The Wide Field Infrared Survey Telescope (WFIRST): from Dark Energy to Exoplanets

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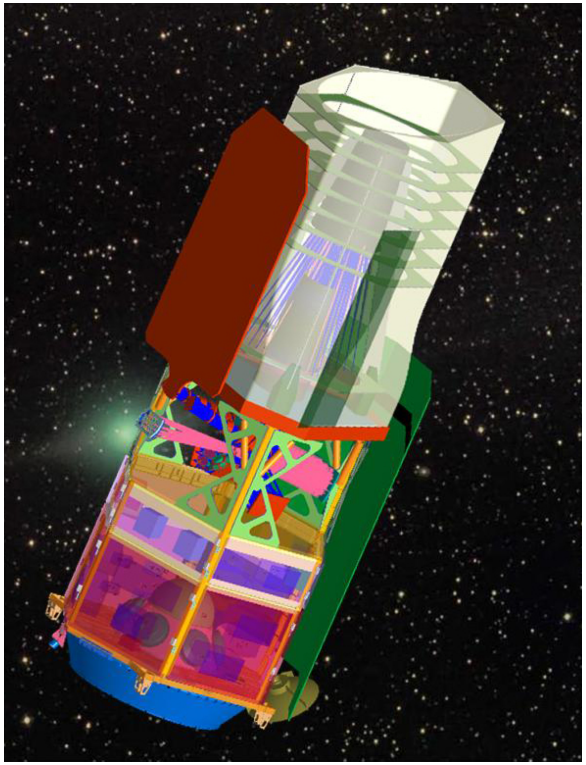
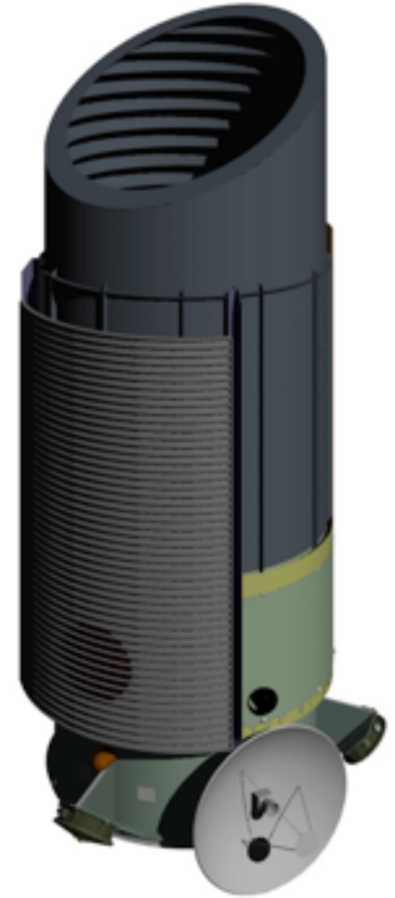
MPIA-JPL Exoplanet Technology Meeting,
Max Planck Institute for Astronomy, Heidelberg, Germany
November 15, 2018

WFIRST =

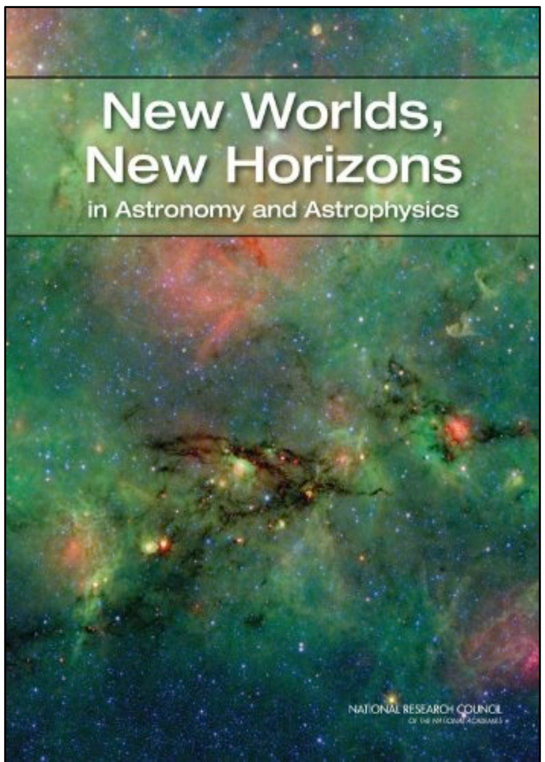
	+		+	
JDEM		MPF		NIRSS
Dark Energy		*Exoplanet Census*		*Infrared Sky Survey*

WFIRST Checks Many Boxes

Top Priority from the 2010 astrophysics Decadal survey

#1 In Space Large-Scale Priority - Dark Energy, Exoplanets

WFIRST covers many other NWNH science goals



5 Discovery Science Areas

ID & Characterize Nearby Habitable Exoplanets
Time-Domain Astronomy
Astrometry
Epoch of Reionization
Gravitational Wave Astrometry

20 Key Science Questions

Origins **(7/7 key areas)**
Understanding the Cosmic Order **(6/10 key areas)**
Frontiers of Knowledge **(3/4 key areas)**

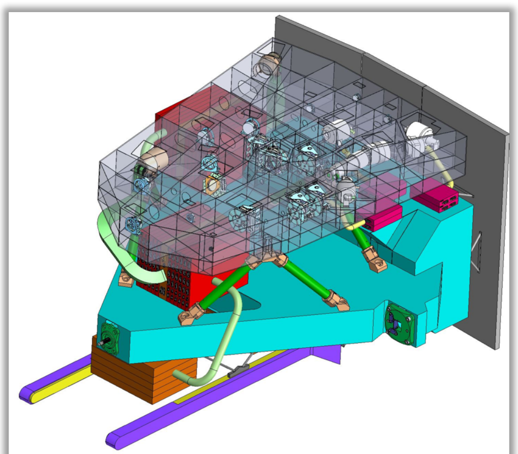
WFIRST

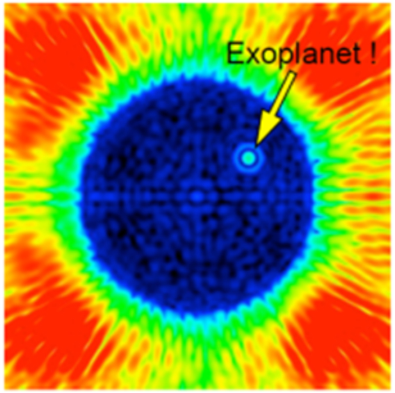
WIDE-FIELD INFRARED SURVEY TELESCOPE

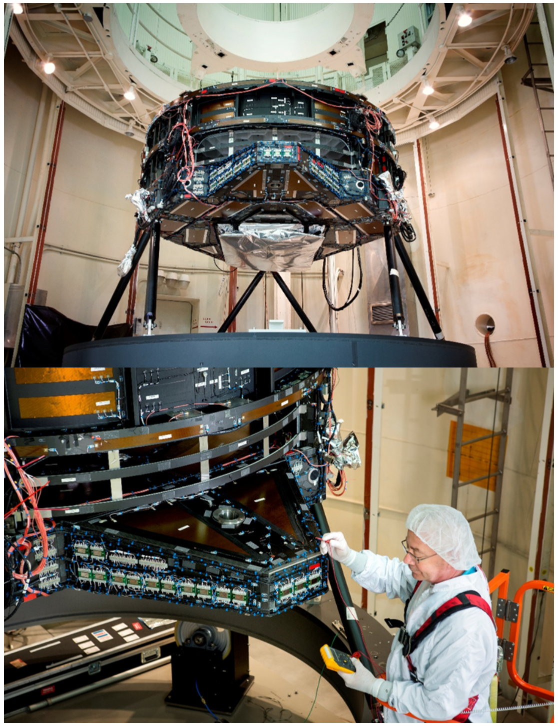
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

WFIRST Inherits a Larger Telescope (2012)

- Latest Design Reference Mission is based on "AFTA" (Astrophysics Focused Telescope Asset)
- AFTA is a repurposed 2.4 m telescope from the US National Reconnaissance office (NRO)
- The AFTA telescope is already built, and sitting in a storage facility
- WFIRST now includes a coronagraph to image exoplanets:
    - This was not envisaged by the decadal survey
    - Enabled by the 2.4 meter mirror
    - Tech Demo to build the "Search for Life" foundation







