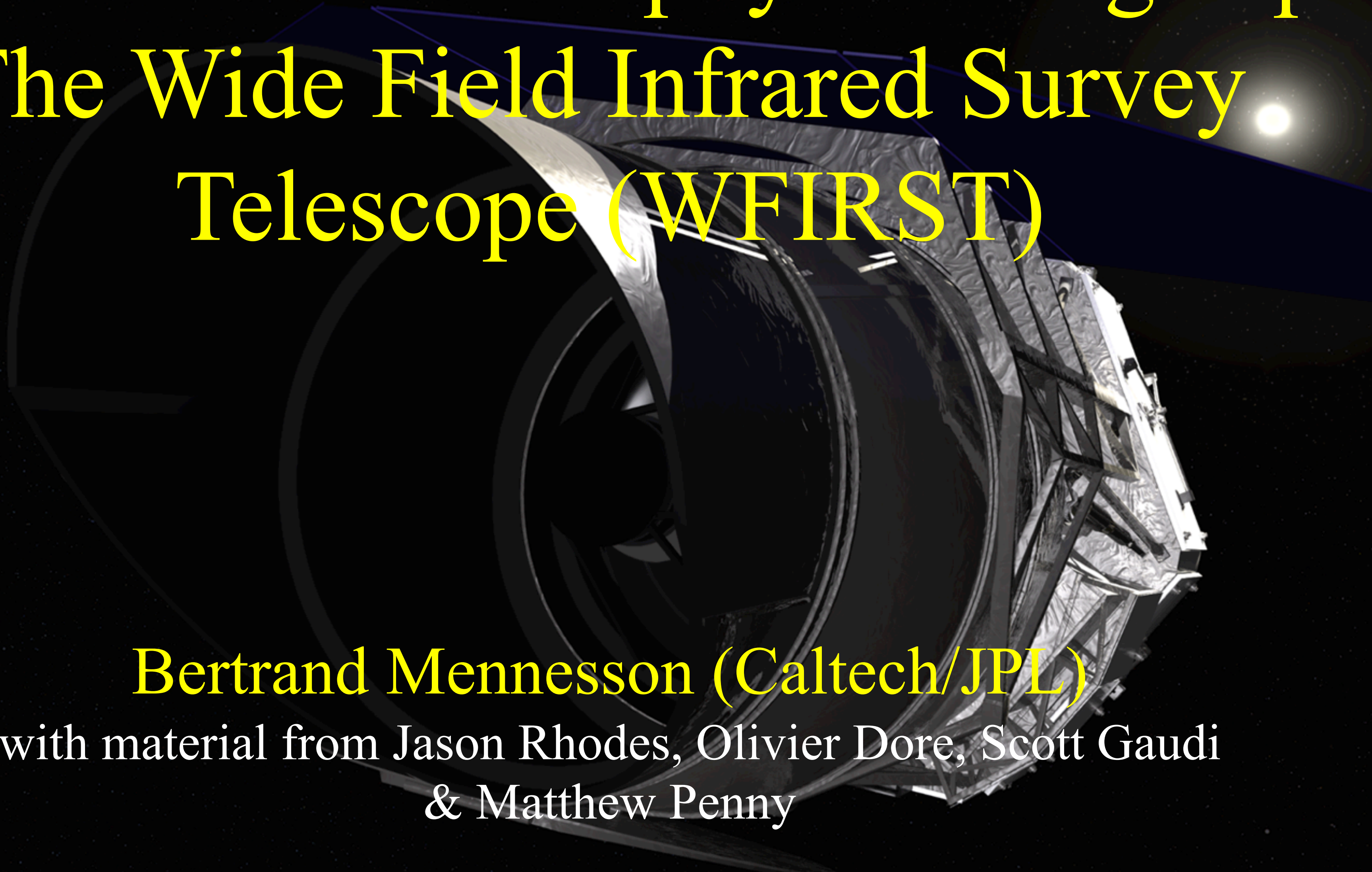
# NASA's Next Astrophysics Flagship: The Wide Field Infrared Survey Telescope (WFIRST)



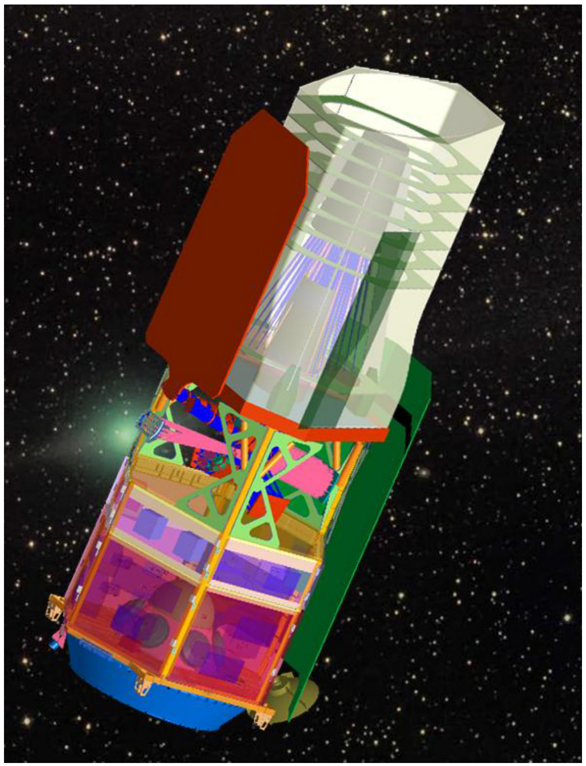
Bertrand Mennesson (Caltech/JPL)

with material from Jason Rhodes, Olivier Dore, Scott Gaudi & Matthew Penny

2017 Sagan Exoplanet Summer Workshop

"Microlensing in the era of WFIRST", August 10, 2017


# WFIRST =



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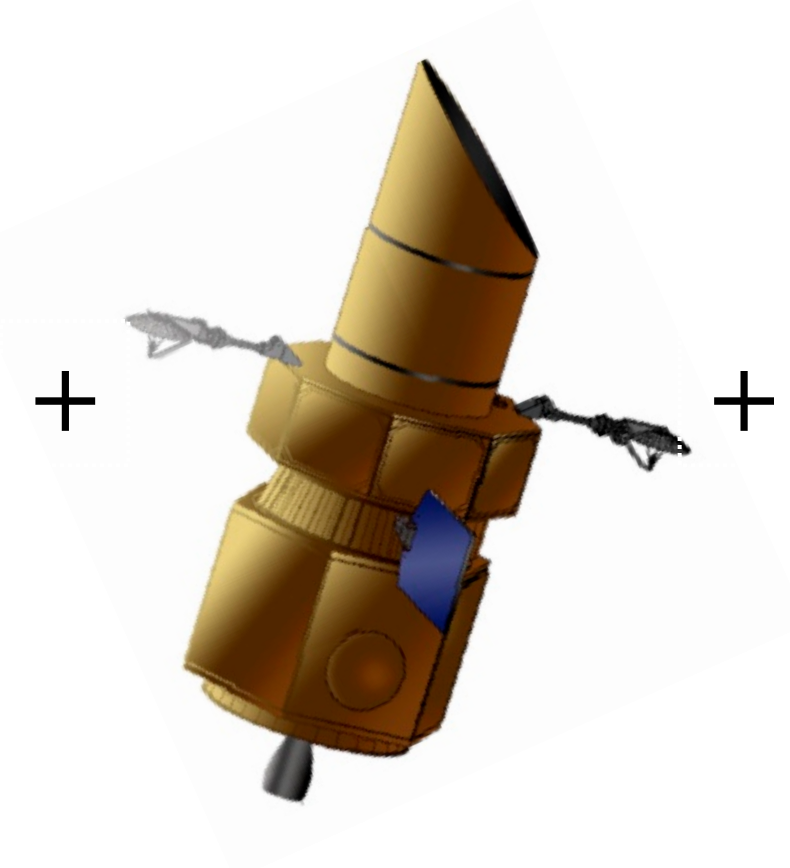

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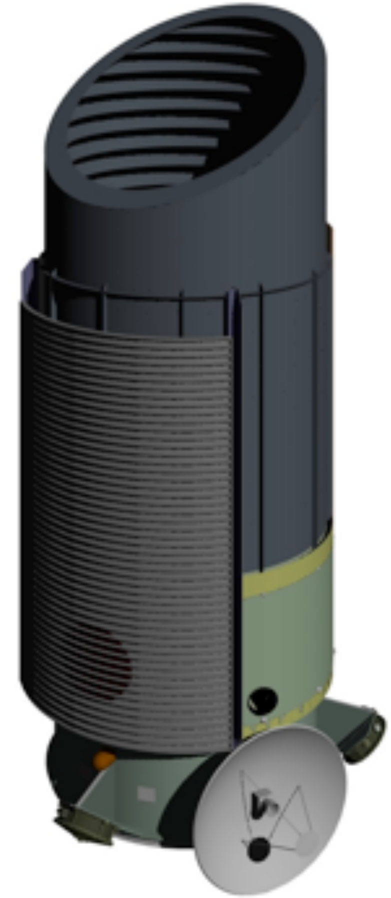


JDEM

*Dark Energy*

MPF

*Exoplanet Census*

NIRSS

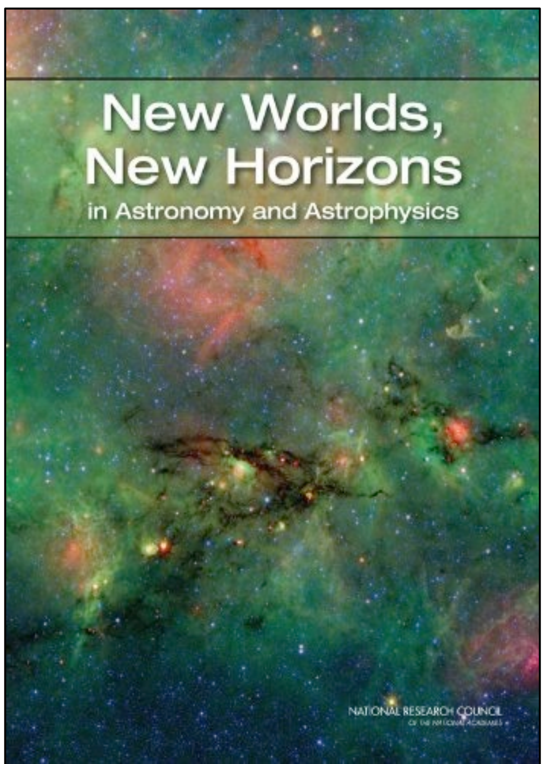
*Infrared Sky Survey*


# 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

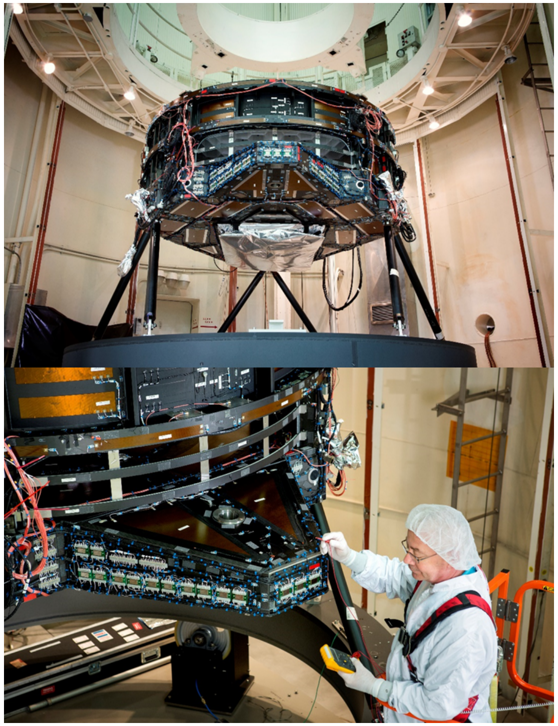
### 20 Key Science Questions

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

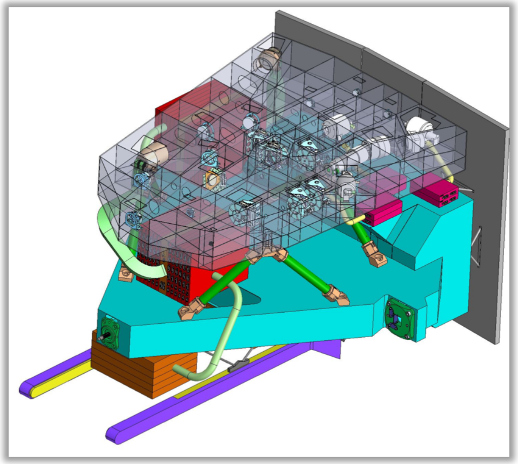
# WFIRST Inherits a Larger Telescope (2012)

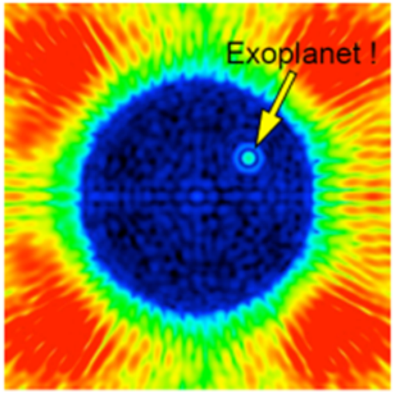
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

- 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





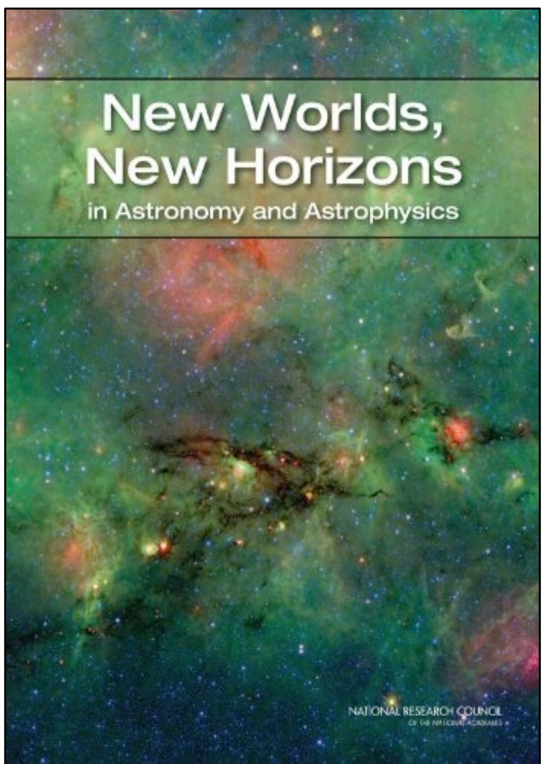
WFIRST
Wide-Field Infrared Survey Telescope
Astrophysics • Dark Energy • Exoplanets

# WFIRST Checks Many Boxes

## 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




### 5 Discovery Science Areas

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

### 20 Key Science Questions

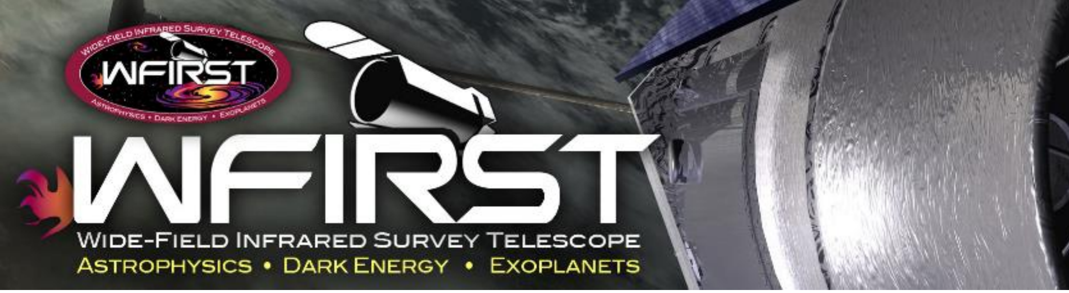
- Origins **(7/7 key areas)**
- Understanding the Cosmic Order **(6/10 key areas)**
- Frontiers of Knowledge **(3/4 key areas)**


