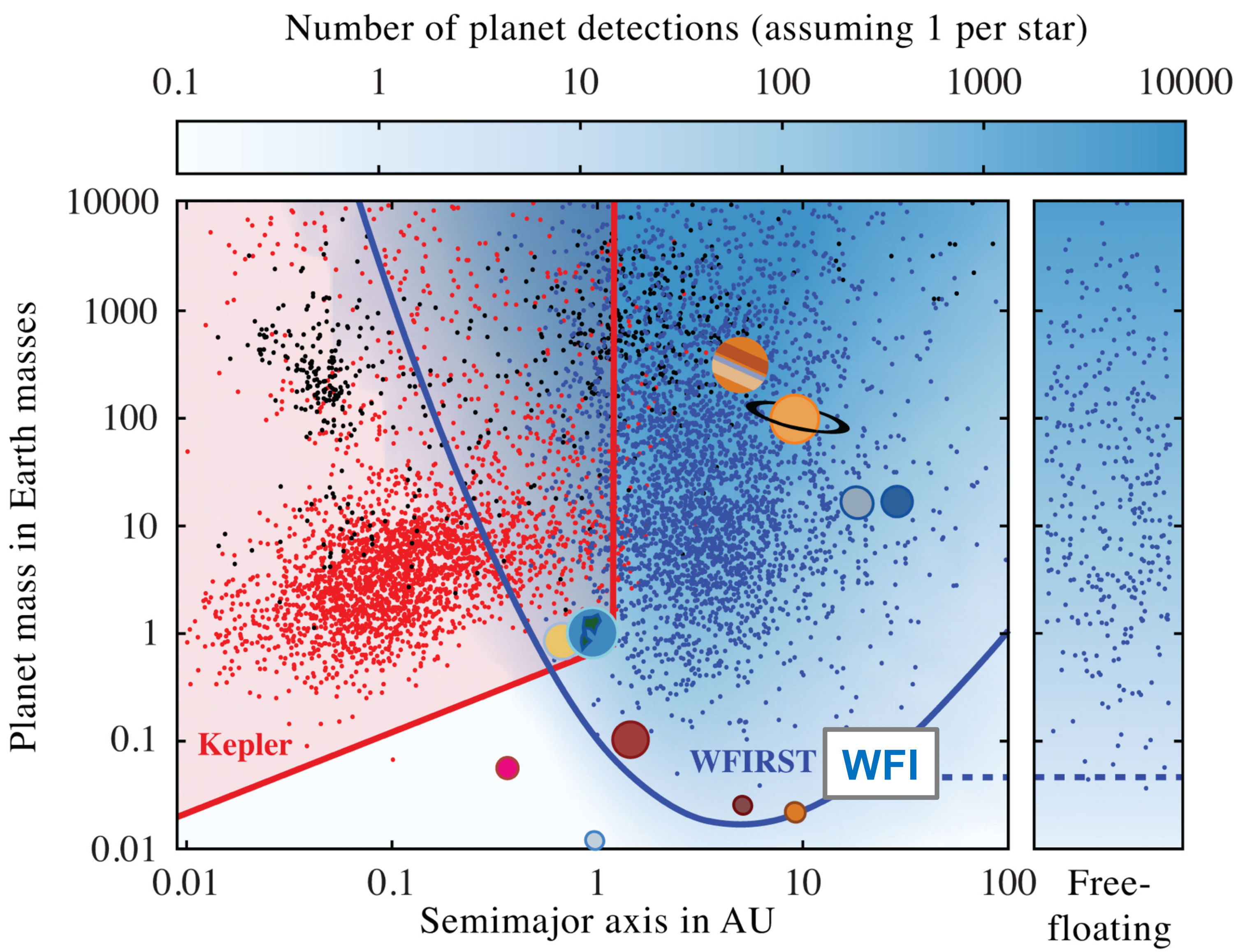
Jet Propulsion Laboratory
California Institute of Technology

WFIRST CGI (Coronagraph Instrument) Technology overview & exoplanet science

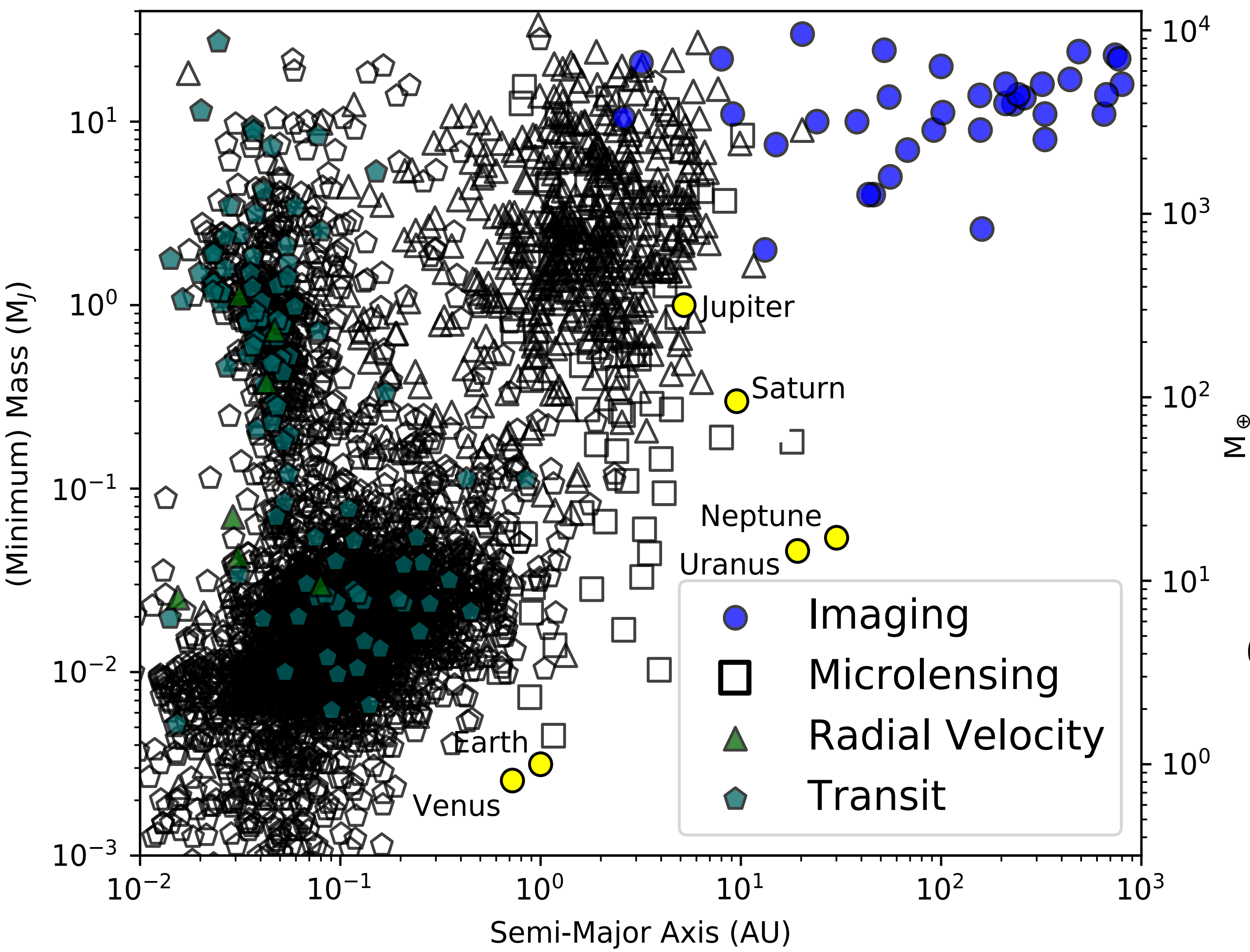
Vanessa Bailey
Jet Propulsion Laboratory, California Institute of Technology

On behalf of CGI Project Science and Science Investigation Teams

June 20, 2019

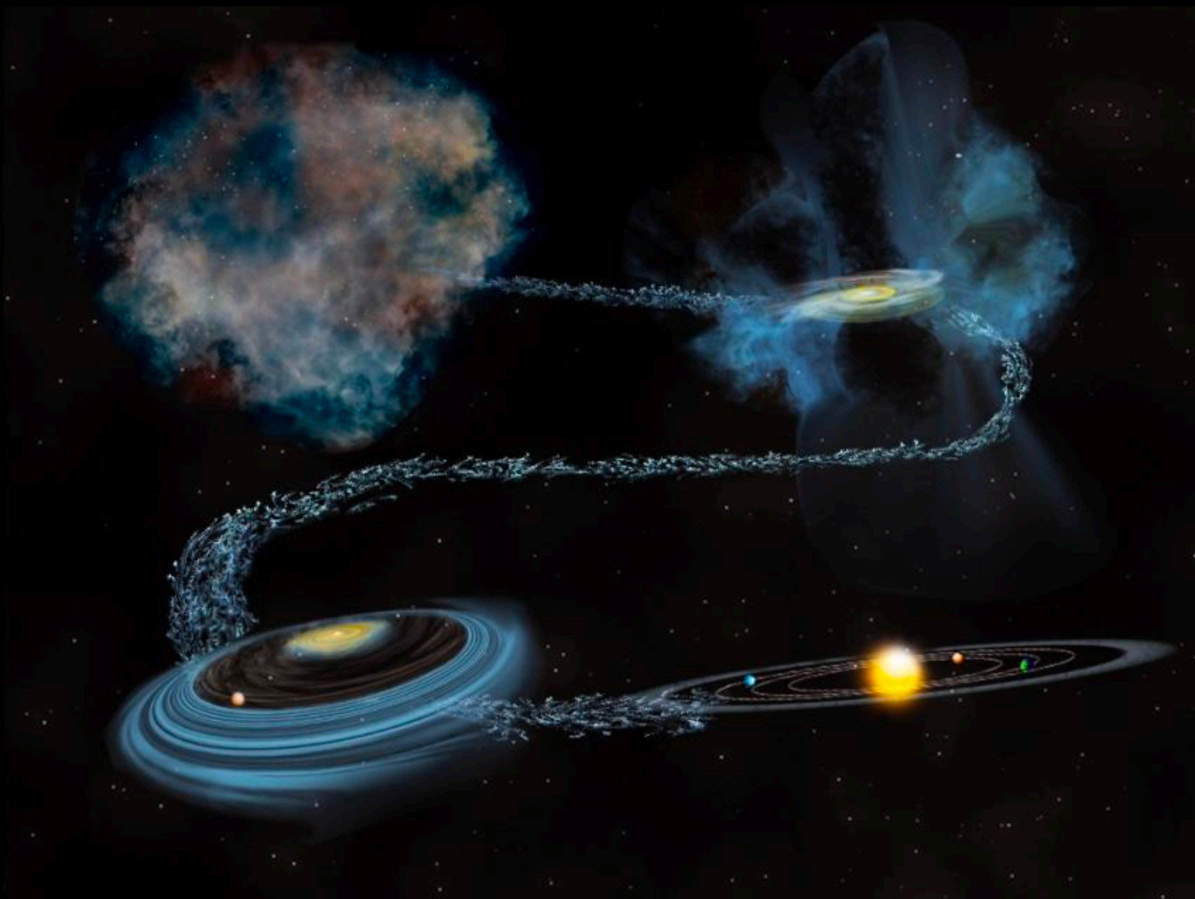


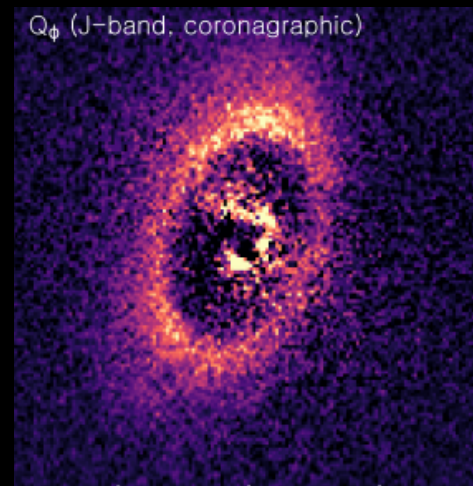
Number of planet detections (assuming 1 per star)
0.1
1
10
100
1000
10000
Planet mass in Earth masses
10000
1000
100
10
1
0.1
0.01
Kepler
WFIRST
WFI
0.01
0.1
1
10
100
Semimajor axis in AU
Free-floating