Harris Corporation / TJT Photography

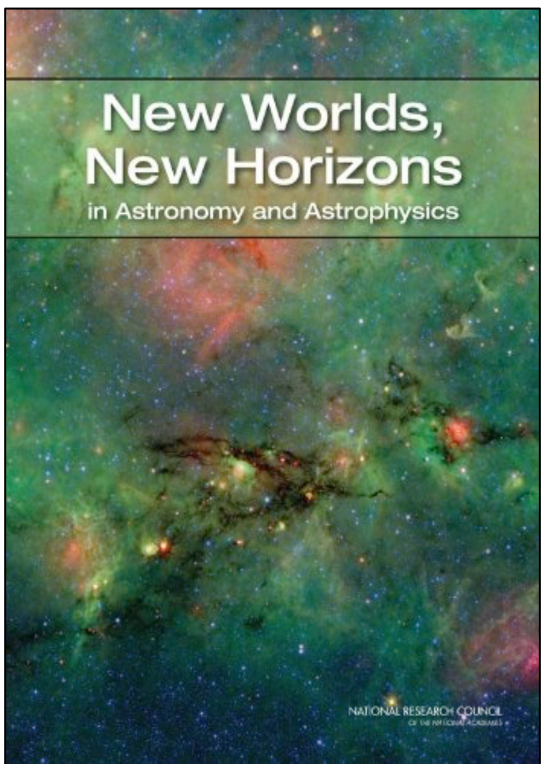
WFIRST Checks Many Boxes

WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

Top Priority from the 2010 astrophysics Decadal survey

#1 In Space Large-Scale Priority - Dark Energy, Exoplanets
#1 In Space Medium-Scale Priority - New Worlds Tech. Development (prepare for 2020s planet imaging mission)

WFIRST covers many other NWNH science goals



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WFIRST Science Goals

- Characterize the history of cosmic acceleration and structure growth to constrain Dark Energy → Wide Field Instrument (WFI) High Latitude and Supernova Surveys

- Understand how planetary systems form and evolve
  - determine prevalence of planets from habitable zone to cold outer regions of planetary systems → Microlensing Survey of Stars in Galactic Bulge
  - Characterize atmospheres of mature giant planets around nearby stars → Coronagraph Direct Imaging, Multi-band Photometry and Spectroscopy
  - Study PP disks and debris disks to characterize the relationship between disks and planets → Coronagraph Imaging

- Maintain robust peer-reviewed Guest Observer program, with ~25% of nominal mission lifetime

WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

WFIRST Science Goals

complements Euclid

Baryon Acoustic Oscillations

Gravitational Lensing

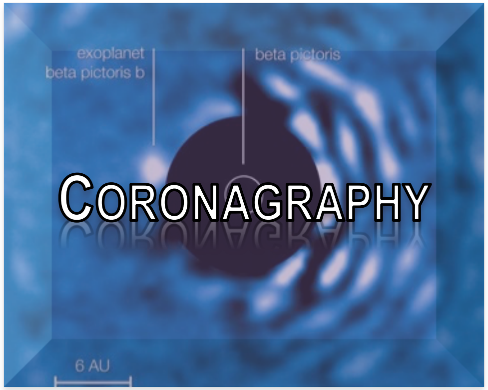
complements LSST

Supernovae

complements Kepler

Legacy Science with Surveys

Microlensing Census



Guest Observer Program

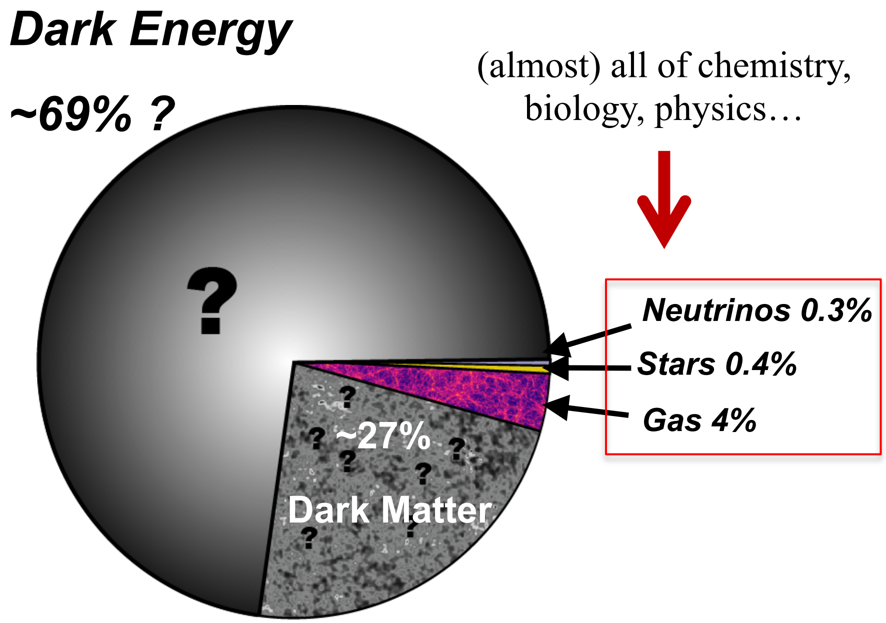
continues Great Observatory legacy

WFIRST Science Goals: Dark Energy

Answer fundamental questions:

1. Is cosmic acceleration caused by a new energy component or by the breakdown of General Relativity (GR) on cosmological scales?

2. If the cause is a new energy component, is its energy density constant in space and time, or has it evolved over the history of the universe?



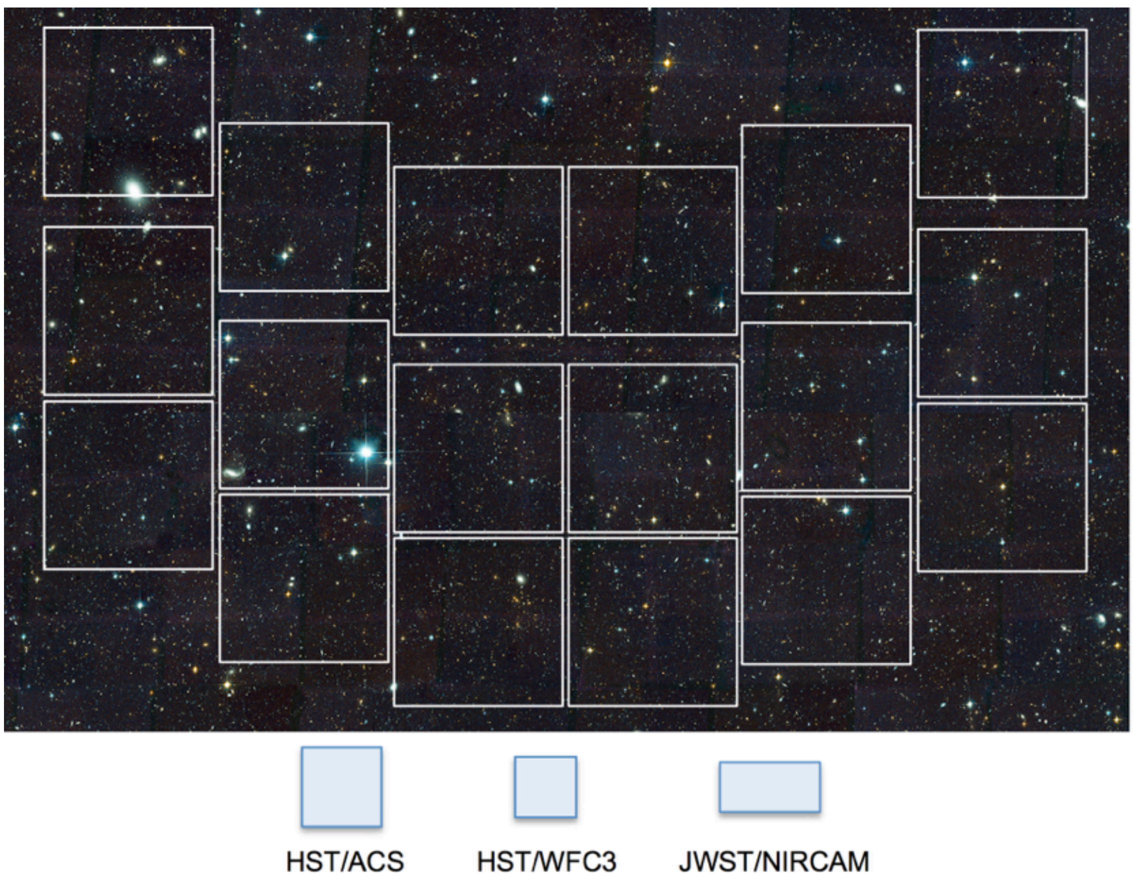
The Universe as a Pie Chart

WFIRST Science Goals: Dark Energy

- In order to test possible explanations of the Universe's apparent accelerating expansion, including Dark Energy and modification to Einstein's gravity, WFIRST will determine:
  - The **expansion history of the Universe using the supernova, weak lensing, and baryon acoustic oscillation** techniques, at redshifts up to z = 2
  - The **growth history of the largest structures in the Universe** using **weak lensing, redshift space distortions, and galaxy cluster techniques,** at redshifts up to z = 2
  - With high-precision cross-checks between the different techniques

