Exoplanet Probe to Medium Scale Direct Imaging Mission Requirements and Characteristics - (SAG9)

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SAG9 group (37 members, open membership to the community)
Apai, Belikov, Breckinridge, Brown, Cahoy, Cash, Choquet, Cowan, Danchi, Fortney, Gaudi Goldman, Greene, Kasting, Lawson, Levine, Lillie, Lo, Lyon, Lipscy, McElwain, N'Diaye, Mennesson, Noecker, Plavchan, Roberge, Savransky, Serabyn, Shaklan, Solmaz, Unwin, Stapelfeldt, Thomson, Trauger, Turnbull, Vasicht,

This presentation mainly based on work by Robert A. Brown (STScI)

SAG-9 progress report

- Current context with: SAG9, STDT-C, STDT-S, SDT, ACWG
- SAG9 has refocused on three areas
  - Radial Velocity Complementarity with imaging
  - Cross-Validation of Design Reference Missions
  - Overlap of Probes/AFTA with JWST and Ground-based Imaging

- Actions from SAG9 discussion at ExoPAG-8 in Denver (Oct 2013) - these actions have been completed:
  - cross-validate ETC calculations
  - clarify impact of detector noise, implement EMCCD
  - explore various parameters (Resolution, efficiency, IWA)
  - establish Design Reference Missions
  - evaluate impact of mission start date on DRM
  - evaluate maximum science metric

Near-Future ExAO Instruments and Possible Future Instruments Approximate Timescales

		2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
8m Class	VLT + SPHERE	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	Gemini + GPI	Young jovian planets: detection + spectroscopy (1–1.6 μm)															
	LBT/AO	Young + Older Super-jupiters: detection + photometry (1–5 μm)															
	Subaru/ScExAO	Super-jupiters: detection + photometry (1–2 μm)															
30m Class	GMT/ExAO?														No approved concept; Super-earths?		
	TMT/ExAO?														No approved concept; Super-earths?		
	EELT/EPIC												HZ low-mass planets, few Earth analogs, old GPs in reflected light (1–1.7 μm)				
	EELT/METIS												MIR imaging spectroscopy of disks and planets (3–10 μm)				
Space	HST	Photometry of exceptionally bright super-jupiters (1–1.7 μm)															
	JWST				Young GPs + Few Older Jovian planets (2 M_J at 4pc): detection + LR/MR spectroscopy. Disk Imaging + MR spectroscopy; IWA 0.5" 10^{-5} (1–5 μm)												
	WFIRST-2.4m Coron?									Jupiter analogs and disks, RV planets, Imaging+Spectra, 10^{-9} IWA 0.1" (0.3–1 μm);								
	Probe-class Off-Axis Mission?									Jupiter analogs; Disks and some RV planets, Imaging+LR Spectra, 10^{-9}–10^{-10} IWA 0.1"–0.3" (0.3–1 μm)							

Maximum science metric

- Target list of 15 RV planets with a(1+e)/d<0.2" (9 for 0.274")
- Assumes a limiting delta magnitude of 22.5
- zero operations considerations (exposure times, observing constraints
- This has a 3year mission limit built in (will be redone for 6 years)

IWA	0.200″	0.274″
epsilon Eri b	1.000	1.000
47 UMa c	1.000	0.000
mu Ara c	1.000	1.000
55 Cnc d	1.000	1.000
upsilon And d	0.167	…
14 Her b	1.000	…
HD 154345 b	1.000	…
HD 39091 b	0.263	0.262
HD 190360 b	0.172	0.000
HD 87883 b	1.000	0.000
GJ 832 b	0.355	0.362
HD 217107 c	0.069	0.008
HD 134987 c	0.002	…
GJ 849 b	1.000	…
GJ 179 b	1.000	…
$\hat{N}_{\max}$	10.028	3.632

h	0.30		0.05	
$\mathcal{R}$	20	50	20	50
epsilon Eri b	0.57	1.44	3.53	9.21
47 UMa c	2.54	6.55	16.79	48.89
mu Ara c	2.58	6.65	17.07	49.79
55 Cnc d	5.17	13.61	36.54	116.29
upsilon And d	1.13	2.88	7.14	19.34
14 Her b	10.37	28.20	80.37	282.50
HD 154345 b	14.33	39.62	116.40	428.04
HD 39091 b	4.90	12.89	34.46	108.89
HD 190360 b	4.54	11.89	31.61	98.84
HD 87883 b	30.14	87.02	274.12	1104.95
GJ 832 b	25.28	72.23	223.92	884.87
HD 217107 c	7.26	19.39	53.53	178.76
HD 134987 c	10.71	29.16	83.34	294.30
GJ 849 b	316.21	1021.54	3745.44	17680.52
GJ 179 b	2425.58	8207.00	31697.84	156394.22

