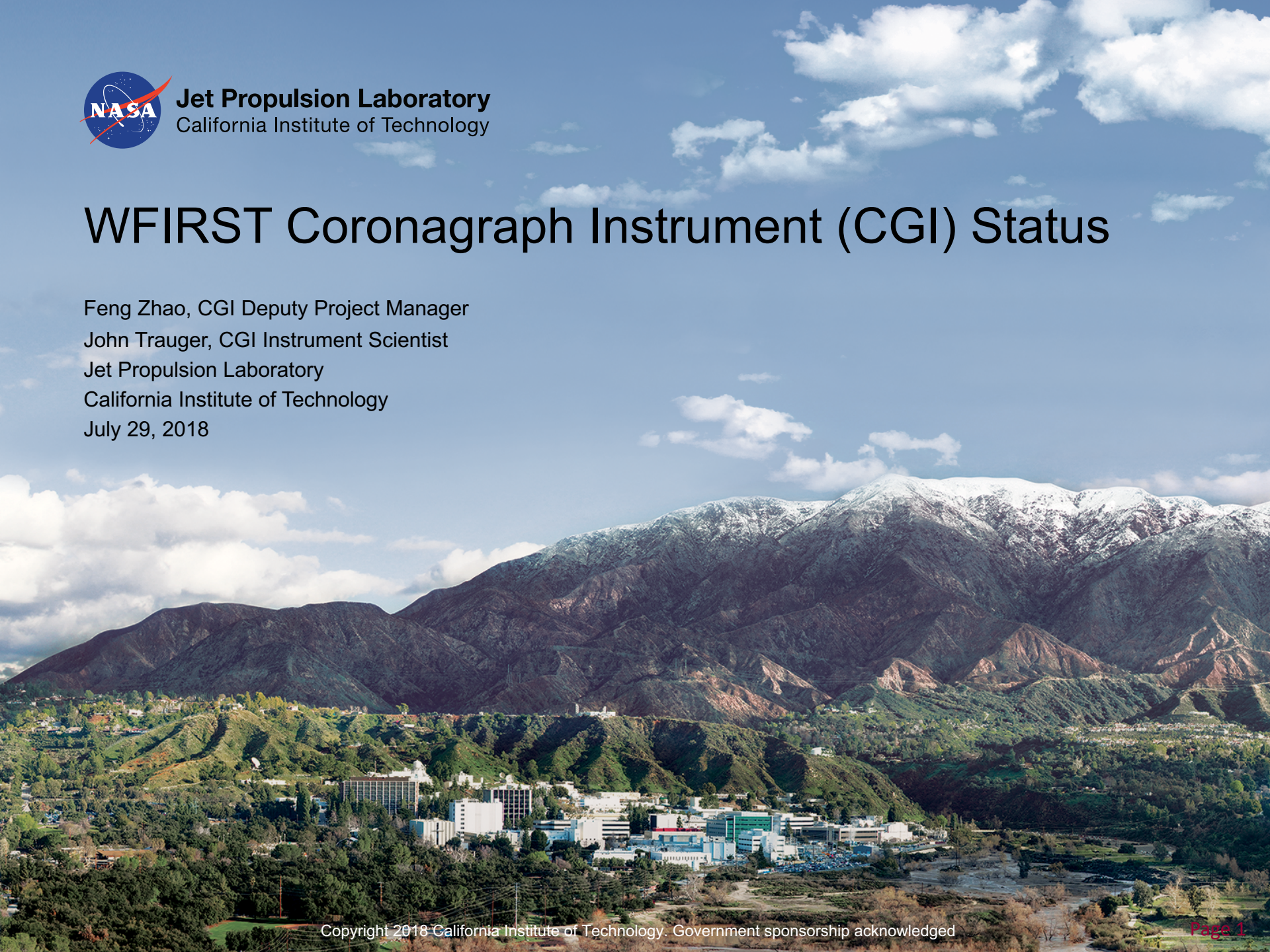


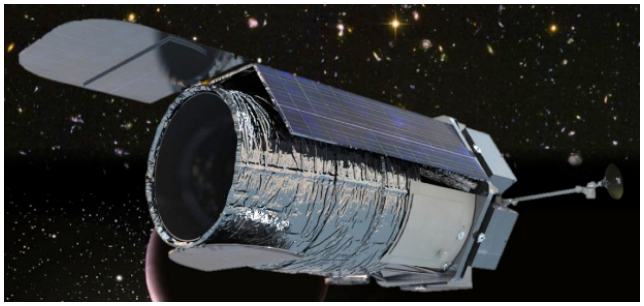
Jet Propulsion Laboratory
California Institute of Technology

WFIRST Coronagraph Instrument (CGI) Status

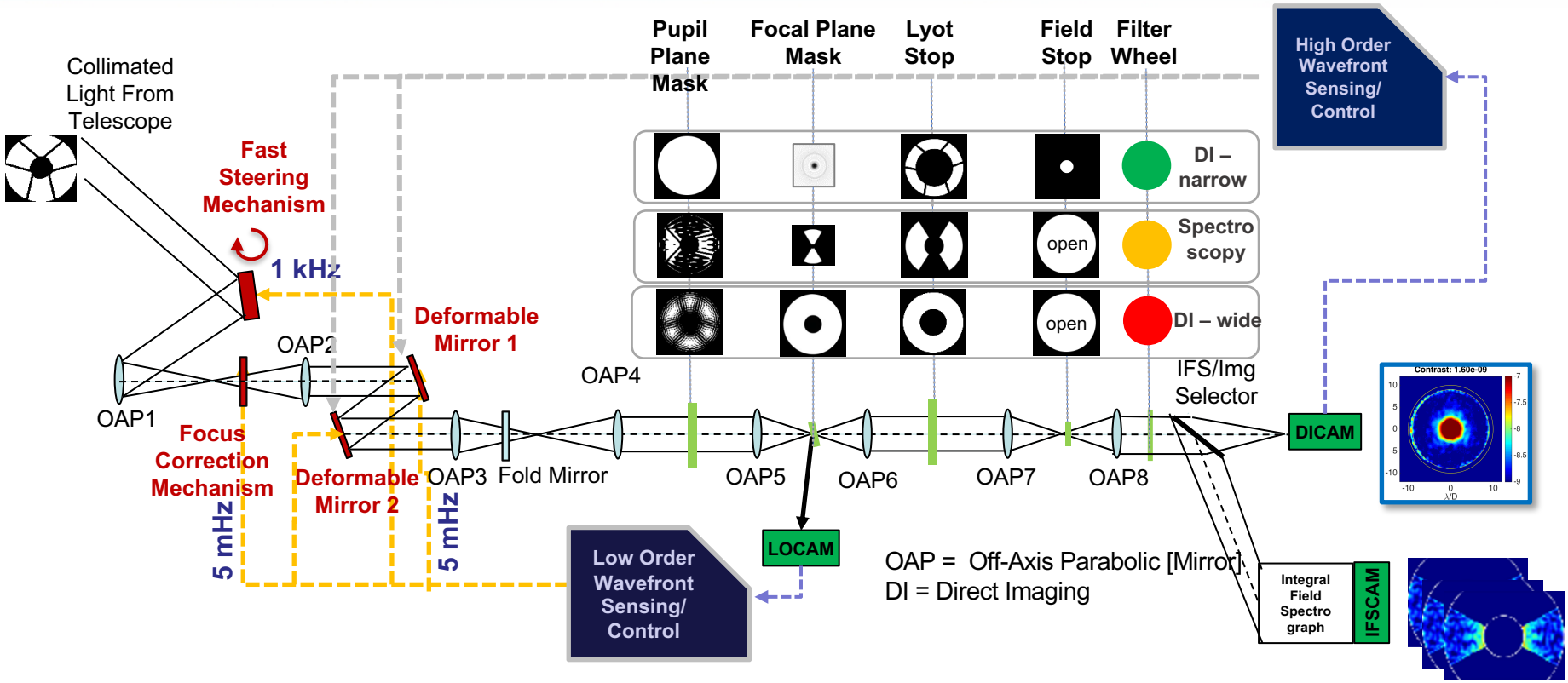
Feng Zhao, CGI Deputy Project Manager
John Trauger, CGI Instrument Scientist
Jet Propulsion Laboratory
California Institute of Technology
July 29, 2018