WFIRST Observational Requirements: Dark Energy

- WFIRST will conduct near-infrared sky surveys in both imaging and spectroscopic modes, providing an imaging sensitivity for unresolved sources better than 27 AB magnitude



- 0.28 deg^2 instantaneous FoV covered by 18 H4RGs
- Hubble-like Image Quality over 100x more sky
- Imaging & Spectroscopy HL Survey over ~ 2000 deg^2

WFIRST Observational Requirements: Dark Energy

- In order to separate between the 2 scenarios, Dark Energy Surveys shall yield 2 of the following:
  - The detection of at least 10 million galaxies spectroscopically over a redshift range of 1-2
  - The shape measurement of at least 100 million galaxies over a redshift range of 1-3
  - The light curve measurement of at least 2000 supernovae at redshifts reaching at least 1

High Latitude Survey

spectroscopic: galaxy redshifts

16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

380 million lensed galaxies
40,000 massive clusters

Supernova Survey

wide, medium, & deep imaging
+ IFC spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

Microlensing Survey Goals

Primary Microlensing Science Objective:

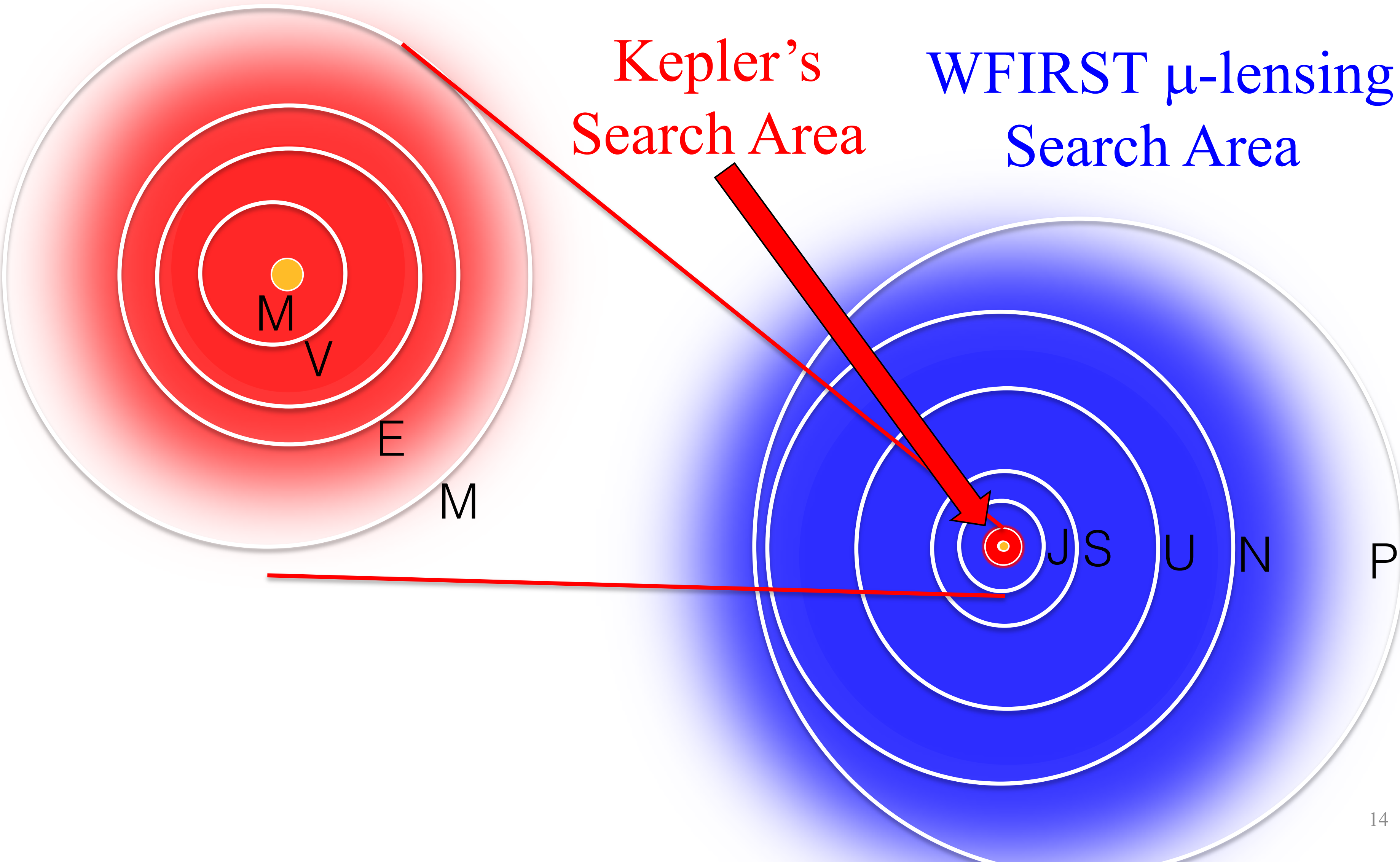
The WFIRST microlensing survey will carry out a statistical census of exo-planetary systems in the Galaxy, **from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater**, by monitoring stars toward the Galactic bulge using the microlensing technique.

Exoplanet Demographics: Why do we care?

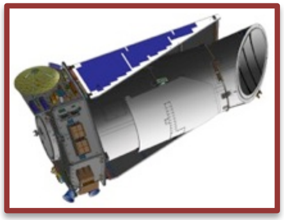
- Despite enormous progress on many fronts, we still don't fully understand planet formation.
- The planet distribution function may have the physics of planet formation imprinted on it.
- But, it's hard: we know that the planet distribution function depends on at least four parameters (planet mass, planet period, stellar mass, stellar metallicity) + a mass/radius relation that depends on these parameters.
- Furthermore, we must piece together this multi-parameter distribution function via many methods, each with their own selection biases and sometimes with little overlap for cross-checks.