Credit: Bob Brown

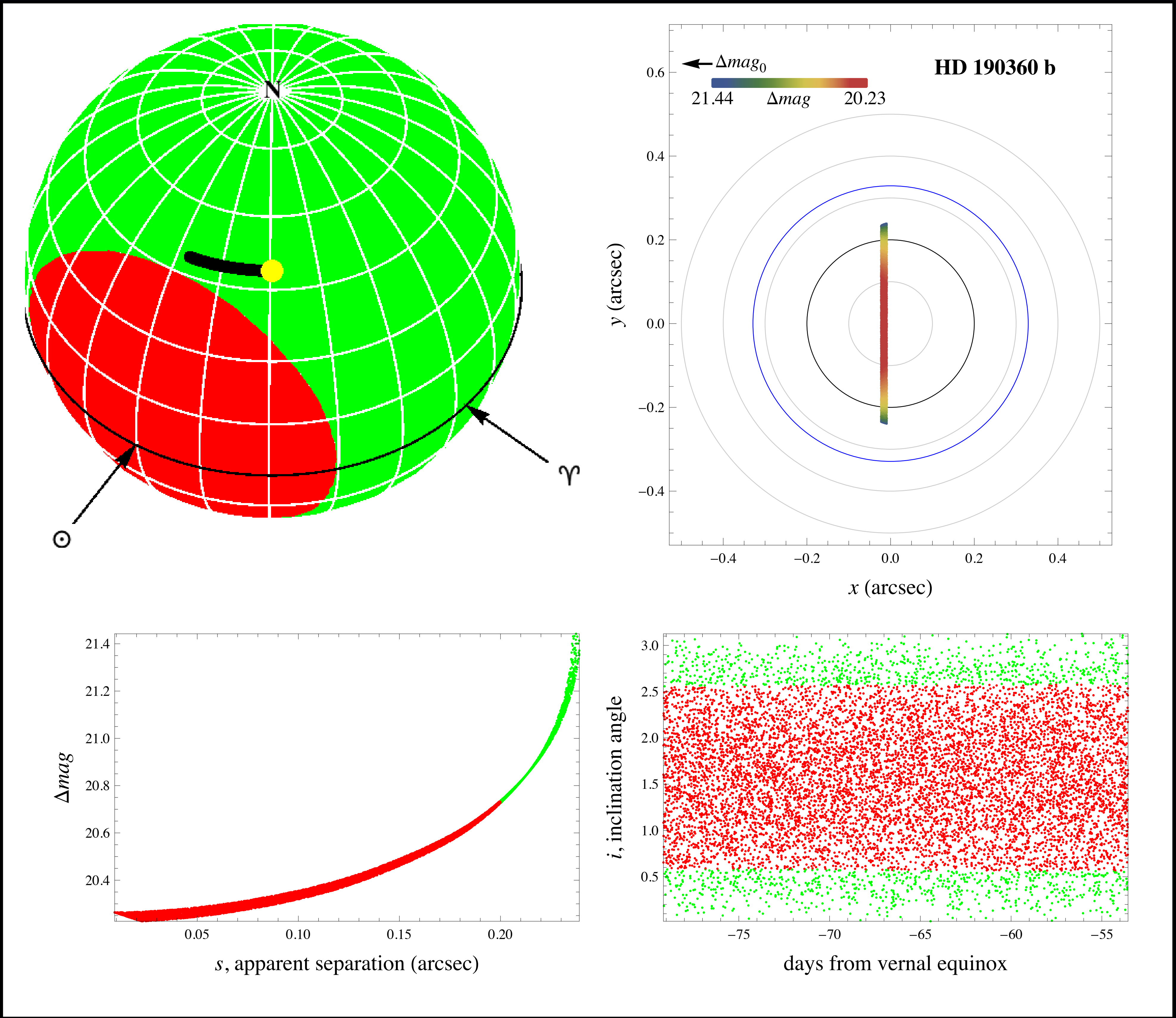
Design reference missions (DRMs)