# WFIRST 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 Science Goals

*complements Euclid*

*complements LSST*

*complements Kepler*

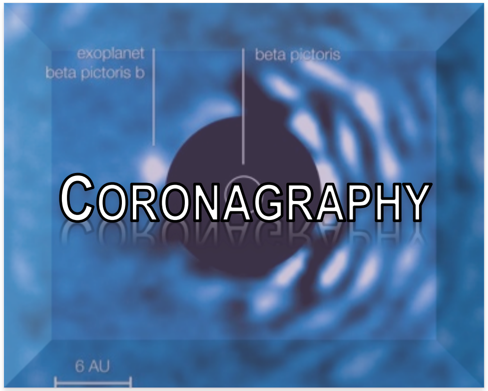
Baryon Acoustic Oscillations

Gravitational Lensing

Supernovae

Legacy Science with Surveys

Microlensing Census




Coronagraphy

Guest Observer Program

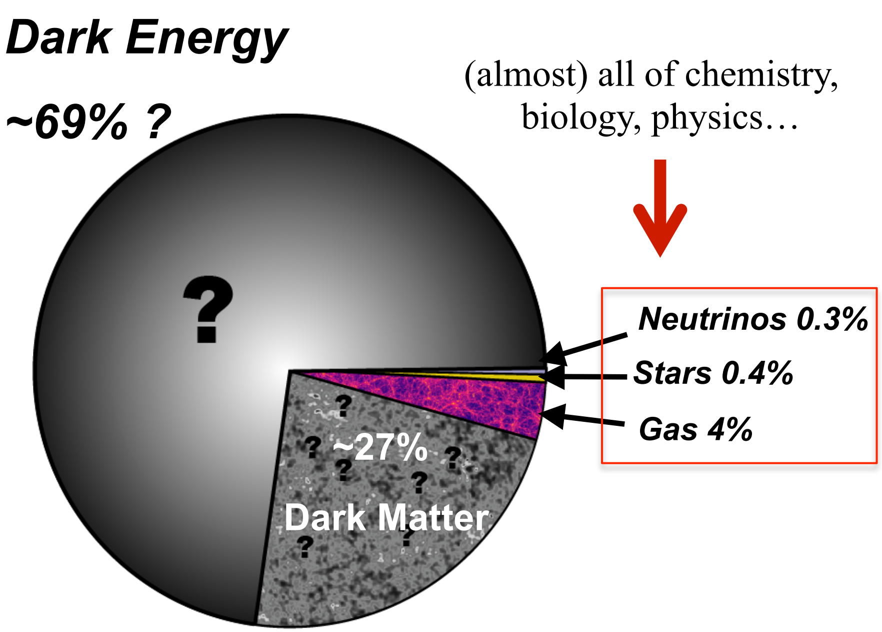
*continues Great Observatory legacy*

# 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?



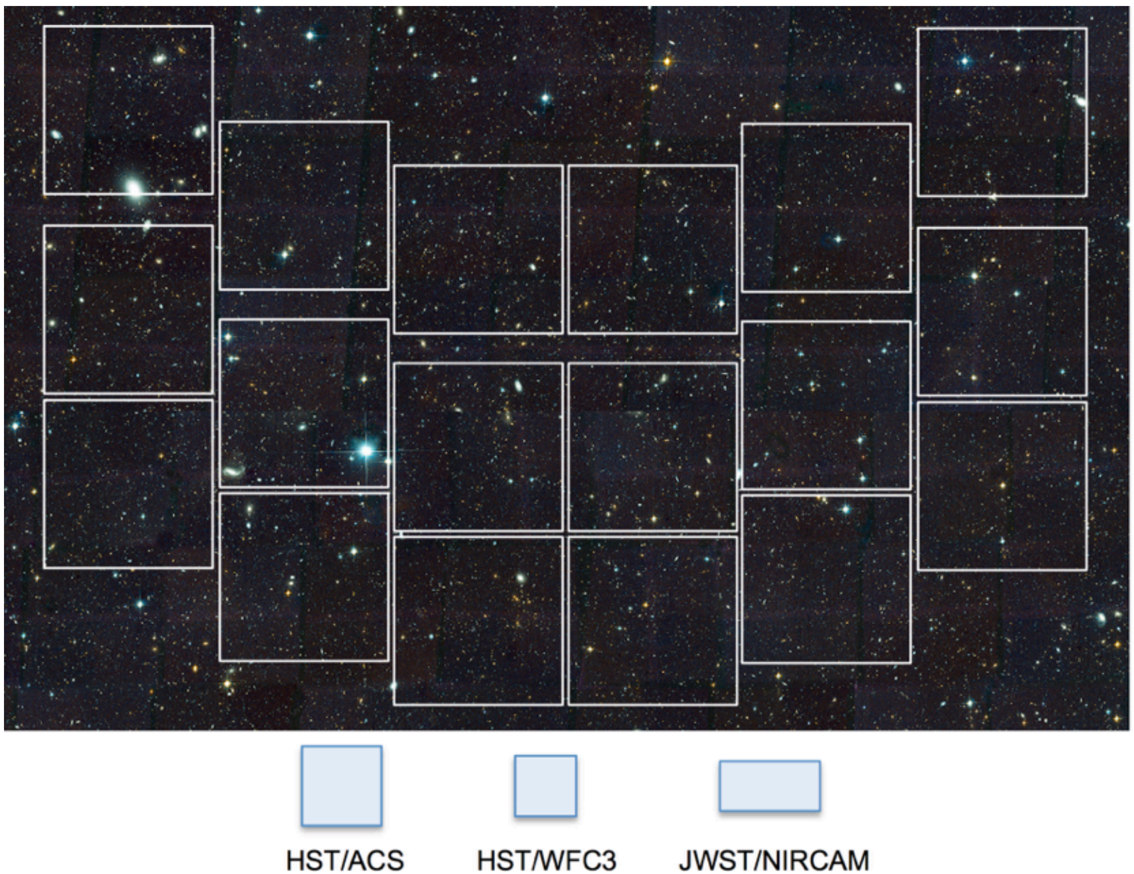

*The Universe as a Pie Chart*

# 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

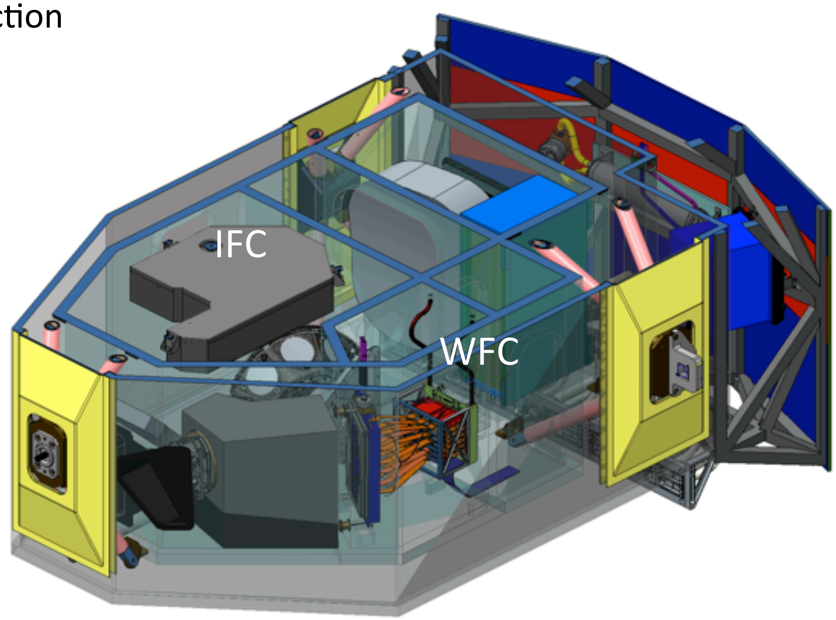
wide, medium, & deep imaging
+ IFC spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

# Wide Field Instrument Specifications

## The Wide-field instrument is split into two optical channels:

- Wide Field Channel (WFC)
  - Very large instantaneous imaging field of view (FOV) (0.28 deg$^2$)
  - Spatial resolution: 0.11 arcsec/pixel (~Nyquist sampled at 2μm)
  - Image stability: 1.0 nm RMS wave front error (WFE) variation in 180 sec
  - Near-infrared pass band (0.76 to 2.0μm)
  - 6 imaging filters*: z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)
  - Grism (1.35 to 1.89 μm ) for multi-object, medium (~400) resolution spectroscopy
  - Guide star sensing interleaved with science data collection
- Integral Field Channel (IFC) spectrograph with two Fields of View
  - Supernova FOV (IFC-S)
    - 3 x 3 arcsec, 0.075 arcsec/pixel resolution
  - Galaxy Photometric Redshift Calibration FOV (IFC-G)
    - 6 x 6 arcsec, 0.15 arcsec/pixel resolution
  - Very high sensitivity, NIR pass band (0.6-2.0μm)
  - Low spectral resolving power (~100)



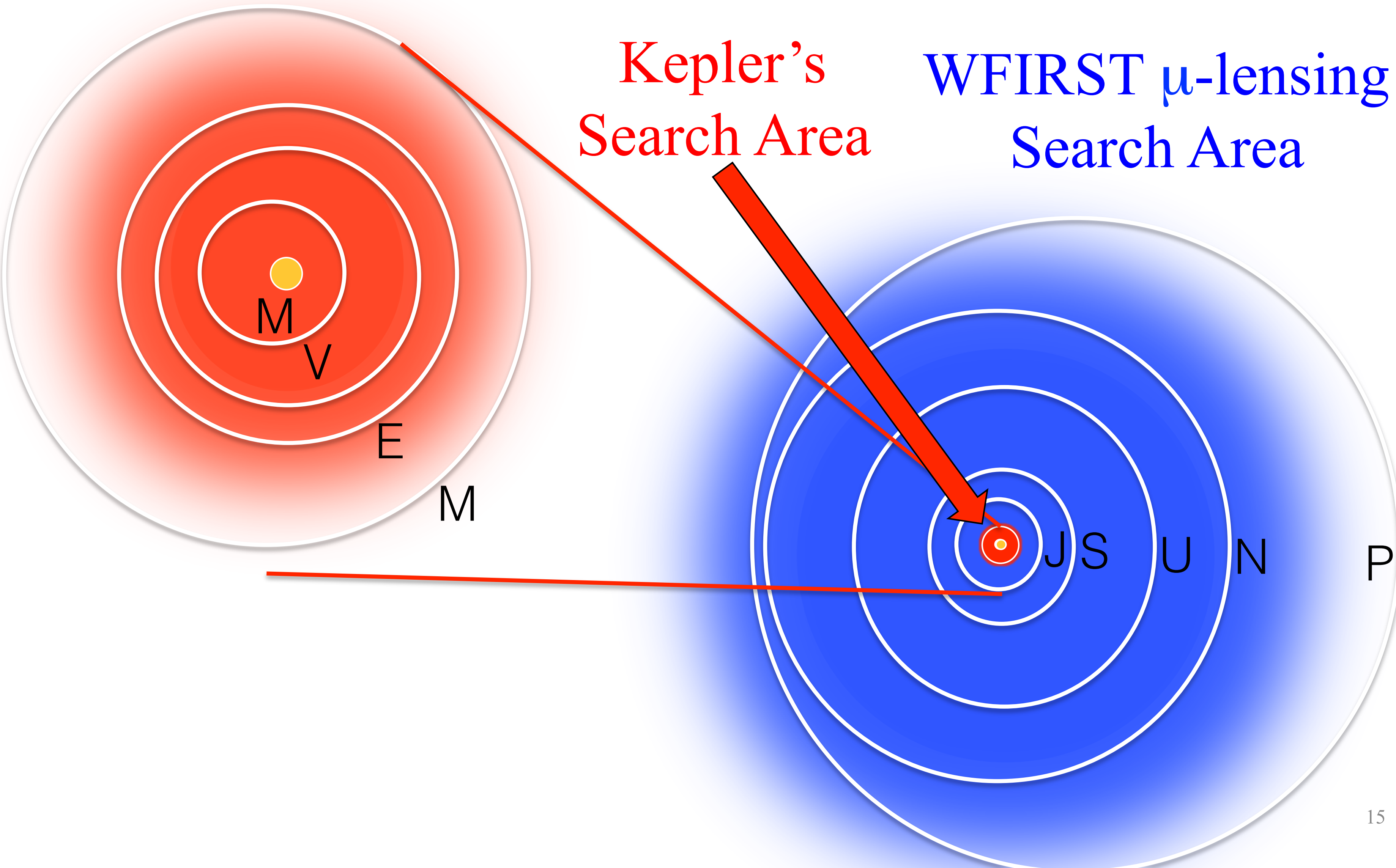
**Primary Microlensing Science Objective:**

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.

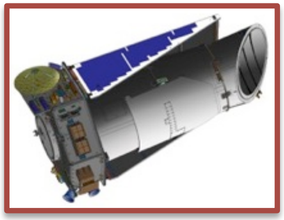
# Exoplanet Demographics: Why do we care?

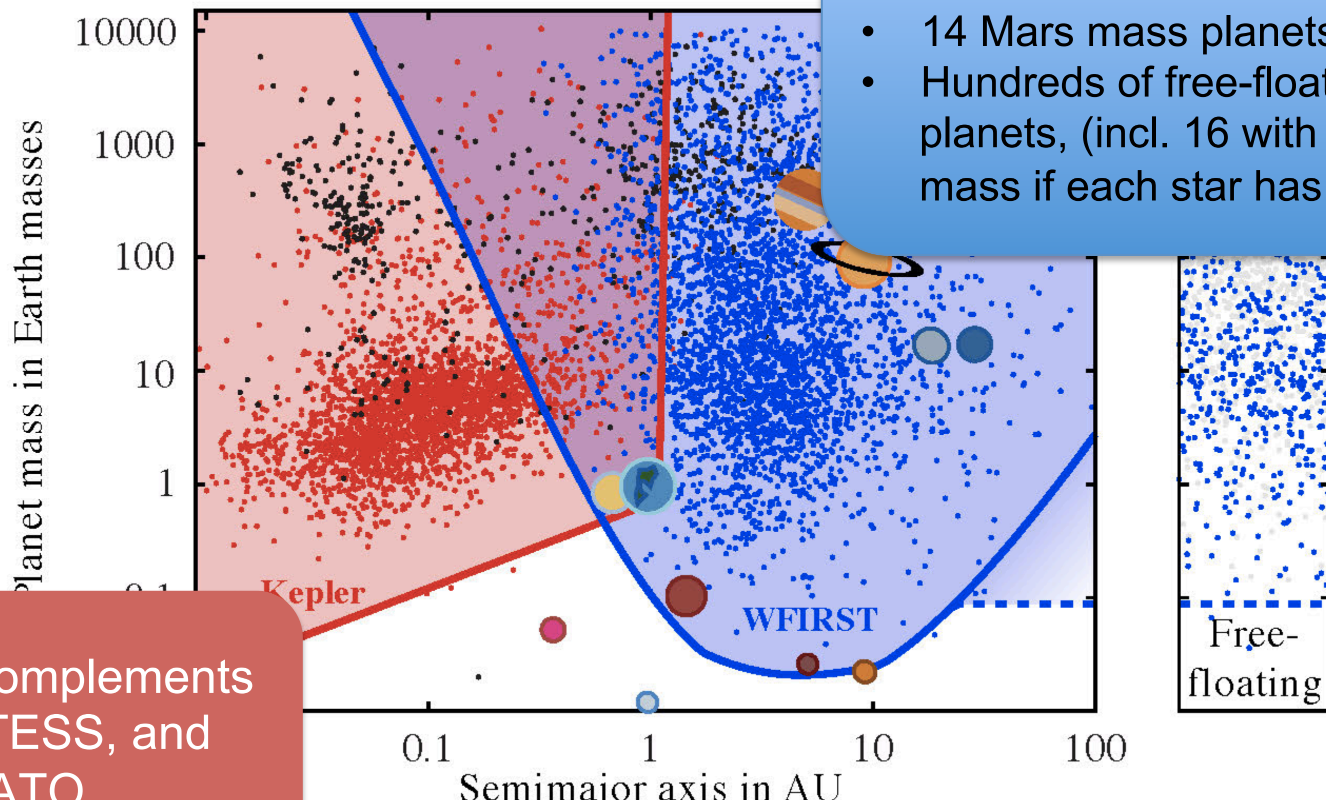
- Despite enormous progress on many fronts, we still don't fully understand planet formation.
- The planet distribution function may have the physics of planet formation imprinted on it.
- But, it's hard: we know that the planet distribution function depends on at least four parameters (planet mass, 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