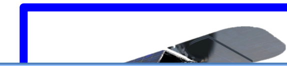
Exoplanet Surveys: Kepler & WFIRST

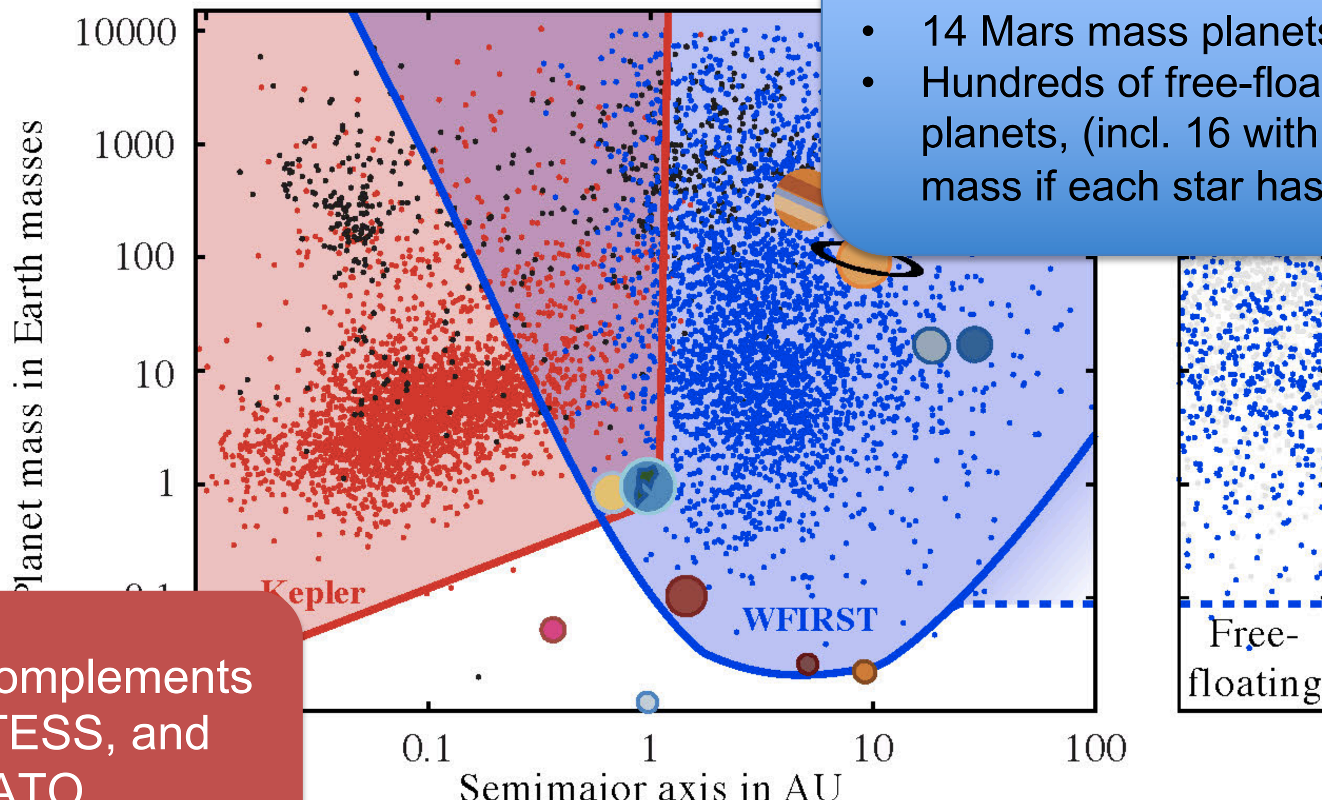
WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS



Completing the census ("Penny Plot")







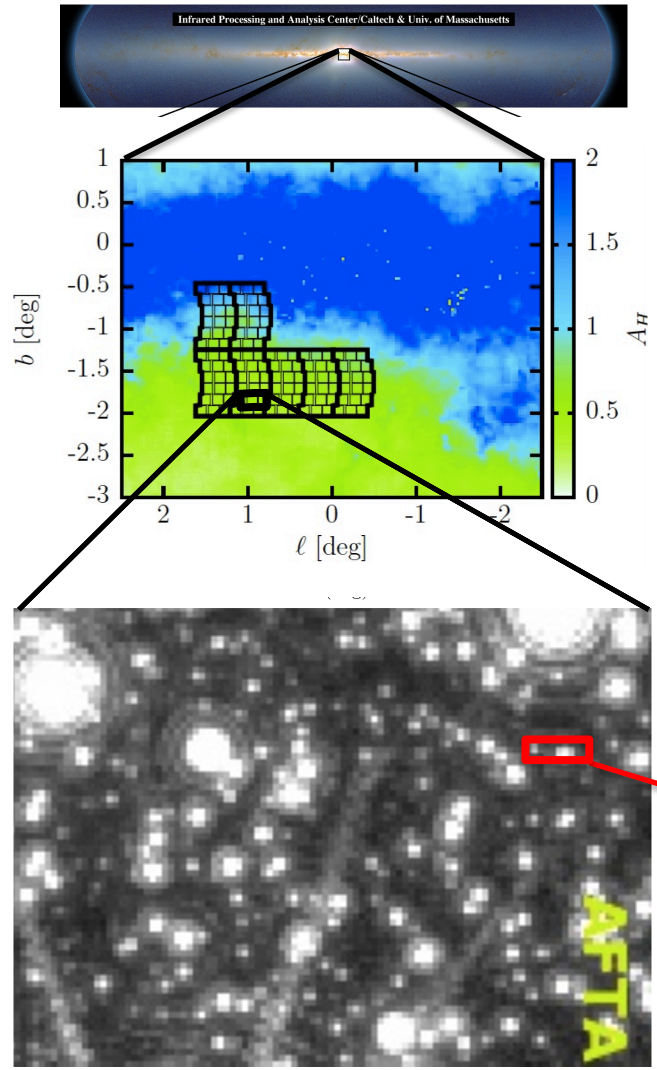
- 1000 planet detections.
- 120 with Earth mass and below
- 14 Mars mass planets
- Hundreds of free-floating planets, (incl. 16 with Earth mass if each star has one)

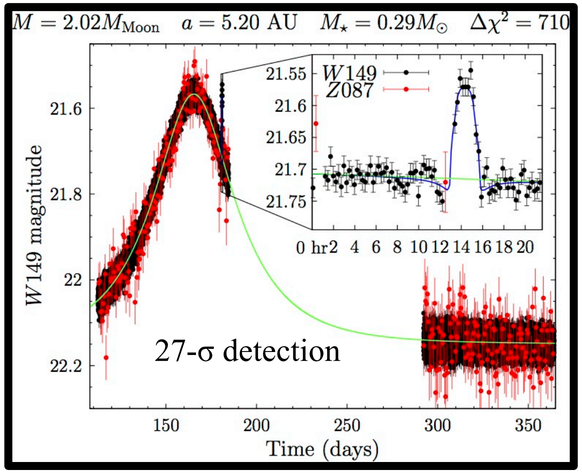
WFIRST complements Kepler, TESS, and PLATO.

(Penny et al., in prep)

WFIRST μLensing Survey Advantages

- Will monitor 7 fields of 0.28 deg^2 each
- Every 15 minutes (HZ Earth amplification anomaly is ~few hours long)
- With ~45s individual exposures in 2 filters:
  - 0.93-2 μm (W149) & 0.76-0.98 mm (Z087)
- High precision photometry on short timescales enables detection of weaker signals: smaller planets, HZ planets





(Penny et al., in prep)

WFIRST Coronagraph (CGI) Science Goals

1. **Direct optical imaging and spectroscopy of known RV extrasolar giant planets (EGPs) orbiting mature Sun-like stars**

2. **Search for previously undetected planets around nearby stars (no RV data, or sub-Neptunes > 1AU)**

3. **Image faint debris disks structures aroudn nearby stars down to a level of ~ a few times that of our solar system's zodiacal dust**

4. **Characterize protoplanetary disks structure and potential self-luminous / accreting planets around very young stars (< 10Myr old)**

