Jet Propulsion Laboratory
California Institute of Technology

WFIRST Coronagraph Instrument: Technology overview & exoplanet science

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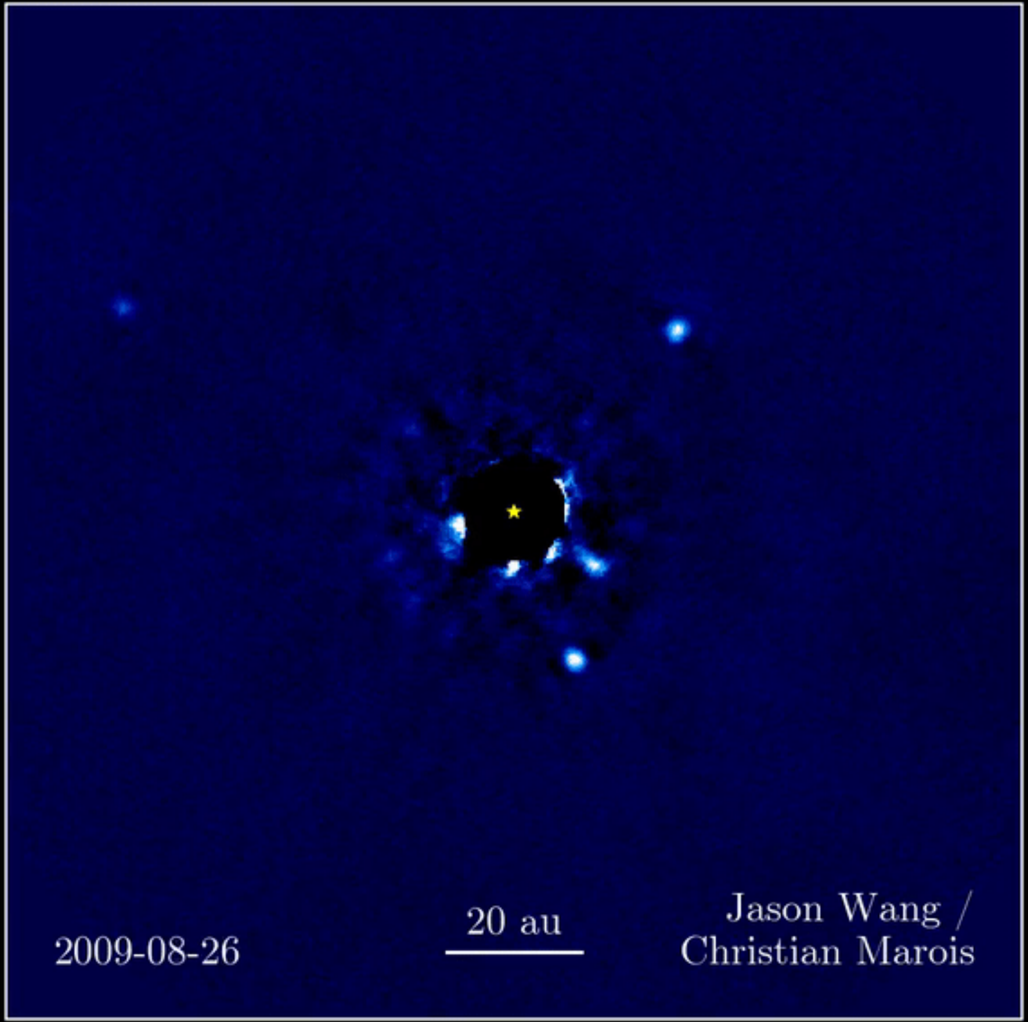
On behalf of CGI Project Science and Science Investigation Teams

June 20, 2019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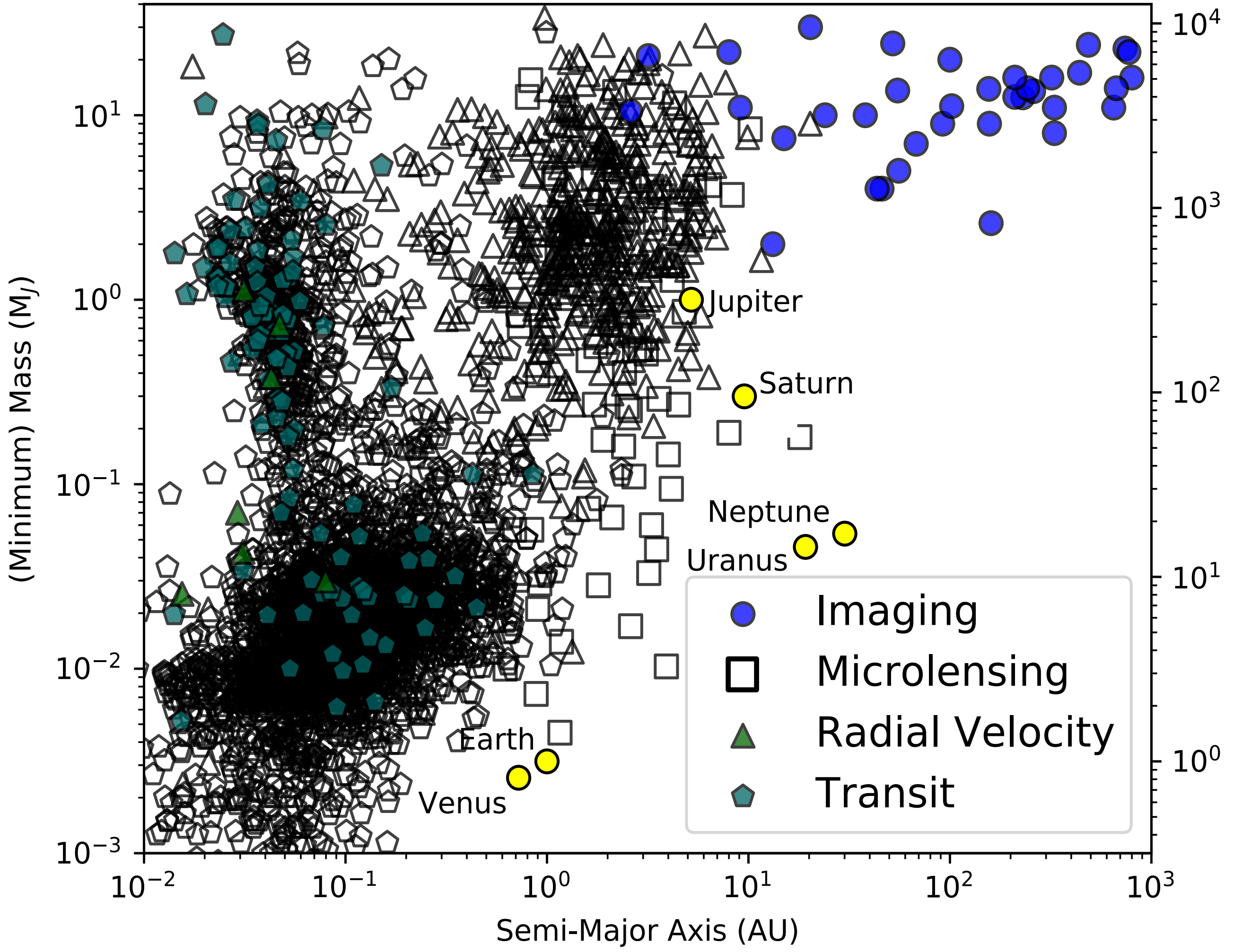
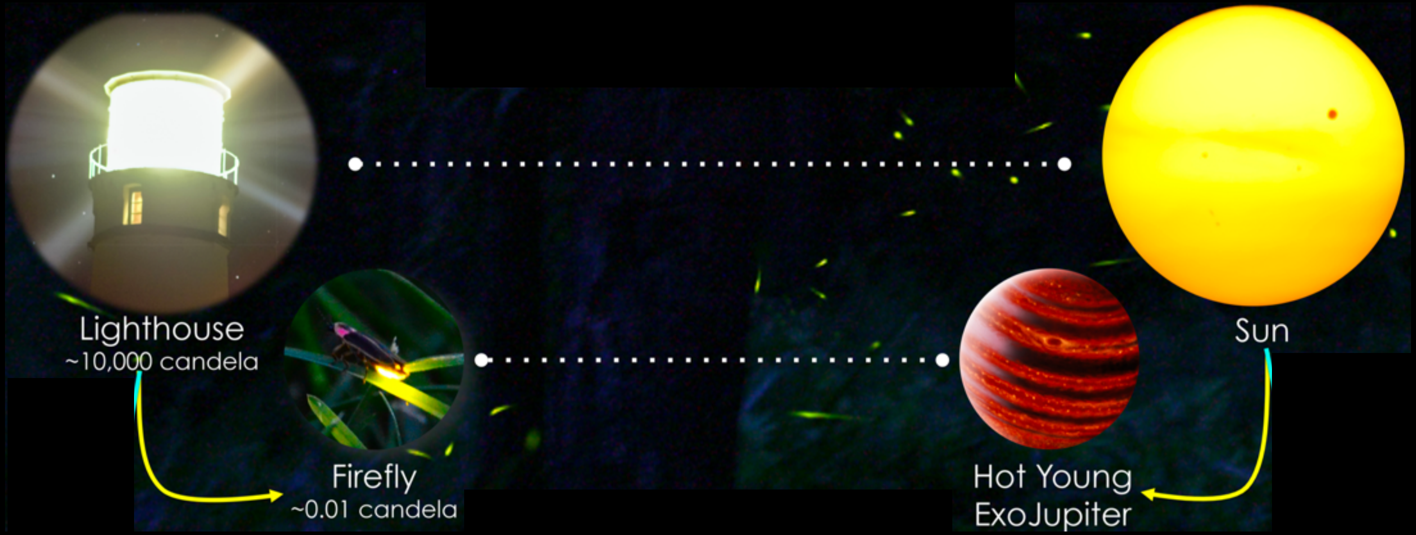
Jason Wang /
Christian Marois



