High Contrast Imaging of Exoplanetary Systems and the WFIRST Coronagraph (Part I)

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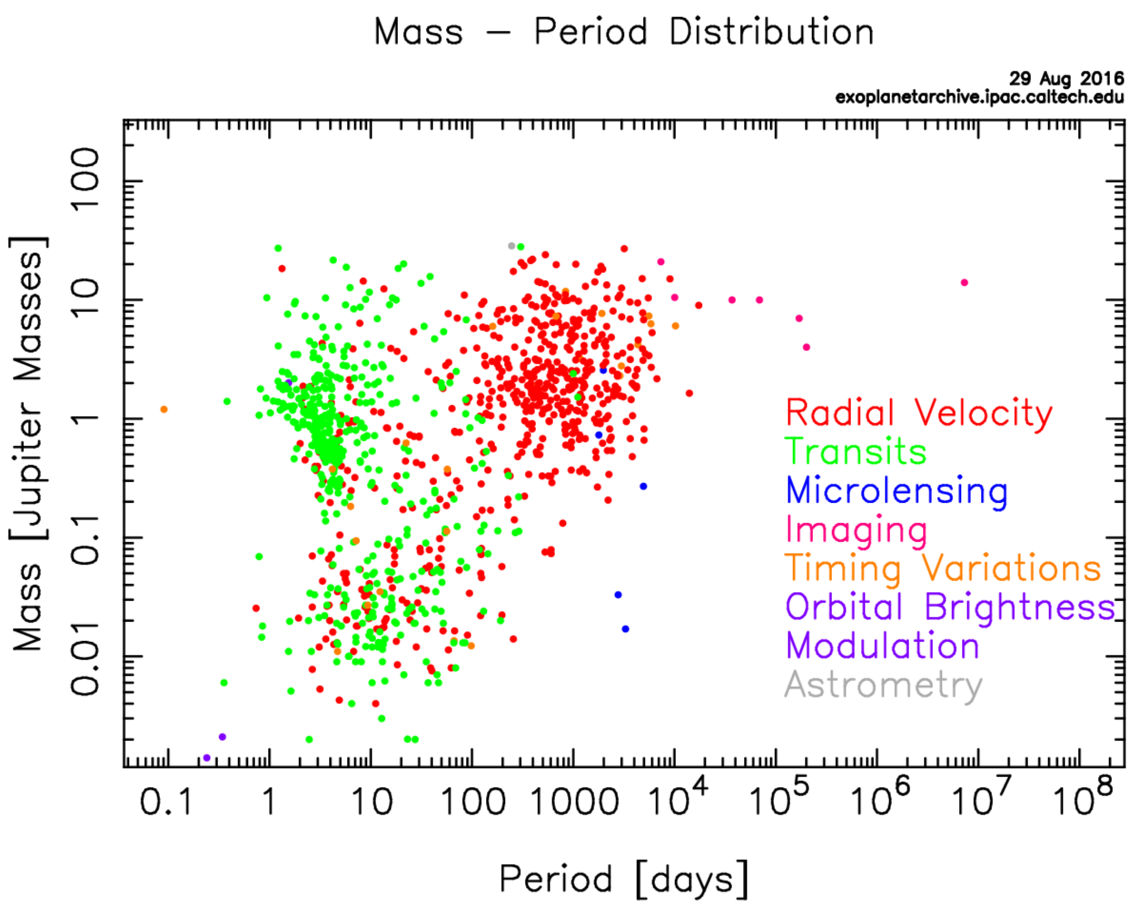
Recent Progress in Exoplanet Science and Technology has been Staggering!

Credit: IPAC Exoplanet Archive

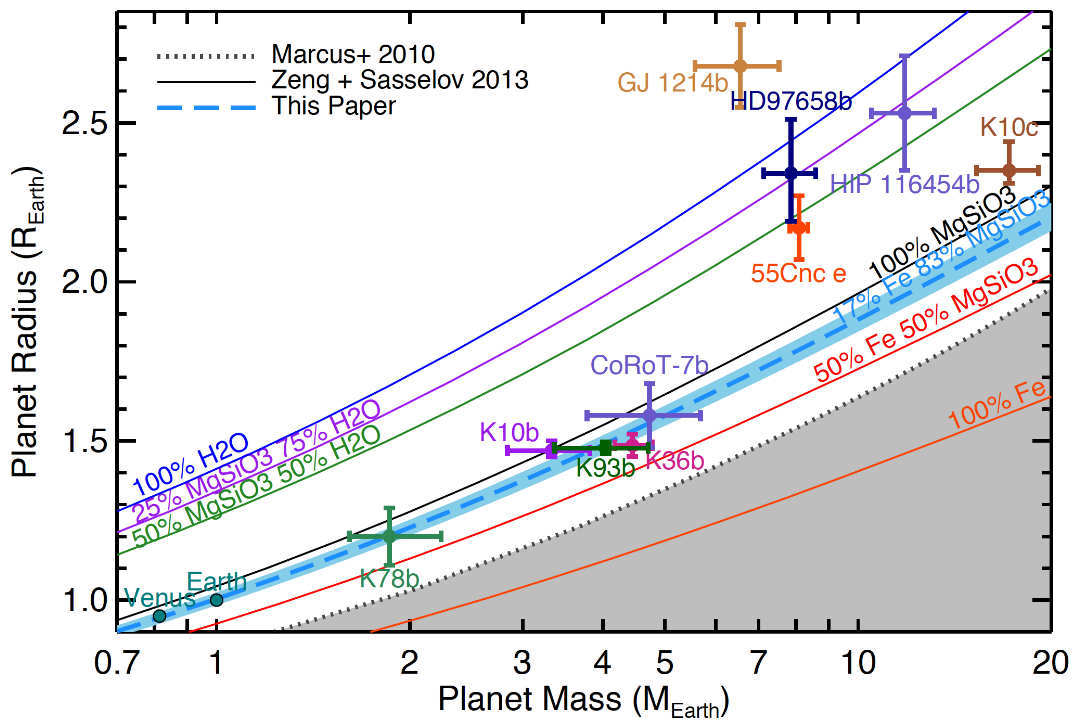
Recent Progress in Exoplanet Science and Technology has been Staggering!



- *Often detecting the oddballs first ! (e.g. neutron star planets, 51 Peg, HR 8799)*
- *Complementarity in terms of parameter space accessible (mass, period and age)*

“Vis Unita Fortior” (Unity makes strength)

- Complementarity in terms of physical information: e.g. Mass (RV) and Radius (Transits)



Dressing et al. 2015

Different techniques generally answer different questions in exoplanet research

How do Planets Form & Evolve?

	Radial Velocity	Transits	Grav. Lensing	Astro metry	Direct Imaging	Space Required ?
• *Exoplanets demographics around very young stars*				✔ (partial)	✔ (full)	**N**
• *Mass vs luminosity for very young planets*				✔ (partial)	✔ (partial)	**N**
• *Full orbital and spin rotation properties (eccentricty, spin velocity and obliquity)*	✔ (partial)	✔ (partial)		✔ (partial)	✔ (full)	**Y/N**
• *Properties of CS dust (exozodi and exo-Kuiper belts) vs system's age*					✔ (full)	**N**
• *Exo-moons and exoplanet rings*		✔ (partial)	✔? (partial)		✔ (full)	**?**

✔ : Partially Respondent (orange) ✔ : Fully Respondent (green)

How Normal or Unusual is our Solar System?

	Radial Velocity	Transits	Grav. Lensing	Astro metry	Direct Imaging	Space Required ?
• *Basic Exoplanets Characteristics and Demographics (M,r,a,e)*	✔	✔	✔	✔	✔	**N**
• *Dependence on stellar properties*	✔	✔			✔	**Y**
• *Characterize entire planetary systems*			✔	✔	✔	**Y**

What are the Physico-Chemical Characteristics of Exoplanets Atmospheres and Interiors?

	Radial Velocity	Transits	Grav. Lensing	Astro metry	Direct Imaging	Space Required ?
• *Abundance of chemical elements*		✔			✔	Y/N
• *T,P profiles*		✔			✔	Y/N
• *Global circulation, oblateness, differential rotation, clouds*		✔			✔	Y/N

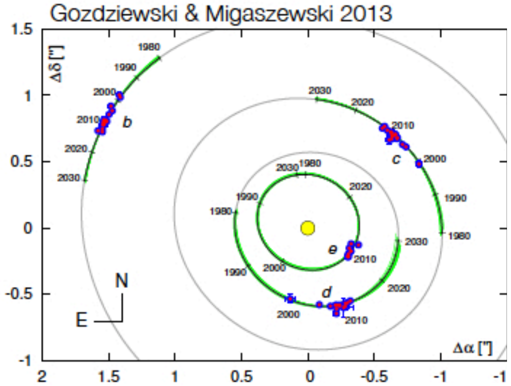
How Common or Rare are Earth-like planets?

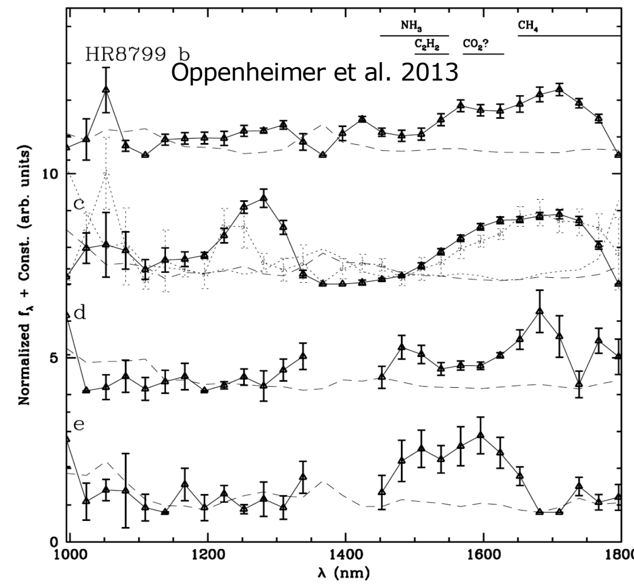
	Radial Velocity	Transits	Grav. Lensing	Astro metry	Direct Imaging	Space Required ?
• *Frequency of rocky planets in the HZ*	✔	✔	✔	✔	✔	**Y**
• *In the HZ and with liquid water*		✔			✔	**Y**
• *Measure dividing line btw terrestrial and giant planets*	✔	✔	✔	✔	✔	**N**
• *How common is life on exo-Earths?*		✔?			✔	**Y(?)**

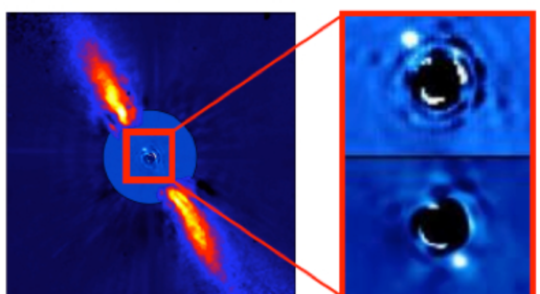
Direct Imaging is the last Characterization Technique to come online but also the most powerful one (I)

- High scientific value of isolating the source for fine characterization:
  - full orbit determination
  - measurement of emergent spectra in multi-planet systems
  - planet-disk interaction