# Completing the census ("Penny Plot")



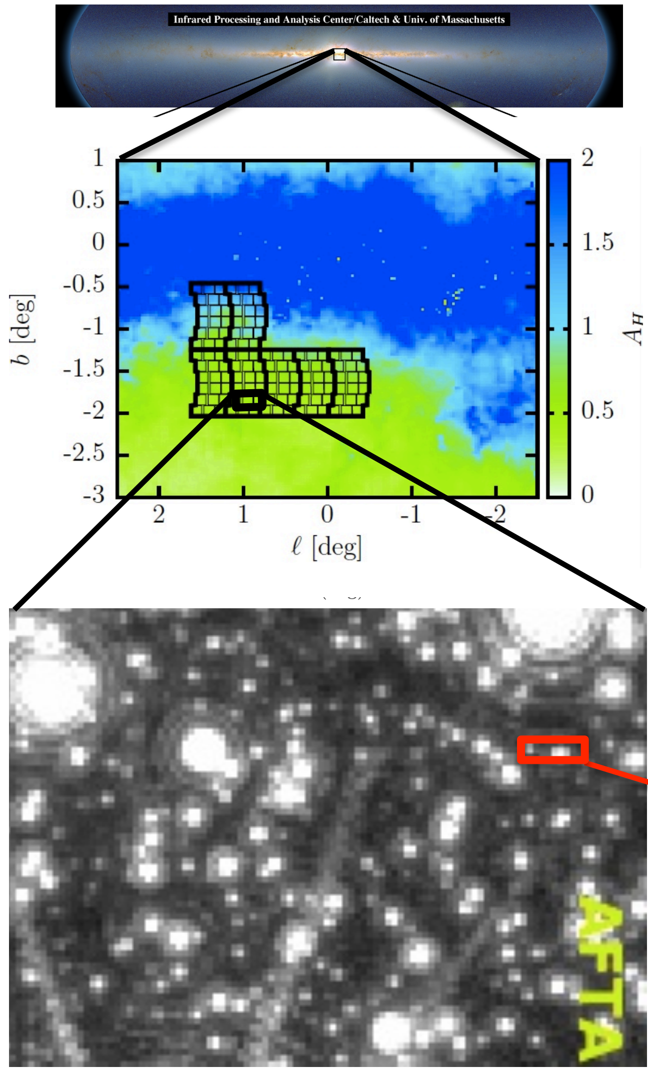



- 1000 planet detections.
- 120 with Earth mass and below
- 14 Mars mass planets
- Hundreds of free-floating planets, (incl. 16 with Earth mass if each star has one)

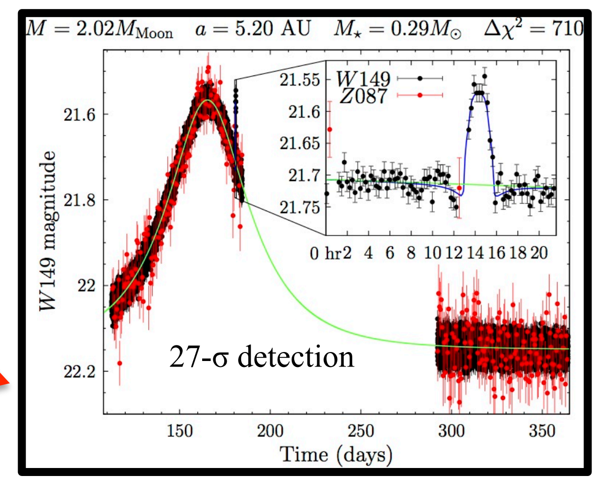
WFIRST complements Kepler, TESS, and PLATO.

(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)**

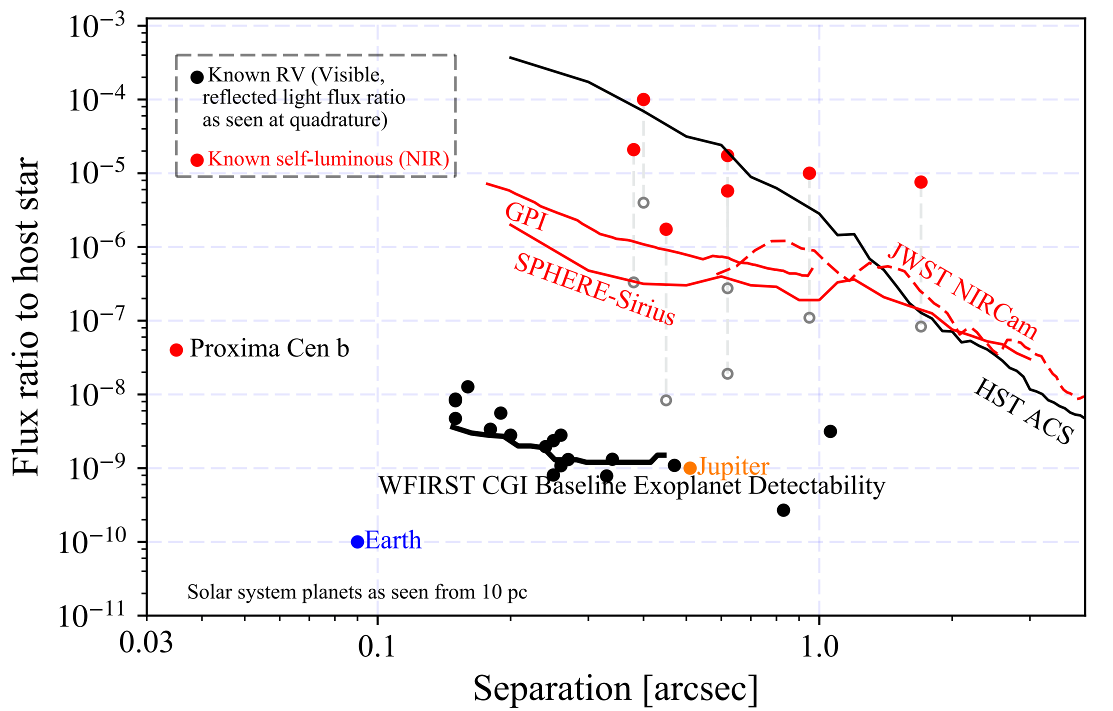
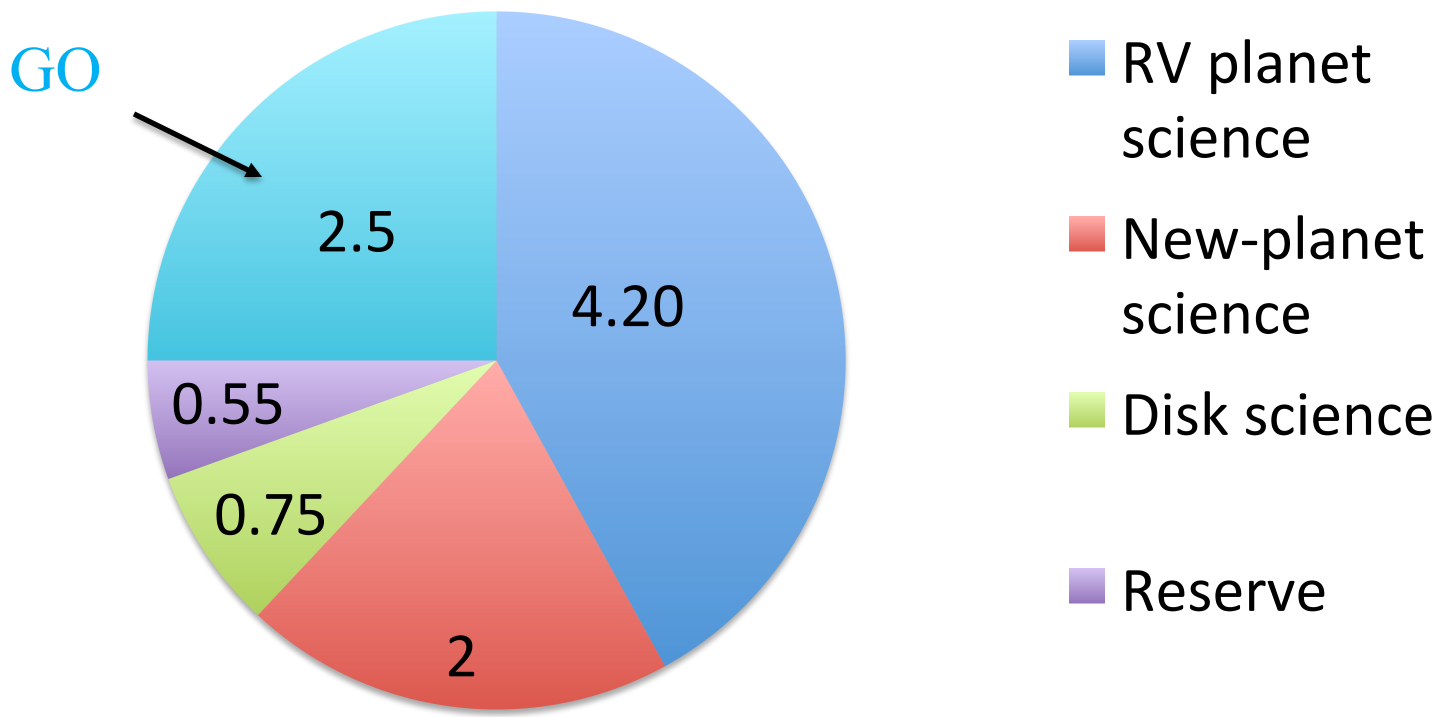



***Figure courtesy of Tiffany Meshkat (IPAC) & Karl Stapelfeldt (NASA-JPL)***

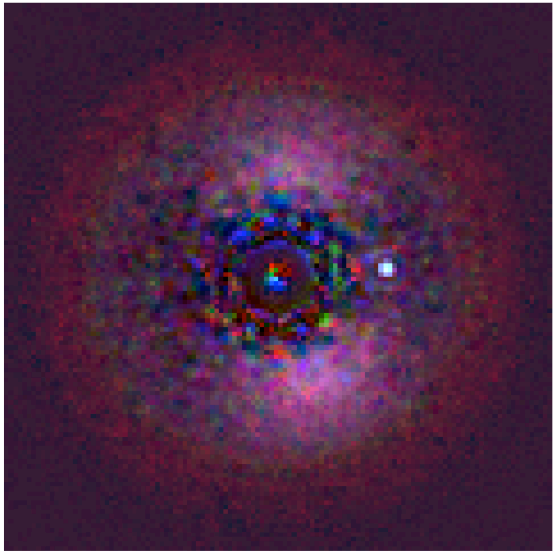
# WFIRST CGI Science Pie Chart

## "Strawman" CGI Science Time Allocation (months)

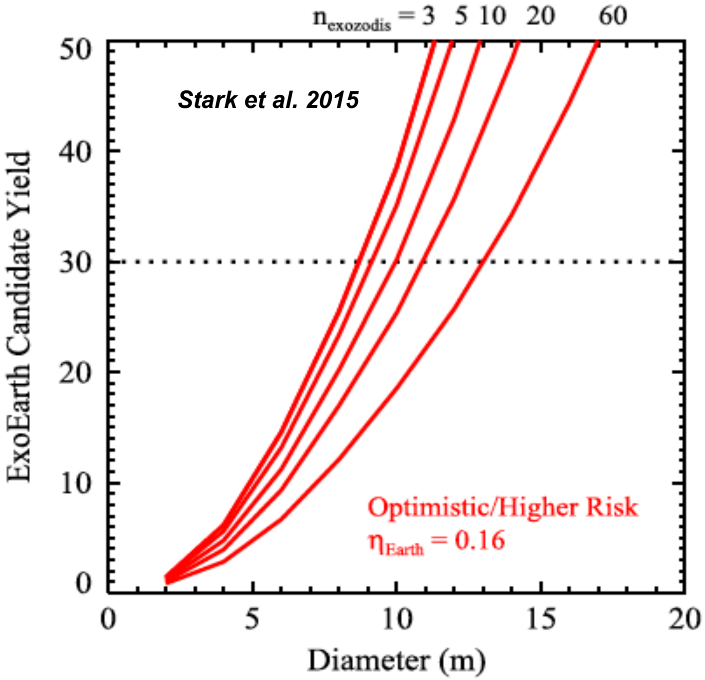


# CGI Exoplanet & Exo-zodiacal Disks Imaging

- 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)

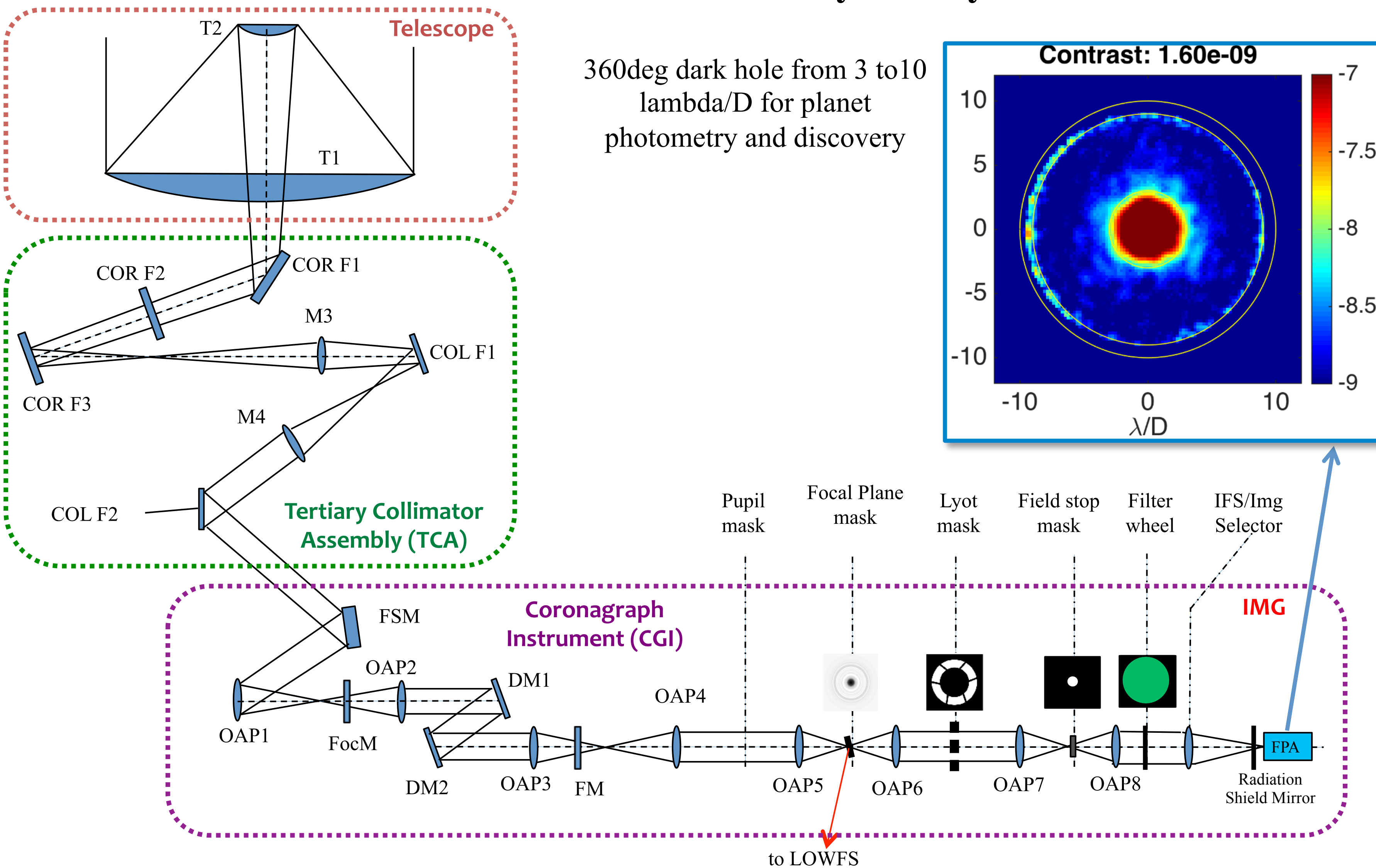


***WFIRST CGI multi-color imaging simulation of a Jupiter mass planet at 2 AU from a Sun-like star at 3pc, with a 10-zodi interplanetary dust structure.***
*Image Credit: M. Rizzo, N. Zimmerman, A. Roberge / E. Douglas / L. Pueyo*