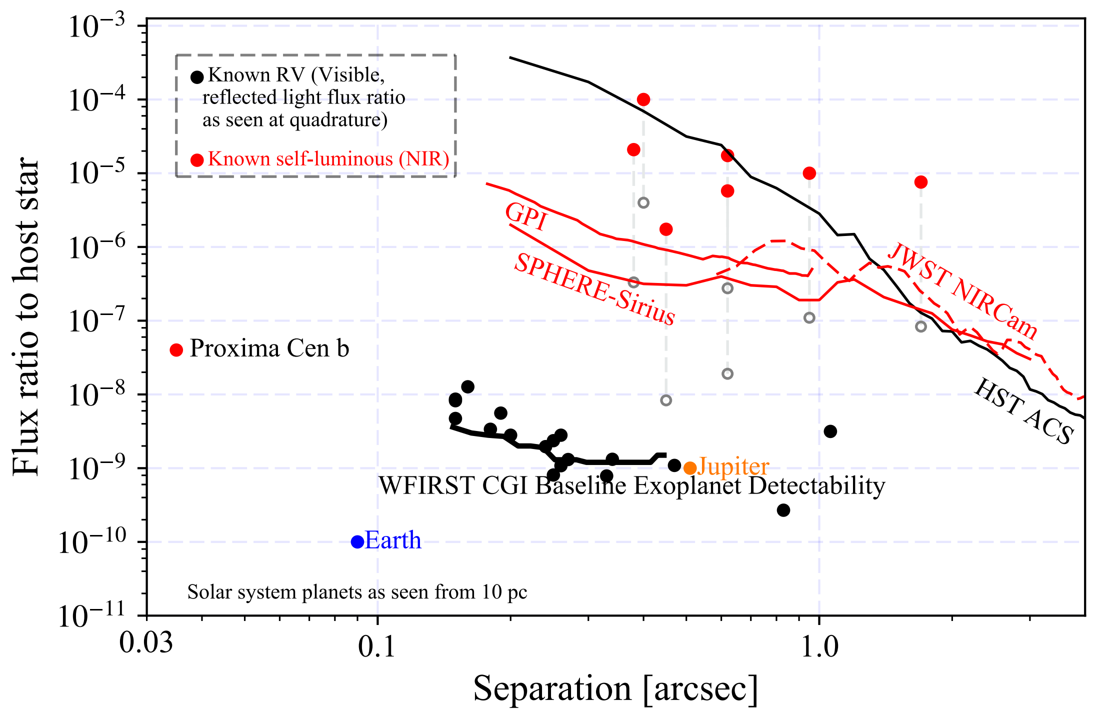
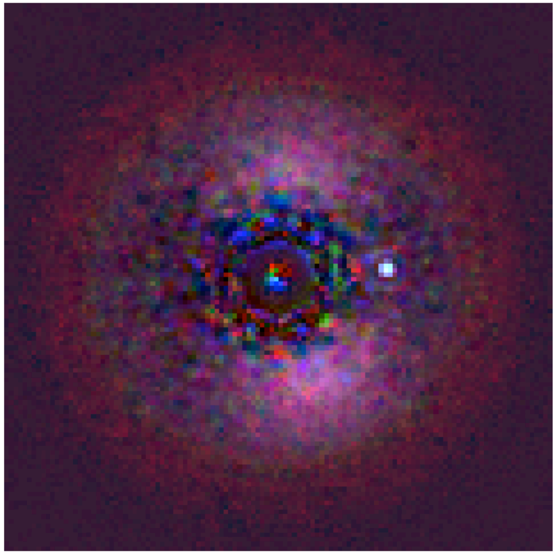


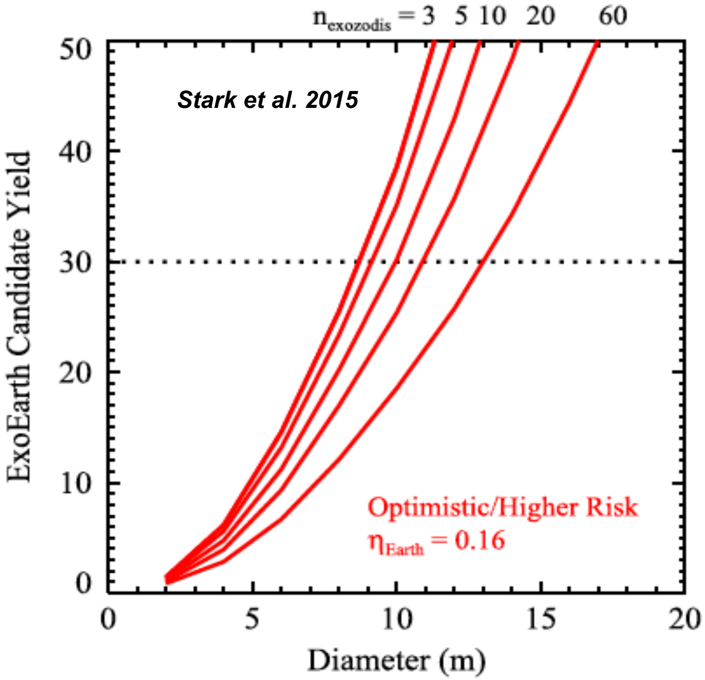
Figure courtesy of Tiffany Meshkat (IPAC) & Karl Stapelfeldt (NASA-JPL)

CGI Exoplanet & Exo-zodiacal Disks Imaging

- CGI will obtain the first ever direct images of cool mature planets like our own Jupiter, and other types of extrasolar giant planets (EGPs) orbiting Sun-like stars
- CGI blind searches will start exploring the transition between EGPs and super Earths
- CGI will take the first ***optical*** images of faint debris disks structures ("exozodis") down to a level of few times that of our solar system's zodiacal dust, a key information to optimize the design and yield of possible future direct imaging exoplanet missions (HabEx / LUVOIR)

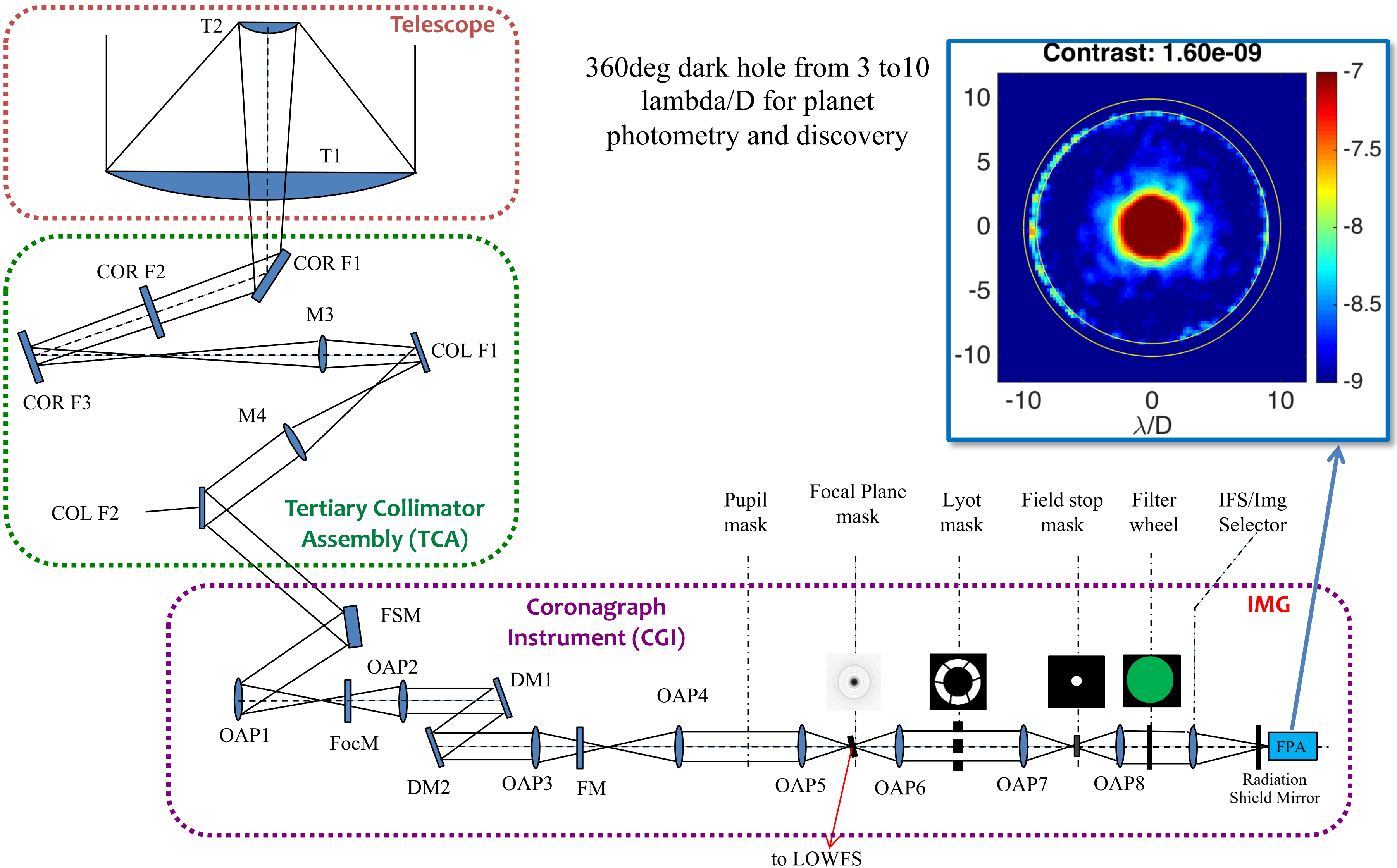


WFIRST CGI multi-color imaging simulation of a Jupiter mass planet at 2 AU from a Sun-like star at 3pc, with a 10-zodi interplanetary dust structure.
Image Credit: M. Rizzo, N. Zimmerman, A. Roberge / E. Douglas / L. Pueyo



