Consistent Analysis of Direct Imaging of Exoplanets with WFIRST, Exo-C, Exo-S, & Rendezvous

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ExoPAG Meeting, Chicago
13 June 2015

Purpose

- Estimate science yield (detections & spectra) of direct-imaging missions, with focus on WFIRST, Exo-C, and Exo-S/Rendezvous
- Use consistent assumptions
- Use the respective final reports
- Also use information from engineers on each project
- Use the same set of targets (RV planets and estimated Kepler population of planets), detectors, and SNR for each
- Analysis can be updated as new Kepler data becomes available.
- TESS will not impact results (short periods only).

Common parameters

Parameter	Value	Units
orbit angle	70	deg.
orbit inclination	60	deg.
planet phase angle	73	deg.
zodi brightness	22.7	mag/square arcsec
local dust	1	zodi
exo dust	6	zodi
planet albedo	0.50 >1 AU/$L^{1/2}$, 0.20 inside	
no. of spectral bands	3	
central wavelengths of bands	450, 650, 850	nm
detector read noise	16	rms elec./read
dark rate	0.0005	elec./pixel/read
CIC	0.001	elec./pixel/frame
time per frame	300	sec
ENF (extra noise factor)	1	
gain	500	
SNR_0	5	
post-processing factors	10, 30	
telescope pointng jitter	1.6 / 0.8 / 0.4	mas rms per axis
max integration time (images)	1	day
no. pixels per planet image	Nyquist at 450 nm	
QE (each band)	0.78, 0.91, 0.50	
reflectivity of mirrors (each band)	0.966, 0.988, 0.981	

- Orbit location gives good brightness and separation angle for about 25% of the time
- Exo dust assumed to be about 1.5 times Solar System dust
- 3-color bands: chosen to represent possible range
- EMCCD detector assumed, in photon-counting mode
- Best case is 30x post-processing and 0.4 mas jitter
- Worst case is 10x post processing and 1.8 mas jitter
- Nyquist-sampled pixels at short wavelengths, over-sampled at longer wavelengths

Specific parameters

Parameter	WFIRST HLC	WFIRST SPC	WFIRST PIAA	Exo-C	Exo-S	Rendez-vous
throughput factor 1: coronagraph	0.038	0.036	0.084	0.080	0.468	0.348
throughput factor 2: area factor	0.826	0.826	0.826	1.000	0.910	0.826
throughput factor 3: optics	0.321	0.321	0.321	0.405	0.444	0.321
throughput factor 4: detector	0.93	0.93	0.93	0.93	0.93	0.93
throughput factor 5: polarization	0.5	1.0	0.5	1.0	1.0	1.0
bandwidth $\Delta\lambda/\lambda_0$	0.10	0.10	0.10	0.20	0.47	0.34
diameter of telescope (cm)	237	237	237	140	110	237
area factor of telescope	0.83	0.83	0.83	0.85	0.91	0.83
azimuth coverage	1.00	0.33	0.50	1.00	1.00	1.00

Factor 1 is the fraction of light, within the diameter of the telescope, that falls within the FWHM of the planet image, times the transmission of the coronagraph masks. This is 0.468 for a perfect Airy pattern from a clear aperture, and no coronagraph.

Factor 2 is the clear (unblocked) fraction of the full pupil.

Factor 3 is the transmission of the mirrors and filters.

Factor 4 is the detector quantum efficiency.

Factor 5 is polarization: 1.00 for unpolarized, 0.50 for single polarization.

All factors are shown for λ = 550 nm, sky angle 0.200 arcsec, and unpolarized light.