# 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

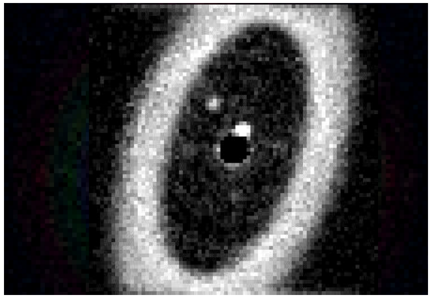
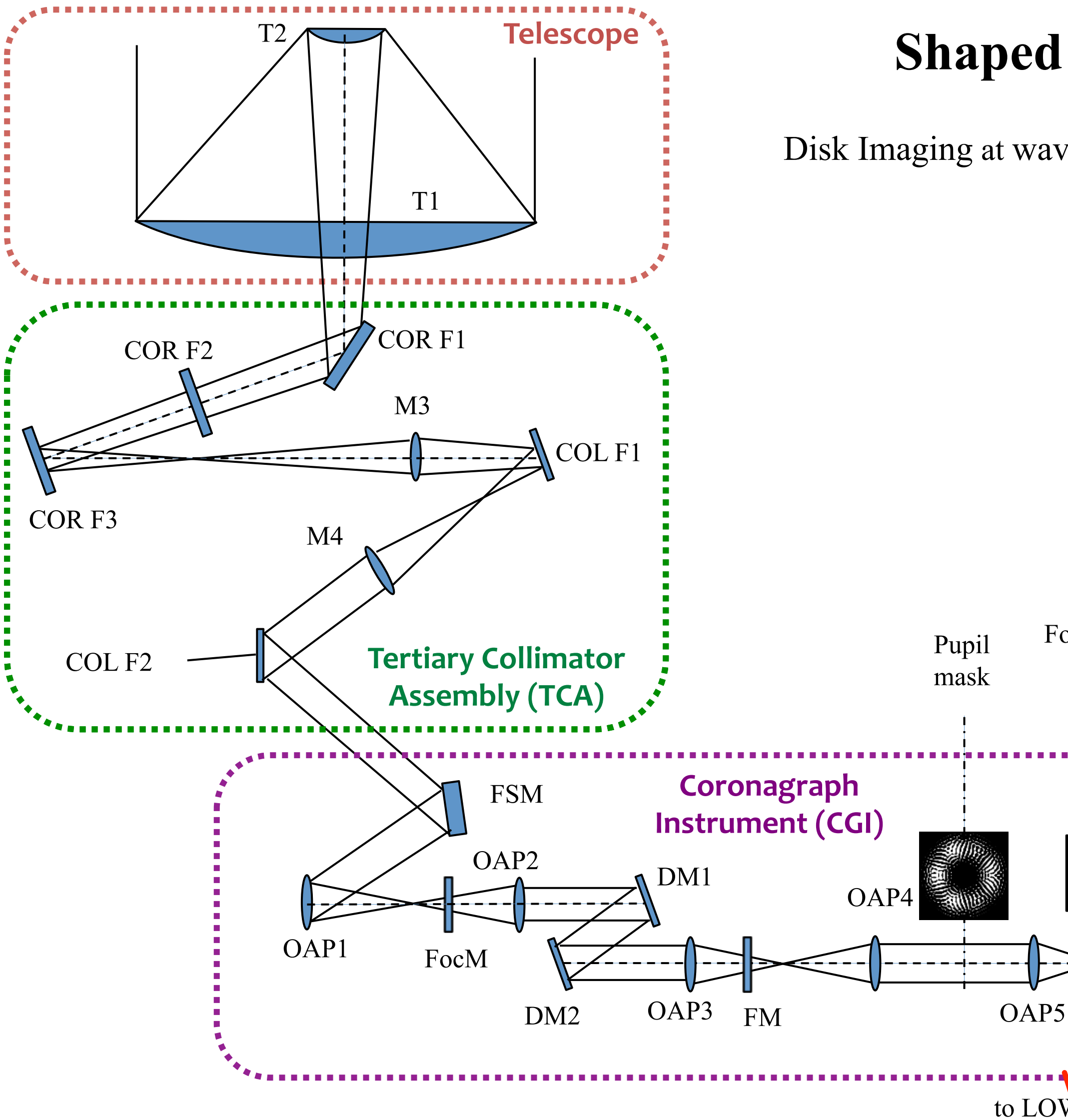
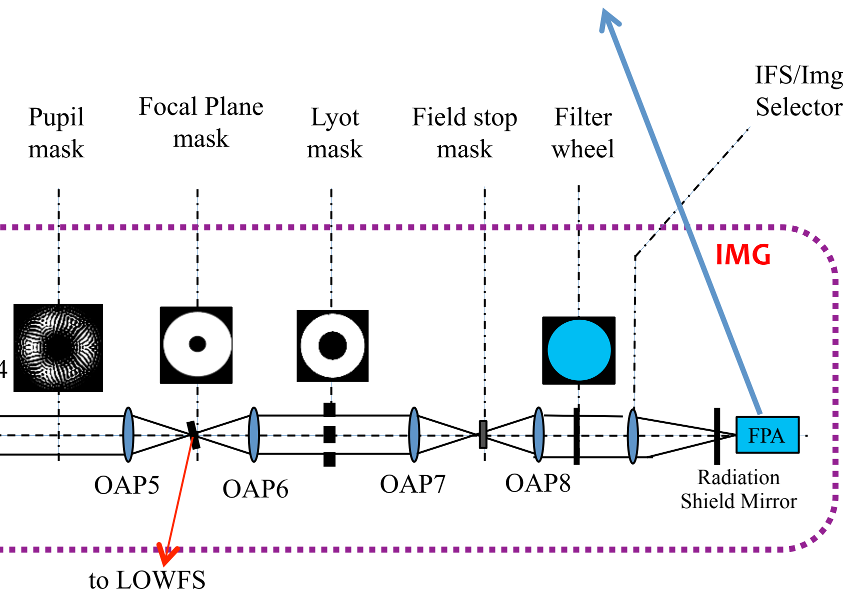


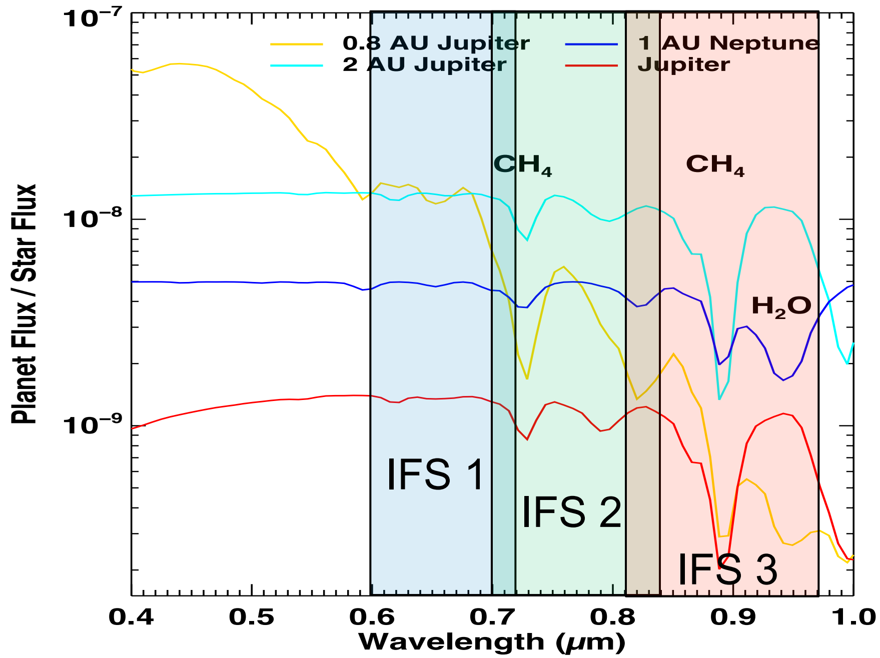
Image from 2015 Exo-C STDT Final Report

# CGI Spectroscopy of Extrasolar Giant Planets

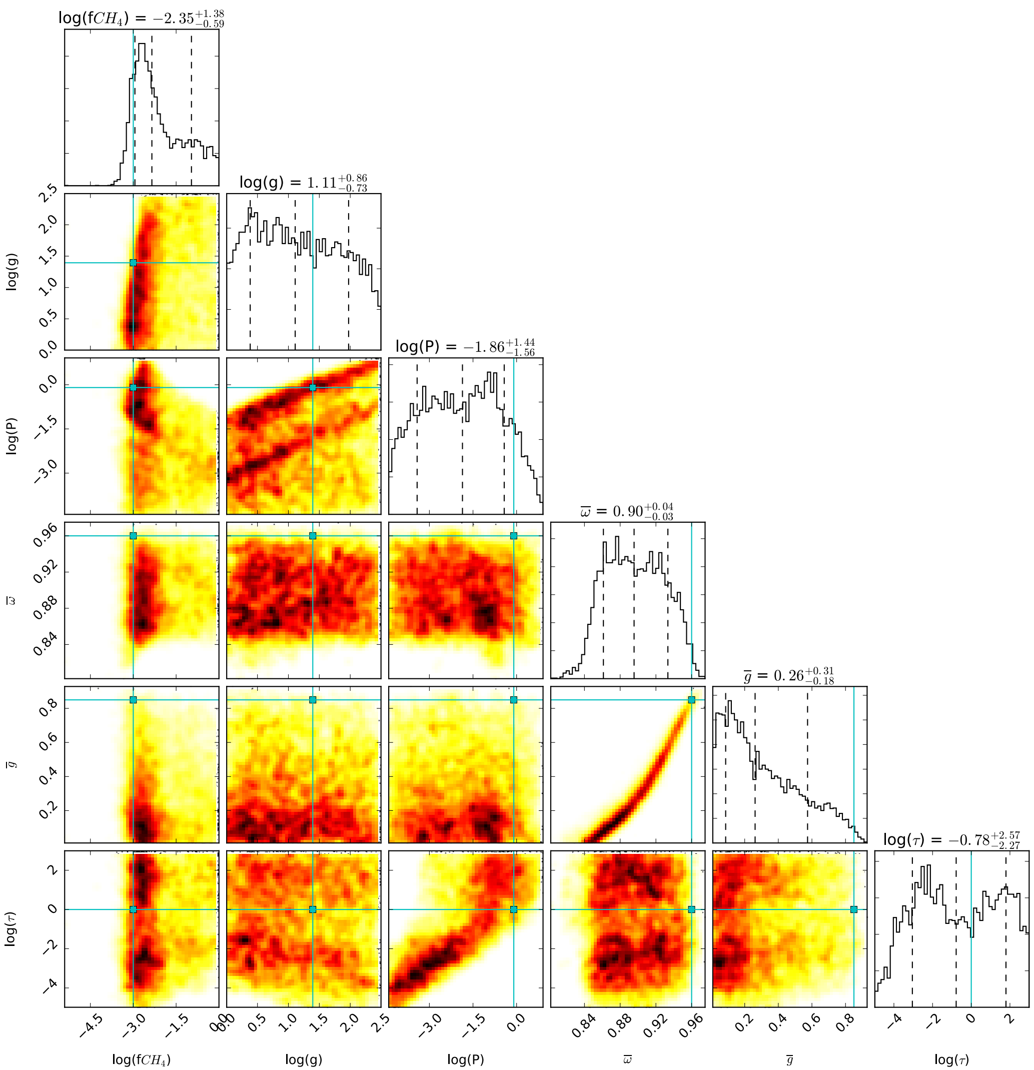
- CGI will *study the composition and bulk properties of giant planets via multi-band photometry and spectroscopy of features such as methane, to constrain their atmospheric metallicity,* as well as aerosol and cloud properties, providing unique constraints on their formation and evolution

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




***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 $\tau$.

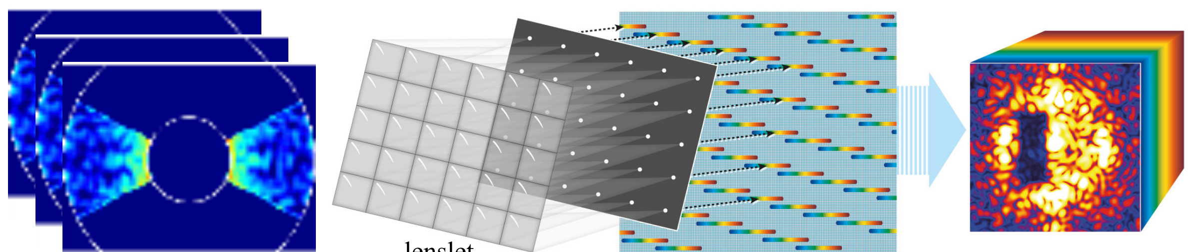
*Posterior PDF for key atm. parameters, for simulated R=50 CGI spectra of a giant planet, from Lupu et al. 2016.*

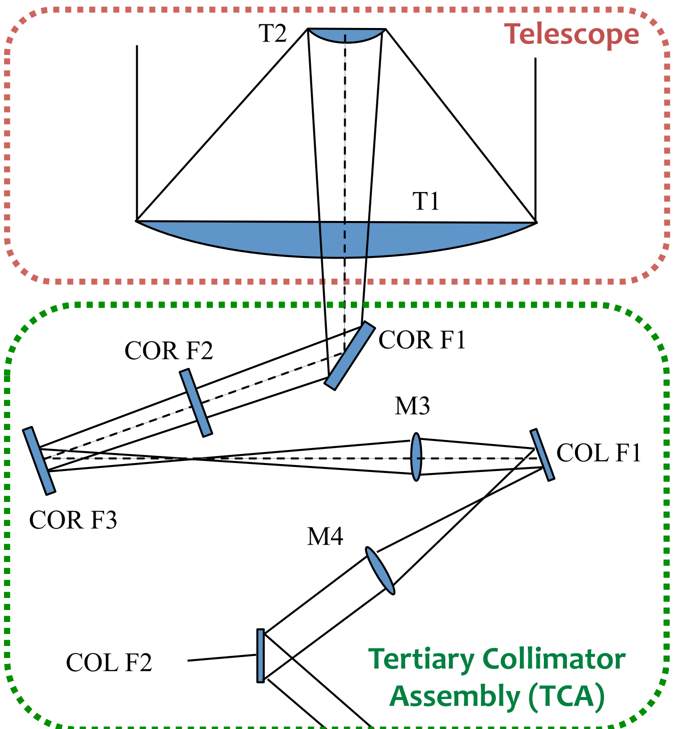
# CGI Spectroscopy Mode: Shaped Pupil +IFS

