High Contrast Imaging from Space and the WFIRST Coronagraph Instrument

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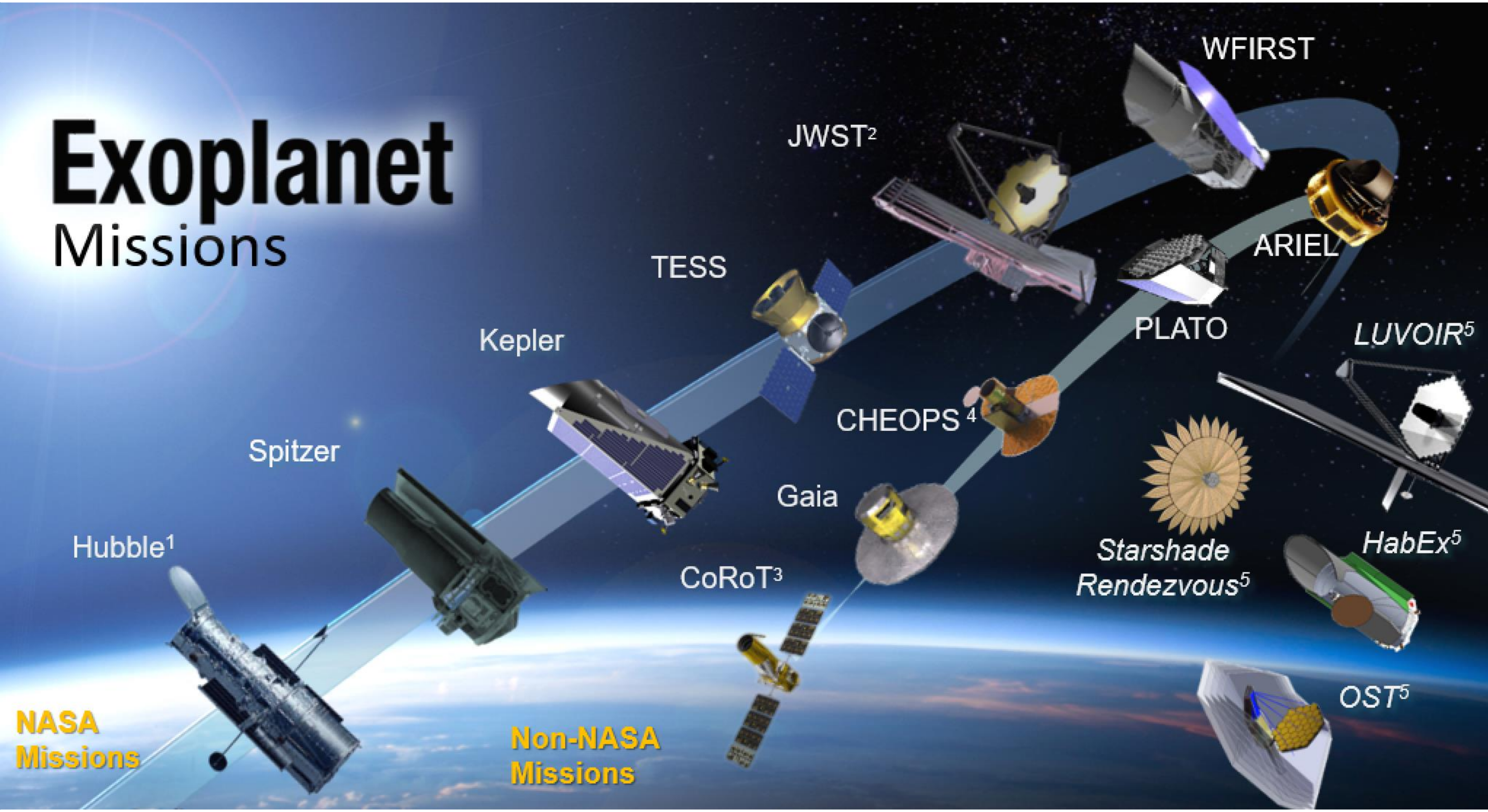
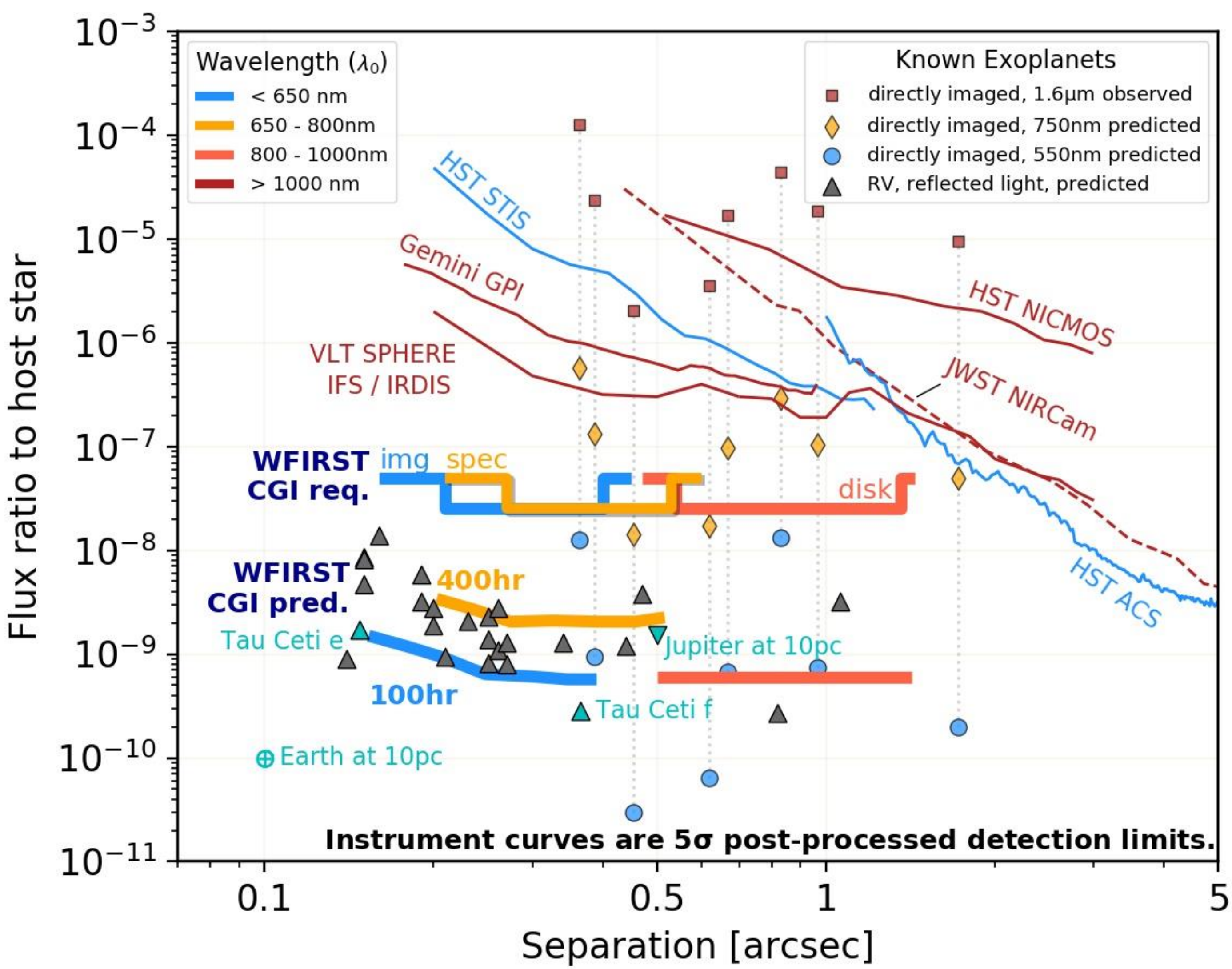

Exoplanet
Missions
Hubble1
Spitzer
Kepler
TESS
JWST2
WFIRST
ARIEL
PLATO
CHEOPS 4
Gaia
CoRoT3
LUVOIR5
Starshade
Rendezvous5
HabEx5
OST5
NASA
Missions
Non-NASA
Missions

CGI in Context



Giant Planet Imaging Photometry

Narrow-band Spectroscopy of Self-luminous & RV Planets

New Planet Discovery

Exozodiacal Disk Imaging

Visible light characterization of Debris Disks

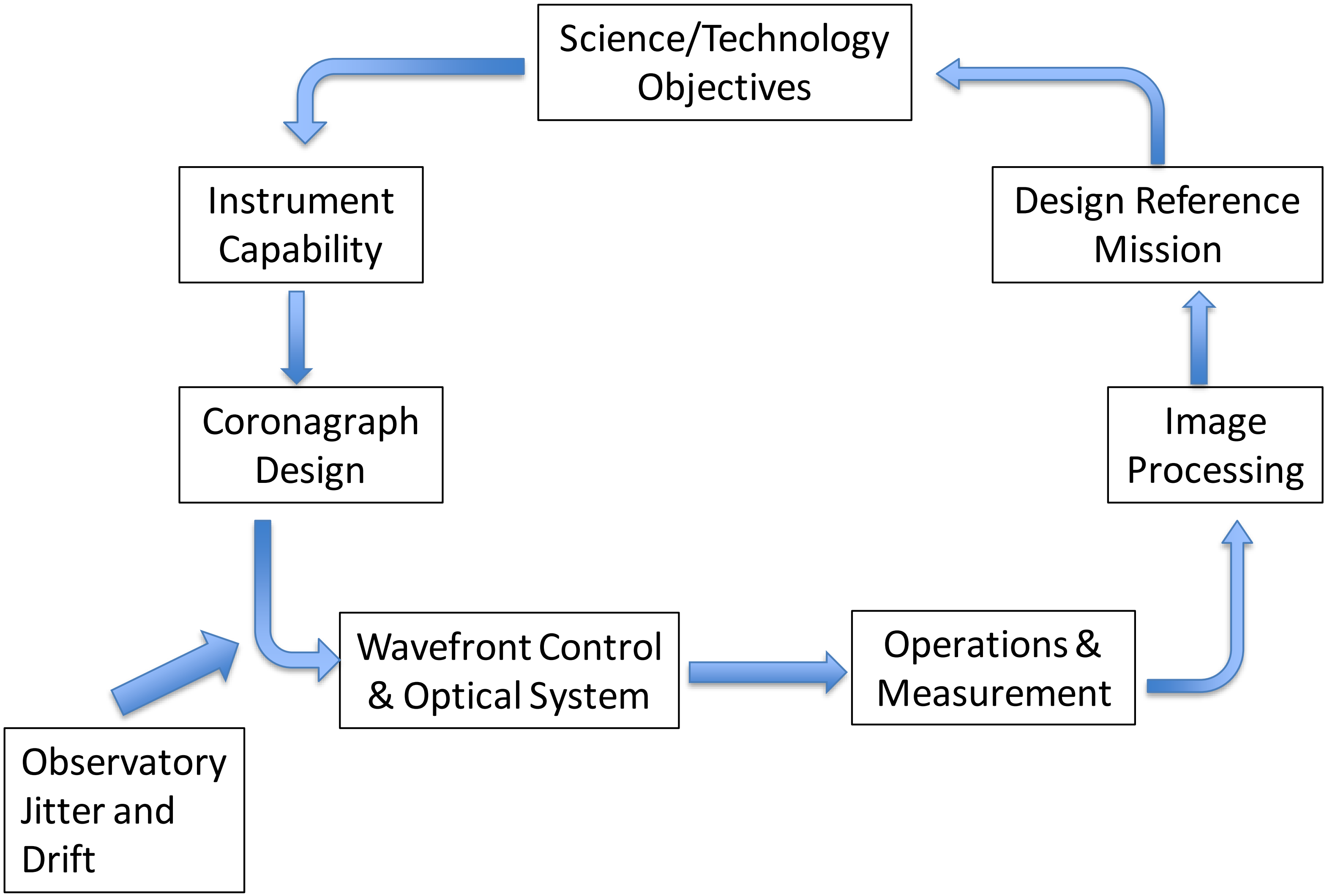
WFIRST after WIETR

- The Coronagraph Instrument is a technology demonstration only
- Requirements established using standard engineering practice
- Reduction in modes and science center role
- If successful, "Participating Science Program" following tech demo
- Design to support possible starshade (pending Decadal recommendation)

<u>Notional CGI Program</u>

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

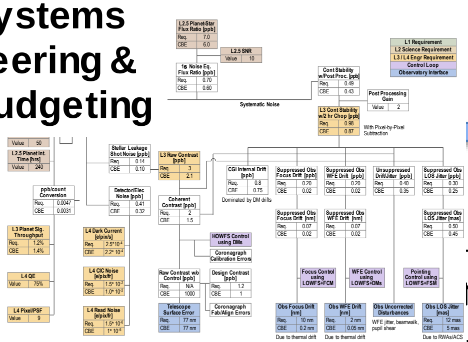
Realizing a Coronagraph Mission



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

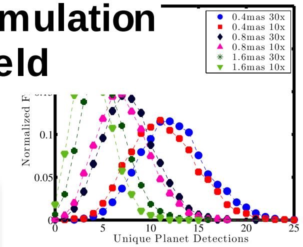
WFIRST as a Pathfinder

Full Systems Engineering & Error Budgeting



Science/Technology Objectives

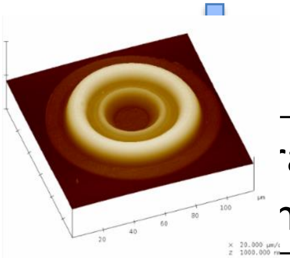
Mission Simulation & Yield



Design Reference Mission

nt
Capability

High Contrast Coronagraph Elements



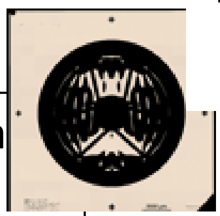
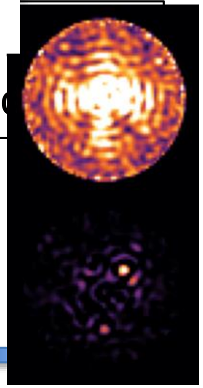
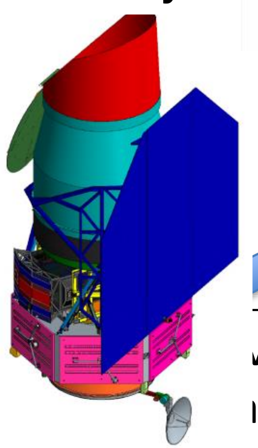


Image Processing at Unprecedented Contrast Levels

Proc



Stable Space Telescope & Observatory



vatory
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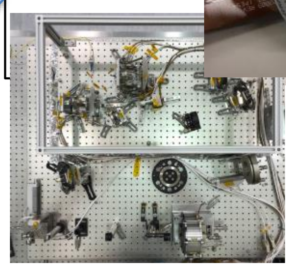
Drift

First Use of Deformable Mirrors in Space

Wavefron



Autonomous Precision Wavefront Sensing & Control

Operations &
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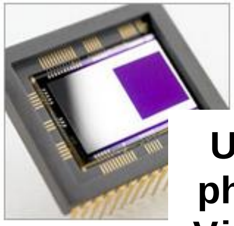


Ultra-low noise photon counting Visible Detectors

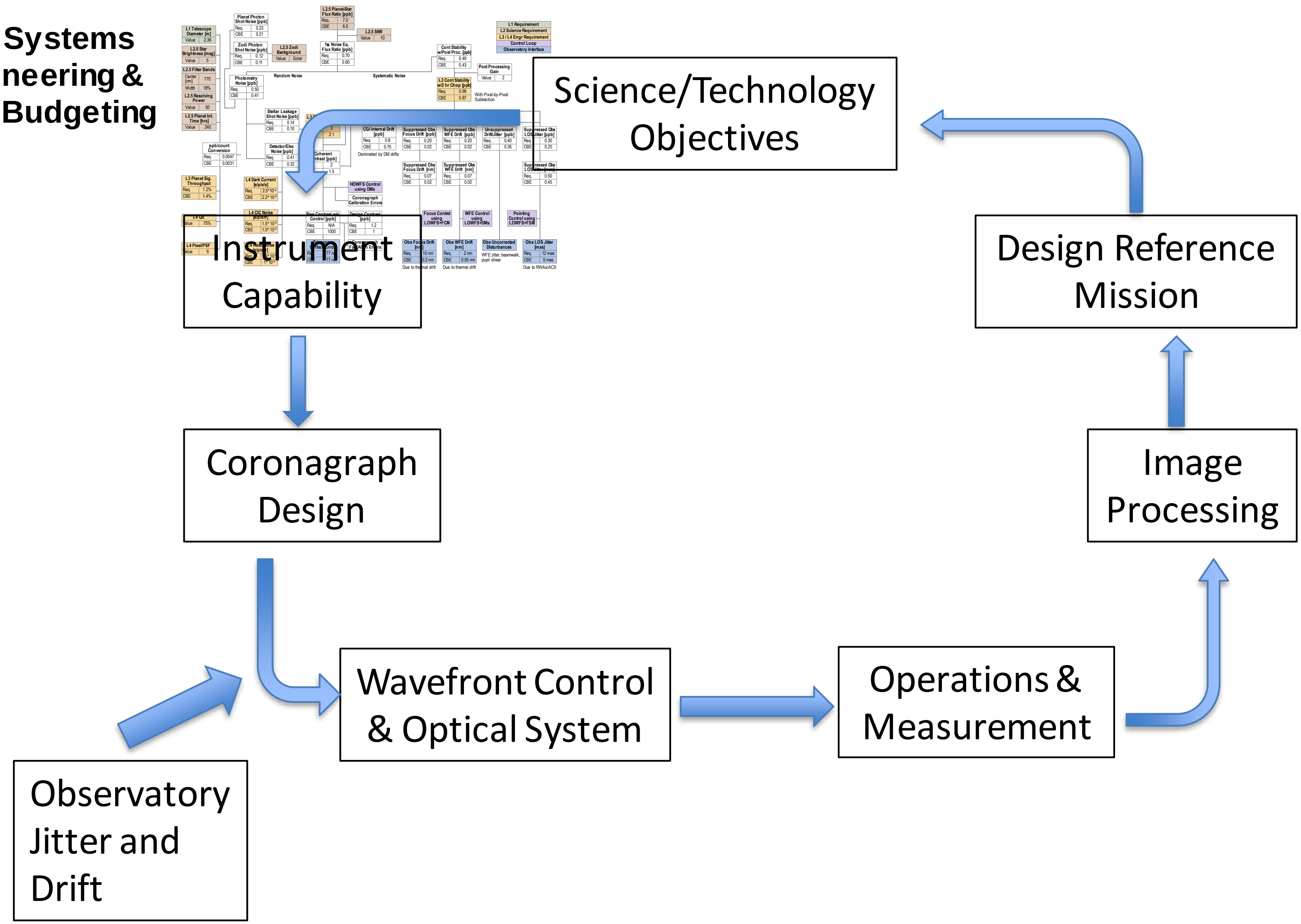
CGI Will . . . .

- Demonstrate in space critical coronagraph technology and state of the art wavefront control.
- Advance the state of the art in direct imaging and spectra toward future missions.
- Characterize the in-flight interactions between coronagraph and observatory.
- Prototype systems engineering for space coronagraph.
- Validate end-to-end data analysis for space coronagraph.
- Potentially perform important science in spectral retrieval, direct imaging of RV planets, blind searches, and zodi and debris disk characterization.

Results will inform requirements (particularly stability) and design of future missions such as HabEx and LUVOIR.

Realizing a Coronagraph Mission

Full Systems Engineering & Error Budgeting



CGI Technology Objectives

- **Demonstrate Coronagraphy with Active Wavefront Control in space**
- **Advance Engineering & Readiness of Coronagraph Elements**
- **Development and Demonstration of Advanced Coronagraph Algorithms**
- **Integrated Observatory Performance Characterization**
- **Demonstration of Advanced High-Contrast Data Processing**

In short, WFIRST will validate our models and assumptions for the entire system, including data processing, in a space environment.

CGI Level 2 Requirements

- High-Contrast Direct Imaging
- High-Contrast Imaging Spectroscopy
- Extended Source Imaging with Large FOV
- Polarization Measurements of Disks
- Exoplanet Astrometric Accuracy
- Wavefront Sensing and Control Telemetry
- Telescope Polarization
- Measure Pointing Jitter
- Measure Slow Wavefront Aberrations

Example Level 2 Requirements

1) High-Contrast Direct Imaging

WFIRST CGI shall be able to measure the brightness of an astrophysical point source to an SNR of 10 or greater within 10 hours of integration time on the target in CGI Filter Band 1 for an object with a source-to-star flux ratio as faint as 1e-7 at separations from 0.16 arcsec to 0.21 arcsec, 5e-8 at separations from 0.21 arcsec to 0.4 arcsec, and 1e-7 at separations from 0.4 arcsec to 0.45 arcsec.

2) High-Contrast Imaging Spectroscopy

WFIRST CGI shall be able to measure spectra of an astrophysical point source with R = 50 or greater spectral resolution with a wavelength accuracy of 5 nm or smaller (TBR) to an SNR of 10 within 100 hours of integration time on the target in CGI Filter Band 3 for an object with a source-to-star flux ratio as faint as 1e-7 at separations from 0.21 arcsec to 0.27 arscec, 5e-8 at separations from 0.27 arcsec to 0.53 arcsec, and 1e-7 at separations from 0.53 arcsec to 0.60 arcsec.