Only a small fraction of known exoplanets have been characterized

"Bright" young super-Jupiters

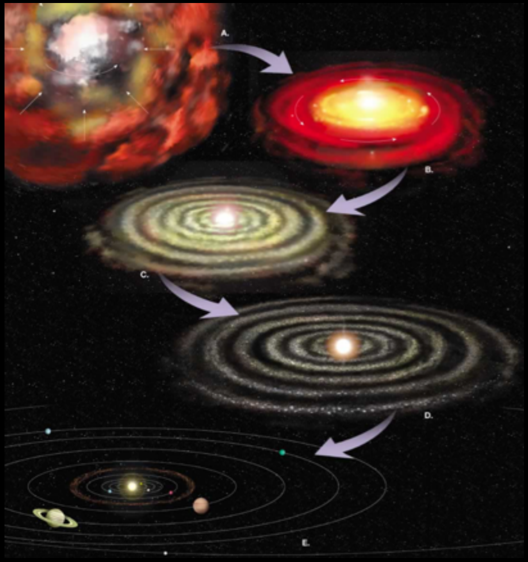
10^6 times fainter than their stars in **NIR**

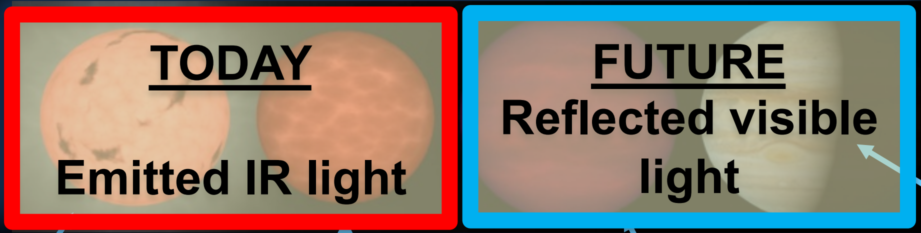


credits: Kate Follette; NASA/IPAC

Adaptive Optics
“de-twinkle” the stars

Young planets are hot and glowing, but cool with time





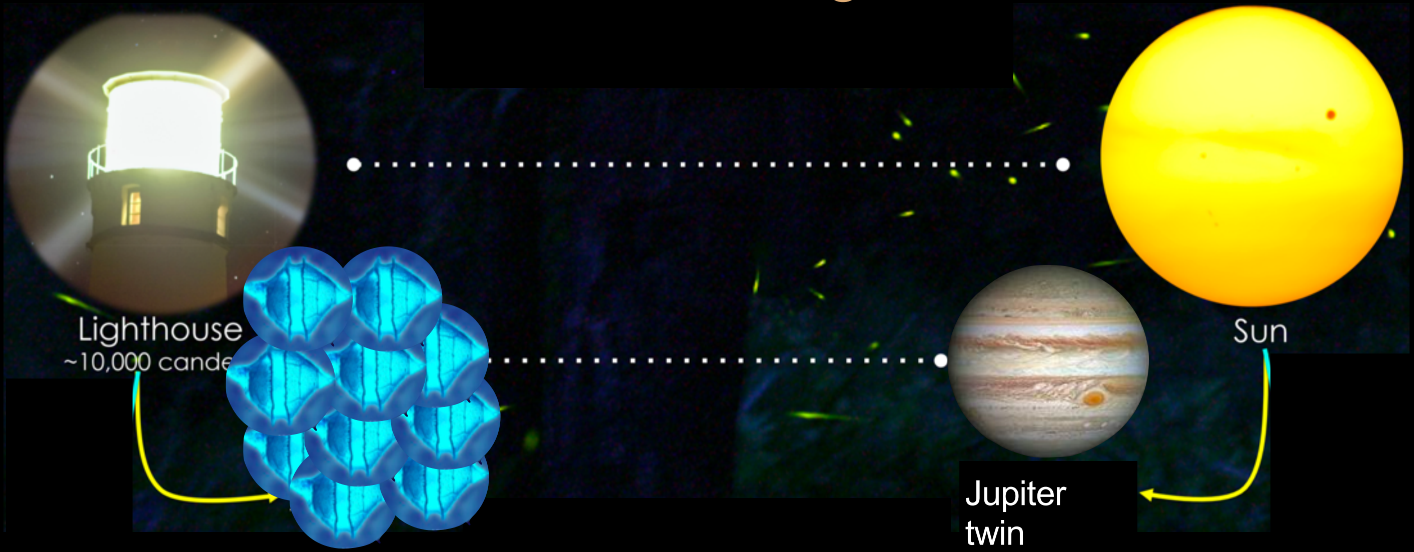
New planet:
1000-3000K

10 million years:
600K

100 million years:
300K

4600 million years:
110K

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



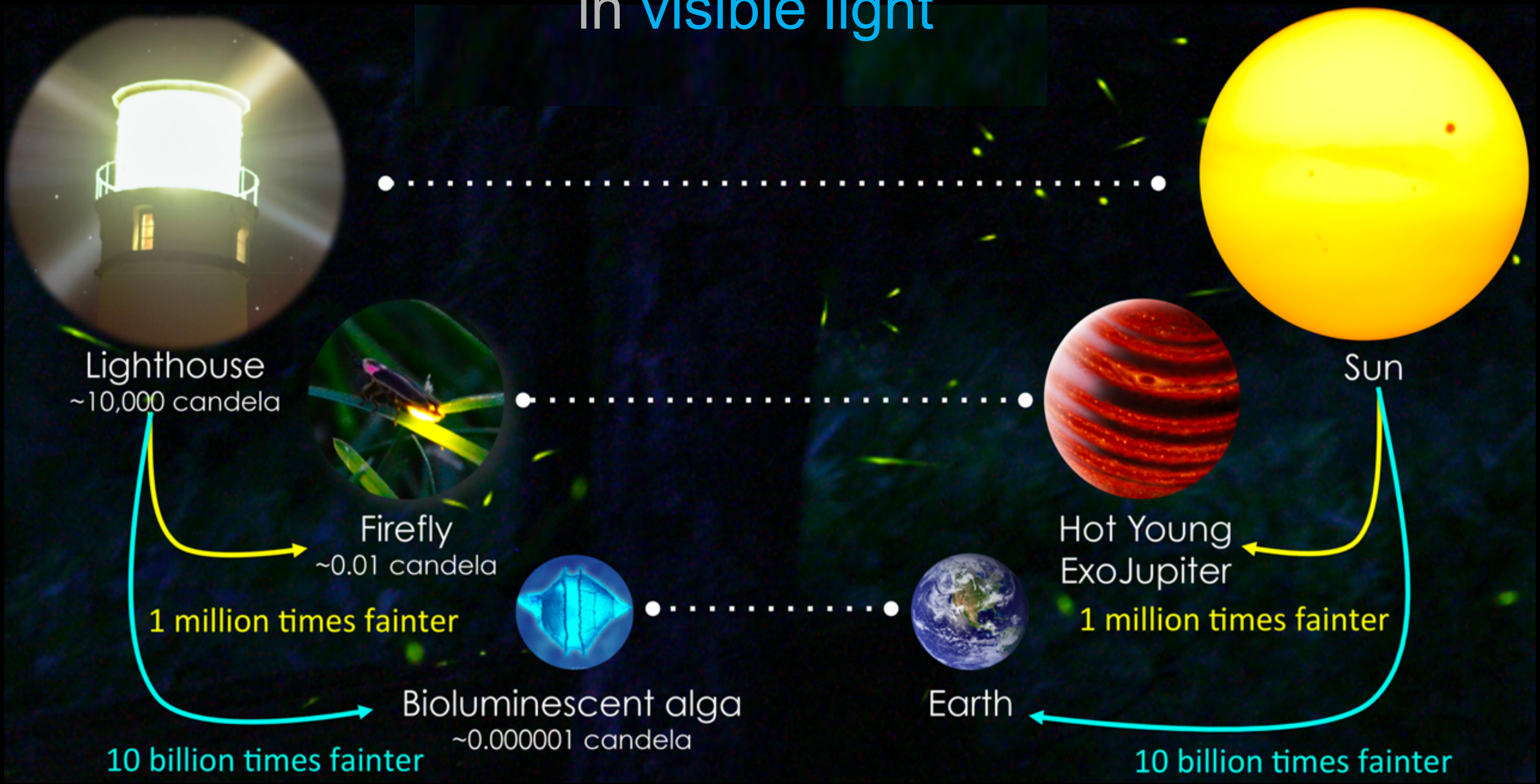
We can't remove atmosphere turbulence well enough to do this from the ground