- Science Metric: number of RV planets characterized by the mission
- Merit function for the DRM: information rate, i.e. net completeness per unit time.
    - about 30 parameters included in the merit function
        - *IWA, Resolution, detector parameters, telescope diameter, sharpness, albedo, radius of planet, etc.*
    - At each step in the DRM the merit function is calculated with remaining planets in play
    - Next target scheduled has the highest merit function
- a DRM is the complete list of observations, exposure times, science metric

- DRM here presented for the case of AFTA
    - IWA of 3 or 4 lambda/D at 800nm
    - limiting delta magnitude 22.5 (1E-9) , raw contrast: 1E-8

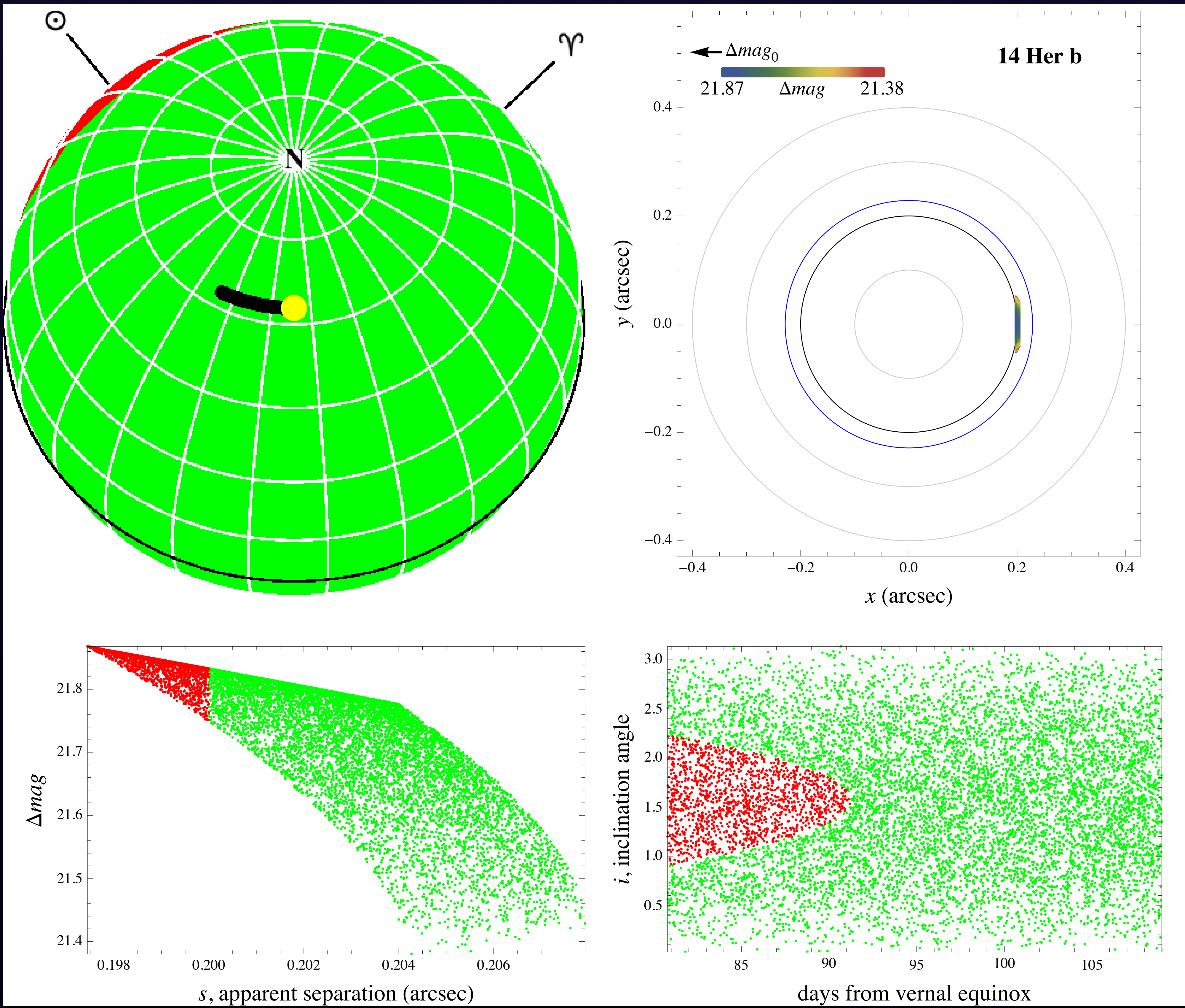
Credit: Bob Brown

Example for a particular star (I)



Credit: Bob Brown

Example for a particular star (II)



Credit: Bob Brown

Merit function example

- Example form a typical DRM at a given step in the DRM

RV exoplanet	SVP&OC	τ_{exp} (days)	pointing permitted?	net completeness	merit (days^{-1})
GJ 832 b	0.3339	25.2814	No	0.	0.
14 Her b	0.	10.3723	Yes	0.	0.
GJ 849 b	0.9906	316.207	No	0.	0.
HD 217107 c	0.0045	7.25702	Yes	0.0045	0.000620089
HD 39091 b	0.	4.90139	Yes	0.	0.
epsilon Eri b	1.	0.572872	Yes	1.	1.74559
HD 154345 b	1.	14.3254	Yes	1.	0.0698059