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

L2 to L3 Requirements

Level 2 requirements specify ***system level performance*** *independent of instrument design.*

- Direct Imaging
- Spectroscopy
- Extended Sources
- Polarization Measurements
- Astrometry
- Telemetry
- Polarization errors
- Pointing Jitter

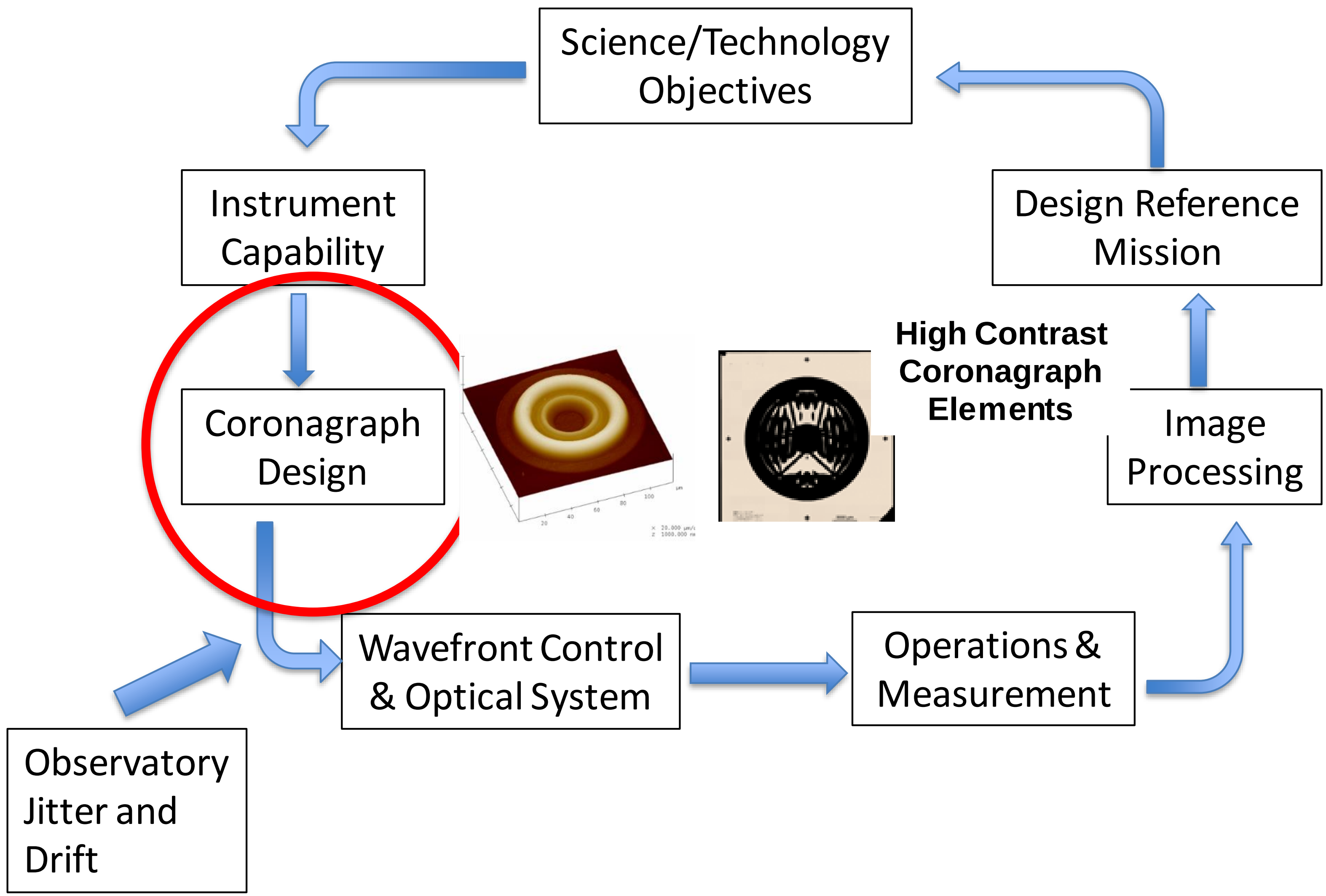
Level 2 Technology Requirements

Level 3/4 Requirements

- Instrument Contrast
- Stability
- Pointing
- Throughput
- Polarization
- Detector
- Post-Processing
- Operations

WFIRST is pioneering the entire systems engineering process.

Coronagraph Design

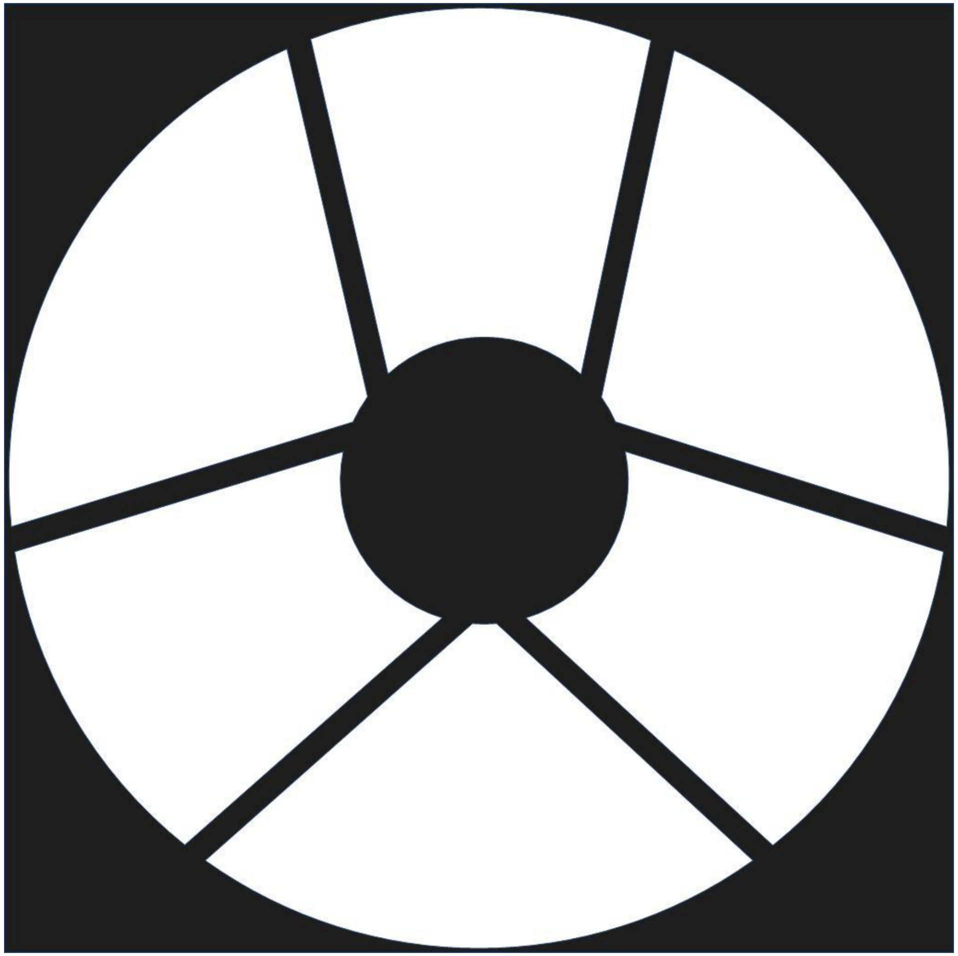


Coronagraph Metrics

- Contrast: The ratio of the peak of the stellar point spread function to the halo at the planet location.
- Inner Working Angle: The smallest angle on the sky at which the needed contrast is achieved and the planet is reduced by no more than 50% relative to other angles.
- Throughput: The ratio of the open telescope area remaining after high-contrast is achieved.
- Bandwidth: The wavelengths at which high contrast is achieved.
- Sensitivity: The degree to which contrast is degraded in the presence of abberations.

Coronagraph performance also differs depending upon aperture. All previous coronagraphs were for open apertures (off-axis telescopes).

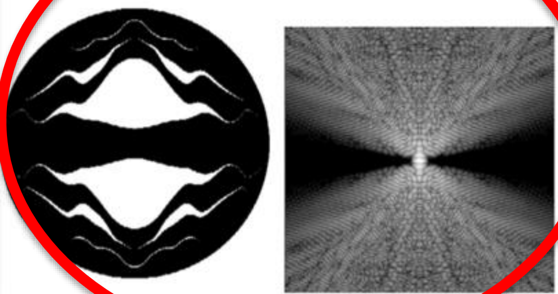
WFIRST/AFTA Pupil



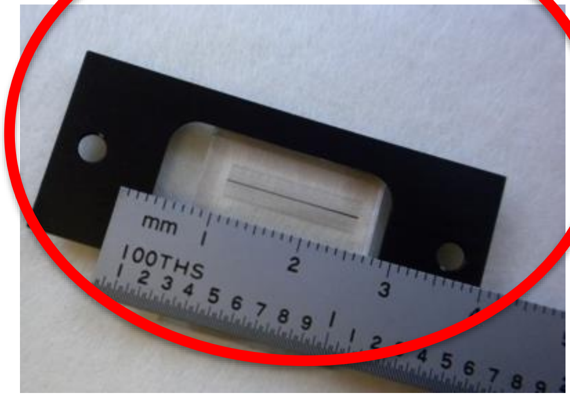
Highest Instrument Risk is a Change to the Pupil.

Coronagraph Selection

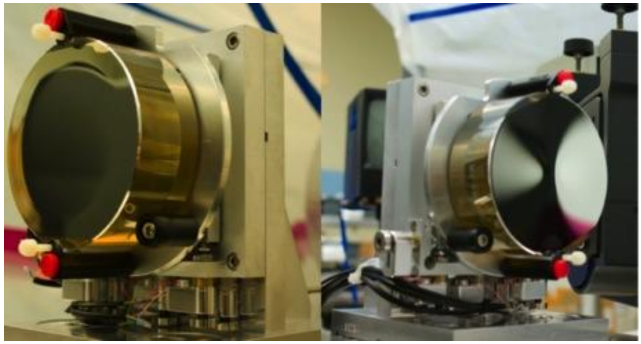
SPC



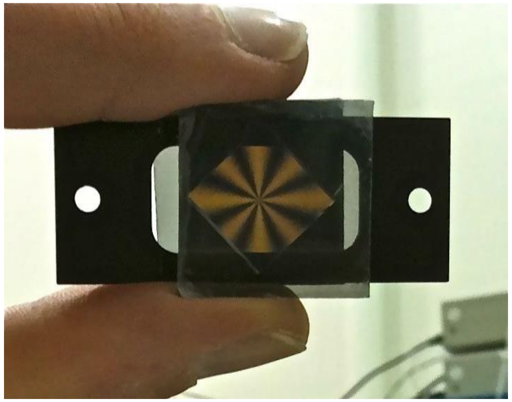
HLC



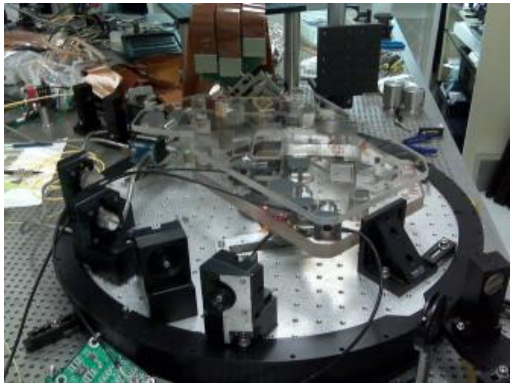
PIAA-CMC



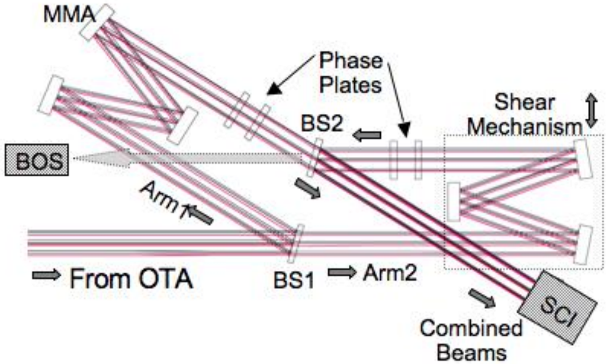
VVC



VNC-Davinci



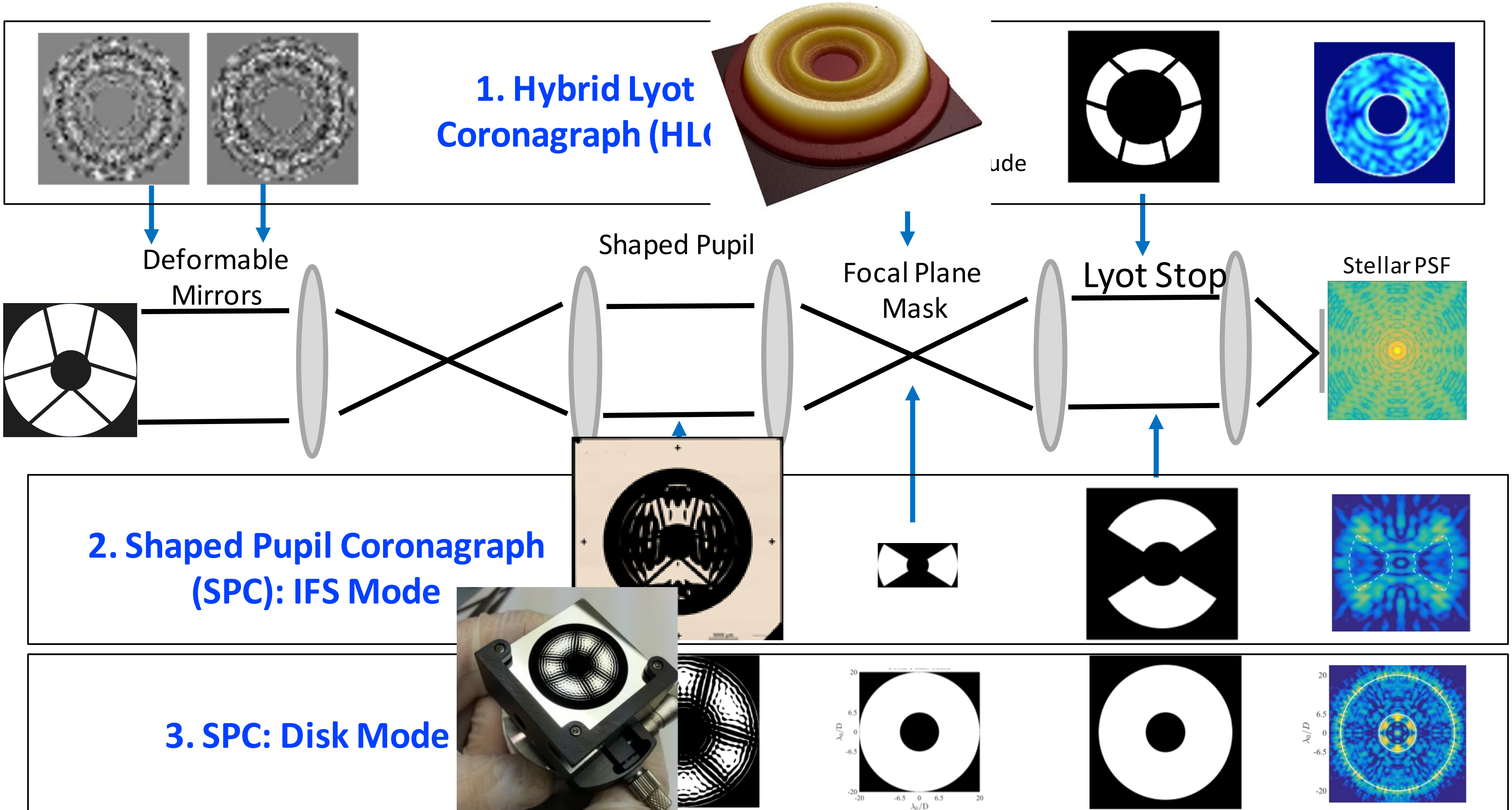
VNC-PO



WFIRST Coronagraph Modes

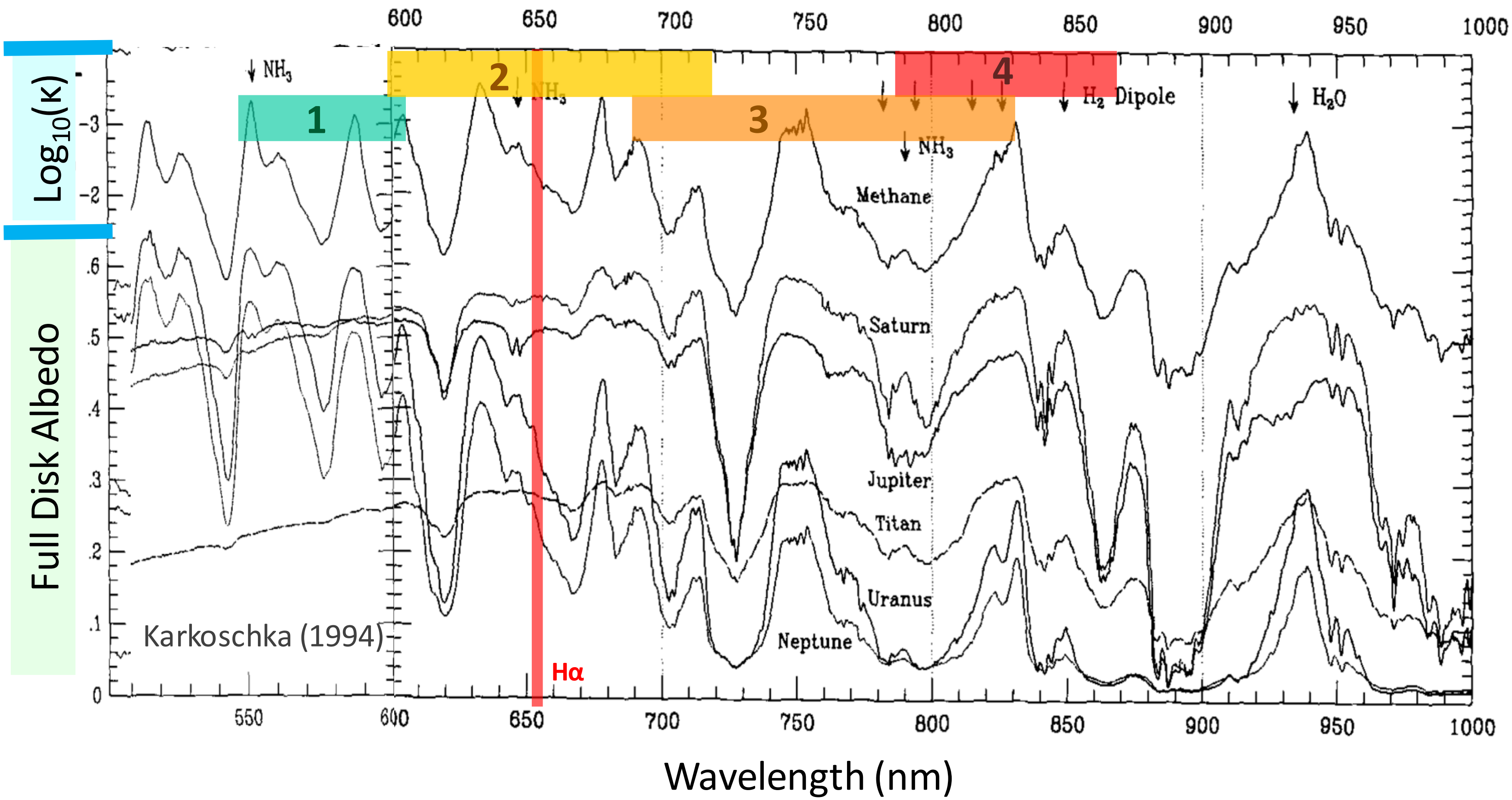
- Three interchangeable coronagraph observing modes via mask selection mechanisms

Courtesy A J Riggs.



Filters and Modes

3 Tested Modes: 575nm HLC Imaging (10%), 760 nm SPC IFS (18%, R50), 825 SPC Disk Imaging (10%)



Hybridization

WFIRST design jump-started the trend toward hybridizing, or combining, different coronagraph features.

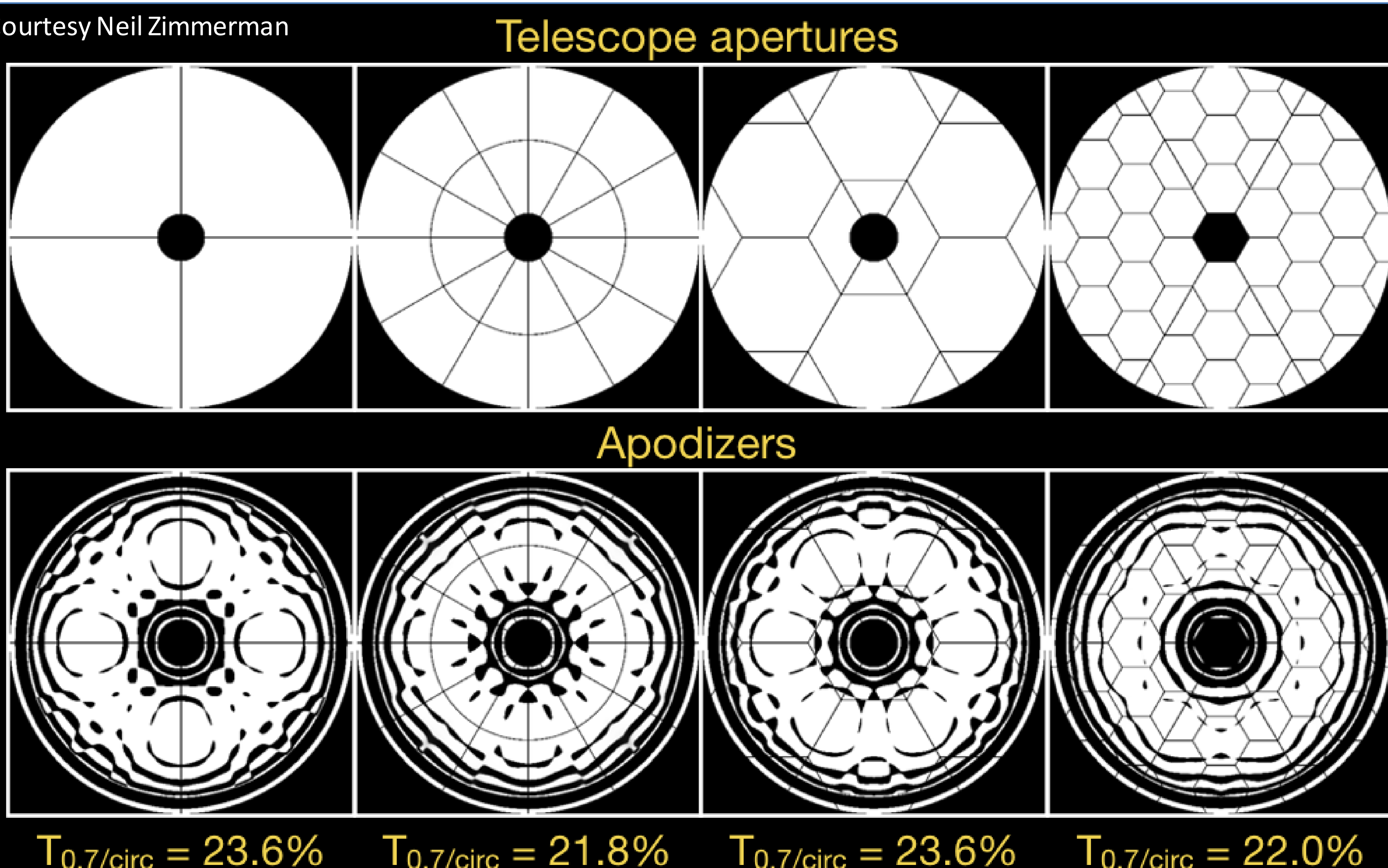
Modern design efforts now incorporate DMs, apodizers, focal plan masks, and Lyot Stops into the design process. Resulting optimization is challenging. (ACAD, HLC, Ring Vortex, SPLC)

As a result, it has become possible to consider coronagraphs for on-axis and segmented telescopes. This has been enabling for large mission concepts such as HabEX and LUVOIR.