Only a small fraction of known exoplanets have been characterized

Study complete planetary systems





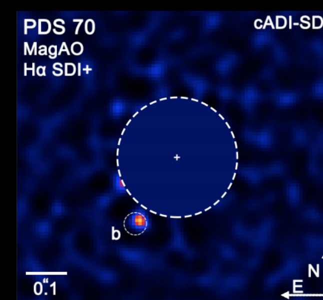
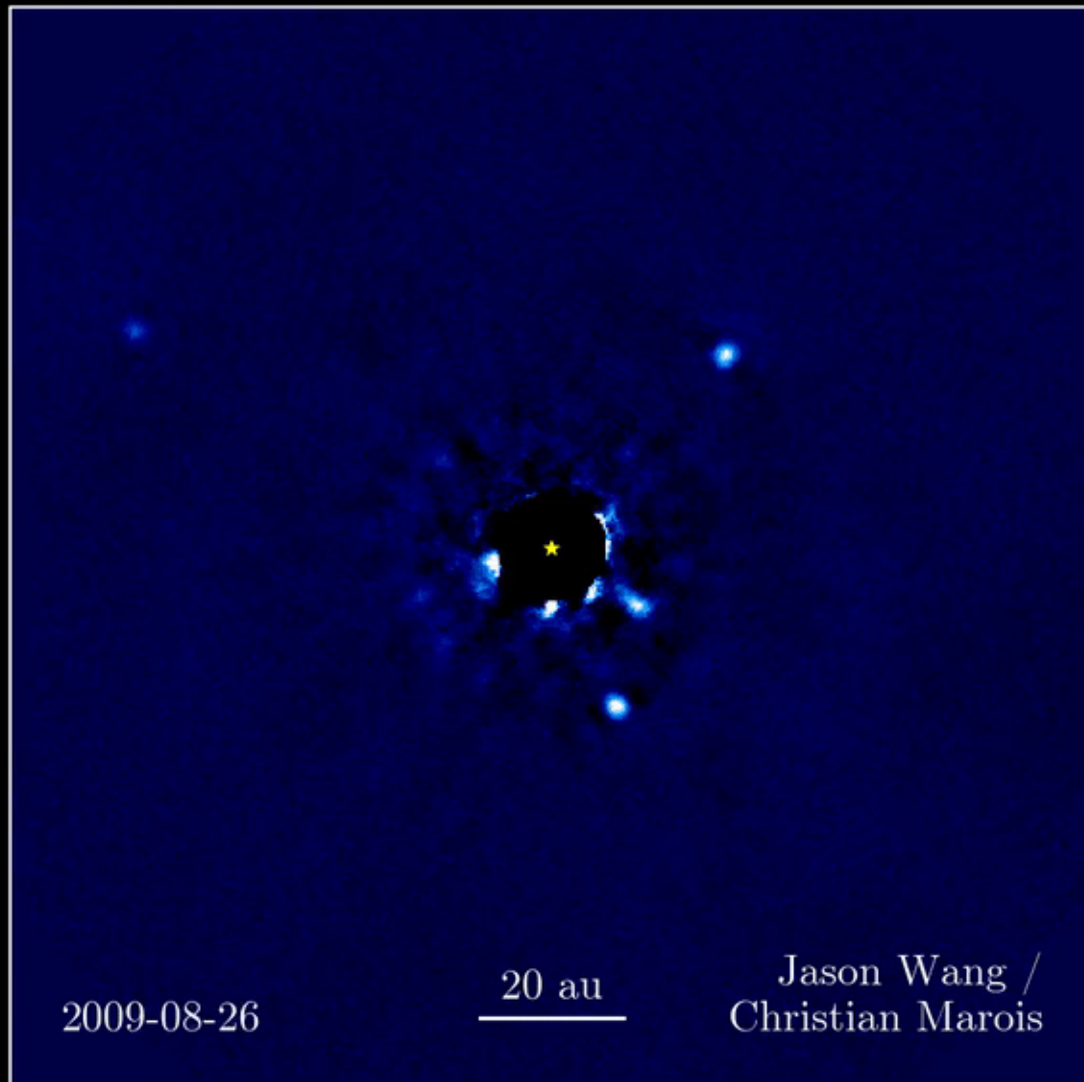


image credit: Bill Saxton, NSF/AUI/NRAO


2009-08-26
20 au
Jason Wang /
Christian Marois

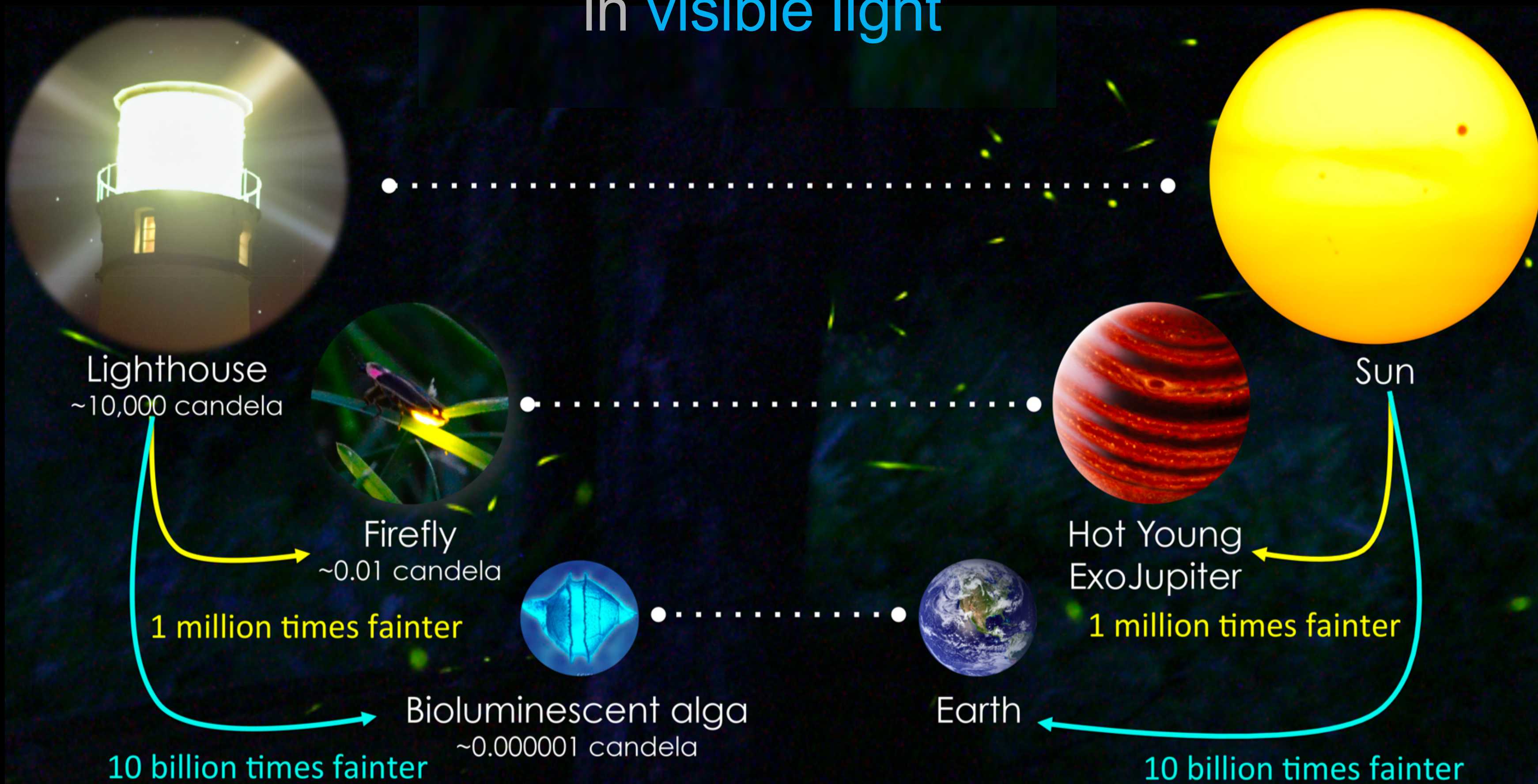
"Bright" young super-Jupiters
10^6 times fainter than their stars in **NIR**

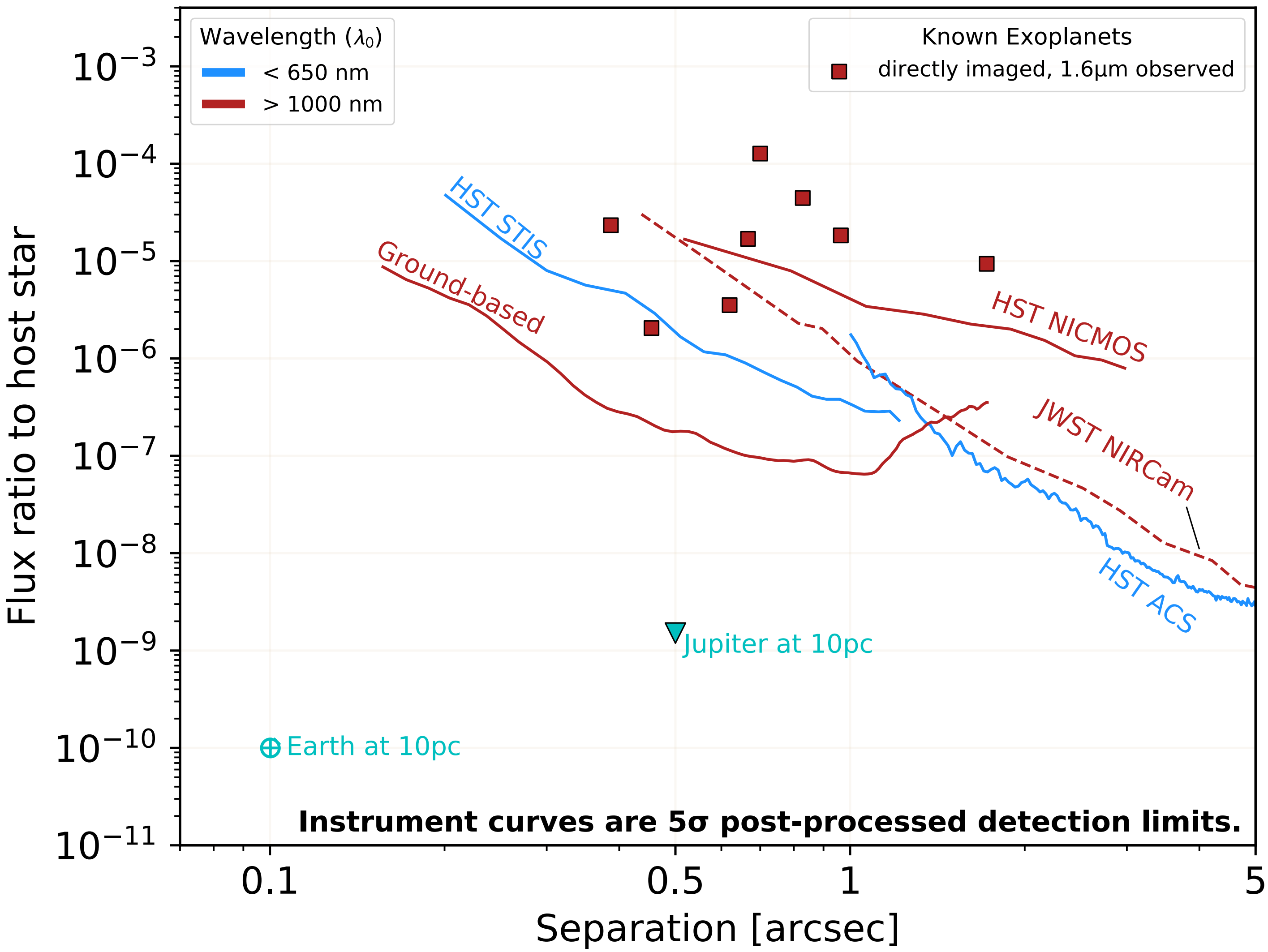
credits: Kate Follette; NASA/IPAC

Image credit: Kate Follette

Goal: Earth Twins

10^{10} times fainter than their host stars in visible light





Wavelength (λ_0)
< 650 nm
> 1000 nm
Known Exoplanets
directly imaged, 1.6μm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
0.5
1
5

