WFIRST Coronagraphy

Historic

- Astrodecal **2010** : recommandation **WFIRST** (Wide Field IR Survey Telescope) for ***New Worlds New Horizons***
    1. ***Expansion rate of the Universe*** => wide FOV and low resolution spectroscopy
    2. ***other Solar Systems like ours*** => Micro lensing
- **2012** : Science Definition Team (SDT) report
  Telescope 1.3~1.1m sans obstruction, L2, 0.6-2.4 microns
- **2013** : AFTA (Astrophysics Facility Telescope Assets) received by NASA
  Telescope HST-like, D=2.4m => need to redefine the science cases
- **05/2013** : SDT Report with optional Coronagraph
- **2014** : NRC review - concerns on coronagraph performance
  => milestones plan to meet TRL 5
  => lab demonstration of contrast with AFTA pupil
- **2014-2015** : European interests (chair : M. Cropper) => UK declines official commitments
- **03/2015** : SDT Report with optional Coronagraph
- **2016** : Science Investigation Teams (SITs) selected
- **06/2016** : call ESA - "Opportunity for European scientists on the WFIRST Formulation Science Working Group (FSWG)" => T. Henning / A. Boccaletti
- **04/2017** : independent external technical and cost review of WFIRST

SITs + Adjudants

- B. **Macintosh** et al. "Optimizing WFIRST Coronagraph Science"
- M. **Turnbull** et al. "Harnessing the power of the WFIRST-coronagraph: a coordinated plan for exoplanet and disk science"
- J. **Kasdin** : WFIRST CGI adjudant scientist

CGI Working Groups :

- CGI Simulations (Bruce Macintosh, chair, Maggie Turnbull deputy chair)
- CGI Targets (Maggie Turnbull, chair, Andrew Howard, deputy chair)
- CGI Requirements Development (Kerri Cahoy, chair, Avi Mandell, deputy chair)
- CGI Data Management and Post-Processing (Laurent Pueyo, chair)

Potential contributions (NASA suggestions)

Filter and mask wheels: Europe could provide the wheels inside the coronagraph that hold the filters and mask.

Detectors: Europe could provide the e2V CCD201 detectors for the coronagraph and IFS.

Detector calibration and radiation testing: Europe could work with NASA to calibrate and perform radiation testing on the CCD detector for the coronagraph instrument.

Star trackers: Europe could provide star trackers for the WFIRST spacecraft.

Solar array: Europe could provide the solar array for the WFIRST spacecraft.

S-band transmitter: Europe could provide the S-band transmitter for the WFIRST spacecraft.

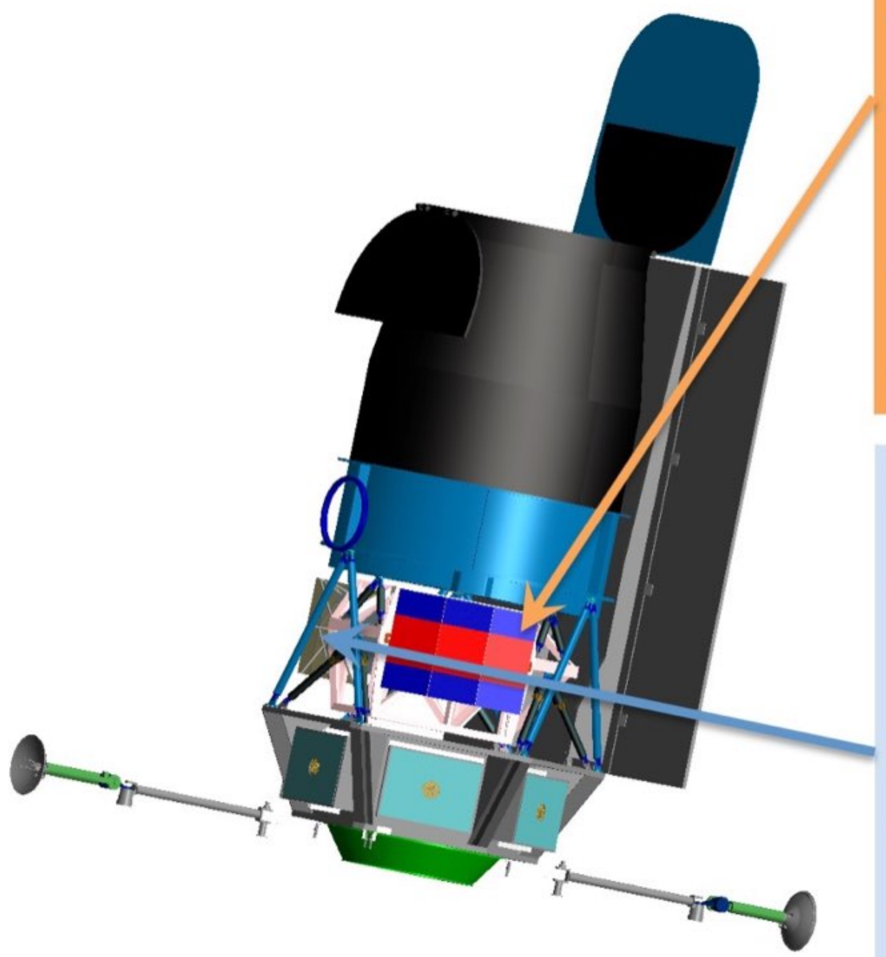
Ground station Support: Europe would provide ground station support for downlink of S-band and Ka-band data

Any ESA contribution would be the subject of a Mission of Opportunity Proposal and a subsequent SPC decision

WFIRST in brief

phase A started on Feb 2016
Launch in mid 2020'
6.25 years nominal mission
1 year CGI
starshade ready …

managed at GSFC
participation : JPL, STScI, IPAC
june 2017 : SRR, decide participation ESA
Oct 2017 : start phase B



WFI

Wide-Field Instrument

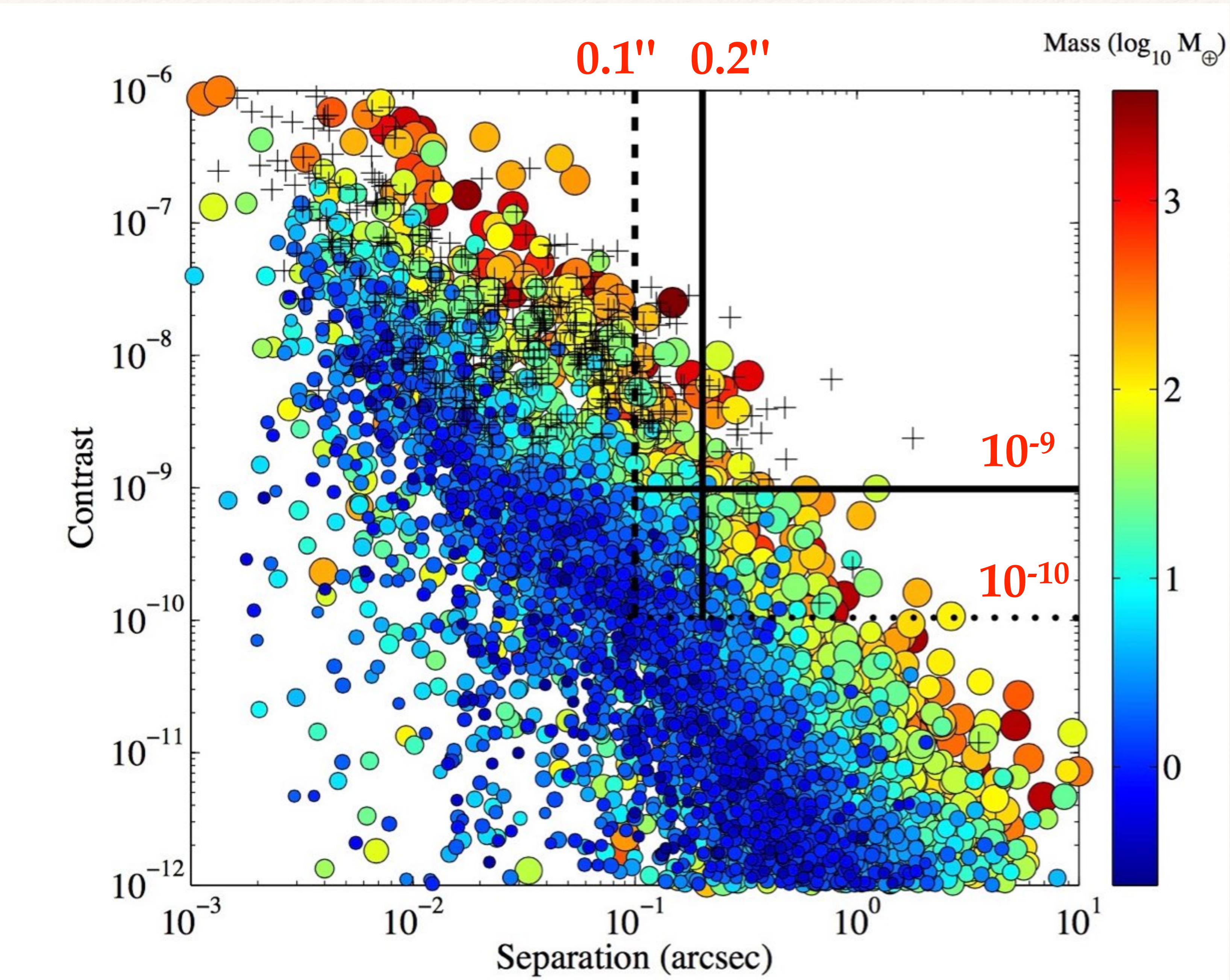
- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 μm (imaging) & 1.35-1.89 μm (spec.)
- 0.28 deg² FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

CGI

Coronagraph

- *Image and spectra of exoplanets from super-Earths to giants*
- *Images of debris disks*
- 430 – 970 nm (imaging) & 600 – 970 nm (spec.)
- Final contrast of 10^{-9} or better
- Exoplanet images from 0.1 to 1.0 arcsec

Science Objectives



model :
200 stars <30pc
4 planets per star (gas, ice, rocky)

objectives :

- known RV planets(primary goal)
- new gas/ice giants (primary goal)
- new water/Super Earths (ultimate goal)