WFIRST Coronagraph Instrument (CGI)

- **Coronagraph (CGI) is the 2nd instrument on WFIRST,**
  - Exo-planet direct imaging technology demonstration
  - Participating Science Programs (PSP) if tech demo successful
- **CGI has two science cameras:**
  - Imaging camera
  - Integral field spectrograph (IFS)
- **CGI advances a number of new technologies:**
  - Novel coronagraph masks (shaped pupil coronagraph and hybrid Lyot coronagraph)
  - Precision wavefront sensing and control with 2 deformable mirrors Ultra-low noise detector
- **Coronagraph instrument is managed by JPL**
  - Instrument Project Manager: Peg Frerking
  - Deputy Instrument Project Manager: Feng Zhao
- **Other coronagraph partner institutions:**
  - NASA centers:
    - GSFC (responsible for integral field spectrograph)
  - Industry:
    - Northrup Grumman Xinetics (deformable mirror)
    - Boston Micromachines Corp (deformable mirror)
    - e2v (Electron Multiplying CCD – EMCCD)
  - Science Investigations Teams (SIT):
    - SIT #1 PI: Bruce Macintosh, Stanford University
    - SIT #2 PI: Maggie Turnbull, SETI Institute
  - Coronagraph Adjutant Scientist (CAS):
    - Jeremy Kasdin, Princeton University
  - Science Center:
    - IPAC/Caltech, STScI
  - Potential International Partners:
    - Germany -- Max Planck Institute of Astronomy (mask filter wheels)
    - UK – e2v (EMCCD)
    - Japan – JAXA (polarization module)
    - France – LAM/CNES (Super-polished coronagraph optics)



CGI Functional Overview



- **Active components**
  - Fast Steering Mirror (FSM) for line of sight control
  - Focus Correction Mechanism (FocM) for focus control
  - Deformable mirrors (DM1, DM2) for wavefront control
- **Control loops**
  - High order wavefront sensing and control (HOWFS/C) for achieving starlight suppression
  - Low order wavefront sensing and control (LOWFS/C) for continuously maintaining starlight suppression

Active Wavefront sensing and control enables CGI ~1000x deeper starlight suppression than previous space coronagraphs

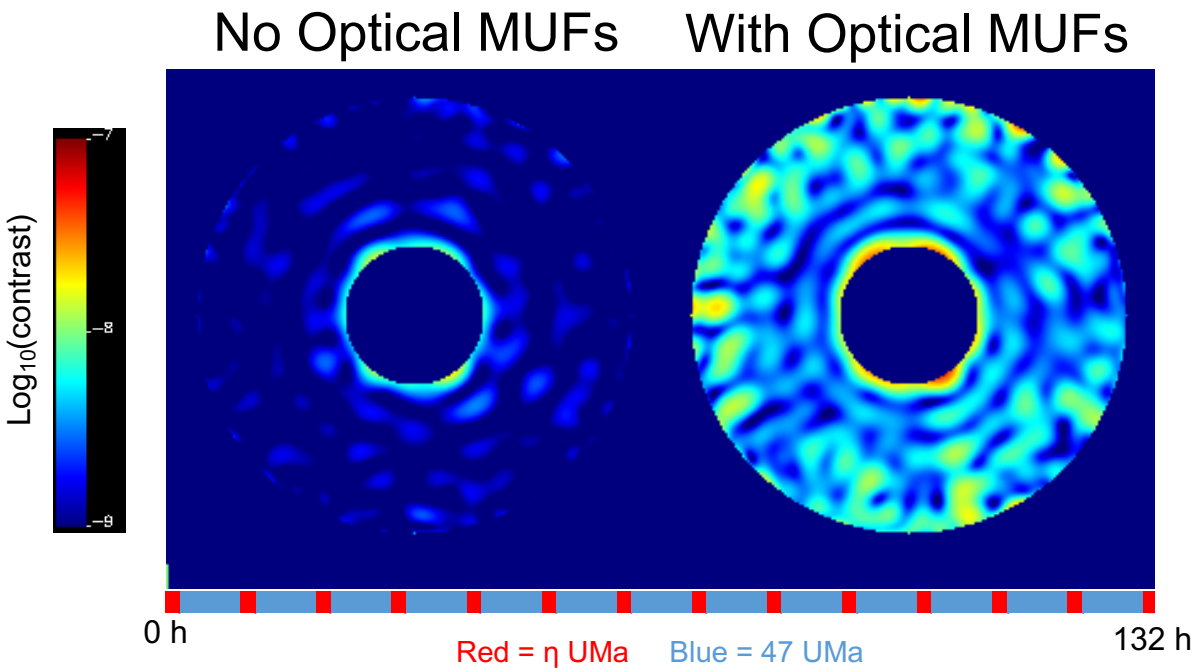
Status Since WIETR Report

- **CGI has passed Systems Requirement Review (SRR) in May 2018!**
- **WFIRST in in Phase B**
- **The Coronagraph Instrument is a technology demonstration only**
- **Requirements established using standard engineering practice**
  - Model uncertainty factors (MUFs)
  - Margins and reserves
- **Reduction in modes and science center role (descoping)**
- **If successful, "Participating Science Program" following tech demo**
- **Design to be "starshade ready" to support possible starshade rendezvous mission (pending Decadal recommendation)**

Notional CGI Programs:

- **3 months of technology demonstration observing in first 1.5 years of WFIRST mission**
- **If meet success criteria, 1 year Participating Science Program**
- **If successful, follow-on 2.5 year science program**