Image credit: Kate Follette

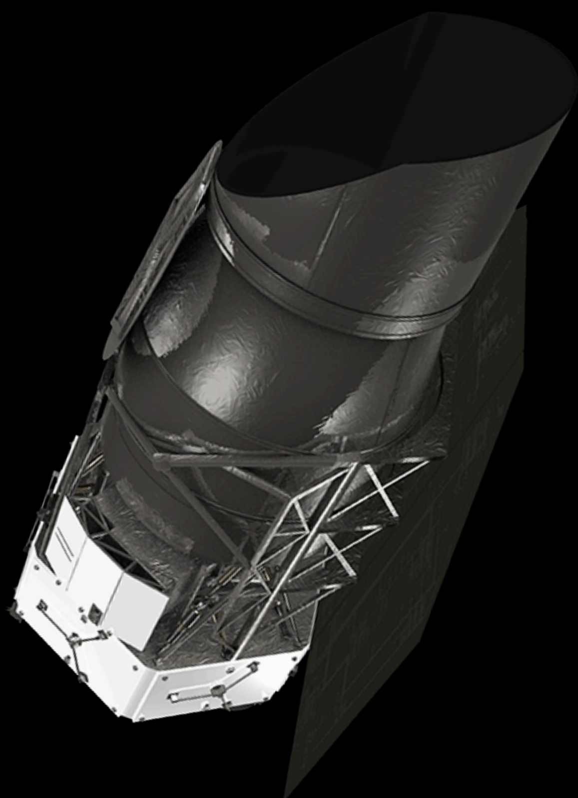
Goal: Earth Twins

10^{10} times fainter than their host stars in visible light

https://exoplanets.nasa.gov/resources/266/exoplanet-missions/

WFIRST CGI

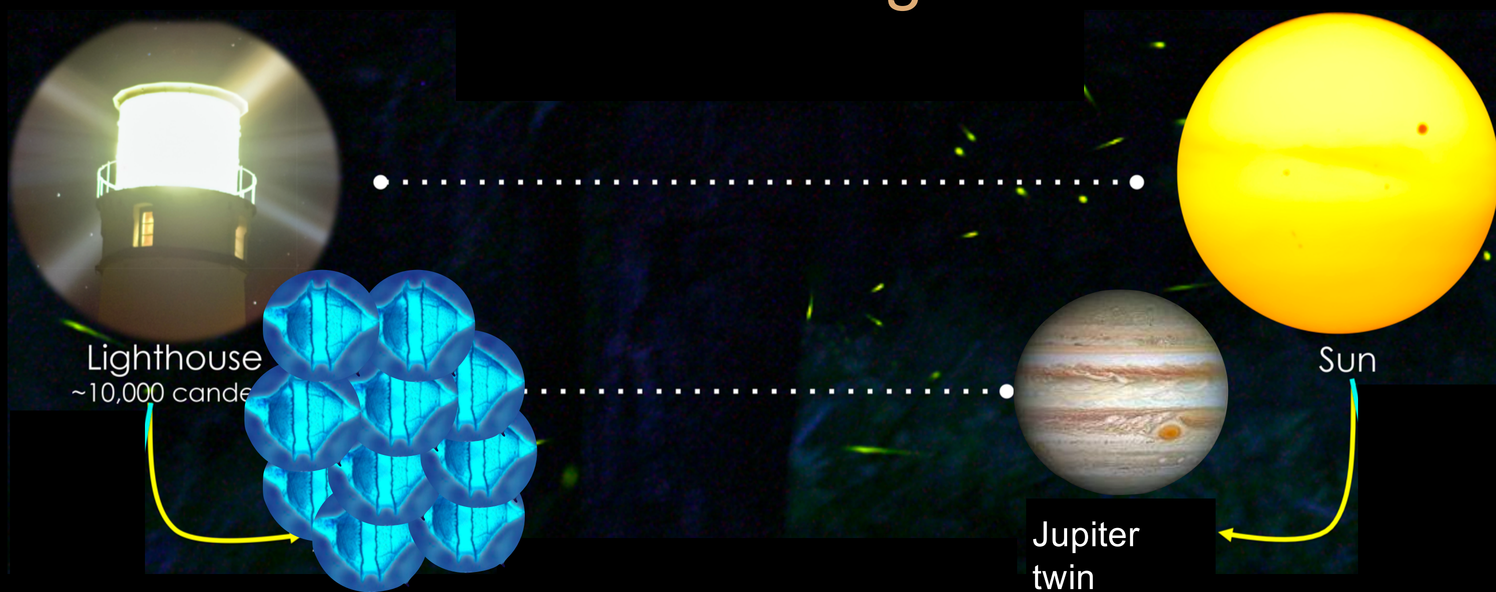
Wide Field Infrared Survey Telescope — Coronagraph Instrument



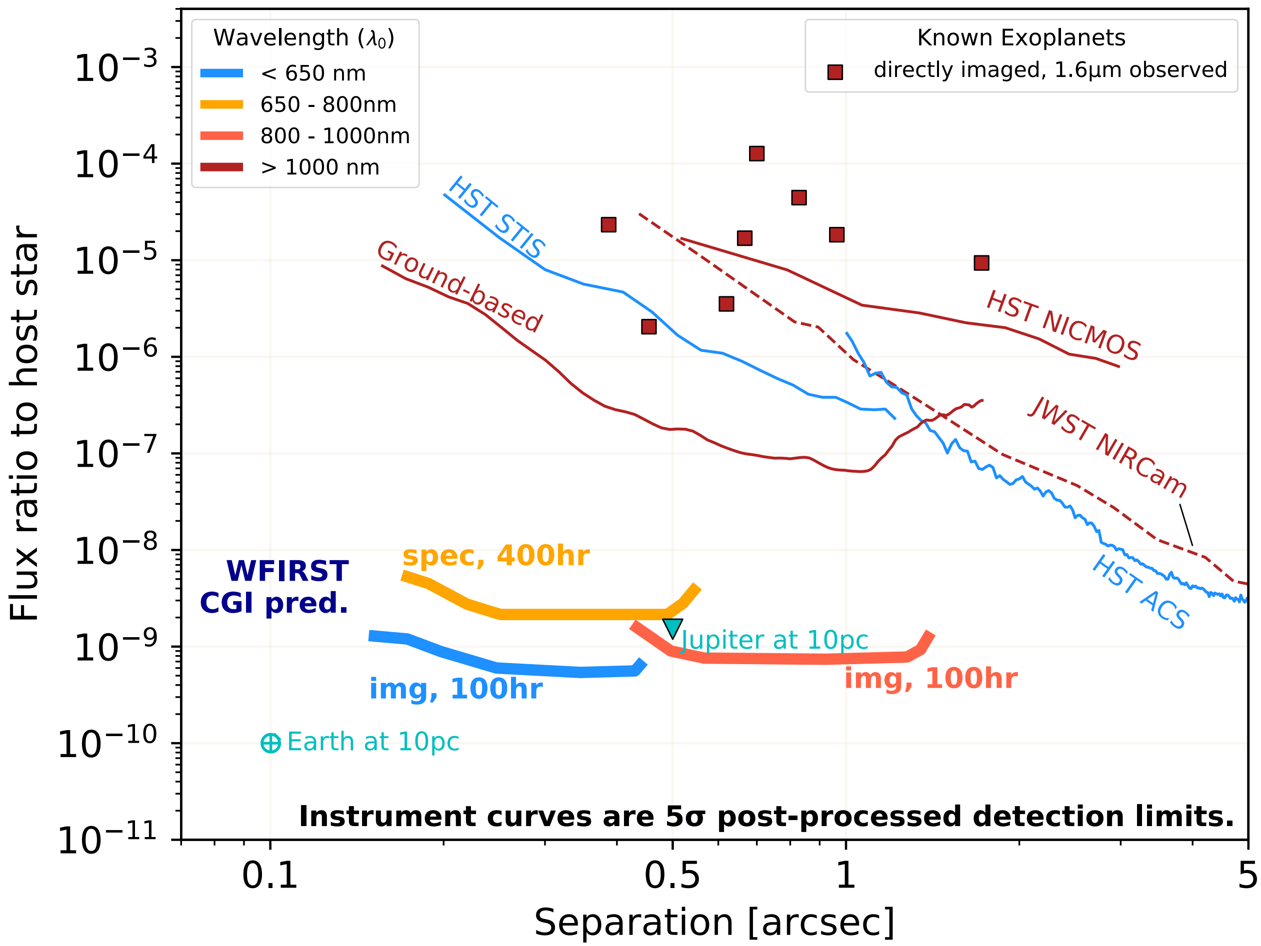
Visible light imager/polarimeter & spectrograph

- ~ 550 – 860nm, 10^9 contrast
- "Technology Demonstrator"

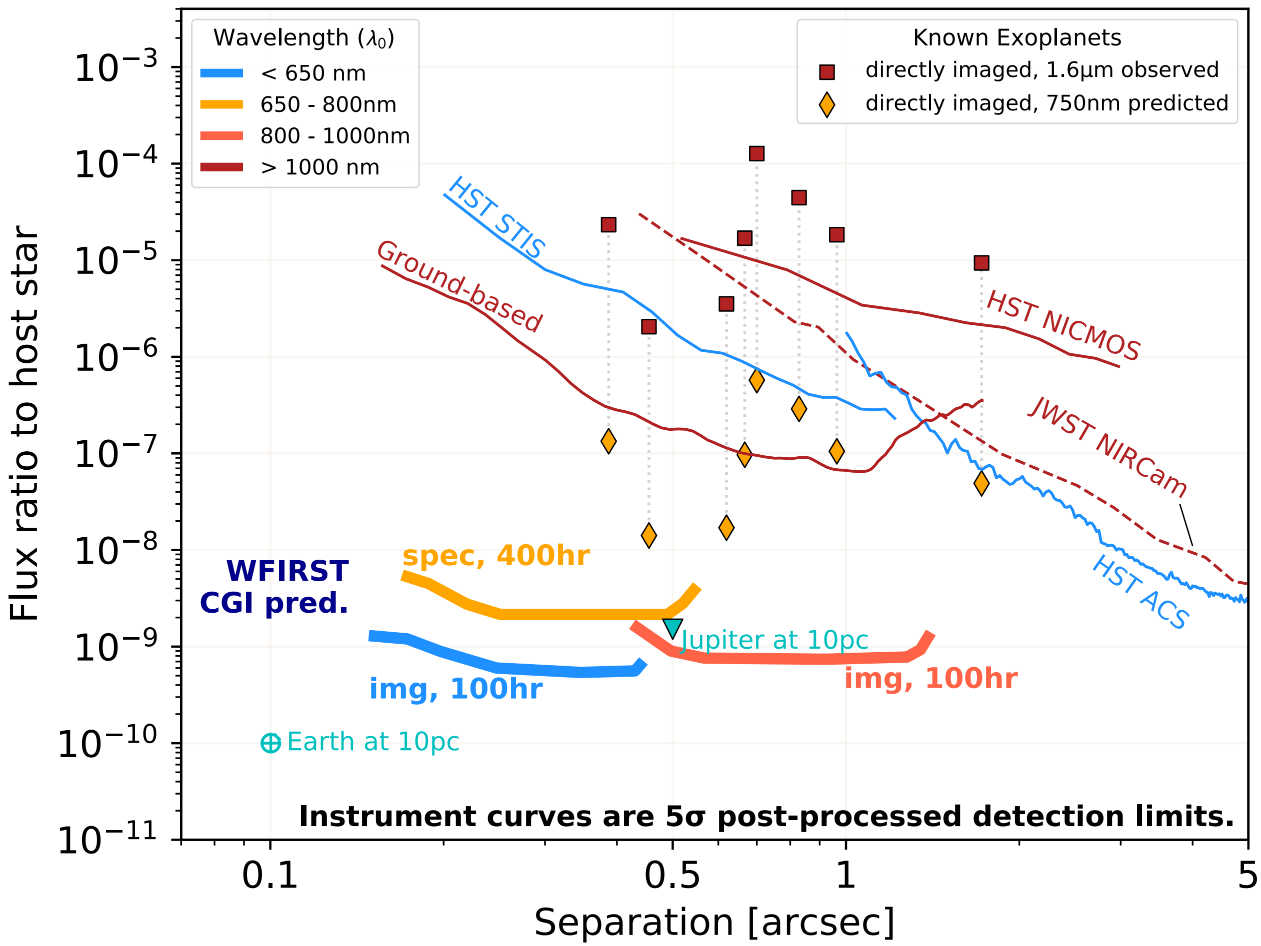
Mature Jupiter analogs
10^9 times fainter than their stars
in visible light

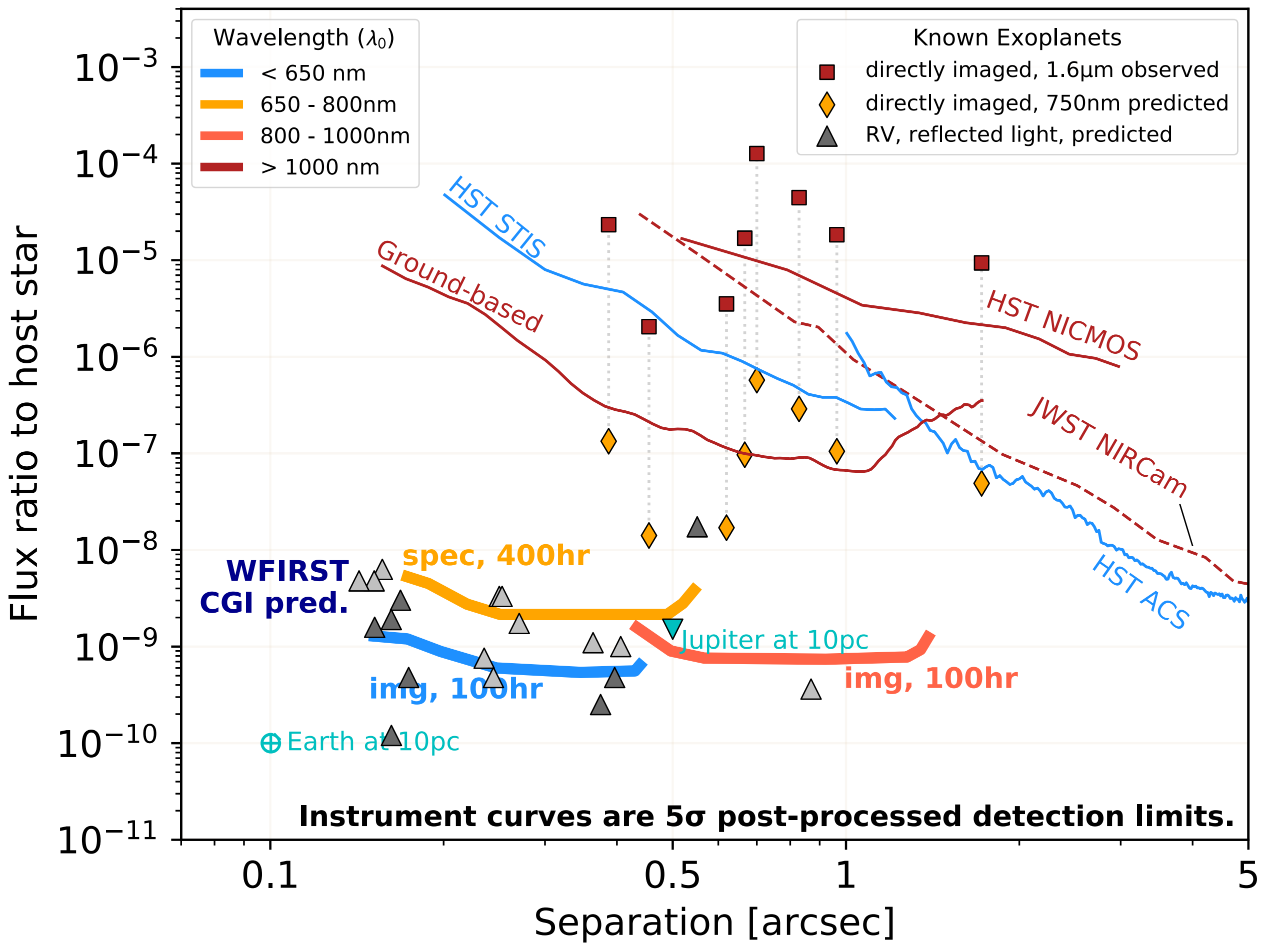


credit: Kate Follette; with modifications



Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
directly imaged, 1.6µm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
WFIRST
CGI pred.
spec, 400hr
Jupiter at 10pc
img, 100hr
img, 100hr
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]


Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
directly imaged, 1.6µm observed
directly imaged, 750nm predicted
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
WFIRST
CGI pred.
spec, 400hr
img, 100hr
Jupiter at 10pc
img, 100hr
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
0.5
1
5

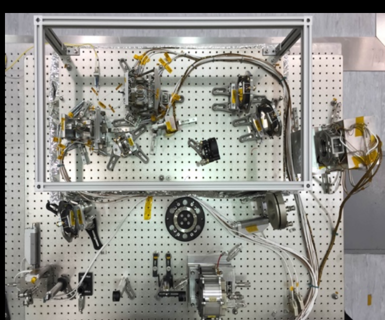


Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
directly imaged, 1.6µm observed
directly imaged, 750nm predicted
RV, reflected light, predicted
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
WFIRST
CGI pred.
spec, 400hr
img, 100hr
img, 100hr
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
0.5
1
5

[redacted]

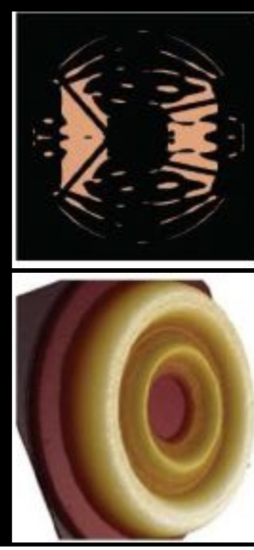
CGI will demonstrate key technologies for future missions

Autonomous Ultra-Precise Wavefront Sensing & Control

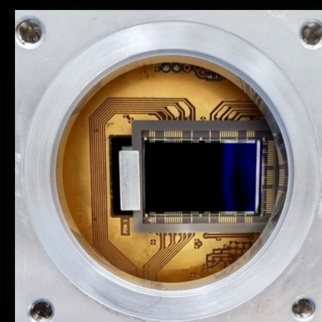


Large-format Deformable Mirrors

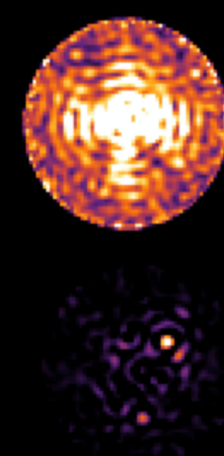
High-contrast Coronagraph Masks



Ultra-low noise photon counting visible detectors



Data Post-Processing

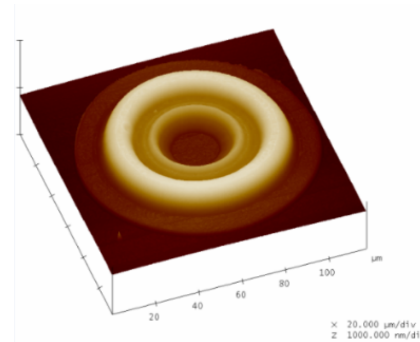


CGI is a “technology demonstration” instrument

Advanced coronagraphs suppress starlight by a factor of 100 million

- Hybrid Lyot Coronagraph (HLC)
  - Optimized for imaging (10% bandpass)
- Shaped Pupil Coronagraph (SPC)
  - Optimized for spectroscopy (15% bandpass)
- 100-1000x better than current

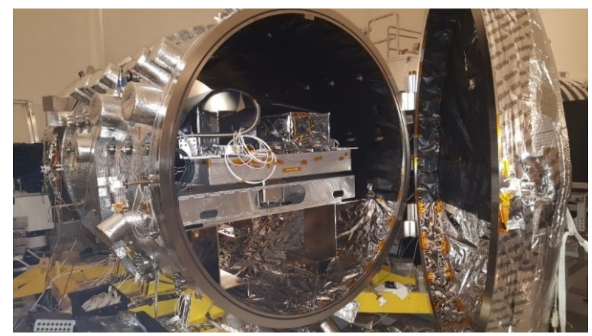
Mask images taken with atomic force microscopes



Wavefront sensing and control

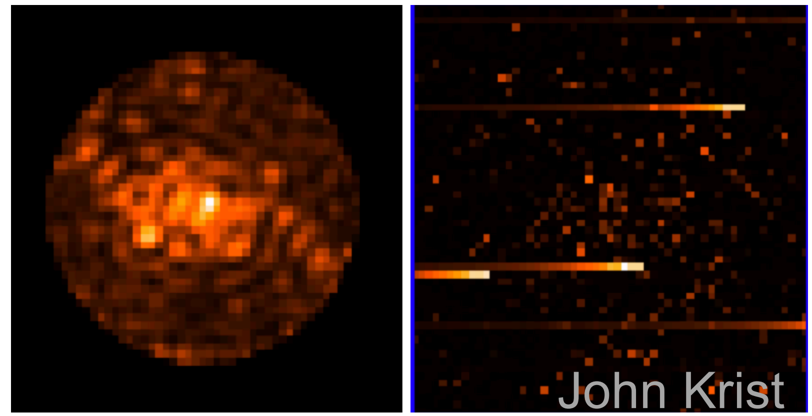
- Deformable mirrors correct optical errors
  - **Both phase and amplitude errors**
  - **< 1 nm RMS**
  - Based on science camera data, not separate wavefront sensor
  - Xinetics use Electrostrictive PMN (lead magnesium niobate)
- Separate Low Order Wavefront Sensor
  - 1 kHz loop controls telescope pointing jitter to < 1 mas RMS
    - Requires V < 5 stars for best performance
  - Slow loop controls telescope low order drifts (eg: focus)
  - Uses starlight rejected by coronagraph
- JPL High Contrast Imaging Testbed (HCIT) is demonstrating system-level performance
  - Flight-like conditions: pointing jitter, optical & thermal drifts

Xinetics 48 x 48 DM

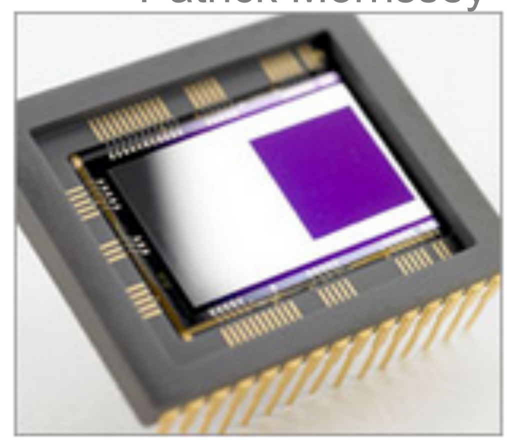


JPL's HCIT: High Contrast Testbed

Electron-Multiplying CCDs count photons



Patrick Morrissey

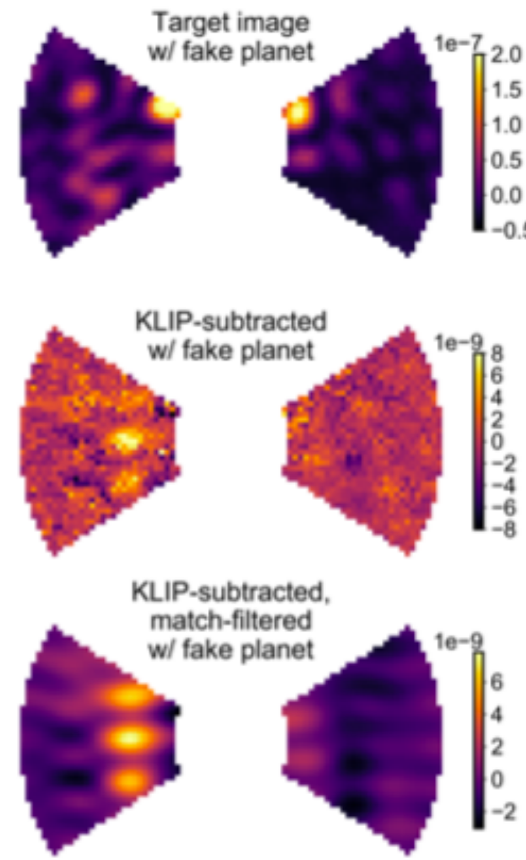


- Jupiter analogs V ~ 27
  - < 1 planet photon per minute
- Teledyne e2v, 1k×1k EMCCD
  - EM => no read noise
- Tech & data processing development
  - mitigation and characterization of charge traps from radiation damage
  - Mitigation of cosmic ray effects (overspill)

Advanced integrated modeling and data processing

John Krist
Neil Zimmerman
Tiffany Meshkat

- Realistic end-to-end simulations of telescope + instrument
  - “speckle” field and variability
  - detector systematics
  - Added astrophysical sources
- PSF subtraction
  - Reference & Angular (RDI & ADI)
  - Spectral DI (SDI) may not work; chromatic speckles
  - Additional benefits of photon counting data??

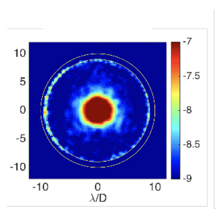


CGI Official Modes

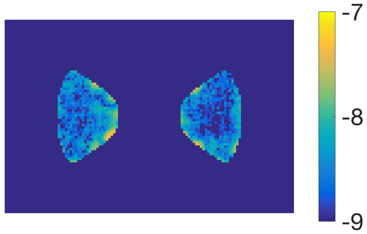
These three "official" modes will be fully commissioned before launch.
ie: the flight hardware will by fully tested with flight software prior to launch.

CGI Filter	λ_{center} (nm)	BW	Channel	Mask Type	Working Angle	FOV radius	Can use w/ linear polarizers	Starlight Suppression Region
1	575	10%	Imager	HLC	3-9 λ/D	0.14" – 0.45"	Y	360°
3	730	15%	IFS	SPC bowtie	3-9 λ/D	0.18" – 0.55"		130°
4	825	10%	Imager	SPC wide FOV	6.5-20 λ/D	0.45" – 1.4"	Y	360°

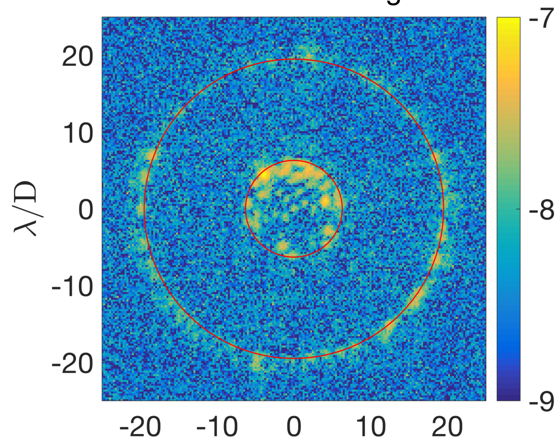
Imaging w/ Narrow FoV
HCIT Lab Image



Spectroscopy
HCIT Lab Image



Imaging w/ Wide FoV
HCIT Lab Image



22

CGI Installed Coronagraphs

CGI Filter	λ_{center} (nm)	BW	Mask Type	Working Angle	Starlight Suppression Region
1	**575**	**10%**	**HLC**	**3-9 λ/D**	**360°**
2	660	15%	SPC bowtie	3-9 λ/D	130°
2	656	1%	SPC bowtie	3-9 λ/D	130°
3	**730**	**15%**	**SPC bowtie**	**3-9 λ/D**	**130°**
4	**825**	**10%**	**SPC wide FOV**	**6.5-20 λ/D**	**360°**
4	825	10%	HLC	3-9 λ/D	360°

These five masks will be installed in CGI. However, only those listed in the “official modes table” correspond to CGI requirements and will be officially supported for the tech demo phase.
Only 1 orientation of each SPC bowtie is baselined.

* Bands submitted to CCB for change, not yet accepted.

λ_1 = 575 nm, 10% ***λ_2 = 660 nm, 15%** ***λ_3 = 730 nm, 15%** **λ_4 = 825 nm, 10%**

Mission Timeline

You can get involved : Participating Scientist Program

Instrument commissioning, observation planning, data processing,…
Proposal call expected in 2021.