New Effects with Starshade, From Exo-S Report

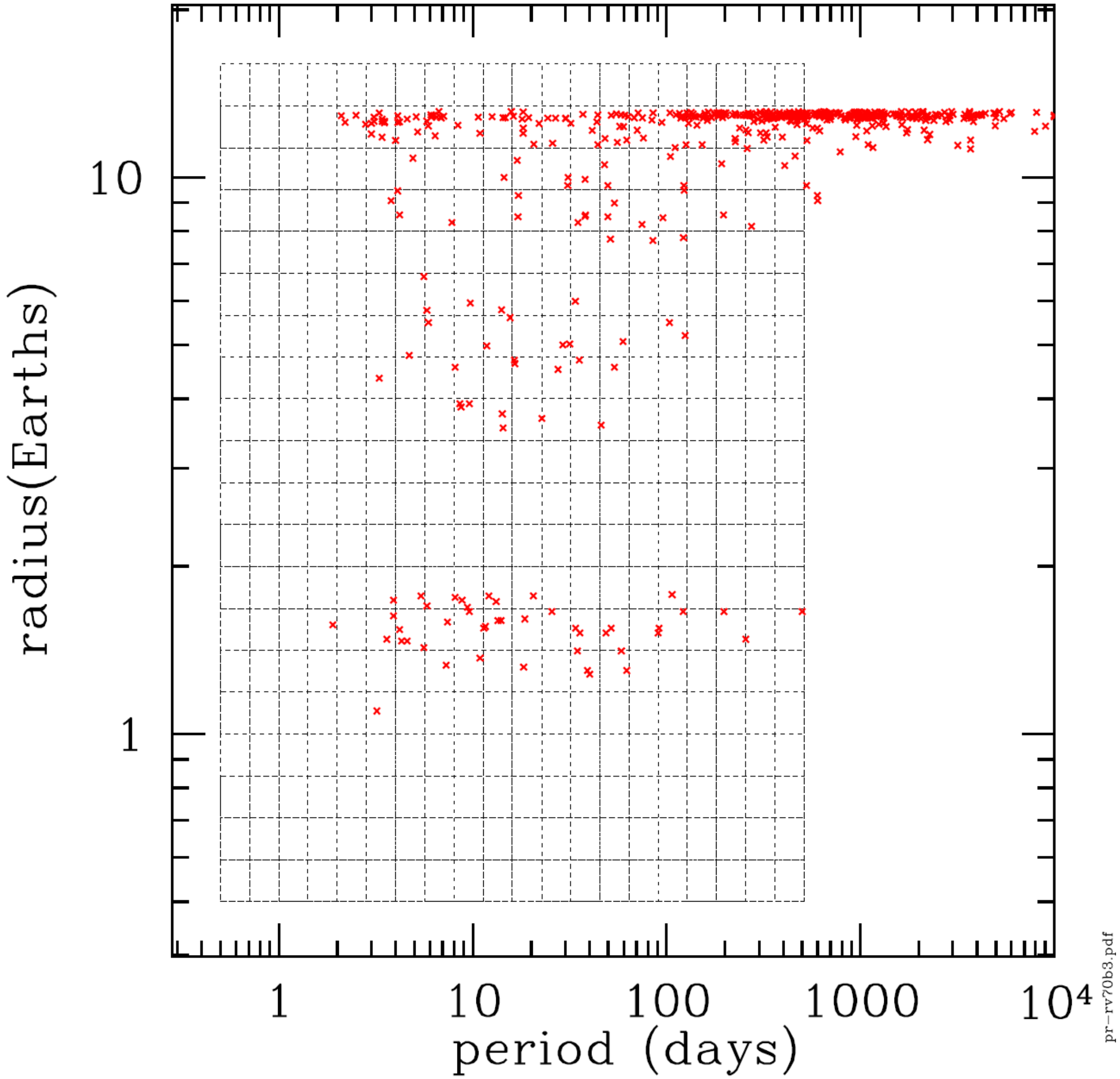
- Glint, sun on petal edges
- Zodi, reflecting from telescope side of starshade
- Holes, or broken tips (roughly 10 times weaker)
- Leakage from out-of-band light (~100 times weaker)

I develop expressions for each of these, treating each as a point source of light on the starshade, with an inverse-cube fall-off in angle from that point.

I add these as background, and treat like speckles, i.e., a background that needs to be estimated and subtracted, with the noise level reduced by an assumed post-processing factor 10 or 30, worst and best cases.