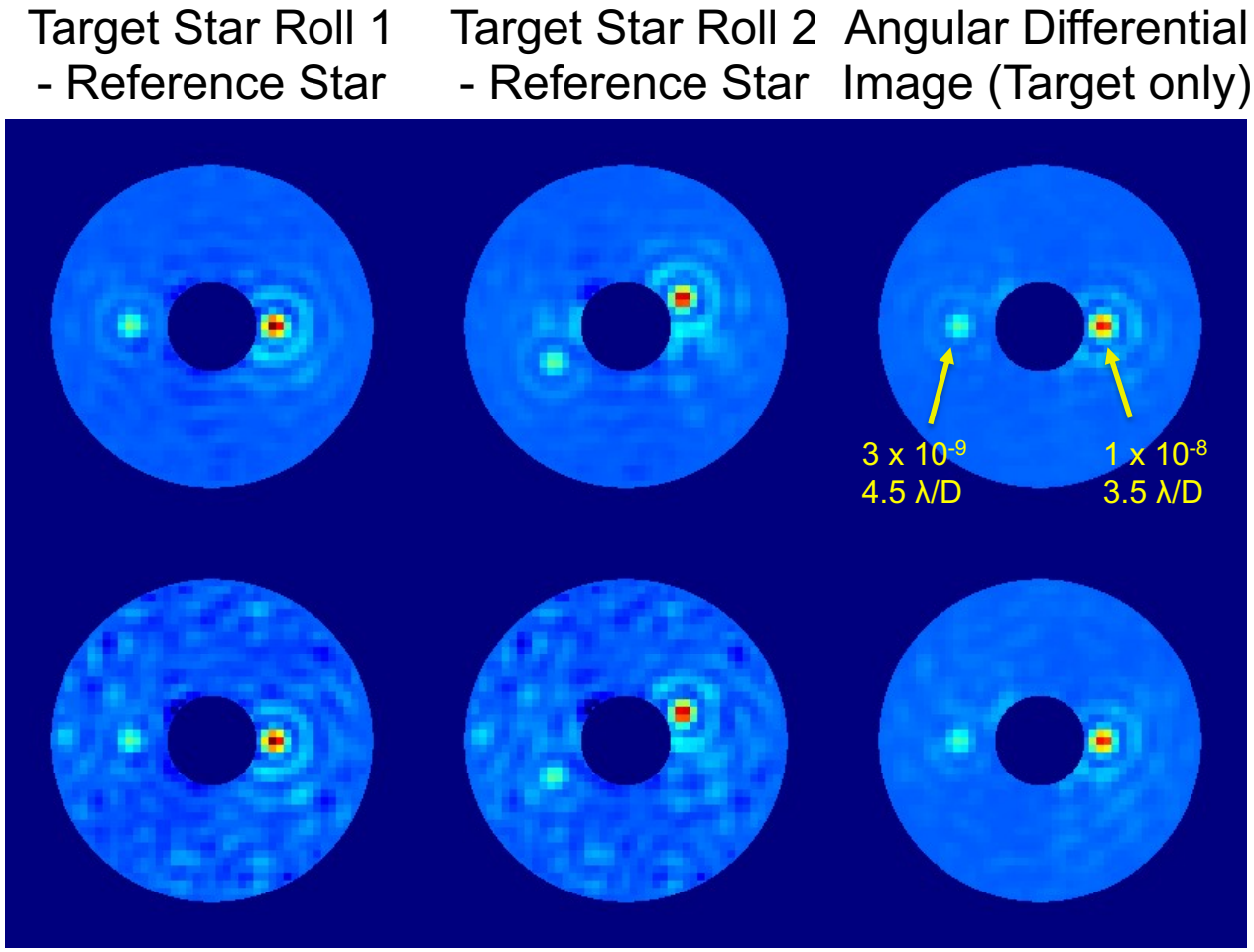
Operations Scenario #6 (OS6) Simulations -- Speckle Field Time Series



Includes: static aberrations (surface errors & polarization), high and low order wavefront control, thermally-induced wavefront aberration & pupil position changes, deformable mirror thermal drift, pointing & wavefront jitter, stellar diameters & colors

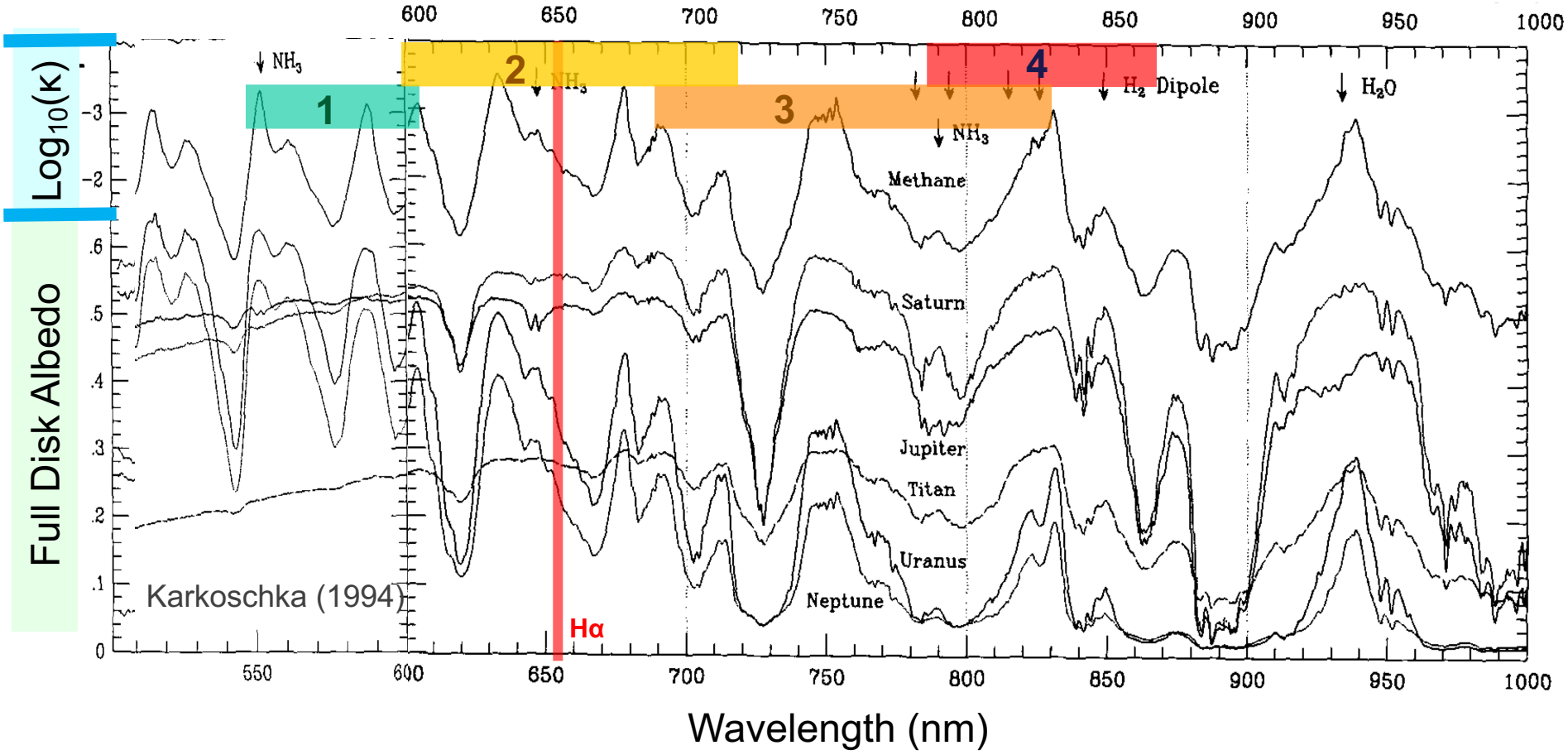
This OS6 simulated time series data available at
wfirst.ipac.caltech.edu