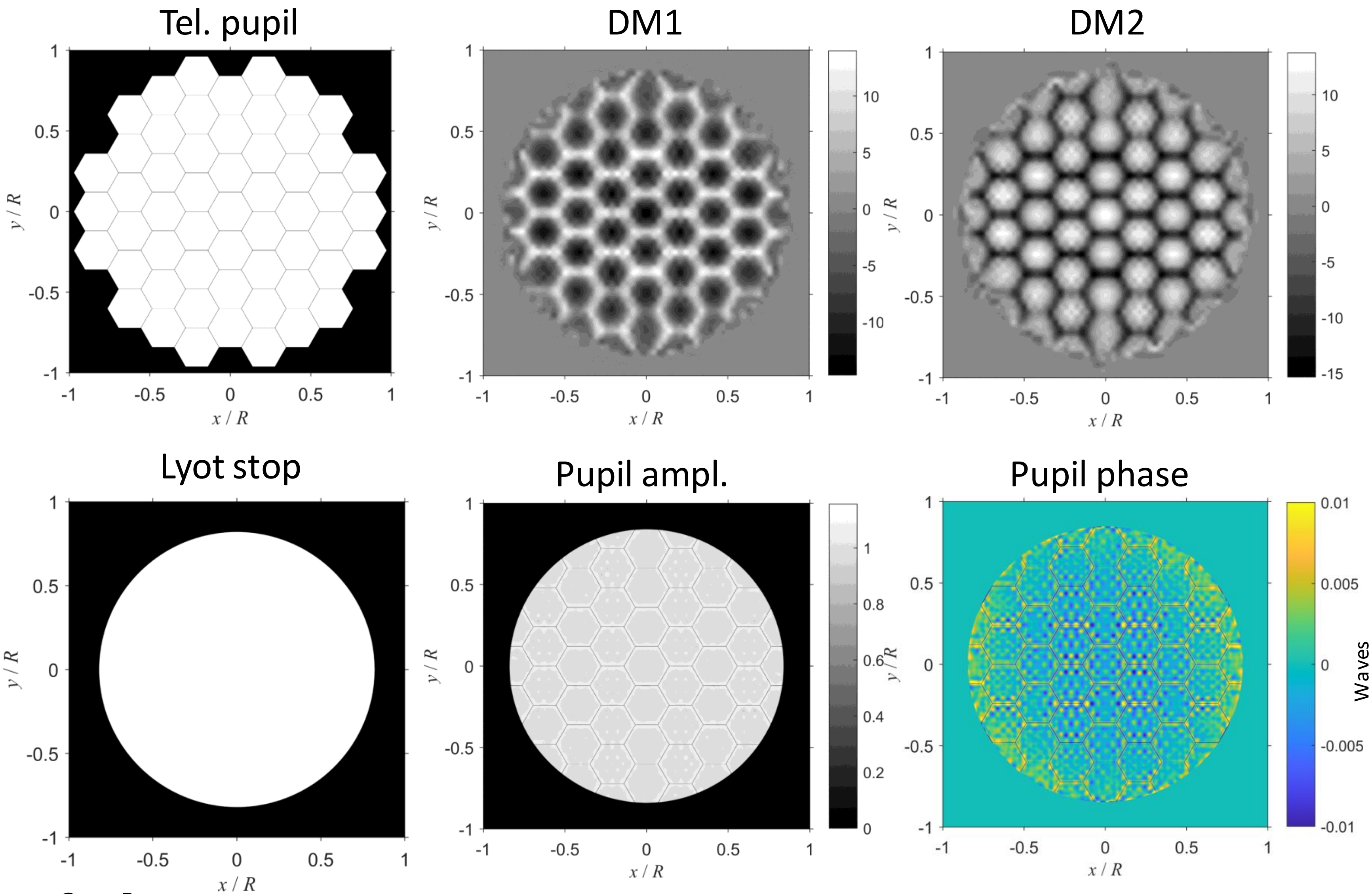
SCDA–Segmented Coronagraph Design & Analysis

SCDA– STScI
Apodized/Shaped Pupil Lyot Coronagraph

Courtesy Neil Zimmerman

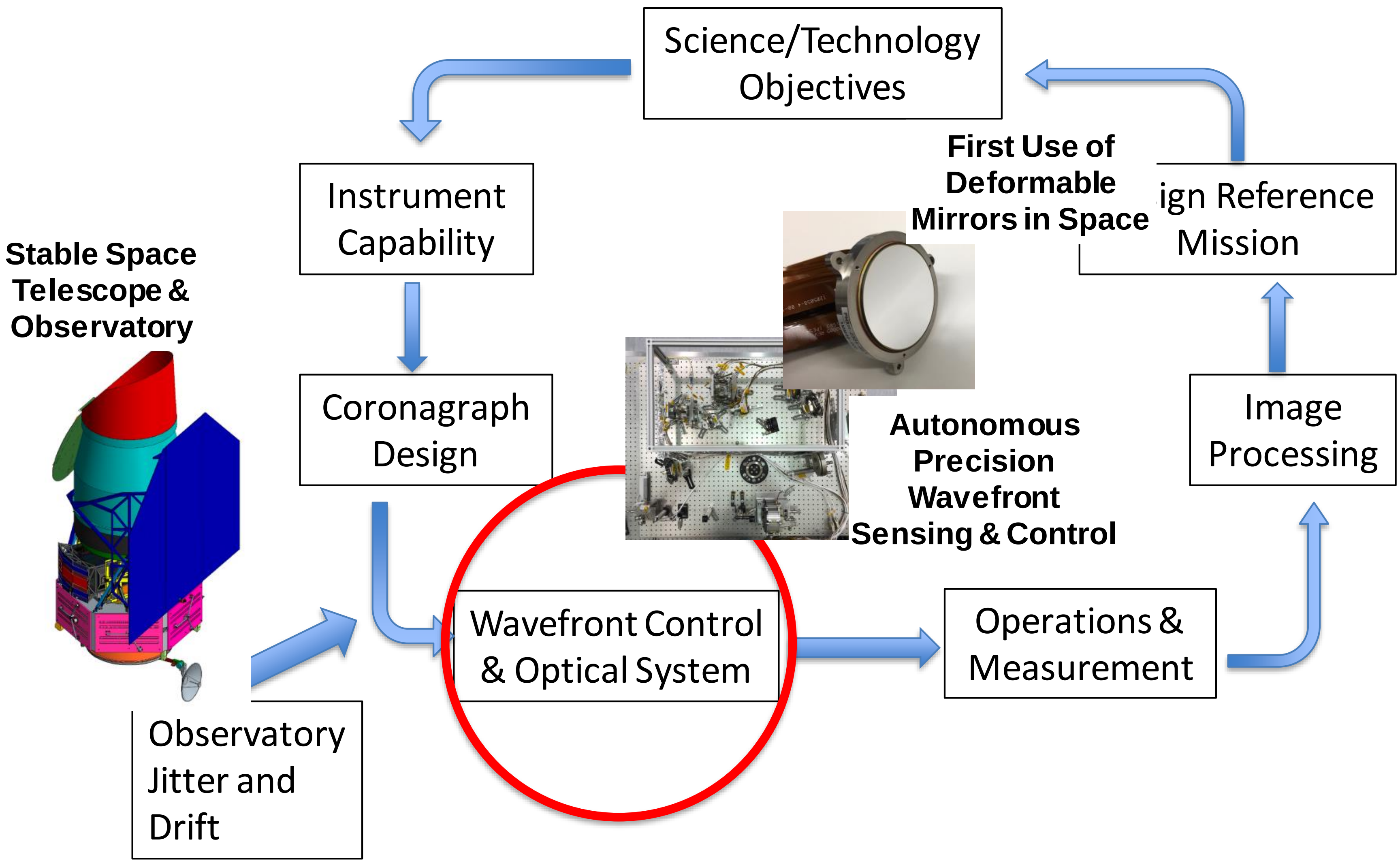


SCDA–Caltech DM Apodized Vortex Coronagraph

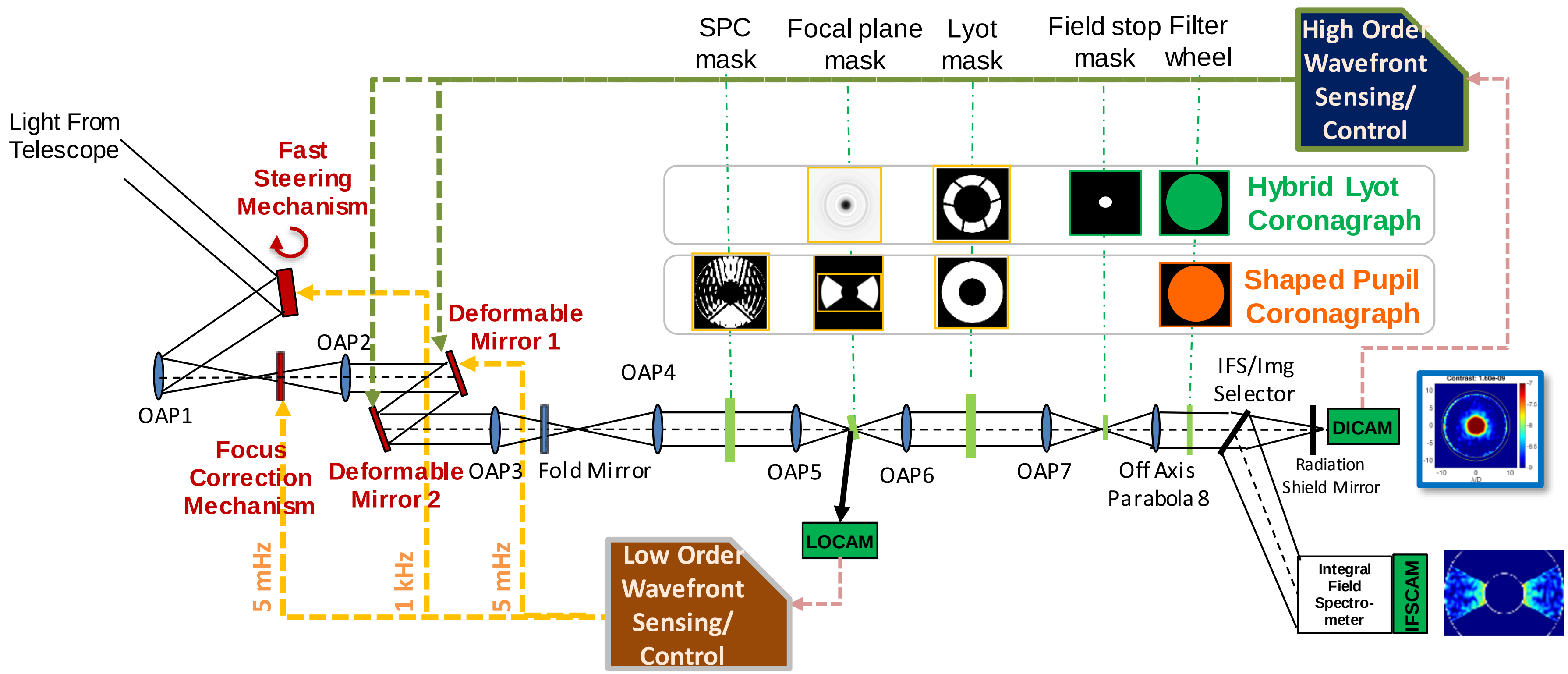


Courtesy Gary Rouane.

Coronagraph Design



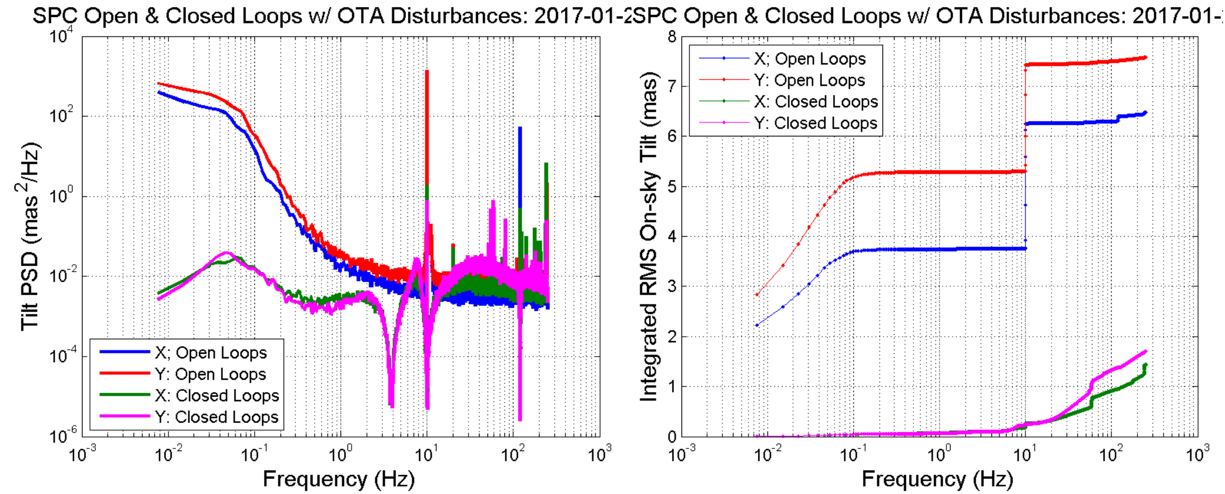
WFIRST Wavefront Control System



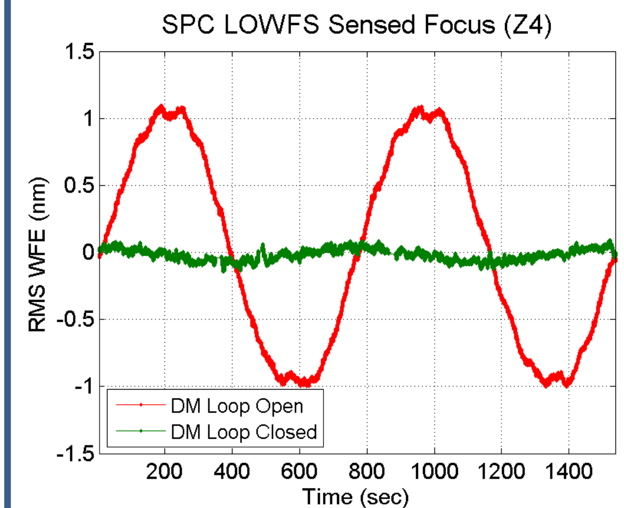
WFIRST will pioneer space based active wavefront control with both high-order (slow) and low-order (fast) correction and large format DMs. DMs 2nd Highest Risk.

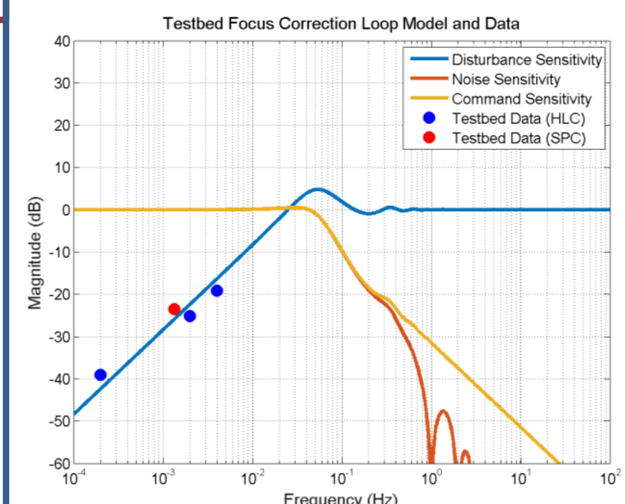
Low-Order Wavefront Control

Line-of-Sight Control



Focus Control

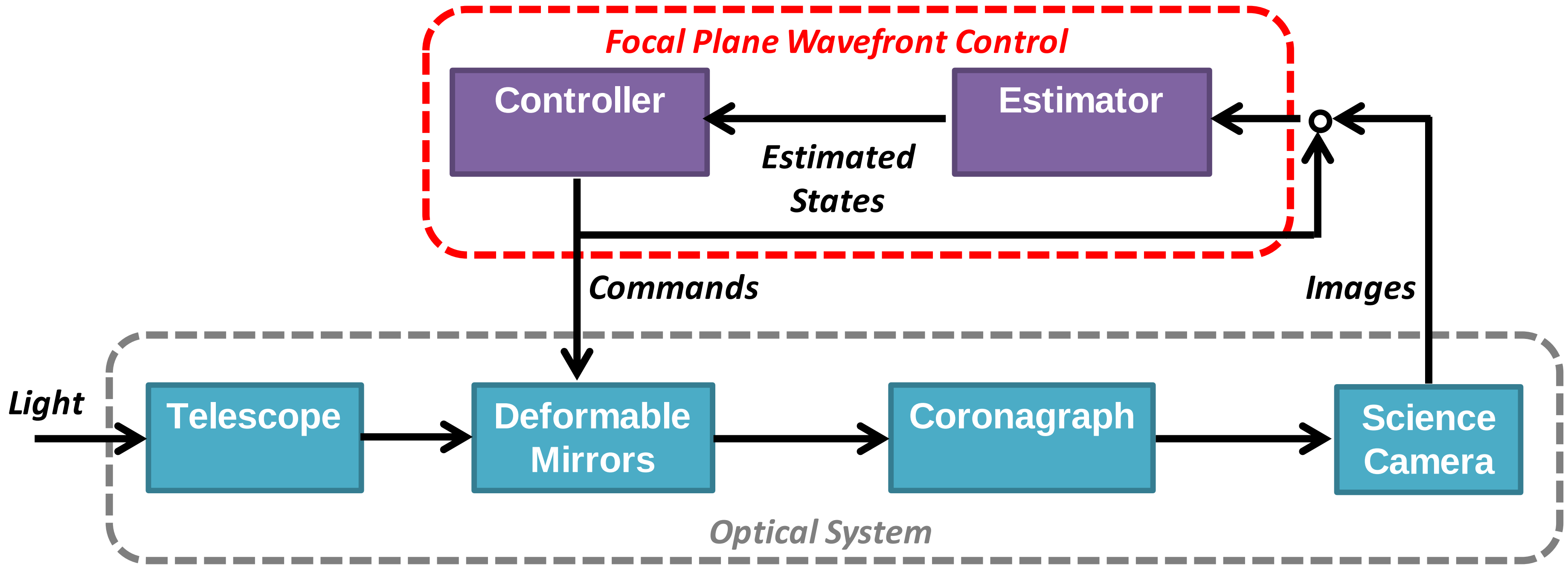




Corrects Tip/Tilt, Focus and lower order Zernike errors from telescope interface on fast timescales.

Courtesy Eric Cady

High-Order Wavefront Control



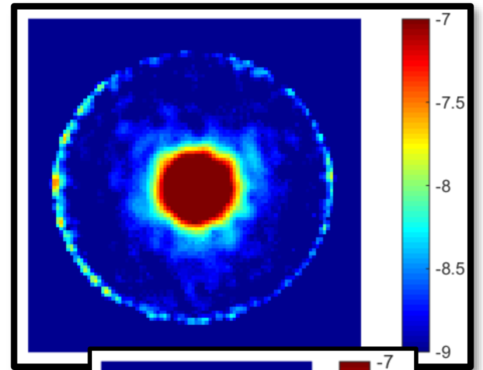
Corrects quasi-static aberrations at high spatial frequencies to create "dark hole". Aberration changes assumed slow compared to correction and observation times. Source of stability requirement on future telescopes (currently assumed at 10-100 pm rms).

HOWFS Performance

Imaging with Narrow FoV
Initial Static Raw Contrast

	Initial contrast vs. working angle		
Working angle	**3-4 λ/D**	**4-8 λ/D**	**8-9 λ/D**
Band 1 (575 nm)	1×10^{-8}	0.7×10^{-8}	1×10^{-8}

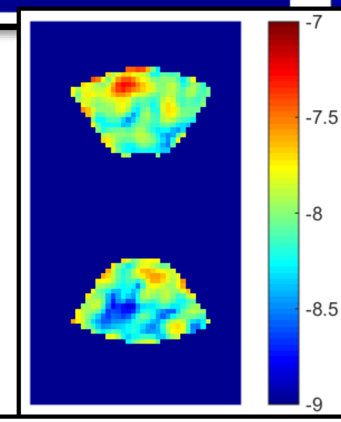
Best testbed result: 1.6e-9 in 10% at 550nm



Spectroscopy
Initial Static Raw Contrast

	Initial contrast vs. working angle		
Working angle	**3-4 λ/D**	**4-8 λ/D**	**8-9 λ/D**
Band 3 (760 nm)	2×10^{-8}	1.5×10^{-8}	2×10^{-8}

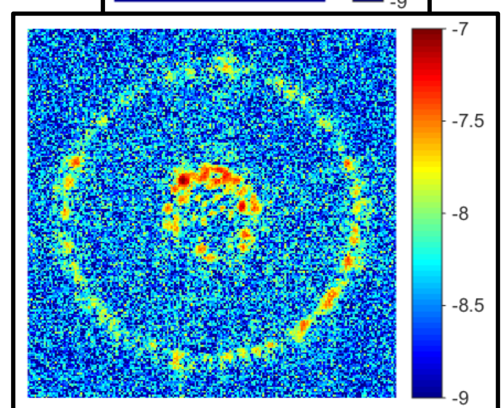
Best testbed result: 1.1e-8 in 18% at 660nm



Imaging with Wide FoV
Initial Static Raw Contrast

	Initial contrast vs. working angle		
Working angle	**6.5-7.5 λ/D**	**7.5-19 λ/D**	**19-20 λ/D**
Band 4 (825nm)	2×10^{-8}	1.5×10^{-8}	2×10^{-8}