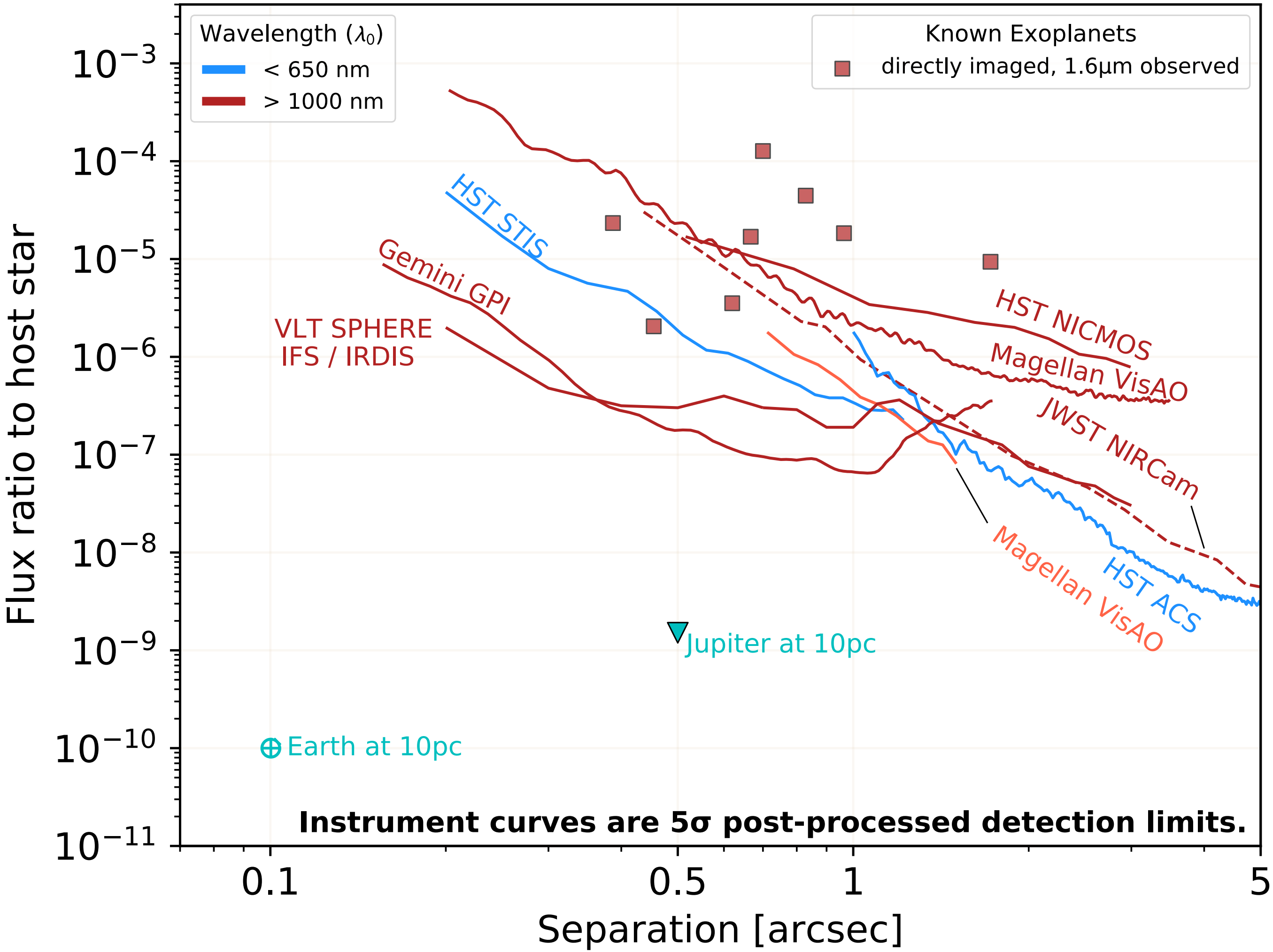
credit: Kate Follette; with modifications

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
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
Magellan VisAO
JWST NIRCam
Magellan VisAO
HST ACS
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.1
0.5
1
5
Separation [arcsec]

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

WFIRST CGI

Wide Field Infrared Survey Telescope

Coronagraph Instrument

Visible light imager/polarimeter & spectrograph

~ 550 – 860nm

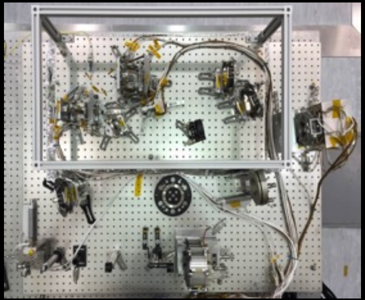
10^9 contrast

Coronagraph video

https://exoplanets.nasa.gov/exep/coronagraphvideo/

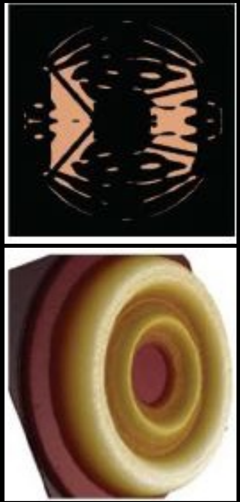
CGI will demonstrate key technologies for future missions

Autonomous Ultra-Precise Wavefront Sensing & Control

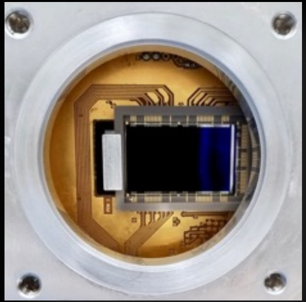


Large-format Deformable Mirrors

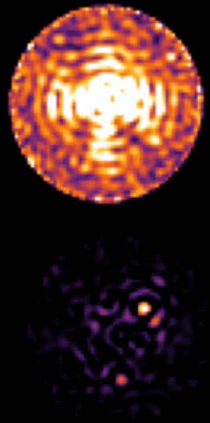
High-contrast Coronagraph Masks



Ultra-low noise photon counting visible detectors



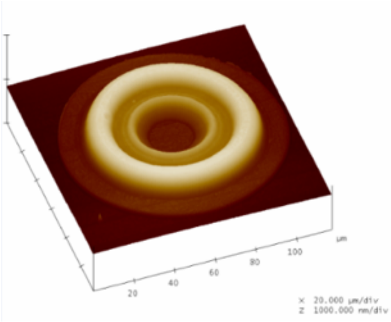
Data Post-Processing



CGI is a "technology demonstration" instrument

Advanced coronagraphs suppress starlight by a factor of 100 million

Mask images taken with atomic force microscopes



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

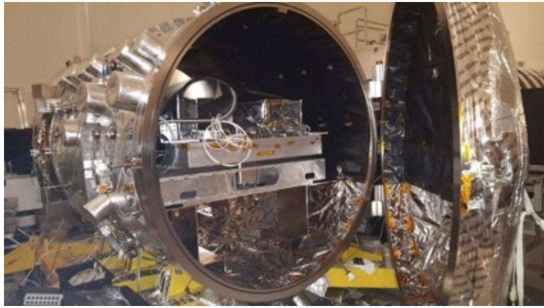
Wavefront sensing and control

Xinetics
48 x 48 DM

- Deformable mirrors correct optical errors
  - **Both** phase and amplitude errors
  - < 1 Angstrom 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

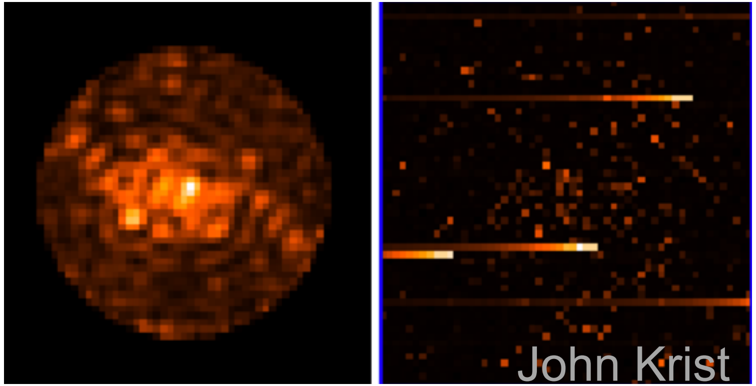
- JPL High Contrast Imaging Testbed (HCIT) is demonstrating system-level performance
  - Flight-like conditions: pointing jitter, optical & thermal drifts



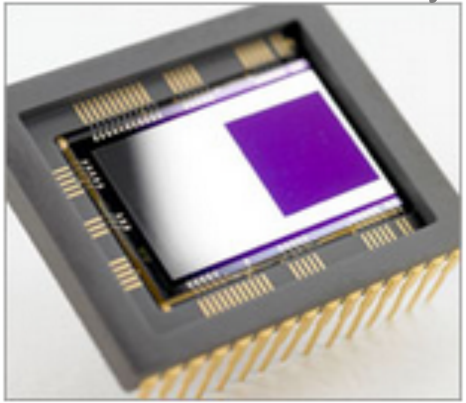
JPL's HCIT: High Contrast Testbed

Electron-Multiplying CCDs count photons

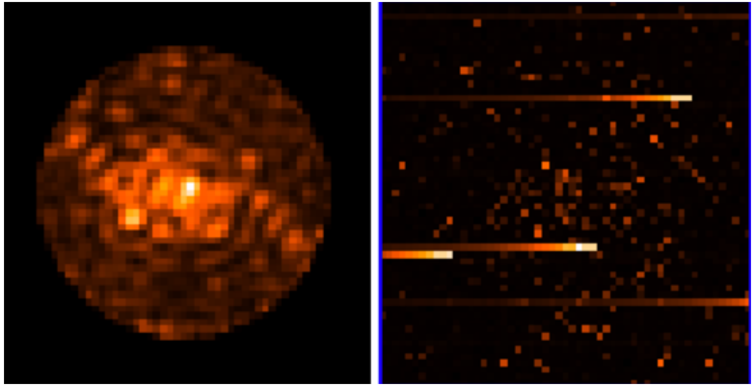
- Jupiter analogs V ~ 27
  - < 1 planet photon per minute
- Teledyne e2v, 1k×1k EMCCD
  - EM => no read noise
- Tech & data processing development
  - mitigation and characterization of charge traps from radiation damage
  - Mitigation of cosmic ray effects (overspill)



Patrick Morrissey



Advanced integrated modeling and data processing



- Realistic end-to-end simulations of telescope + instrument
  - “speckle” field and variability
  - detector systematics
  - Added astrophysical sources

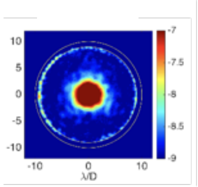
- PSF subtraction
  - Reference & Angular (RDI & ADI)
  - Spectral DI (SDI) may not work; speckle chromaticity
  - Additional benefits of photon counting data??