Design

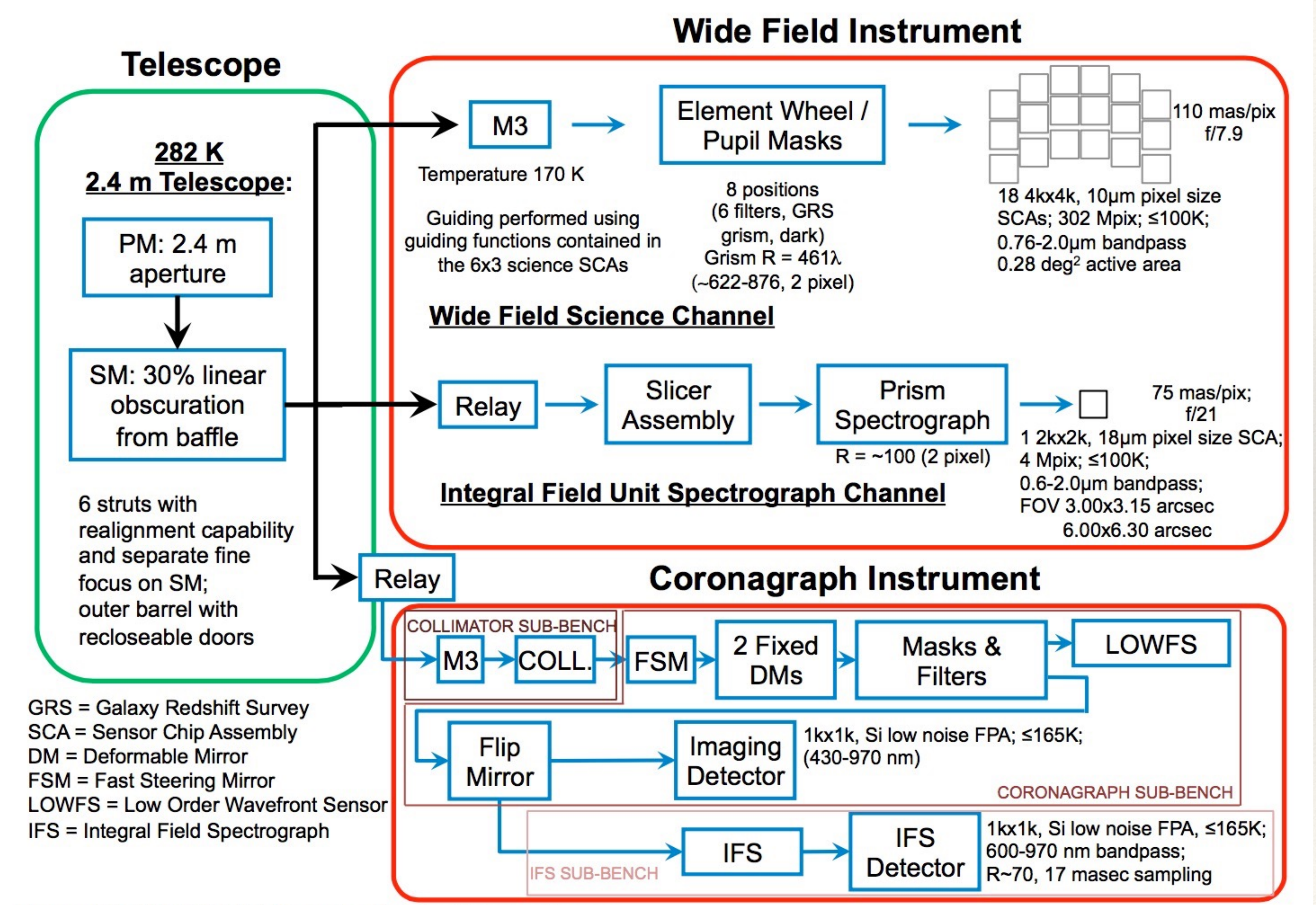
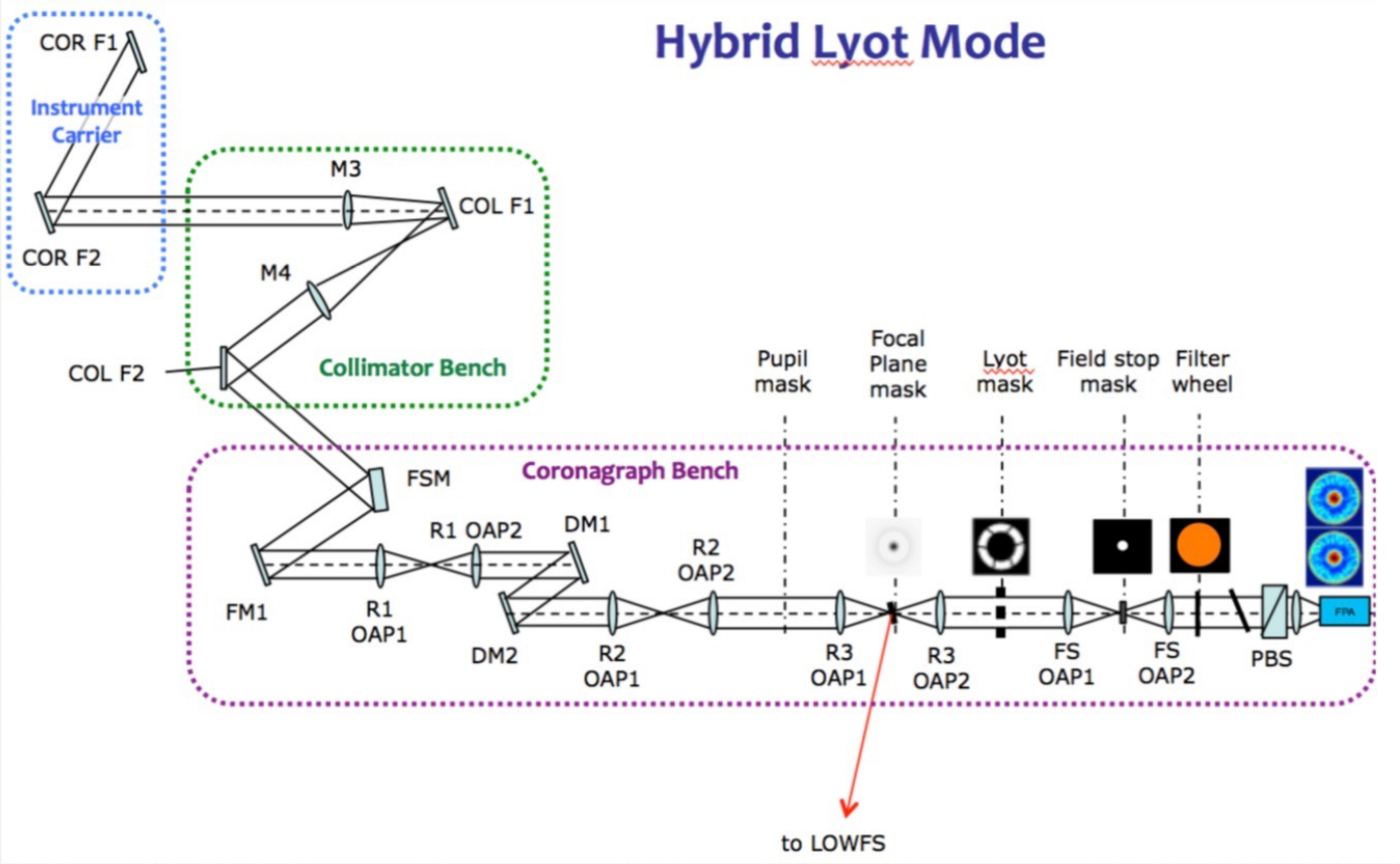


Figure 3-2: WFIRST-AFTA payload optical block diagram.

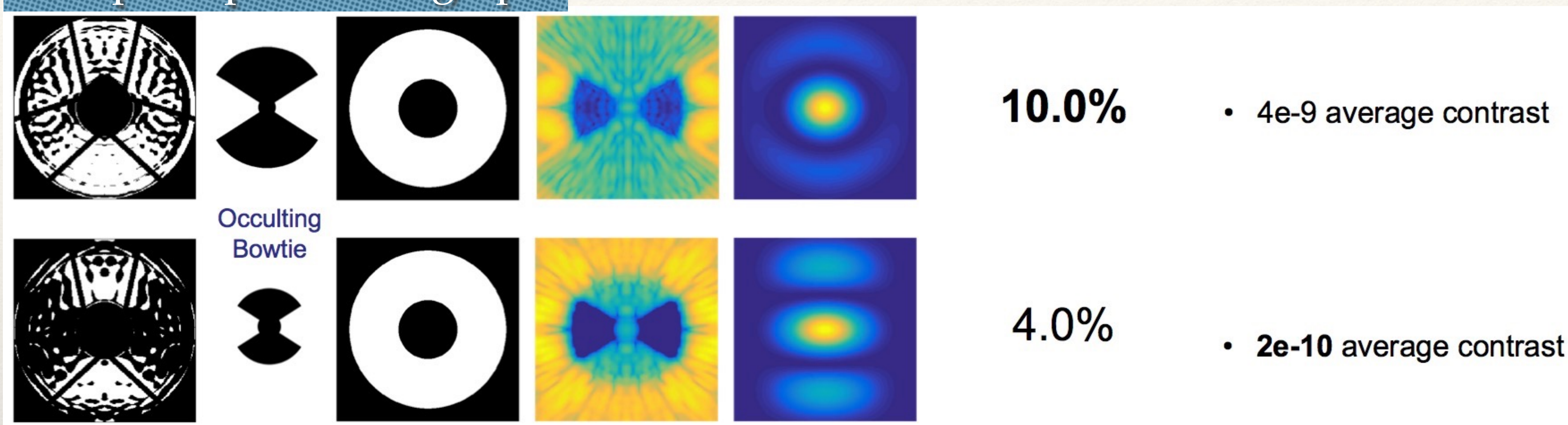
Design

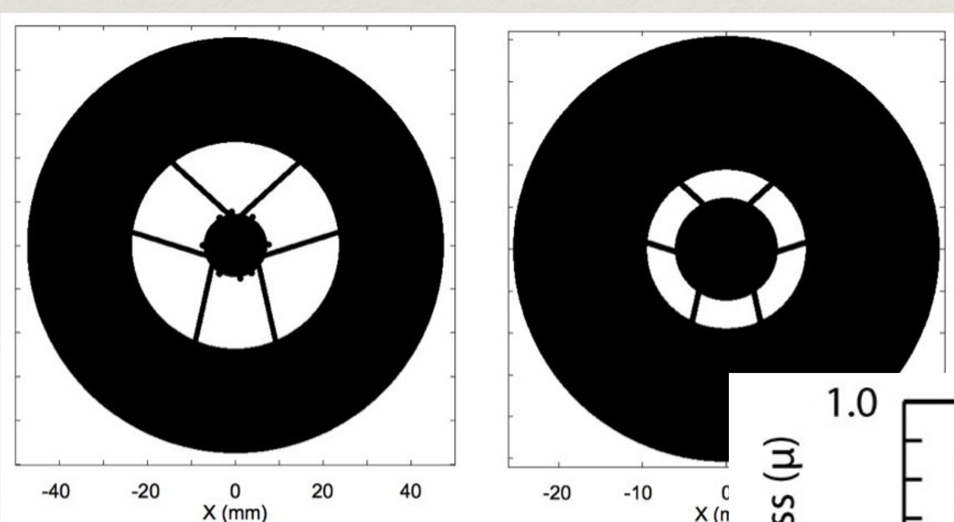


Hybrid Lyot Mode
COR F1
Instrument Carrier
COR F2
M3
COL F1
M4
COL F2
Collimator Bench
Pupil mask
Focal Plane mask
Lyot mask
Field stop mask
Filter wheel
Coronagraph Bench
FSM
R1 OAP2
DM1
R2 OAP2
FM1
R1 OAP1
DM2
R2 OAP1
R3 OAP1
R3 OAP2
FS OAP1
FS OAP2
PBS
FPA
to LOWFS

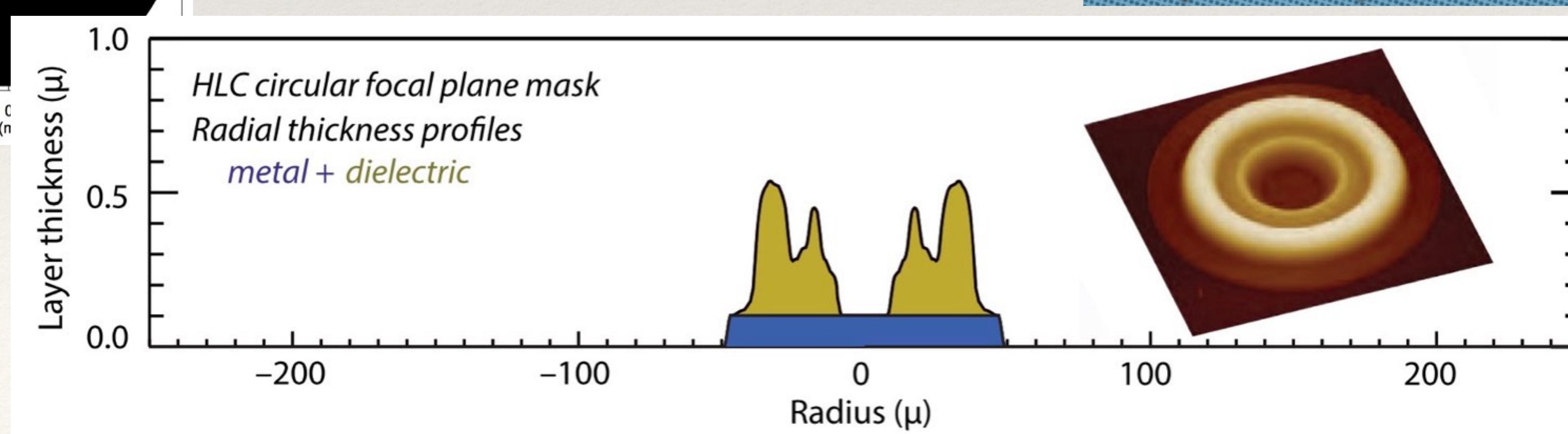
Two Coronagraphs (Occulting Mask)