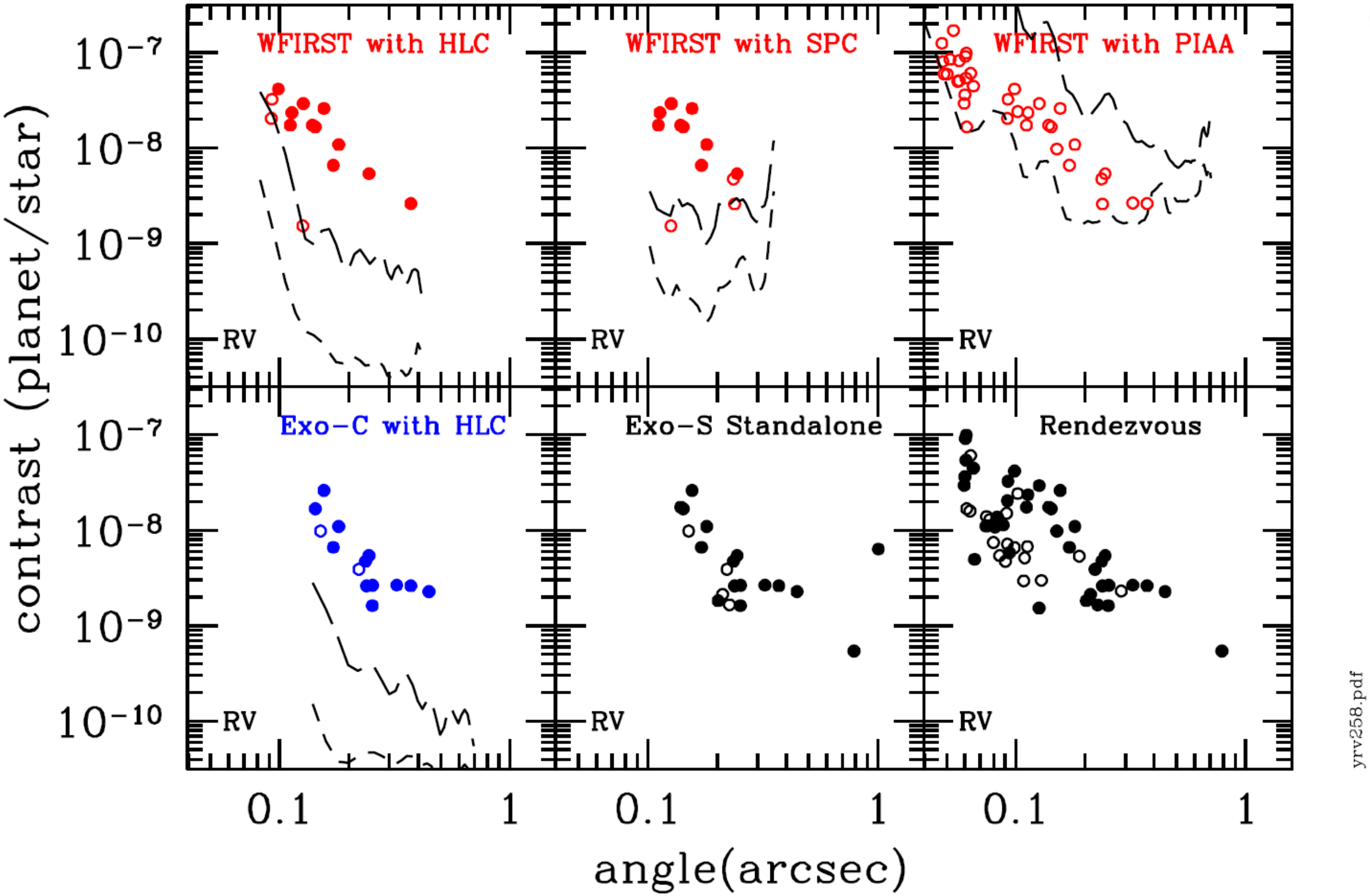
Radial-Velocity Planets

Known RV planets



- Known RV planets have observed m*sin(i) values
-
- Assume sin(i) ~ 1
- Convert mass to radius using empirical relation
- Most RV planets are Jupiter size, about 11 Earth radii
- Clustering near 12 Earth radii is probably in part from observing bias, and in part from the conversion algorithm
- A few have Neptune-like radii
- A few have super-Earth radii
- Assume Jupiter-like albedo of 0.50 for all, unless inside 1 AU/$L^{1/2}$ then assume Earth-like albedo of 0.20
- All RV planets have measured semi-major axes