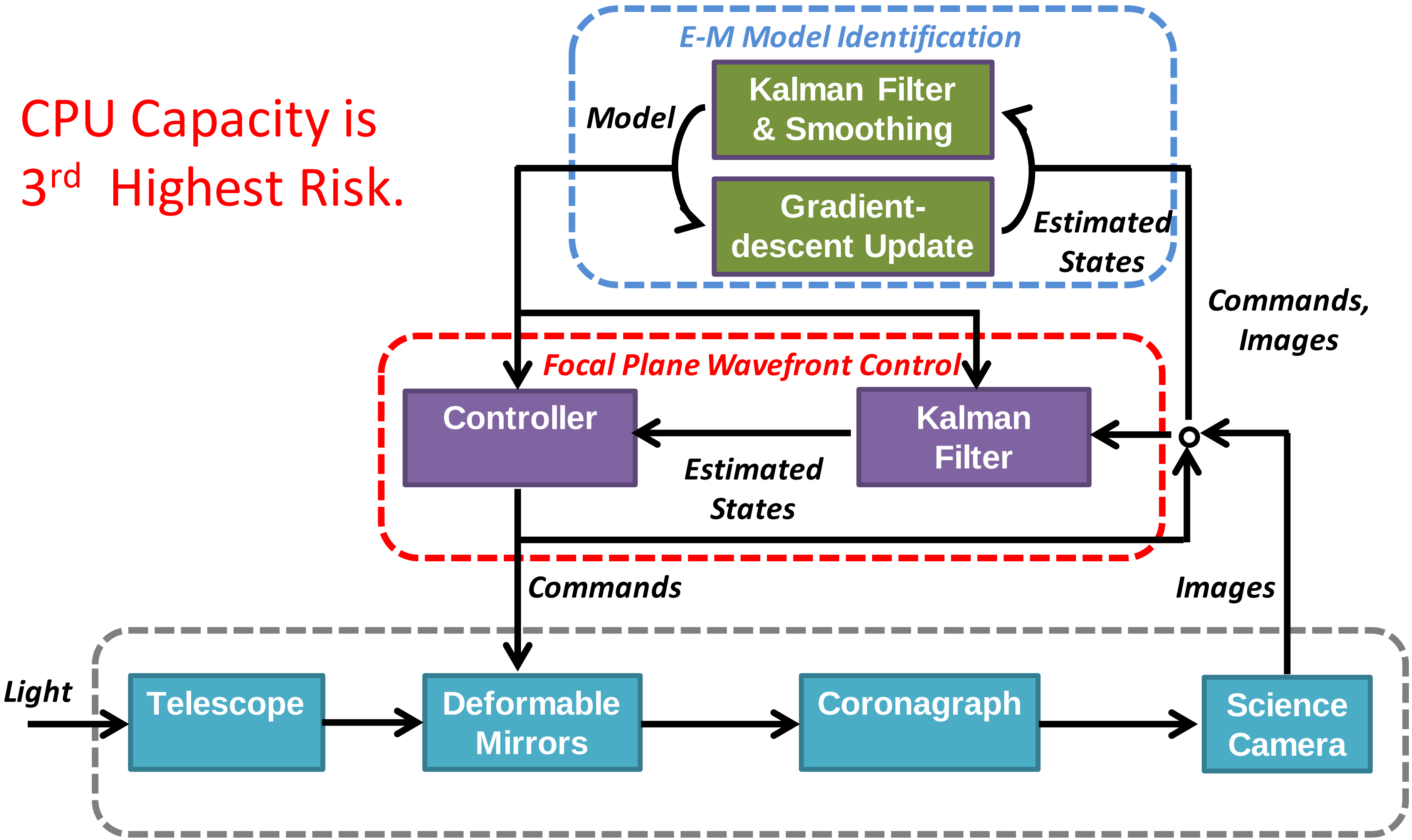
Best testbed result: 4.3e-9 in 10% at 565nm



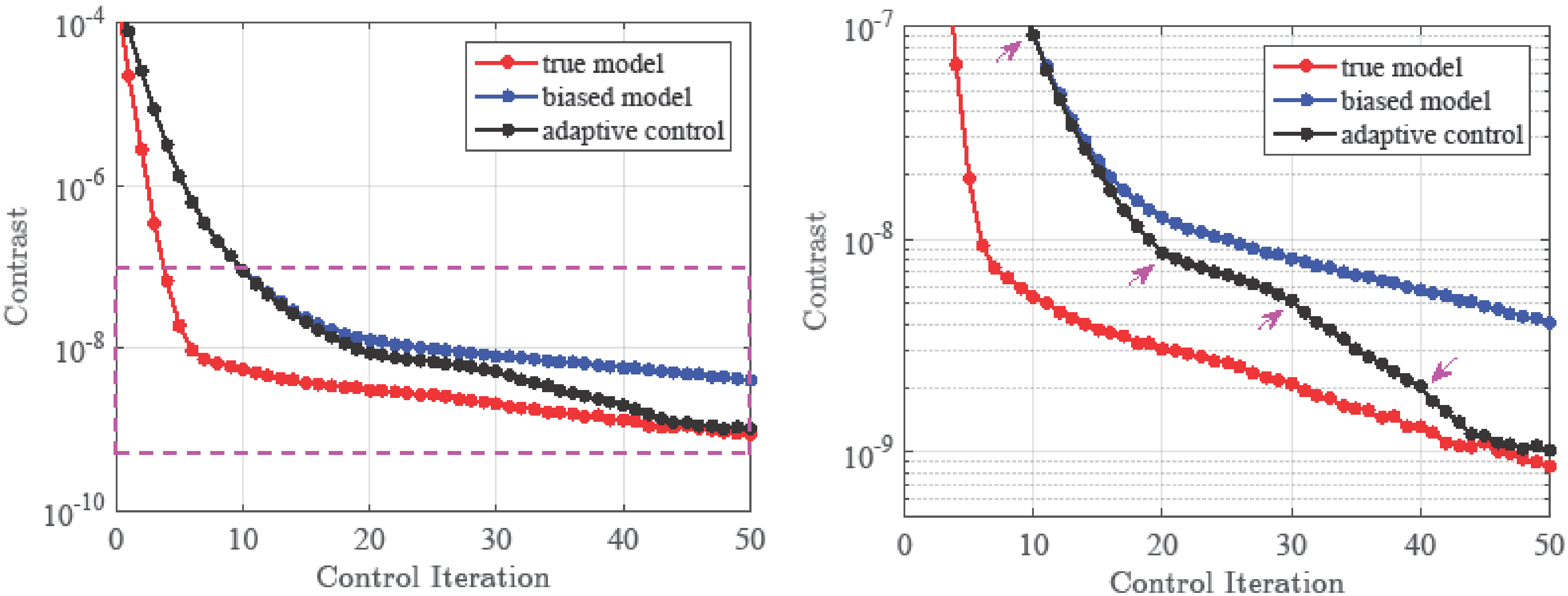
Courtesy Eric Cady

Adaptive High-Order Wavefront Control

CPU Capacity is 3rd Highest Risk.

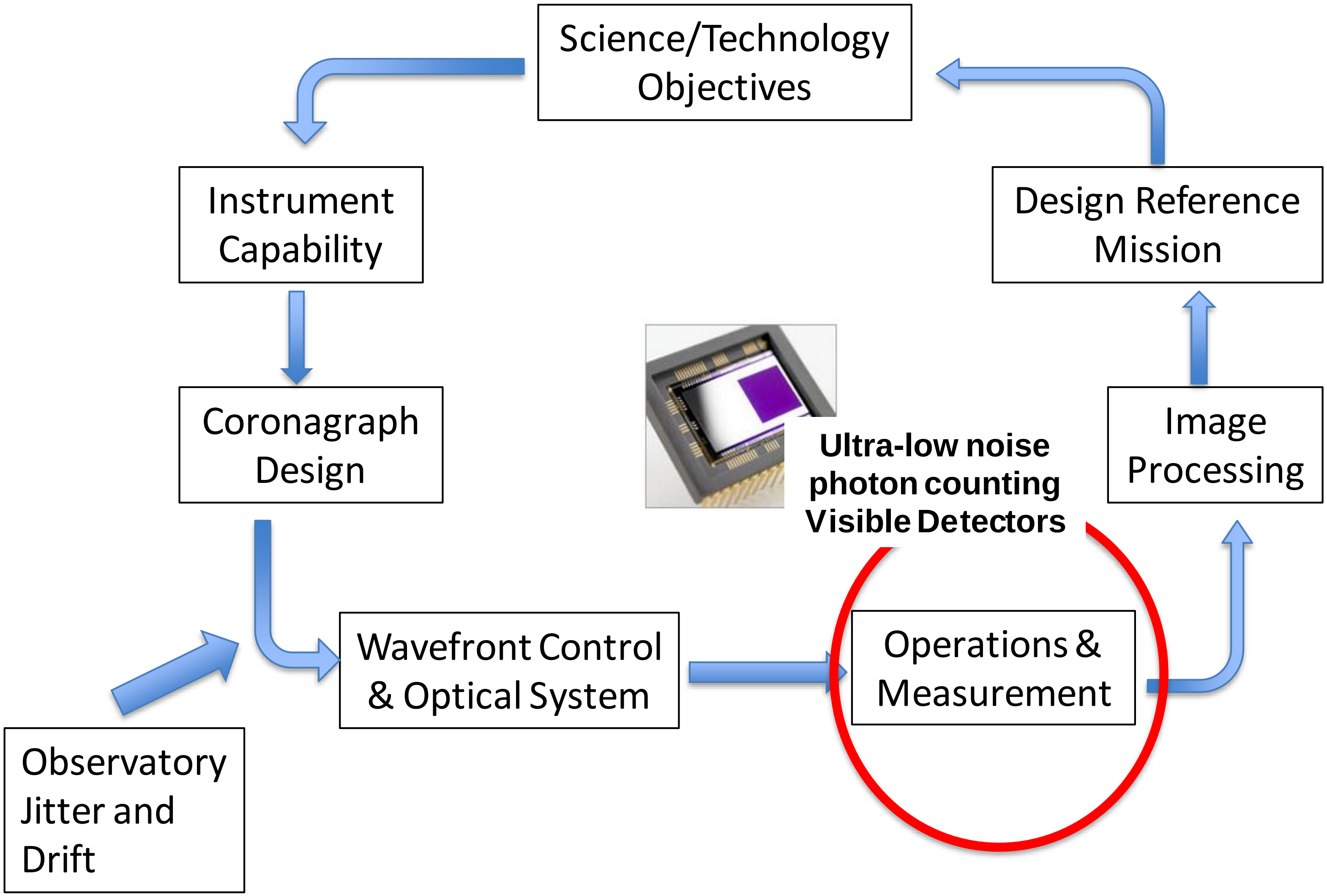


Simulation Results

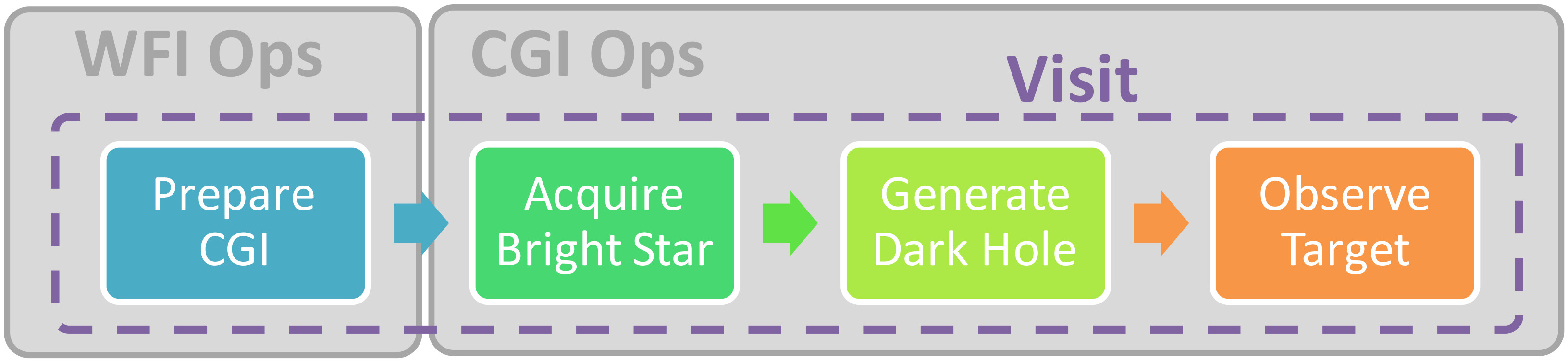


- The DM actuators' influence functions are biased by 20% in amplitude; optical aberrations are added to the shaped pupil plane and DM planes;
- Three test cases: true model control, biased model control, and adaptive control with biased model;
- Adapt the model after every ten iterations;

Coronagraph Design



Single Observation

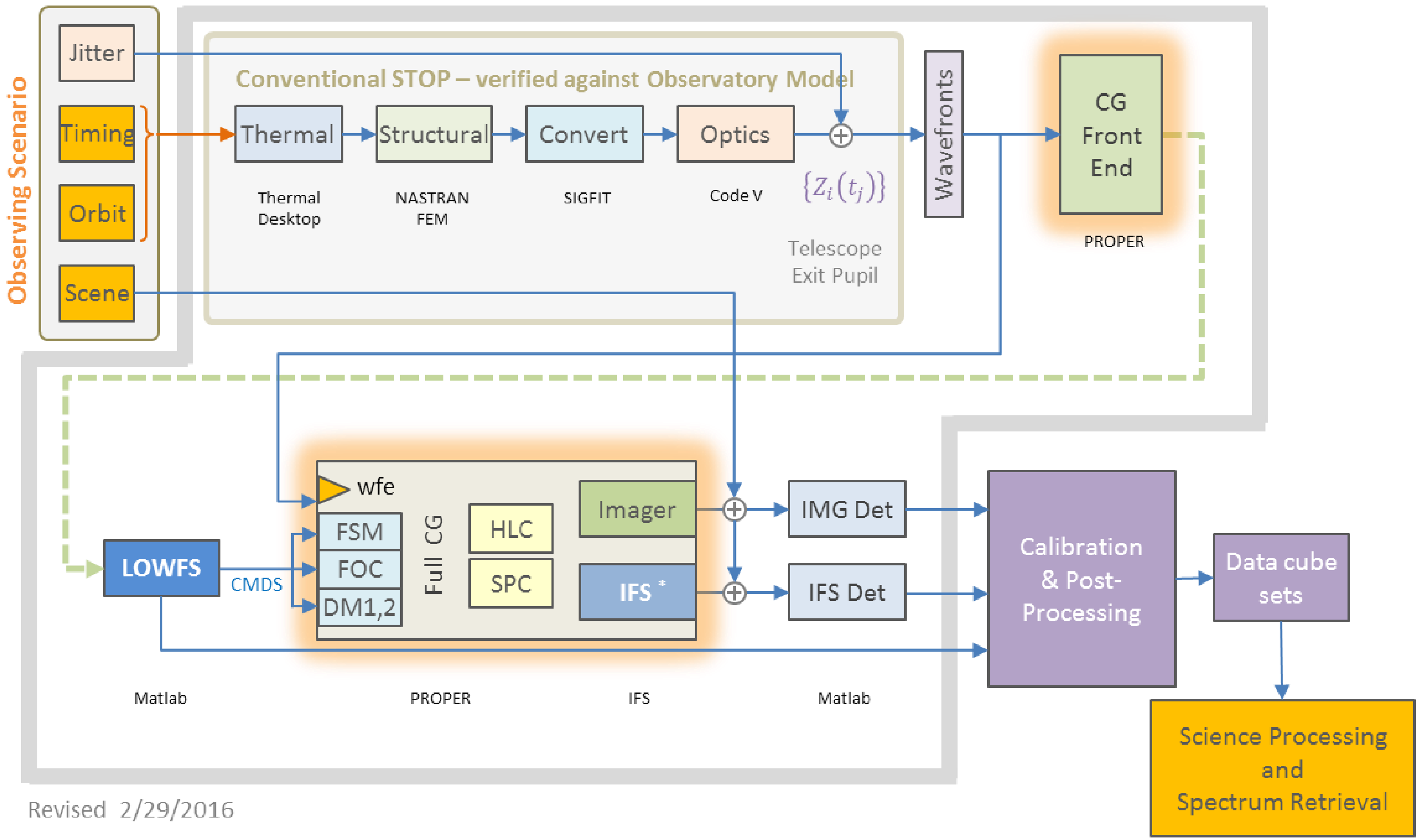


Simple single visit scenario: generate dark hole on a bright reference star, slew to target star, assume residual speckles unchanged and stable on time scale to observe target.

Integrated Modeling of Spacecraft and Coronagraph inform model for speckle level, stability, and noises.

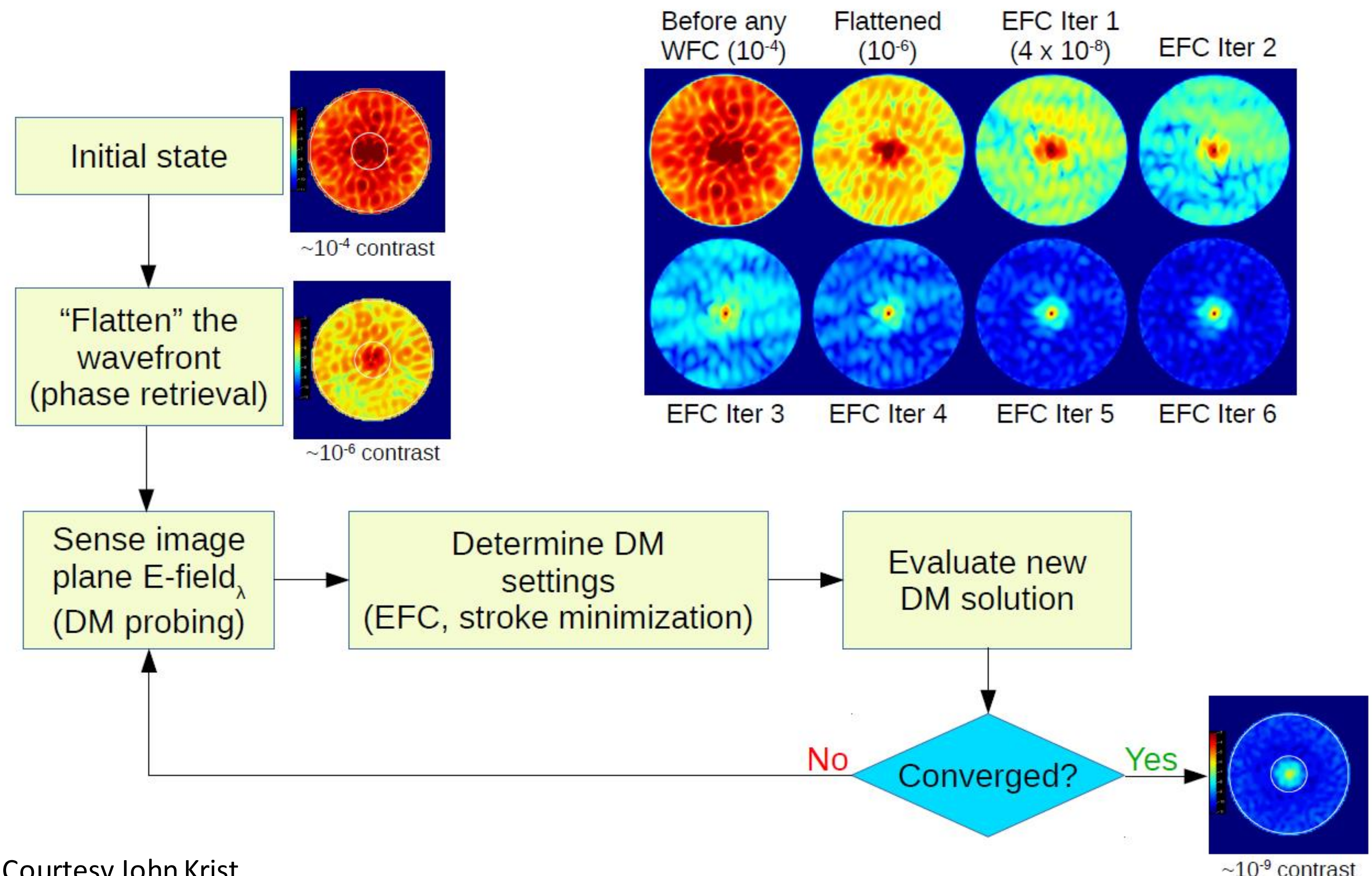
Courtesy Bijan Nemati.

Integrated Modeling



Courtesy John Krist.

Integrated Modeling



Courtesy John Krist.

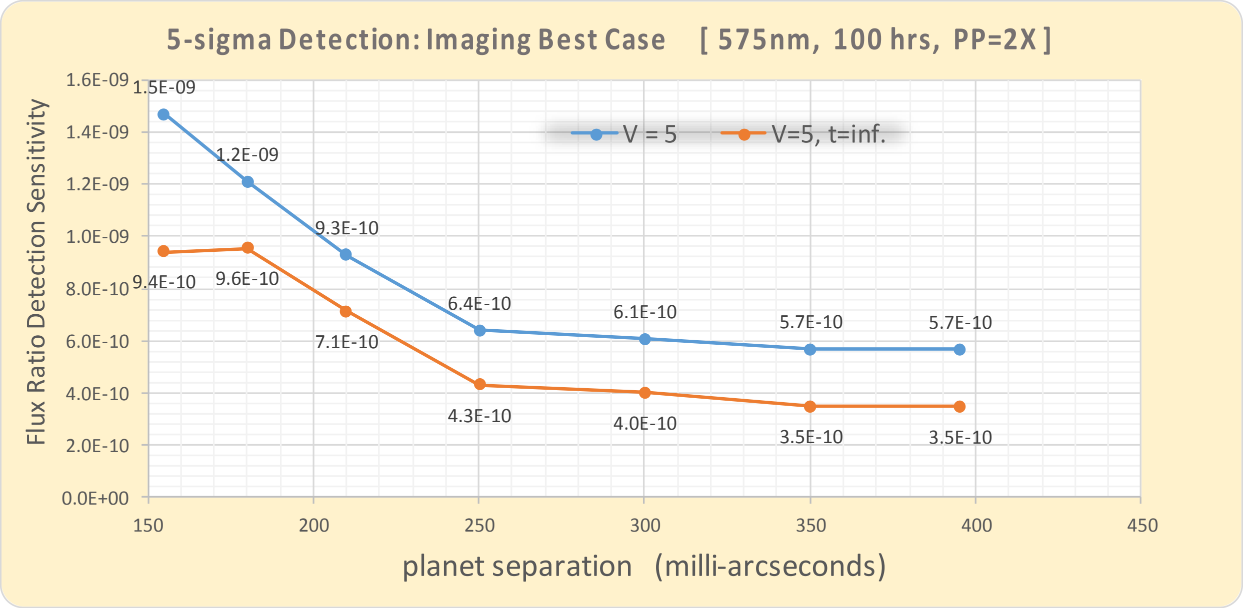
Integration Time Calculator

Models for camera noise, shot noise, and speckle stability used to calculated "detection threshold" and integration times.

What is the minimum flux ratio planet we can see with a specified SNR in the allocated integration time?

Integration time calculator was developed by Bijan Nemati for WFIRST.

See backup for information on EMCCD camera and degradation.