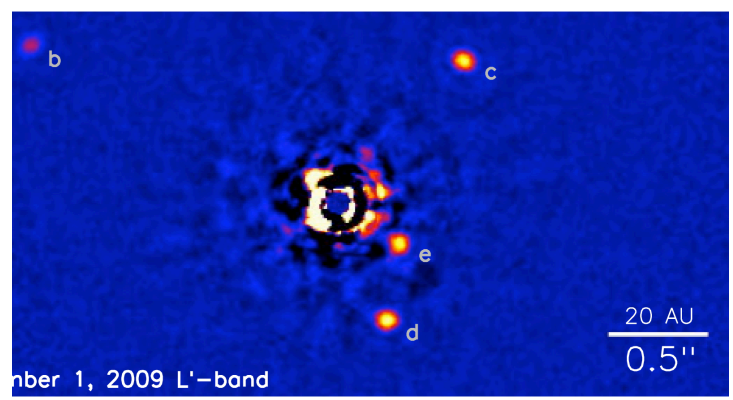
Gozdziewski & Migaszewski 2013







Lagrange et al. 2010

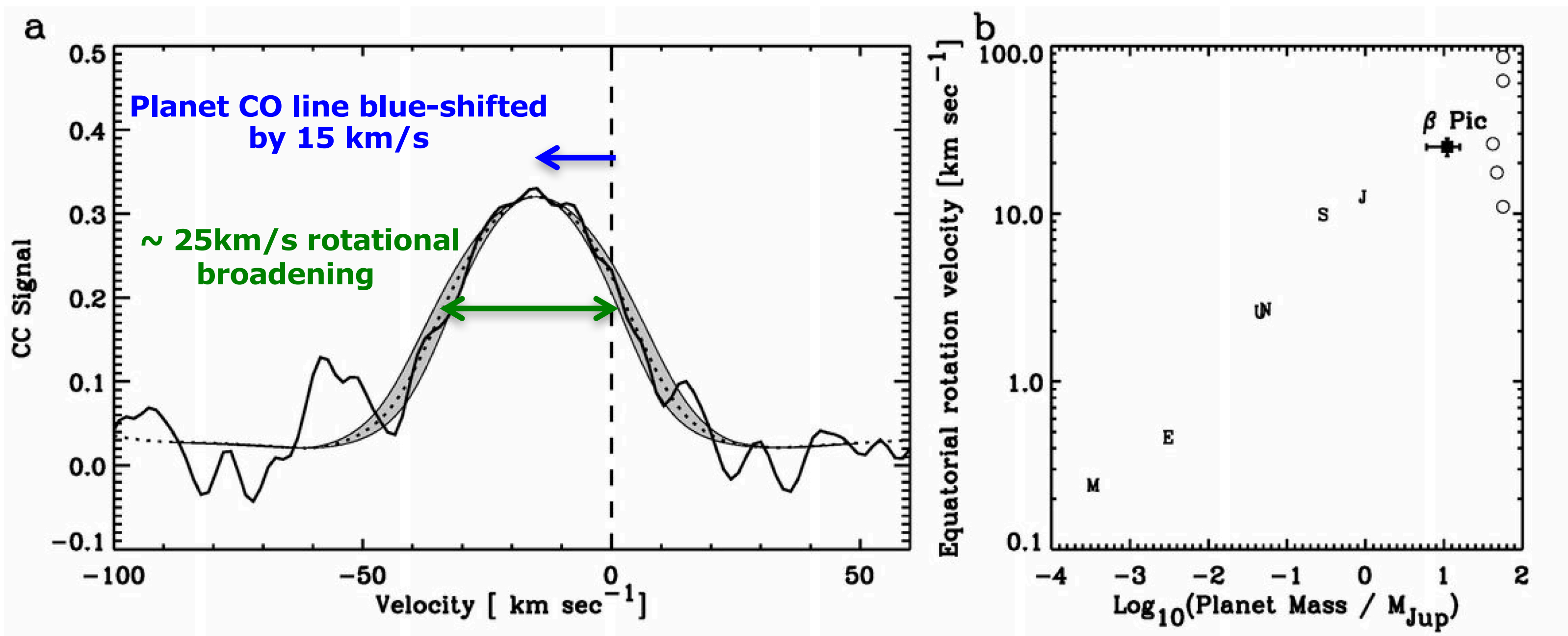


Marois et al. 2010

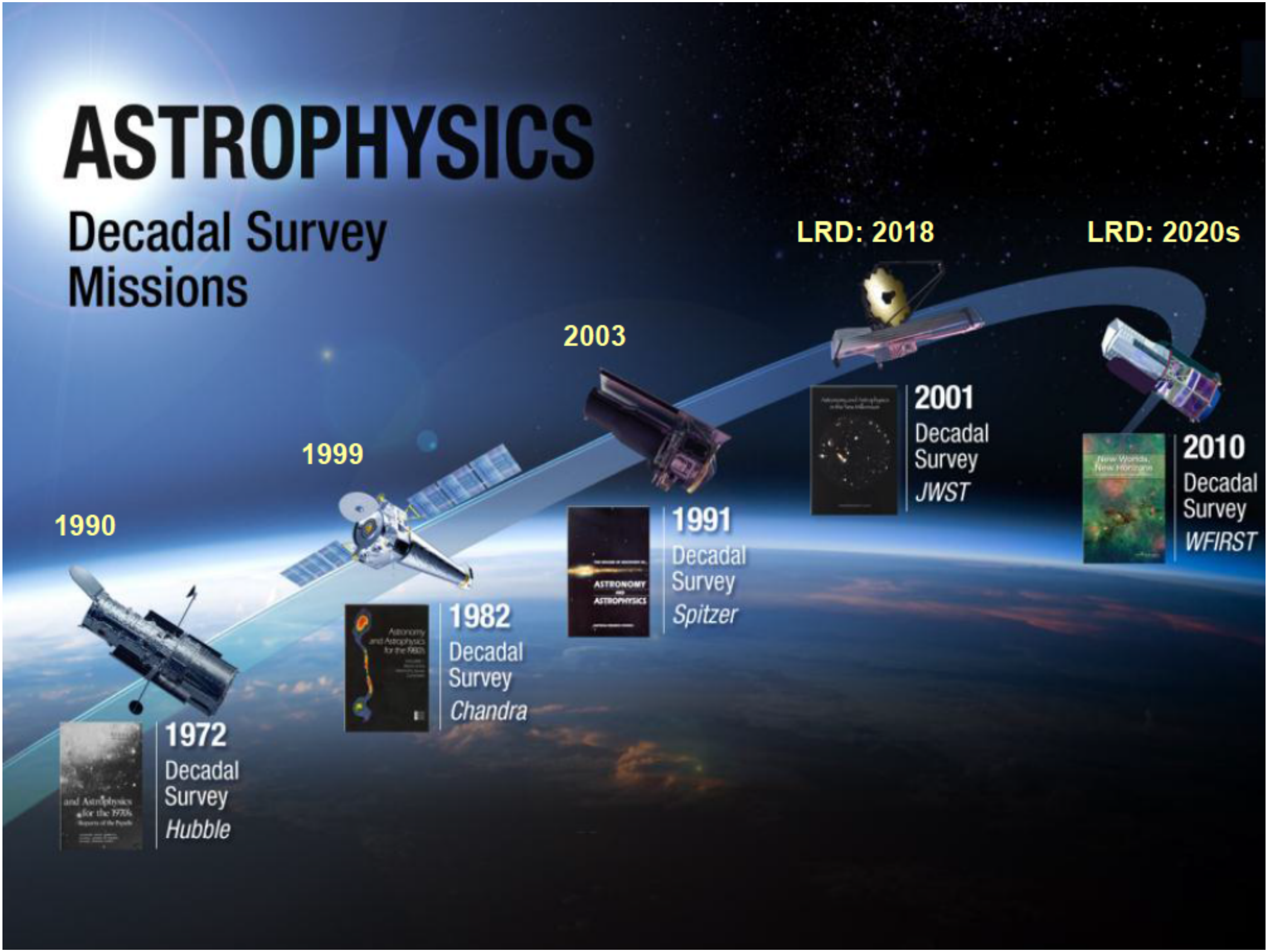
Direct Imaging is the last Characterization Technique to come online but also the most powerful one (II)

AFTA WFIRST
Wide-Field Infrared Survey Telescope

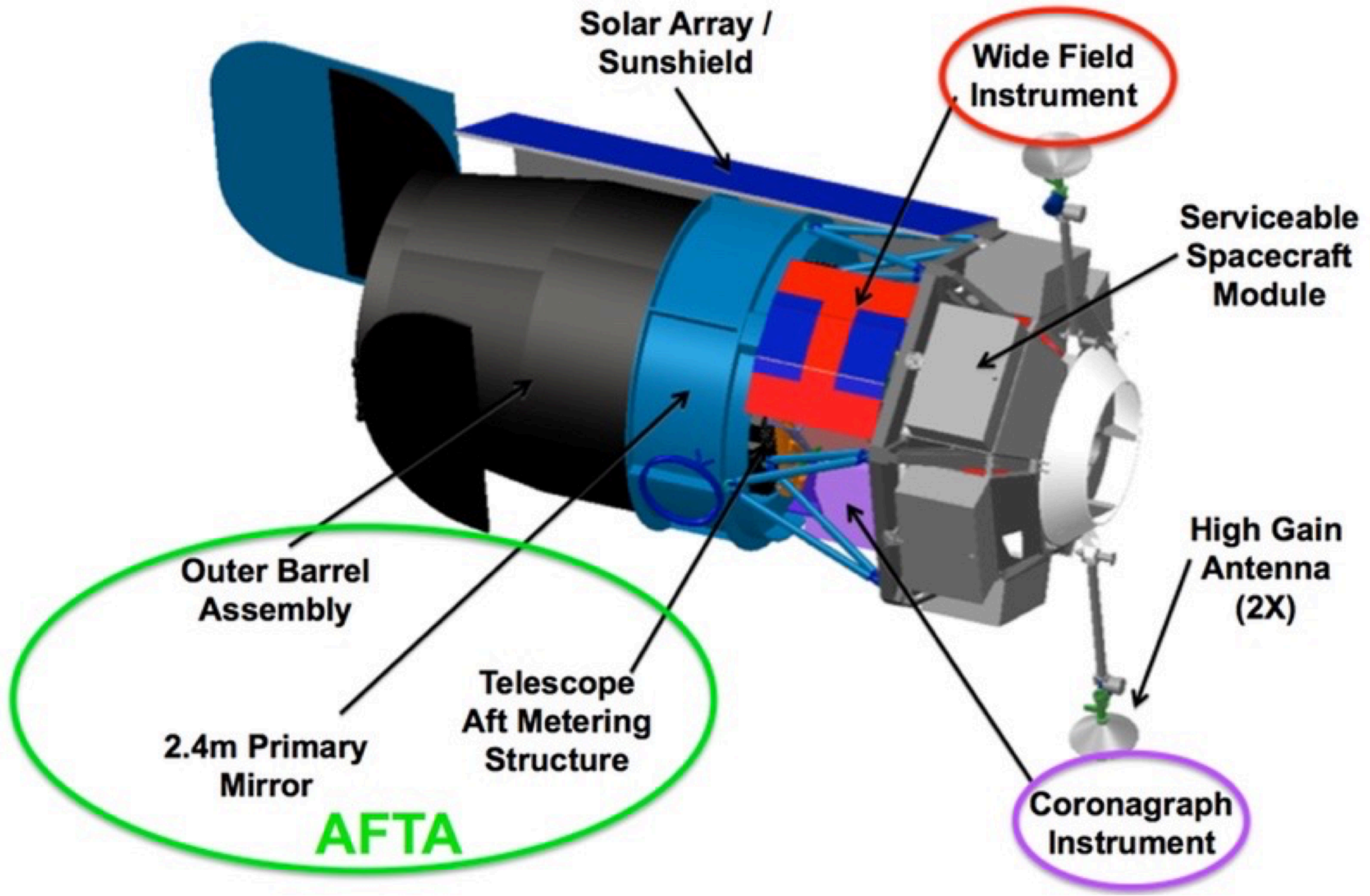
- *Already* measuring spin velocity of β Pic b via high resolution (R=10^5) spectroscopy!



Snellen et al.
VLT /CRIRES, Nature, 2014

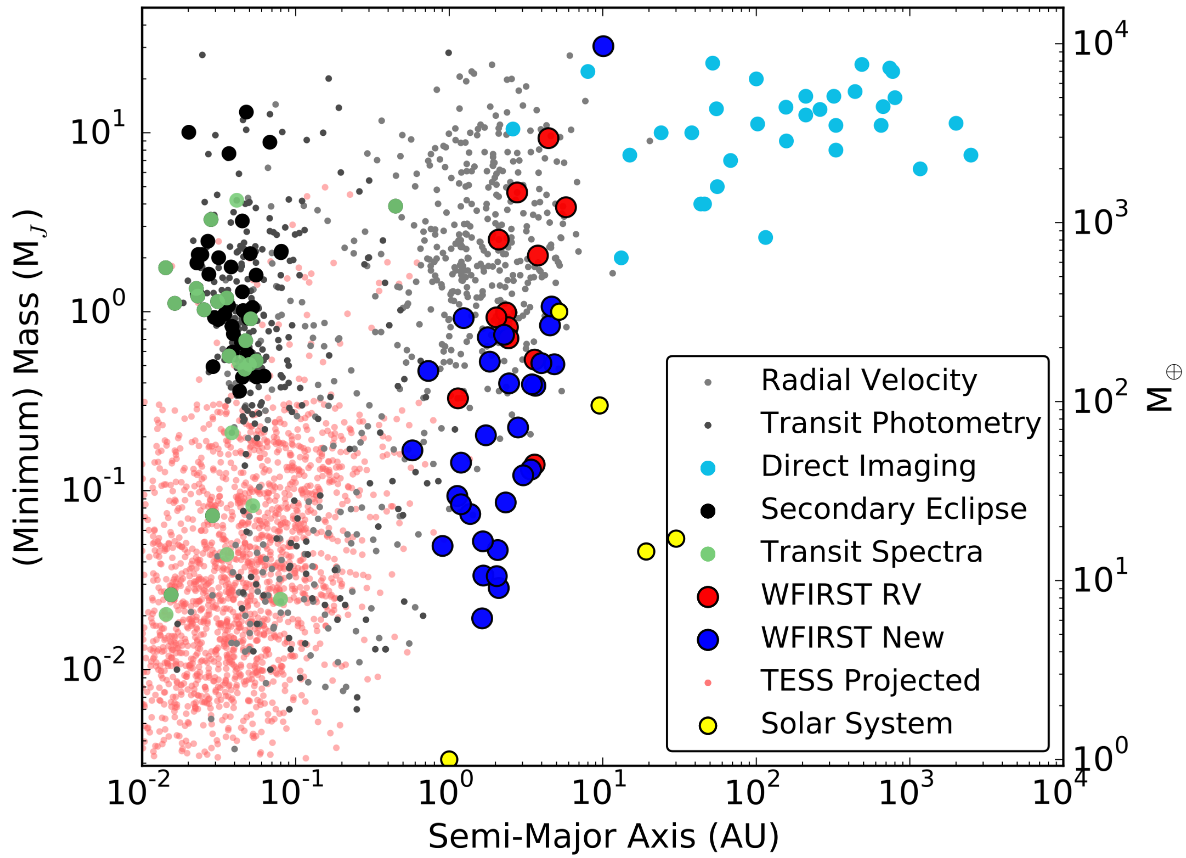

ASTROPHYSICS
Decadal Survey Missions
LRD: 2018
LRD: 2020s
2003
1999
1990
1972
Decadal Survey
Hubble
1982
Decadal Survey
Chandra
1991
Decadal Survey
Spitzer
2001
Decadal Survey
JWST
2010
Decadal Survey
WFIRST

WFIRST


Solar Array /
Sunshield
Wide Field
Instrument
Serviceable
Spacecraft
Module
High Gain
Antenna
(2X)
Outer Barrel
Assembly
Telescope
Aft Metering
Structure
2.4m Primary
Mirror
AFTA
Coronagraph
Instrument

WFIRST CGI Primary Science Goals: *Planets*

✓ Detects planets spanning a range of physical properties, probing populations beyond the limits of current surveys

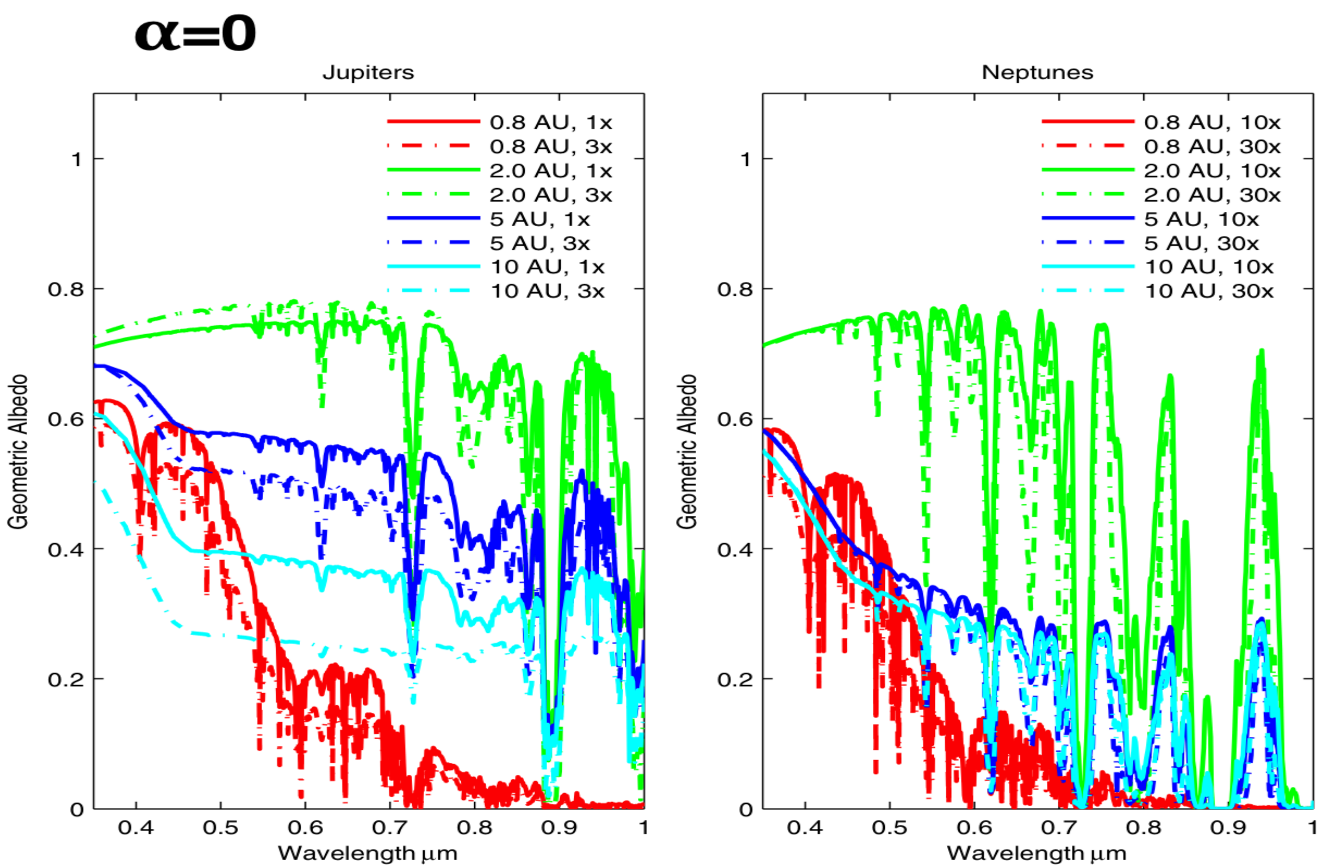


- **Direct imaging of planets around mature stars**
- **Jupiter analogs**
- **Warmer Jupiters**
- **Sub-Neptunes and Super-Earths**