Shape Pupil Coronagraph





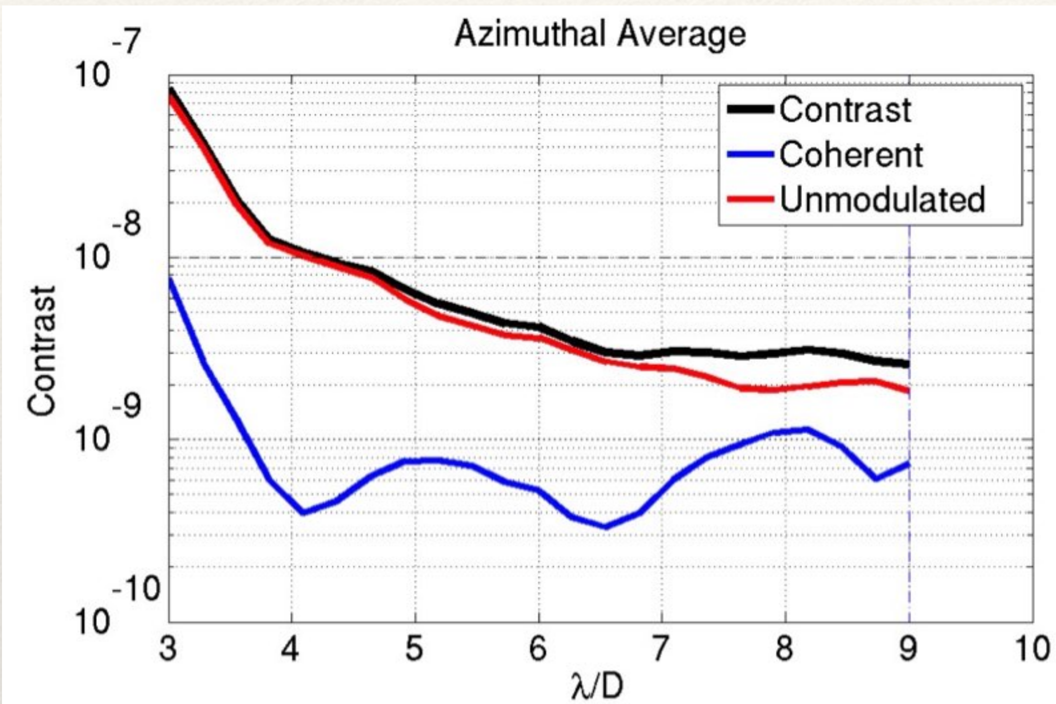
Hybrid Lyot Mask

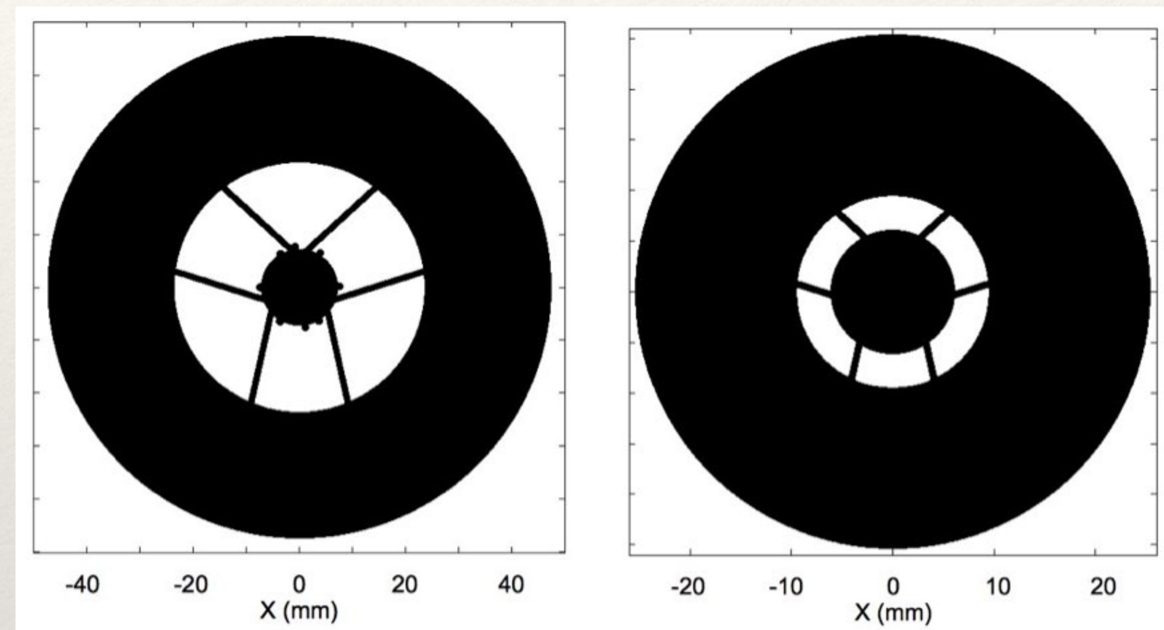


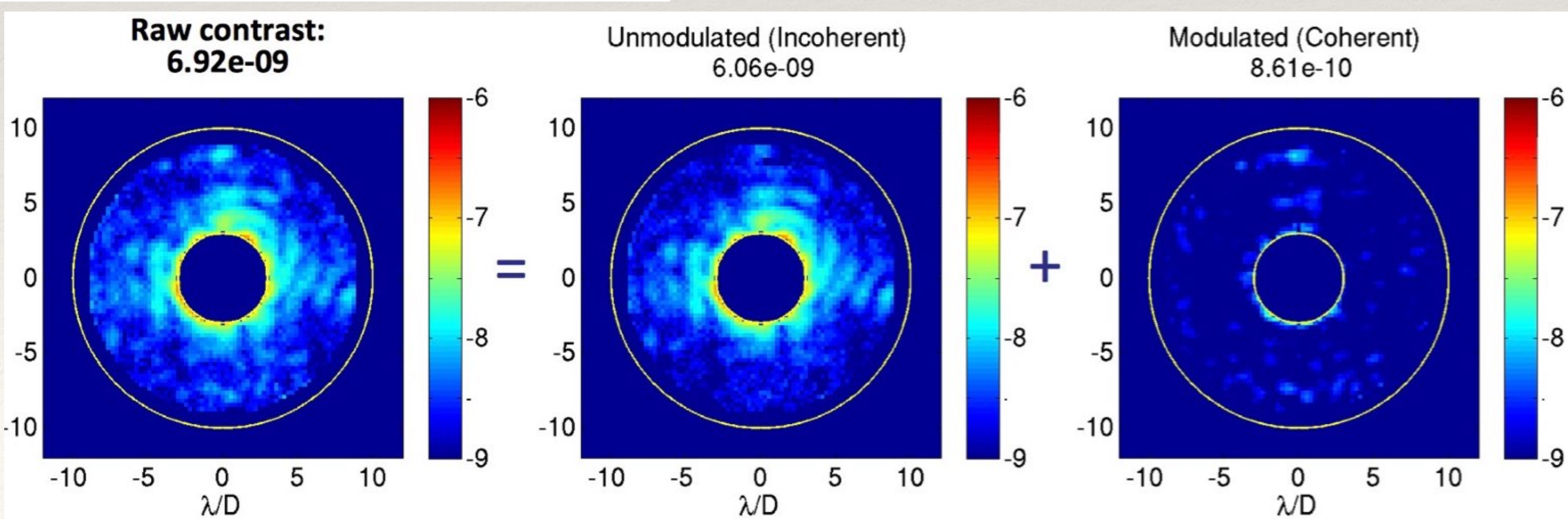
Milestones coronagraphs

07/2015

- **Milestone #4:** HLC in HCIT demonstrates 10−8 raw contrast with narrowband light at 550 nm in a static environment.





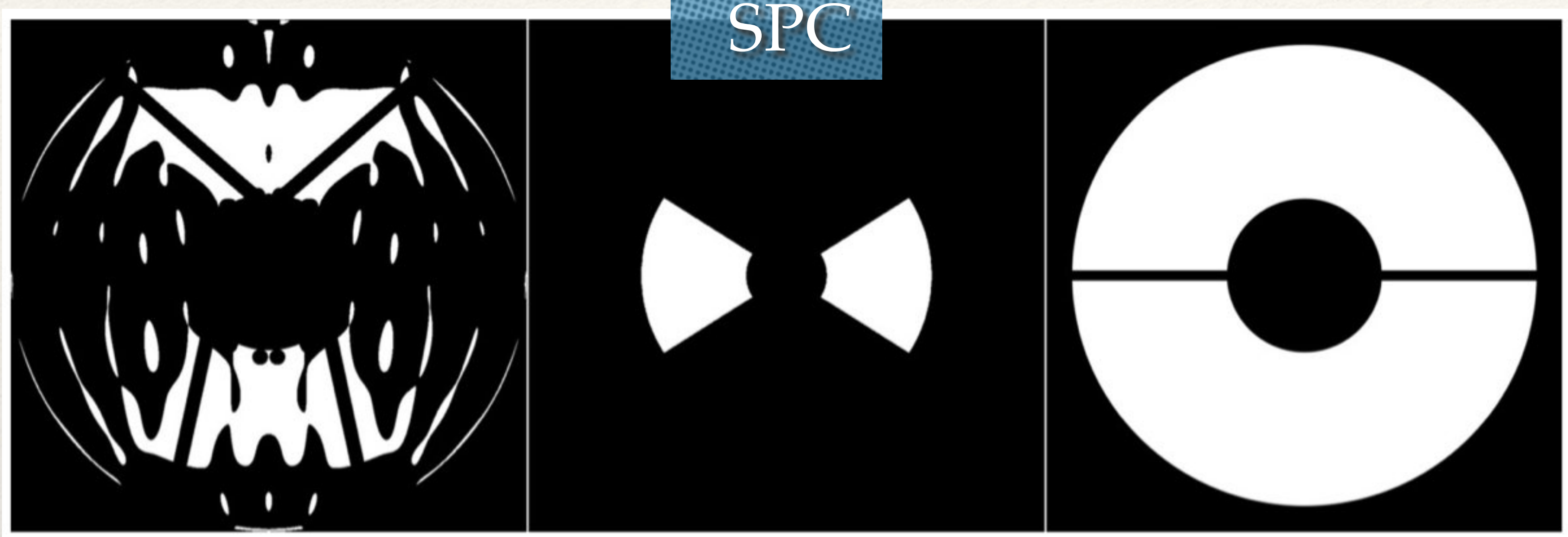


Milestones coronagraphs

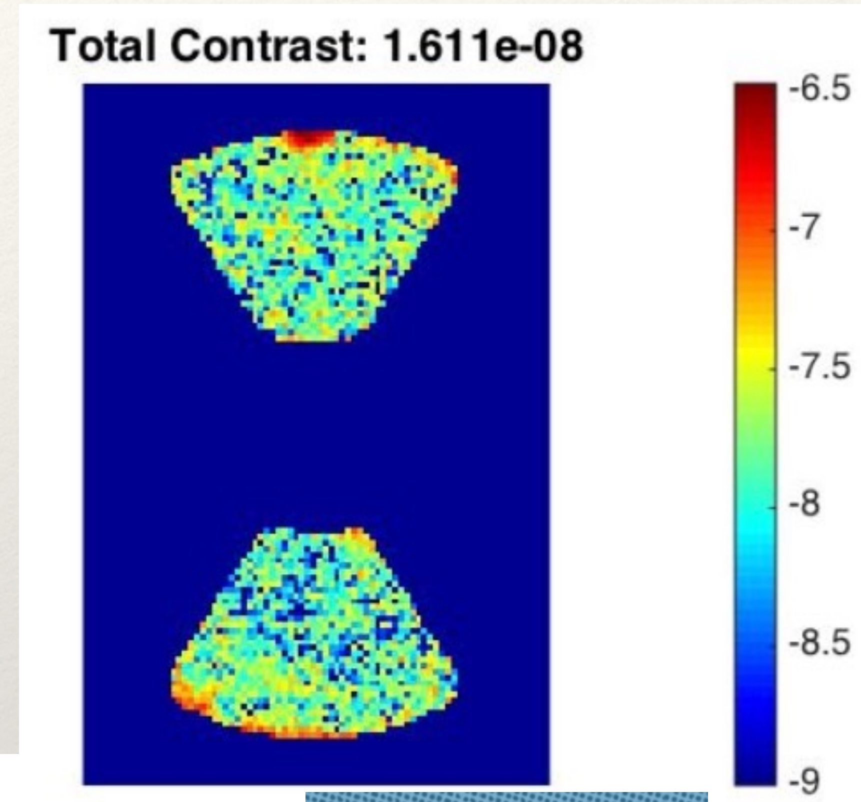
12/2015

- **Milestone #5:** OMC (HLC or SPC) in HCIT demonstrates 10−8 raw contrast with broad band light (10%) at 550 nm in a static environment.