Courtesy Bijan Nemati

Ex.: Direct Imaging

WFIRST Exoplanet Yield Among Known Planets: Imaging Best Case viewed: 3/8/2018

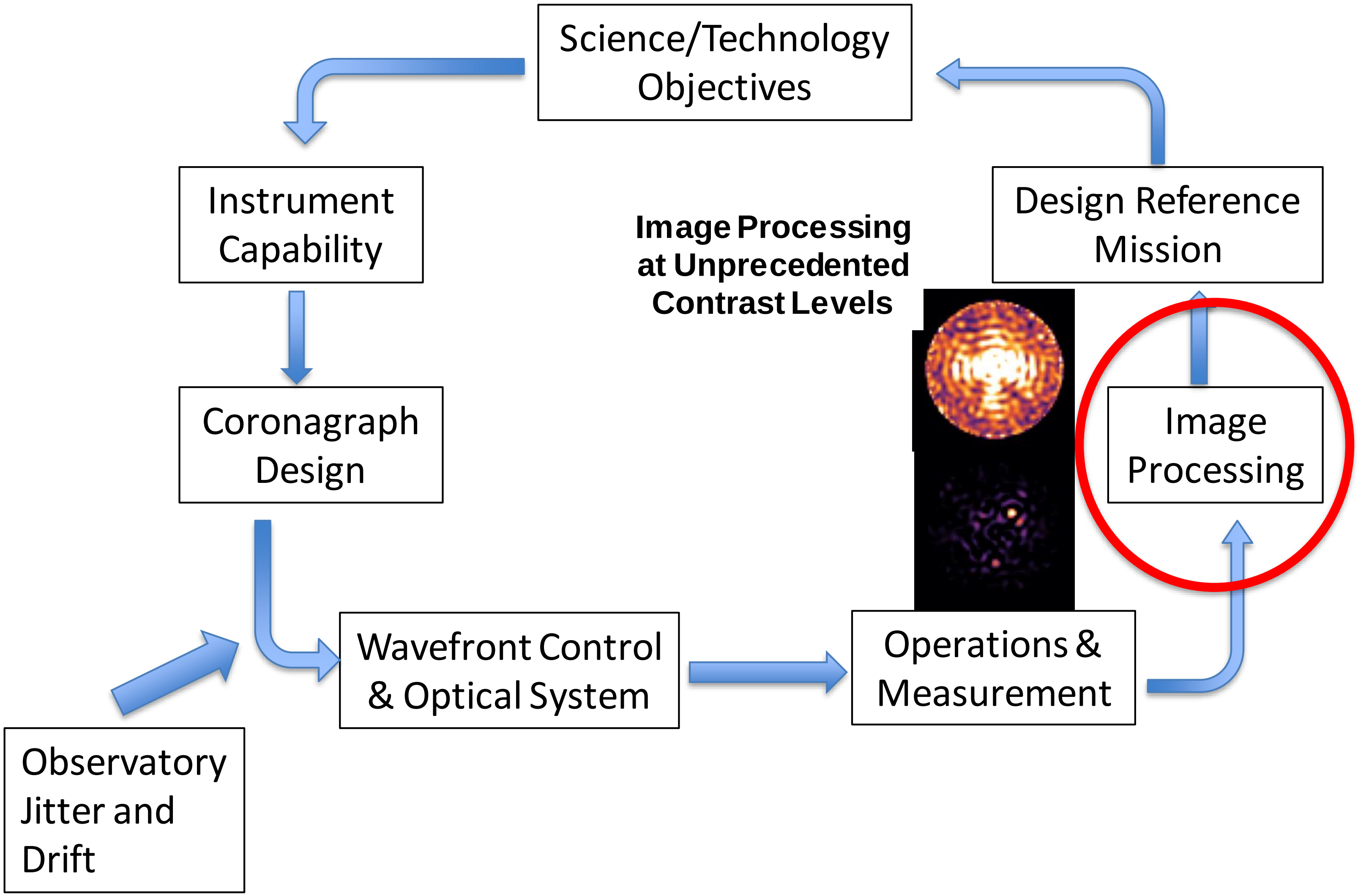
Imaging Best Case RDI : Dmag = 3.0 20% time on Reference, Mult= 1.3

Mode	CG	l , nm	Dl , nm	SNR	f_pp	Mission Life	time, hrs
Imaging Best Case	HLC CG TDemo	575	57.5	5	50%	35%	100

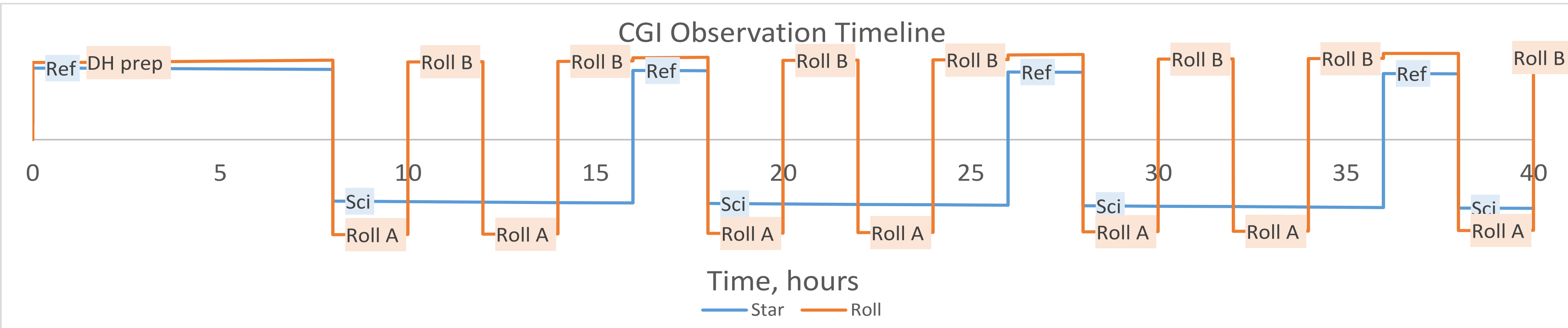
	18	Planets
set:	400	hrs max /pl.
	571	hrs all planets

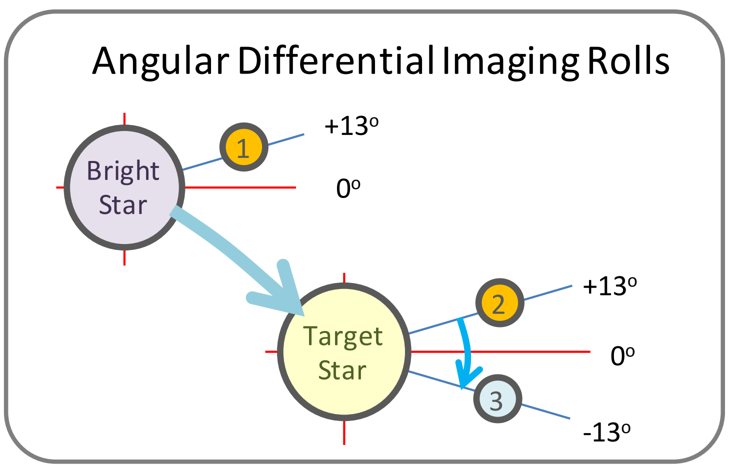
No.	Pl. Name	Vmag	Sep (mas)	WA (l /D)	Critical SNR	Fl Ratio, ppb	Time Margin	t (SNR), hrs	tot ph/px/fr	SMA (AU)	phase, deg	Sep, mas
2	*Planet Sensitivity*	5.0	200	4.00	90.4	12.9	99%	1	1.5	2.21	65	200.2
11	*epsilon Eri b*	3.7	347	6.94	141.7	11.4	100%	0.1	4.5	3.38	65	951.3
36	*GJ 832 b*	8.7	347	6.94	86.5	6.9	-100%	157.9	0.2	3.56	65	651.6
24	*55 Cnc d*	6.0	347	6.94	30.6	2.5	82%	17.9	0.3	5.47	65	402.0
7	*tau Cet f*	3.5	330	6.60	6.6	0.5	71%	28.7	0.9	1.33	65	330.2
21	*mu Ara e*	5.1	312	6.24	34.9	2.8	95%	4.7	0.5	5.34	65	312.0
38	*HD 142 c*	5.7	299	5.98	18.0	1.6	70%	30.1	0.3	6.80	65	299.2
26	*HD 217107 c*	6.2	243	4.86	18.9	2.7	74%	26.4	0.3	5.33	65	243.5
18	*HD 114613 b*	4.9	233	4.65	22.4	3.2	96%	4.0	0.8	5.31	65	232.9
16	*47 UMa c*	5.0	230	4.60	48.7	6.9	99%	1.4	1.0	3.57	65	230.2
20	*Gliese 777 b*	5.7	227	4.54	35.8	5.1	95%	5.0	0.5	3.97	65	227.1
27	*HD 154345 b*	6.8	205	4.11	32.5	4.7	74%	26.5	0.3	4.21	65	205.5
29	*HD 134987 c*	6.5	201	4.03	17.0	2.4	40%	60.4	0.3	5.83	65	201.5
40	*psi Dra B b*	5.8	182	3.64	21.3	4.1	88%	12.2	0.5	4.43	65	182.2
30	*HD 87883 b*	7.6	178	3.56	32.5	6.3	25%	74.8	0.2	3.58	65	178.0
10	*upsilon And d*	4.1	170	3.39	58.9	11.3	100%	0.4	2.6	2.52	65	169.6
17	*HD 39091 b*	5.7	166	3.31	31.2	6.0	94%	6.2	0.5	3.35	65	165.6
8	*beta Gem b*	1.2	154	3.07	130.7	24.6	100%	0.01	54.1	1.76	65	153.8
22	*14 Her b*	6.6	151	3.02	45.3	8.5	81%	19.1	0.3	2.93	65	151.3
12	*47 UMa b*	5.0	135	2.71	-1.0	17.5	-100%	-1.0	-1.0	2.10	65	135.4
6	*tau Cet e*	3.5	148	2.96	-1.0	1.8	-100%	-1.0	-1.0	0.54	90	147.9

Coronagraph Design



WFIRST Differential Imaging

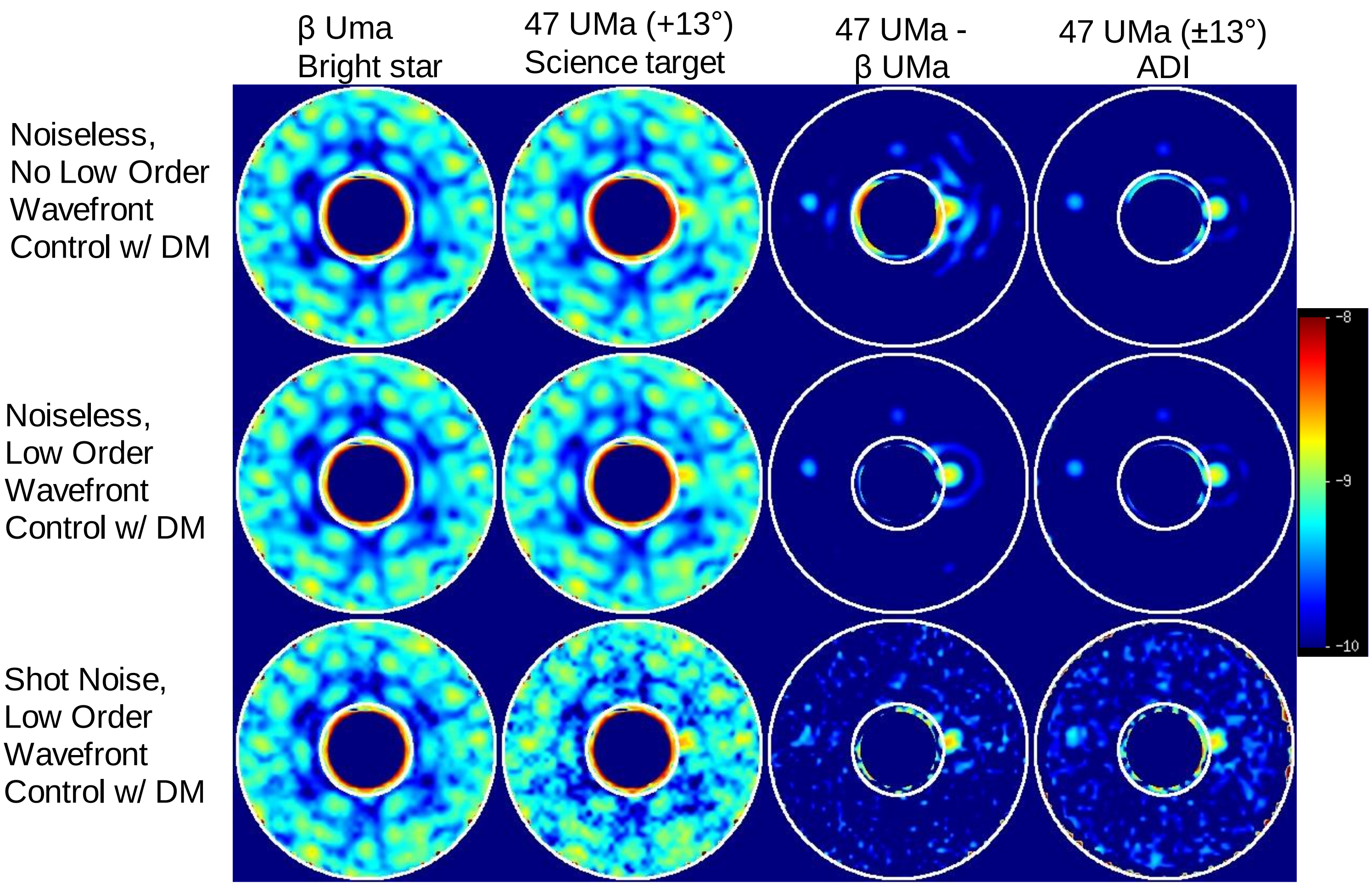




Courtesy Bijan Nemati

- Use both Roll-chop and Star-chop to mitigate drift on long integrations
- CGI dark hole prepared while pointed at Reference star
- 2-hour cadence of roll-chop maneuvers on target star
- 10-hour cadence of revisits to Reference star

OS6 Example Post-Processing

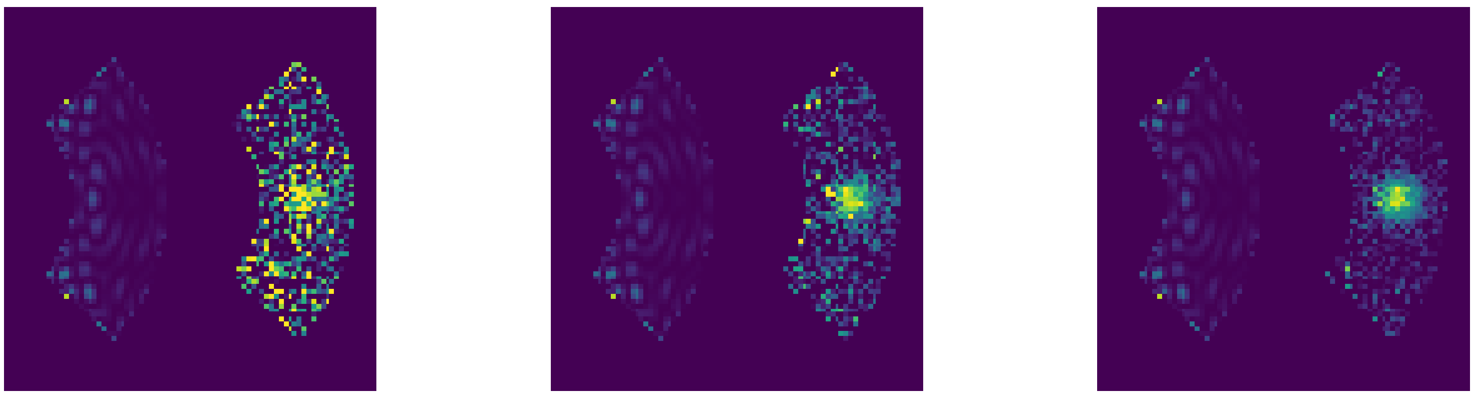


Courtesy John Krist.

Coherent Differential Imaging

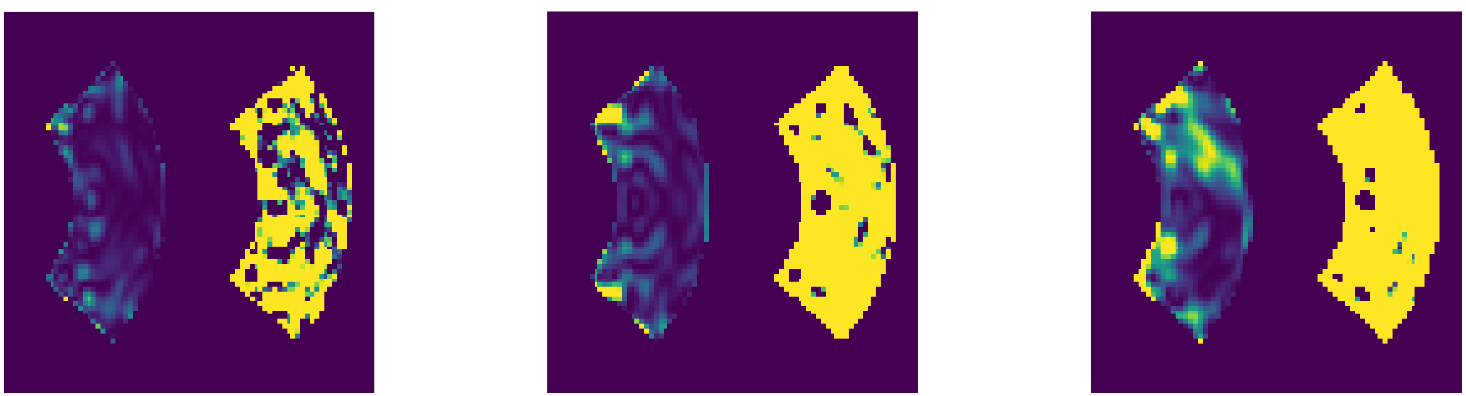
Comparison of RDI with perfect stability (top) and wavefront drift (bottom)

K=100 K=500 K=2000



Left: Measurement, Right: After PSF subtraction. Speckles x5 planet at start.

K=100 K=500 K=2000



100s Frames

10 planet photons per frame

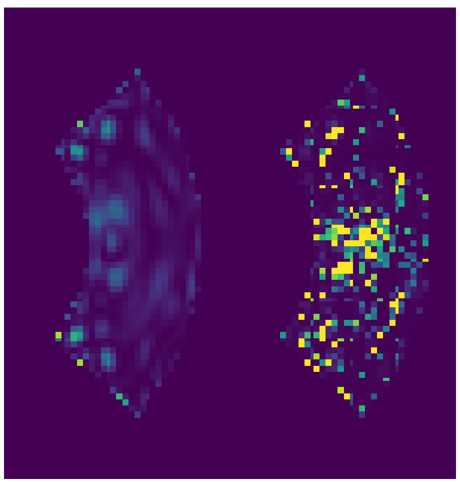
100 pm wavefront drift per frame.

No camera noise.

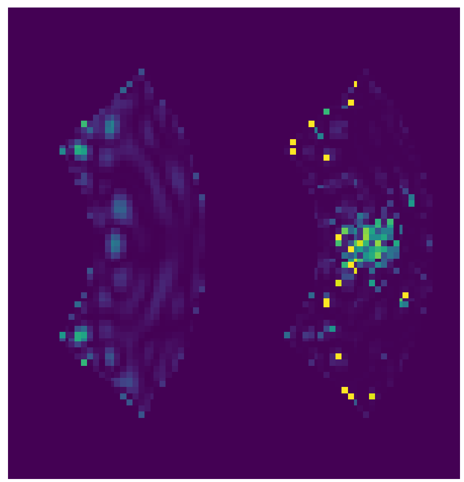
Coherent Differential Imaging

Continuous closed-loop wavefront control during long integration using random DM dither.

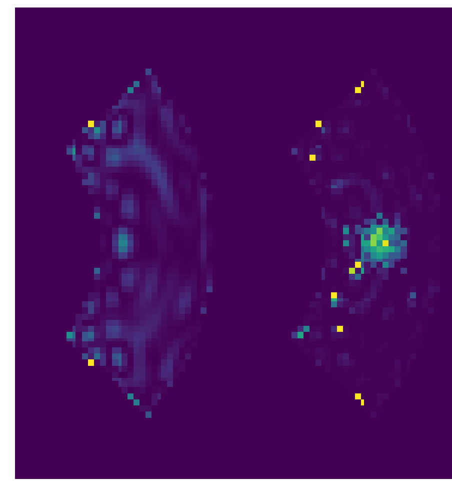
K=100



K=500

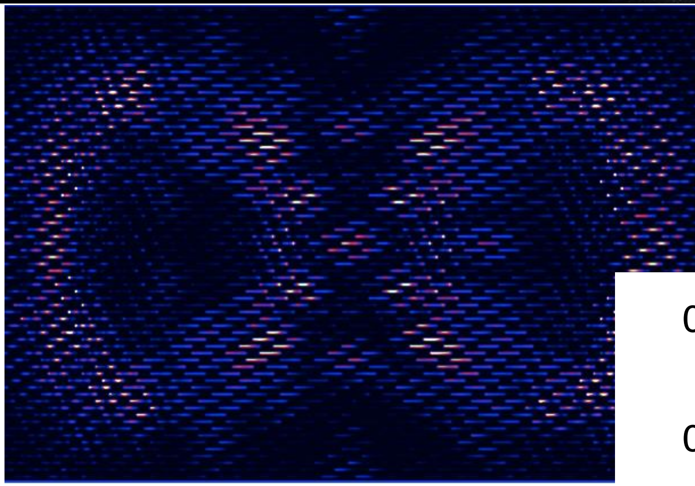


K=2000

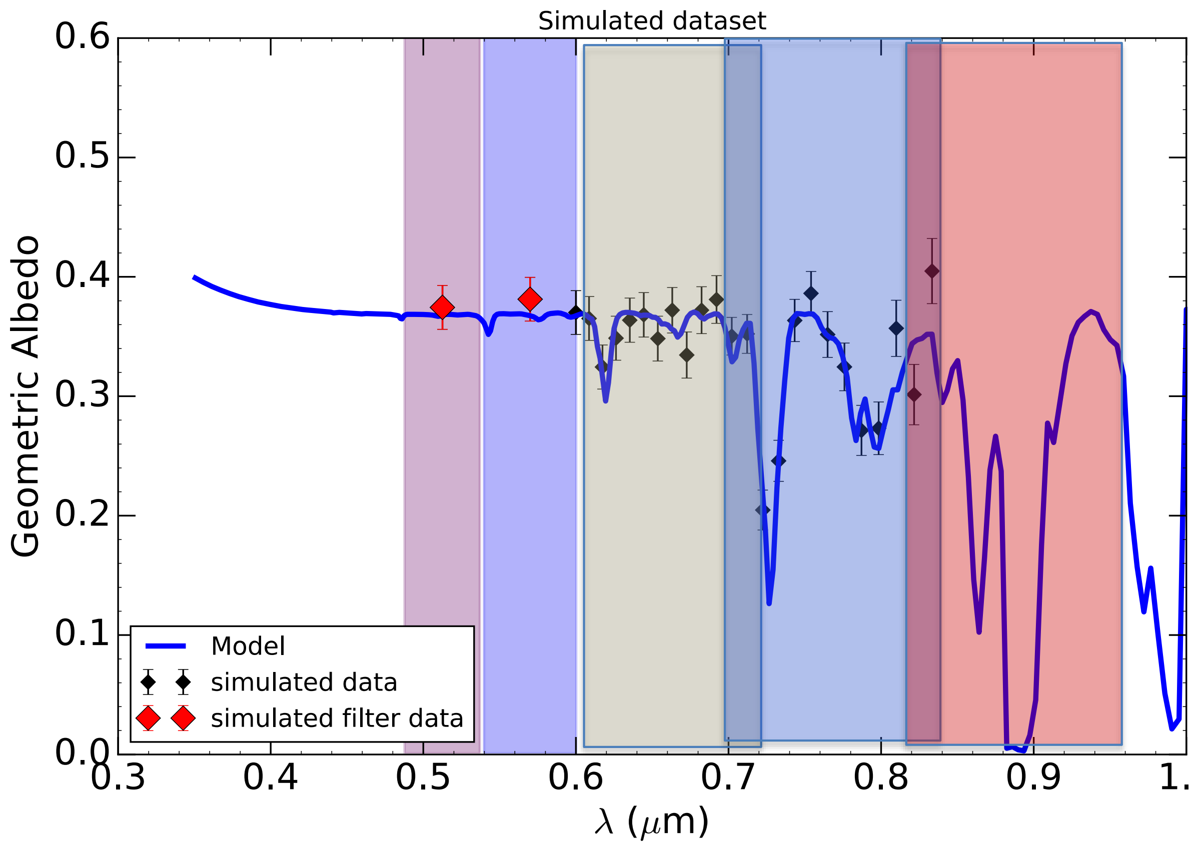


Same 100 pm per frame wavefront drift.