CGI Exoplanet Imaging Mode: Hybrid Lyot Coronagraph

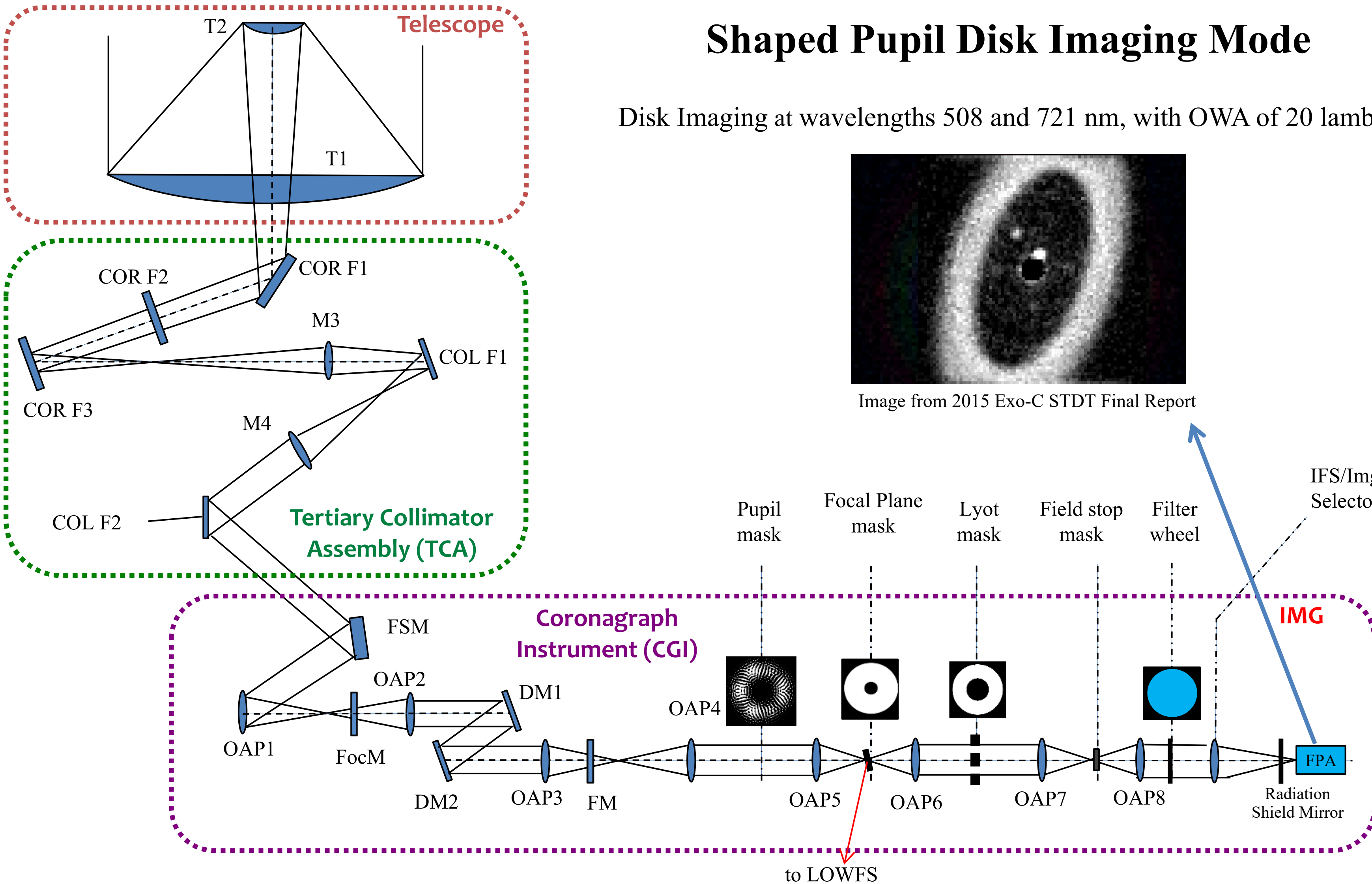
360deg dark hole from 3 to10 lambda/D for planet photometry and discovery



CGI Disk Imaging Mode: Shaped Pupil Coronograph

Shaped Pupil Disk Imaging Mode

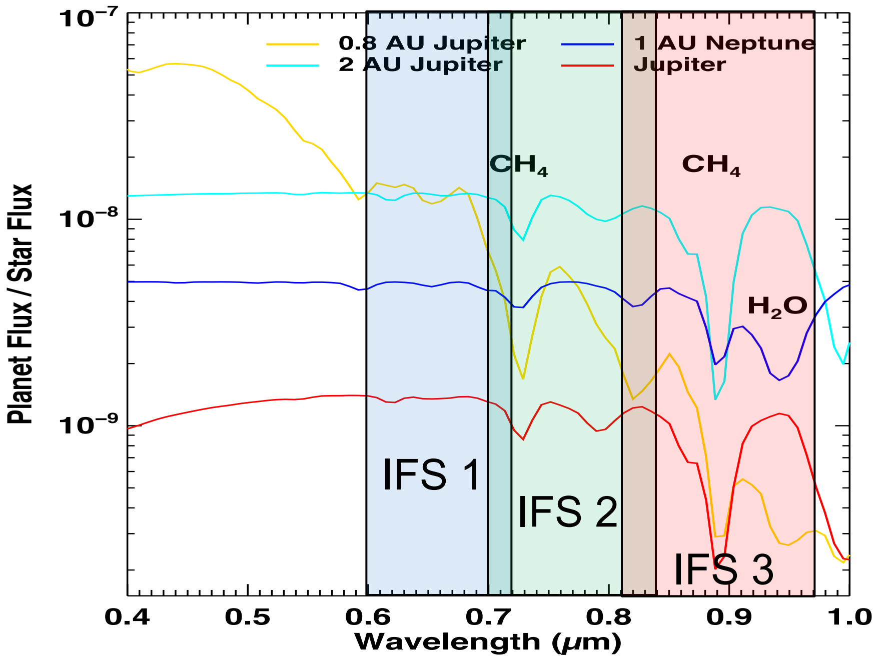
Disk Imaging at wavelengths 508 and 721 nm, with OWA of 20 lambda/D



CGI Spectroscopy of Extrasolar Giant Planets

- CGI will *study the composition and bulk properties of giant planets via multi-band photometry and spectroscopy of features such as methane, to constrain their atmospheric metallicity,* as well as aerosol and cloud properties, providing unique constraints on their formation and evolution