OS6 Simulations



Field incident on detector shown. Detector effects not included

CGI Filters



- **Post-WIETR descope: number of color filters (and associated coronagraph masks) reduced**
- **No change in the number of slots in the filter wheel**

CGI Operating Modes

➢ Three Required Technology Demonstration Modes:

Name	CGI Filter	λ_{center} (nm)	BW	Channel	Masks	Working Angle	Can use w/ linear polarizers	Starlight Suppression Region
Imaging w/ Narrow FoV	1	575	10%	Imager	HLC	3-9 λ/D	Y	360°
Spectroscopy	3	760	18%	IFS	SPC	3-9 λ/D		130°
Imaging w/ Wide FoV	4	825	10%	Imager	SPC disk	6.5-20 λ/D	Y	360°

➢ Other possible modes with required masks and filters:

CGI Filters	λ_{center} (nm)	BW	Channel	Masks	Working Angle	Can use w/ linear polarizers	Starlight Suppression Region
2	660	18%	IFS	SPC	3-9 λ/D		130°
2	660	18%	Imager	SPC	3-9 λ/D	Y	130°
3	760	18%	Imager	SPC	3-9 λ/D	Y	130°
4	825	10%	Imager	HLC	3-9 λ/D	Y	360°
4	825	10%	IFS	HLC	3-9 λ/D		360°

3 primary Tech Demo Modes identified in CGI requirements. Other mask combinations exist and can be used during participating science program.

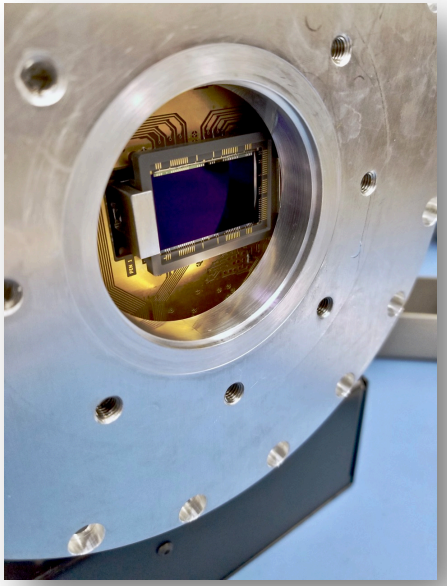
CGI Low-noise Detectors

Science Cameras (Direct imaging and IFS)

Item		Requirement@5 years		CBE (5 years)	Margin
Total Noise@165K (σ^2)					
575 nm	Band 1	41.0 e^--px^{-1}–hr^{-1}	@6s	19.6	52.2%
760 nm	Band 3	3.7 e^--px^{-1}–hr^{-1}	@80s	2.8	24.3%
825 nm	Band 4	28.1 e^--px^{-1}–hr^{-1}	@10s	11.0	60.9%

Engineering Camera (LOWFS)

Item		Requirement	CBE (5 years)	Margin
Total Noise@165K (σ^2)		158.8 e^--s^{-1}	126.7	19.8%
	Read	5 e^-	4	
	CIC	<0.1 e^--$pixel^{-1}$-fr^{-1}	0.03	
	Dark	<1 e^--$pixel^{-1}$-s^{-1}	<0.00056	
Full Well		25,000 e^-	29,200	16.8%
Frame rate		1000 frames-s^{-1}	1961	96%
Latency		0.5 ms	0.25	96%
Bits		14	14	✓



e2v 1K X 1K Electron Multiplying CCDs
For all cameras, running at different modes

Infusing New Wavefront Sensing & Control algorithms

- CGI is an actively controlled instrument, performance driven by both hardware (masks, DMs) and algorithms/software (DM solutions)
- CGI plans to fly the most capable flight-ready processor, optimized with both CPU and FPGAs
- WFIRST supports CGI software uploads during Phase E
- Welcome new algorithms development from future PSP programs
- CGI maintains an ops testbed during Phase E, that can proof-test new algorithms before upload