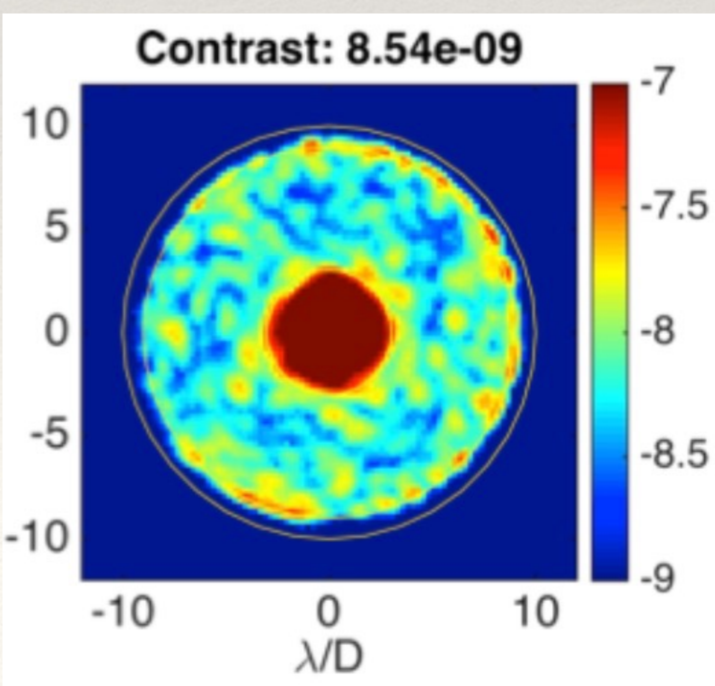
SPC

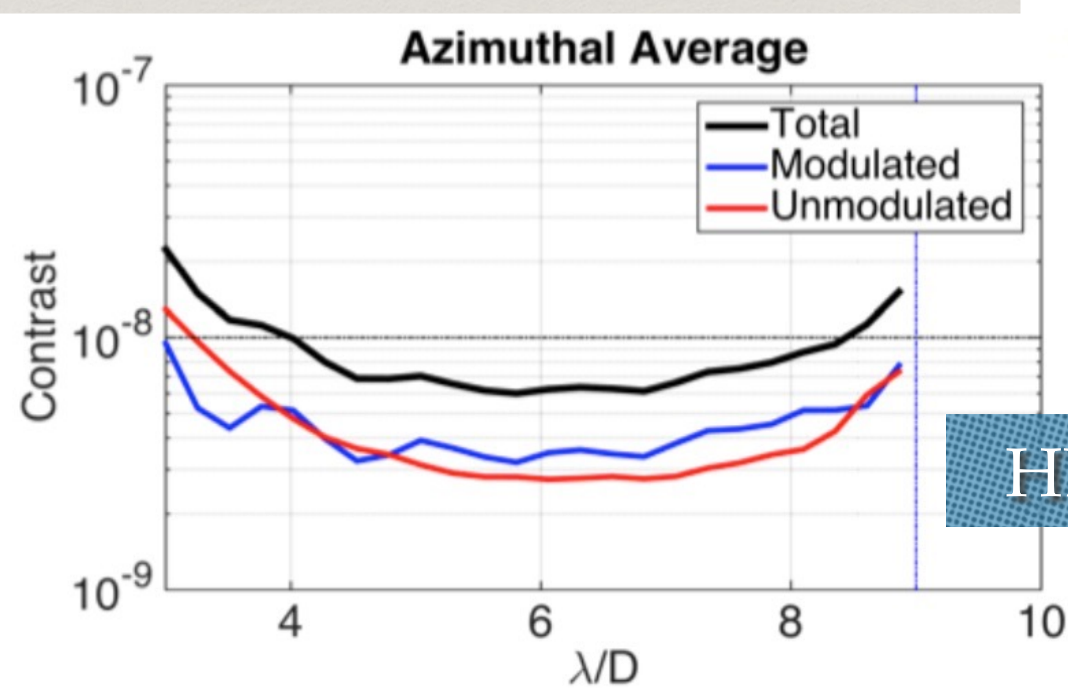


pupil focal plane stop



SPC - 18%





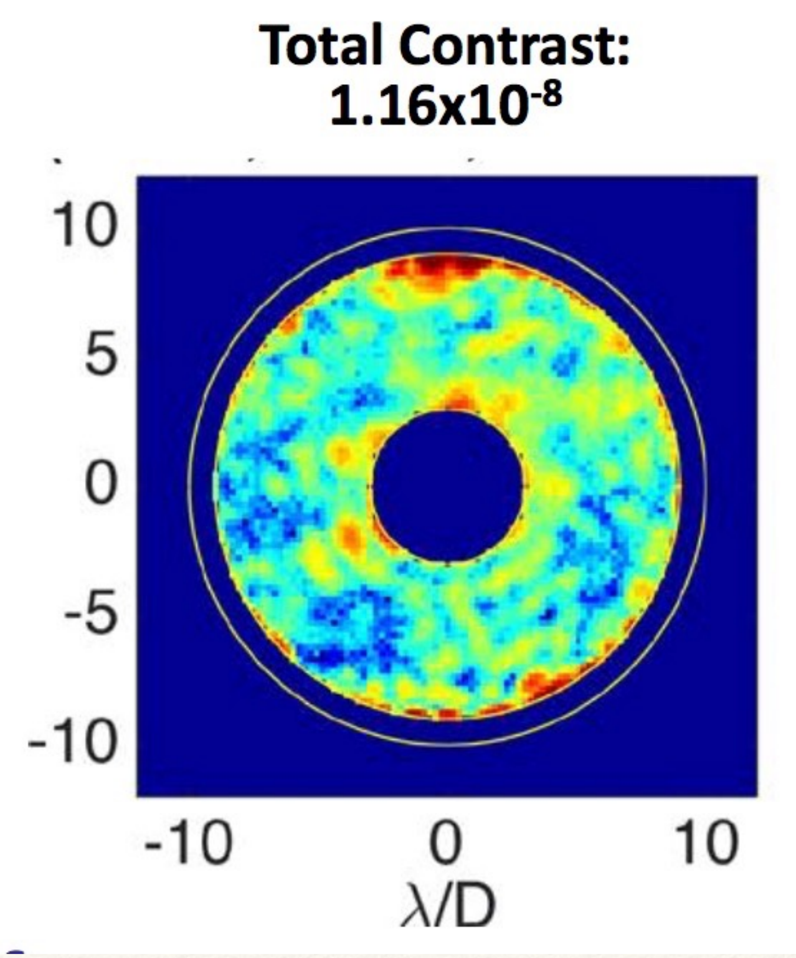
HLC - 10%

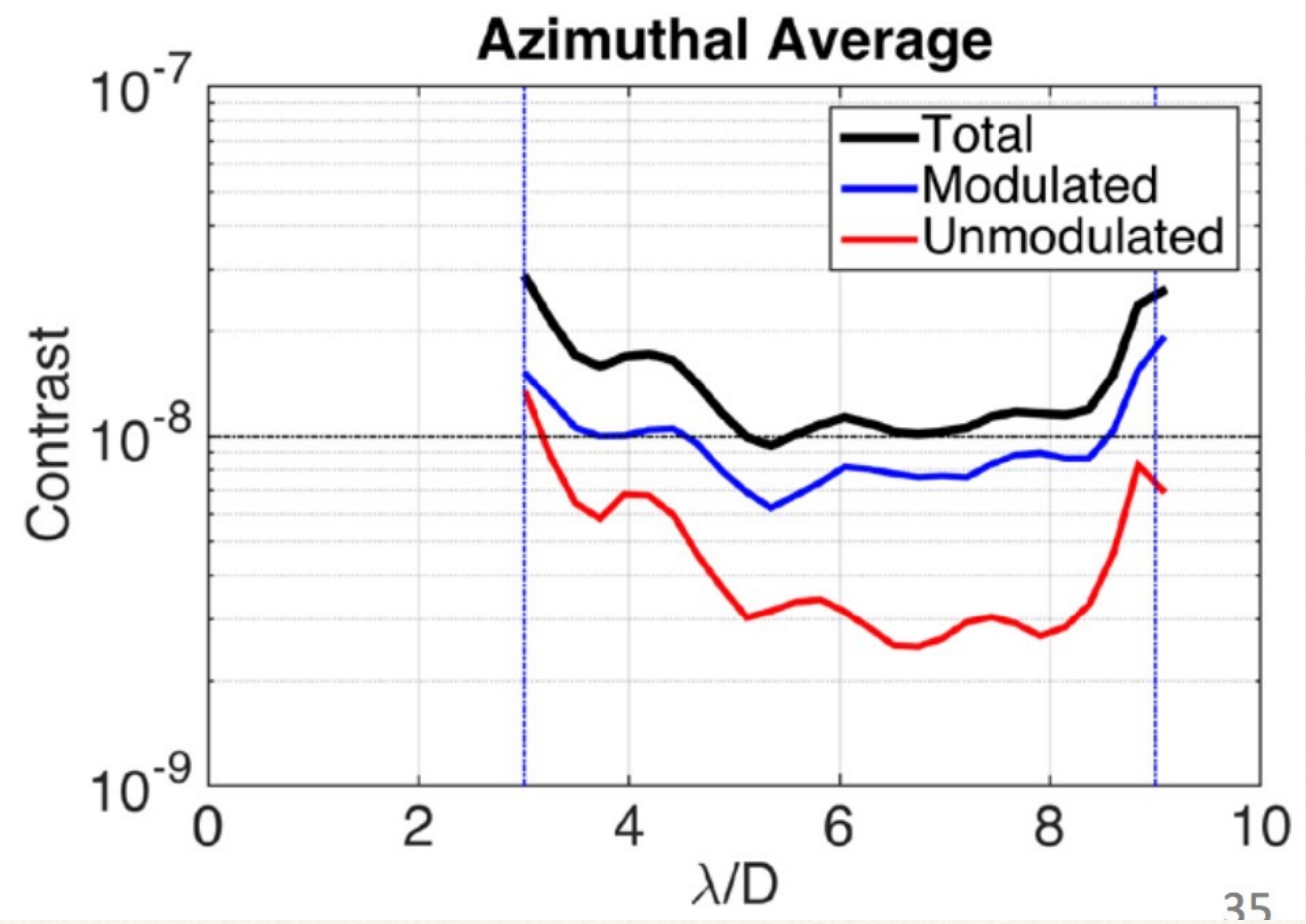
Milestones coronagraphs

03 / 2017

- **Milestone #9:** OMC (HLC or SPC) in HCIT demonstrates 10−8 raw contrast with broad band light (10%) at 550 nm in a dynamic environment.

- WFIRST on-orbit dynamic disturbance and LOWFS architecture
- Pointing correction tests using FSM
- Low order correction tests using DM





Next Milestones

- **Key milestones for FY 17 concentrate on flight like configurations and operations:**

Milestones	Milestone Date	Status	Comments
PISCES commissioning done. Calibration and data pipeline in place	12/31/2016	Done	In HCIT2
Close out Milestone 9.	1/31/2017	Done	Review slides cleared
HLC wavefront control with <=3 bandpass filters (# engineering filters for flight).	3/31/2017	Done	In HCIT1, 3 bandpass done and has reached ~4e-9
Demonstrate simultaneous EFC and LOWFS/C operation.	5/31/2017		In HCIT1
SPC wavefront control using PISCES IFS. 18% band high contrast.	5/31/2017	Started	In HCIT2,
Demonstrate SPC disc science mask performance with the imager, 6.5-20 l/D.	9/30/2017	Design finished	In HCIT2, design in progress
Low light (low SNR) OMC tests	12/31/2017		In HCIT1, current testbed drift investigation will be important for this task

CGI Requirements L2

CGI 2.2

Photometric characterization of known RV exoplanets

WFIRST CGI shall be able to measure the brightness in the **565 nm** filter of an exoplanet at **SNR=5 within 10 hours** of integration time, assuming a scattered light background equal to the solar zodiacal dust at 1 AU, a planet-star flux ratio of **8e-9 at 0.2 arcsec from a V=5 mag** star with a stellar radius of 0.4 milliarcsec.

Rationale:
This 8e-9 contrast is derived from a composite the physical parameters of 47 Uma c and 47 Uma b, 2.85 AU semimajor axis, e=0.05 and a distance of 14 parsecs: assuming a radius of 1.1 R J and an albedo of 0.28 since the 60 degree phase function is 0.50 and the Jupiter albedo at this wavelength is 0.55 (Mayorga et al. 2016).

CGI Requirements L2

CGI 2.3

Detection of new exoplanets

WFIRST CGI shall be able to detect point sources at a 50% confidence level at a planet-star flux ratio of **6e-10** (TBR) and an angular separation of **0.16 arcsec** (TBR) around a star of **V=4** mag or brighter in an exposure time of **48 hours** or less (TBR).

Rationale:
SuperEarth detection, confidence derivation described in Macintosh, Savransky et al. (???).

CGI Requirements L2

CGI 2.5

High Contrast Spectra

WFIRST CGI shall be able to measure exoplanet spectra with **R = 50** or greater spectral resolution from **600 nm to 970 nm** with bands shown in the CGI Science Filter Table, with a wavelength accuracy of 5 nm or smaller, and achieve an **SNR of 10** (TBR) or greater in two bands of 18% (TBR) or greater bandwidth, for a confirmed RV exoplanet (e.g. HD 47 UMa c) at flux ratio of **7e-9** orbiting a star of V = 5 mag at separation of **0.25 arcsec in 24 hours** integration time.

Rationale:

Atmospheric retrieval, e.g. Lupu et al 2016 through the broad IFS filters defined in the Science Filter Table.

Simulations Performance

Raw Contrast vs. Working Angle

λ , Δλ \ Working Angle	3-4 λ/D	4-5 λ/D	5-8 λ/D
565 nm, 10%	$6x10^{-9}$ ($2x10^{-9}$)	$3x10^{-9}$ ($1x10^{-9}$)	$2x10^{-9}$ ($1x10^{-9}$)

Raw Contrast vs. Working Angle

λ , Δλ \ Working Angle	3-4 λ/D	4-5 λ/D	5-8 λ/D
660 nm	$9x10^{-9}$ for 10% BW ($6x10^{-9}$ for 18% BW)	$7x10^{-9}$ for 10% BW ($4x10^{-9}$ for 18% BW)	$5x10^{-9}$ for 10% BW ($4x10^{-9}$ for 18% BW)
770 nm	$1x10^{-8}$ for 10% BW) ($7x10^{-9}$ for 18% BW)	$8x10^{-9}$ for 10% BW) ($5x10^{-9}$ for 18% BW)	$5x10^{-9}$ for 10% BW) ($4x10^{-9}$ for 18% BW)

Yields Imaging

Calculations by B. Nemanti (analystical)

Mode	CG	λ, nm	Δλ, nm	SNR	f_pp	Mission Life	time, hrs
Imag Goal 2.2	G2.2Fit565	565	56.5	5	10%	12%	50

Threshold	0%	Time Margin Threshold
Planets	17	No. of planets above the time margin threshold

400	hrs max time / planet
230	hrs total integ time

No.	Pl. Name	Vmag	Sep (mas)	WA (λ/D)	Albedo (65)	Fl Ratio, ppb	Time Margin	t (SNR), hrs	vr(det) e/s	vr(pl) e/s	vr(sp) e/s	vr(zo) e/s
35	Fid1: 47 UMa bc	5.0	208	4.2	0.2	9.30	99%	0.3	0.0	0.0	3.1E-03	0.0
1	beta Gem b	1.2	170	3.5	10%	9.85	100%	0.01	6.5E-04	1.16E+00	8.14E-02	8.95E-02
2	gamma Cep b	3.2	140	2.9	5%	4.15	93%	3.5	6.5E-04	2.72E-02	3.69E-02	3.93E-04
5	upsilon And d	4.1	187	3.8	11%	4.99	99%	0.3	6.5E-04	4.60E-02	5.03E-03	7.87E-03
11	HD 114613 b	4.9	257	5.2	20%	2.54	98%	1.2	6.5E-04	1.45E-02	2.62E-03	4.49E-03
7	47 UMa b	5.0	149	3.0	16%	11.21	99%	0.7	6.5E-04	2.43E-02	3.92E-03	7.25E-03
9	47 UMa c	5.0	254	5.2	28%	7.73	99%	0.3	6.5E-04	3.75E-02	2.22E-03	4.32E-03
14	mu Ara e	5.1	344	7.0	28%	3.14	97%	1.3	6.5E-04	1.39E-02	2.70E-03	3.83E-03
10	HD 39091 b	5.7	183	3.7	5%	1.20	67%	16.5	6.5E-04	2.66E-03	1.21E-03	4.43E-03
31	HD 142 c	5.7	330	6.7	19%	1.19	74%	13.1	6.5E-04	3.09E-03	1.71E-03	3.64E-03
4	HD 192310 c	5.7	133	2.7	14%	5.24	67%	16.6	6.5E-04	3.37E-03	3.63E-03	9.57E-05
13	Gliese 777 b	5.7	251	5.1	28%	5.67	98%	1.1	6.5E-04	1.42E-02	1.21E-03	3.85E-03
33	psi Dra B b	5.8	201	4.1	29%	4.73	96%	2.0	6.5E-04	9.61E-03	1.32E-03	4.15E-03
17	55 Cnc d	6.0	381	7.7	28%	2.75	92%	4.2	6.5E-04	5.57E-03	1.26E-03	3.44E-03
19	HD 217107 c	6.2	269	5.5	28%	2.99	91%	4.7	6.5E-04	5.09E-03	8.66E-04	3.64E-03
22	HD 134987 c	6.5	222	4.5	23%	2.24	74%	12.9	6.5E-04	2.75E-03	7.20E-04	3.72E-03
15	14 Her b	6.6	167	3.4	20%	6.83	91%	4.4	6.5E-04	5.28E-03	5.33E-04	3.91E-03
20	HD 154345 b	6.8	227	4.6	24%	4.47	88%	6.2	6.5E-04	4.20E-03	5.52E-04	3.62E-03
23	HD 87883 b	7.6	196	4.0	9%	2.25	-100%	83.0	6.5E-04	9.05E-04	2.62E-04	3.49E-03
29	GJ 832 b	8.7	381	7.7	22%	6.17	-100%	58.4	6.5E-04	1.04E-03	1.05E-04	3.29E-03
35	Fid1: 47 UMa bc	5.0	208	4.2	22%	9.30	99%	0.3	6.5E-04	4.22E-02	3.08E-03	4.99E-03