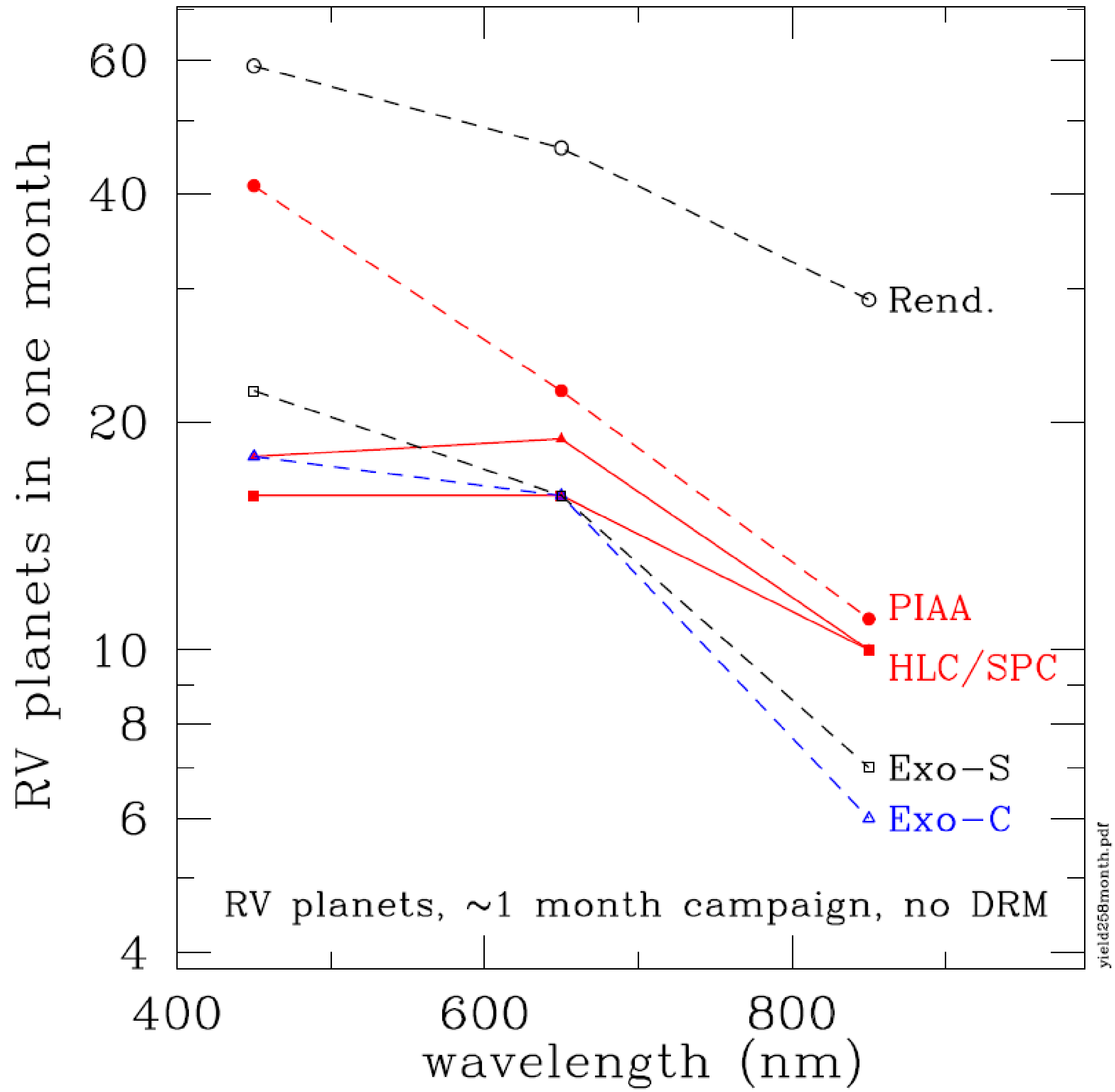
Known RV planet yield, <1 day/target, blue channel



Legend: Upper dashed line & filled dots: worst case of jitter and post-processing
Lower dashed line & open dots: best case of jitter and post-processing

Current status of WFIRST coronagraphs (upper row) and Exo-C:
all 4 have better performance than the Final Report cases shown here.

Known RV planets: number of 3-color direct images in ~1 month total for all 3 colors



- Accessible for ~25% of each orbit
- Blue/green/red images
- DRM not included here
- Known RV targets
- SNR = 5 each image
- Overheads not included
- All images can be taken in about 1 month total, but Exo-S ~2 weeks, and Rendezvous ~1 week
- Demonstrates that WFIRST-AFTA can meet imaging requirement

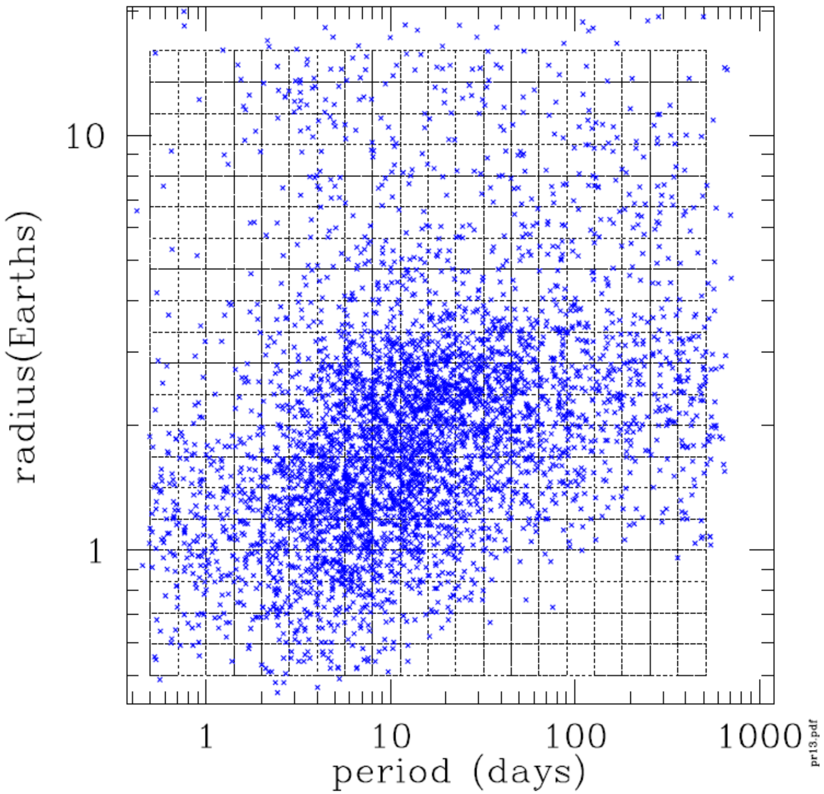
Known RV planets: IFS spectra possible, in 1 month total time, for all 3 colors