CGI Official Modes

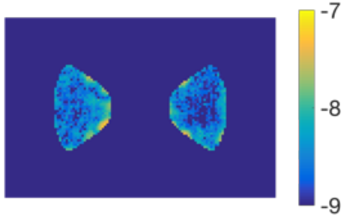
These three "official" modes will be fully commissioned before launch.
ie: the flight hardware will by fully tested with flight software prior to launch.

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

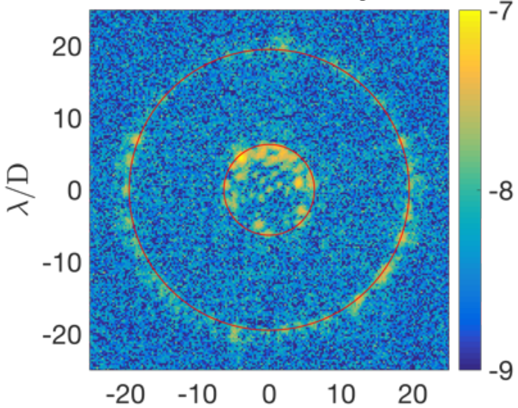
Imaging w/ Narrow FoV
HCIT Lab Image



Spectroscopy
HCIT Lab Image



Imaging w/ Wide FoV
HCIT Lab Image



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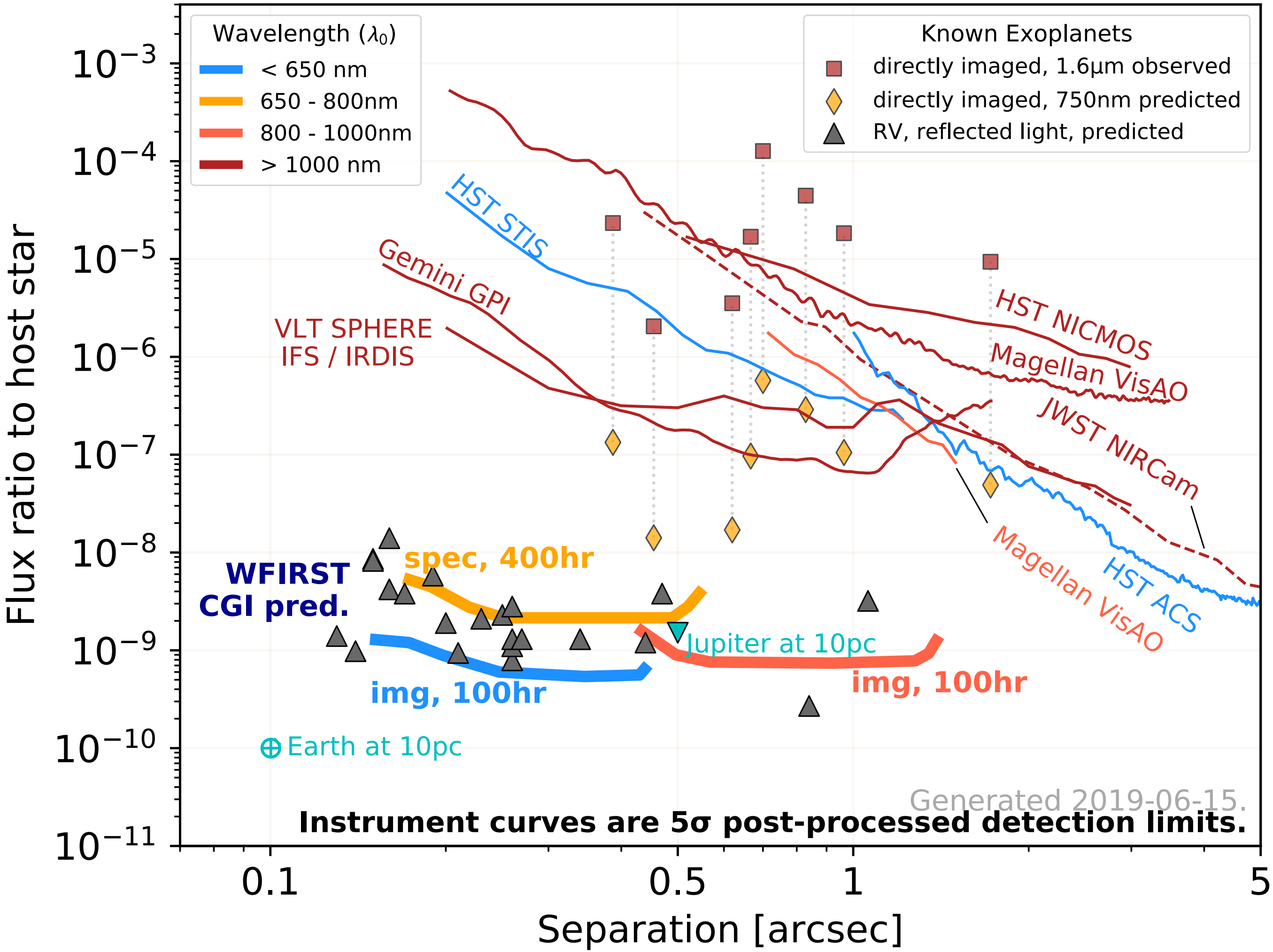
CGI Installed Coronagraphs

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°
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%**


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
Gemini GPI
VLT SPHERE
IFS / IRDIS
HST NICMOS
Magellan VisAO
JWST NIRCam
Magellan VisAO
HST ACS
WFIRST
CGI pred.
spec, 400hr
img, 100hr
Jupiter at 10pc
img, 100hr
Earth at 10pc
Generated 2019-06-15.
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

Study complete planetary systems
+ Catching planets in the act of formation (Hα)

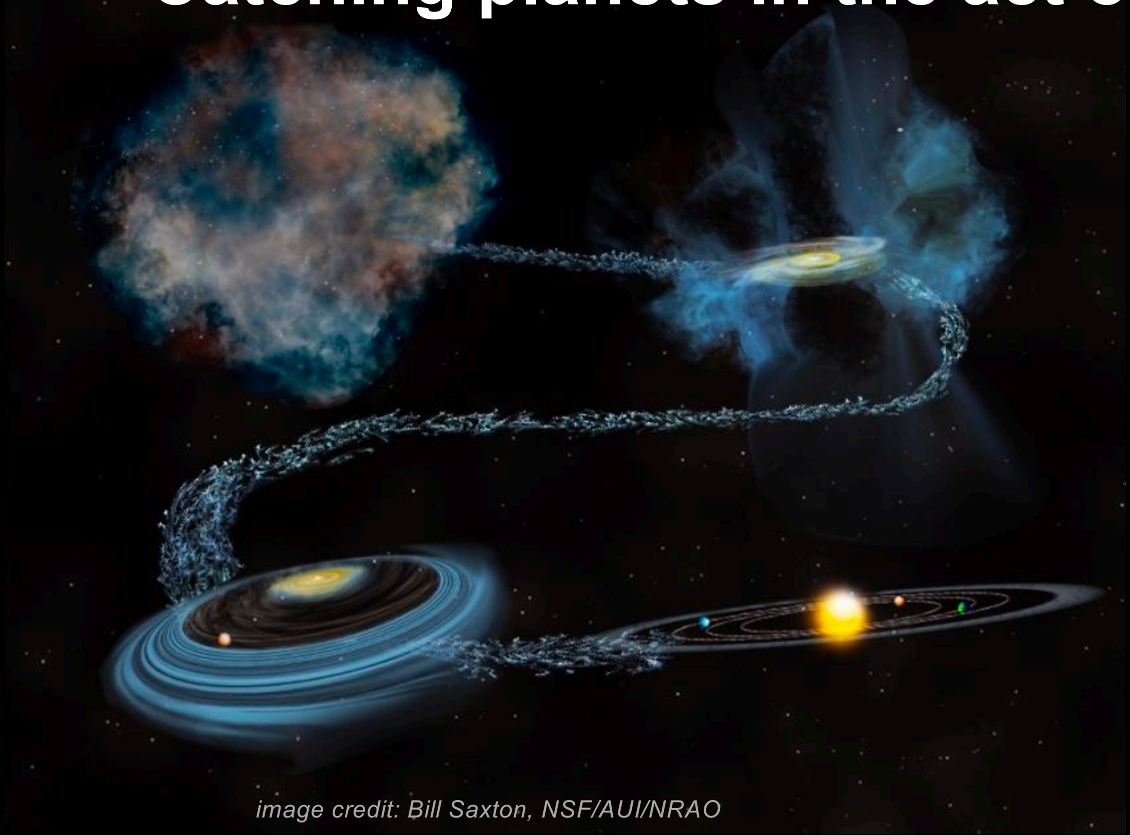
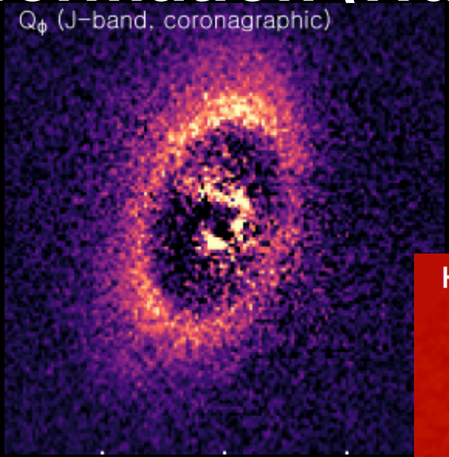
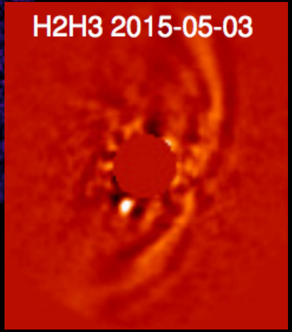
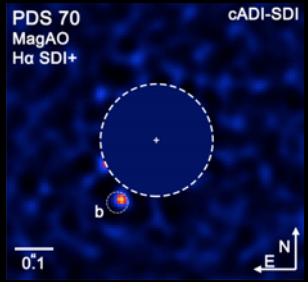