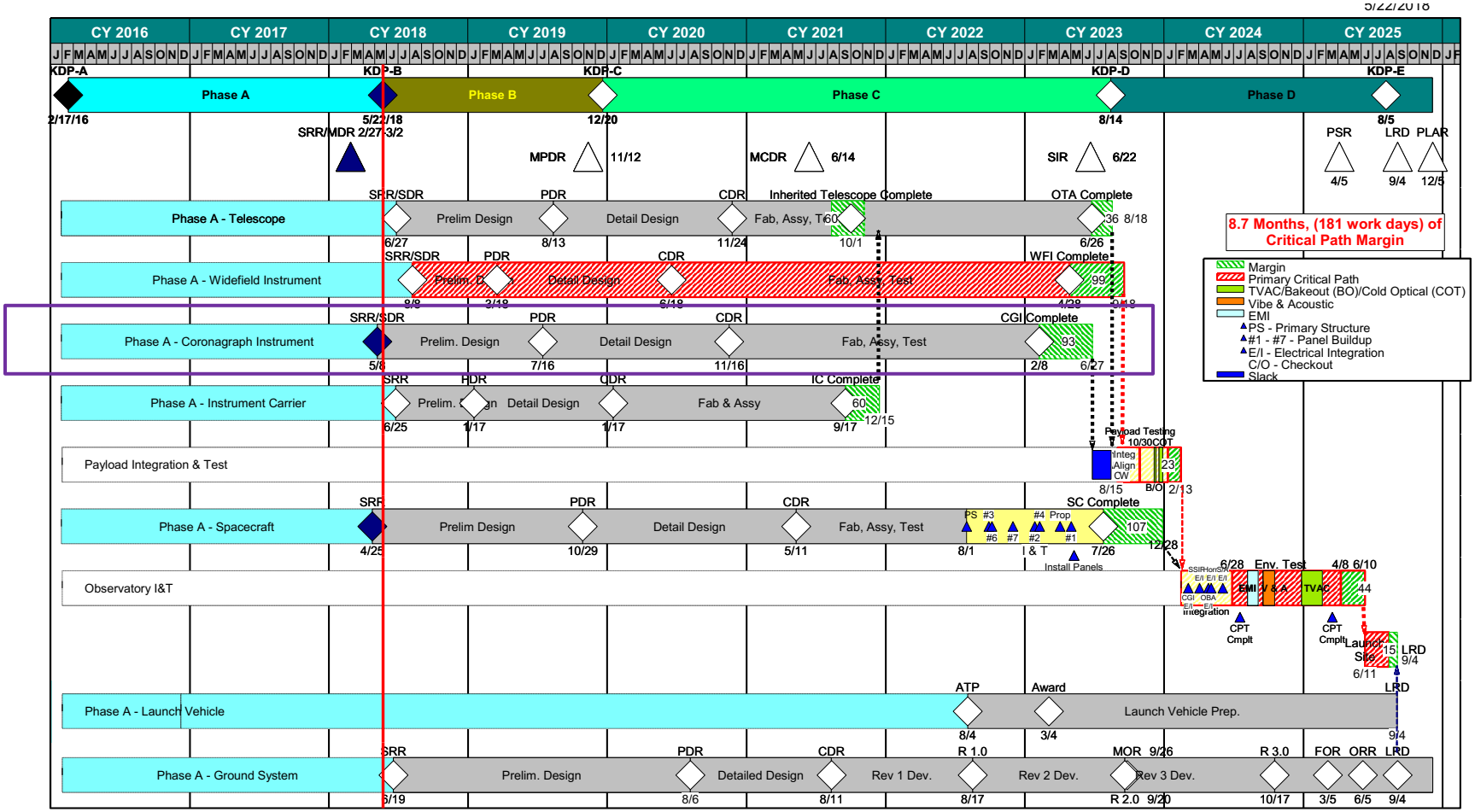
Summary

- **CGI is tech demo, using standard technology flight project practices**
- **CGI team is making good progress**
- **Current performance estimates show a healthy margin against L1 tech demo requirements**
  - Starlight suppression
  - Unltra-low noise detectors
  - ➢ Exciting participating science programs
- **CGI maintains capability of infusion new algorithms**
  - Testbeds to verify new algorithms for upload
- **CGI is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets**

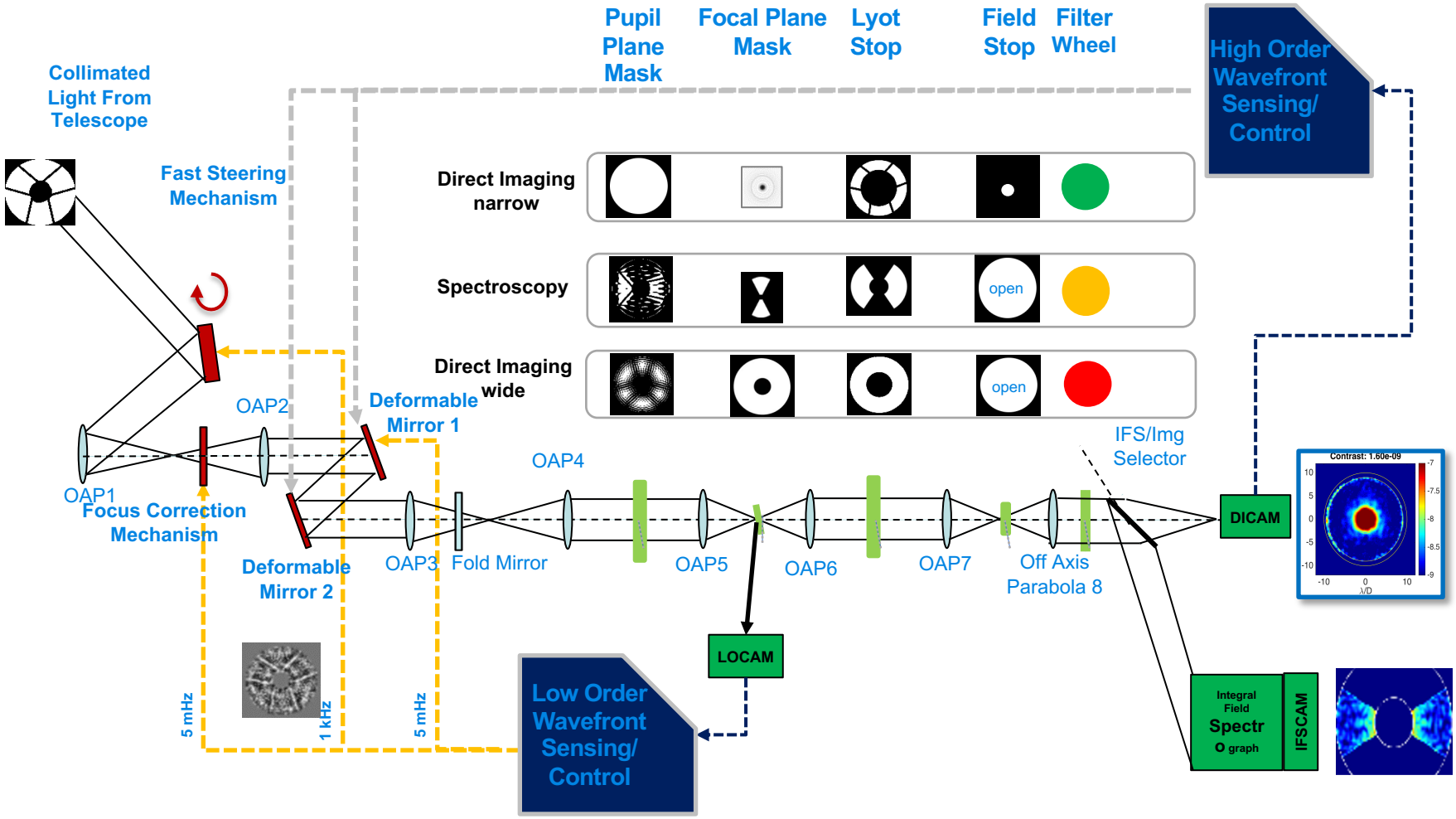
Backup charts

WFIRST in Phase B

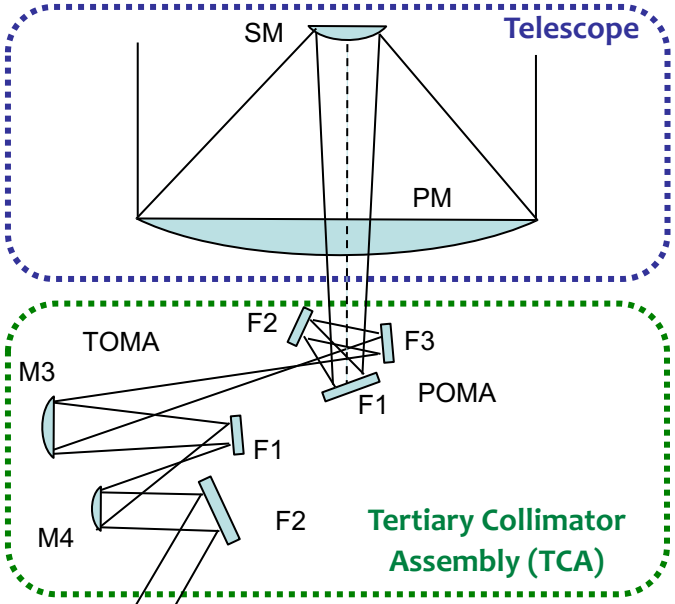
- **CGI has passed Systems Requirement Review (SRR) in May 2018!**
- **WFIRST in in Phase B**
- **Next major CGI gate review: PDR July 2019**