Yields Spectroscopy

Calculations by
B. Nemanti
(analystical)

Mode	CG	λ, nm	Δλ, nm	SNR	f_pp	Mission Life	time, hrs
IFS1 Goal 2.5	G2.5Fit660	660	118.8	10	10%	12%	250

Threshold	0%	Time Margin Threshold
Planets	4	No. of planets above the time margin threshold

400	hrs max time / planet
443	hrs total integ time

No.	Pl. Name	Vmag	Sep (mas)	WA (λ/D)	Albedo (65)	Fl Ratio, ppb	Time Margin	t (SNR), hrs	vr(det) e/s	vr(pl) e/s	vr(sp) e/s	vr(zo) e/s
35	*Fid1: 47 UMa bc*	5.0	208	3.6	0.2	9.30	95%	12.7	0.0	0.0	2.2E-03	0.0
1	*beta Gem b*	1.2	170	3.0	10%	9.85	-100%	-1.00	2.1E-03	-1.00E+00	-1.00E+00	-1.00E+00
2	*gamma Cep b*	3.2	140	2.4	5%	4.15	-100%	-1.0	2.1E-03	-1.00E+00	-1.00E+00	-1.00E+00
5	*upsilon And d*	4.1	187	3.3	11%	4.99	-100%	895.4	2.1E-03	8.03E-03	5.98E-03	1.81E-03
11	*HD 114613 b*	4.9	257	4.5	20%	2.54	32%	170.5	2.1E-03	2.91E-03	1.78E-03	1.61E-03
7	*47 UMa b*	5.0	149	2.6	16%	11.21	-100%	-1.0	2.1E-03	-1.00E+00	-1.00E+00	-1.00E+00
9	*47 UMa c*	5.0	254	4.4	28%	7.73	95%	12.2	2.1E-03	7.52E-03	1.51E-03	1.55E-03
14	*mu Ara e*	5.1	344	6.0	28%	3.14	19%	202.8	2.1E-03	2.81E-03	1.76E-03	1.42E-03
10	*HD 39091 b*	5.7	183	3.2	5%	1.20	-100%	-51.4	2.1E-03	3.98E-04	1.67E-03	8.50E-04
31	*HD 142 c*	5.7	330	5.7	19%	1.19	-100%	-165.0	2.1E-03	6.35E-04	1.03E-03	1.37E-03
4	*HD 192310 c*	5.7	133	2.3	14%	5.24	-100%	-1.0	2.1E-03	-1.00E+00	-1.00E+00	-1.00E+00
13	*Gliese 777 b*	5.7	251	4.4	28%	5.67	77%	57.7	2.1E-03	2.81E-03	8.74E-04	1.32E-03
33	*psi Dra B b*	5.8	201	3.5	29%	4.73	-100%	3516.5	2.1E-03	1.78E-03	1.26E-03	1.10E-03
17	*55 Cnc d*	6.0	444	7.7	28%	2.75	-100%	-591.8	2.1E-03	1.01E-03	8.75E-04	1.10E-03
19	*HD 217107 c*	6.2	269	4.7	28%	2.99	-100%	508.3	2.1E-03	1.04E-03	5.29E-04	1.33E-03
22	*HD 134987 c*	6.5	222	3.9	23%	2.24	-100%	-802.0	2.1E-03	5.18E-04	5.32E-04	1.13E-03
15	*14 Her b*	6.6	167	2.9	20%	6.83	-100%	-1.0	2.1E-03	-1.00E+00	-1.00E+00	-1.00E+00
20	*HD 154345 b*	6.8	227	3.9	24%	4.47	-100%	814.9	2.1E-03	7.91E-04	4.07E-04	1.10E-03
23	*HD 87883 b*	7.6	196	3.4	9%	2.25	-100%	-1953.5	2.1E-03	1.67E-04	2.50E-04	9.27E-04
29	*GJ 832 b*	8.7	402	7.0	22%	6.17	-100%	6737.0	2.1E-03	1.99E-04	7.03E-05	1.13E-03
35	*Fid1: 47 UMa bc*	5.0	208	3.6	22%	9.30	95%	12.7	2.1E-03	7.89E-03	2.19E-03	1.43E-03

Simulations

Observing Scenario 5 (OS5) by J. Krist

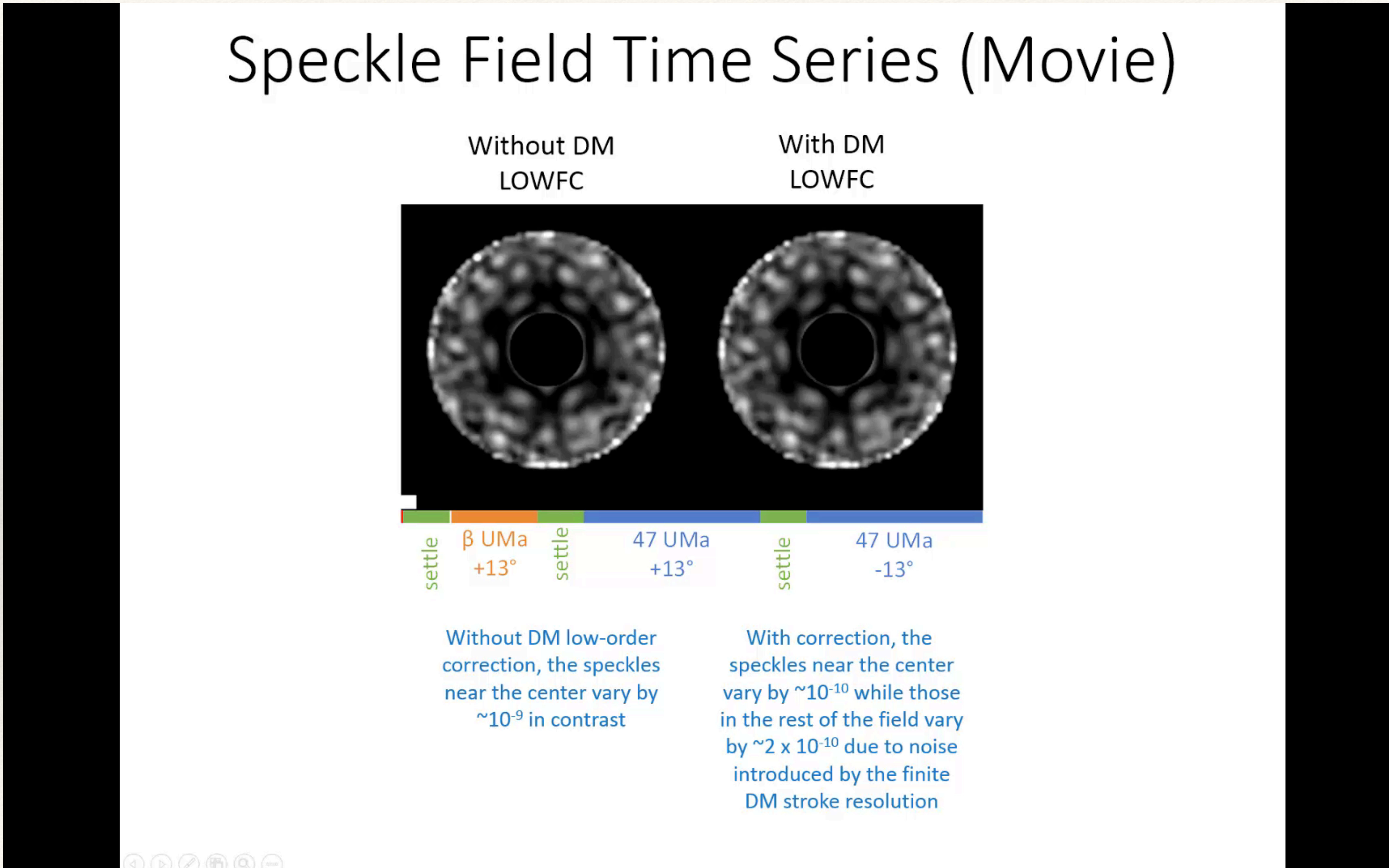
- thermal models / wavefront maps (GSFC)
- Propagation (PROPER) includes LOWFS/C + DM correction (7.6pm resolution) => speckle field

- Hybrid Lyot Coronagraph (HLC)
  - 509-591 nm bandpass (15%)
  - single polarization
  - Two 48x48 deformable mirrors (one at pupil, other 1 m away)
  - r = 3 – 9 λ/D (0.14" – 0.43") dark hole field size
  - dark hole computed using EFC

SPIE papers
Krist et al. 2015
Krist et al. 2016

- 25 Ksec on 61 UMa to reach steady state
- 600 sec slew to β UMa (V = 2.4, A1IV)
- 30 Ksec on β UMa at roll +13°, including 10 Ksec settle
- 600 sec slew to 47 UMa (V = 5.0, G1V)
- 50 Ksec on 47 UMa at roll +13°, including 10 Ksec settle
- 100 sec to roll 26° around 47 UMa
- 50 Ksec on 47 UMa at roll -13°, including 10 Ksec settle