mu Ara c	1.	2.58249	No	0.	0.
47 UMa c	1.	2.54281	Yes	1.	0.393265
HD 134987 c	0.	10.7077	Yes	0.	0.
55 Cnc d	0.6433	5.16599	Yes	0.6433	0.124526
GJ 179 b	0.3272	2425.58	No	0.	0.
HD 87883 b	1.	30.1448	Yes	1.	0.0331732
HD 190360 b	0.1655	4.53514	Yes	0.1655	0.0364928
upsilon And d	0.	1.13461	Yes	0.	0.

Example of a particular DRM

planet	exp start	exp stop	exp time	completeness	merit function	cumulative exposure time	cumulati complete
47 UMa c	2458982.631	2458989.180	6.549	1.000	0.153	6.549	1.000
mu Ara c	2458989.180	2458995.834	6.654	1.000	0.150	13.203	2.000
55 Cnc d	2458995.834	2459009.442	13.608	1.000	0.073	26.810	3.000
14 Her b	2459009.442	2459037.639	28.197	0.841	0.030	55.008	3.841
epsilon Eri b	2459037.639	2459039.082	1.443	1.000	0.693	56.451	4.841
HD 154345 b	2459039.082	2459078.702	39.620	1.000	0.025	96.071	5.841
HD 39091 b	2459078.702	2459091.587	12.885	0.078	0.006	108.956	5.918
HD 217107 c	2459091.587	2459110.978	19.391	0.043	0.002	128.347	5.961
GJ 832 b	2459110.978	2459183.211	72.233	0.134	0.002	200.580	6.095
upsilon And d	2459373.211	2459376.089	2.878	0.020	0.007	203.458	6.115
HD 190360 b	2459666.089	2459677.977	11.888	0.004	0.000	215.346	6.120
HD 134987 c	2459697.977	2459727.134	29.157	0.000	0.000	244.502	6.120
HD 87883 b	2459847.134	2459934.153	87.019	0.034	0.000	331.521	6.153