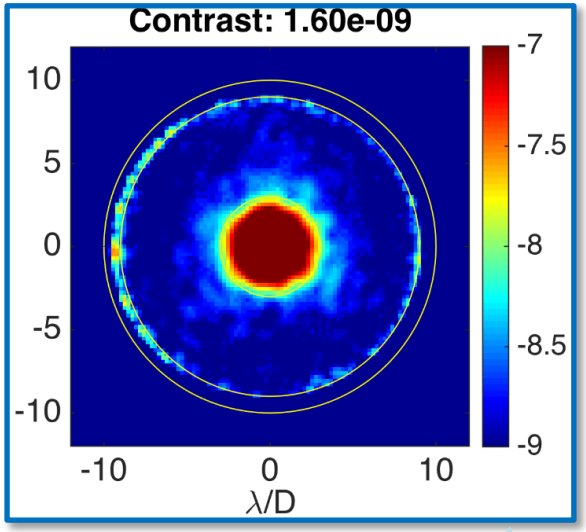
Coronagraph Instrument – Actively Controlled High-Contrast Imaging Instrument



Imaging with Narrow Field of View Mode

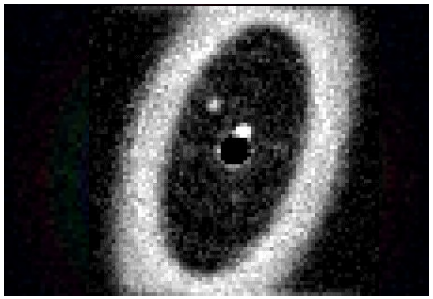


Dark hole for planet photometry and discovery centered at 575 nm with annular FOV from 3-9 λ/D



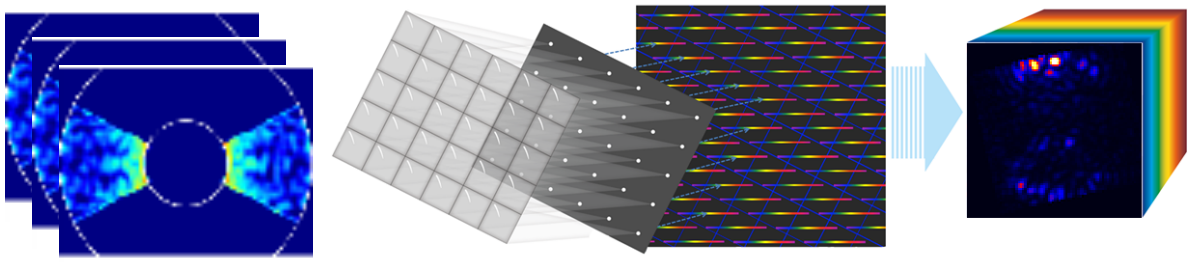
Imaging with Wide Field of View Mode

Disk imaging at wavelengths 508 and 721 nm, with outer working angle of 20 λ/D

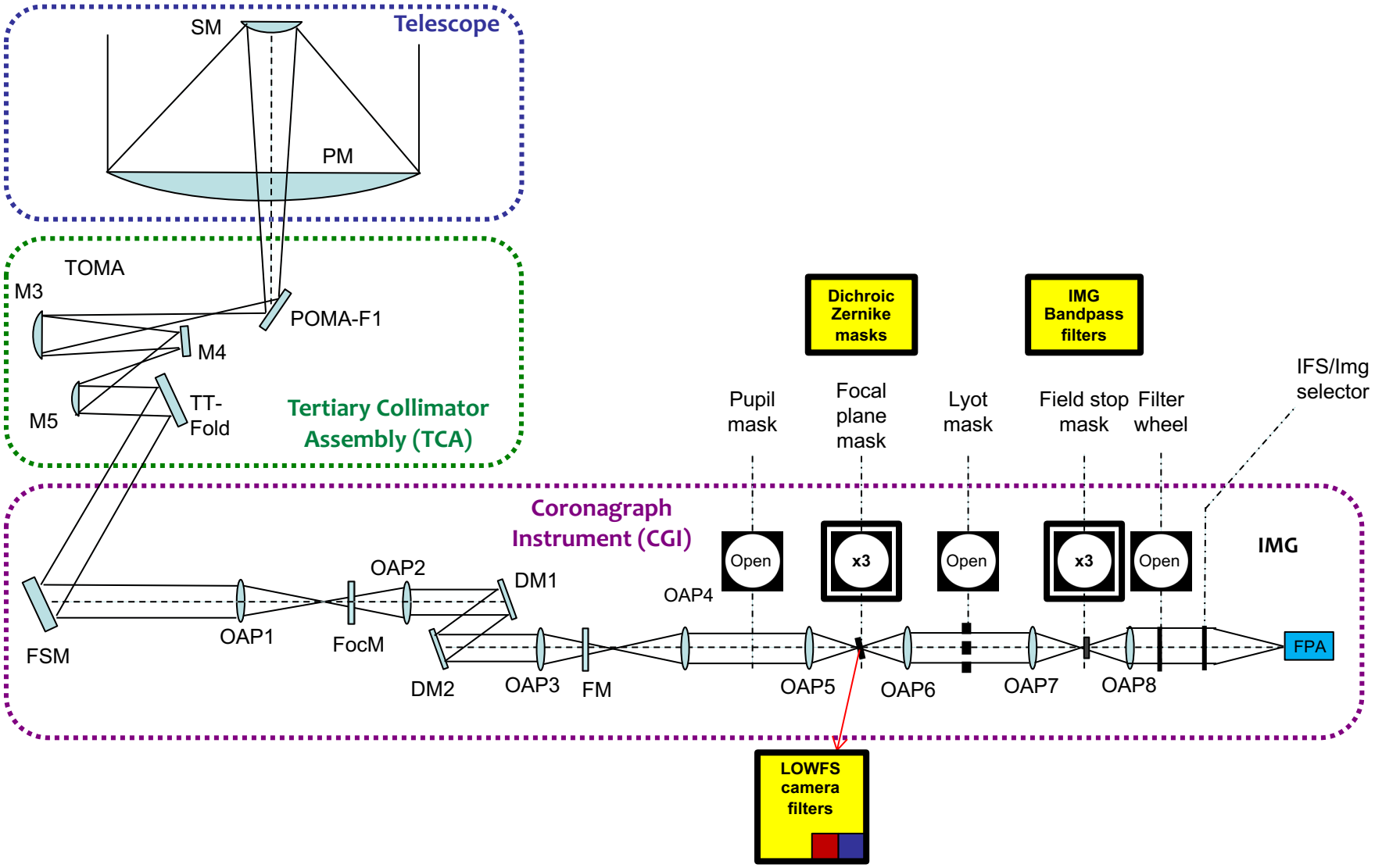


Spectroscopy Mode with Integral Field Spectrograph (IFS)