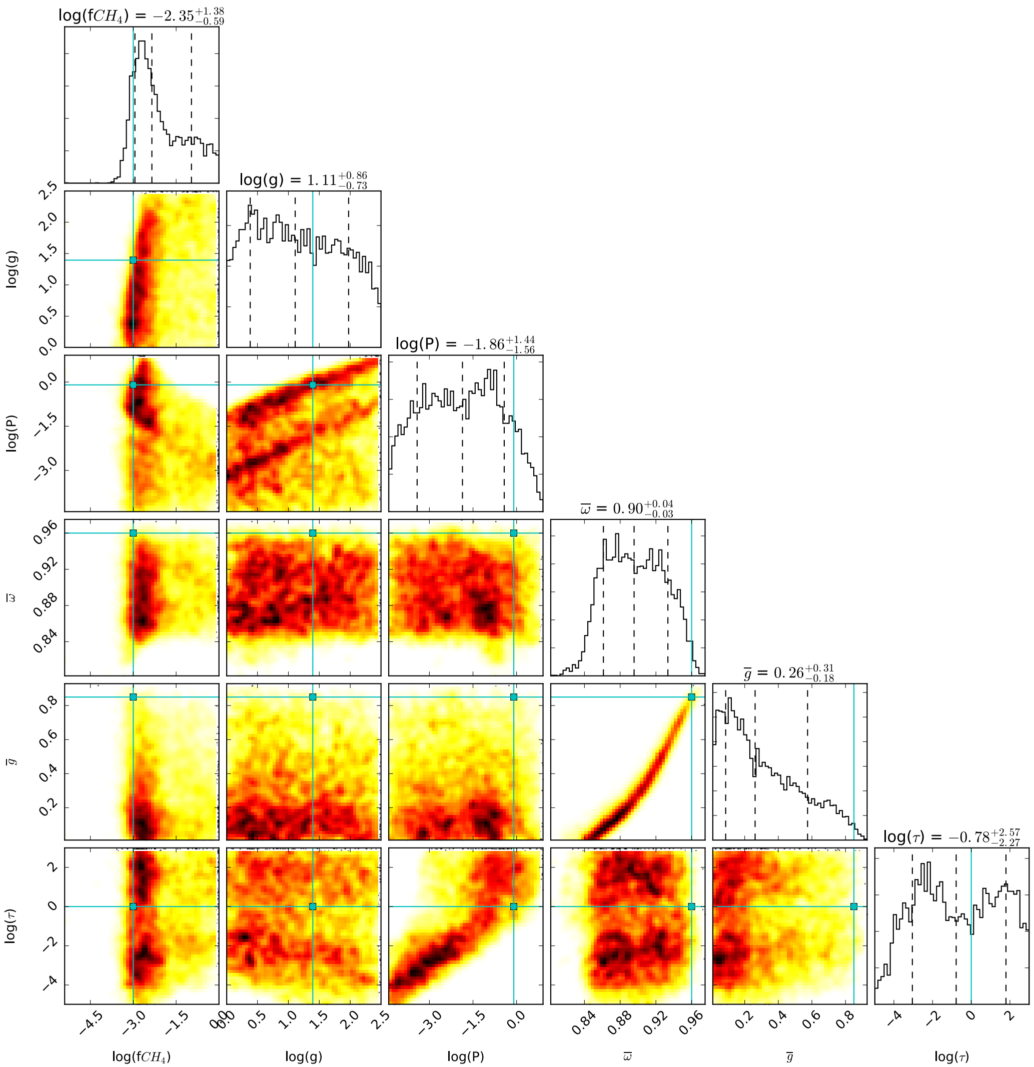
- CGI will obtain the first ever **reflected** light optical spectra of Jupiter analogs and other types of EGPs orbiting mature Sun-like stars



Credit: A. Roberge (NASA GSFC) / Haystacks Team

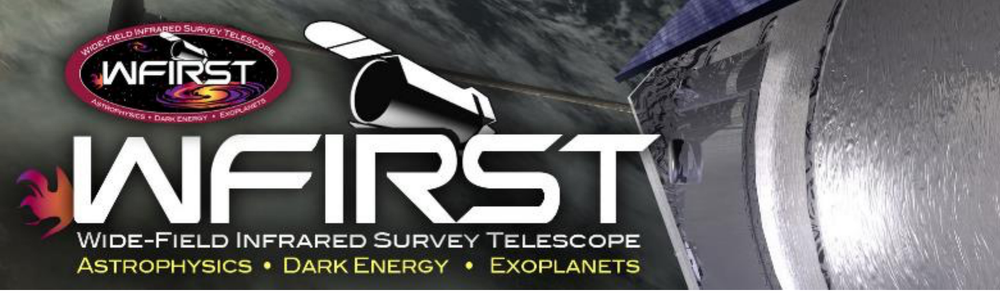
Visible spectra (R=50) of Extrasolar Giant Planets of different masses and separations accessible to the WFIRST CGI.
Image credit: A. Roberge (NASA/GSFC). Original spectra from Karkoschka (1998), Cahoy et al. (2010), Hu & Seager (2014).

CGI Spectroscopy of Extrasolar Giant Planets



- WFIRST CGI spectra of giant planets can strongly constrain the abundance of methane (CH_4) in the planet's atmosphere, which can then be used to determine the bulk metallicity of the atmosphere.
- WFIRST CGI spectra can also provide constraints on cloud properties such as the pressures P at which the cloud(s) reside and their scattering properties τ.

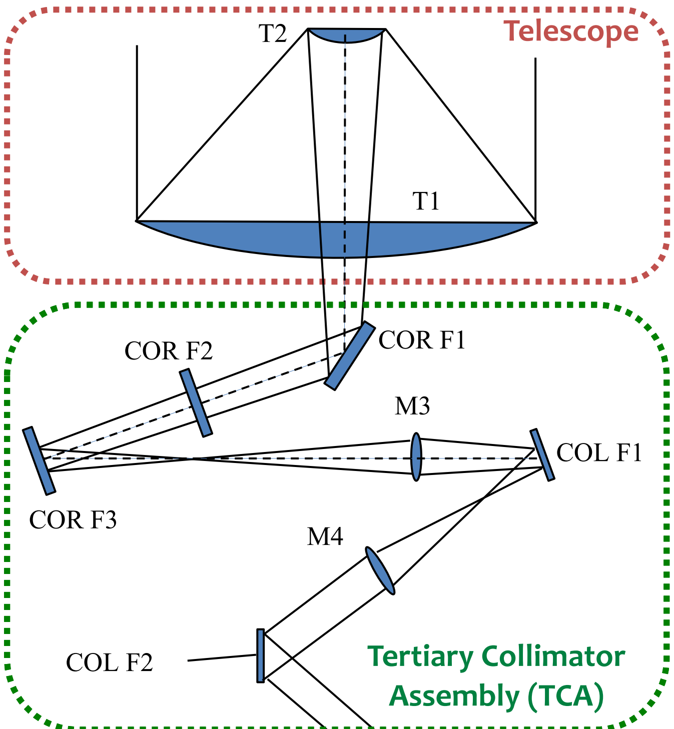
Posterior PDF for key atm. parameters, for simulated R=50 CGI spectra of a giant planet, from Lupu et al. 2016.

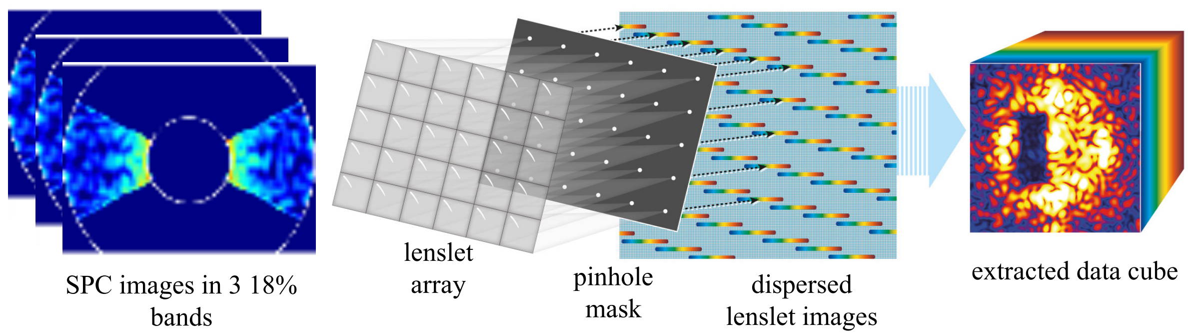


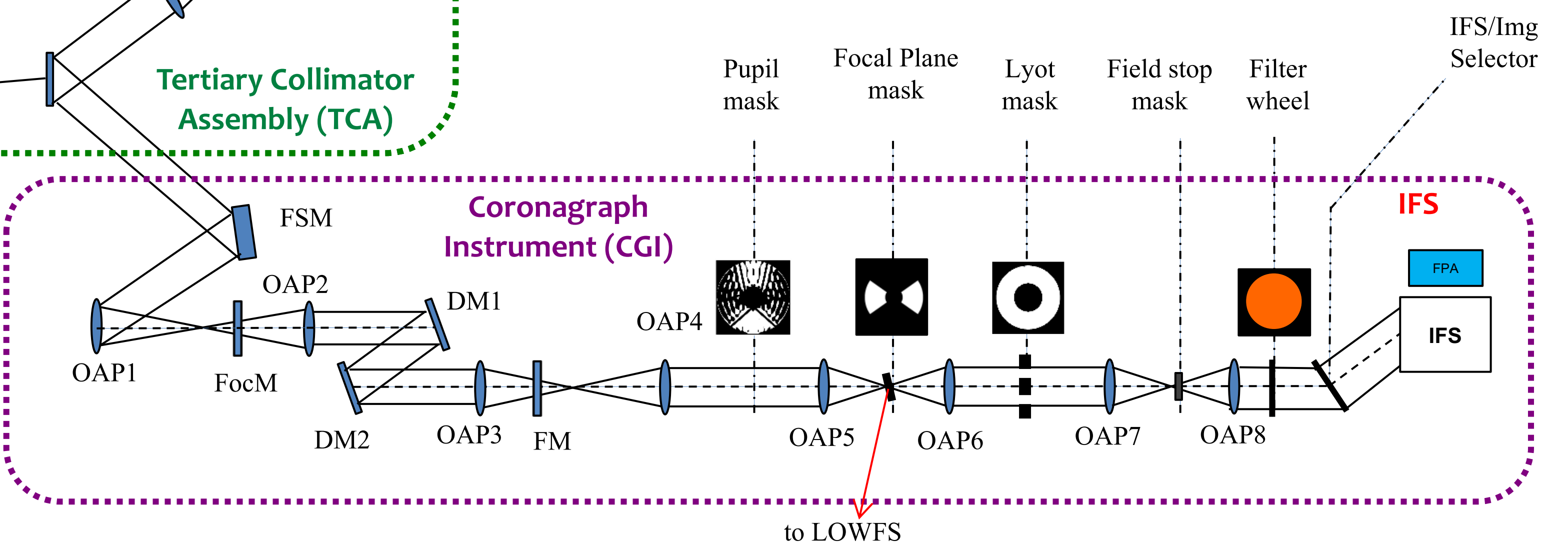
CGI Spectroscopy Mode: Shaped Pupil +IFS