Credit: D. Savransky and E. Neilsen

WFIRST CGI Primary Science Goals: *Planets*

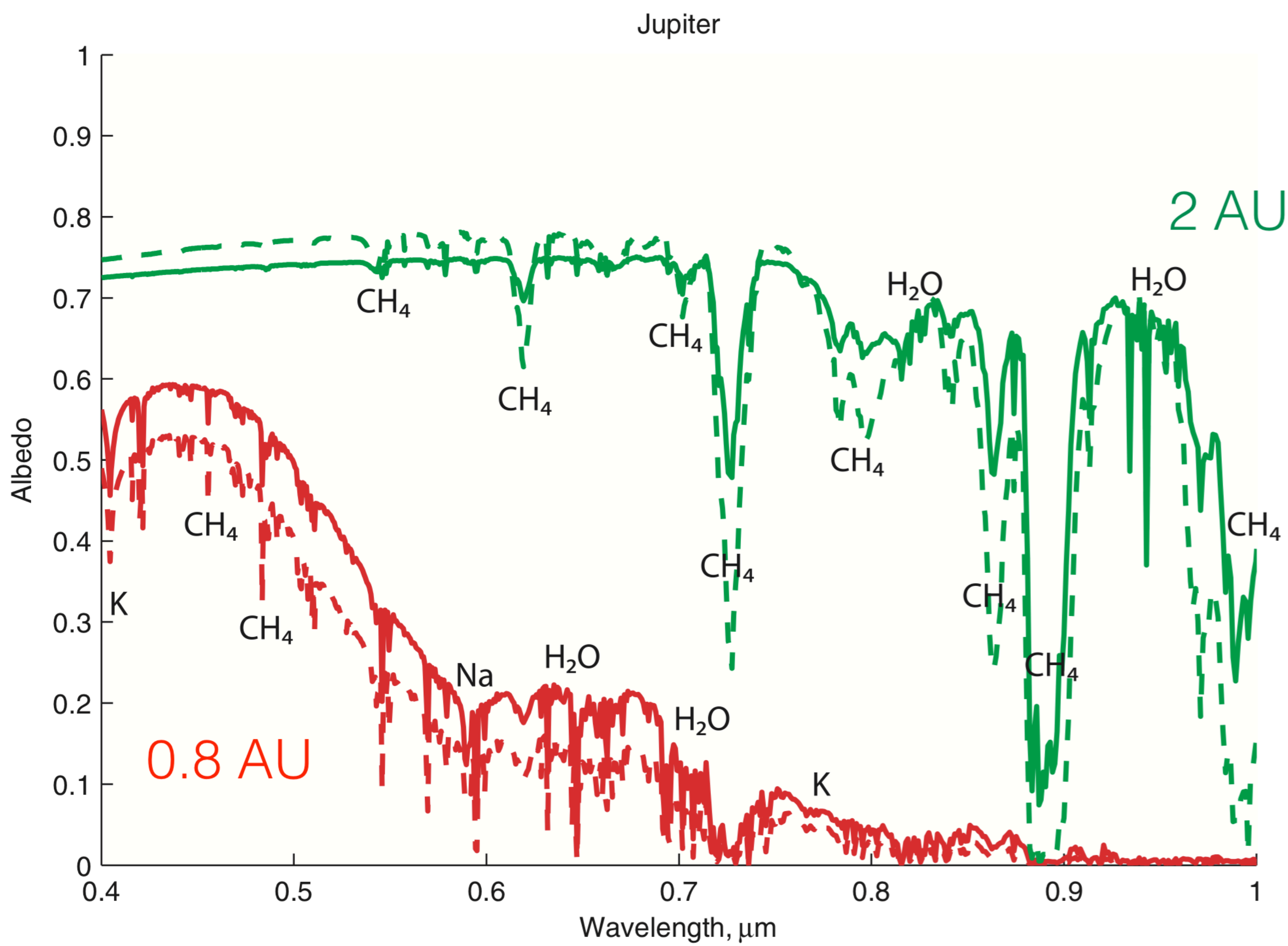
- ✓ Use broad-band photometry to provide initial discriminators for the nature of the planet and explore planetary diversity
- ✓ Use spectroscopy to explore composition / metallicity, cloud/hazes formation as a function of stellar distance: **giant planets**



Cahoy et al. 2010

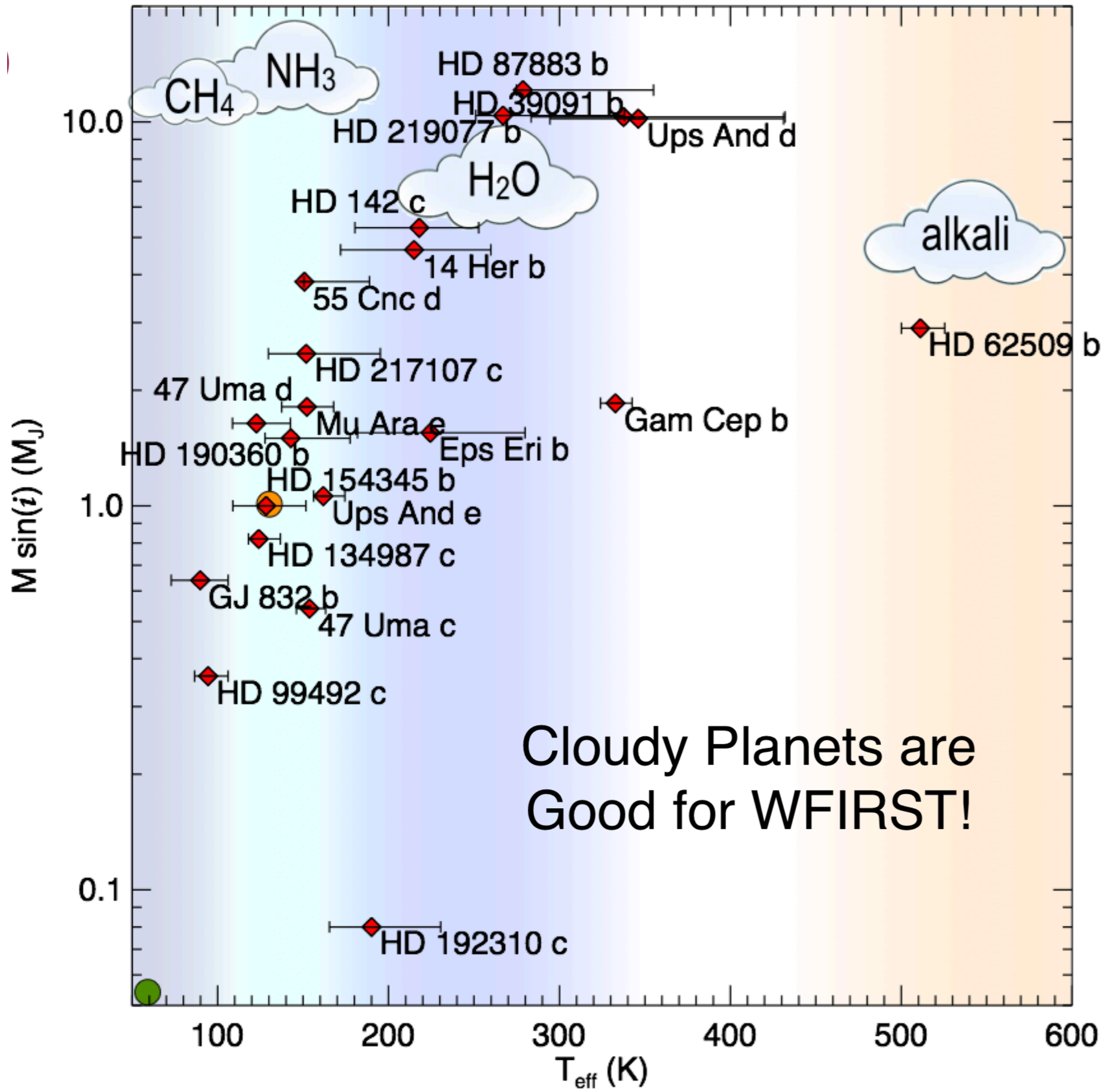
WFIRST CGI Primary Science Goals: *Planets*

✓ Use spectroscopy to explore composition / metallicity, cloud/hazes formation as a function of stellar distance: **giant planets**



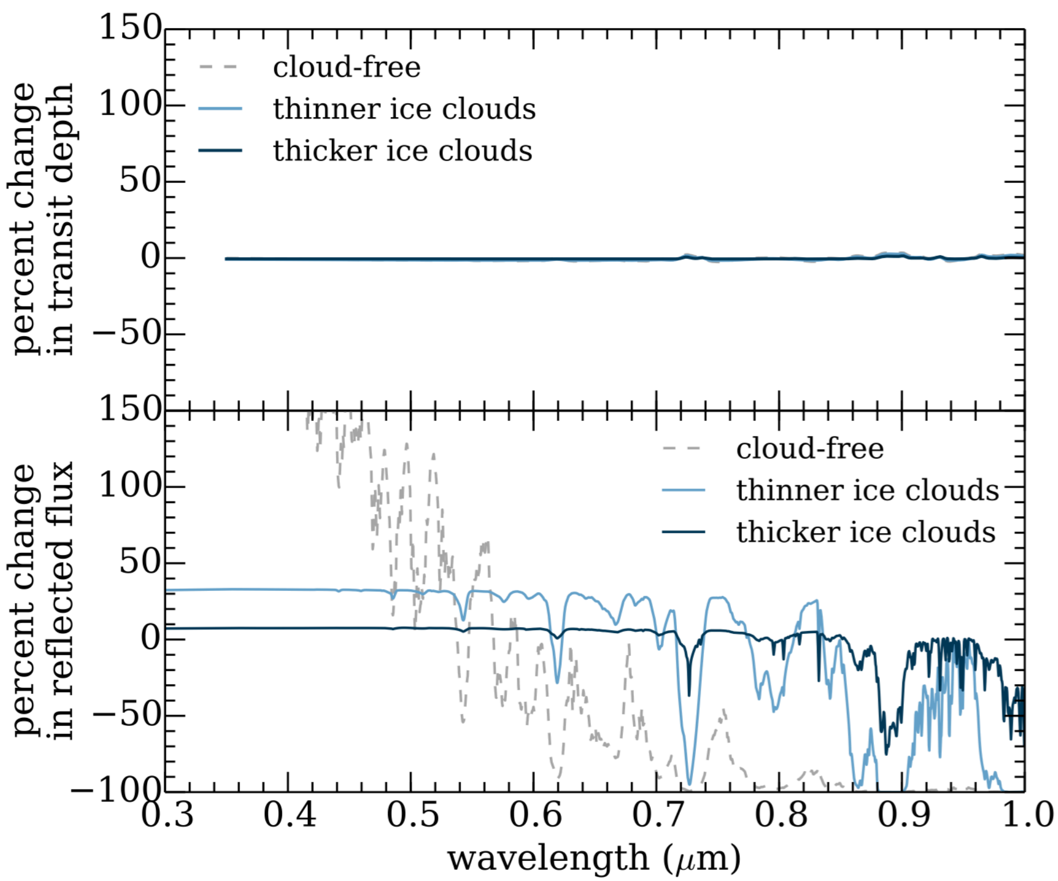
WFIRST CGI Primary Science Goals: *Planets*

✓ Use spectroscopy to explore composition / metallicity, cloud/hazes formation as a function of stellar distance: **giant planets**



WFIRST CGI Primary Science Goals: *Planets*

- ✓ Use broad-band photometry to provide initial discriminators for the nature of the planet and explore planetary diversity
- ✓ Use spectroscopy to explore composition / metallicity, cloud/hazes formation as a function of stellar distance: **sub-Neptunes and super Earths**



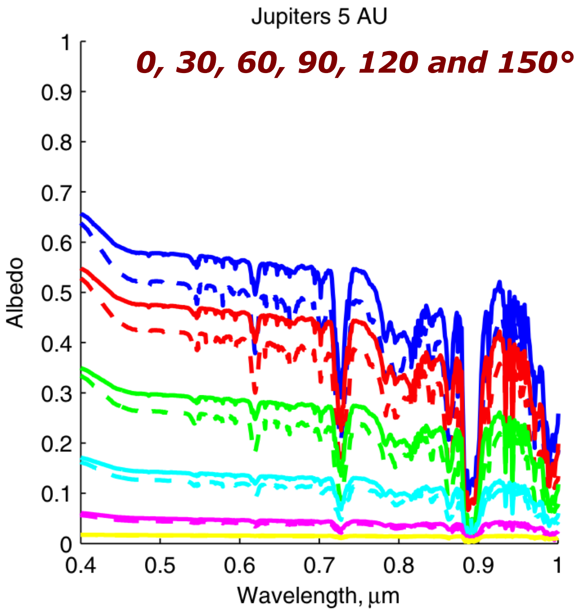
- reflected light spectra of cold super-Earths (~200K) shall be more informative than flat transit transmission spectra (e.g. cold GJ 1214b)

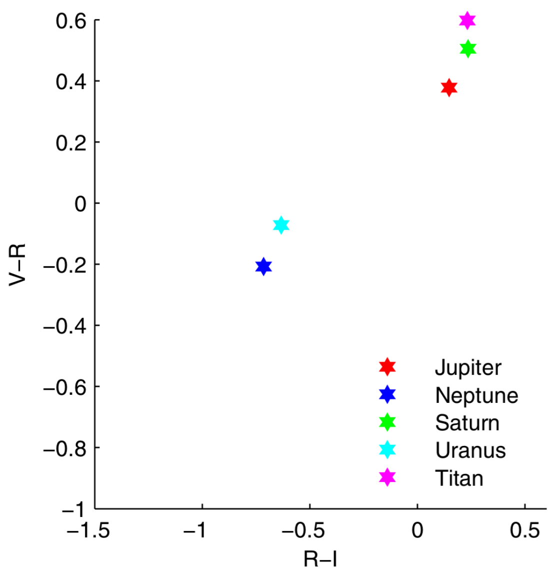
Credit: C. Morley et al. (2015)

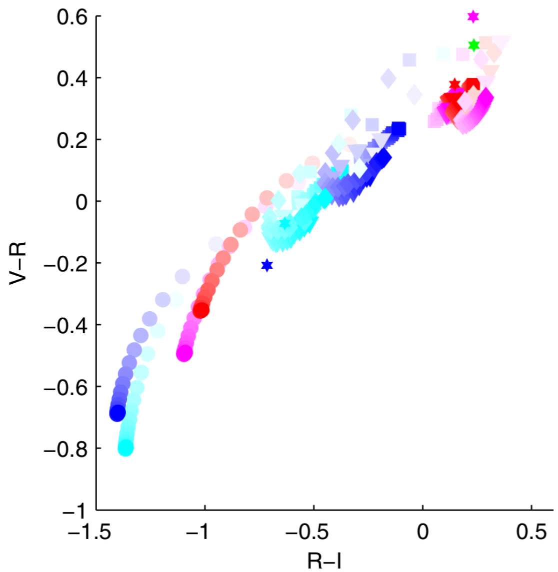
WFIRST CGI Primary Science Goals: *Planets*

✓ Watch out for phase effects!!