Launch 2025

(Stage 1) Tech demo phase: 3 months observing in first 1.5 years

If meet success criteria…

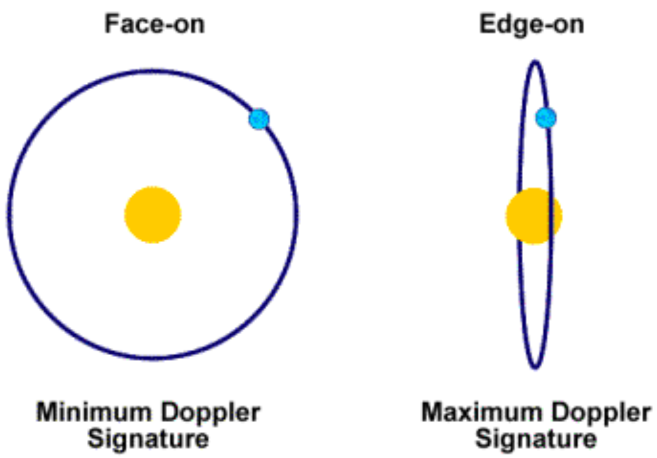
(Stage 2) Augment PSP for science observations for years 1.5 - 2.5.
(Stage 3) Augment PSP and/or open to GO time for remainder of mission

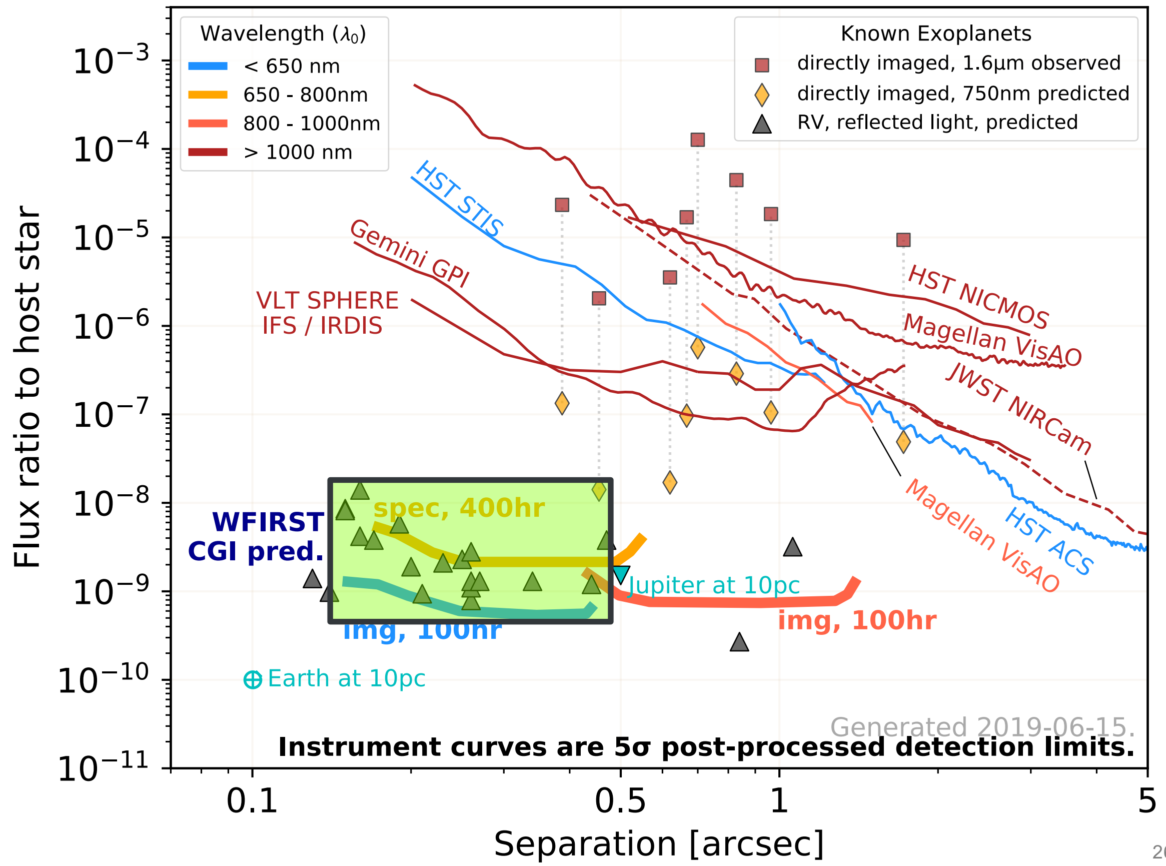
Still on a TD budget…No promise of robust pipeline or substantial user support

“Tech Demo” Phase

3 months observing
in first 1.5 years of mission

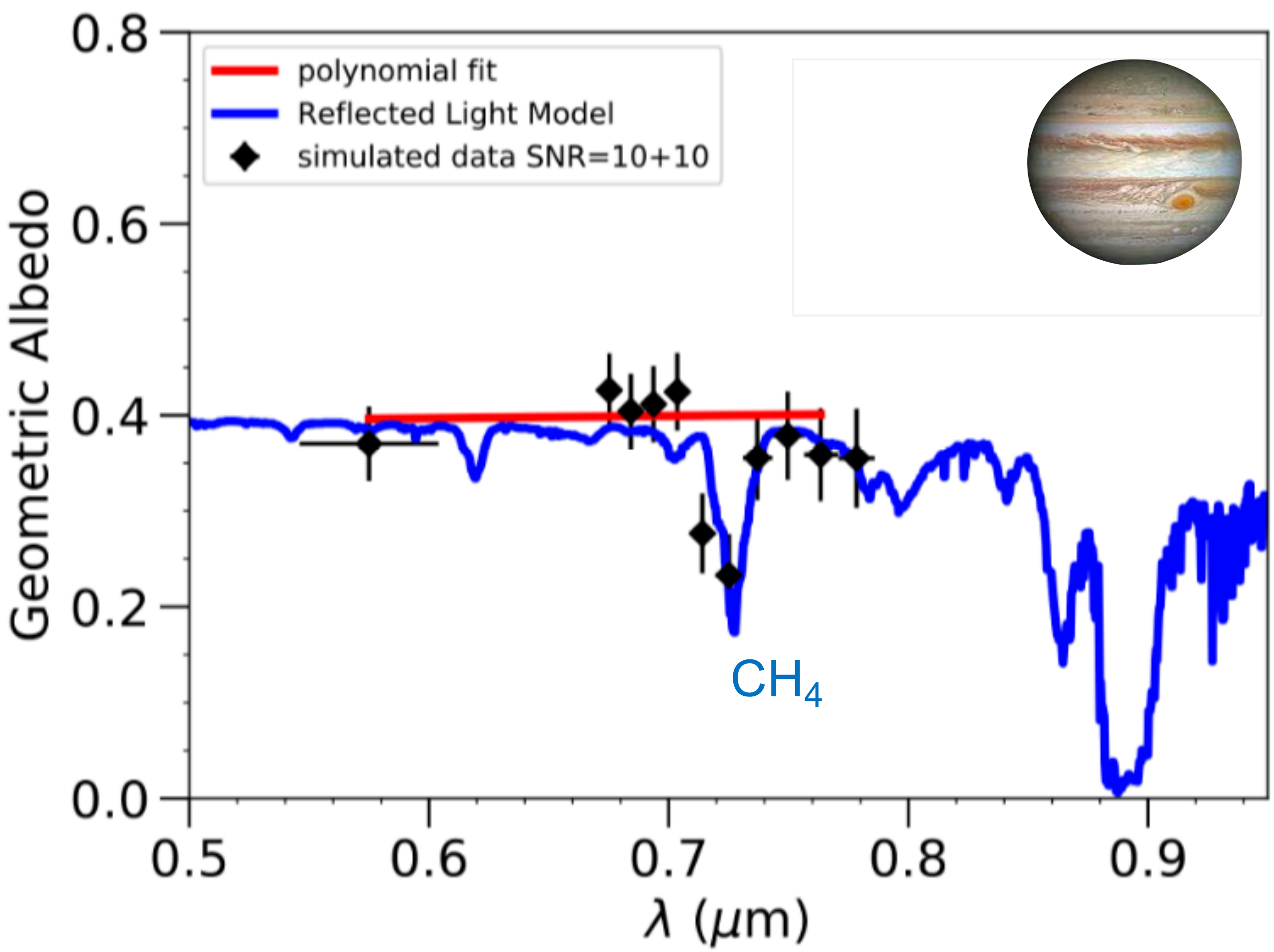
Break vsin(i) mass degeneracy for RV planets with reflected light imaging





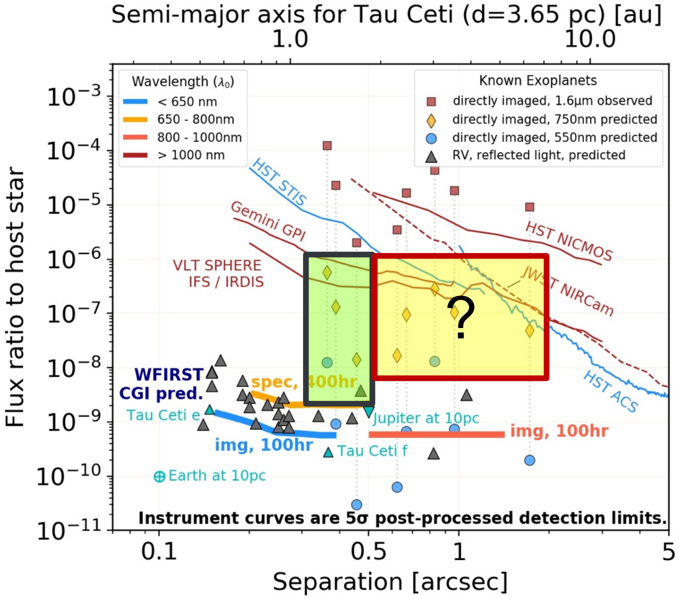
Eric Nielsen
Stephen Kane

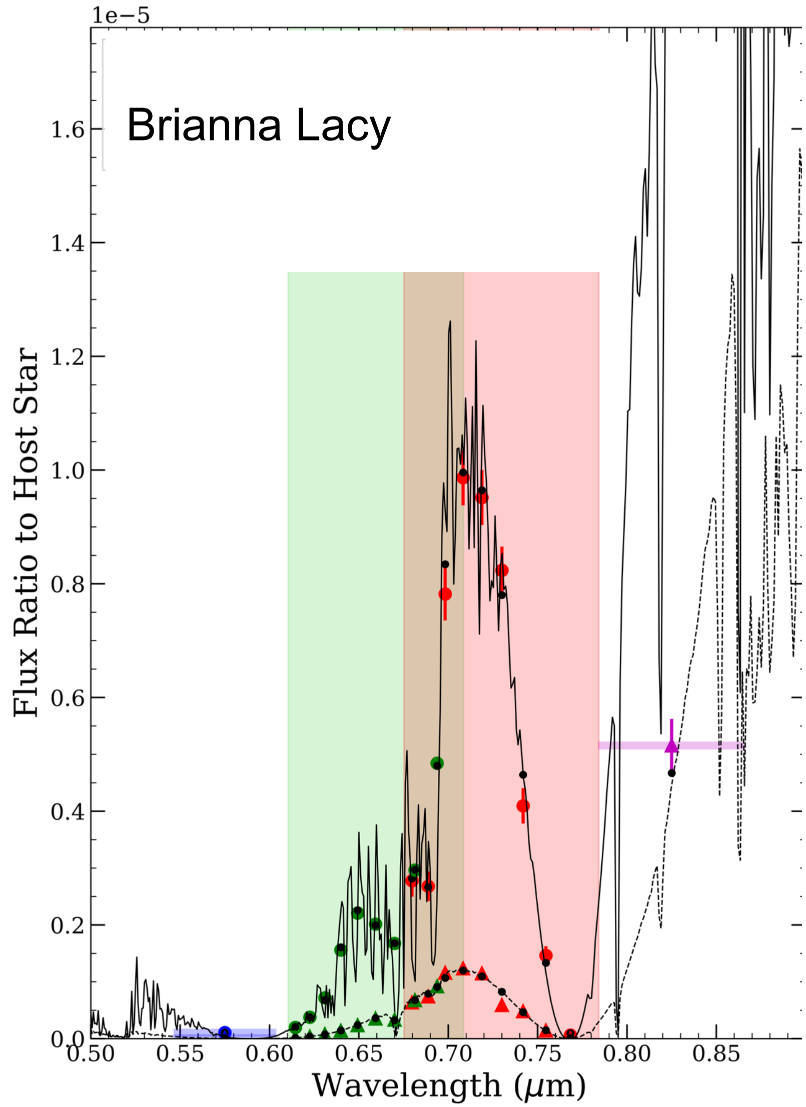
First reflected light images & spectrum of a mature Jupiter analog



Roxana Lupu
Mark Marley
Nikole Lewis

young self-luminous planets: complement NIR ground-based data to probe metallicity & clouds





PSP Phase

Stretch Goals

Potential PSP science case: Catching planets in the act of formation (Hα)