Specral Retrieval

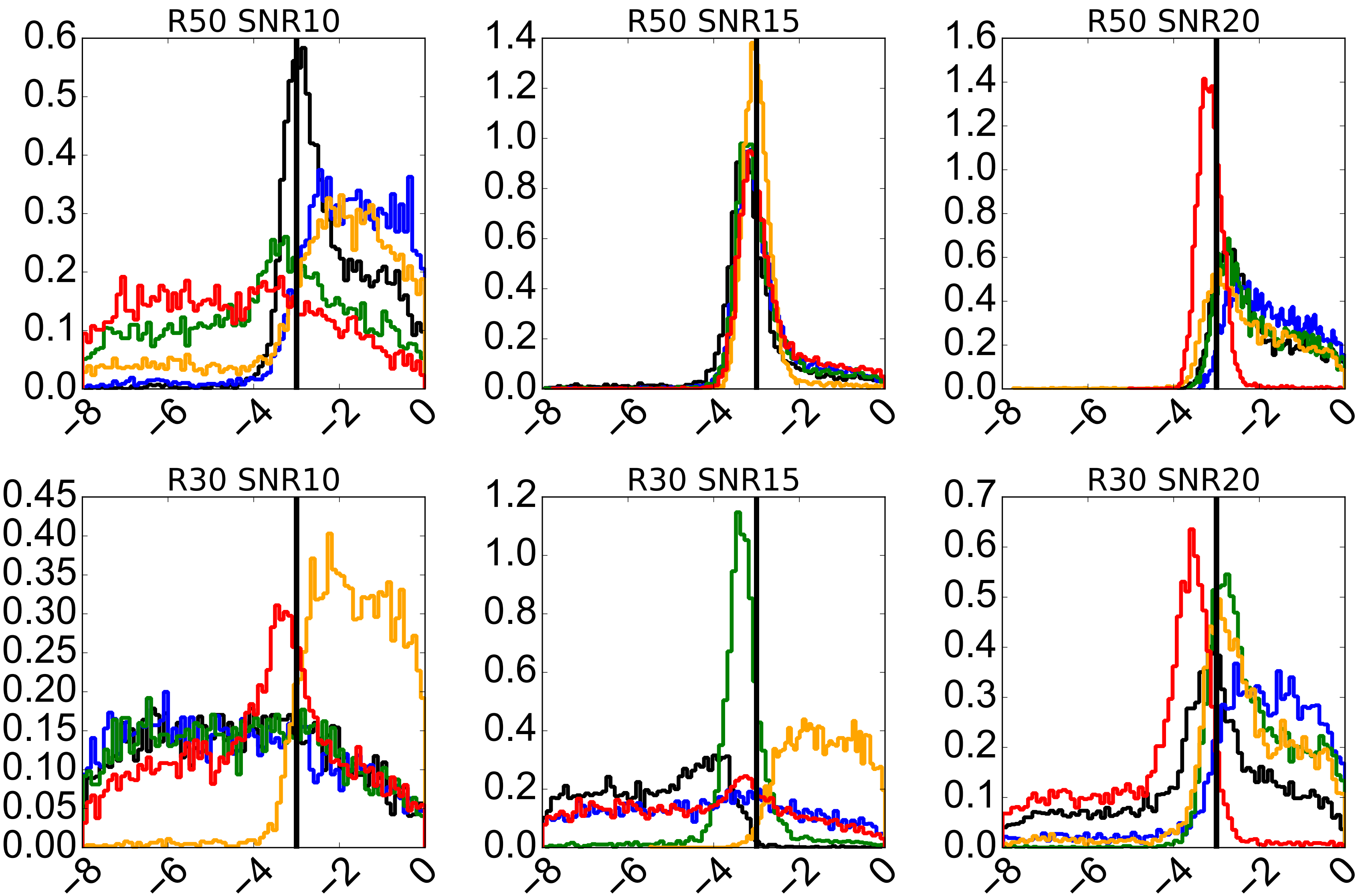


GPI / P1640 / CHARIS style IFS

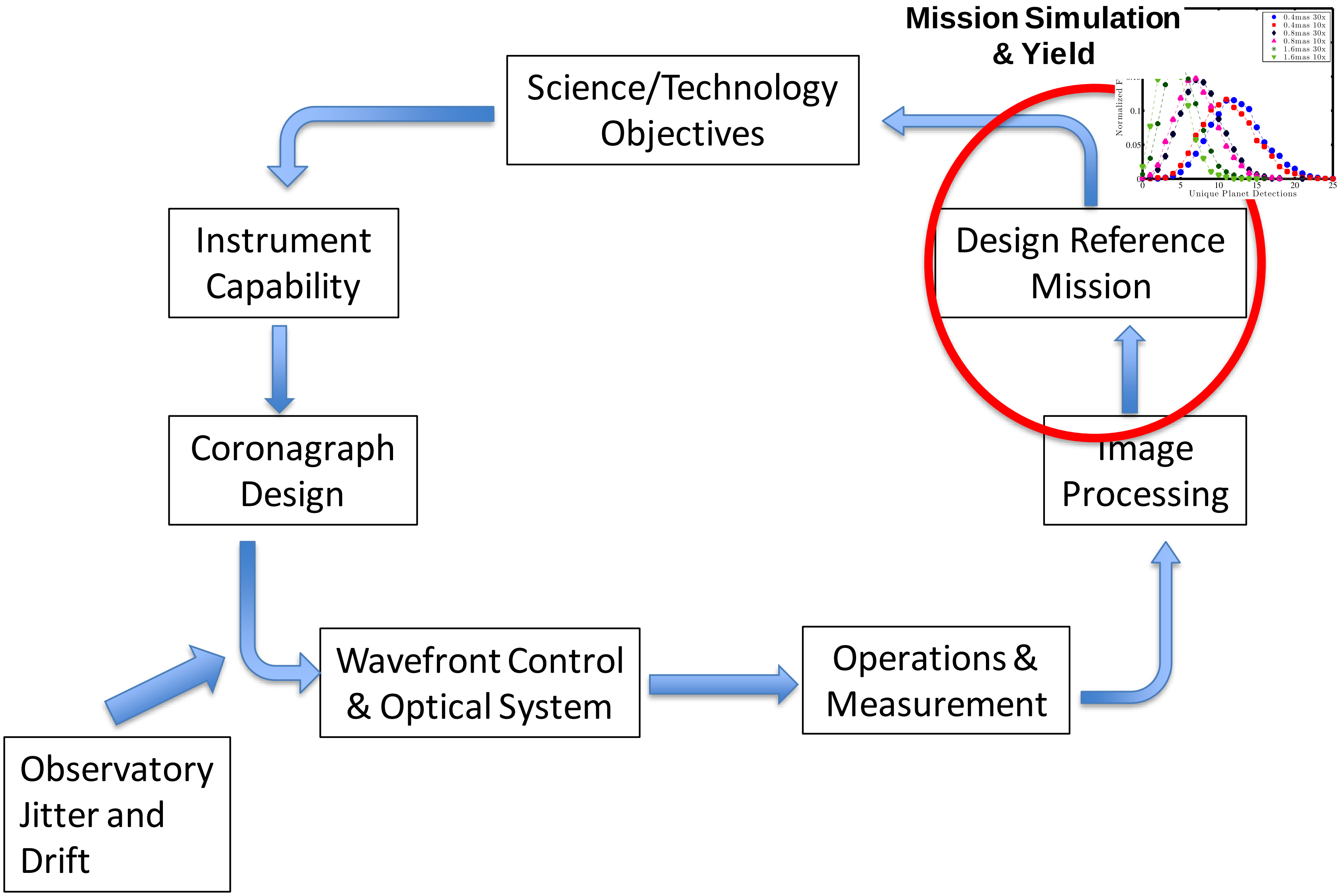


Multiple SIT members developing spectral retrieval approaches. Verified through a community data challenge.

Ex.: Spectral Resolution & SNR for Methane Detection



Coronagraph Design



DRM Development

With integration time calculations can build a ”Design Reference Mission”, the order of observing to determine total science yield.

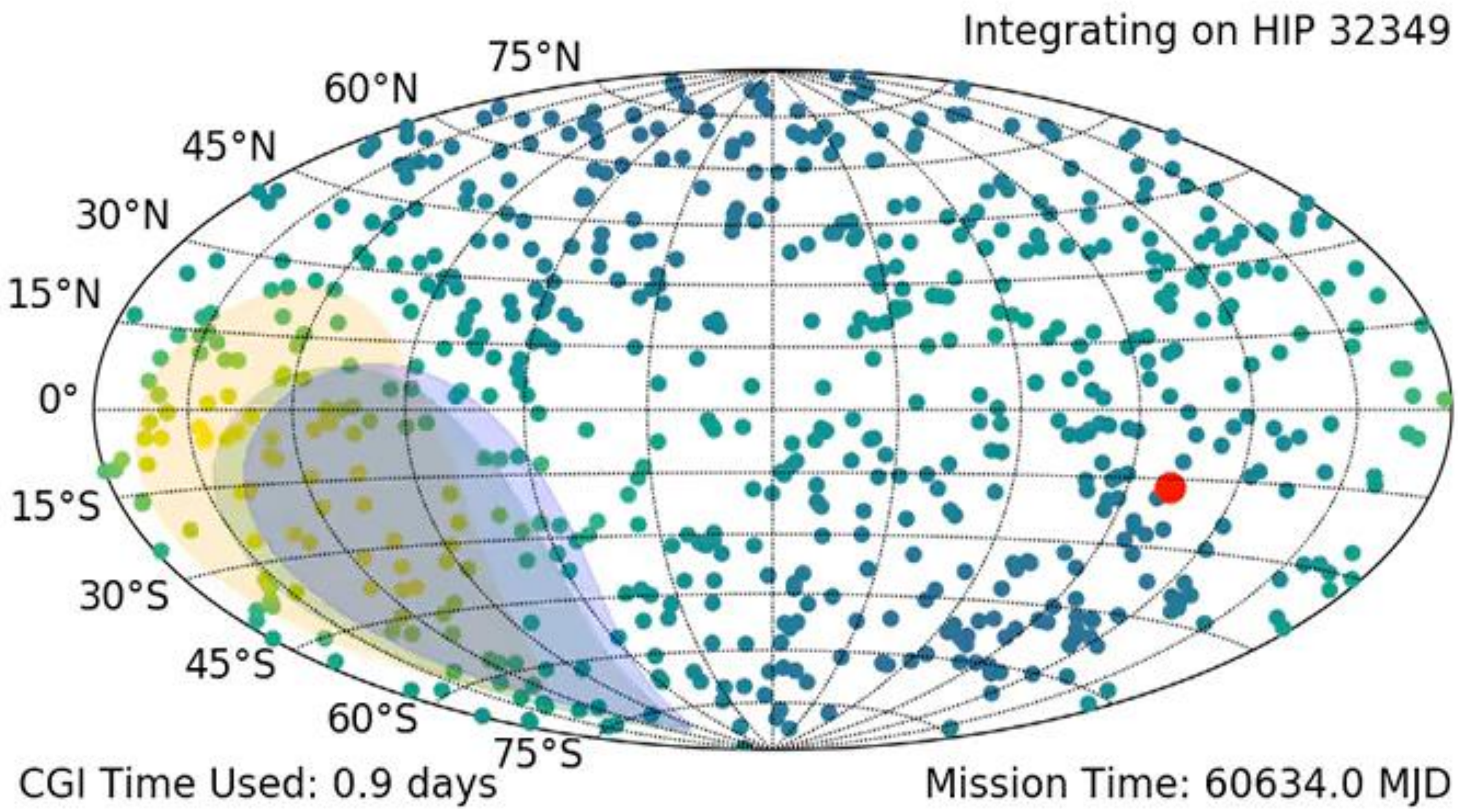
Two general approaches:

- Semi-analytical optimization (Stark, see talk)

- Monte-Carlo Mission Buider (ExoSim – Savransky)

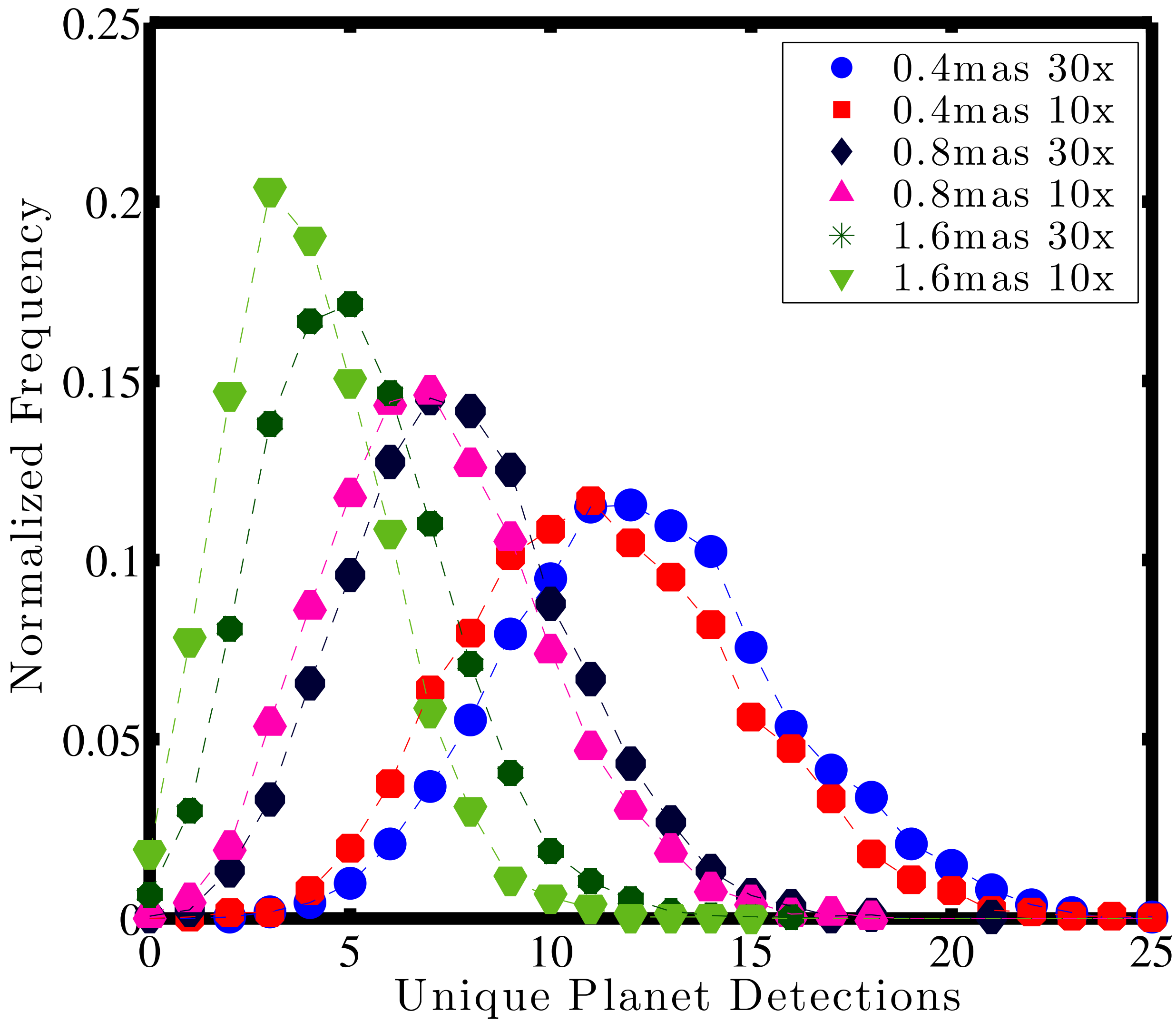
ExoSIM

Courtesy Dmitry Savransky



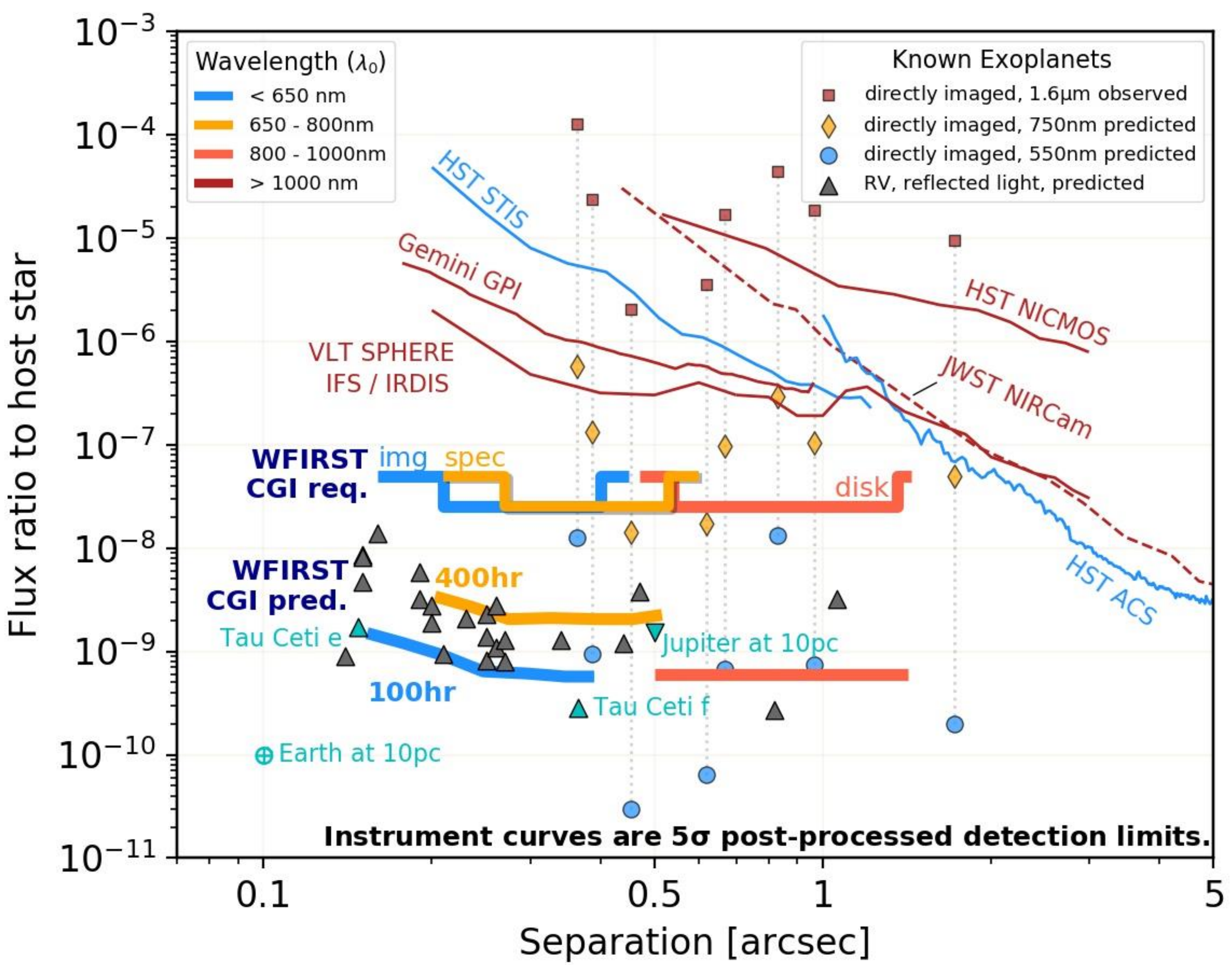
ExoSIM

Courtesy Dmitry Savransky



All of these pieces then come together to produce estimates of capability and potential science yield.