image credit: Bill Saxton, NSF/AUI/NRAO

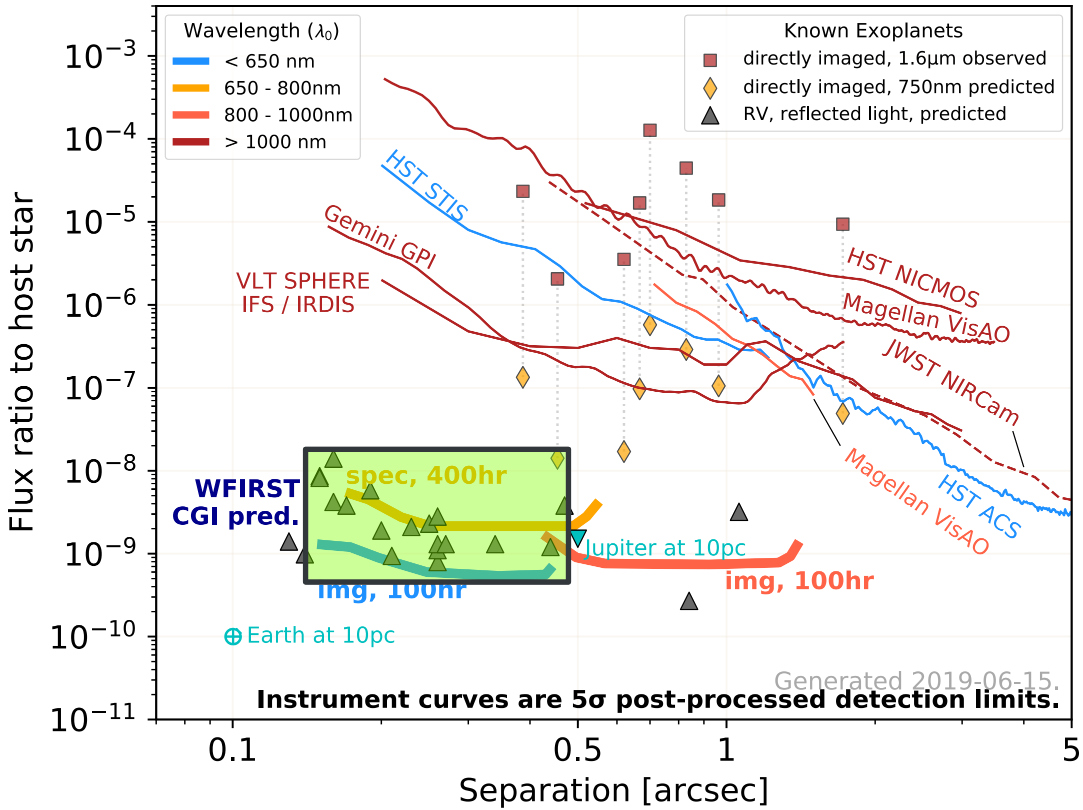




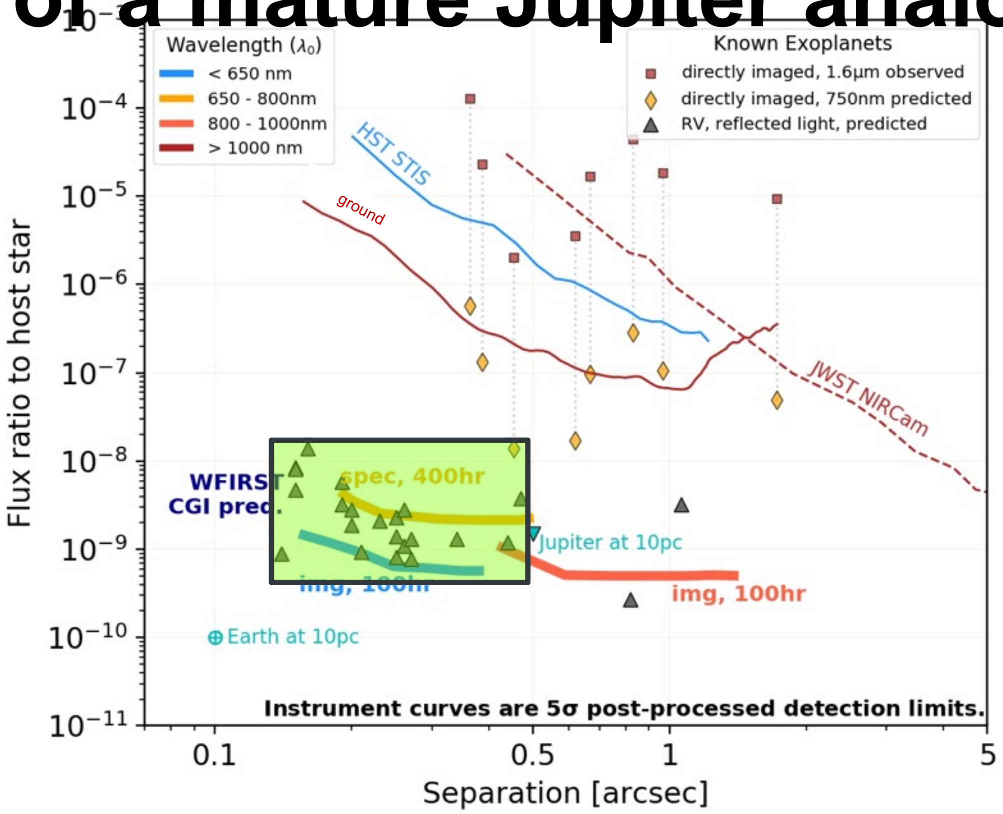


Keppler+2018; Wagner+2018

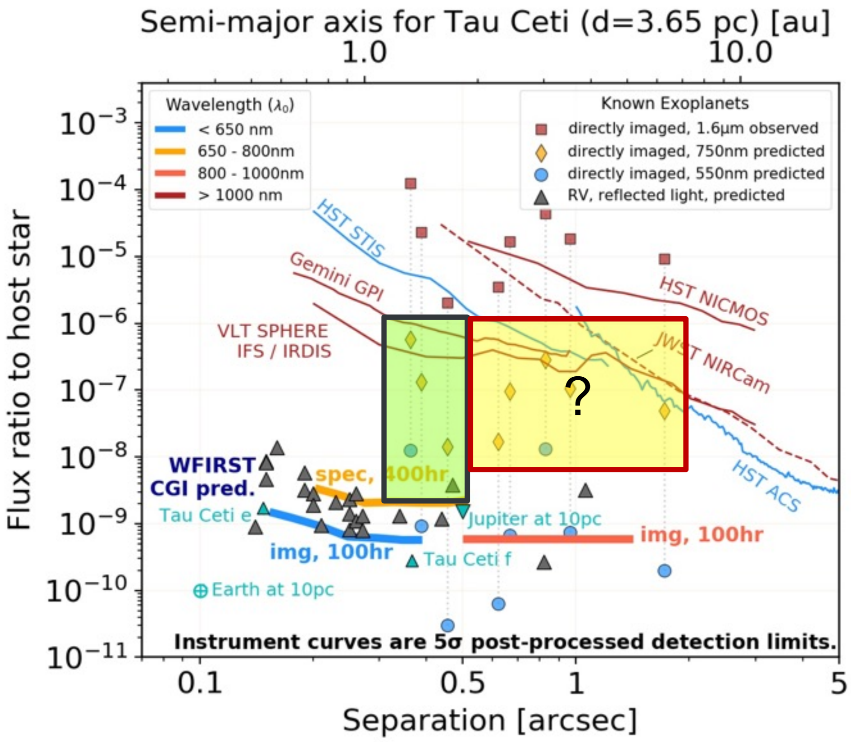
Break vsin(i) mass degeneracy for RV planets with reflected light imaging