color	λ(nm)	HLC	SPC	Exo-C	Exo-S	Rend.	PIAA
blue	450	6	8	9	18	40	30
green	650	11	10	9	13	35	18
red	850	4	5	4	5	21	8

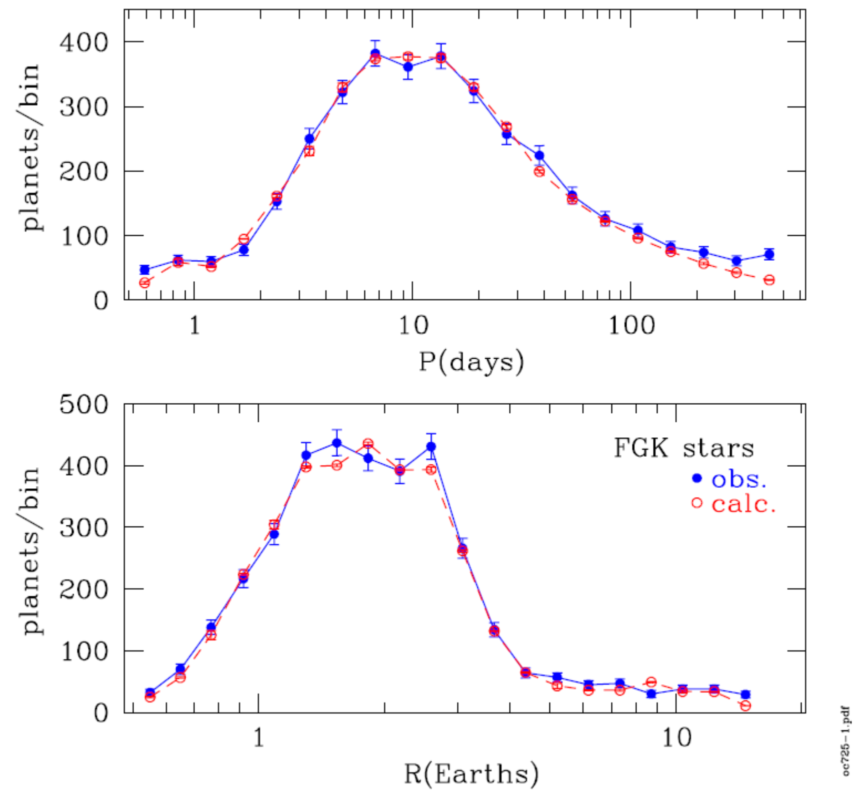
- Number of known RV planets with spectra
- Assumes each band has an IFS, at resolution 70
- Known RV targets
- Total of 1 month integration time for all 3 spectra
- SNR = 5 for each spectrum
- Demonstrates that red spectra are possible, but harder