✓ Broad-band colors are not enough to discriminate between the effects of planet separation, composition, metallicity and phase (Cahoy et al. 2010)



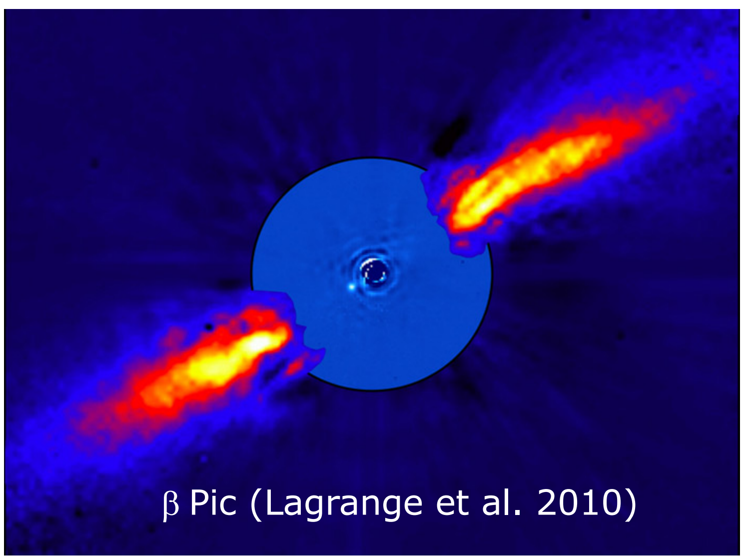


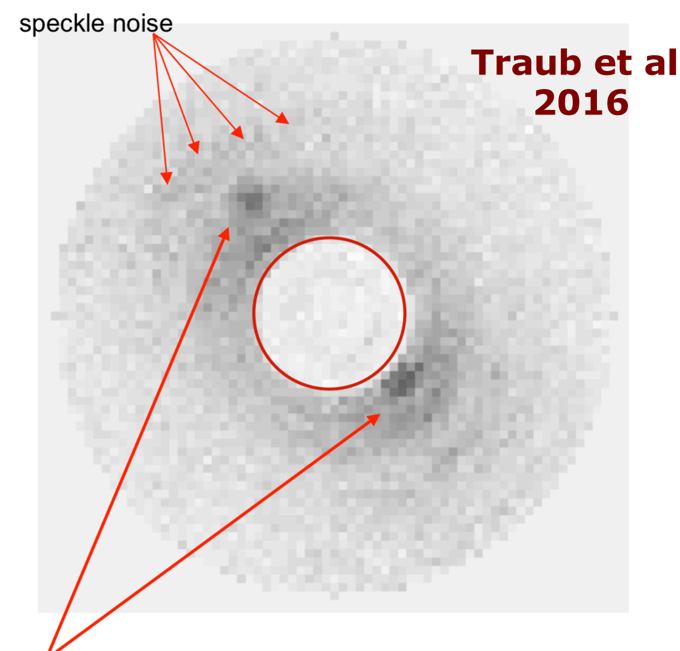


✓ Use orbital info and R=50-70 spectroscopy

WFIRST CGI Primary Science Goals: *Debris Disks*

- ✓ Image exo-zodiacal disks at ~10x solar level, identifying gaps and bright structures in the HZ (close stars) and outside
- ✓ Study the inner region (HZ to 10 AU) of known massive extended debris disks
- ✓ Study the inner region (HZ to 10 AU) of warm disks discovered in the IR but not resolved
- ✓ Conduct planet formation and dynamical evolution studies, including planet/disk interactions

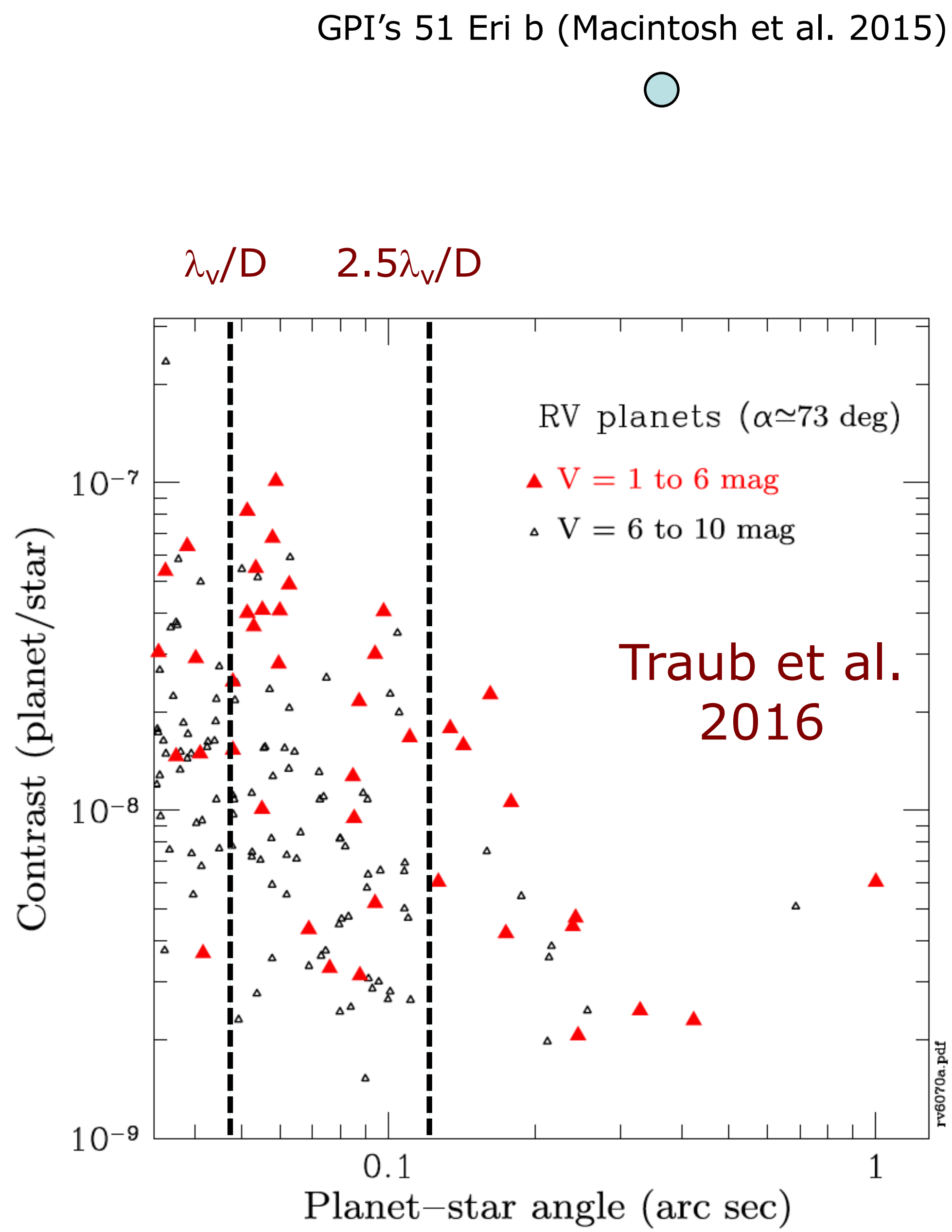




- 47 Uma + 30 zodi disk detected at low SNR in multiple resolution elements
- Planets b(2.1 AU) and c (3.6 AU) easily seen

Stringent contrast requirements

- Requires contrasts of ~10^{-9} at small inner working angles (a few λ/D) in the visible
- 5x closer in and 100x deeper than state of the art

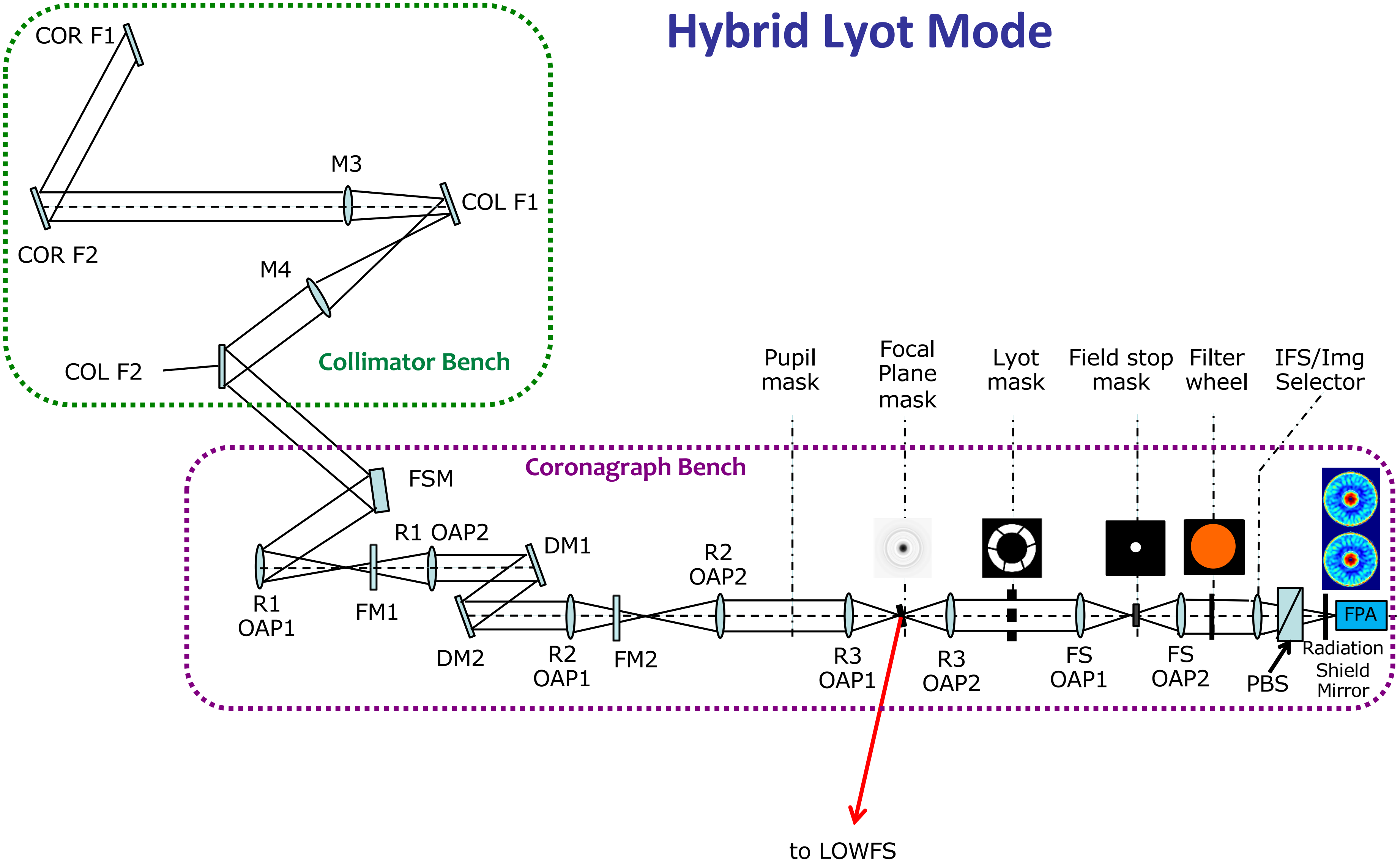


WFIRST Coronagraph Architectures

- Broad-band Imaging: Hybrid Lyot Coronagraph (HLC)
- IFS Spectroscopy: Shaped Pupil Coronagraph (SPC)
- Back Up: Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)

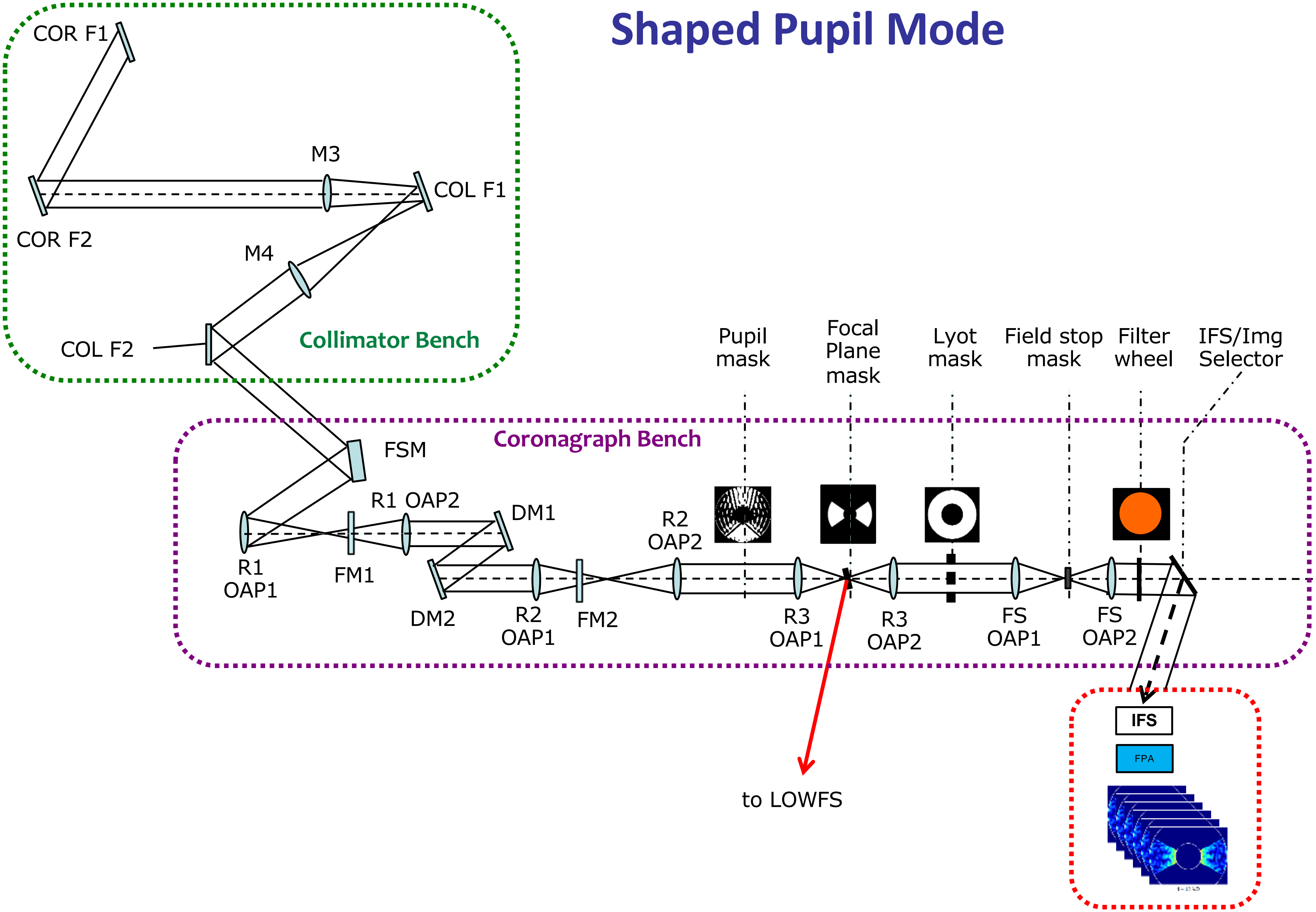
WFIRST HLC Configuration (cycle 6)