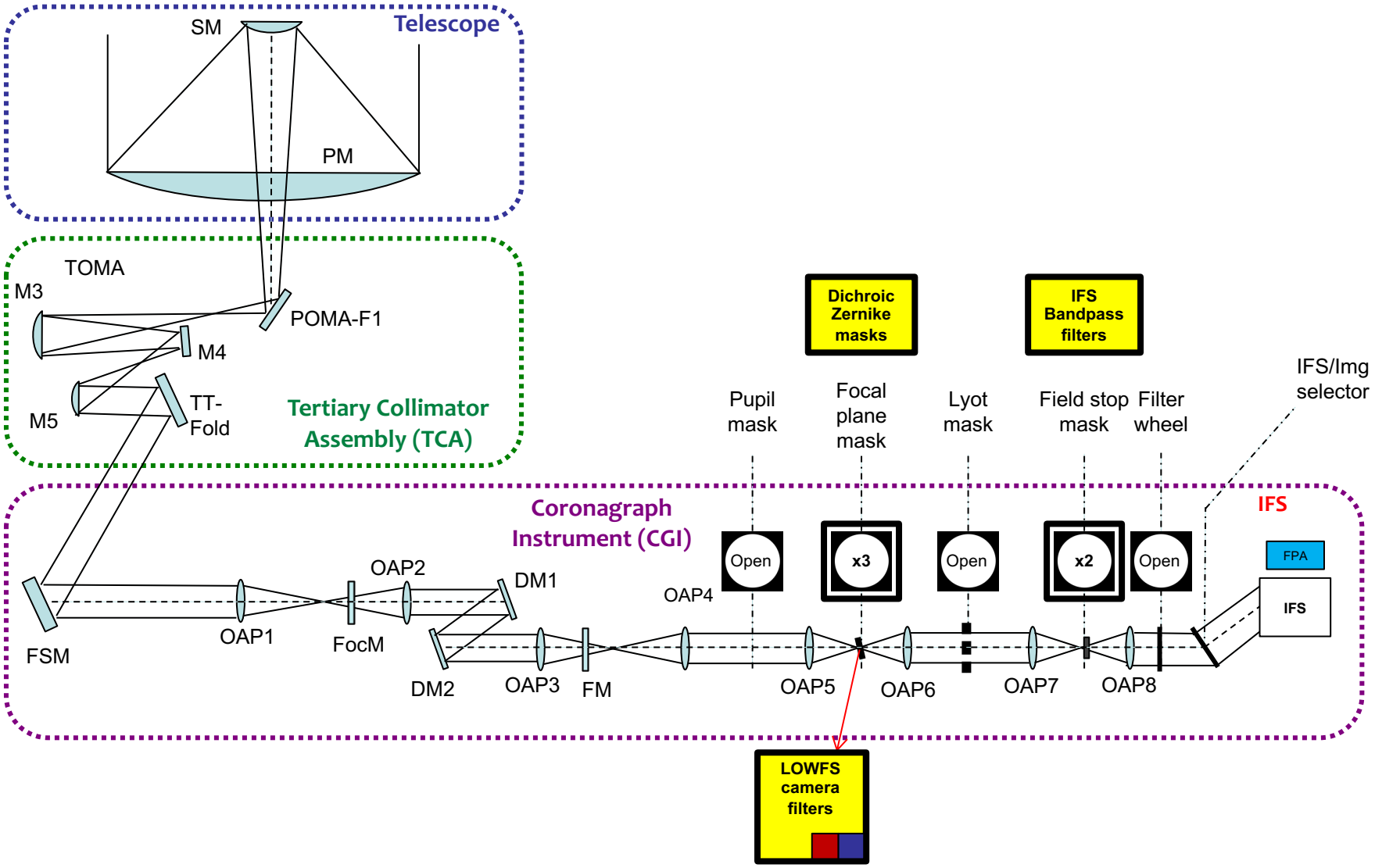
The IFS uses 3 18% bands to produce R=50 spectra from 600 to 830 nm



Starshade Imaging Mode

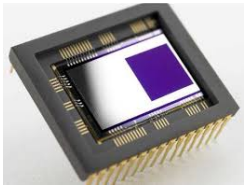


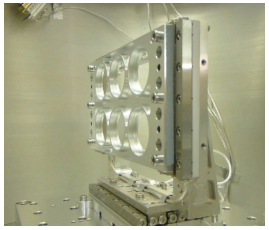
Starshade Spectroscopy Mode

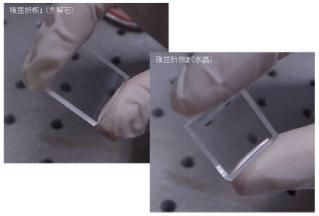


International Contributions

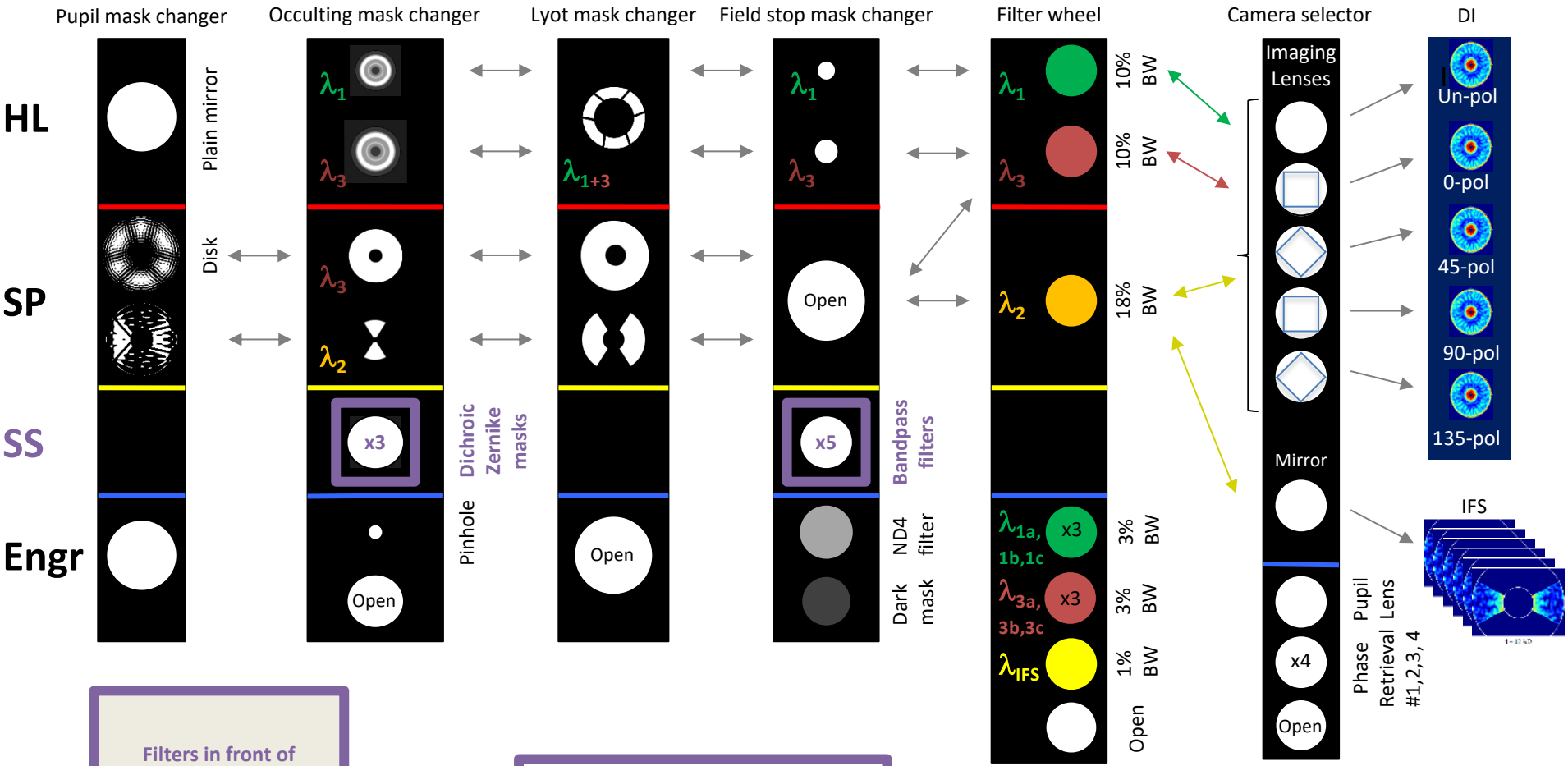
Notes	Technical Point of Contact
Contribution scope: 1. Flight package development 2. Engineering grade detectors: qty=6 3. Flight grade detectors: qty=14 4. Non-functional mechanical sample detectors: qty=3	Andrea Santovincenzo Head of Astrophysics and Fundamental Physics Missions Section ESA/ESTEC SCI-FMA Tel: 0031 71 5653966 Fax: 0031 71 5656024 Email: Andrea.Santovincenzo@esa.int
Contribution scope: Detector performance analysis, tests	Prof. Andrew Holland CEI/Open University, London, UK mailto:andrew.holland@open.ac.uk Chris Lee Space Science Programme Manager UK Space Agency chris.lee@ukspaceagency.bis.gsi.gov.uk
Total six mechanisms under consideration: 1. Shaped pupil wheel mechanism (SPWM) 2. Lyot stop wheel mechanism (LSWM) 3. Camera/polarizer selector wheel mechanism (CSWM) 4. Occulter wheel mechanism (OCWM) 5. Field stop wheel mechanism (FSWM) 6. Color filter wheel mechanism (CFWM)	Oliver Krause Max-Planck-Institut fuer Astronomie Koenigstuhl 17 D-69117 Heidelberg, Germany Tel. : +49 6221 528352 FAX : +49 6221 528246 E-Mail: krause@mpia-hd.mpg.de
Contribution scope could include: 1. Polarizer optics with mounts 2. Polarization compensator 3. Polished Si wafer for Shaped-pupil mask	Toru Yamada JAXA, Institute of Space and Astronautical Science (ISAS) Tsukuba-shi, Ibaraki, JAPAN Email: yamada@ir.isas.jaxa.jp
Total eight (8) off-axis parabola mirrors, options include un-coated mirrors, coated mirrors, and mounted mirrors. Need dates reflect CGI I&T accommodations of LAM sequential delivery.	Marc FERRARI - Ph.D. Astronomer & Deputy Director R&D, Technological Facilities, Industrial Partnership Laboratoire d'Astrophysique de Marseille - LAM Email: marc.ferrari@lam.fr Tel: +33 (0) 495 044 191 Mobile: +33 (0) 607 537 607