New-Discovery Planets

New-discovery planets, based on Kepler data



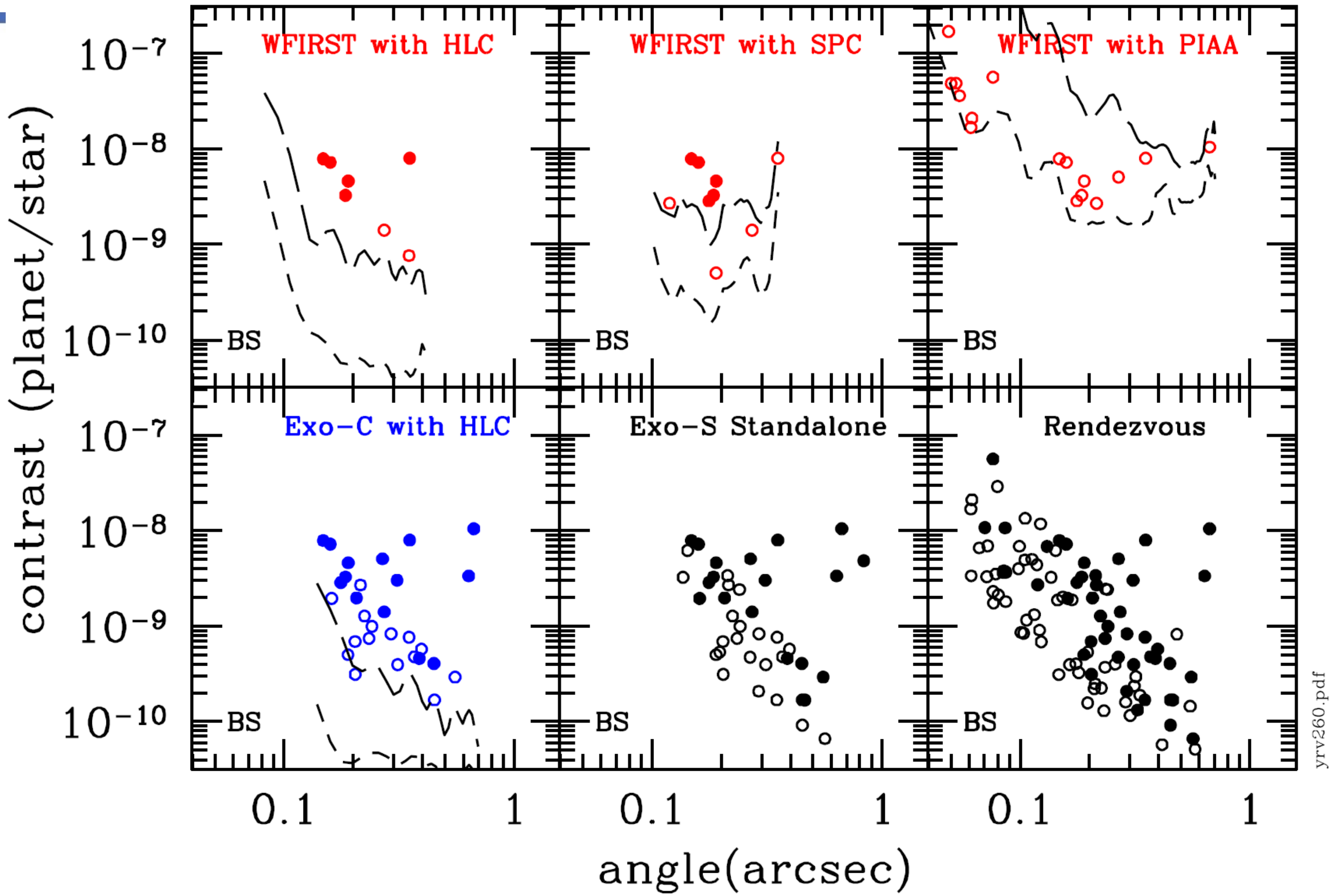
~ 5000 observed Kepler planets, confirmed plus candidate



Model fit to observed planets, projected onto the period and radius axes.

The model population of planets that best fits the Kepler data is used in the next charts, to estimate direct imaging yields.