Shaped Pupil Spectroscopy Mode

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



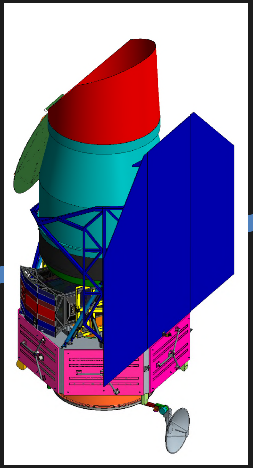




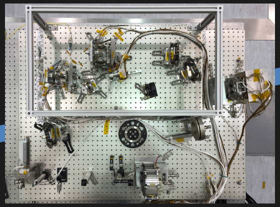
CGI as a Technology Demo for Future Missions

CGI is a direct & necessary predecessor to potential future flagship direct imaging & spectroscopy missions targeting small planets in the Habitable Zone of nearby stars

Large Ultra-stable Space Telescope & Observatory

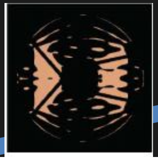


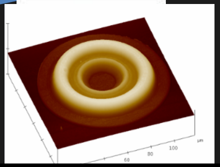
Autonomous Ultra-Precise Wavefront Sensing & Control System



First Use of Deformable Mirrors in Space

High Contrast Coronagraph Masks





Ultra-low Noise Photon Counting Visible Detectors

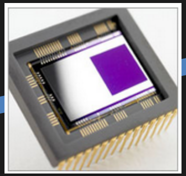
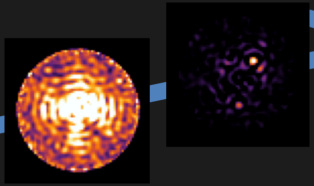
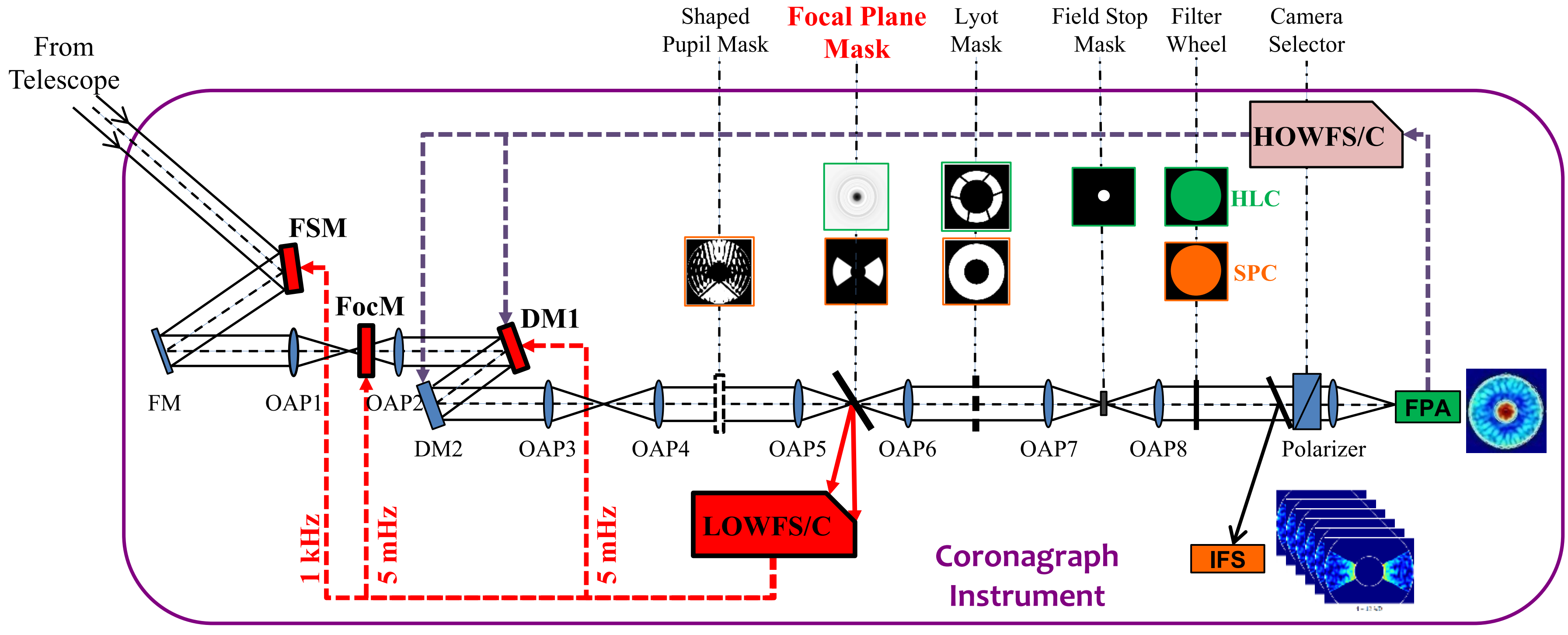


Image Processing at Unprecedented Contrast Levels



WFIRST CGI will premiere or significantly improve many in-space key technologies required for these missions, significantly reducing their risk and cost

CGI Exquisite Wavefront Sensing & Control



- CGI will demonstrate ***active*** line of sight jitter correction down to ***sub-mas*** level for the first time in space, using a Fast Steering Mirror (~10x better pointing stability than HST)
- CGI will demonstrate record WF Sensing and Control capabilities at the tens of pm rms levels required, and over timescales commensurate with the characterization of faint exoplanets (10's of hours)

Extra Material

Summary and Nominal DRM

- Top priority from the 2010 Astrophysics Decadal Survey
- Now with a Hubble sized telescope donated by the
- Hubble power and resolution, with 100x the field of view
- Providing unprecedented science capabilities in:
  - Dark energy studies,
  - exoplanet population studies,
  - NIR wide-field surveys
- Coronagraph tech demo to build the "Search for Life" foundation

Nominal 6 (?) yrs design reference mission

- 2 yrs High-Latitude Survey (HLS) → Imaging & spectroscopy
- ~6 months SNe search and IFC follow-up
- ~1 yr for coronograph
- ~1 yr for repeated galactic bulge observations for microlensing
- ~1.5 yr (25%) Guest Observer program. An extended mission (10+ years) would consist of an expanded GO program
- All data public days after they are taken

Design Reference Mission Yields

Attributes	WFIRST Yields
Imaging survey	J ~ 27 AB over 2200 sq deg
	J ~ 29 AB over 3 sq deg deep fields
Slitless spectroscopy	R~461λ over 2200 sq deg
Number of SN Ia SNe	2700 to z~1.7
Number galaxies with spectra	$2x10^7$
Number galaxies with shapes	$4x10^8$
Number of galaxies detected	few x 10^9
Number of massive clusters	$4x10^4$
Number of microlens exoplanets	2600
Number of imaged exoplanets	10s

WFIRST CGI Science Pie Chart