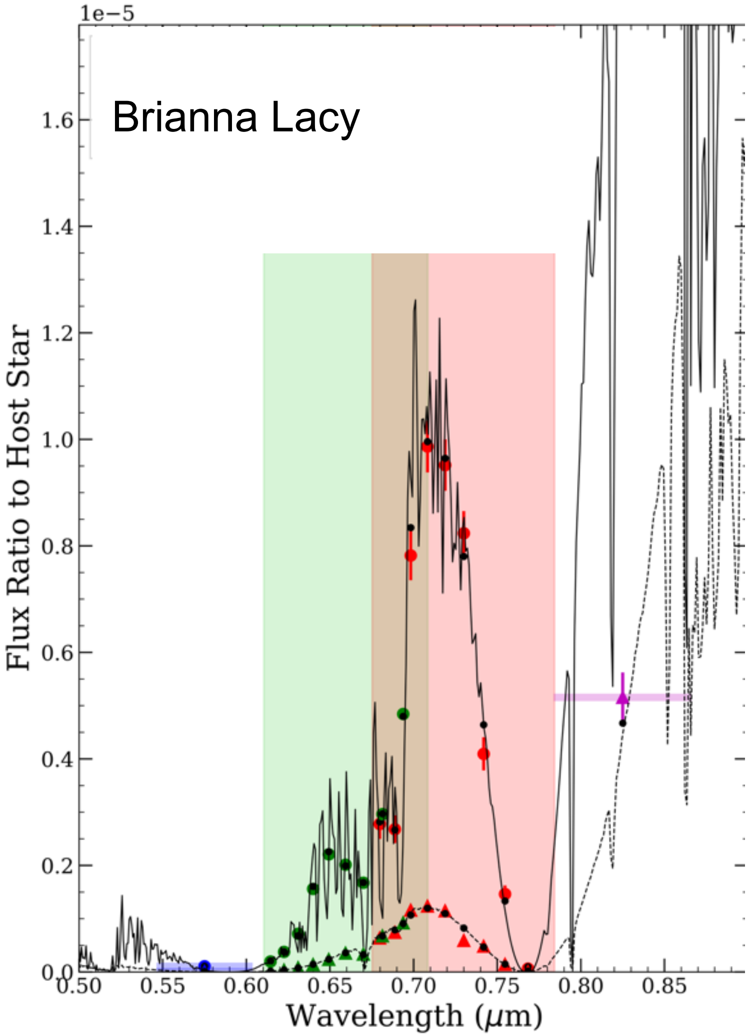


First reflected light images & spectrum of a mature Jupiter analog



Spectra of known young self-luminous planets probe metallicity & clouds





Mission timeline

Launch ~2025

Guaranteed

3 months of “tech demo” observing in first 1.5 years of mission

If meet success criteria:

~3 months Participating Science Program during the next year.
~25% of observing time for remainder of mission (2.5yr)

You can get involved in the PSP

instrument commissioning, observation planning, data processing,…
Proposal call expected in 2020.

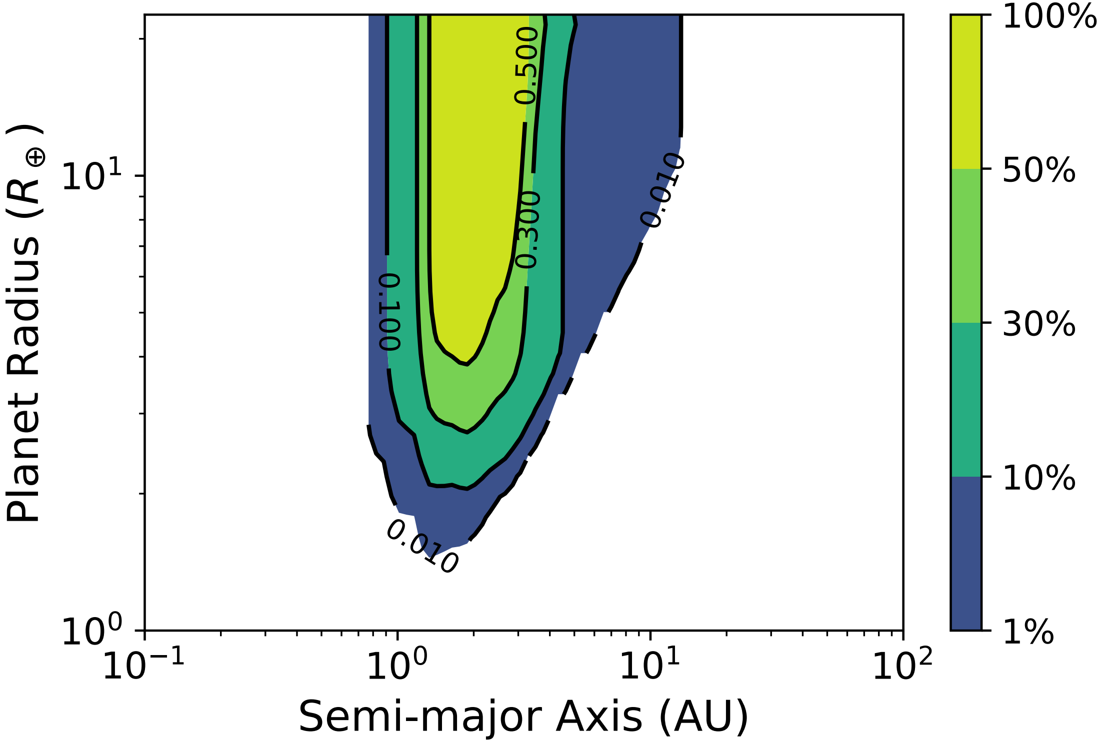
observing plan for Tech Demo Phase

- Required:
  - 575nm images of several reflected light Jupiter analogs and circumstellar disks
  - 730nm spectrum of 1 reflected light Jupiter and 1 self-luminous Jupiter or brown dwarf
  - 825nm imaging of 1 faint debris disk & polarimetry of 1 bright debris disk
- Perhaps:
  - 575nm image 1-2 exozodi
  - imaging of protoplanetary disk(s)
  - H_{alpha} imaging of protoplanet

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



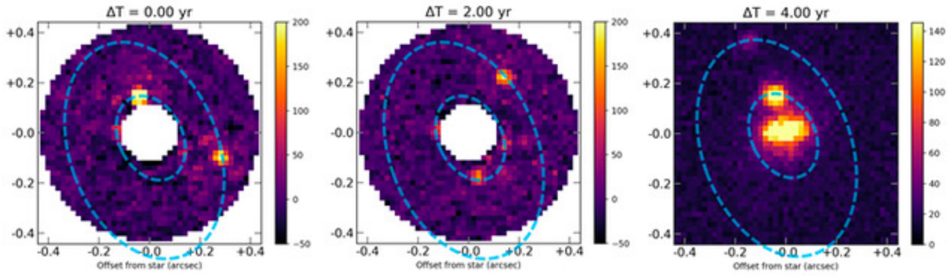
Potential Starshade Rendezvous with WFIRST