New-discovery planets, each detectable in less than 1 day

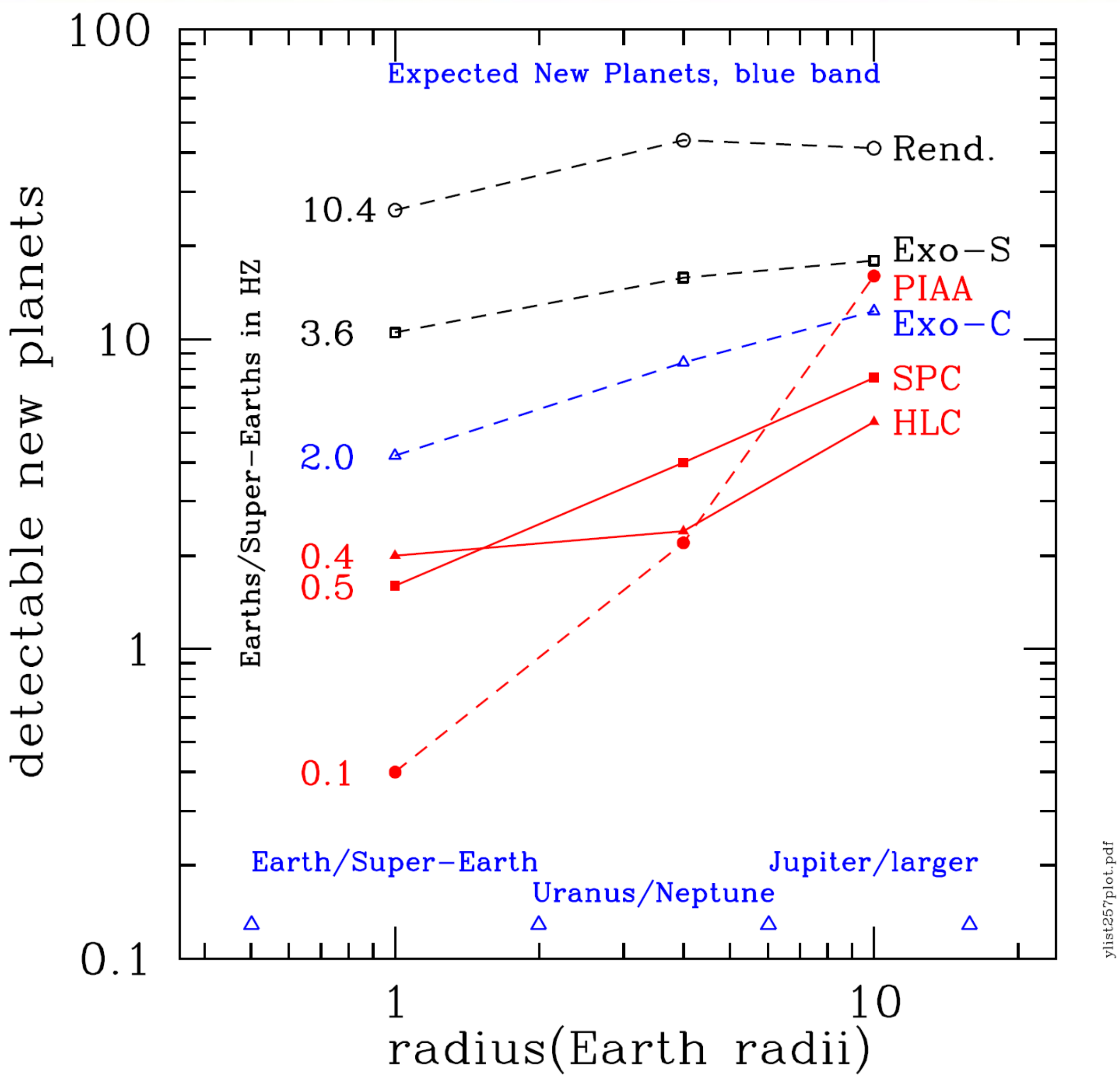


Legend: Upper dashed line & filled dots: worst case of jitter and post-processing
Lower dashed line & open dots: best case of jitter and post-processing

Current status of WFIRST coronagraphs (upper row) and Exo-C:
all 4 have better performance than the Final Report cases shown here.

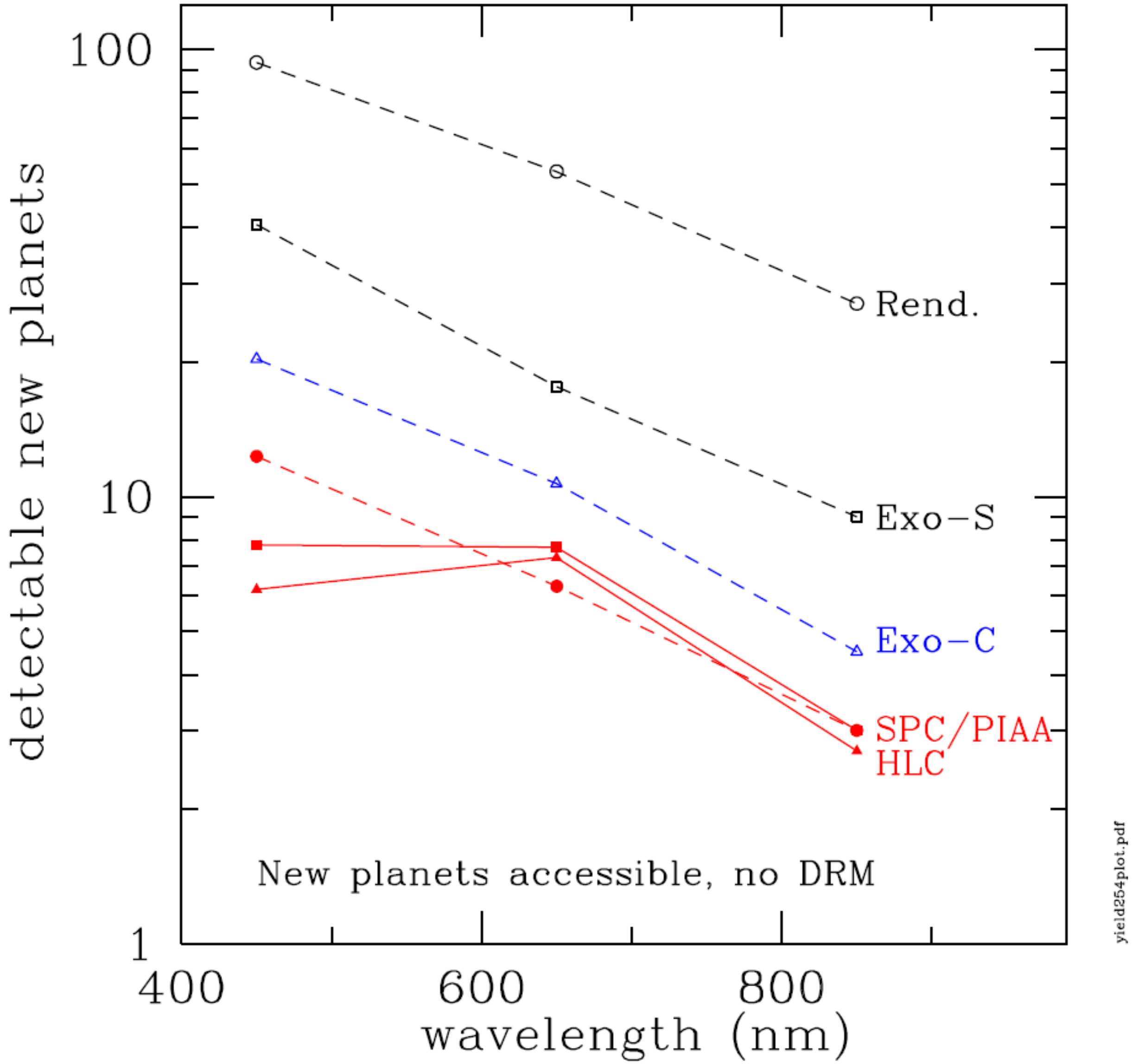
AFTA WFIRST
Wide-Field Infrared Survey Telescope