Simulations



Simulations

Simulations by M. Ygouf

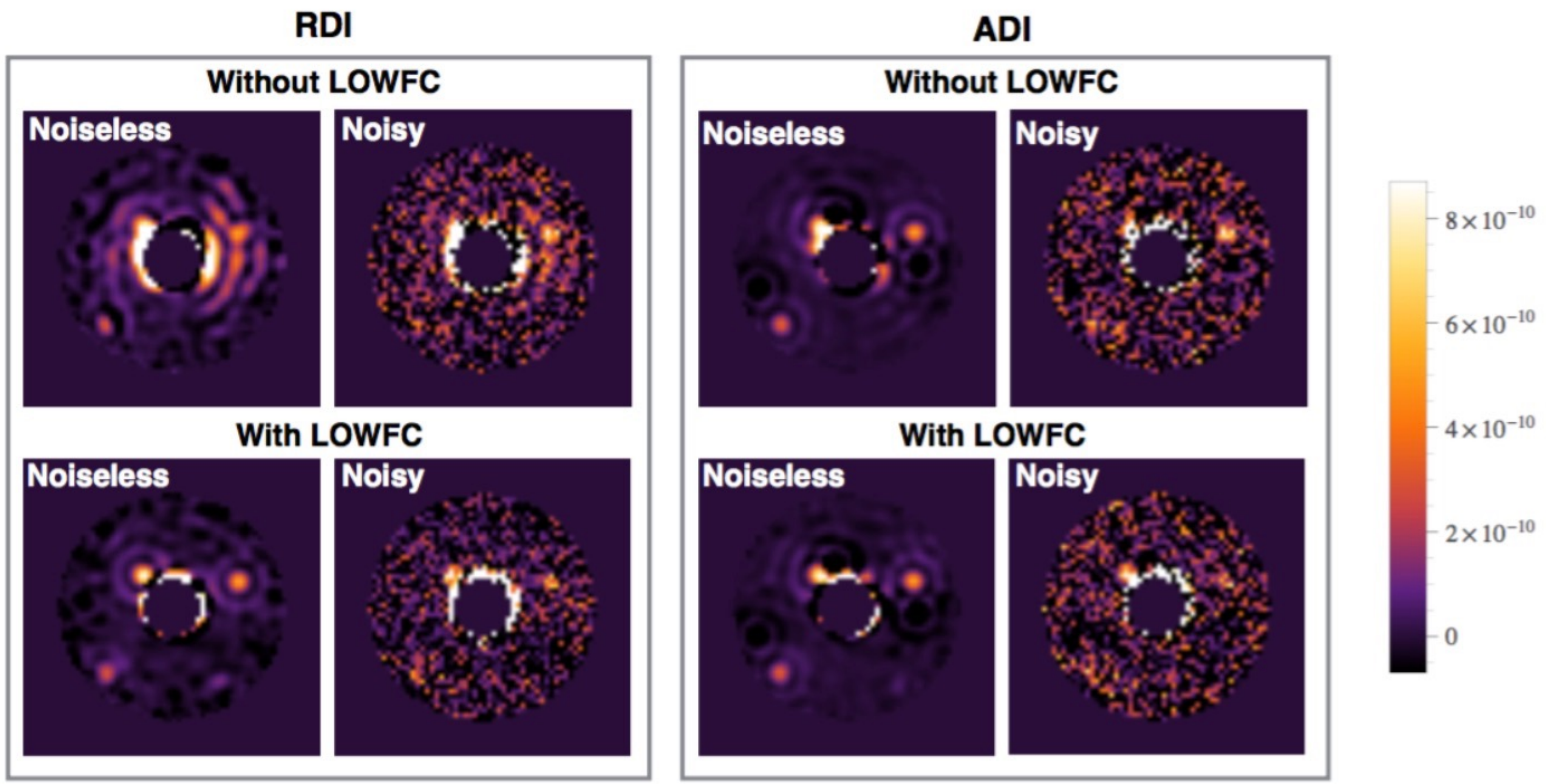
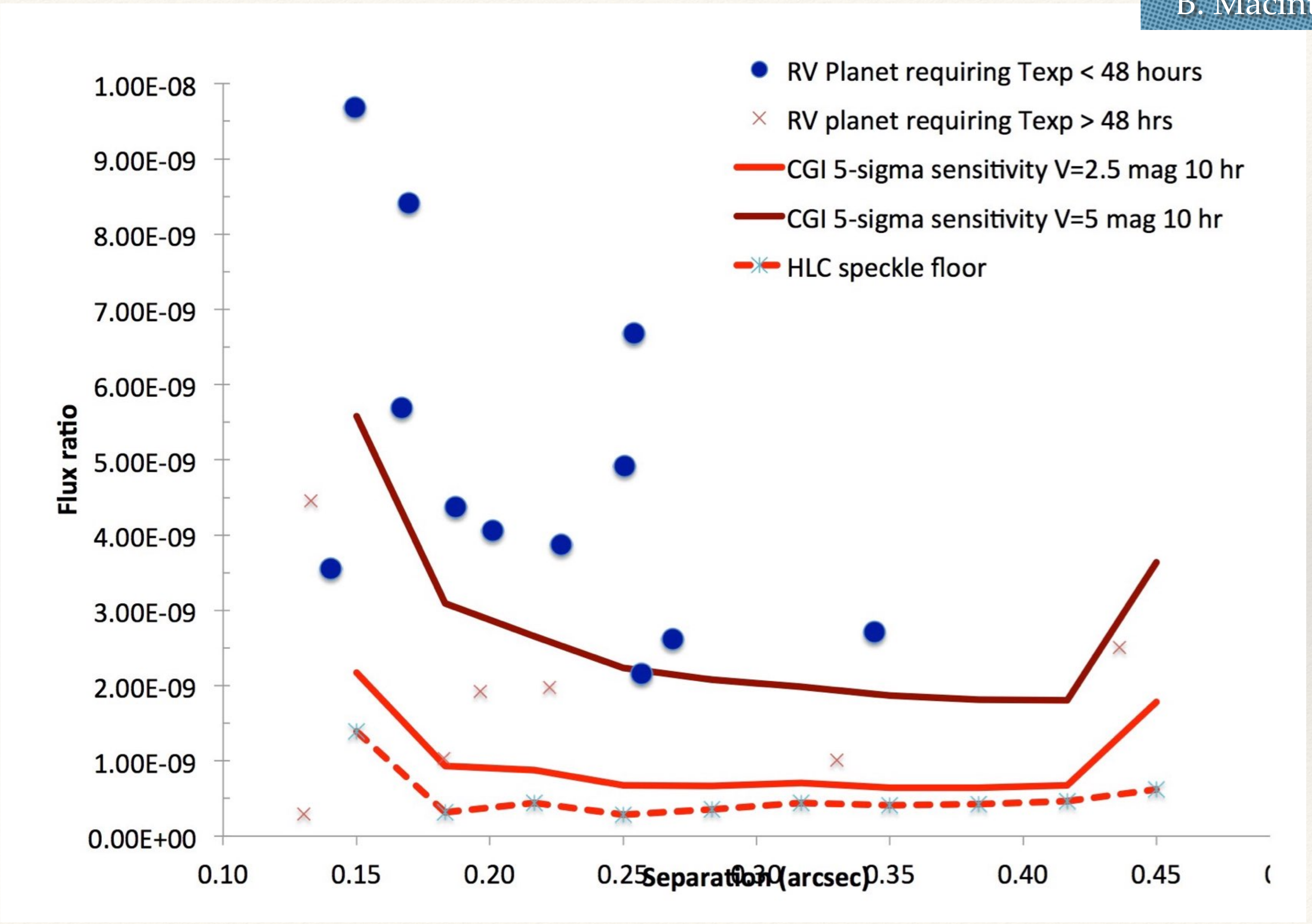


Figure 5: **Post-processed data for both RDI and ADI observing scenarios.** Comparison of [left] RDI and [right] ADI reductions of the long exposure image of 47 UMa for the noiseless and noisy data sets, without and with LOWFC. Reductions have been performed with the classical PSF subtraction technique. The ADI strategy enables a slightly better speckle subtraction than the RDI strategy, helping to better discriminate between planets and residual

	RDI				ADI			
	Noiseless		Noisy		Noiseless		Noisy	
	Contrast	Gain	Contrast	Gain	Contrast	Gain	Contrast	Gain
Without LOWFC	2.3×10^{-10}	5.0	8.0×10^{-10}	1.7	7.8×10^{-11}	14.8	6.6×10^{-10}	2.0
LOWFC random	1.7×10^{-10}	6.9	7.3×10^{-10}	1.8	8.6×10^{-11}	13.1	6.4×10^{-10}	2.1

Simulations

Calculations by
B. Macintosh



Data Challenge

from M. Turnbull

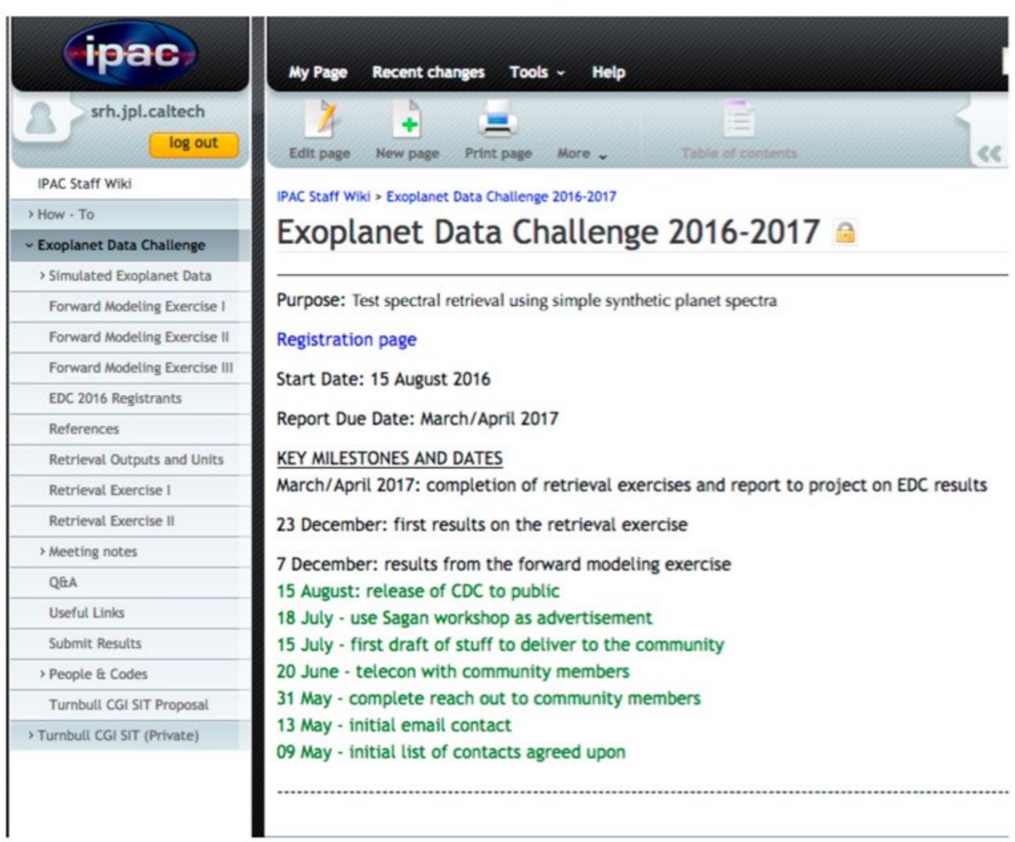
Community Data Challenge #1: Test spectral retrieval using simple synthetic planet spectra. This exercise will help reveal model-dependent interpretations of noisy data.

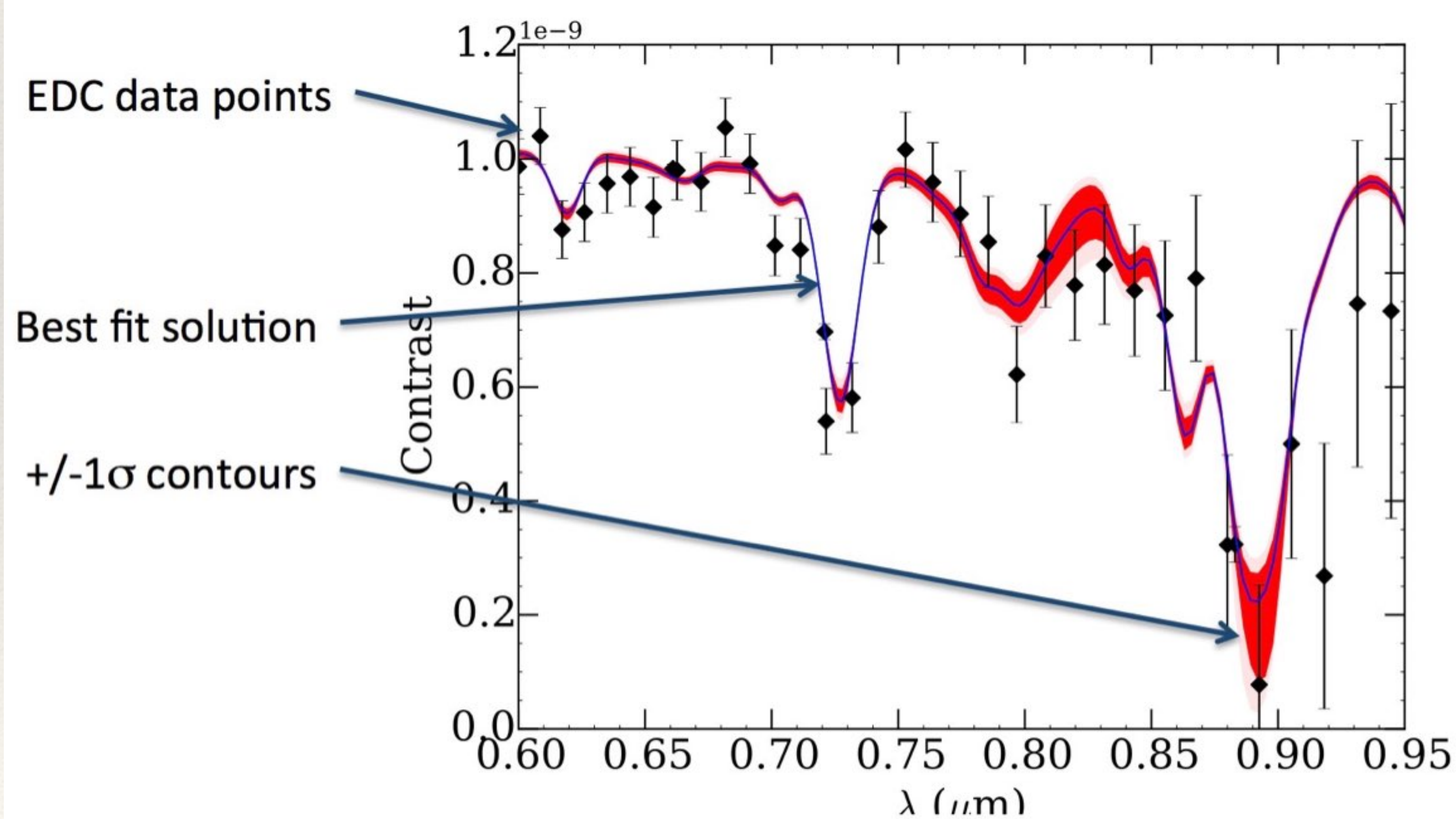
Community Data Challenge #2: Test post-processing and source extraction techniques with spectral image cubes containing only a star and planets, processed with a simple instrument model. This exercise is intended as practice to begin developing the techniques.

Community Data Challenge #3: Add astrophysical background sources to the data cubes, processed with the project's WFIRST instrument model.

Community Data Challenge #4: Add interplanetary dust for a complete exercise in harvesting scientific results from realistic simulated data.