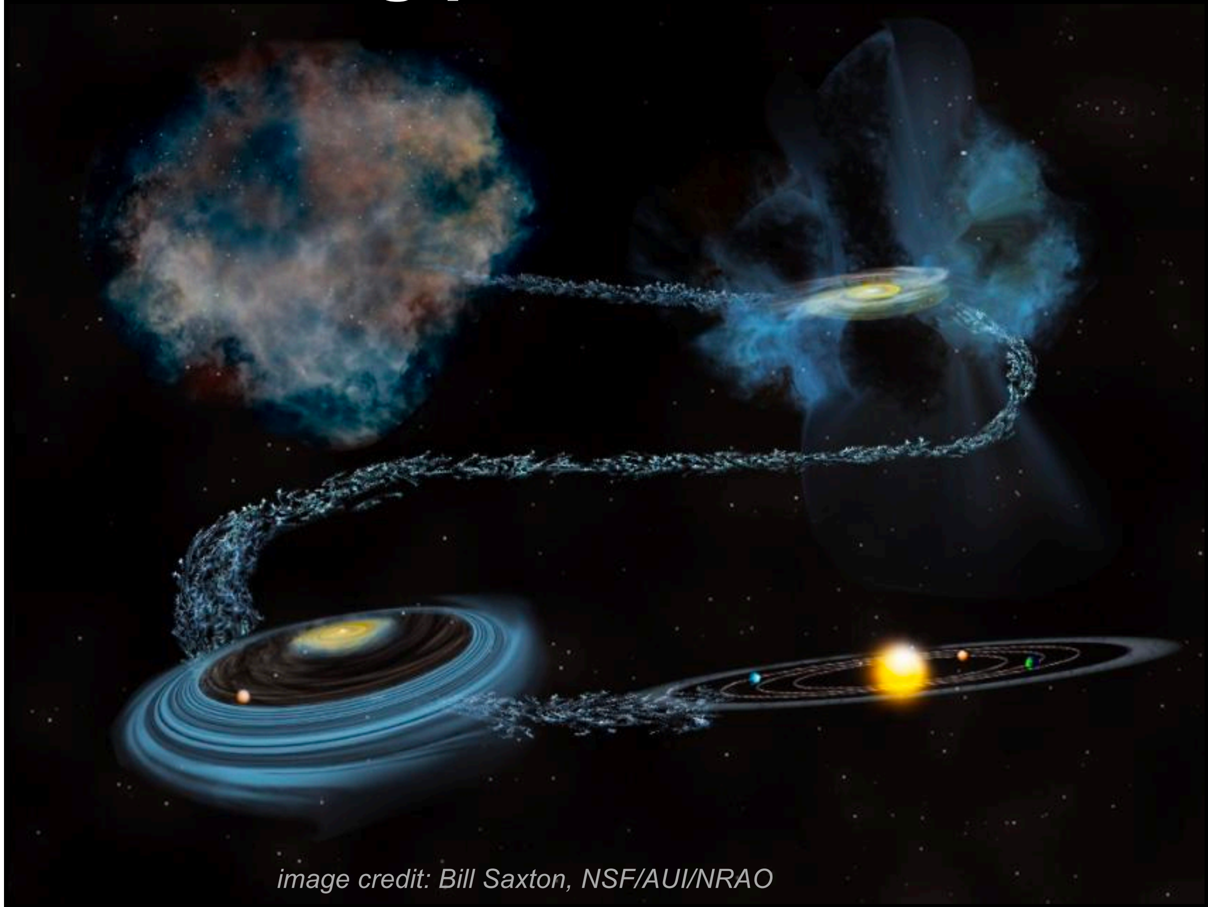
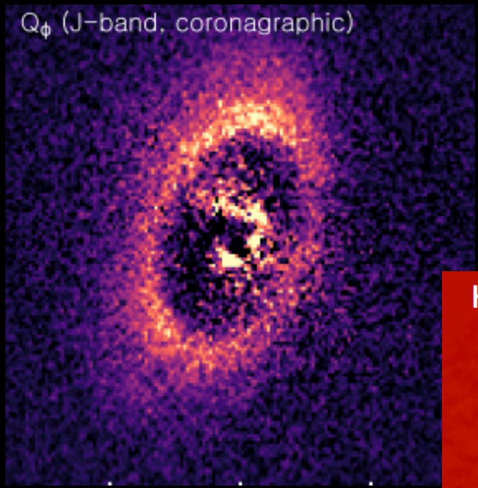
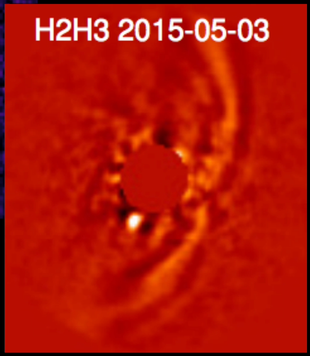
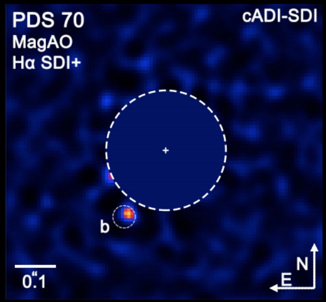


image credit: Bill Saxton, NSF/AUI/NRAO





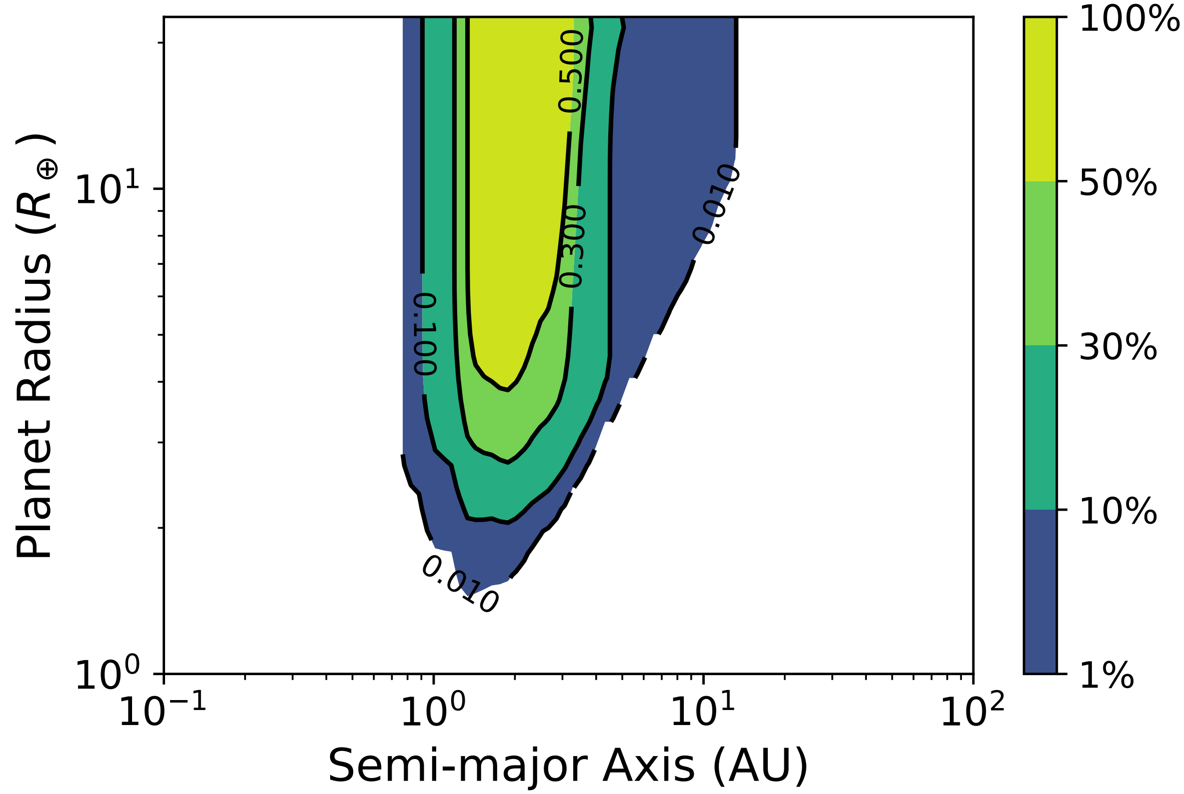


Keppler+2018; Wagner+2018

Potential PSP science case: blind search for small planets in nearby systems

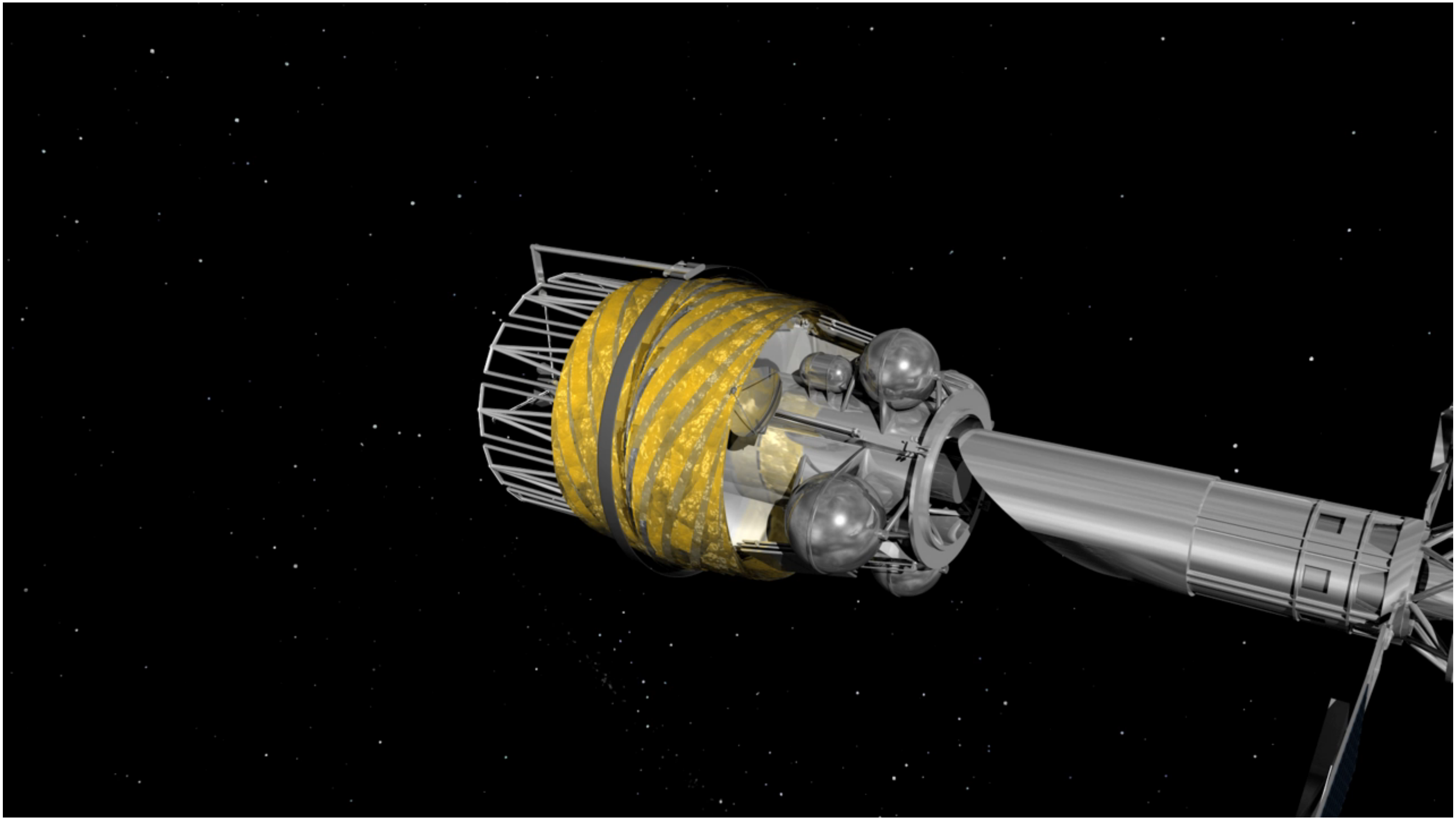
Average completeness for 10 best stars:

- ~50% for gas giants
- 10% - 30% for super-Earths & mini-Neptunes

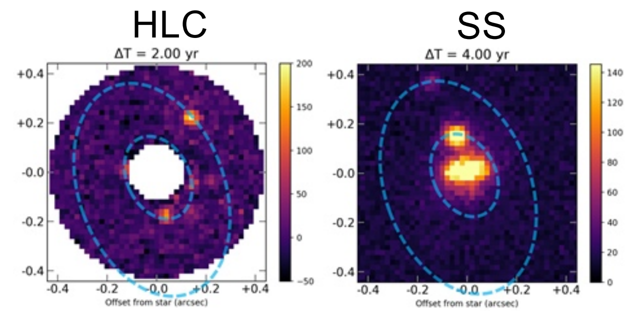


Potential Starshade Rendezvous with WFIRST

Credit Joby Harris, NASA JPL



2019 CGI Data Challenge



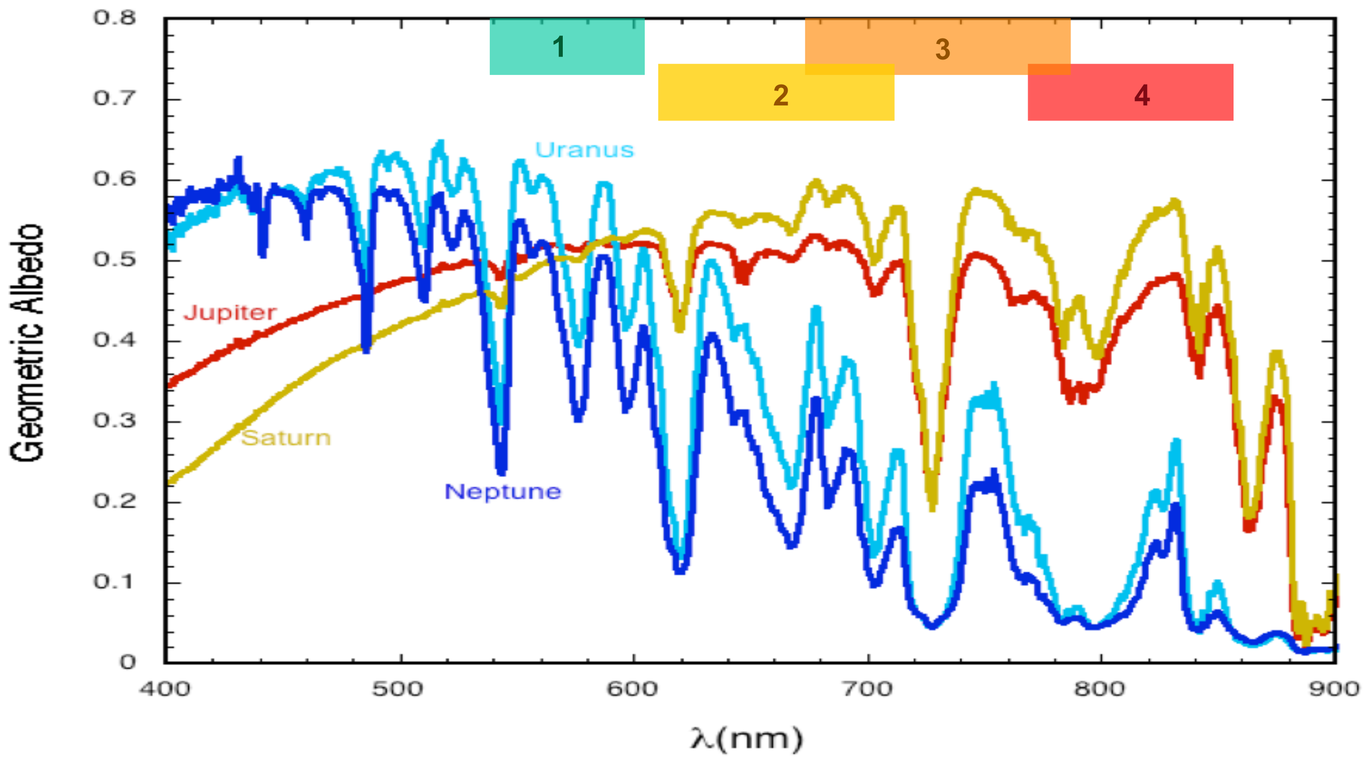
- **Talk Today** at 1:50pm by **Julien Girard**
- **Led by Turnbull SIT** with STScI and IPAC
  - Hackathon #2 @IPAC June 24-25 (next week)
  - Kick Off of DC on October 20th 2019
  - Dead line: December 20th 2019 (2 month)
  - OS6 simulations/strategy
  - > 1 injected planet(s), includes exozodiacal light, extragalactic background
  - 4 HLC and 2 Star Shade epochs, astrometry and photometry oriented, involves radial velocity (simulated) data that matches imaging epochs.
- **Goals:** broaden and deepen our knowledge (simulations, analysis tools, etc.), get the community acquainted with the CGI data, contrast regime and astrophysics that will be enabled: reflected light giant planets in this case.
- Information: www.exoplanetdatachallenge.com

Summary

- **CGI is a technology demonstrator**
  - first “active” coronagraph in space
  - Important pathfinder for future missions to study exo-Earths
- **CGI is capable of interesting exoplanet science**
  - Imaging & spectroscopy of young & mature planets
- **Get involved**
  - CGI data challenges
  - Participating Scientist Program call in 2021

BACKUP

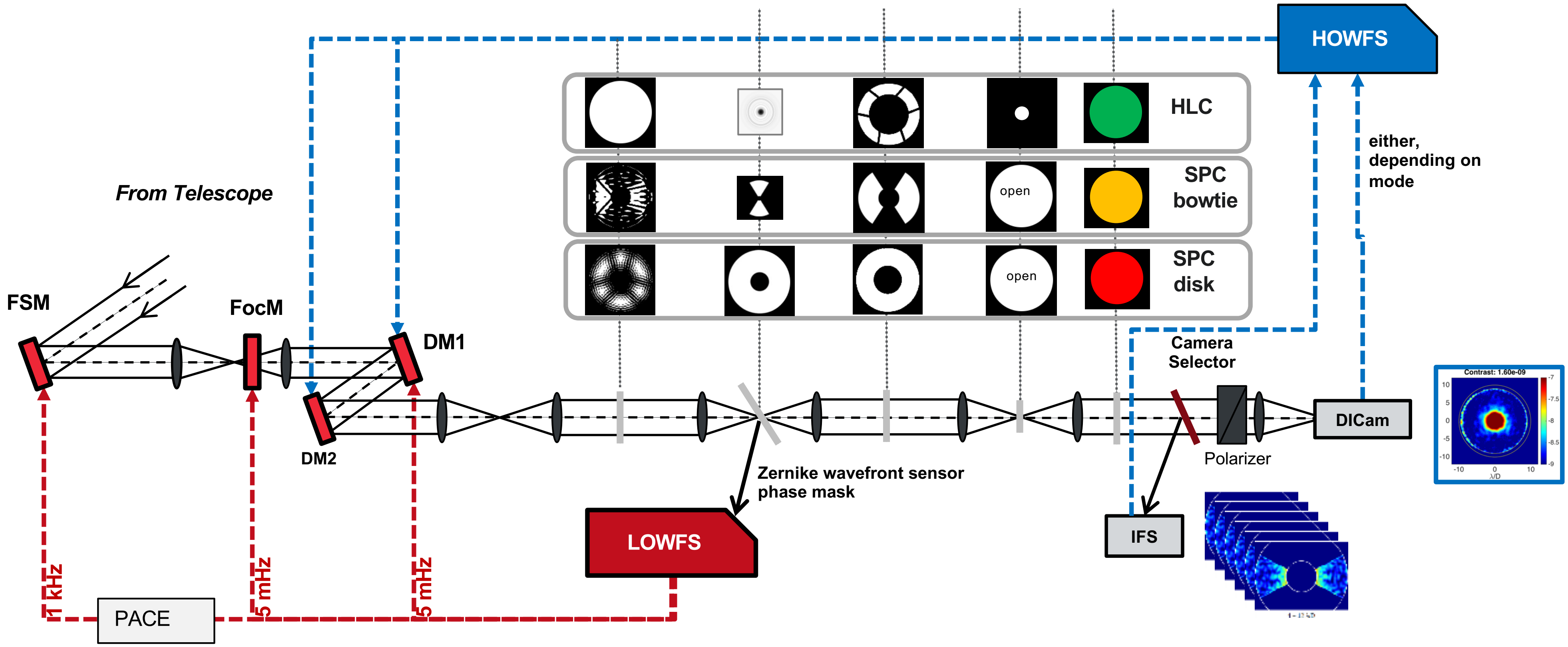
Observing Filters



λ_1 = 575 nm, 10%   *λ_2 = 660 nm, 15%   *λ_3 = 730 nm, 15% λ_4 = 825 nm, 10%

*Band submitted to CCB, not yet

CGI Architecture



- Two selectable coronagraph technologies (HLC, SPC)
- Two deformable mirrors (DMs) for high-order wavefront control
- Low-order wavefront sensing & control (LOWFS&C)
- Direct imaging camera (DICam)
- Integral field spectrograph (IFS, R = 50)
- Photon-counting EMCCD detectors

National Academy of Science: Exoplanet Science Strategy, Sept 2018

WFIRST Will Provide Critical Exoplanet Data and Pave the Way for a Direct-Imaging Mission

FINDING: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.

FINDING: A number of activities, including precursor and concurrent observations using ground- and space-based facilities, would optimize the scientific yield of the WFIRST microlensing survey.

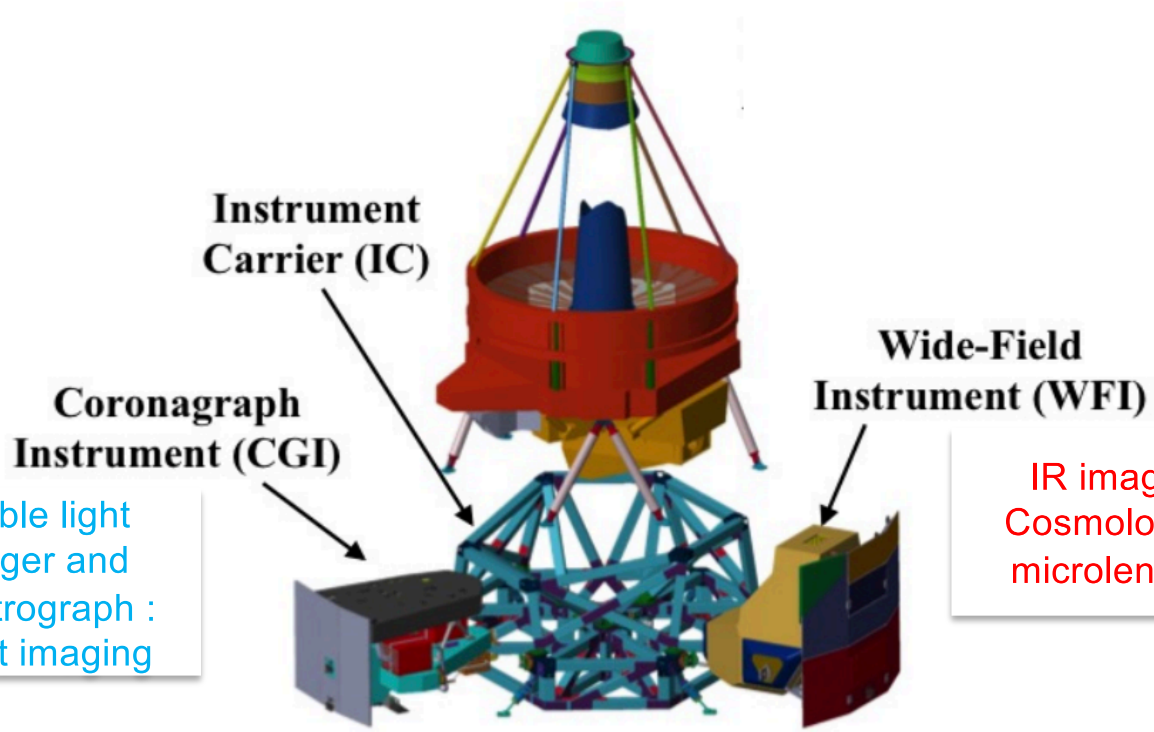
FINDING: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will allow testing of newly developed algorithms and methods.

FINDING: The WFIRST-Coronagraph Instrument (CGI) at current capabilities will carry out important measurements of extrasolar zodiacal dust around nearby stars at greater sensitivity than any other current or near-term facility.