Hybrid Lyot Mode

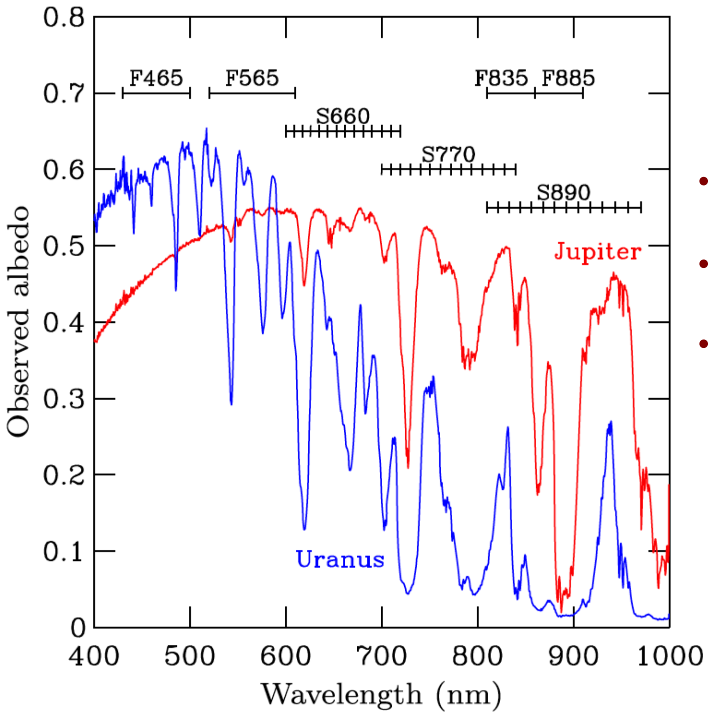


WFIRST SPC Configuration (cycle 6)

Shaped Pupil Mode



WFIRST CGI Broad-band Imaging and Spectroscopy

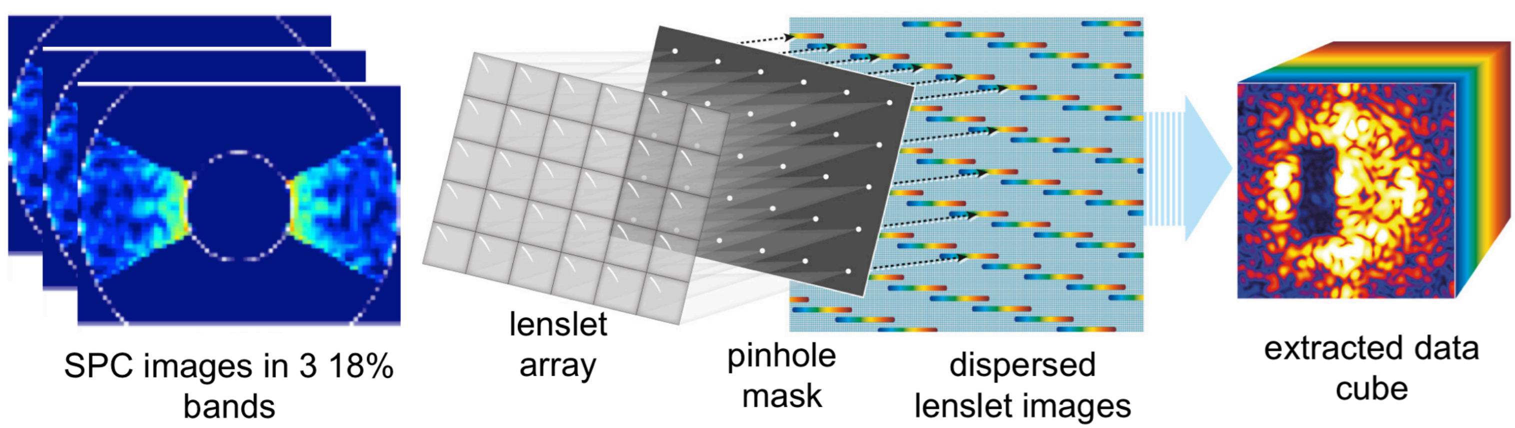


- ~4 broad-band imaging filters
- IFS measurements in 3 filters
- Still in the works (SITs)

(Traub et al. 2016)

λ_0 (nm)	$\Delta\lambda_{FWHM}/\lambda_0$ (%)	Purpose	Polarization	Channel	Coron.
465	15.1	Continuum, Rayleigh	Pol.	Imager	HLC
565	15.9	Continuum, Rayleigh	Pol.	Imager	HLC
835	6.0	CH_4 continuum	Unpol.	Imager	SPC
885	5.6	CH_4 absorption	Unpol.	Imager	SPC
660	18.0	CH_4 spectrum	Unpol.	IFS	SPC
770	18.0	CH_4 spectrum	Unpol.	IFS	SPC
890	18.0	CH_4 spectrum	Unpol.	IFS	SPC

The IFS uses 3 18% bands to produce an R=70 spectra from 600 to 970 nm



Science yield estimates vs instrumental performance (Traub et al. 2016)

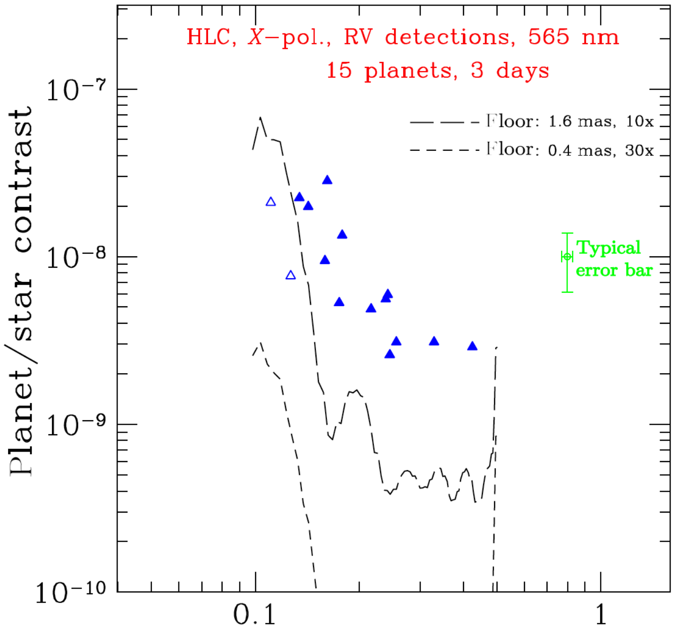
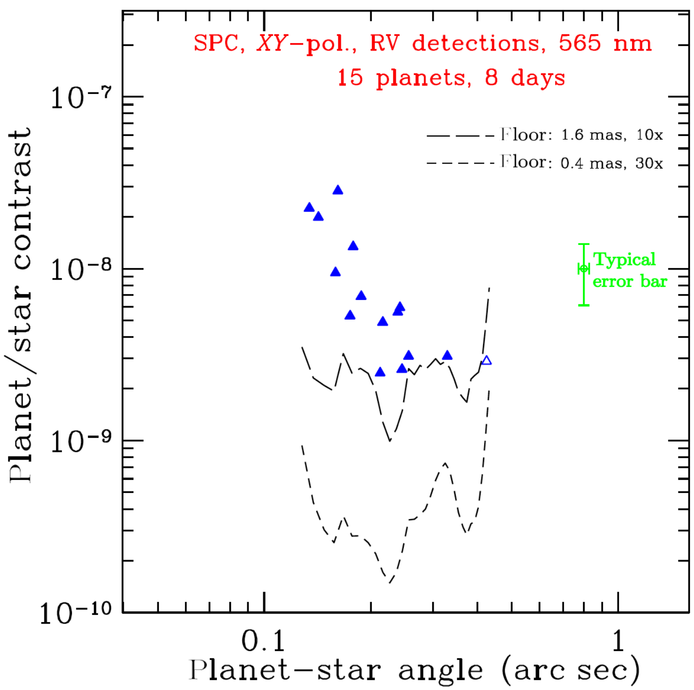
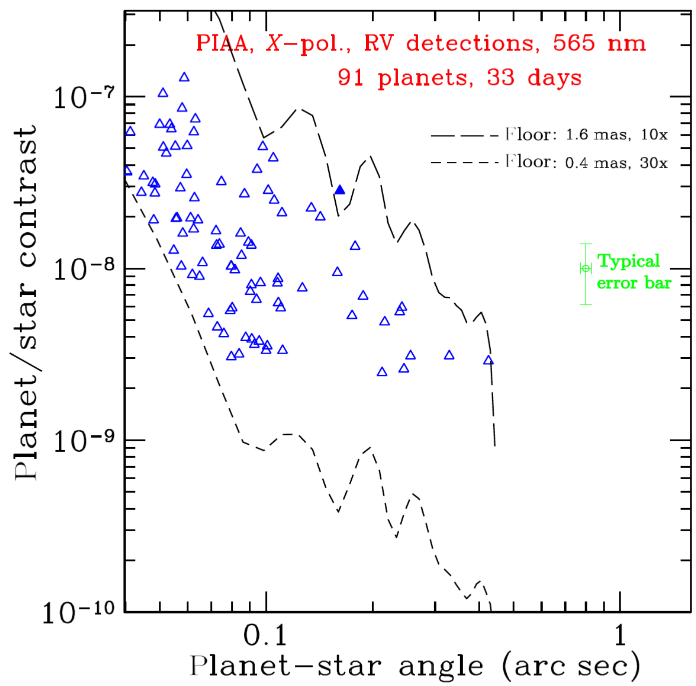


Table 7 The number of $R = 70$ spectra of RV planets that could be obtained from each of the HLC, SPC, and PIAACMC coronagraphs, and the total observing time to obtain these spectra, with further details given in the text. The current plan is to use only the SPC for spectra.

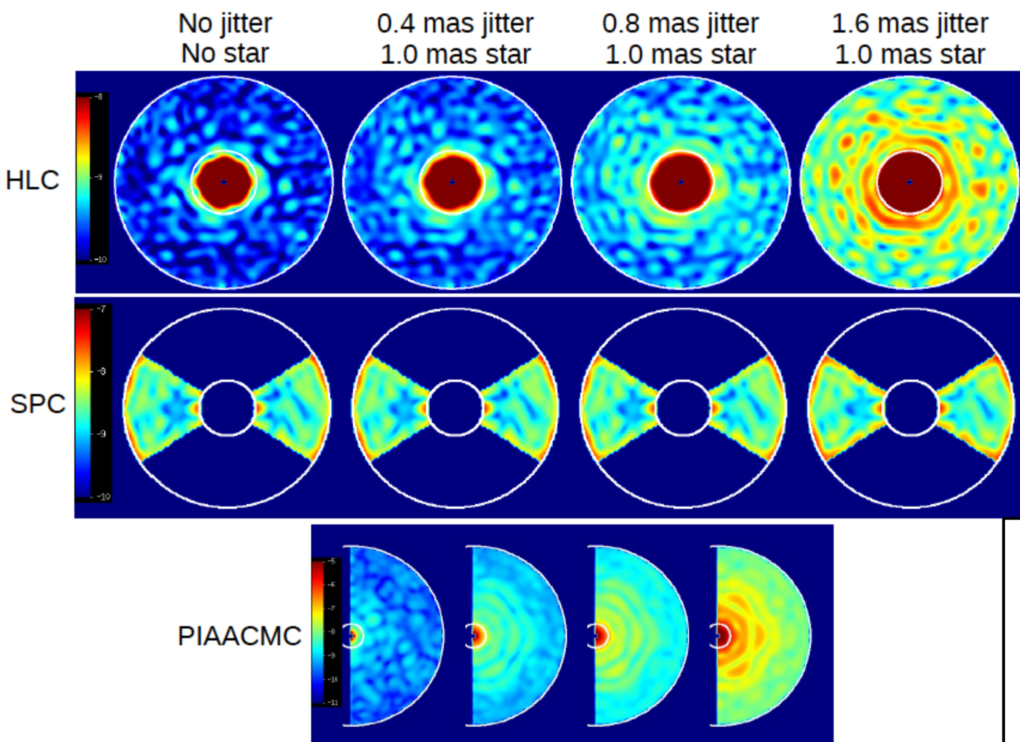
Coron.	*N* (660)	*N* (770)	*N* (890)	Total time (days)
HLC	9	7	1	43
SPC	11	6	1	53
PIAACMC	56	45	21	226