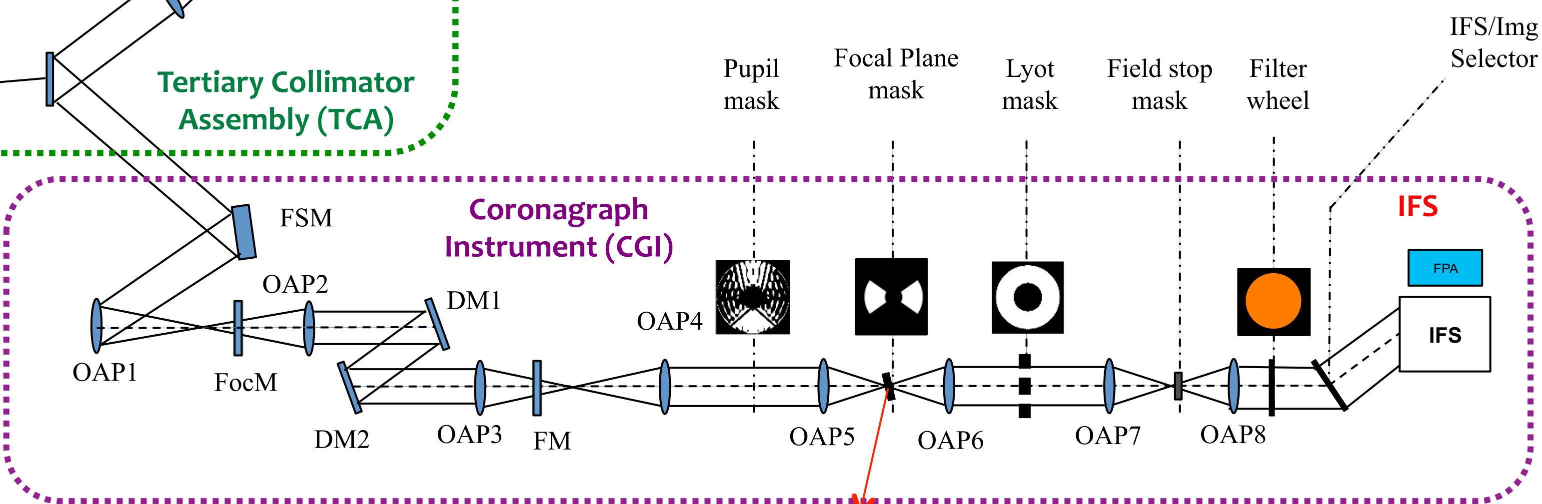
WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
ASTROPHYSICS • DARK ENERGY • EXOPLANETS

## Shaped Pupil Spectroscopy Mode

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

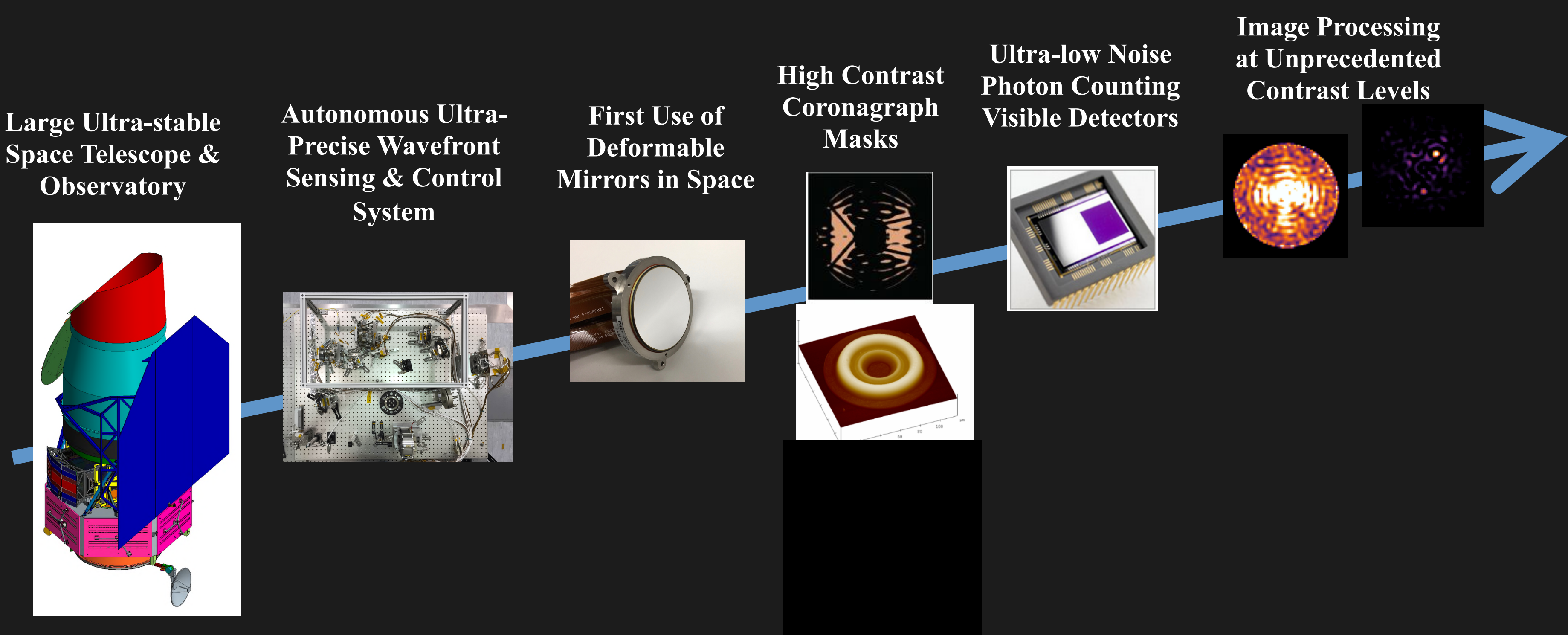


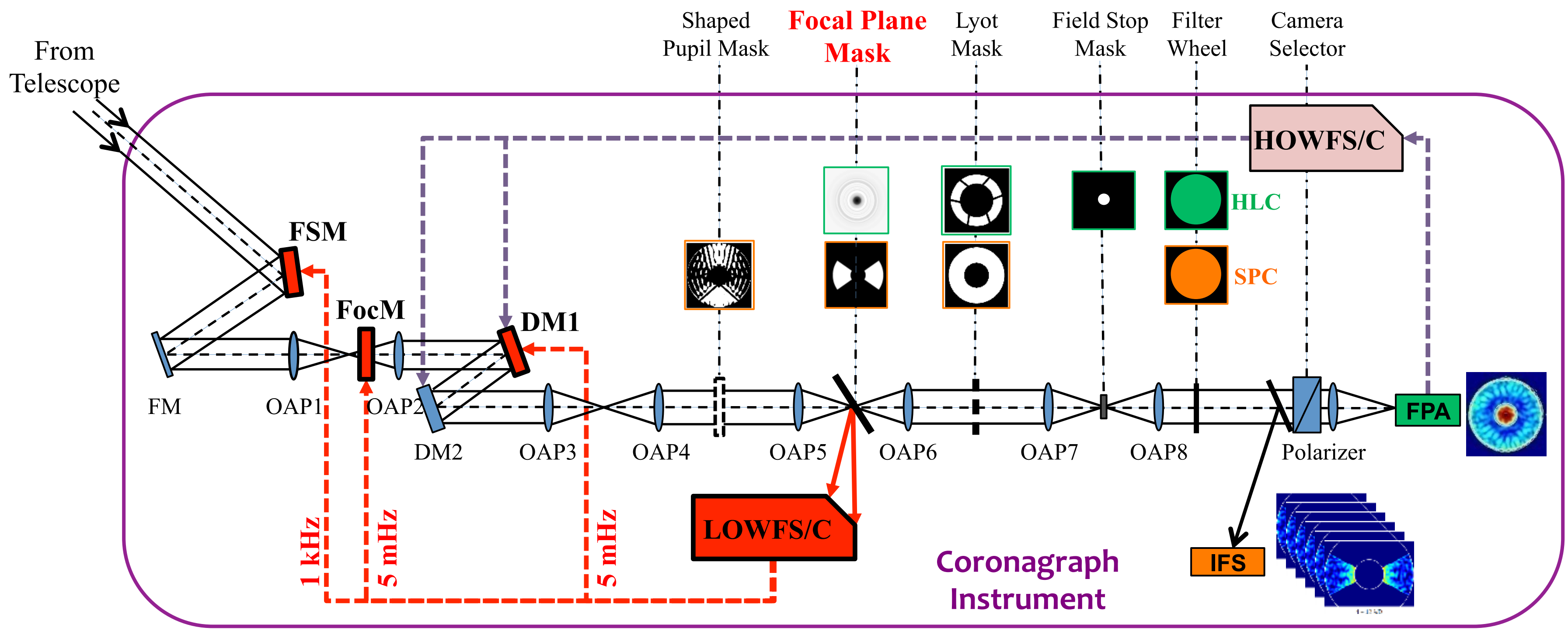

# CGI as a Technology Demo for Future Missions

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




**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)


# 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

# WFIRST Formulation Science Working Group (FSWG)

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Jeremy Kasdin Princeton U. CGI Adjutant Scientist, Co-Chair
David Spergel Princeton U. WFI Adjutant Scientist, Co-Chair

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Bruce Macintosh Stanford U. Coronagraph
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David Weinberg Ohio State U. Weak Lensing,
Redshift Survey

**INTERNATIONAL OBSERVERS**
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Jean Dupuis CSA Representative
Thomas Henning ESA Representative
Toru Yamada JAXA Representative

- *Please contact FSWG members with any specific questions*
- *You will be the ones doing great science with WFIRST !*

# Extra Material

# Overview of Ground System Components (v. 11/28/16)

## GSFC Functions

- Project Mgt. & Project Science
- Director's Office
- Mission Operations
- WFI Instrument Engineering

FDF | MOC

### GSOC (Goddard Science Ops. Center)

- Science Ops. Mgt.
- Manage Survey Science/Long-Term Strategy & Planning
- Manage GO/GI Program & Grants, Issue Call for Proposals
- Mission Outreach/Comm.

### WIEC (WFI Instrument Engineering Center)

- Maintain test beds
- Support commissioning planning & execution
- Support science planning & scheduling
- FSW maintenance
- Trending & calibration
- Generate command procedures
- Anomaly resolution

## STScI Functions

- Supernovae & HLS Science
- WFI Science
- Detailed Planning & Scheduling
- Science Data Archive

### SSOC (STScI Science Ops. Center)

- Science Planning and Scheduling
- WFI Calibrations
- WFI Data Processing Algorithms
- WFI Data Processing Pipeline
- WFI commanding
- WFI Commissioning
- WFI GO Implementation
- WFI Outreach, excluding microlensing
- WFI Data Analysis Tools
- Data Archive
- WFI User Support

**Science Teams**
Requirements Development, etc.

## IPAC Functions

- Microlensing Science
- CGI Science
- GO/GI Peer Review (incl. TAC)

### ISOC (IPAC Science Ops. Center)

- Ingest Proposals
- Run Peer Review Process (TAC)
- Microlensing High-Level Processing
- CGI Calibrations
- CGI Data Processing Algorithms
- CGI Data Processing Pipeline
- CGI Commanding
- CGI Commissioning
- GCI GO Implementation
- CGI and microlensing Outreach
- CGI Data Analysis Tools
- CGI User Support

## JPL Functions

### CIEC (CGI Instrument Eng. Ctr.)

- Maintain test beds
- Support commissioning P&E
- Support science P&S
- FSW maintenance
- Trending & calibration
- Generate command procedures
- Anomaly resolution

# 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 | $2 \times 10^7$ |
| Number galaxies with shapes | $4 \times 10^8$ |
| Number of galaxies detected | few $\times 10^9$ |
| Number of massive clusters | $4 \times 10^4$ |
| Number of microlens exoplanets | 2600 |
| Number of imaged exoplanets | 10s |

# Technological leap

- Current best coronagraphs reach a contrast ratio of $10^7$
- WFIRST design goals (not requirements) are $10^9$
- All technological milestones have been hit ahead of schedule and $10^8$ has been shown in lab
- WFIRST will test two different types of coronagraphs for both spectroscopy (shaped pupil) and photometry (hybrid Lyot)
- What we need for direct imagine of an exo-Earth to show biomarkers is probably $10^{10}$
- The Astro 2020 Decadal Survey will look at Hab-Ex and LUVOIR, two mission concepts that might be able to do this

# The WFIRST Coronagraph Instrument (CGI): a *critical* step in the Exploration of Sun-like planetary systems

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

- CGI *Technical* Premieres in Space & Legacy (I)

❖ CGI will bring us most of the way toward the characterization of rocky planets in the HZ

❖ CGI will demonstrate record Passive Wavefront (WF) Stability

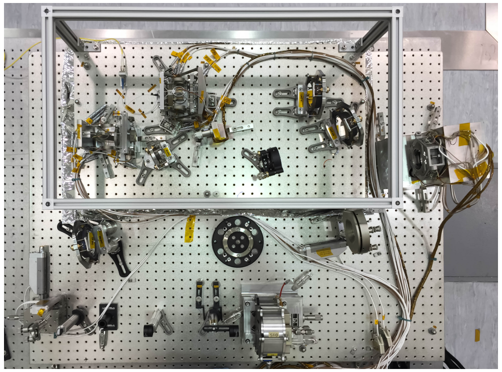
- ❖ Validating **observatory-wide *(STOP)* models** that predict ***passive*** stability at

the ~10-100pm rms level over 100s of seconds (as required for accurate low-order WF sensing using natural starlight, see *Feng Zhao's talk*)

❖ CGI will provide an in-space demonstration of ***active*** line of sight jitter correction down to ***sub-mas*** level for the first time, using a Fast Steering Mirror (~10x better pointing stability than HST)

❖ CGI will demonstrate record WF Sensing and Control capabilities

- ❖ First in space demonstration of low order WF sensing
- ❖ ***Active*** WF correction using Deformable Mirrors
- ❖ Both at the tens of pm rms levels required, and over timescales commensurate with the characterization of faint exoplanets (10's of hours)



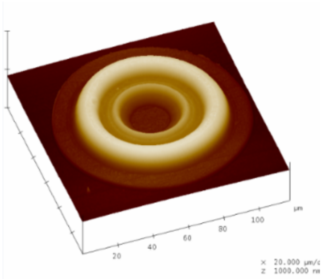
*WFIRST CGI LOWFS System*
*Image Credit: F. Shi (JPL)*

*Xinetics 48 x 48 DM used in JPL's HCIT.*
*Image Credit: J. Trauger (JPL)*

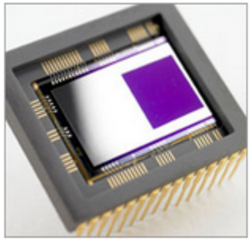
# The WFIRST Coronagraph Instrument (CGI): a *critical* step in the Exploration of Sun-like planetary systems

## • CGI *Technical* Premieres in Space & Legacy (II)

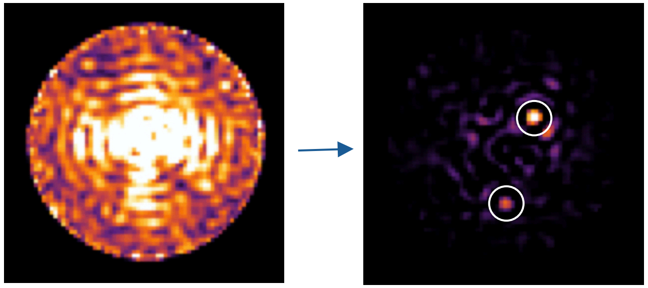
- Coronagraph Optics and Architecture
  - CGI will space qualify very high contrast (~$10^{-9}$) coronagraph masks. HST (and JWST) masks (will) only provide ~$10^{-5,6}$ contrast
  - CGI will provide in-space demonstration of autonomous starlight deep suppression algorithms