EDC Wiki space





Mark Marley, Roxana Lupu and Mikey Nayak

European propositions

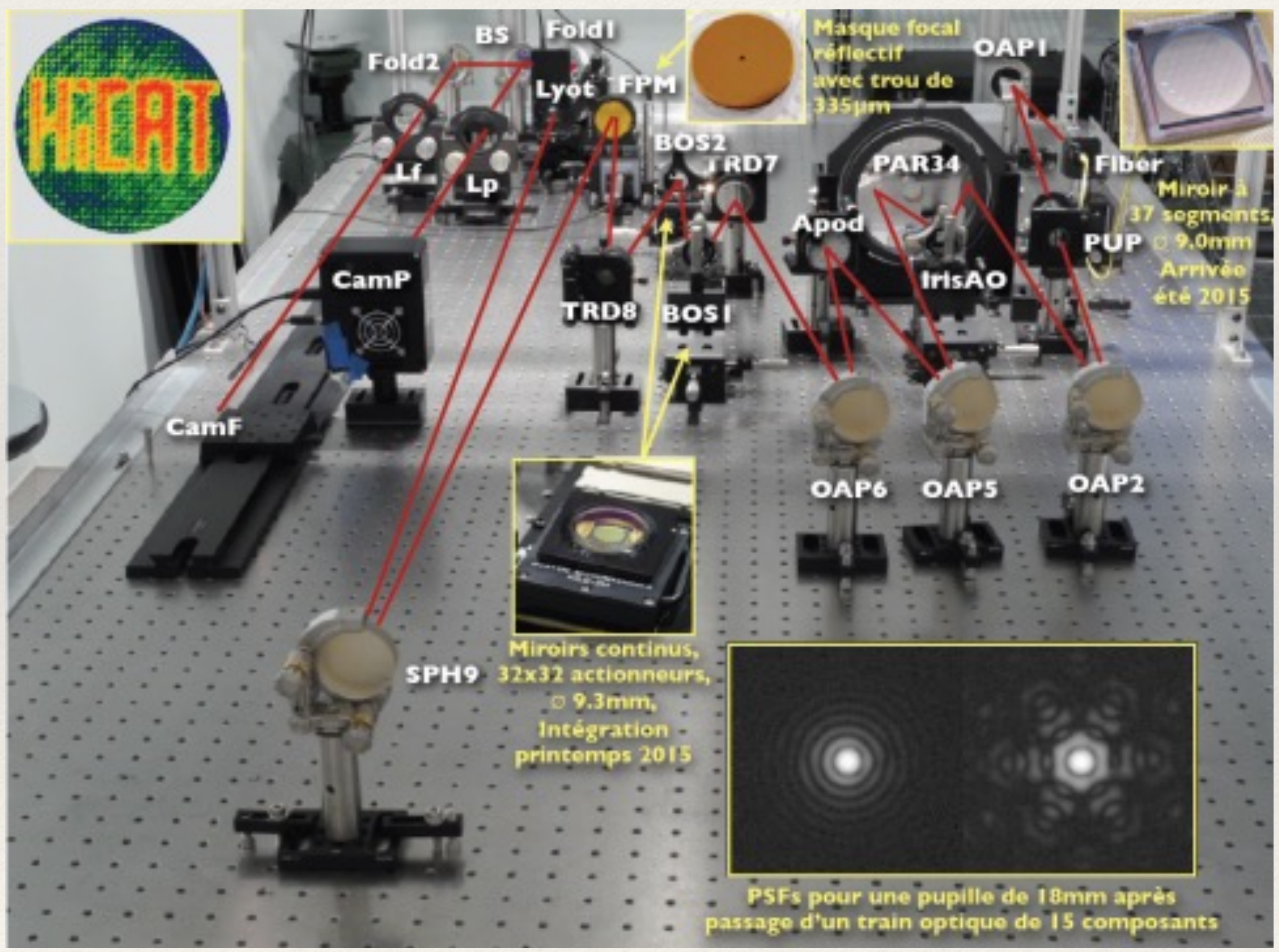
LAM developed a dedicated optical fabrication method, based on active polishing

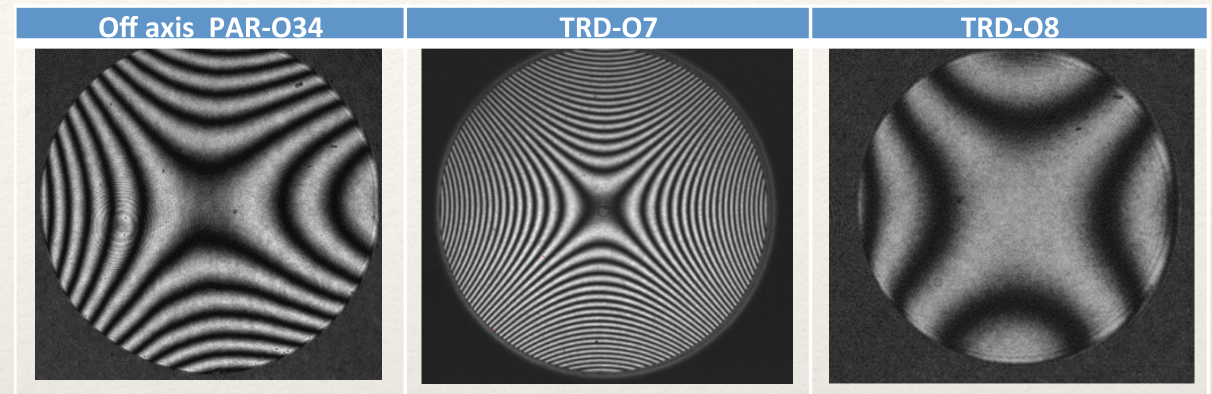
Suitable to TORIC mirrors, OFF-AXIS PARABOLA (<450 mm Ø)

Excellent results : LoF <**10 – 20 nm rms** (including form error)

MiF / HiF ~ **1- 2nm rms**

Roughness ~ **2 – 5 Å rms**





	PAR-O34		TRD-O7		TRD-O8	
	Spec	**Result**	*Spec*	**Result**	*Spec*	**Result**
Clear aperture [mm]	*18.0*	**18.0**	*21.4*	**21.4**	*21.4*	**21.4**
Incidence angle (deg)	*---*	**---**	*5.5*	**---**	*9.44*	**---**
Average Roc [mm]	*400.0*	**400.0**	*430.0*	**430.0+/-1**	*1446.5*	**1446.5+/-1**
Astm3 coef RMS [nm]	*471.0*	**460.0**	*750.0*	**751.0**	*75.0*	**76.0**
Coma3 coef RMS [nm]	*41.0*	**47.0**	*---*	**---**	*---*	**---**
LoF WFE [nm]	*15.8*	**13.0**	*15.8*	**7.0**	*15.8*	**6.4**
MiF WFE [nm]		**1.5**		**2.0**		**1.5**
HiF WFE [nm]		**1.3**		**3.2**		**1.6**
Roughness RMS [nm]	*0.5*	**0.4**	*0.5*	**0.5**	*0.5*	**0.4**

- proposal supported by CNES
- strong interests from CGI

European propositions

Needs: **3 detectors in CGI**
- Imager
- IFS
- LOWFS

developed by Centre for Electronic Imaging at the **Open University** (CEI-OU) and the **Mullard Space Science Laboratory**, University College London (MSSL-UCL)

Picture of CCD201-20

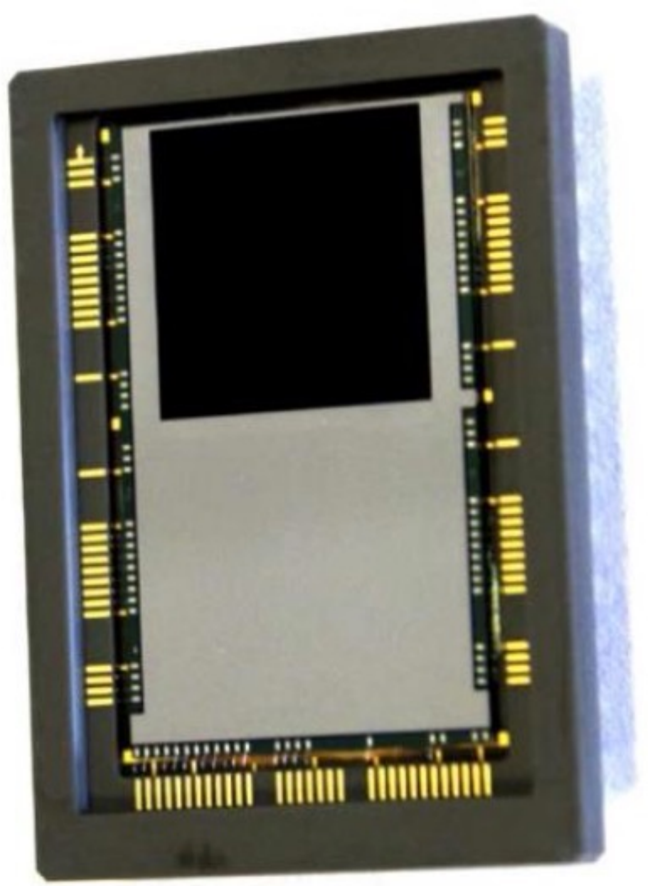


Table 5. Specifications of the CCD201-20 EMCCD, from e2v.

Parameter	Specification
Sensor family	EMCCD
Variant	BI*, 2-Phase
Active pixels (image)	1024 (H) $\times$ 1024 (V)
Frame Transfer (store)	1056 (H) $\times$ 1037 (V)
Image area	13.3 mm $\times$ 13.3 mm
Pixel pitch	13 μm
Active area CHP†	80,000 e^- pix^{-1}
Gain register CHP†	730,000 e^- pix^{-1}
Fill factor	100%
# O/P amplifiers	1 $\times$ Conv., 1 $\times$ EM
Multiplication elements	604
Dark reference columns	32
Overscan elements	16

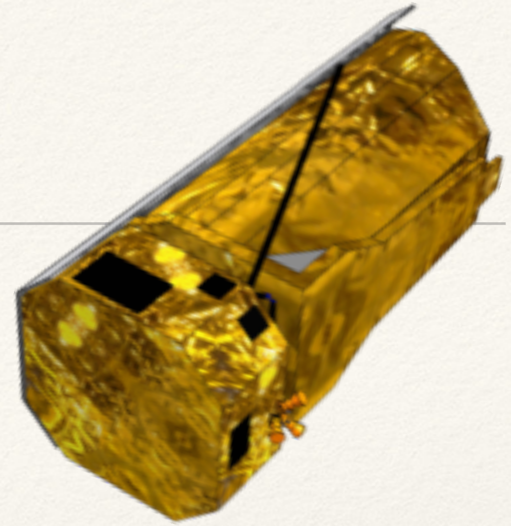
*BI = Back-Illuminated; †CHP = charge handling capacity.

Milestone #7: DARK: 7e-4 e-/pix/s - RON =1.7e-6 e-/pix/frame

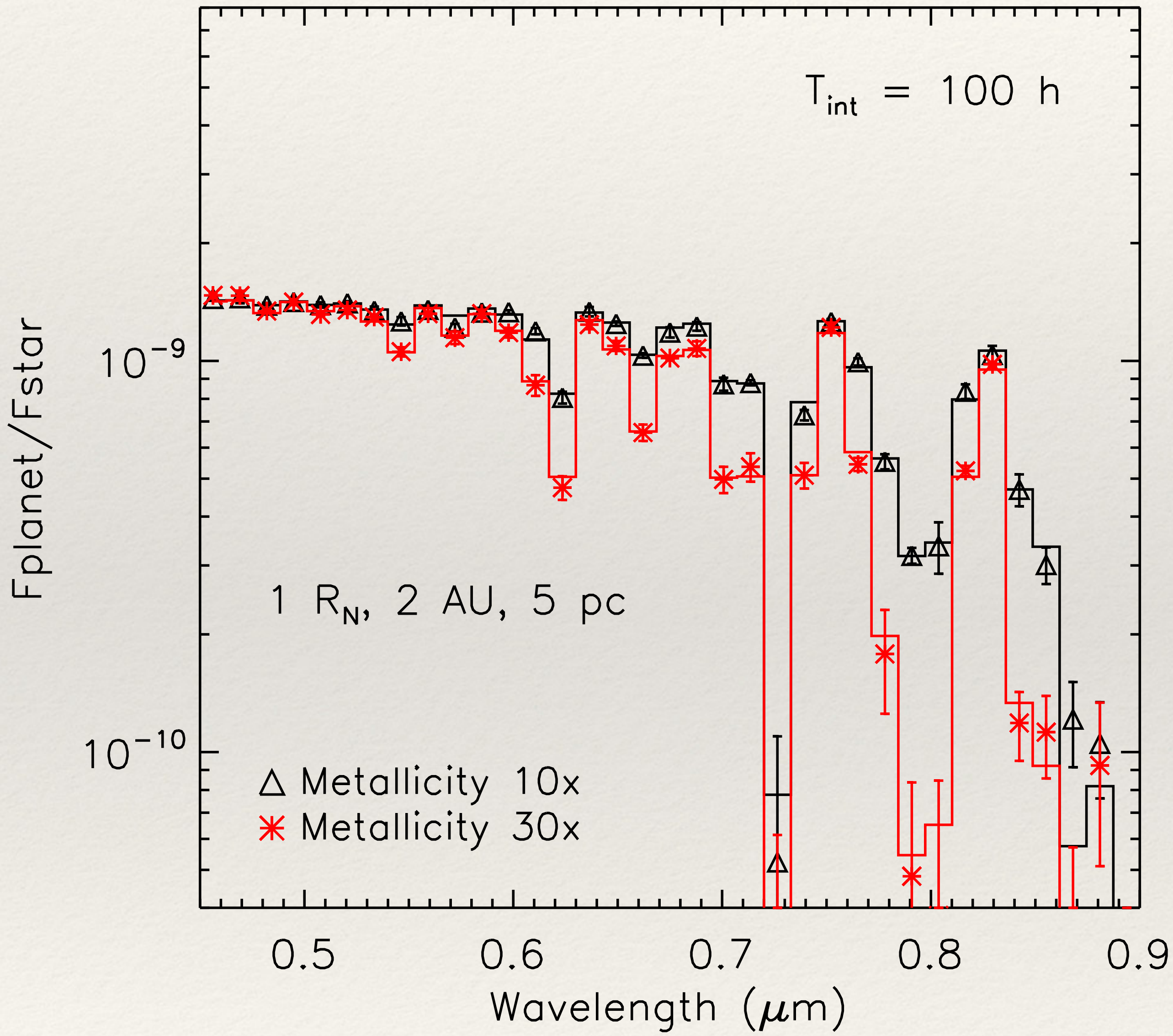
- exposure to radiation (BOL / EOL) twice better than specification