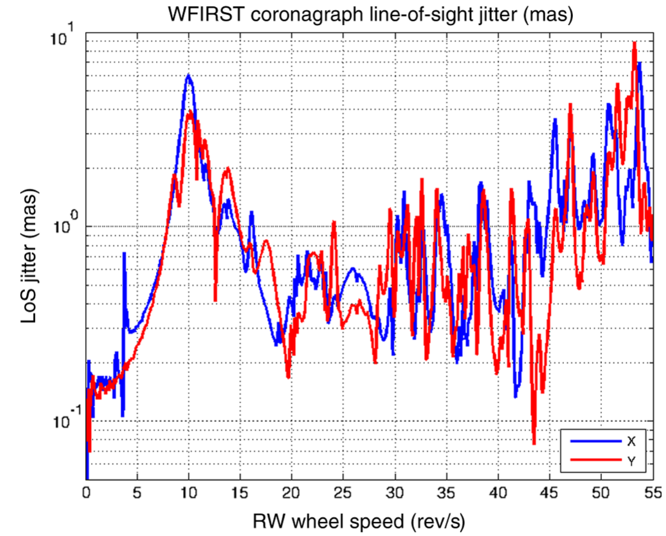


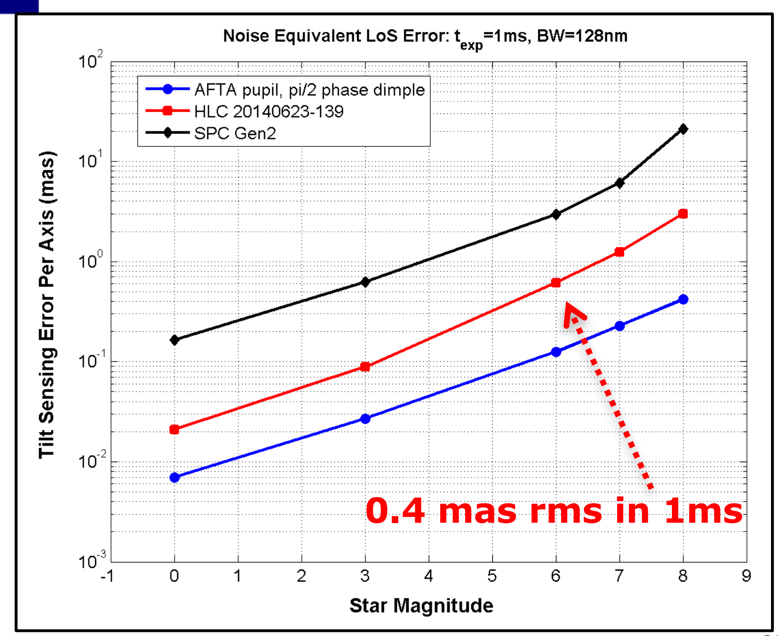


Challenges: Wavefront Sensing and Control – LOS jitter

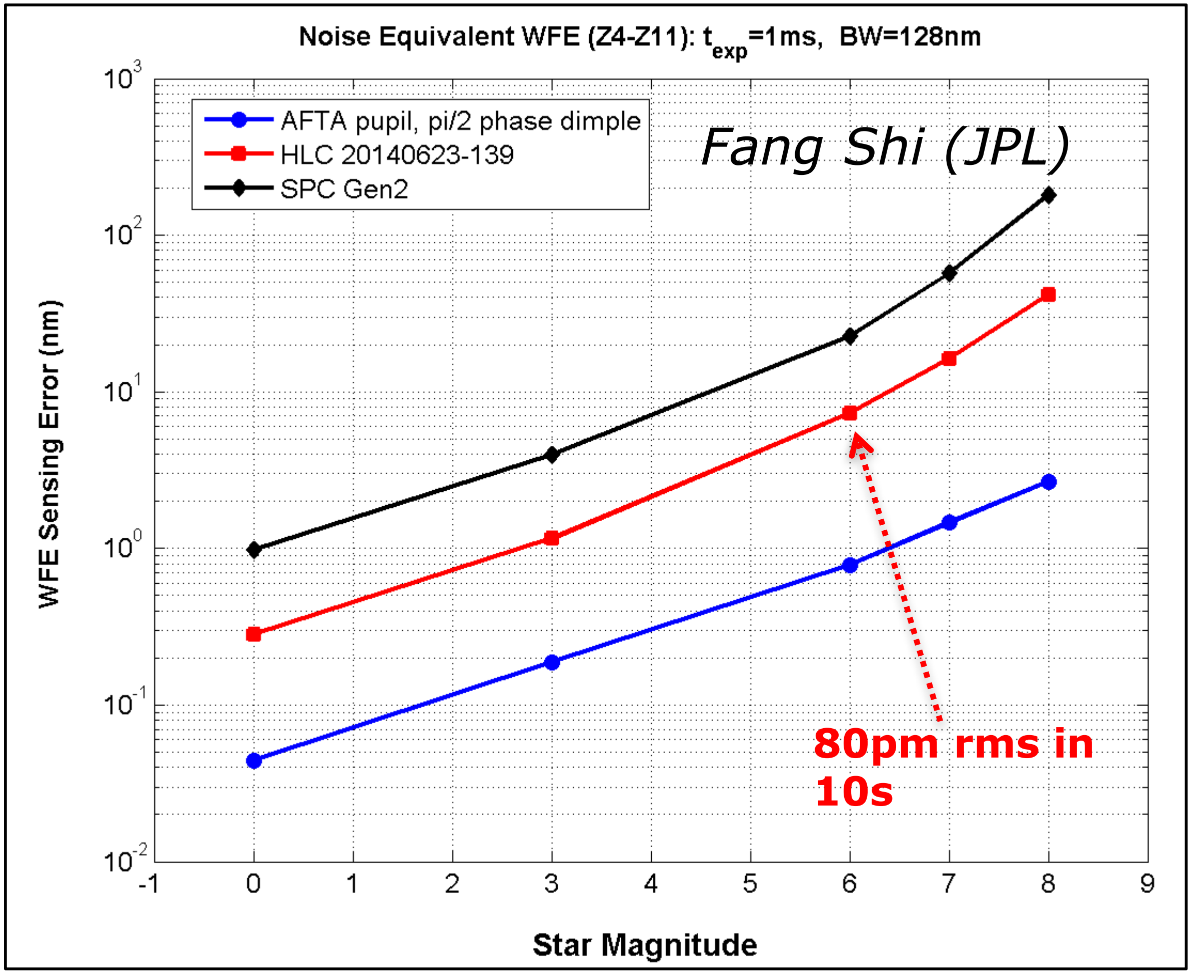
Dark Holes with Pointing Jitter & Finite Star





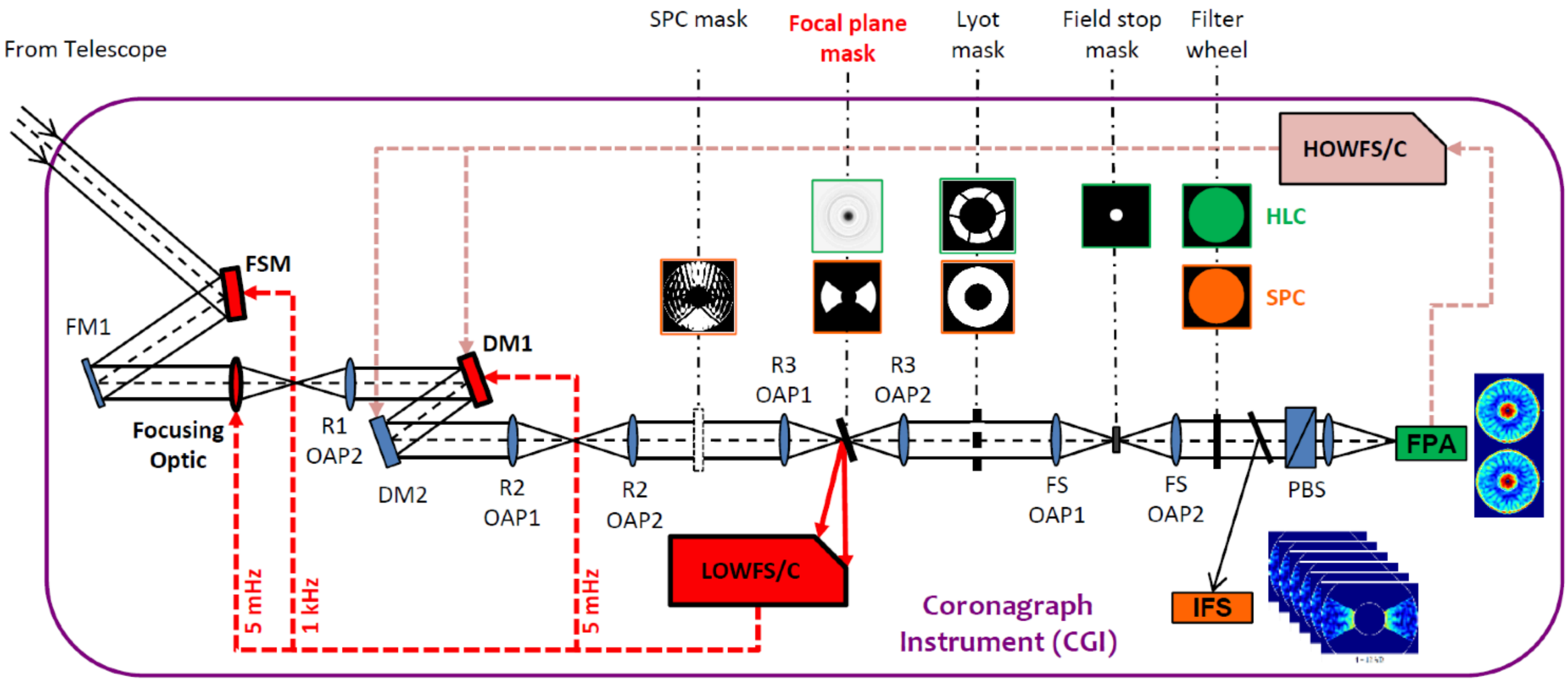


WFIRST LOWFE Sensing



In theory you can get <100 pm residual LOWF (Z4-Z11 total rms) estimation error in 100s on V=6 star, providing telescope wavefront drifts allow it, i.e are not faster

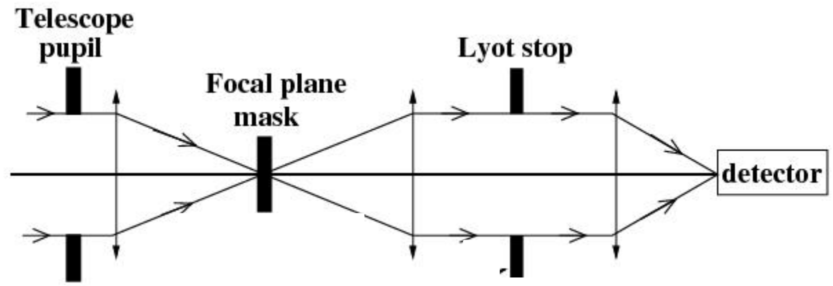
WFIRST CGI Optical Layout and WF Control Loops

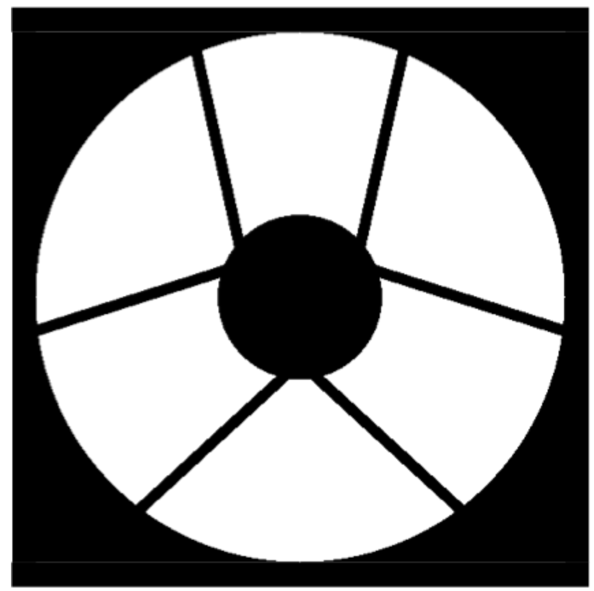


-- Two 48 x 48 DMs (A,ϕ) used for initial Dark Hole generation
-- LOWFS/C loops (tip-tilt, focus, coma, astigmatism, trefoil)

Wheel mechanisms alternating btw different filters and Coronagraphs for BB imaging and IFS spectroscopy

Challenges: “Unfriendly Aperture”





“Only a (her) mother could love this pupil”

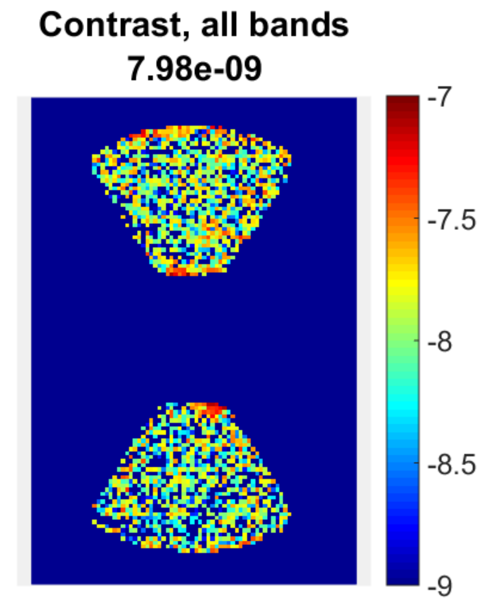
Step 1: Laboratory Testing under relevant conditions: AFTA pupil, dynamic environment, broad-band, vacuum, low flux

MS #	Milestone	Date
1	First-generation reflective Shaped Pupil apodizing mask has been fabricated with black silicon specular reflectivity of less than 10^{-4} and 20 μm pixel size.	7/21/14 DONE
2	Shaped Pupil Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	9/30/14 DONE
3	First-generation PIAACMC focal plane phase mask with at least 12 concentric rings has been fabricated and characterized; results are consistent with model predictions of 10^{-8} raw contrast with 10% broadband light centered at 550 nm.	12/15/14 DONE
4	Hybrid Lyot Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with narrowband light at 550 nm in a static environment.	DONE 2/28/15
5	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment.	DONE 9/15/15
6	Low Order Wavefront Sensing and Control subsystem provides pointing jitter sensing better than 0.4 mas and meets pointing and low order wavefront drift control requirements.	9/30/15 DONE
7	Spectrograph detector and read-out electronics are demonstrated to have dark current less than 0.001 e/pix/s and read noise less than 1 e/pix/frame.	8/25/16
8	PIAACMC coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a static environment; contrast sensitivity to pointing and focus is characterized.	9/30/16
9	Occulting Mask Coronagraph in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.	9/30/16

Where do we stand: successful laboratory testing with AFTA pupil, <u>*static*</u> environment, broad-band, under vacuum

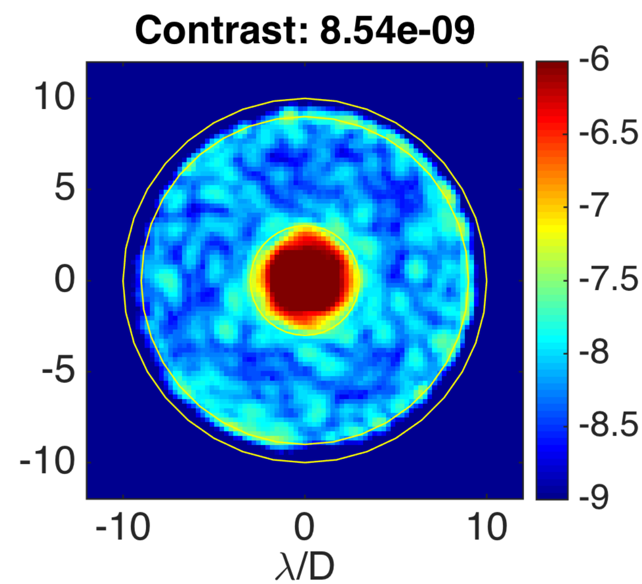
Milestone 5

Occulting Mask Coronagraph (HLC or SPC) in the High Contrast Imaging Testbed demonstrates 10^{-8} raw contrast with broadband light (10%) at 550 nm in a static environment



Results

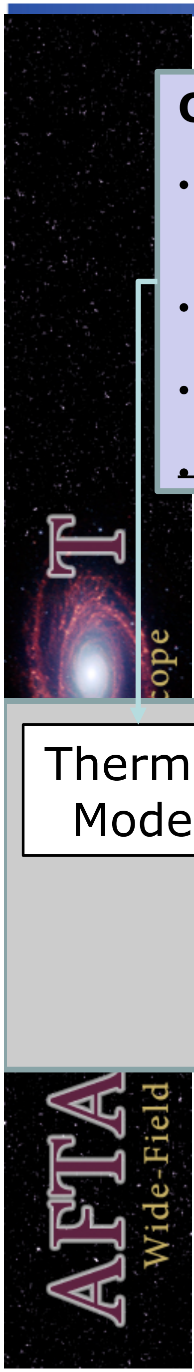
Both shaped pupil and hybrid Lyot coronagraphs have demonstrated repeatable convergence to $<9\times10^{-9}$ mean contrast across a 3-9 λ/D dark hole in broadband light (10%) centered at 550 nm



Next Laboratory (HCIT) Tests coming in FY 17

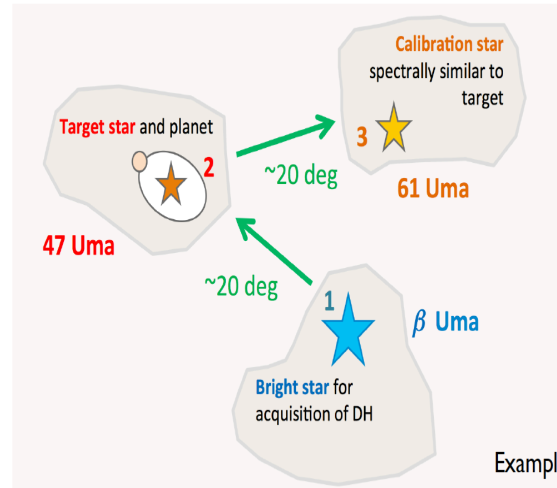
- Dynamic (OTA) testing,
- low flux,
- with IFS
- Push below 10^{-8} raw contrast?