Credit: Bob Brown

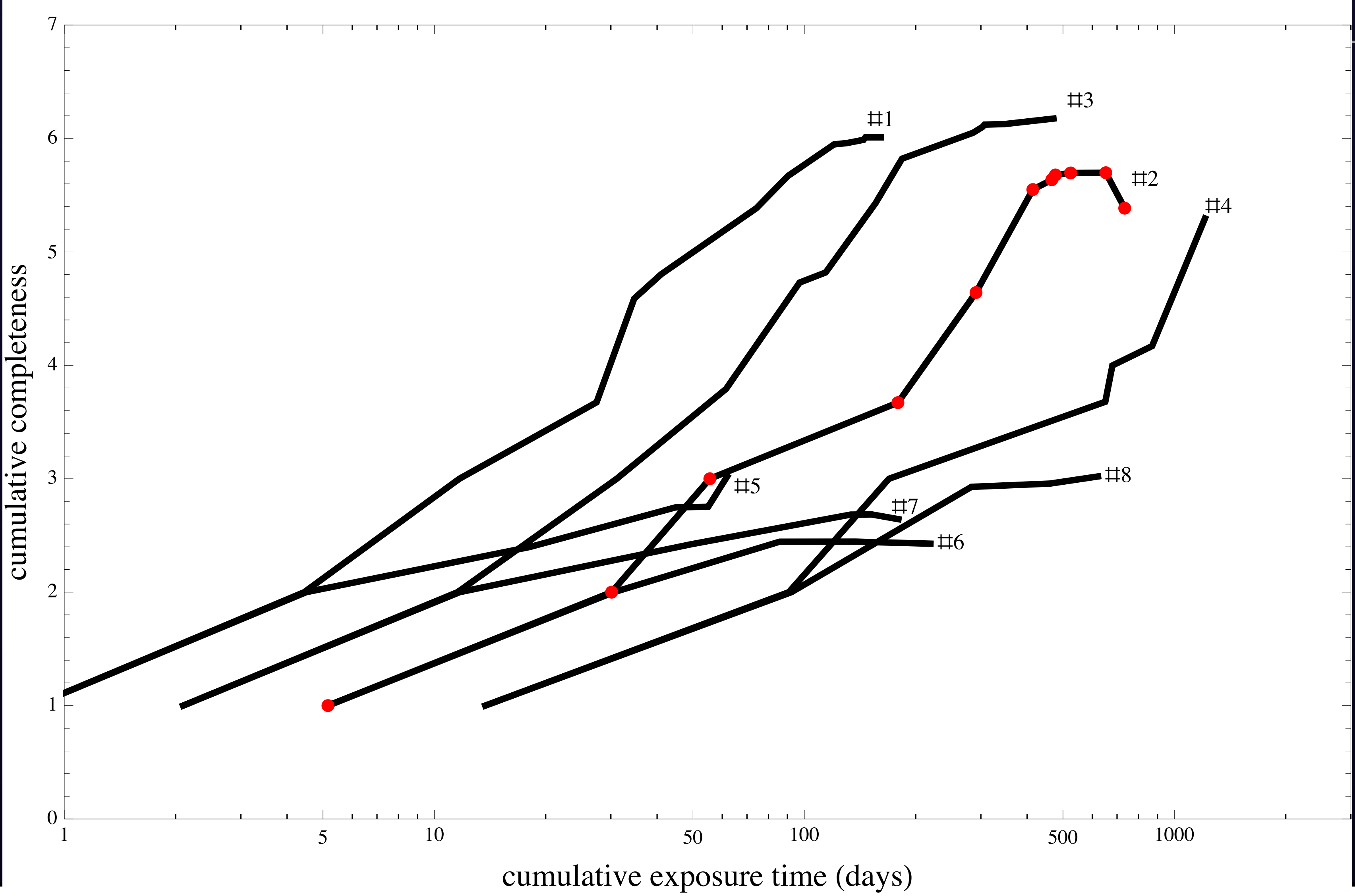
DRM sumary results

- Table shows the science metric (i.e. expected number of planets characterized) for different efficiency (h) and resolution (R) and IWA
- Shows evolution as a function of total exposure time for this activity to observe known RV planets
- Result averaged from 100 DRMs computed for each combination of parameters (IWA, throughput, resolution)
- science metric for an actual DRM is smaller than maximum metric

IWA	0.200"				0.274"			
h	0.05		0.3		0.05		0.3	
R	20	50	20	50	20	50	20	50
50 d	2.50	1.00	4.78	3.64	2.00	1.00	2.74	2.42
100 d	3.63	2.00	6.00	4.84	2.45	2.00	2.74	2.71
200 d	4.75	3.00	6.04	5.73	2.45	2.49	2.74	2.71
400 d	5.48	3.76	6.04	6.18	2.62	2.49	2.74	2.71