- Detectors
  - CGI will demonstrate the first in space operation of ultra-low noise photon counting detectors (EMCCDs) required for R>50 spectroscopy of Vmag ~ 28 exoplanets



- PSF subtraction and source detection algorithms
  - CGI will remove faint starlight "speckles" down to record low residual levels, pushing current post-processing algorithms to the regime of faint exoplanets for the first time ($10^{-9}$ flux ratio, vs ~ $10^{-6}$ today)

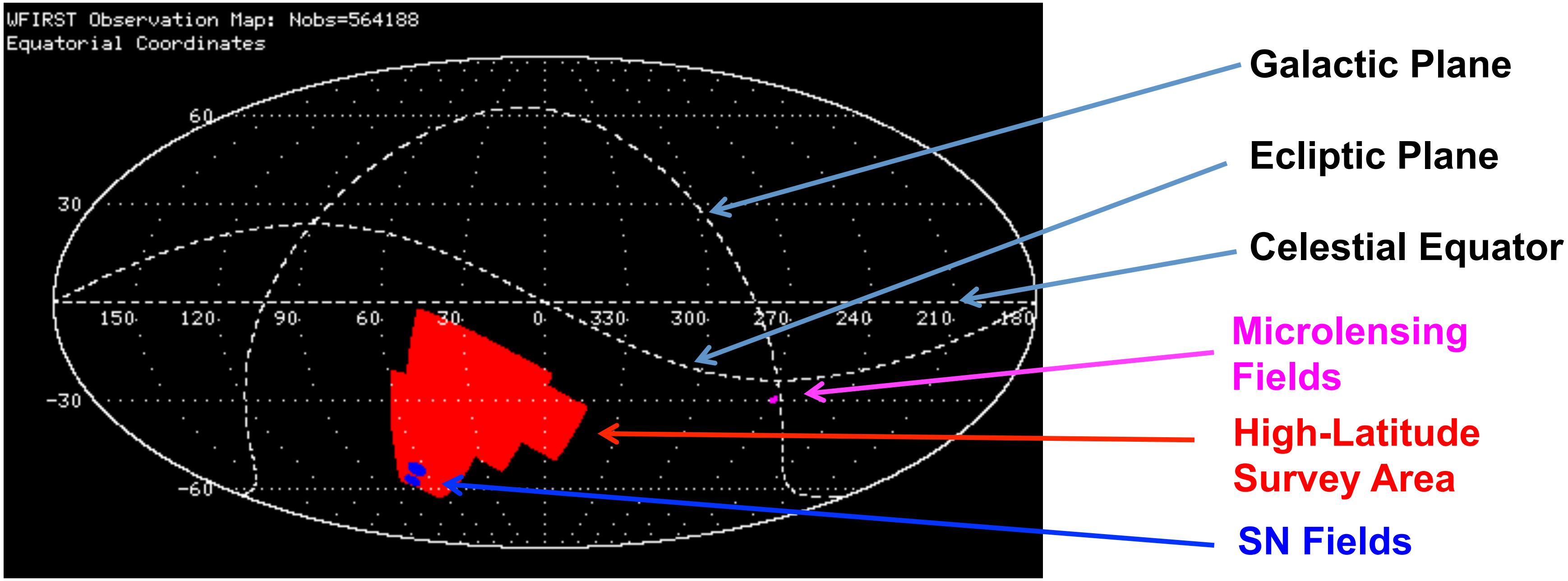


*Results of end-to-end simulations and post-processing of WFIRST CGI observations (47 UMa). Ygouf et al. 2015*

- Heavily obscured telescope apertures
  - CGI will demonstrate high contrast imaging capabilities with a complex/ heavily obscured entrance pupil (relevant to LUVOIR)
  - CGI WF stability may already meet requirements for exo-Earths imaging using unobscured apertures (e.g. HabEx 4m off-axis design)

# Example Observing Schedule (to be revised by future science team)

- High-latitude survey (HLS: imaging + spectroscopy): 2.01 years
  - 2227 deg$^2$ @ ≥3 exposures in all filters (2279 deg$^2$ bounding box)
- 6 microlensing seasons (0.98 years, after lunar cutouts)
- SN survey in 0.63 years, field embedded in HLS footprint
- 1 year for the coronagraph, interspersed throughout the mission
- Unallocated time is 1.33 years (includes GO program)



# Design Reference Mission

This is in a 6 year mission with:

- 2 years High Latitude Survey (HLS) imaging an spectroscopy
- ~6 months SN search and follow-up with IFU
- ~1 year for coronagraph
- ~1 year for microlensing planet search
- ~1.5 years (25%) dedicated to Guest Observers (GO)

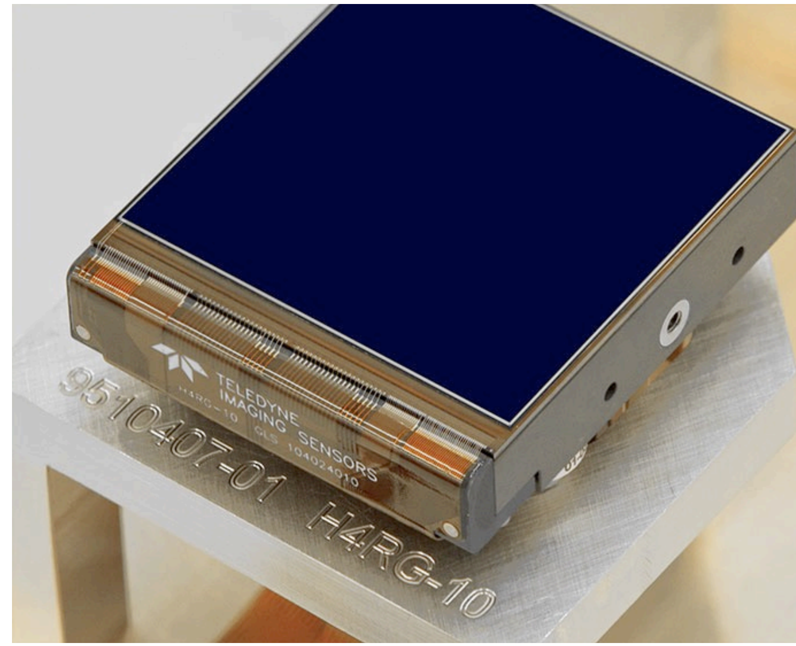
An extended mission (10+ years) would consist of an expanded GO program

WFIRST is **serviceable** has enough propellant for a 10+ year mission, and the WFI detectors don’t suffer extreme radiation degradation like CCDs

# WFIRST Status

WFIRST moving forward – Phase A entered in 2016

- Funding:
  - $203M in FY14-16
  - $120M in FY17 (Senate)
  - Detector, coronagraph development
  - On track for TRL-6 in 2017
- 2025 Launch for a 6 year primary mission
- Reviews:
  - ASM July 2016
  - SRR June 2017
  - KDP-B October 2017
- Upcoming Instrument meetings:
  - CGI Meeting Dec 7, 2016 in Pasadena
  - WFI Meeting Jan 12, 2016 in New York City



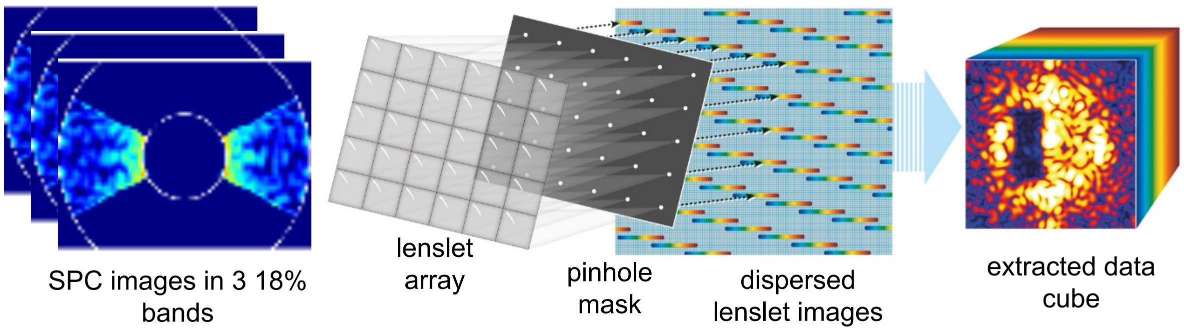

H4RG 10 micron device

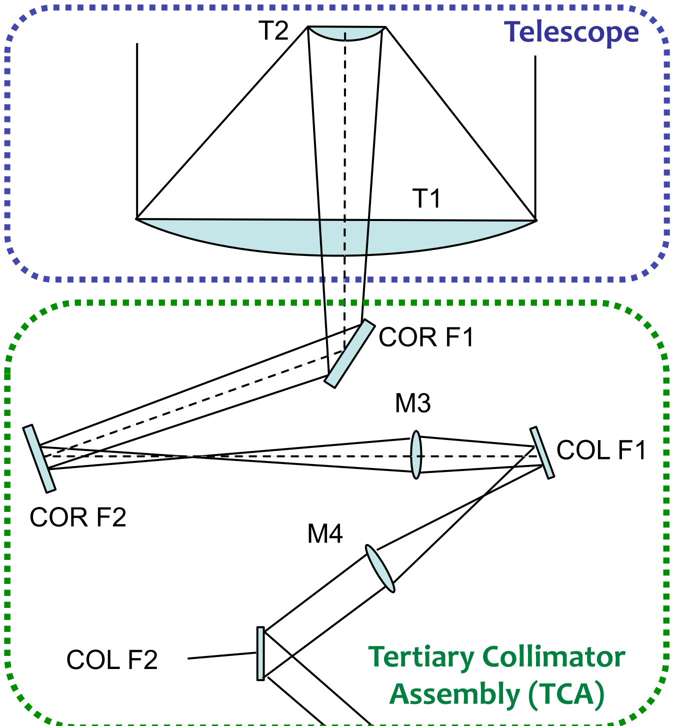
- Science meetings
  - WFIRST-LSST meeting September 13-15, 2016
  - ~~AAS Special Session January 5, 2017~~
  - WFIRST conference June 26-30, 2017

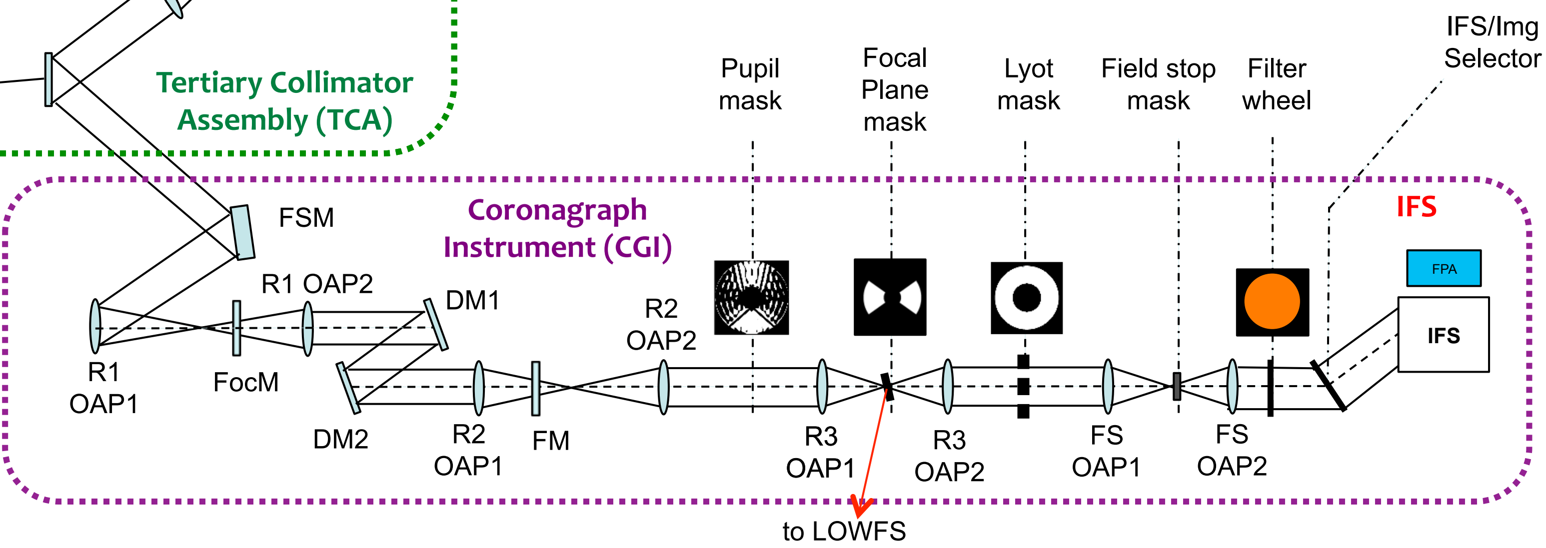
# CGI Operational Modes

## Shaped Pupil Spectroscopy Mode

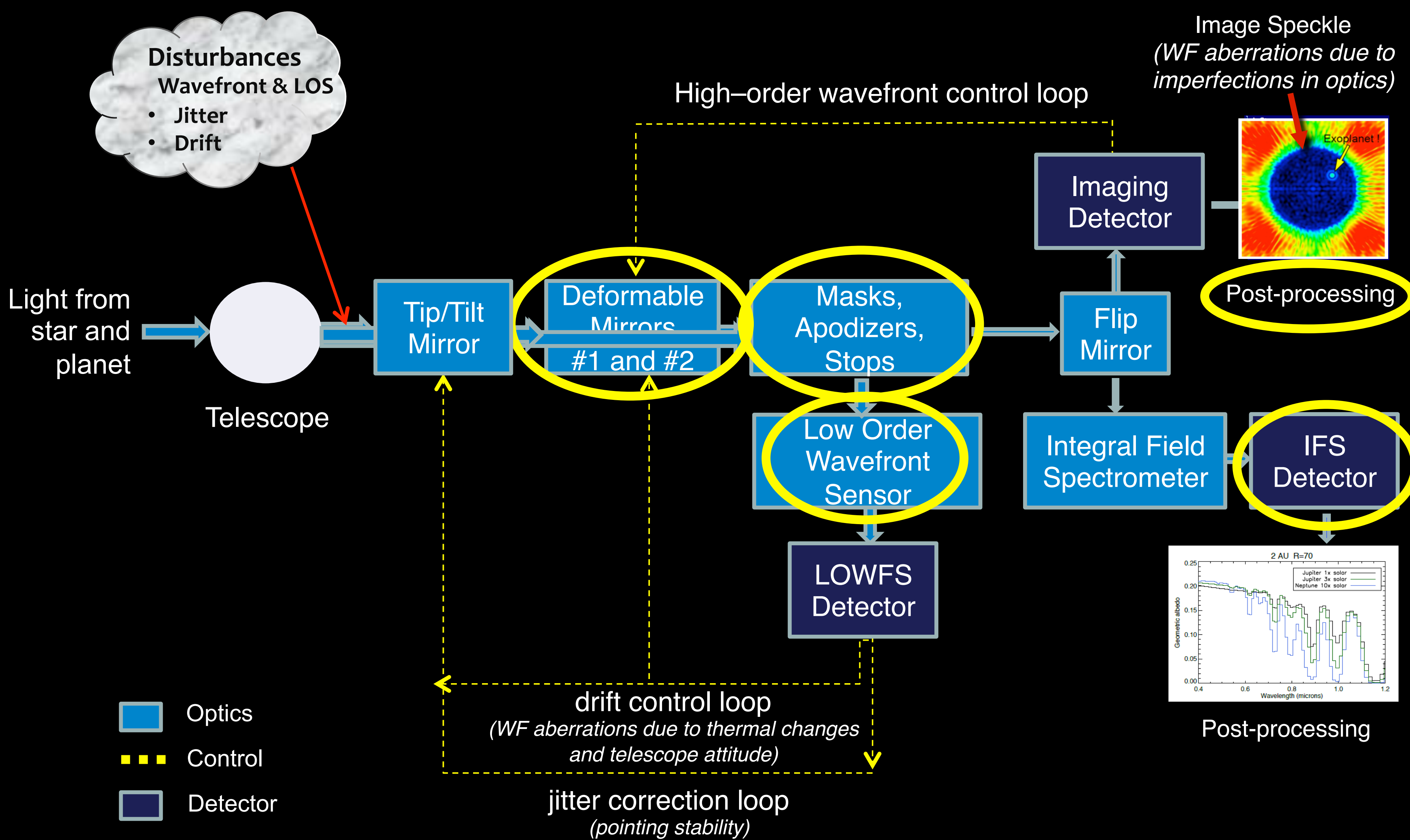
The IFS uses 3 18% bands to produce an R=70 spectra from 600 to 970 nm