Step 2: End-to-end Simulations of full observing sequence and advanced data post-processing (KLIP PCA etc)

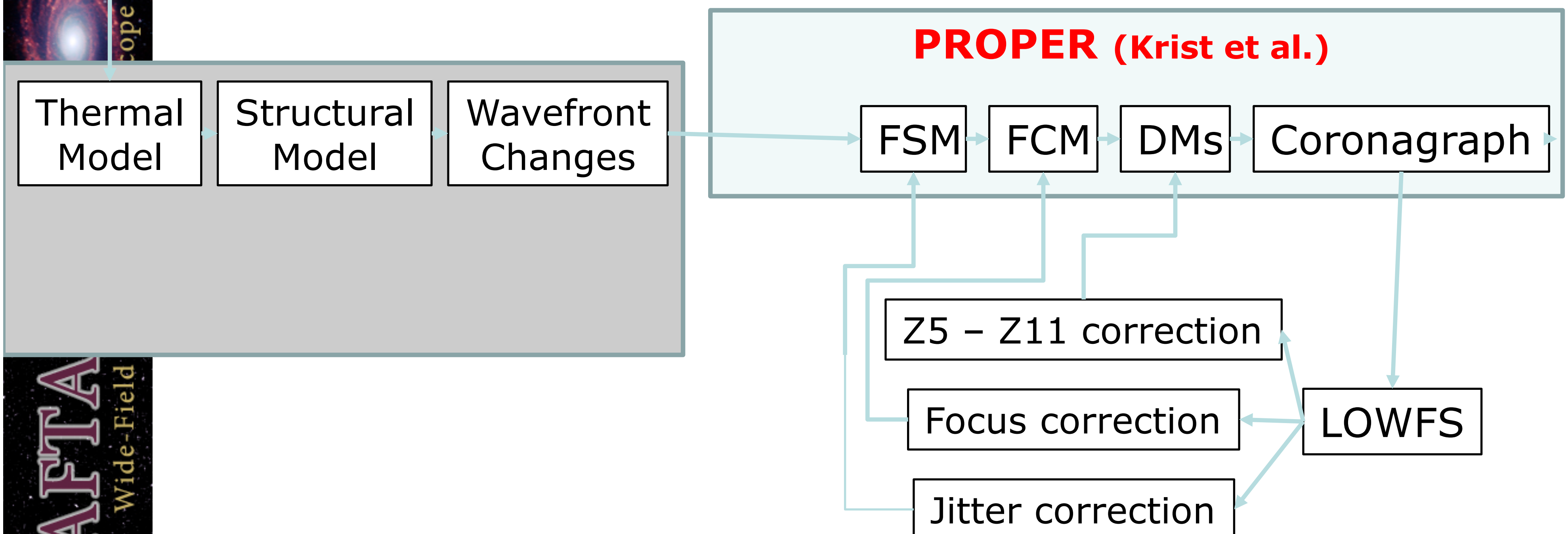


Observing scenario "OS5":

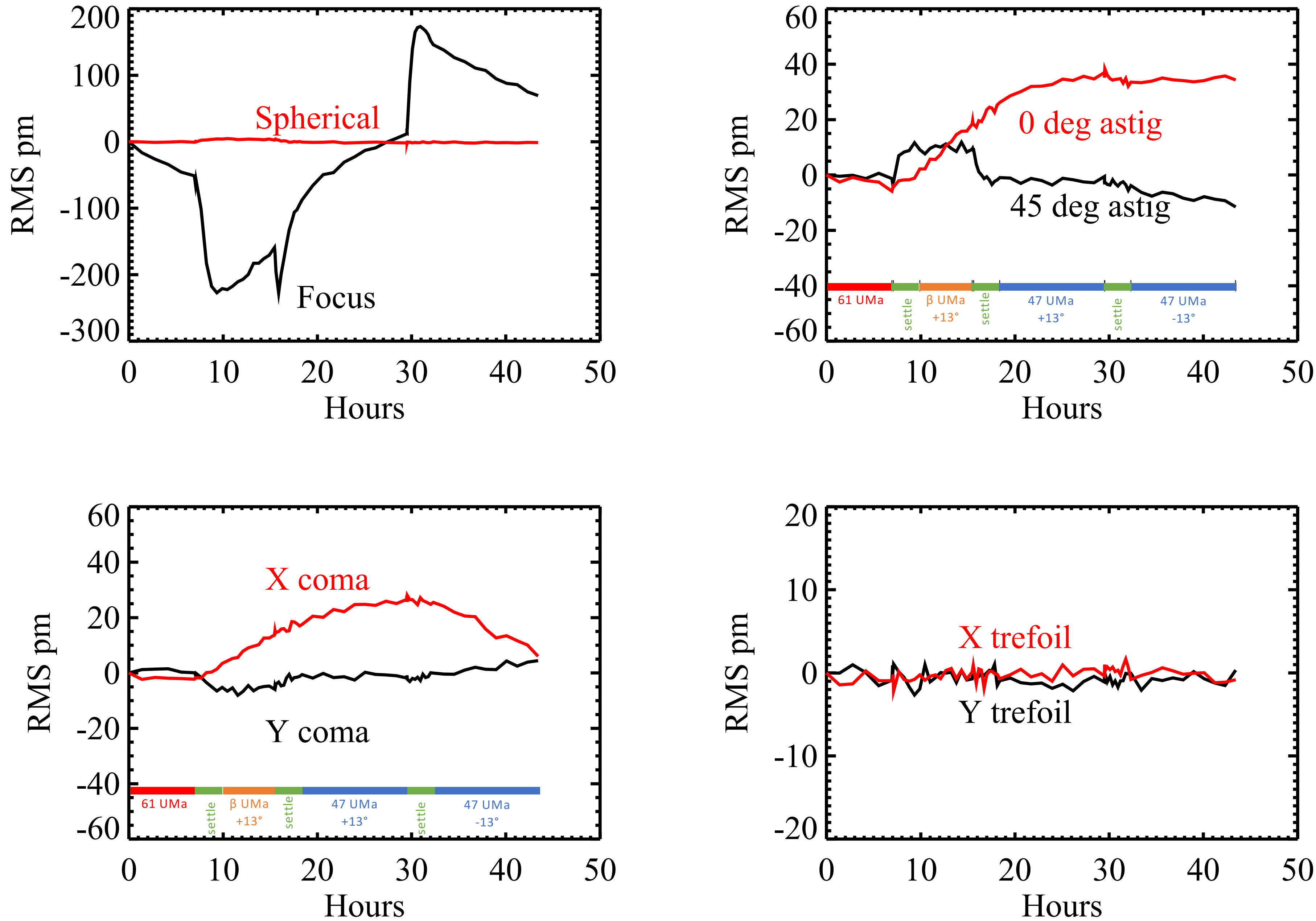
- 8.3 hrs on β UMa +13° roll, bright star (V=2.4, A1IV) for dark hole generation
- 13.9 hrs on 47 UMa +13° roll = science target (V=5.0, G1V)
- 13.9 hrs on 47 Uma @ -13° roll
- ~~13.9 hours on reference star (not used)~~



WFIRST-AFTA
Example of observing scenario
(Nemati)



GSFC OS5 (Final) Result

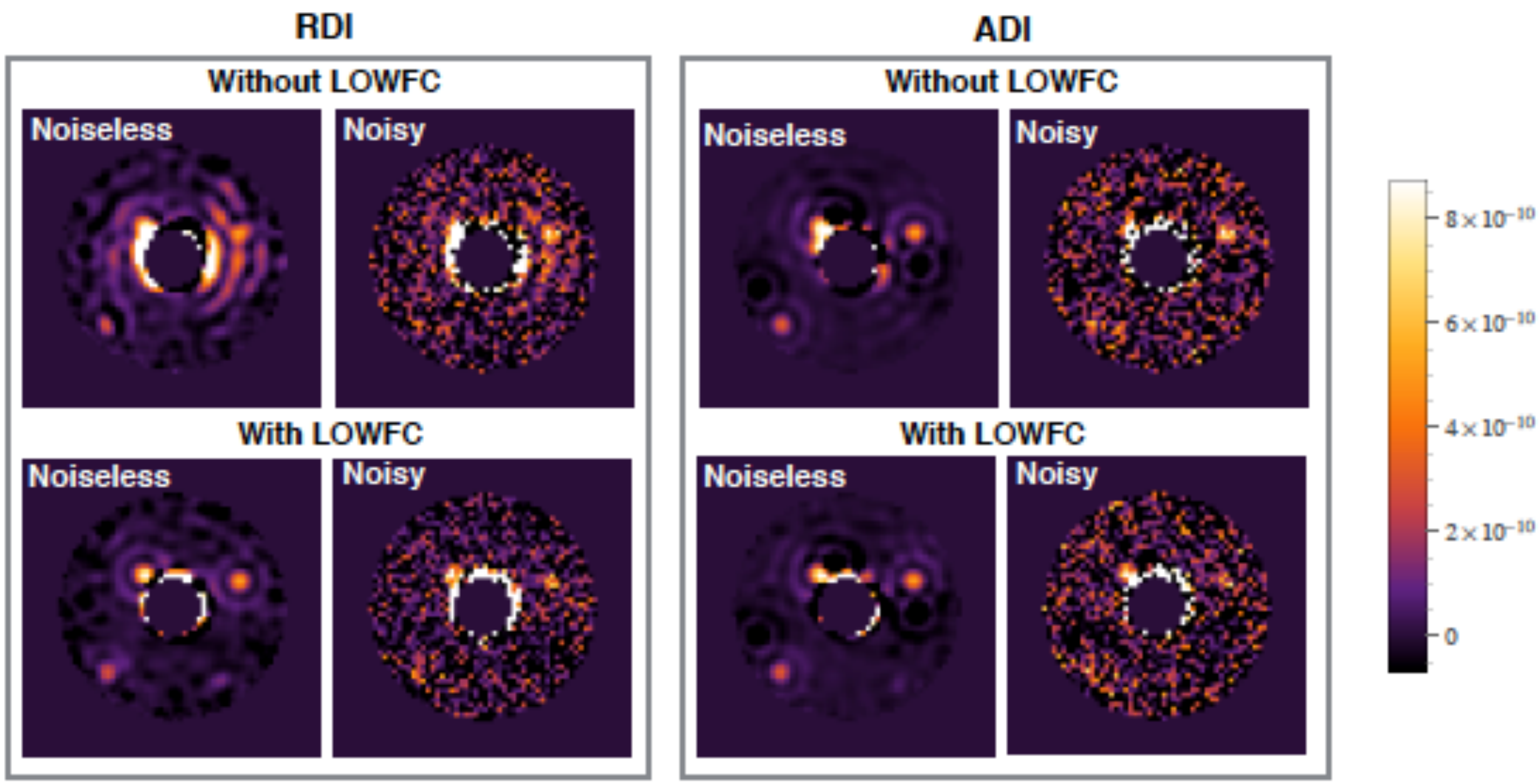


PP of Simulated OS5 HLC Data

AFTA WFIRST
Wide-Field Infrared Survey Telescope

Strategy	Observing sequence	Integration time per star	Total integration time
RDI	β UMa at roll +13° 47 UMa at roll +13°	30000 sec 50000 sec	80000 sec
ADI	47 UMa at roll +13° 47 UMa at roll -13°	50000 sec 50000 sec	100000 sec

Table 5: **RDI and ADI observing strategies.**

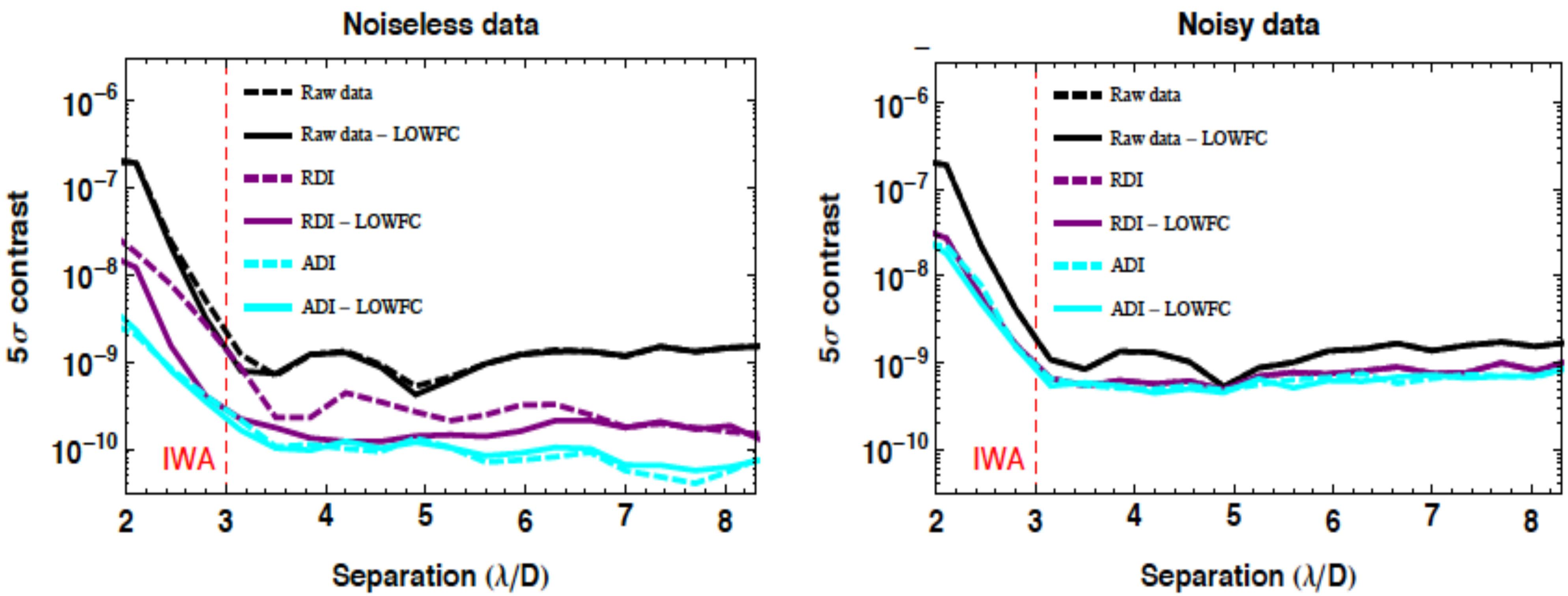


Credit: Ygouf, Pueyo, Zimmerman, Soummer (work managed by CGI project at JPL)