New-discovery planets:
most will be Neptune-Jupiter size, but possibly a few HZ-Earths



- Accessible for ~25% of each orbit
- Blue channel (450 nm)
- DRM not included here
- Rendezvous & Exo-S may need guidance from coronagraph or RV observations to home in on some targets
- Expected numbers of Earth/Super-Earths in HZ are shown on left of each line trend line
- Radius range of each group is shown at bottom
- Numbers of planets are averages of 10 random planets from Kepler model put around each nearby star

New-discovery planets: 3-color images



- Accessible for ~25% of each orbit
- Blue/green/red images
- DRM not included here
- New-discovery targets
- SNR = 5 each image
- Overheads not included
- All images can be taken in about 3 months total, roughly 1 month per color
- Demonstrates that WFIRST-AFTA can explore for new planets, well beyond its baseline imaging requirement

Time Allocations

Time allocation for HLC/SPC on WFIRST

- 3 months, GO time (25%)
- 1 month, disks (10%)
- 3 months, RV planets, detection and spectra
- 5 months, new planets, detection and spectra

- 1 year total

- 32 planets imaged (19 RV, 13 new) exceeds the WFIRST requirement
- Future RV searches (e.g., WIYN) will increase the number of RV candidates

Time allocation for Exo-C

- 9 months, GO time (25%)
- 4 months, disks (10%)
- 9 months, RV planets, detections and spectra
- 14 months, new planets, detections and spectra

- 3 years total

Time allocation for Exo-S and Rendezvous

- 2 days observing, 12 days slewing, 14 days/cycle
- 25 cycles/year
- 75 targets available in 3 years
- Duty cycle is 2/14 or 14%
- Observing time is 5 months total
- Will have fewer targets than HLC on WFIRST, but can get much better signal to noise ratio

- 3 year mission

Conclusions

Summary: estimated planet yields

Known RV planets: 1-month campaign (+OH)

WFIRST (HLC/SPC)
Images: **19** in 1 color, 10 in 3 colors
Spectra: **11** in 1 color, 5 in 3 colors
(all large planets)

PIAA:	~1½ x
Exo-C/S:	~1 x
Rend.:	~3½ x

New-discovery planets: 4-month campaign (+OH)

WFIRST (HLC/SPC)
Images: **13** in 1 color
Spectra: probably **8** in 1 color
(11 large, 2 small planets)

PIAA:	~1½ x
Exo-C/S:	~2½ x
Rend.:	~8 x

Strategic possibilities: WFIRST

- HLC & SPC on WFIRST have comparable yields to Exo-C/S.
- HLC & SPC will easily fill a year with known RV plus new-planet searches, imaging, and characterization.
- PIAA is not as well developed as SPC or HLC. It could have superior inner working angle performance and larger exoplanet yields if it succeeds in the lab.
- Precision, ground-based RV observations could be very helpful in locating targets; the WIYN instrument could make WFIRST more efficient.

Strategic possibilities: Rendezvous

- Rendezvous has a larger number of available targets, but fewer pointing opportunities than WFIRST or Exo-C
- Rendezvous could characterize RV & new planets, but would benefit from finding charts from a coronagraph to allow it to efficiently locate targets
- Rendezvous could easily fill a 3-year period with RV plus new-planet imaging & characterization
- Rendezvous and Exo-S are the only missions that can detect Earth-size planets in the HZ

Thank you!