CGI Modes and Color Bands to Meet Current L1 Tech Demo Requirements



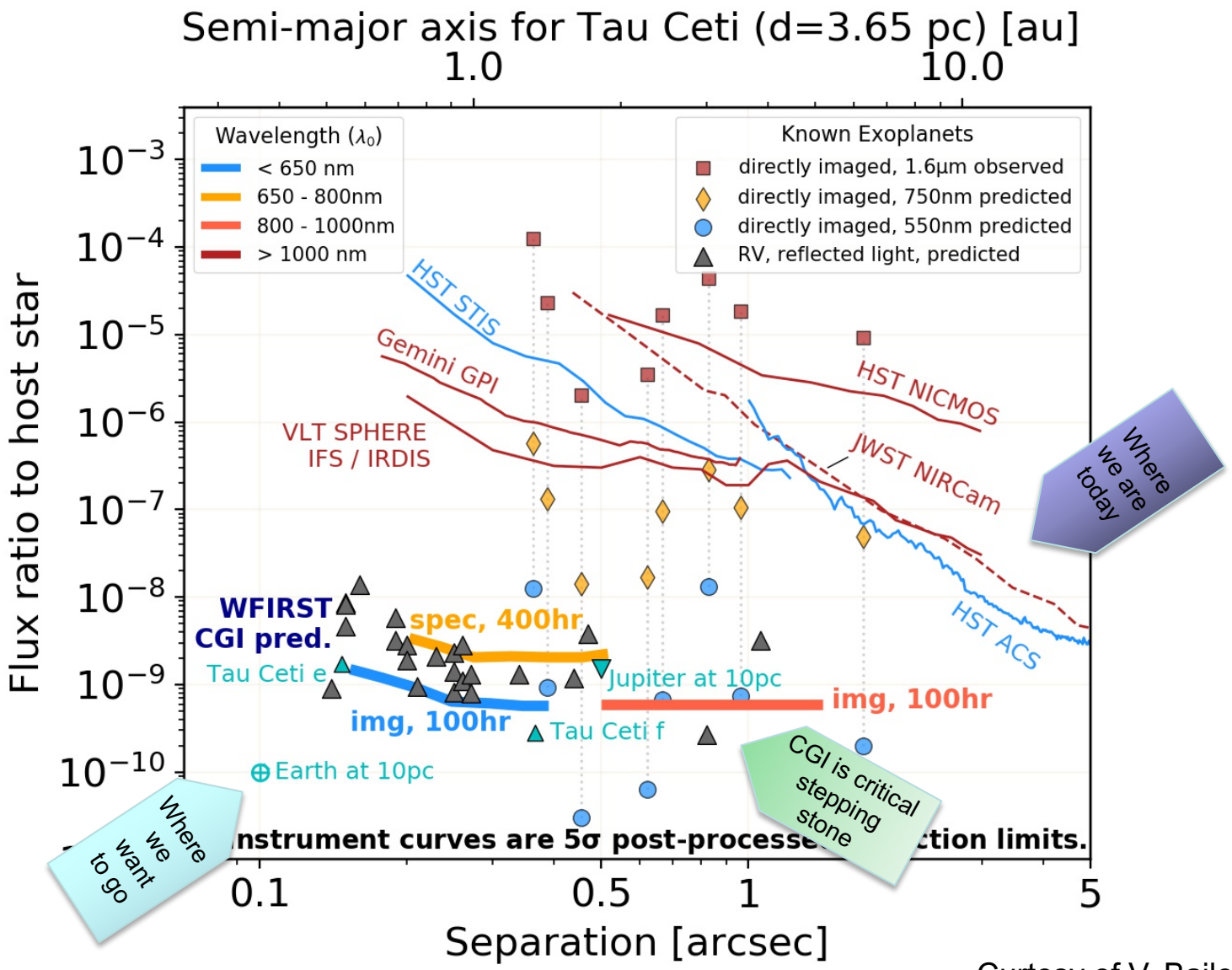
Filters in front of LOWFS camera for Starshade

Added for Starshade

λ_1=575nm (10%)
λ_2=760nm (18%)
λ_3=825nm (10%)

No change in total number of slots in filter wheels

CGI is a Pathfinder for Direct Imaging and Spectroscopy of Earth-like Exoplanets



Curtesy of V. Bailey