Post-processing of Simulated OS5 HLC Data

Strategy	Observing sequence	Integration time per star	Total integration time
RDI	β UMa at roll +13° 47 UMa at roll +13°	30000 sec 50000 sec	80000 sec
ADI	47 UMa at roll +13° 47 UMa at roll -13°	50000 sec 50000 sec	100000 sec

Table 5: **RDI and ADI observing strategies.**



Also looked at spectral extraction using post-processing of simulated raw SPC (OS3) data

SUMMARY

- WFIRST CGI will provide first spectra of cold giant planets and mini-Neptunes in orbit around mature (sun-like) stars

- WFIRST CGI may provide first spectra of a few super-Earths around nearby mature (sun-like) stars

- WFIRST CGI will image exozodiacal disks at ~10x solar systems levels in the visible, in the HZ of nearest stars

- Laboratory testing on track and encouraging end-to-end simulations results so far *(but still a tough pupil for HCI)*

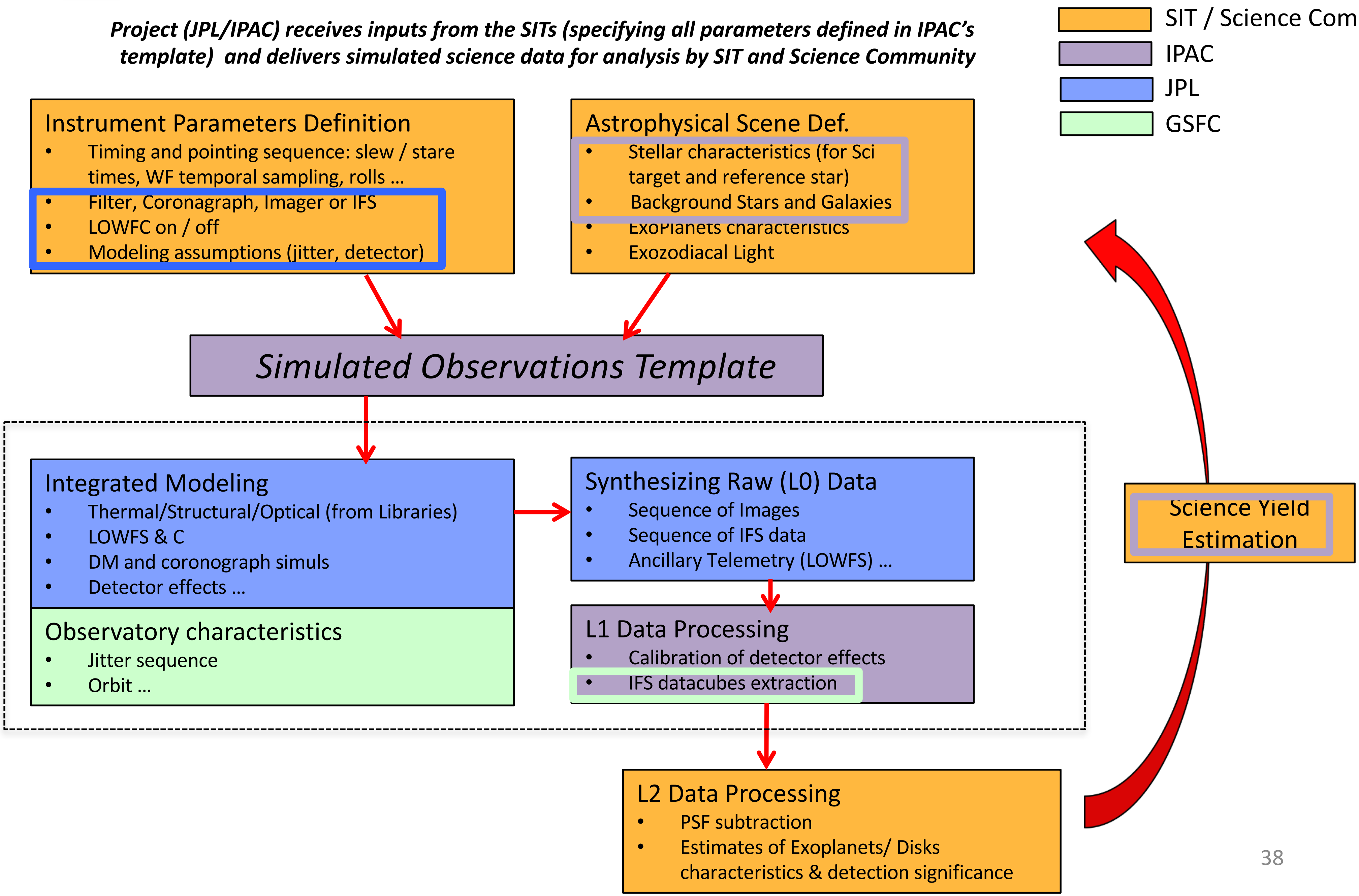
- WFIRST CGI will mature many key technologies to TRL 9 in preparation for future exoplanet imaging mission concepts such as **HabEx** and **LUVOIR** (e.g. high contrast space coronagraphy on complex aperture, active WFS/C in space, large DMs, extra low noise detectors)

For a lot more details about the art of coronagraphy, please come to Dimitri Mawet's tutorial on October 24!

Back-Up

A lot of work ahead to close the loop between science and engineering: Observation Scenario Simulations Interface (project @ JPL / IPAC /SITs)

Project (JPL/IPAC) receives inputs from the SITs (specifying all parameters defined in IPAC's template) and delivers simulated science data for analysis by SIT and Science Community

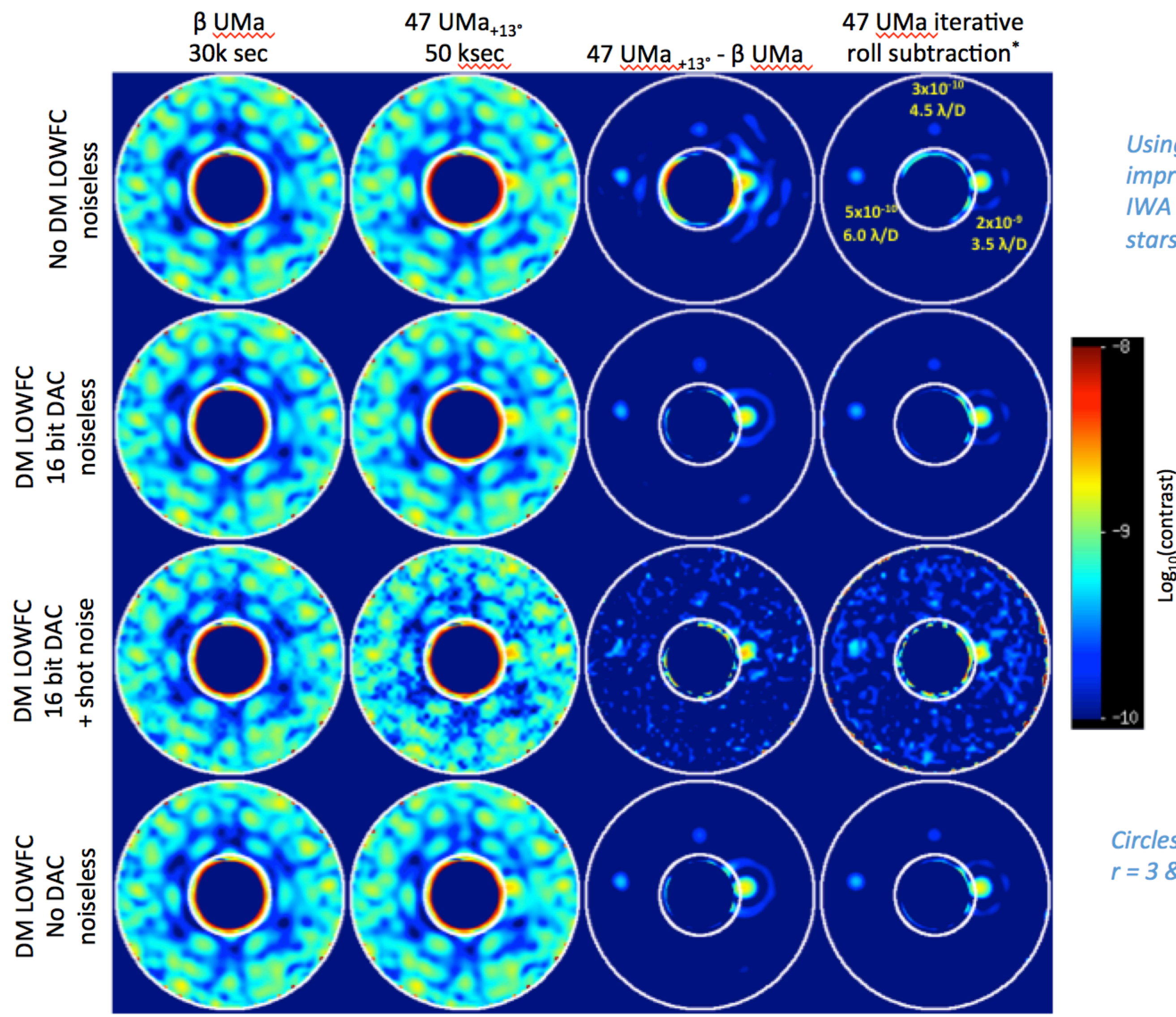


On-going work

(J. Krist, in collab. with GSFC and Nemati's IM group)

Reference and angular differential imaging: co-added images

OS5 scenario, HLC, 15% V bandpass, X polarization

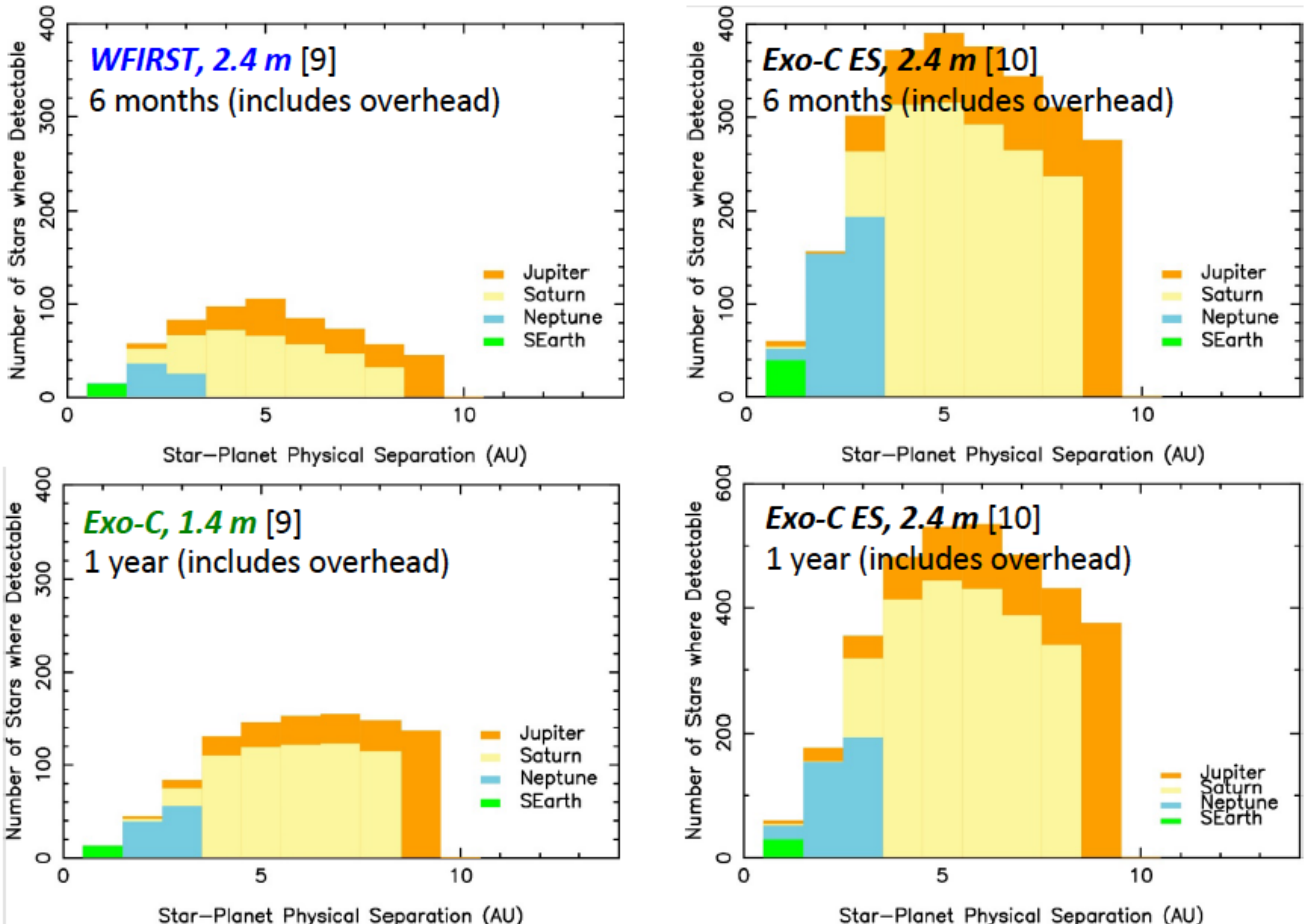


Using DM LOWFC improves stability at IWA and between stars

Circles correspond to r = 3 & 8.5 λ/D

*Described in Krist et al., "HST and Spitzer Observations of the HD 207129 Debris Ring", Astron. J., 140, 1051 (2010).

Exo-C ES increases search yield



K. Stapelfeldt for Exo-C, ES [9,10]