RECOMMENDATION: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

The National Academies of SCIENCES ENGINEERING MEDICINE

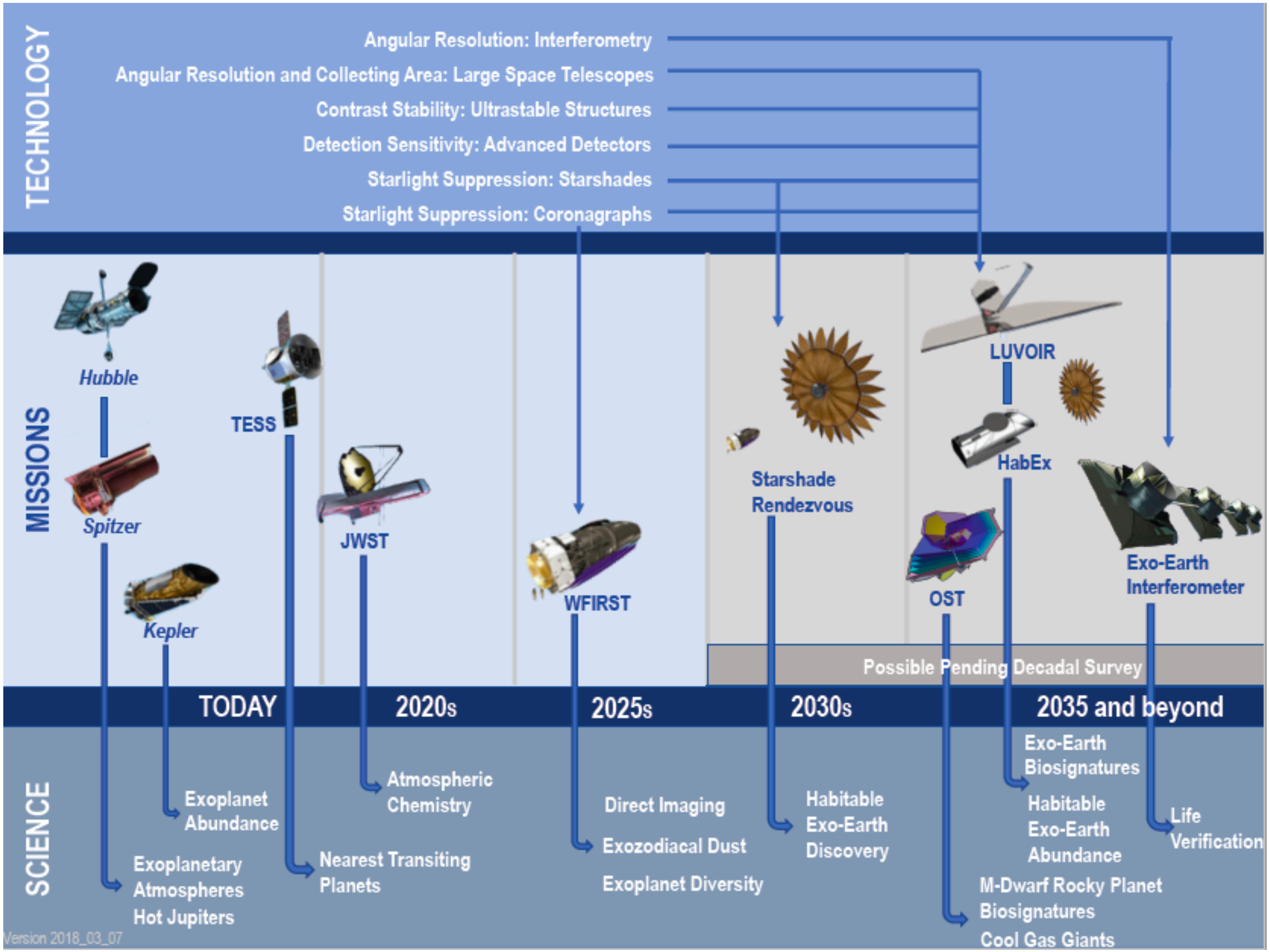
CGI

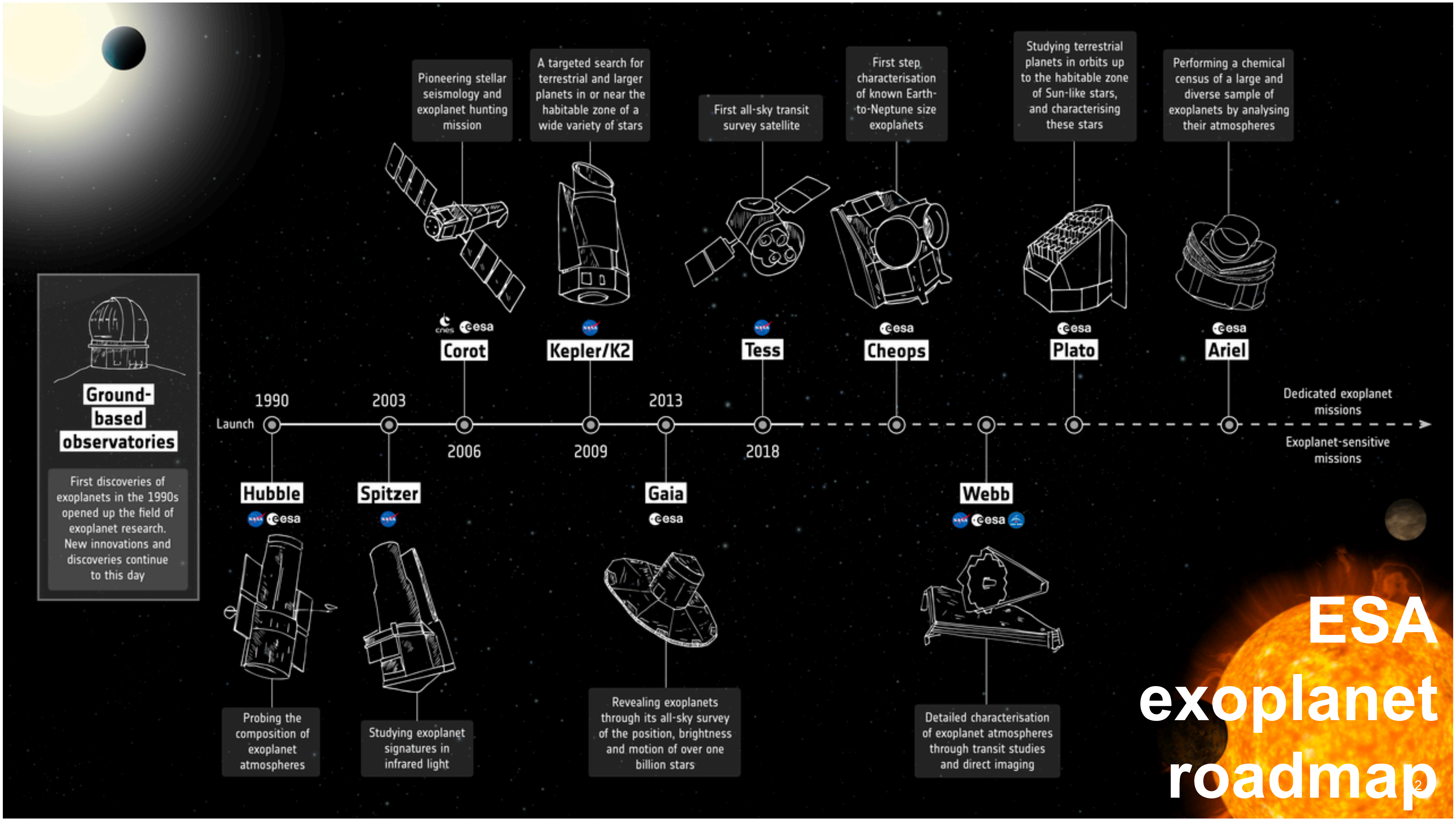


Visible light imager and spectrograph : direct imaging

IR imager: Cosmology & microlensing

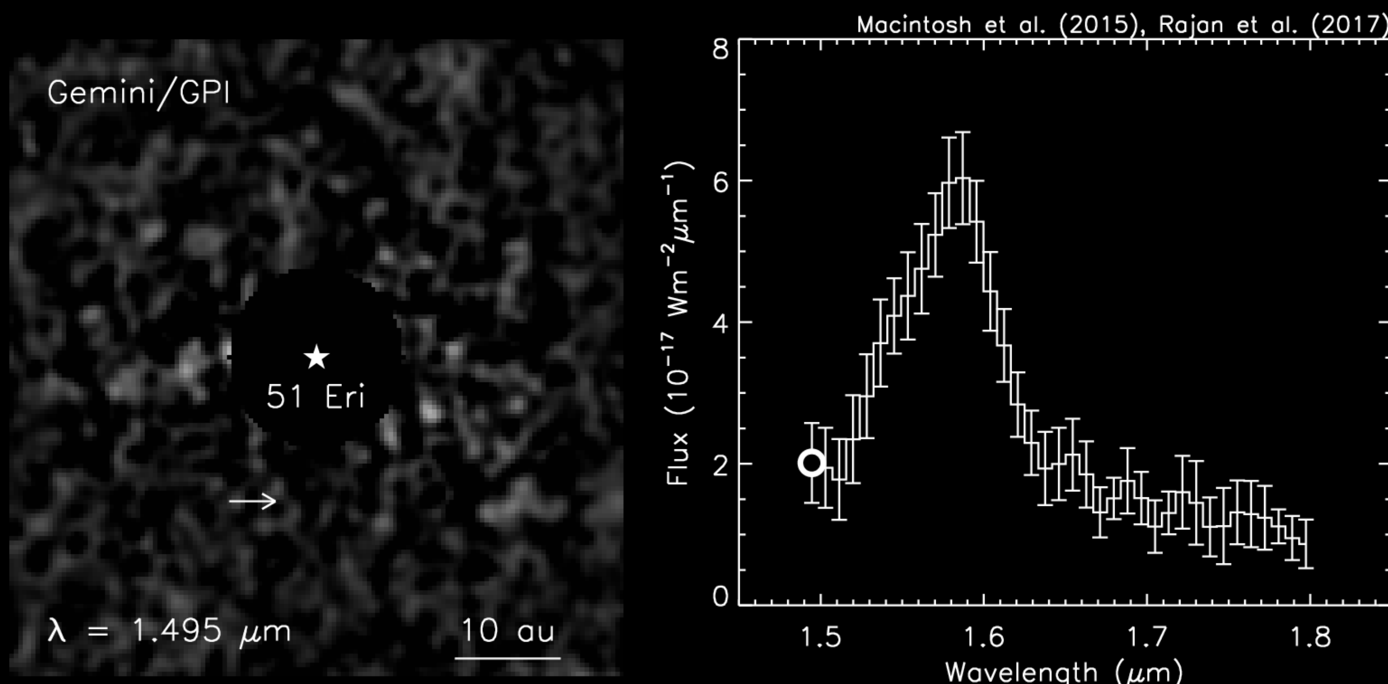
Expanded view of the WFIRST payload


TECHNOLOGY
Angular Resolution: Interferometry
Angular Resolution and Collecting Area: Large Space Telescopes
Contrast Stability: Ultrastable Structures
Detection Sensitivity: Advanced Detectors
Starlight Suppression: Starshades
Starlight Suppression: Coronagraphs
MISSIONS
Hubble
TESS
Spitzer
JWST
Kepler
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanet Abundance
Atmospheric Chemistry
Exoplanetary Atmospheres Hot Jupiters
Nearest Transiting Planets
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
Exo-Earth Biosignatures
Habitable Exo-Earth Abundance
Life Verification
M-Dwarf Rocky Planet Biosignatures
Cool Gas Giants
Version 2018_03_07



Ground-based observatories
First discoveries of exoplanets in the 1990s opened up the field of exoplanet research. New innovations and discoveries continue to this day
Pioneering stellar seismology and exoplanet hunting mission
A targeted search for terrestrial and larger planets in or near the habitable zone of a wide variety of stars
First all-sky transit survey satellite
First step characterisation of known Earth-to-Neptune size exoplanets
Studying terrestrial planets in orbits up to the habitable zone of Sun-like stars, and characterising these stars
Performing a chemical census of a large and diverse sample of exoplanets by analysing their atmospheres
cnes esa
Corot
Kepler/K2
Tess
esa
Cheops
esa
Plato
esa
Ariel
Launch
1990
2003
2006
2009
2013
2018
Dedicated exoplanet missions
Exoplanet-sensitive missions
Hubble
esa
Spitzer
Gaia
esa
Webb
esa
Probing the composition of exoplanet atmospheres
Studying exoplanet signatures in infrared light
Revealing exoplanets through its all-sky survey of the position, brightness and motion of over one billion stars
Detailed characterisation of exoplanet atmospheres through transit studies and direct imaging
ESA exoplanet roadmap

Spectra show molecular absorption signatures



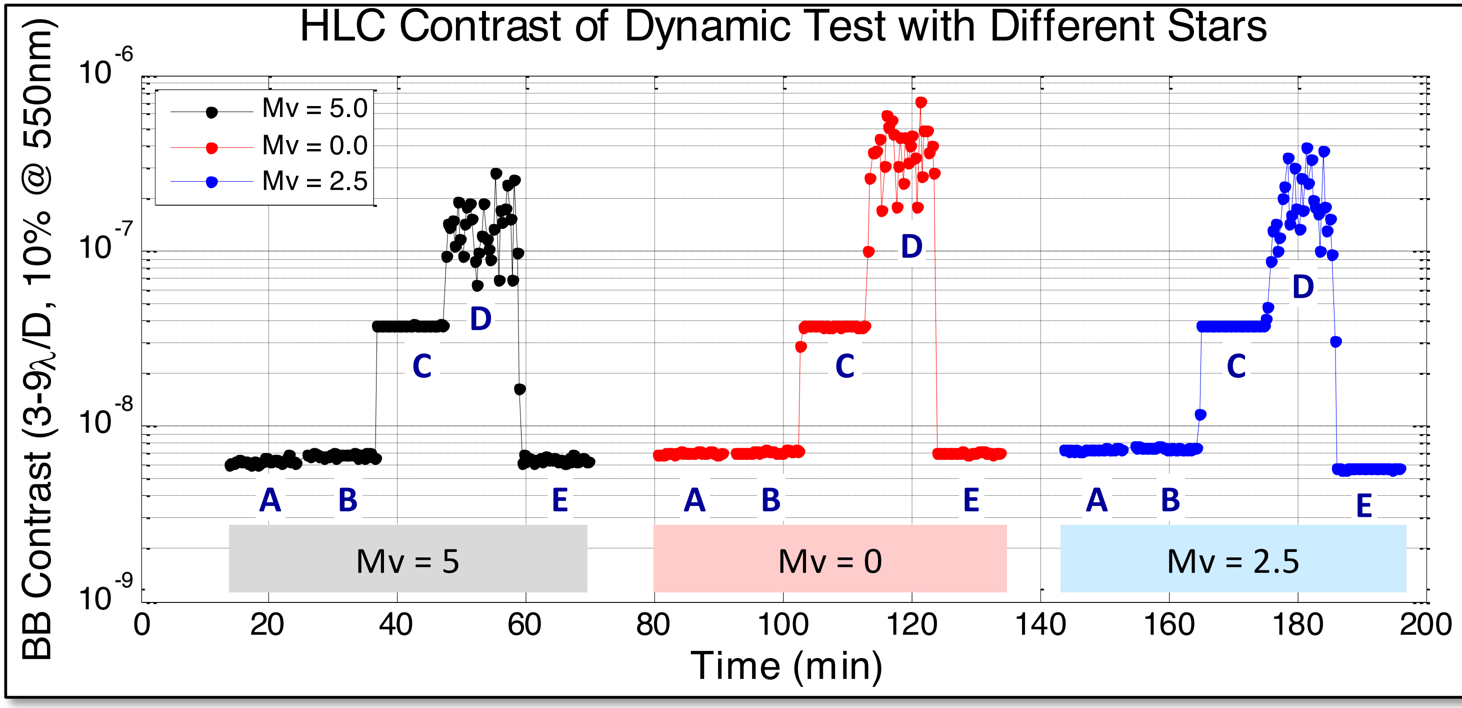
Credit: Rob De Rosa / GPIES

Starshade Filter List

	λ (nm)	BW	Δλ	λ_{min} (nm)	λ_{max} (nm)	mode
Starshade Science Bands	488.5	26.0%	127	425	552	img
	707.5	26.1%	185	615	800	img
	728	19.8%	144	656	800	IFS
	862.5	26.1%	225	750	975	img
	887	19.8%	176	799	975	IFS

Last modified: March 8, 2019

LOWFS/C LoS Dynamic Test with Different Stellar Magnitudes



BB-Broad Band

FB- FeedBack (control drift)

FF- Feed Forward (control jitter, esp. from reaction wheel)

JM- Jitter Mirror

Sequences with each stellar magnitude (Mv = 5.0, Mv = 0.0, Mv = 2.5):

A. FB (drift) on & FF (jitter) on with lab environment
B. FB on & FF on with induced dynamics (ACS + RWA jitter at 600rpm)
C. FB on & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)
D. FB off & FF off with JM induced dynamics (ACS + RWA jitter at 600rpm)
E. FB on & FF on with lab environment (same as A)