# How a Coronagraph Works



# WFC Filters

| Band | Element name | Min (μm) | Max (μm) | Center (μm) | Width (μm) | R |
|---|---|---|---|---|---|---|
| Z | Z087 | 0.76 | 0.977 | 0.869 | 0.217 | 4 |
| Y | Y106 | 0.927 | 1.192 | 1.060 | 0.265 | 4 |
| J | J129 | 1.131 | 1.454 | 1.293 | 0.323 | 4 |
| H | H158 | 1.380 | 1.774 | 1.577 | 0.394 | 4 |
| | F184 | 1.683 | 2.000 | 1.842 | 0.317 | 5.81 |
| Wide | W149 | 0.927 | 2.000 | 1.485 | 1.030 | 1.44 |
| GRS | Grism | 1.0* | 1.89* | 1.445 | 0.890 | 461λ(2pix) |

* Grism bandpass is adjustable, up to $\lambda max \leq 2\times\lambda min$

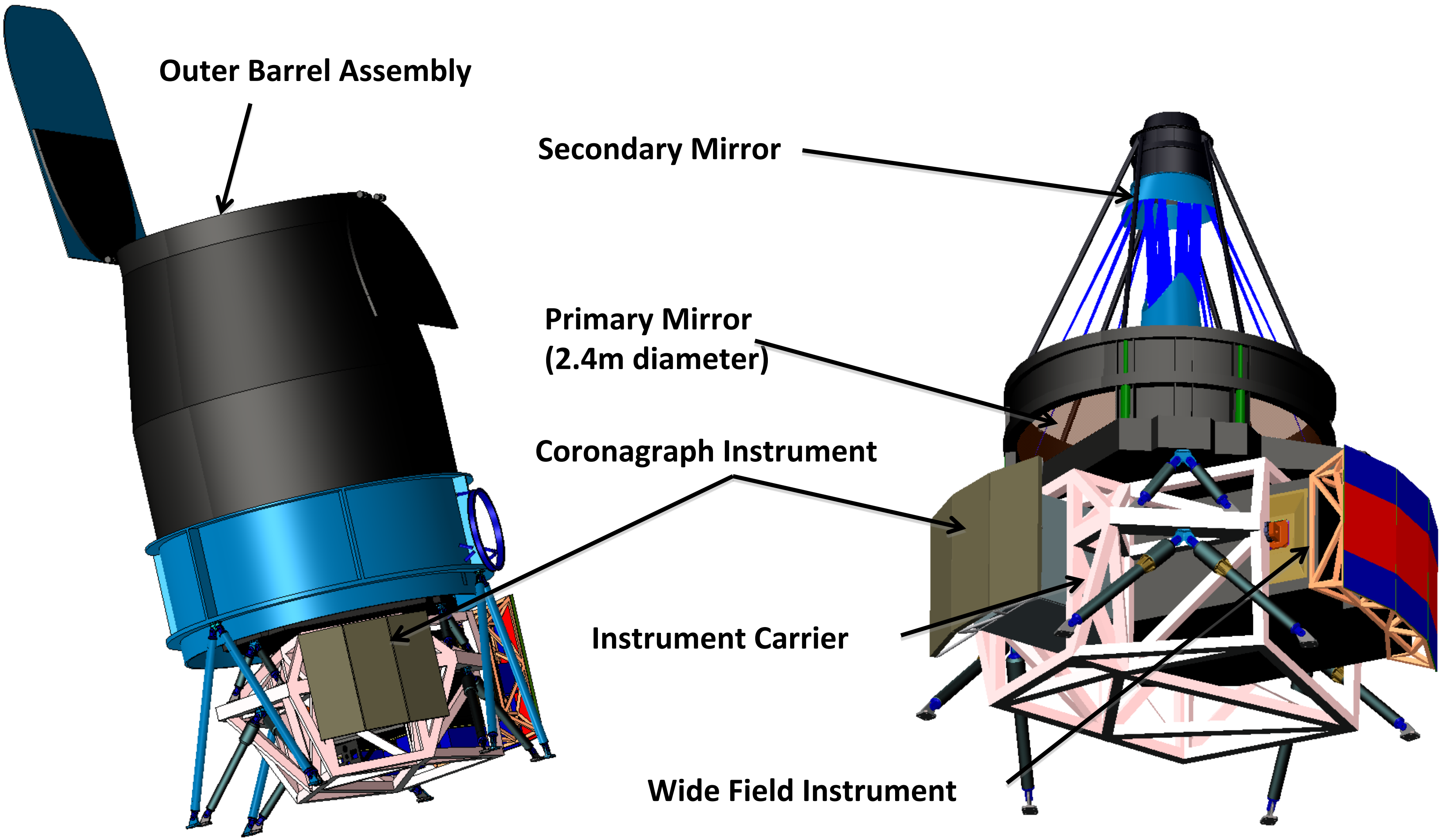
# NIR detector information

Characteristic values for a recent lot of HgCdTe H4RG-10 detectors

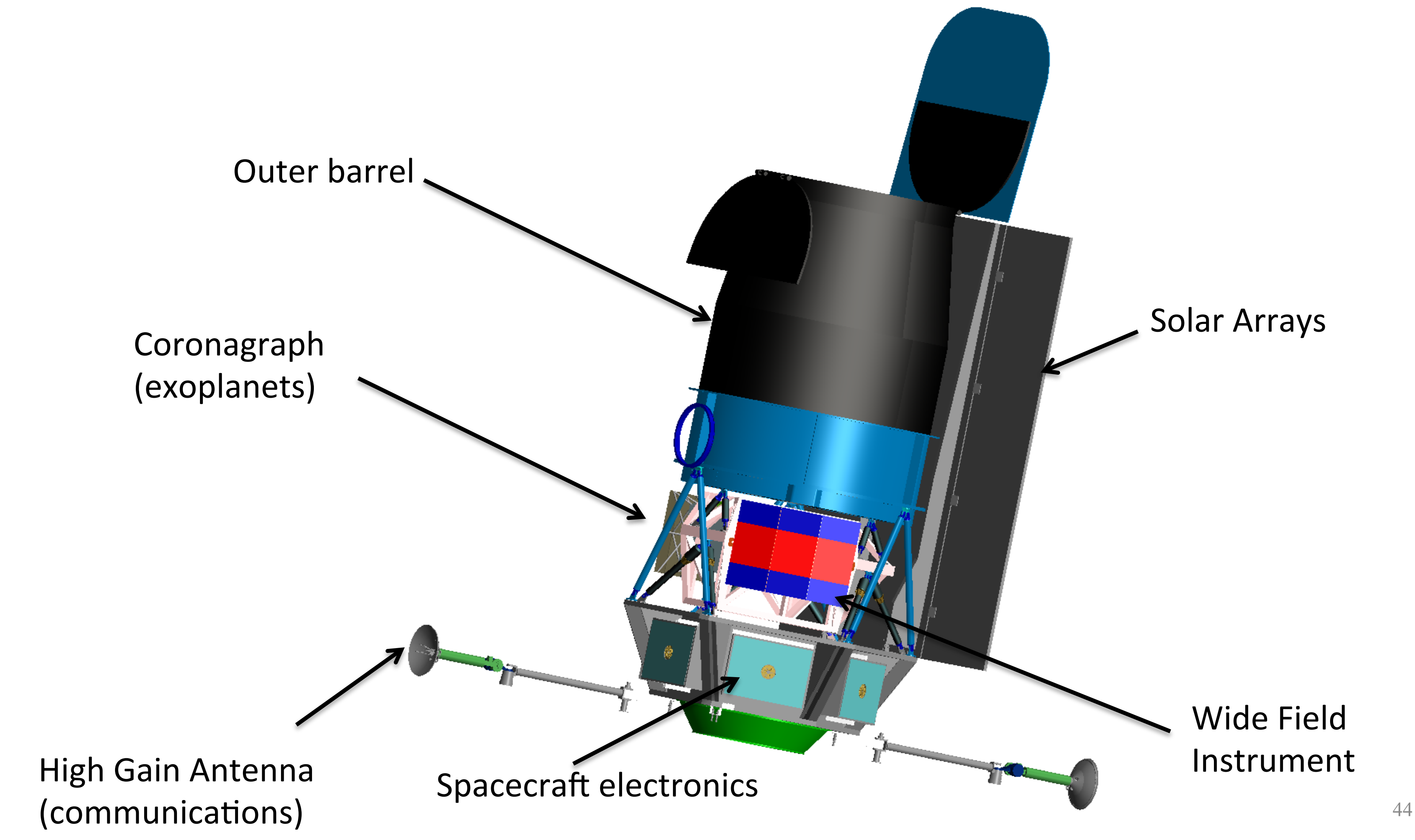
| Quantity | Spec. Value | Units | Typical actual |
|---|---|---|---|
| Dark Current | <0.1 | e-/sec/pixel | 0.005 |
| CDS Read Noise | <20 | e- RMS | 15 |
| Total Noise | | e- RMS | 5-8 |
| Quantum Efficiency | >60% | (avg 0.8-2.35µm) | >90% |
| Pixel operability | >95% | N/A | >98% |
| Total crosstalk | <12% | N/A | <8% |

CDS noise is the RMS noise from the difference of two successive detector readouts
Total noise is uncertainty on slope fit for an exposure time of 180 sec

# WFIRST Payload

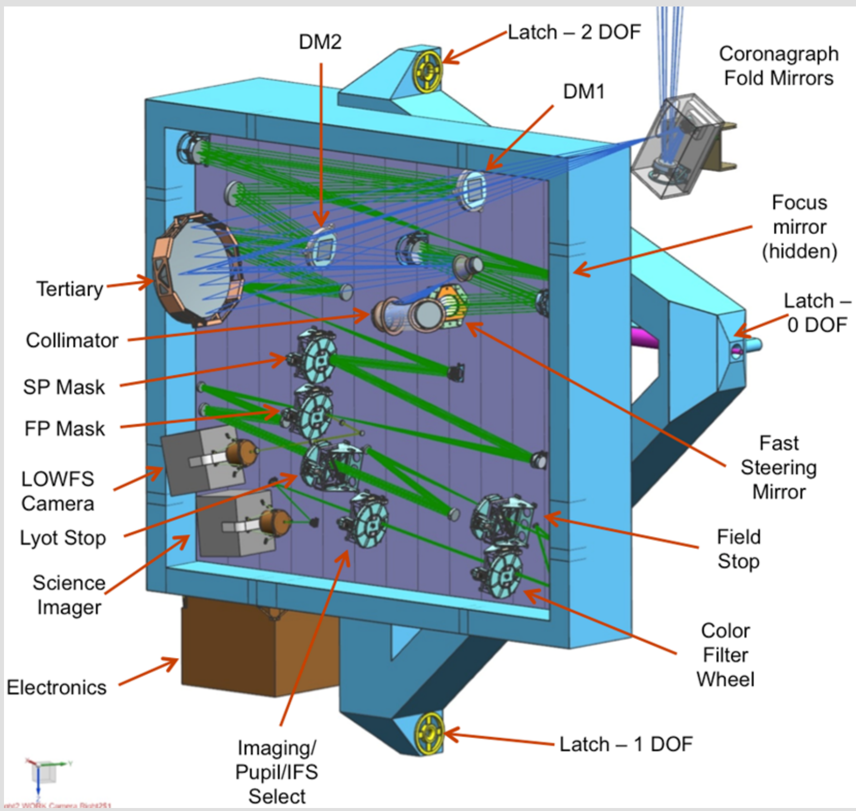


# Anatomy of WFIRST



# WFIRST-AFTA

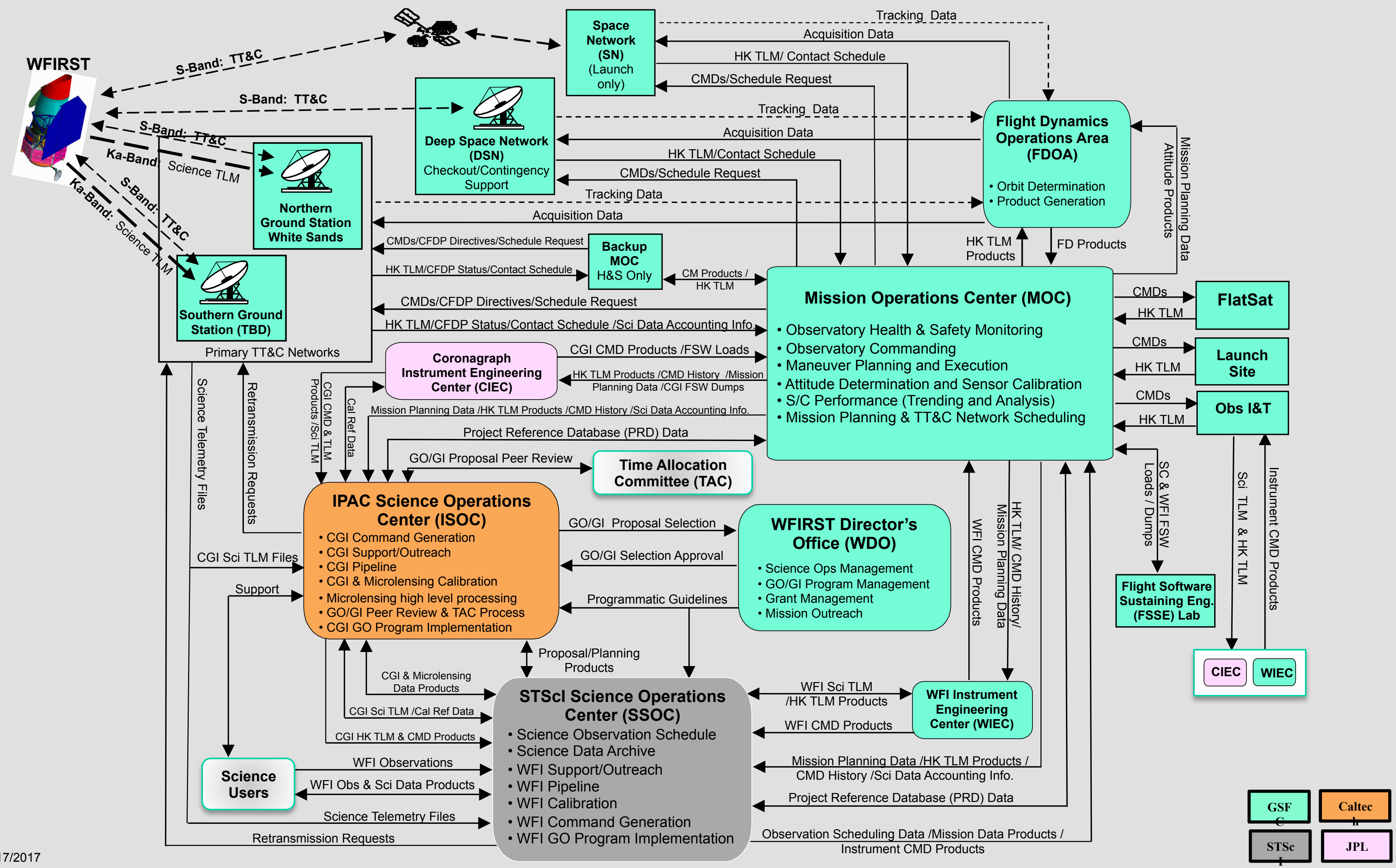
- Latest Design Reference Mission is WFIRS (Astrophysics Focused Telescope Asset)
- AFTA is a repurposed 2.4 m telescope from Reconnaissance office (NRO)
- The AFTA telescope is already built, and si facility