Credit Joby Harris,
NASA JPL

Starshade video

https://www.jpl.nasa.gov/video/details.php?id=1284

Get Involved



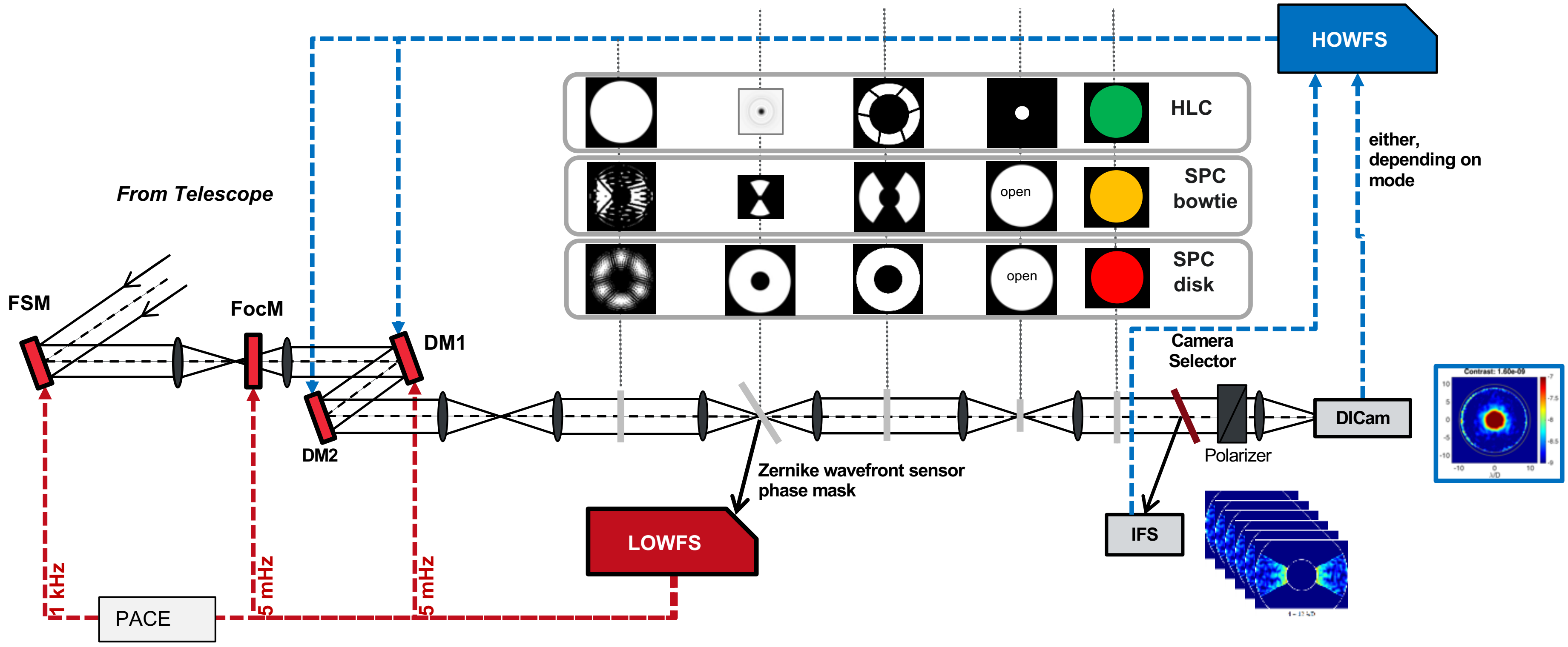
- Data challenge
  - June 24/25 at IPAC
  - Workshop before Lyot conference: Sunday October 20, 2019
- https://wfirst.ipac.caltech.edu/sims/Exoplanet_Data_Challenges.html#CGI_Exoplanet_Challenge_2

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 2020

BACKUP

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.

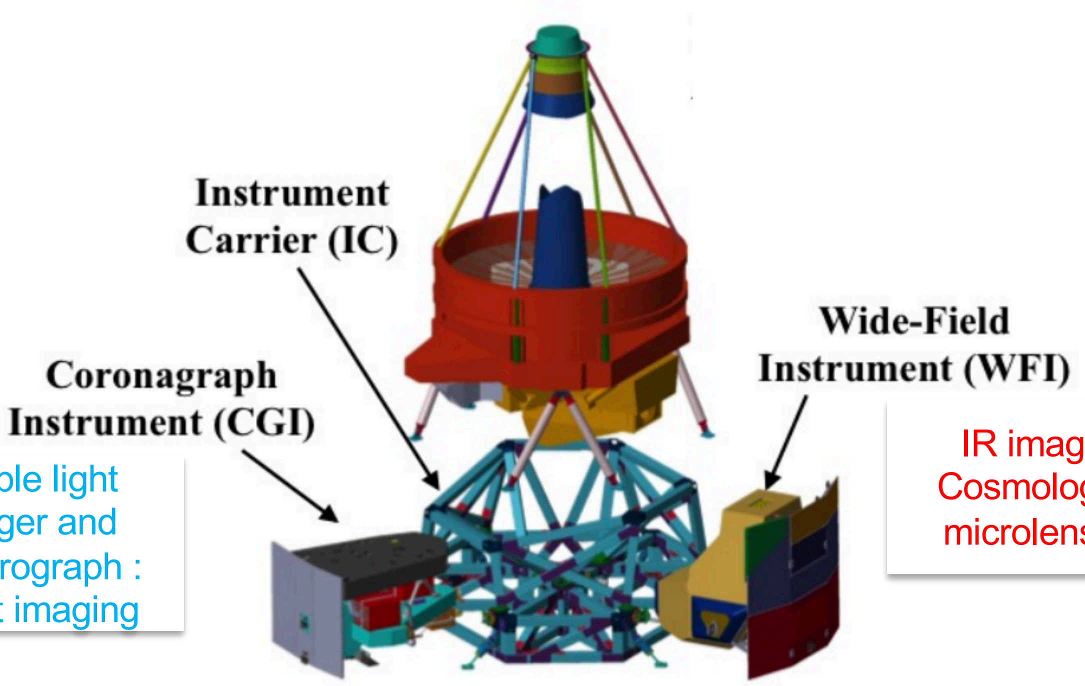
FINDING: Flying a capable coronagraph on WFIRST will provide significant risk reduction and technological advancement for future coronagraph missions. The greatest value compared to ground testing will come from observations and analysis of actual exoplanets, and in a flexible architecture that will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