Potential CGI Science



Giant Planet Imaging Photometry

Narrow-band Spectroscopy of Self-luminous & RV Planets

New Planet Discovery

Exozodiacal Disk Imaging

Visible light characterization of Debris Disks

18 Month Tech Demo

- R50 Spectra of ~2 young, self-luminous super-Jupiters
  - Beta Pic b, HR 8799 e, 51 Eri b
- Masses for ~10 Jupiter analogues
  - Imaging breaks vsin(i) degeneracy in mass of RV planets
- R50 Spectra of 1-2 Jupiter analogues
- Circumstellar disks
  - Image 2-4 bright, known debris & protoplanetary disks
    - More details of inner regions; new wavelengths
  - First images of 1-2 (faint) exozodi disks

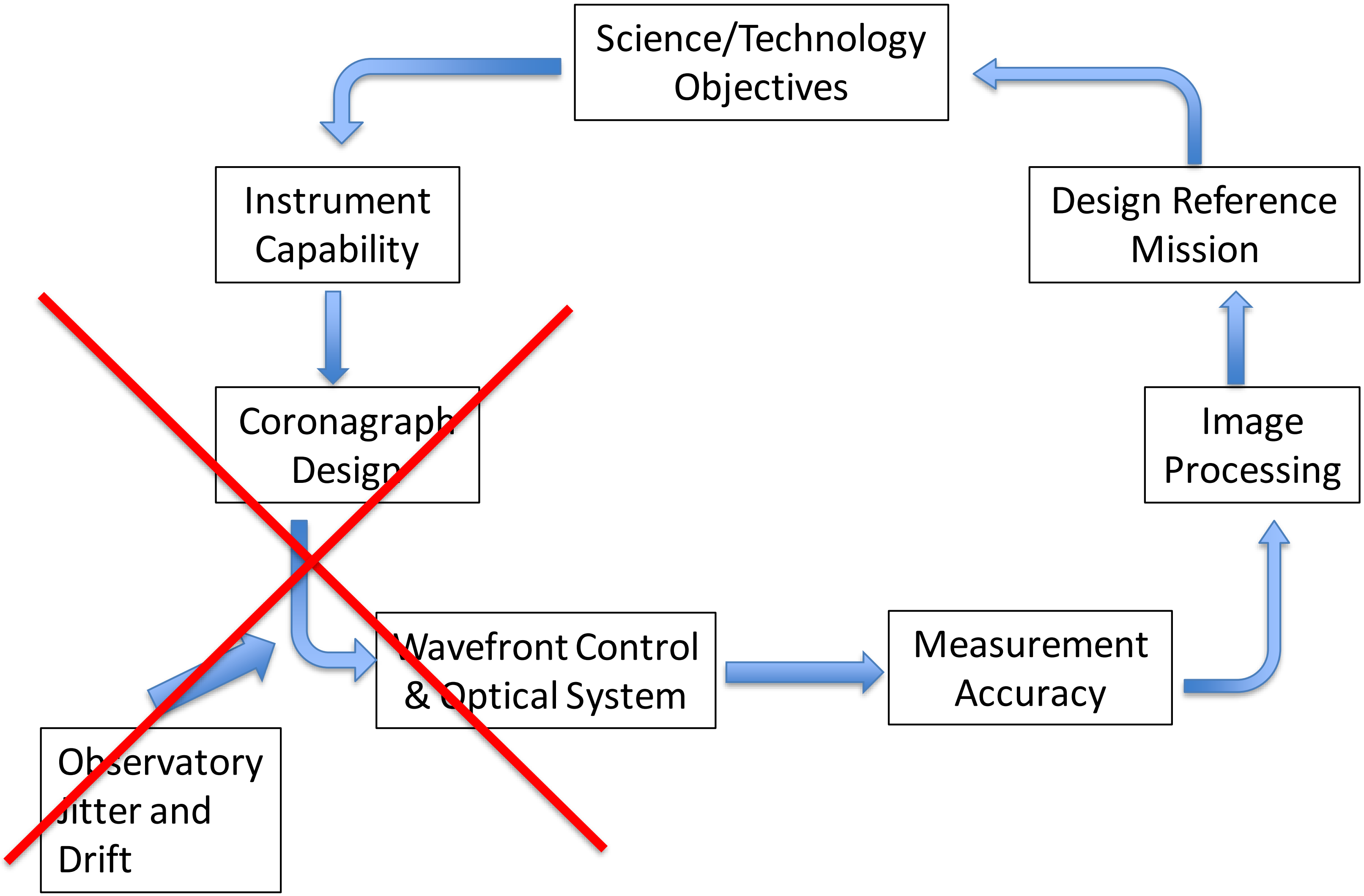
Participating Science Program

- **CGI Exoplanet Potential Science**
  - ~ double the number of planets with imaging and spectroscopy
  - More than double the number of imaged disks
  - ~ 3 months for a search for new planets
    - Could discover ~10 new Jupiter analogues
    - May discover a few Neptunes or mini-Neptunes
  - "pre-imaging" of ~20 highest priority systems for exo-Earth missions
    - Exo-Earth imaging needs "clean" (low dust) systems
    - Detect / rule out Jupiter analogues in systems with poor RV constraints
- Expanded science areas & **possible GO program**
  - new kinds of community-driven exoplanet & disk science
  - evolved stars, quazars, Solar System objects, …
- Possible **starshade rendezvous**

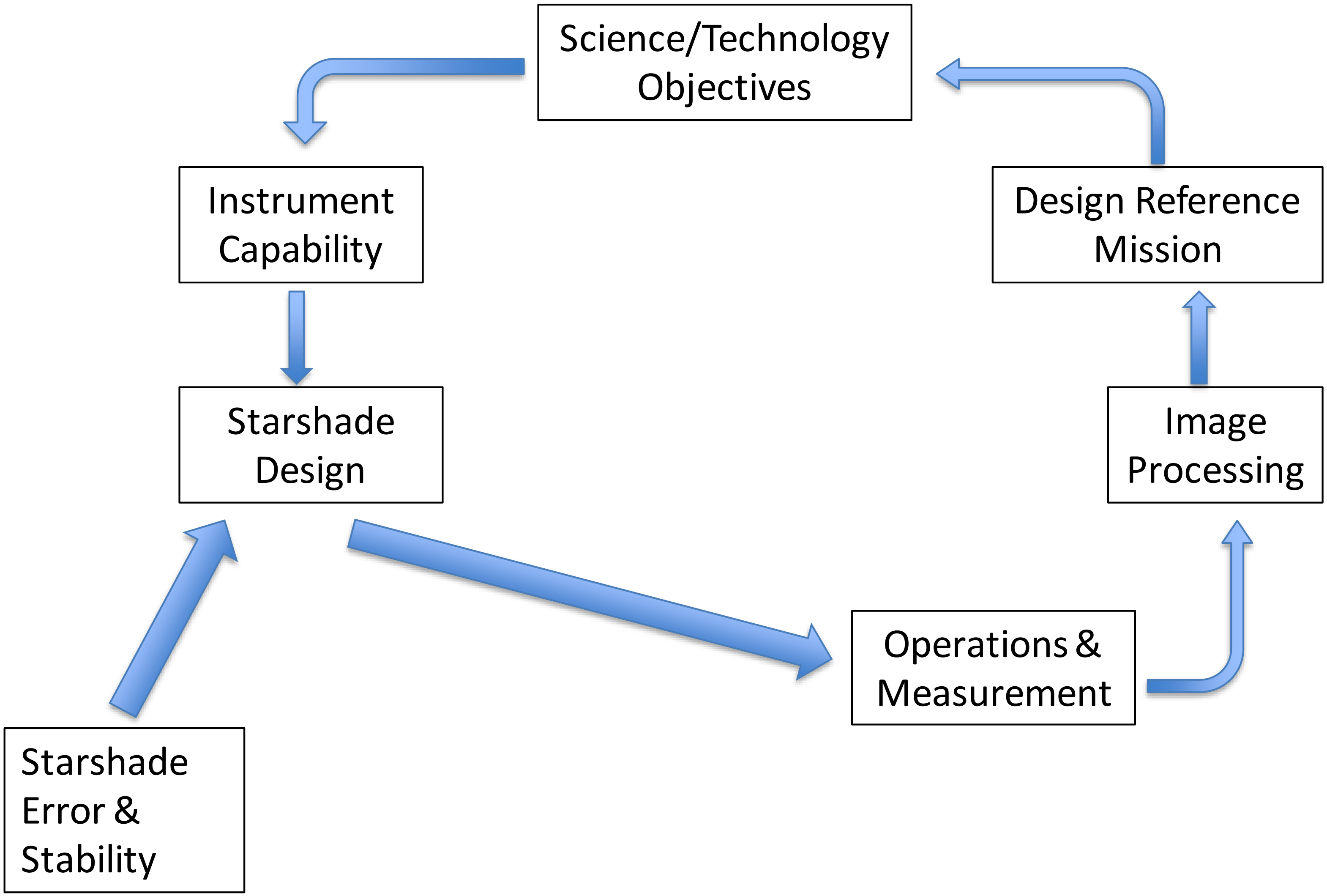
CGI Summary

- CGI is pioneering all elements of an advanced coronagraph in space
- Designing and building CGI is reaping tremendous benefits for future missions
- Flying CGI will demonstrate full active coronagraph capability in space for first time.
- Flight characterization of entire system
- Potential for advances in science is significant.

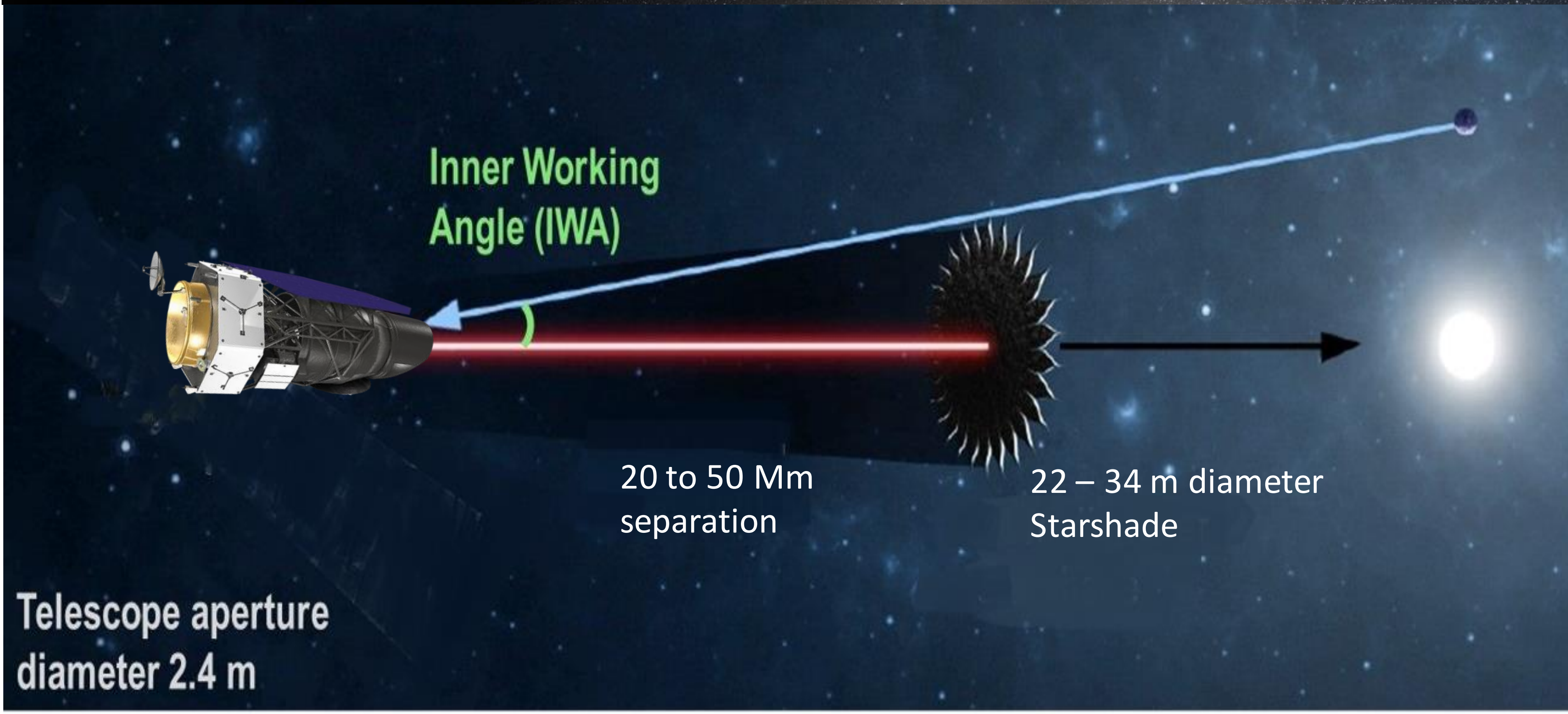
A Starshade Mission



A Starshade Mission



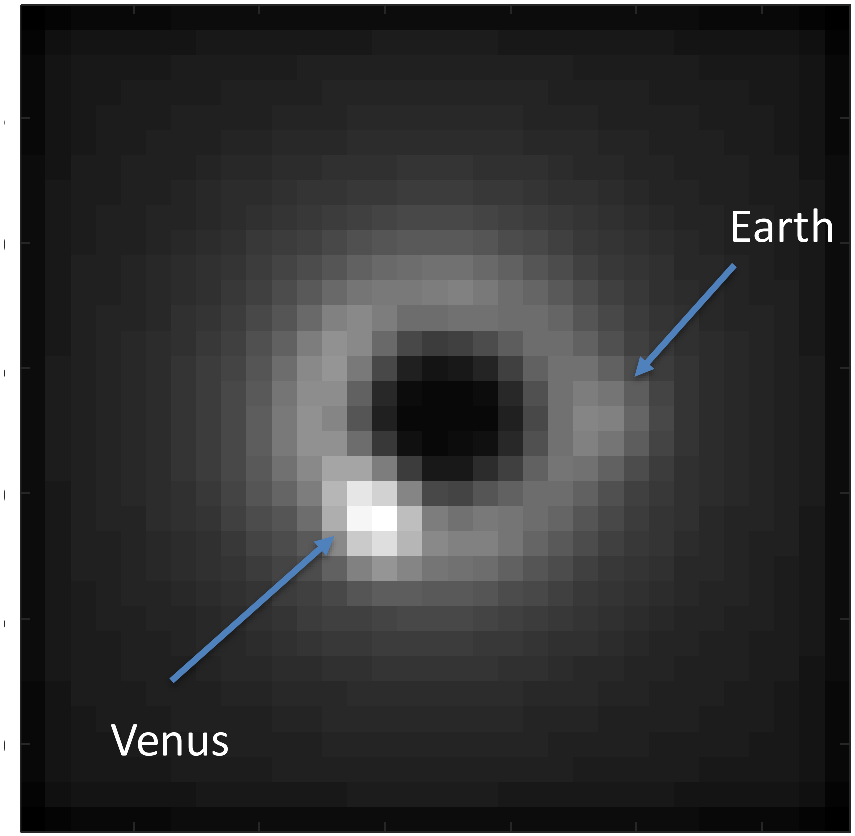
Starshades for Exo-Earth Imaging



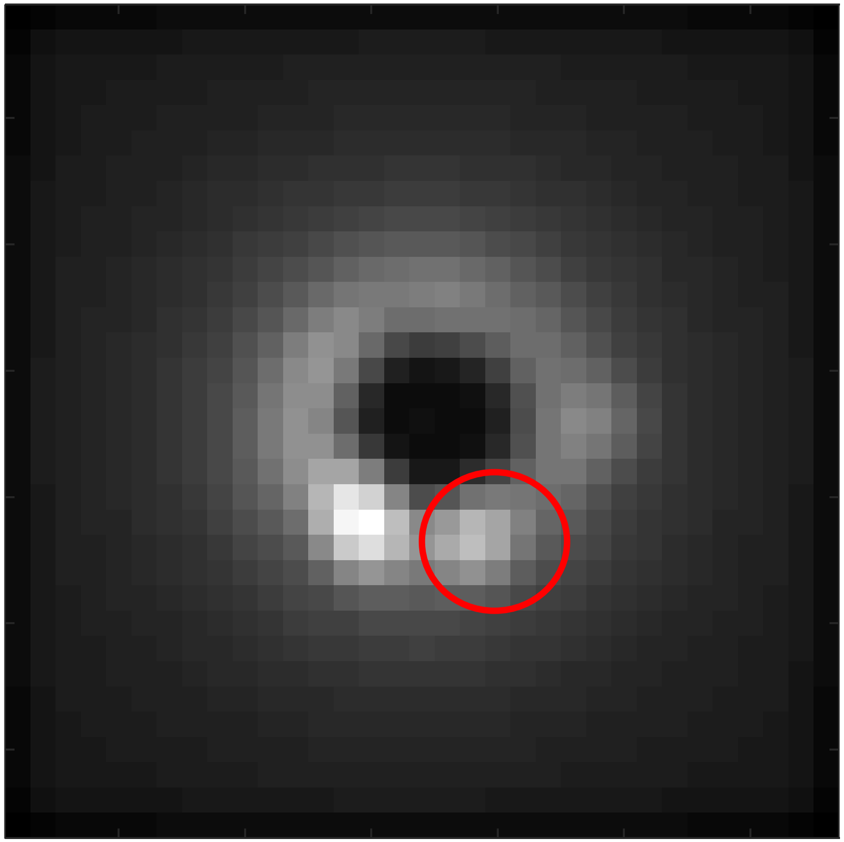
With small impact to WFIRST and CGI, we can give the 2020 Decadal Survey the option to recommend a starshade for enhanced science and technology demonstration.

Simulated Image

Perfect starshade



Truncated Tip



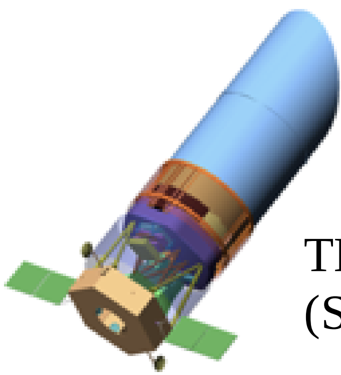
Starshade Basics

- Contrast and IWA independent of telescope aperture size
  - Enables small inner working angle with 2.4 m telescope and access to habitable zone
  - Enables detection of smaller, close-in planets
- No outer working angle – Large FOV
  - Enables imaging of entire planetary systems, mosaicing from within dark shadow
- High throughput, broad wavelength bandpass
  - Enables spectral characterization of smaller planets in feasible time
- Can work in tandem with coronagraph
  - Coronagraph: orbits of brighter planets, Starshade: spectra of smaller planets
  - Potentially enables work on binaries like alpha Cen
- Wavefront correction unnecessary
  - Adds robustness to exoplanet program
- Retargeting requires long starshade slews (days to weeks)
  - Long down times compatible with interleaved observations
  - Starshade revisits are challenging but CPM confirmation is possible for high priority targets within single observation epoch (~2 weeks)

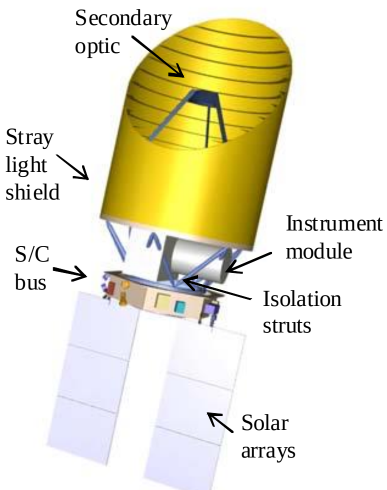
Modern Mission History

First suggested by Lyman Spitzer in 1962. Later, BOSS in 2000 & UMBRA in 2003.

2010 Decadal Survey



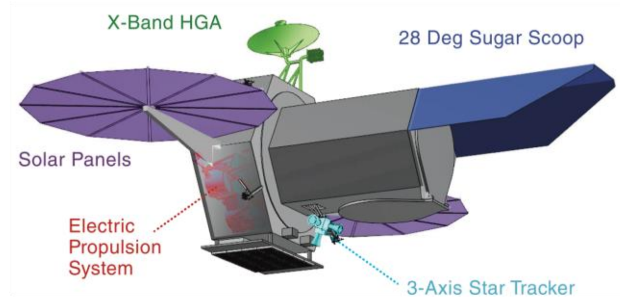
THEIA
(Spergel & Kasdin)



4 m Telescopes with Large Starshade

NWO
(Cash)

2015 Probe Studies



Exo-S
(Seager)

1.1 m Telescope,
30 m Starshade
3-5 Earths in HZ

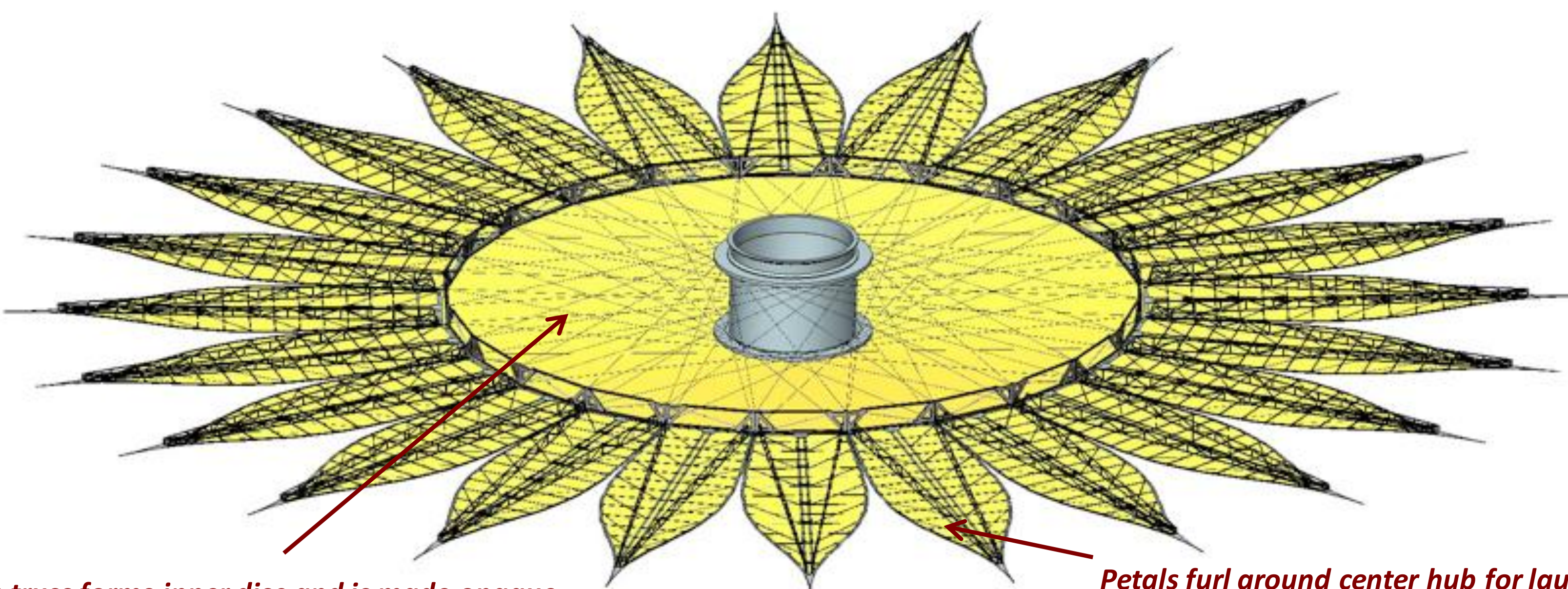
Also recommended was a rendezvous w/ WFIRST

2020 Decadal Probe Studies

WFIRST Rendezvous
(Seager and Kasdin)

Rendezvous Mission Concept

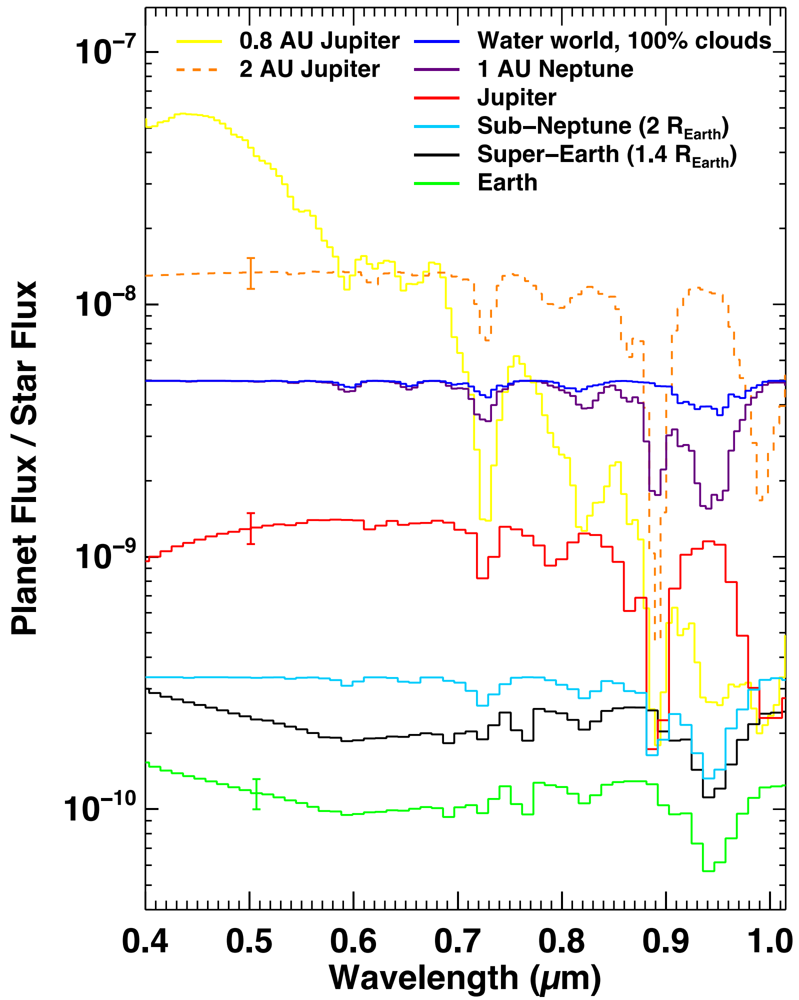
- Starshade launches separately to rendezvous with WFIRST already operating at E-S L2
- Starshade is sized to provide access to habitable zones around nearby stars and create a dark shadow with diameter 2-m larger than the telescope (22 – 34 m)
- Perform "Deep Dive" on systems around a dozen of the nearest sun-like stars
- Starshade performs large translation maneuvers to line up on target stars and fine lateral control maneuvers to keep the dark shadow on the telescope
- WFIRST provides provides instrumentation and fine formation sensing via the CGI



Perimeter truss forms inner disc and is made opaque with an origami folded optical shield

Petals furl around center hub for launch and become rigid with pop-up ribs

Rendezvous Science



Simulated spectra for the Rendezvous mission, with three representative 10% error bars for SNR=10.