Harris Corporation / TJT Photography

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

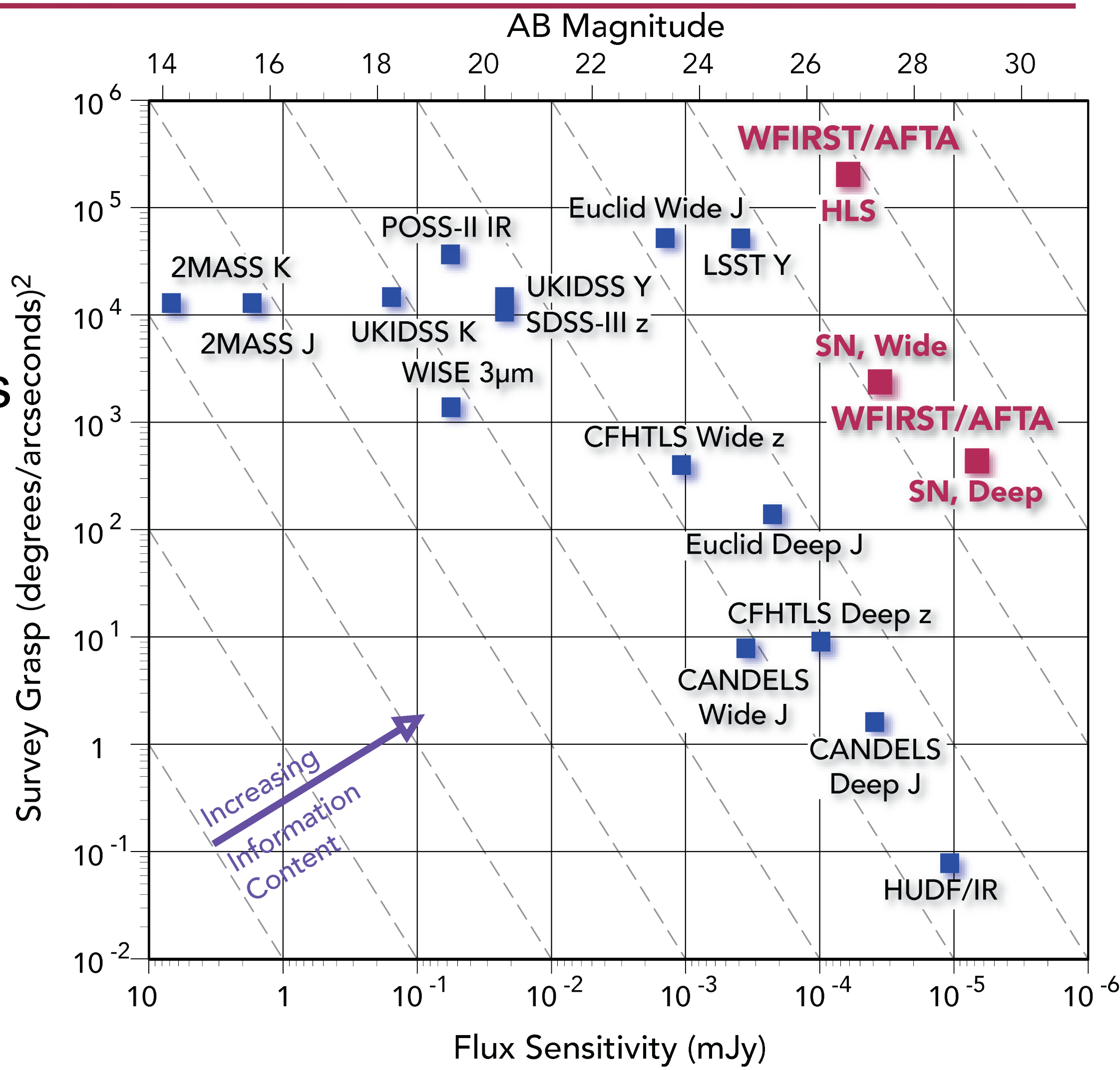
# Overview of WFIRST Baseline Ground System Architecture




Updated 7/17/2017

# WFIRST Surveys

- Multiple surveys:
  - High-Latitude Survey
    - Imaging, spectroscopy, supernova monitoring
  - Repeated Observations of Bulge Fields for microlensing
  - 25% Guest Observer Program
  - Coronagraph Observations
- Flexibility to choose optimal approach



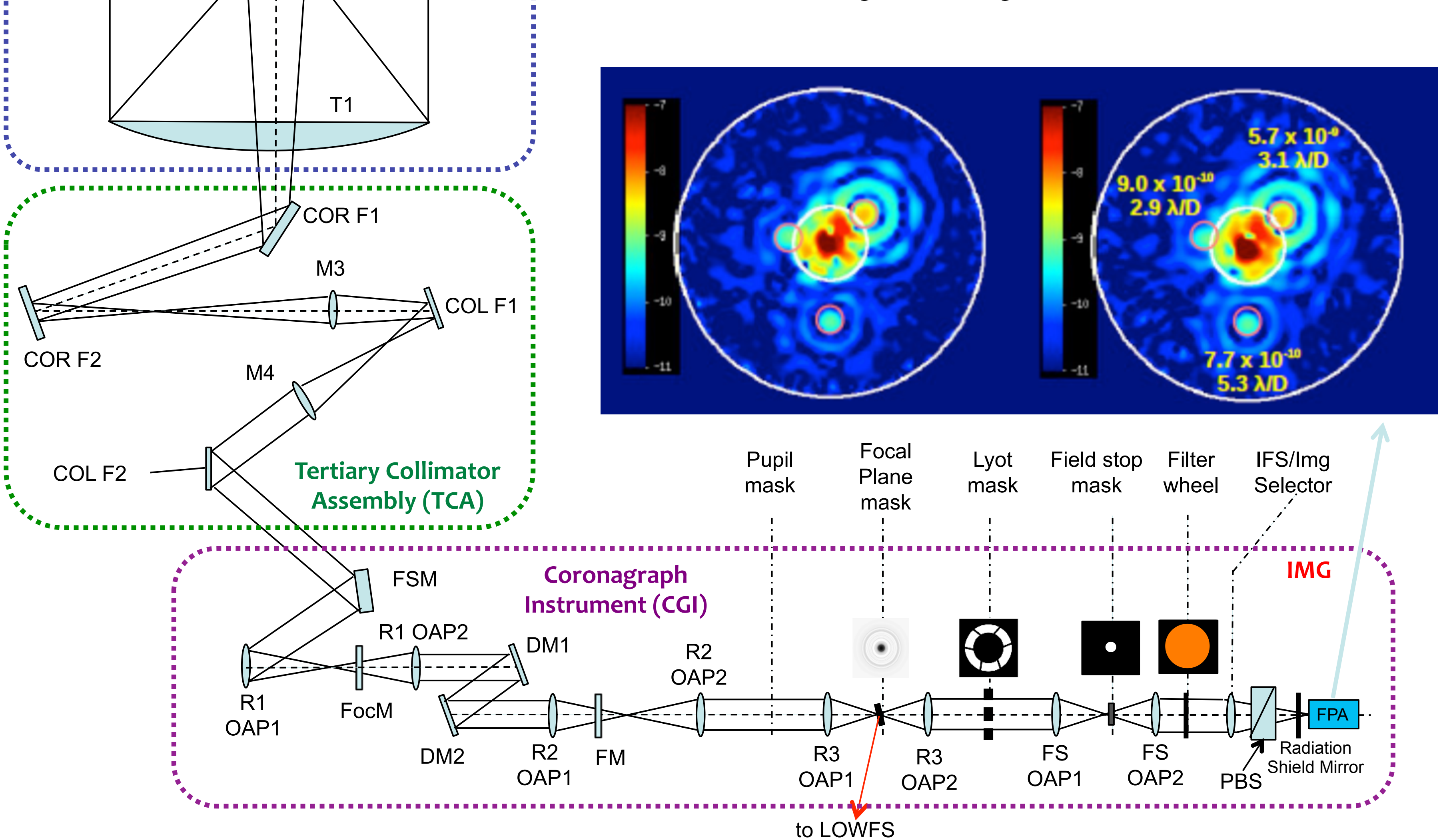

Near Infrared Surveys

# WFIRST's FoV

Jet Propulsion Laboratory
California Institute of Technology

# CGI Operational Modes

## Hybrid Lyot Mode



# Nominal Capabilities*

**WFI:**

Imager **0.76-2.0 microns** 0.28° FoV, 0.11" pixel scale

Filters: z (0.76 - 0.98), Y (0.93-1.19), J (1.13-1.45), H(1.38-1.77), F184 (1.68-2.0), W149 (0.93-2.00)

Photo-z

Shapes

Grism: **1.35-1.89 microns** 0.28° FoV, R=461λ, 0.11" pixel scale

IFC: **0.6-2.0 microns** 3" & 6" FoV, R~100, 0.075" pixel scale

**Coronagraph:**

Imager: **0.43-0.97 microns** 1.63" FoV (radius), 0.01" pixel scale, 1k x 1k EMCCD, $10^{-9}$ final contrast, 100-200 mas inner working angle

IFS: **0.60-0.97 microns** 0.82" FoV (radius), R~70

**Field of Regard:** 54° - 126° 60% of sky available at any given time

*filters and exact wavelength ranges are still being optimized

# Probes of DE

Comparison of expansion history and growth of structure helps distinguish dark energy and modified gravity models

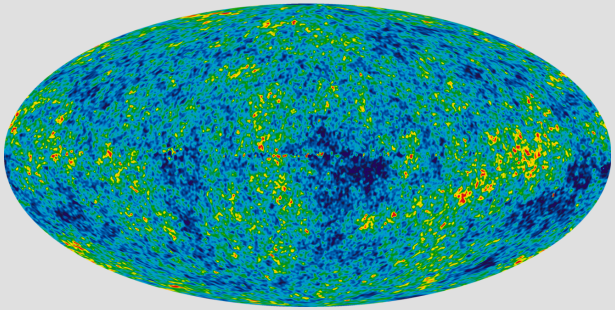
- Supernovae type IA, which act as standard candles to measure the expansion history
- Weak gravitational lensing, the apparent distortion of galaxy shapes by foreground dark matter
  - Measures primarily growth of structure
- Galaxy clustering
  - Baryon acoustic oscillations (BAO), which act as a standard ruler to measure the expansion history
  - Redshift space distortions (RSD) which measure the growth of structure

Dark energy studies are done statistically, and require great precision and attention to systematics

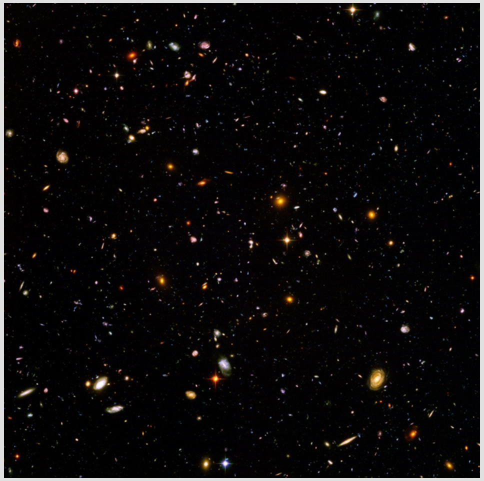
Wide field space missions allow for large statistics and control of systematics

# Consequences of DE

## 1. Dark Energy affects the:



- Expansion history of the Universe
    - How fast did the Universe expand?
    - Also called the geometry of the Universe



- Growth of structures
    - How do structures (which are mostly dark matter) evolve and grow over time
    - Attractive gravity competes with repulsive dark energy

## 2. But if Einstein's General Relativity is wrong, modified gravity theories could also explain the accelerating expansion.

This would change the above observables differently, *so we must measure both the Expansion History of the Universe and the Growth of Structures!*

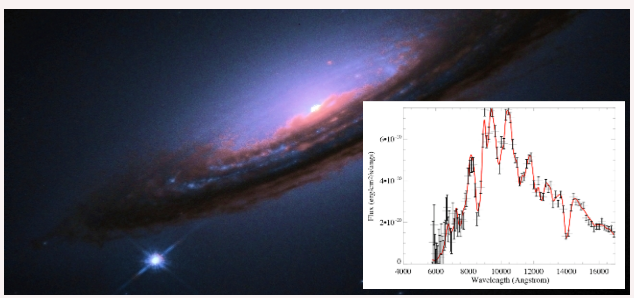
# WFIRST Dark Energy Roadmap

## Supernova Survey

wide, medium, & deep imaging
+
IFU spectroscopy

2700 type Ia supernovae
z = 0.1–1.7

**standard candle distances**
z < 1 to 0.20% and z > 1 to 0.34%



## High Latitude Survey

spectroscopic: galaxy redshifts

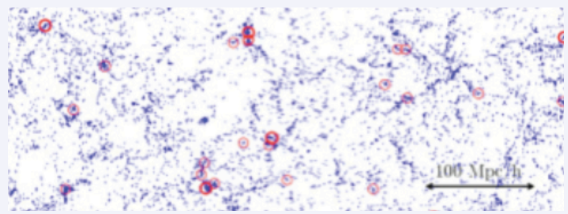
16 million Hα galaxies, z = 1–2
1.4 million [OIII] galaxies, z = 2–3

imaging: weak lensing shapes

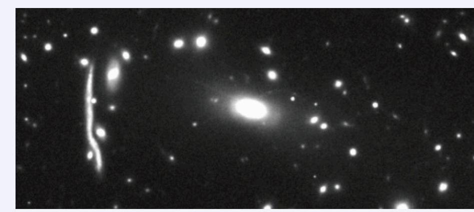
380 million lensed galaxies
40,000 massive clusters

**standard ruler**

| distances | expansion rate |
|---|---|
| z = 1–2 to 0.5% | z = 1–2 to 0.9% |
| z = 2–3 to 1.3% | z = 2–3 to 2.1% |

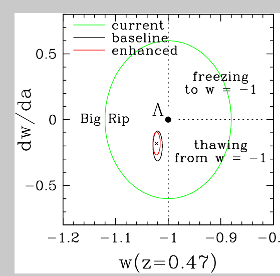



**dark matter clustering**
z < 1 to 0.21% (WL); 0.24% (CL)
z > 1 to 0.78% (WL); 0.88% (CL)
1.1% (RSD)



history of dark energy
+
deviations from GR

$w(z)$, $\Delta G(z)$, $\Phi_{REL}/\Phi_{NREL}$



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# μlensing Survey Science Goals

**Primary Microlensing Science Objective:** WFIRST 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.

- EML 1: WFIRST shall measure the mass function of exoplanets with masses between 1 $M_{Earth}$ and 30 $M_{jupiter}$ and orbital semi-major axes ≥ 1 AU to better than 10% per decade in mass.
- EML 2: WFIRST shall measure the mass function of bound exoplanets with masses in the range 0.1 $M_{Earth} < m < 0.3 M_{Earth}$ to better than 25%.
- EML 3: WFIRST shall determine the masses of, and distances to, host stars of 50% of the detected planets with a precision of 20% or better.
- EML 4: WFIRST shall measure the frequency of free floating planetary-mass objects in the Galaxy from Mars to 10 Jupiter masses in mass. If there is one $M_{Earth}$ free-floating planet per star, measure this frequency to 25%.
- EML 5: WFIRST shall estimate $\eta_{Earth}$ (defined as planets with mass ratio and estimated projected semimajor axis within 20% of the of the Earth orbiting FGK stars) to a precision of 0.15 dex via extrapolation from more massive and longer-period planets