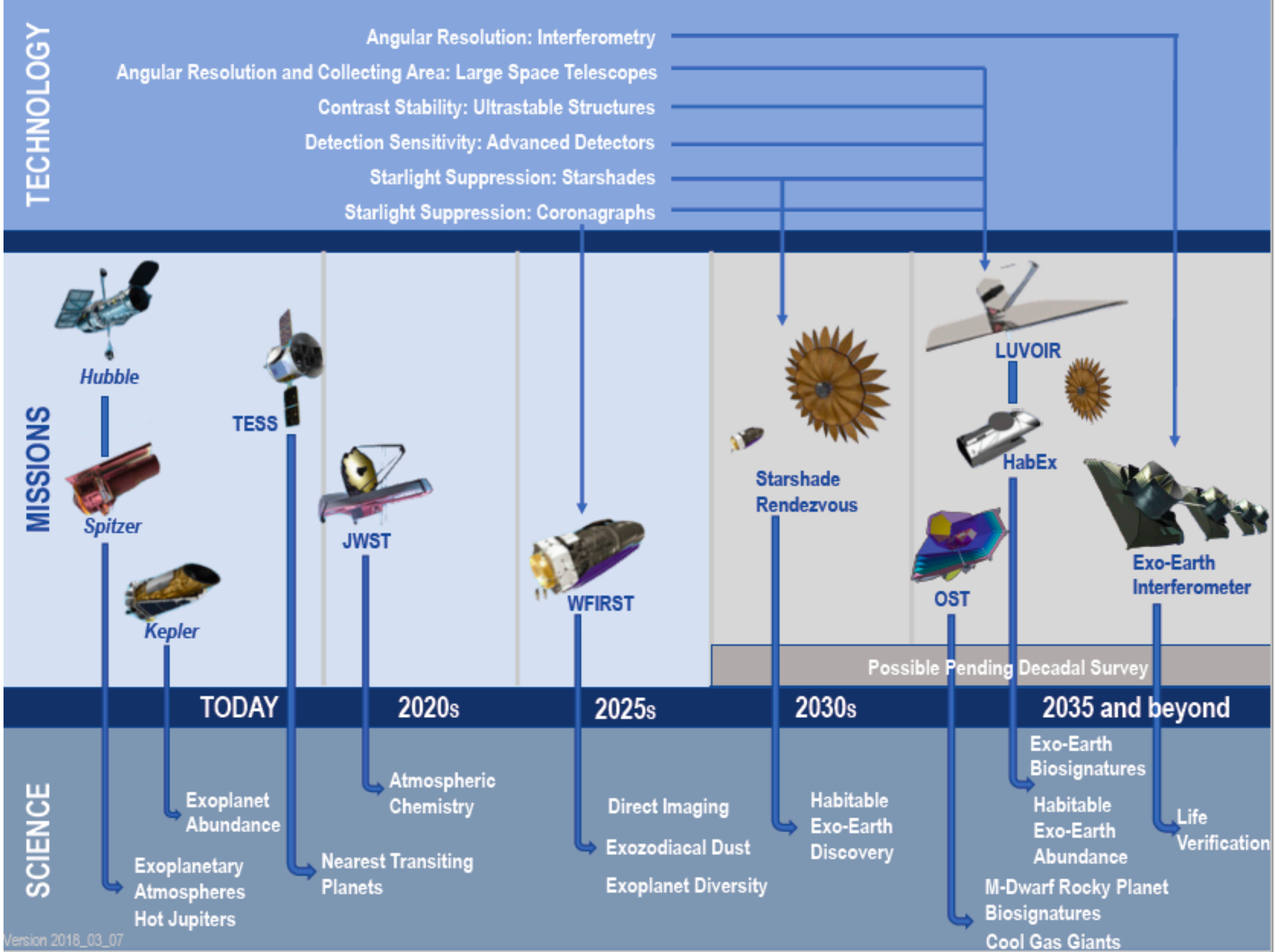
CGI



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
Spitzer
Kepler
TESS
JWST
WFIRST
Starshade Rendezvous
LUVOIR
HabEx
OST
Exo-Earth Interferometer
Possible Pending Decadal Survey
TODAY
2020s
2025s
2030s
2035 and beyond
SCIENCE
Exoplanetary Atmospheres Hot Jupiters
Exoplanet Abundance
Nearest Transiting Planets
Atmospheric Chemistry
Direct Imaging
Exozodiacal Dust
Exoplanet Diversity
Habitable Exo-Earth Discovery
Exo-Earth Biosignatures
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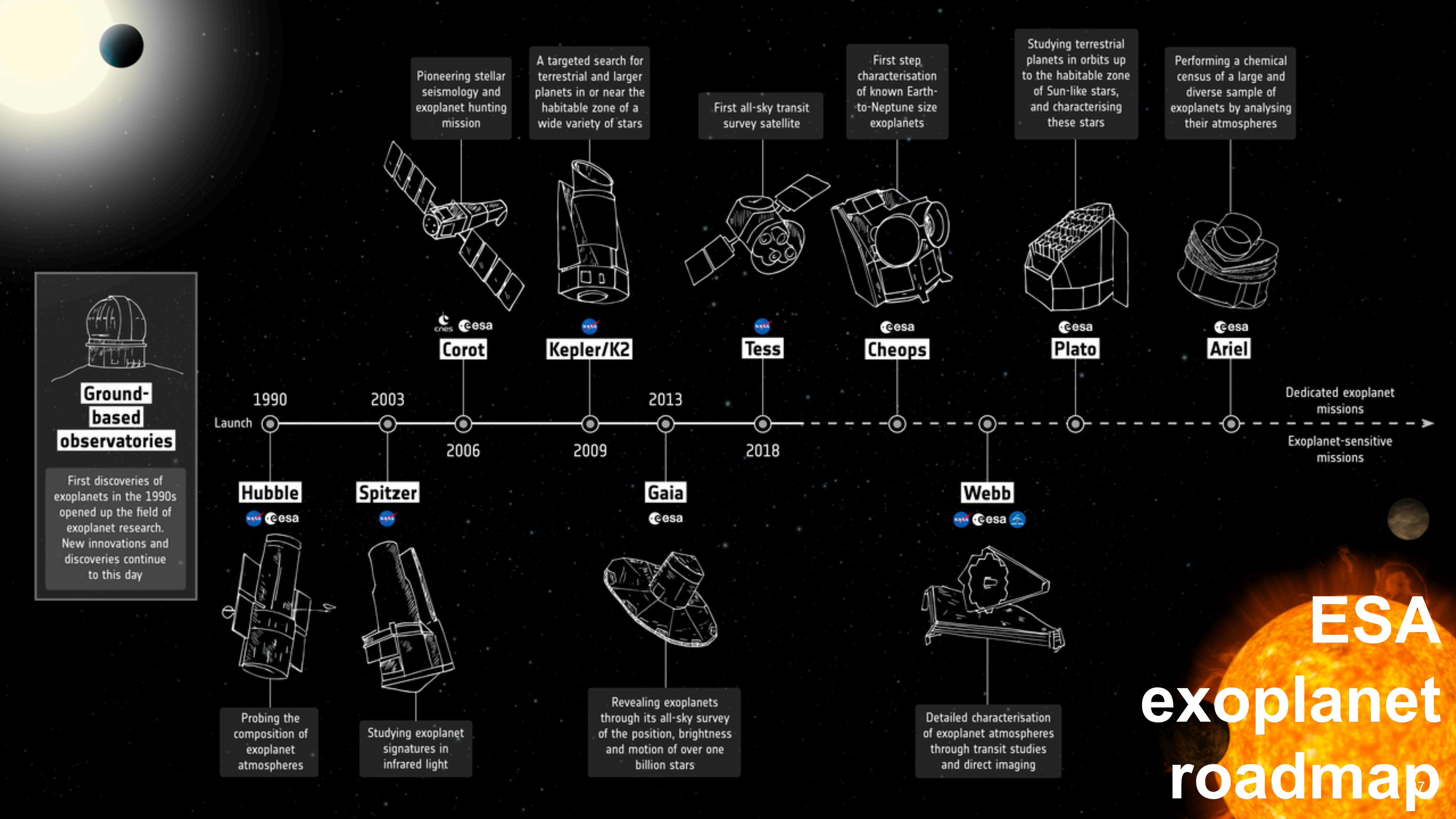
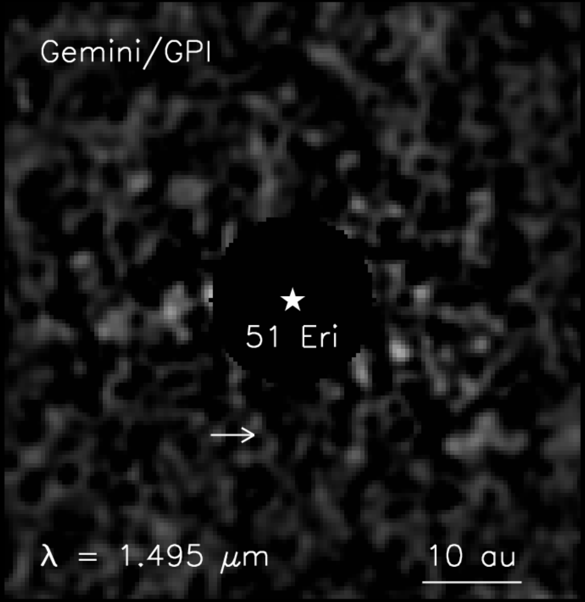
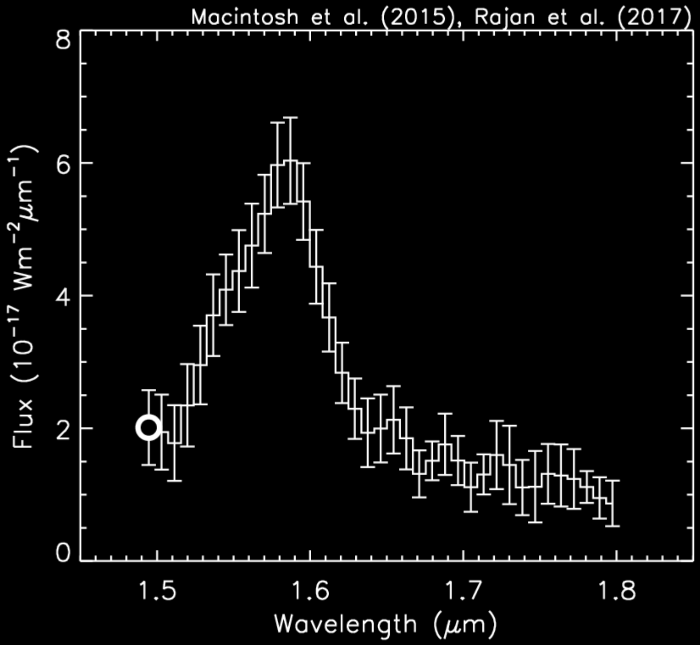
Cool Gas Giants
Life Verification
Version 2018_03_07


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

Spectra show molecular absorption signatures





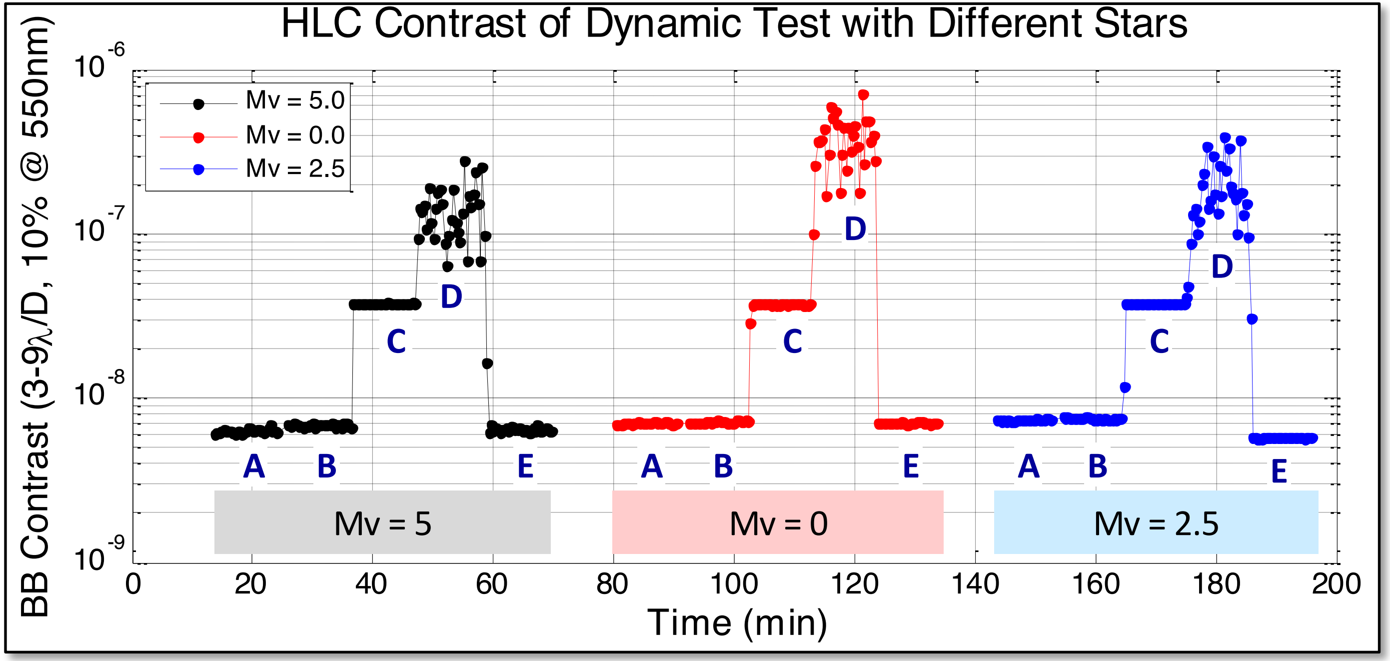
Credit: Rob De Rosa / GPIES

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)