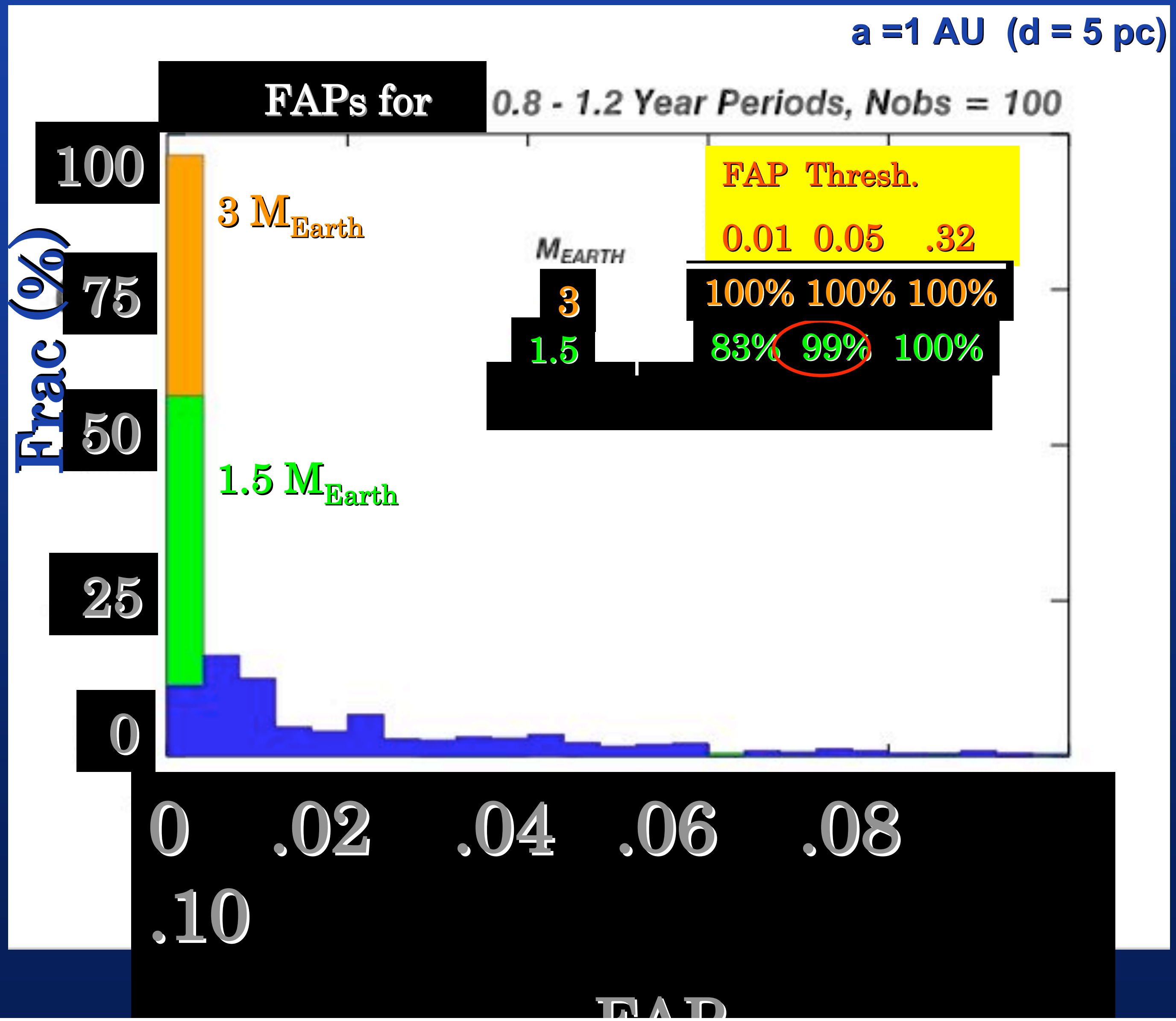
SIM Meas.

Periodogram



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%

For 3 M_{earth}:

100 % have

FAP < 5%

For 1.5 M_{earth}:

99% have

FAP < 5%

Find 99% of earths.

Incur 5% false postives