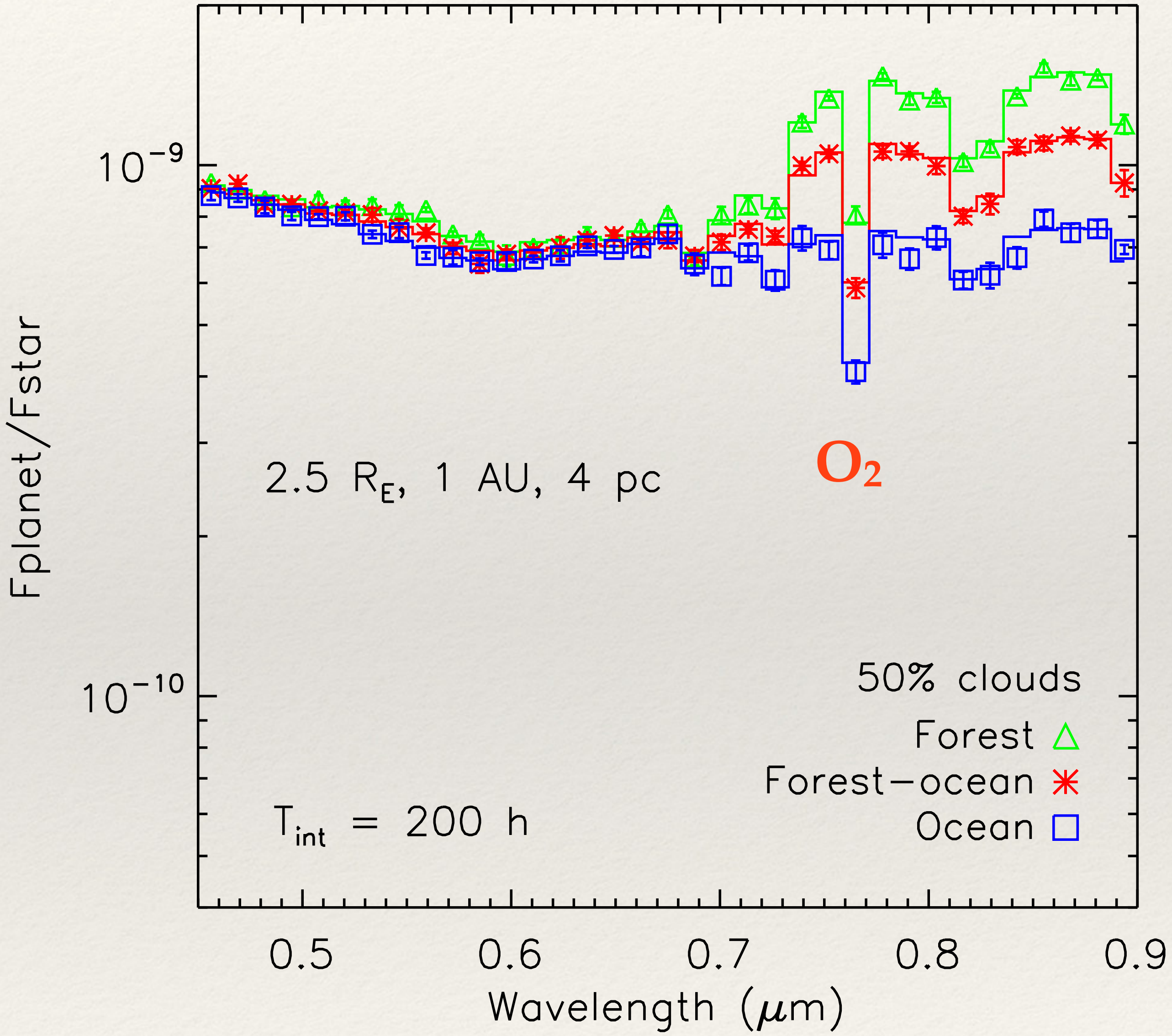
European propositions

comparative planetology of gas/ice giants



based on simulation by Maire et al. 2012

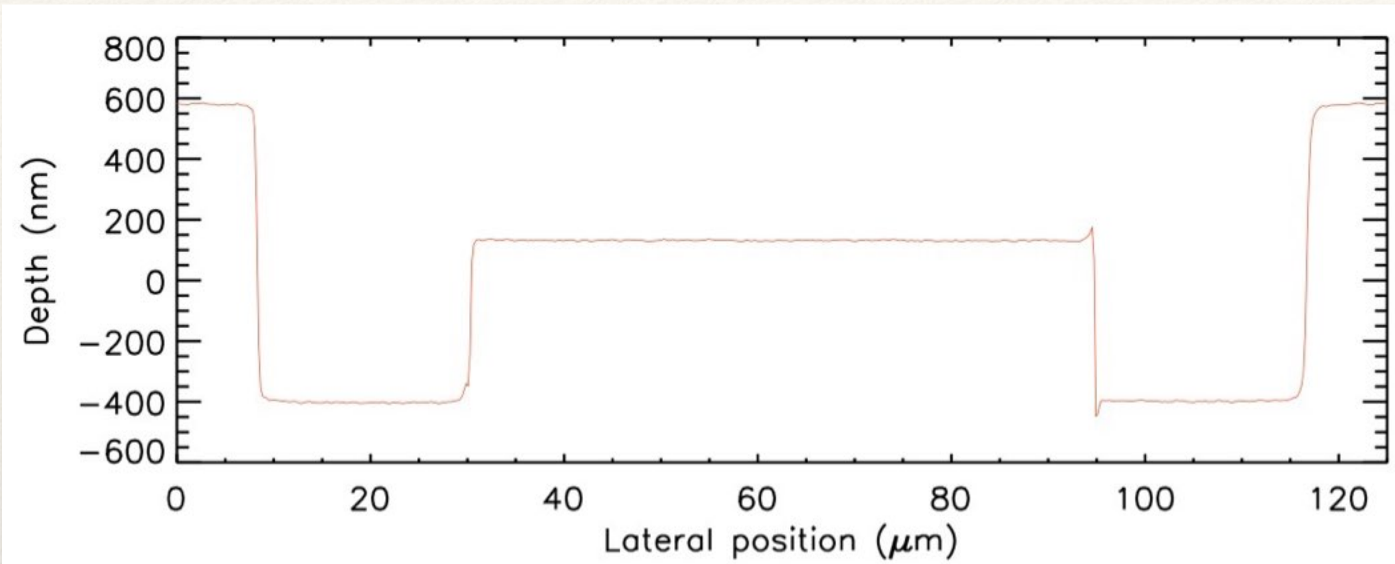


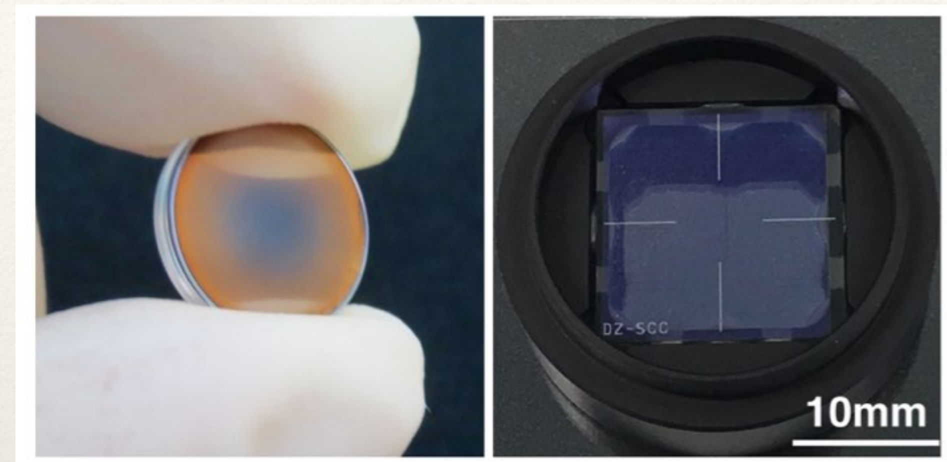


- contribute into estimating science yields exoplanets / disks with the SPICES simulator (in collaboration with SITs)

European propositions

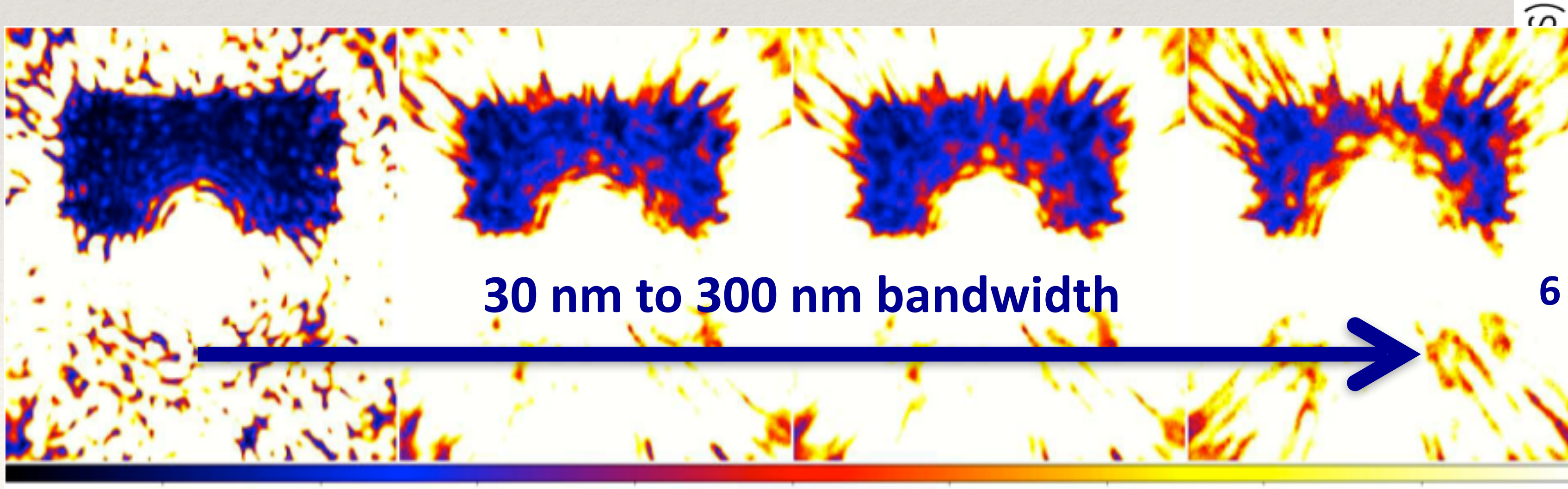
larger throughput <=> other coronagraphs



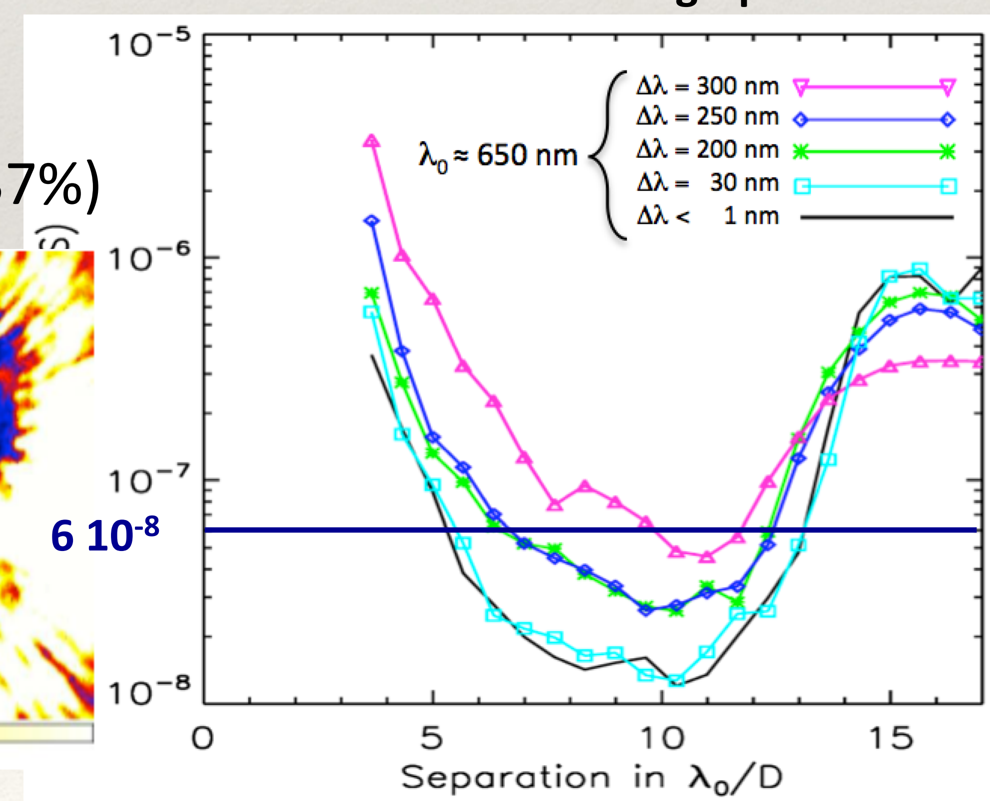


Delorme et al. 2016

Contrast degrades by only a factor 3 for 250 nm bandwidth (37%)



DZPM coronagraph



More informations

- https://wfirst.gsfc.nasa.gov/library.html
- https://wfirst.ipac.caltech.edu