1) Discover new exoplanets from giant planet down to Earth size

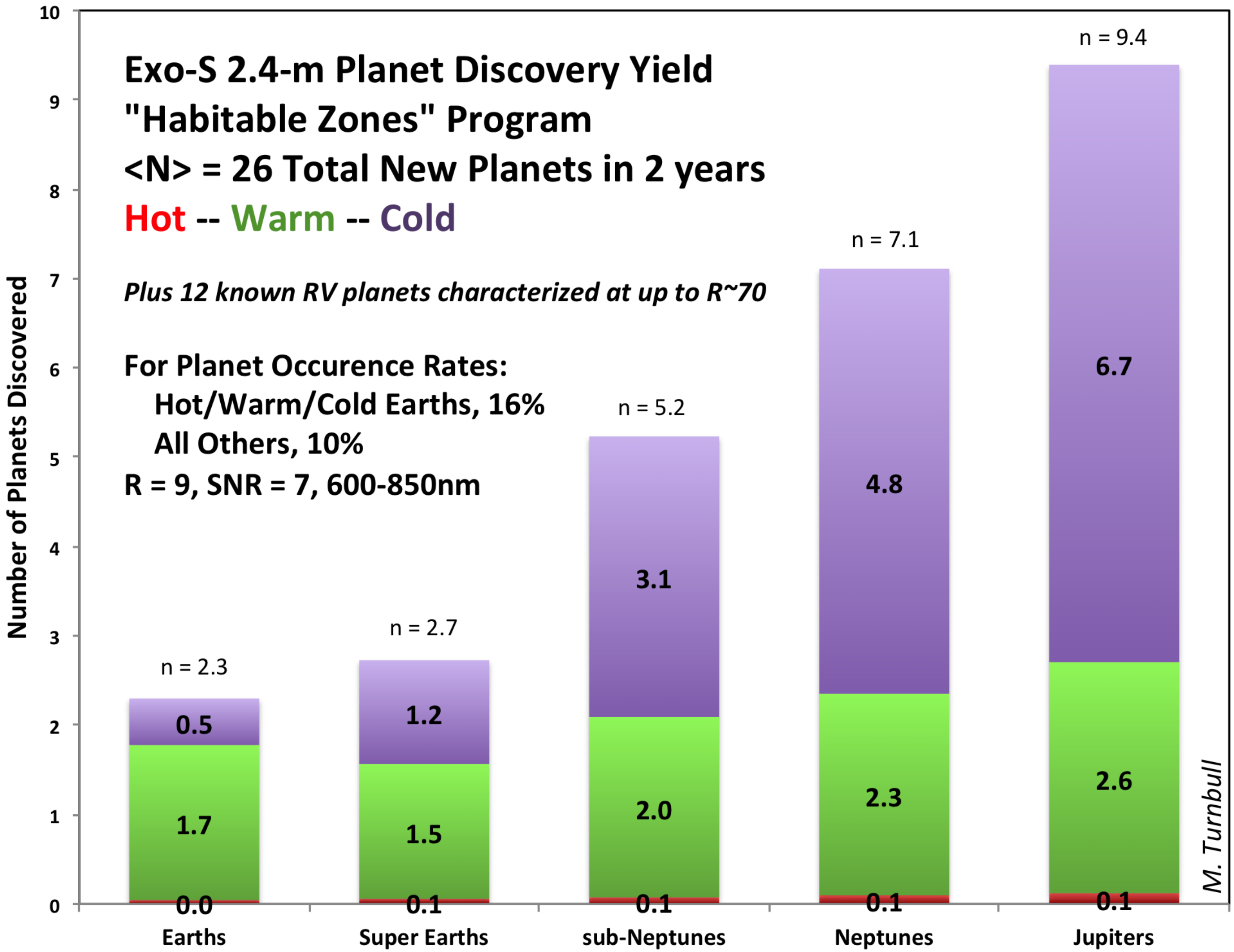
2) Characterize new planets by spectra (*R*=10 to 70)
   - Wavelength range from 400–1,000 nm, in three bands

3) Characterize known giant planets by spectra (*R*=70) and constrain masses
   - detectable by virtue of extrapolated position in mid-to-late 2020 timeframe

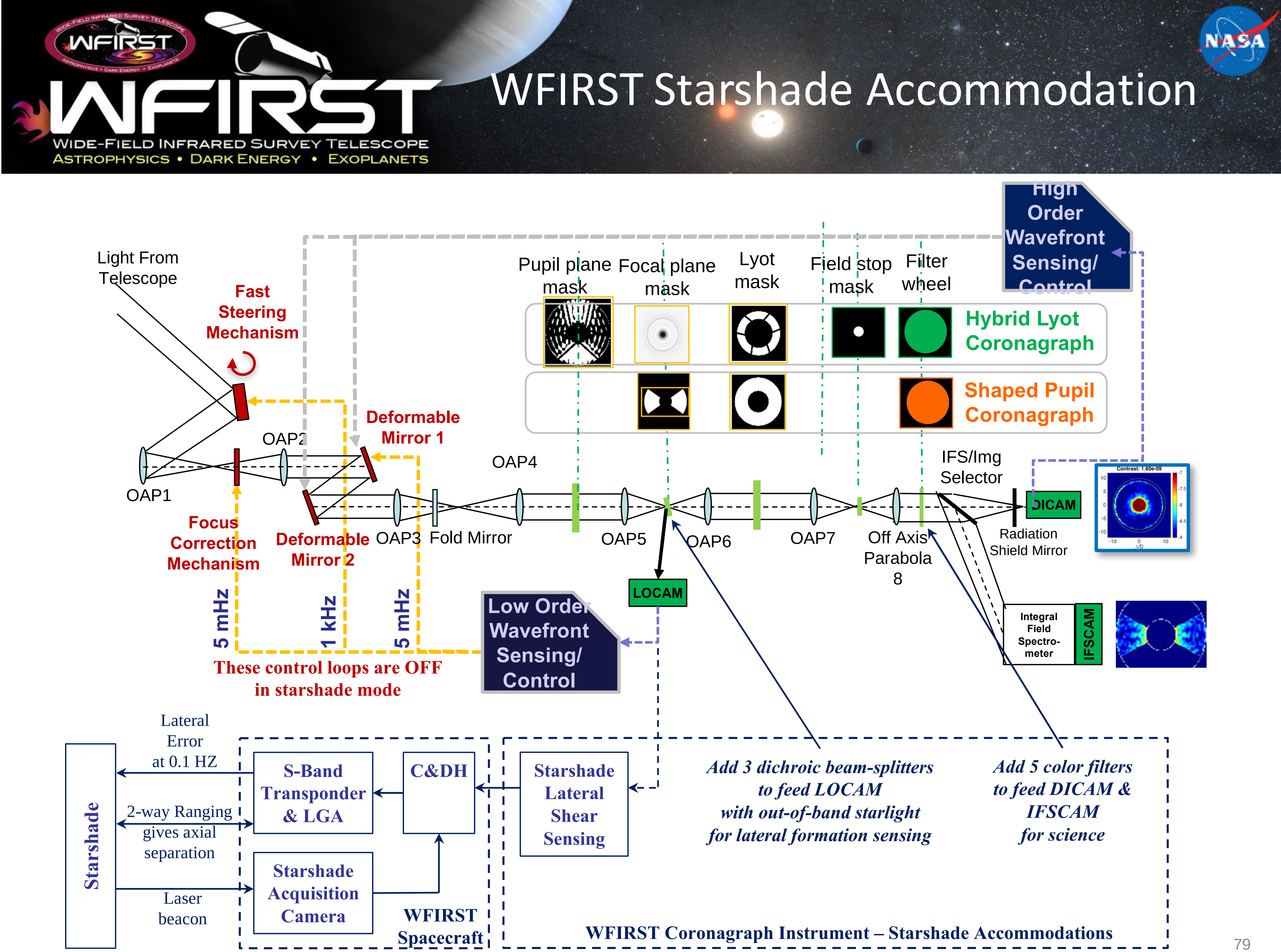
4) Study planetary systems including circumstellar dust in the context of known planets
   - dust-generating parent bodies
   - possible detection of unseen planets
   - assessment of exozodi for future missions

A DRM proof of concept is in process.

Example Yield

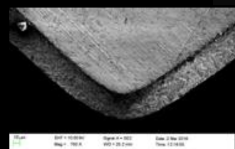


WFIRST Starshade Accommodation

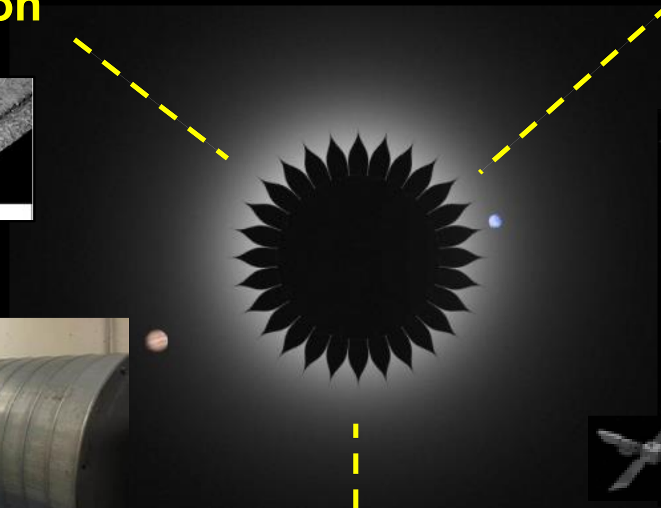


S5 Starshade Technology Gaps

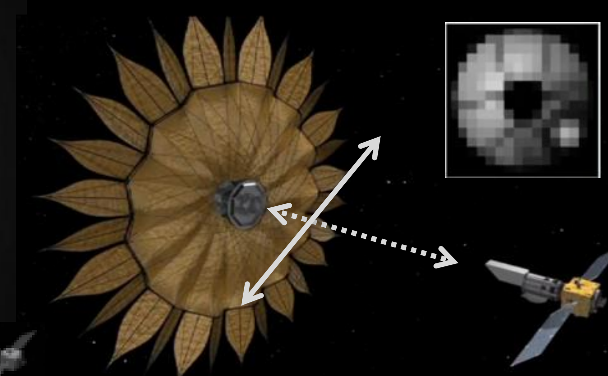
(1) Starlight Suppression

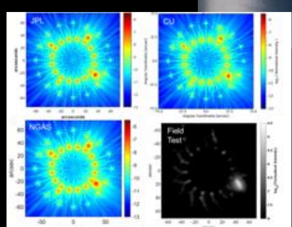
Suppressing scatted light off petal edges from off-axis Sunlight (S-1)



(2) Formation Sensing

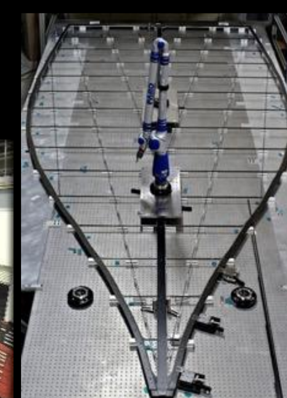


Sensing the lateral offset between the spacecraft (S-3)

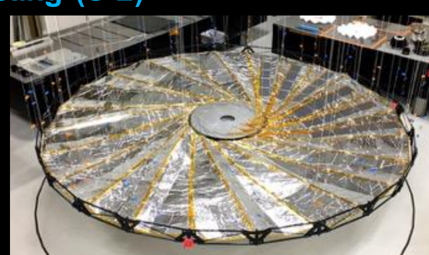




Suppressing diffracted light from on-axis starlight and optical modeling (S-2)

(3) Deployment Accuracy and Shape Stability



Fabricating the petals to high accuracy (S-4)



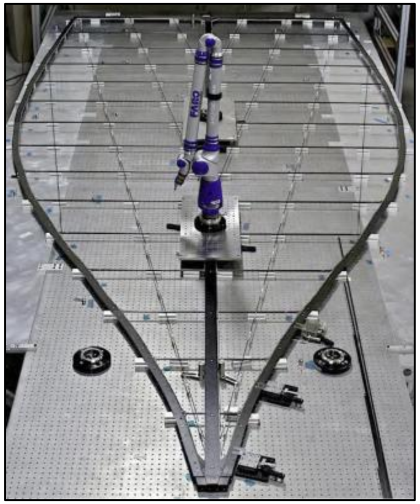

Positioning the petals to high accuracy, blocking on-axis starlight, maintaining overall shape on a highly stable structure (S-5)

S-# corresponds to ExEP Starshade Technology Gap (http://exoplanets.nasa.gov/exep/technology/gap-lists)

Starshade Mechanical Progress

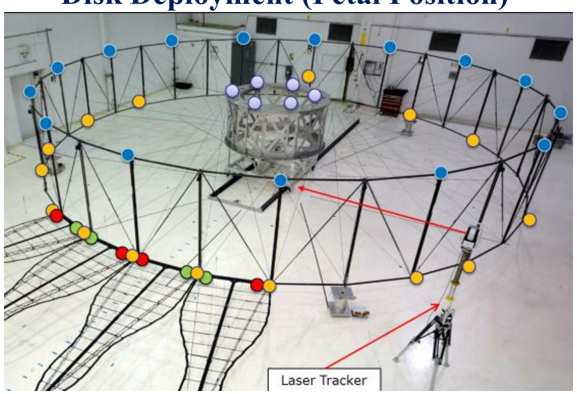
Past efforts demo tolerances for:

Petal Manufactured Shape



TDEM-09: J. Kasdin, PI

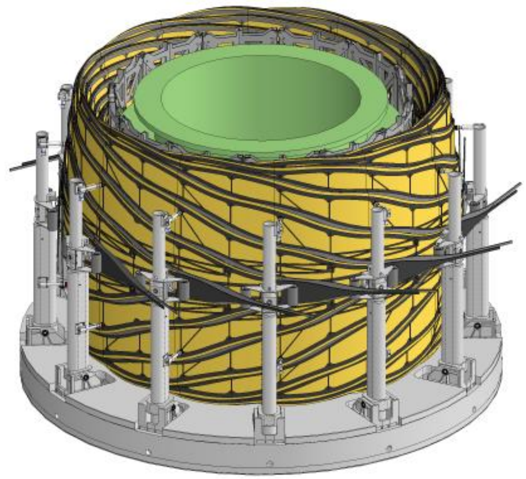
Disk Deployment (Petal Position)



TDEM-10: J. Kasdin, PI

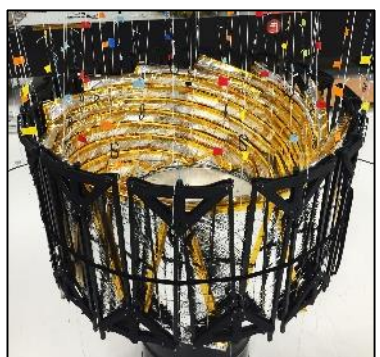
Ongoing efforts demo how to:

Unfurl Petals



Jettisoned rotating carousel

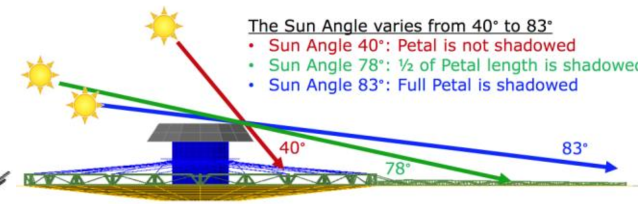
Co-deploy an opaque optical shield



Wrapped spiral gores

Future efforts need to demo:

On-orbit stability over temperature



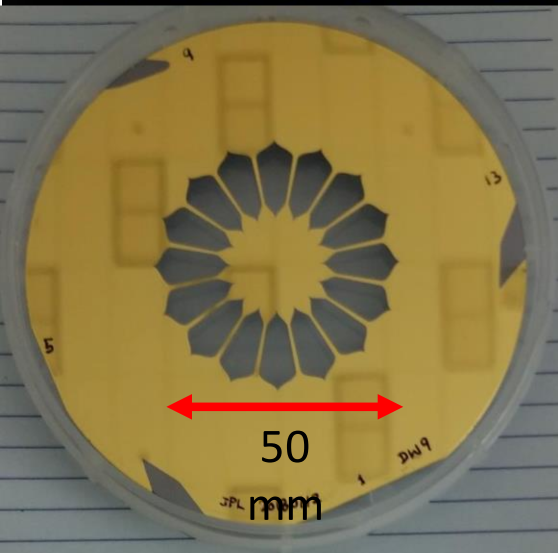
Performance is fortunately insensitive to uniform shape change.

Non-uniform thermal shape changes contribute less than 10% of the total max expected instrument contrast.

Disk deploy tolerances with optical shield installed.

Thin-film solar cells could power SEP

Starshade Optical Model Validation



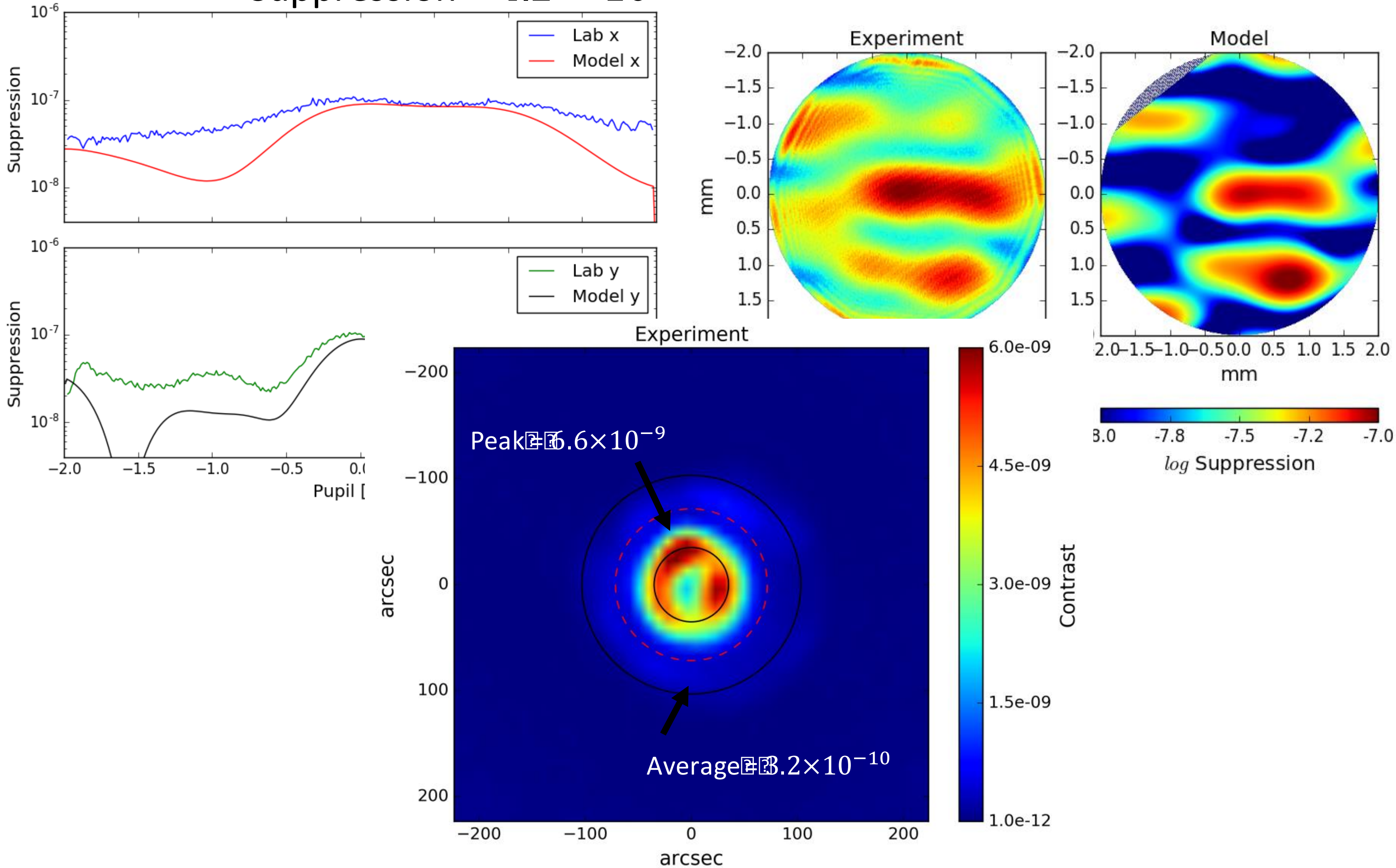
Lack of full-scale starshade test before launch places **strong** reliance on optical models

Princeton Starshade Testbed

Goal to Achieve 1e-9 Suppression and 1e-10 Contrast

Current Status

Suppression = 4.2×10^{-8}



Thank You.