Credit: Bob Brown

DRM results with cumulative exp time



- All DRMs run out of planets, not time (except case #4: 3lambda/D IWA, R=50, 5% efficiency)
- main effect of "h" or "R" is to move the DRM to the right, i.e. increase all exposure times
- IWA here has a factor of two impact on DRM

case number	IWA (arcsec)	h (efficiency)	R (resolution)	Comment
1	0.200	0.3	20	original, 3λ/D
2	0.200	0.05	20	...low h
3	0.200	0.3	50	...high R
4	0.200	0.05	50	...low h, high R
5	0.274	0.3	20	new, 4λ/D
6	0.274	0.05	20	...low h
7	0.274	0.3	50	...high R
8	0.274	0.05	50	...low h, high R

Credit: Bob Brown

Target list

- 15 RV planets with a(1+e)/d<IWA
  - few more ~20 targets if a little less strict (0.19 arcsec)
  - however vanishing small increases in completeness

	mag	*d*	*a*	*T*	ϵ	ω	T_0	$a(1+\epsilon)/d$
epsilon Eri b*	2.78	3.22	3.38	2500.	0.25	6.	1940.	1.312
47 UMa c*	4.34	14.06	3.57	2391.	0.10	295.	5441.	0.279
mu Ara c*	4.35	15.51	5.34	4206.	0.10	58.	5955.	0.378
55 Cnc d*	5.03	12.34	5.47	4909.	0.02	254.	6490.	0.452
upsilon And d	3.51	13.49	2.52	1278.	0.27	270.	6938.	0.237
14 Her b	5.68	17.57	2.93	1773.	0.37	23.	4373.	0.229
HD 154345 b	5.96	18.59	4.21	3342.	0.04	68.	5831.	0.237
HD 39091 b*	4.98	18.32	3.35	2151.	0.64	330.	820.	0.300
HD 190360 b*	4.91	15.86	3.97	2915.	0.31	13.	6542.	0.329
HD 87883 b*	6.57	18.21	3.58	2754.	0.53	291.	4139.	0.301
GJ 832 b*	6.43	4.95	3.40	3416.	0.12	304.	4211.	0.769
HD 217107 c*	5.35	19.86	5.33	4270.	0.52	199.	4106.	0.408
HD 134987 c	5.71	26.21	5.83	5000.	0.12	195.	4100.	0.249
GJ 849 b	8.19	9.10	2.35	1882.	0.04	355.	4488.	0.269
GJ 179 b	9.40	12.29	2.41	2288.	0.21	153.	8140.	0.238

Credit: Bob Brown

RV completeness for nearby stars

- RV census of nearby Sun-like stars is fairly complete for giant planets in <5.5 year orbit
- Out of the 54 stars within 5pc
  - 9/54 = 17% have at least one planet
  - 7/36 = 19% of F5-M5 stars have at least one planet
  - 6/36 = 17% of F5-M5 stars have at least one giant planet
  - 5/36 = 14% of F5-M5 stars have at least one giant planet in a <5.5 yr orbit
- Consistent with Cummings et al. (2008)
  - 10.5% of Sun-like stars (F5-M5, but mostly G and K) host a giant planet with <5.5 yr orbit
  - 17-20% have a giant planet within 20 AU

- RV surveys for nearby M stars is quite incomplete (however not typically good targets for direct imaging with small telescope (faint)

Credit: Nick Cowan

Discussion

- How can we improve the target list?
  - Increase RV surveys for large separation planets with low-cadence monitoring of direct imaging targets (unfunded effort at the moment)
  - Increase RV for earlier types e.g. A stars?

- What optimal science program (e.g. combination of broadband exposures to determine the inclination first, then proceed to spectroscopy)
  - operational impact : what maximum bandpass in a single snapshot with coronagraph?

- Proceed to a planet survey in larger bandpass R~10? around bright targets (shorter exposure time, unknown planets) to be evaluated

- Other areas / suggestions where we can improve this DRM result?

- Please join SAG9 (email soummer@stsci.edu)

- Topics of interest for SAG9
  - Radial Velocity Complementarity with imaging
  - Overlap of Probes/AFTA with JWST and Ground-based Imaging
  - Cross-Validation of Design Reference Missions

- Tentative Schedule: final report in the May-June time frame