



# Early Stage Technology Workshop

## *Astrophysics and Heliophysics*

March 3-4, 2015

### Wavefront Control for High Performance Coronagraphy on Segmented and Centrally Obscured Telescopes

Presenter: Johanan Codona (University of Arizona)

PI: Olivier Guyon (University of Arizona)



# Research Overview: Background



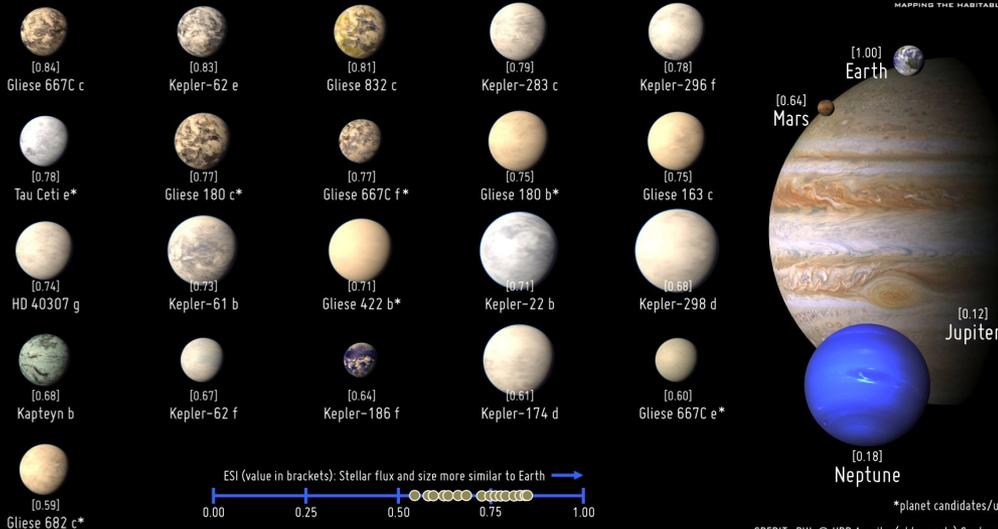
- ~5000 exoplanets have been identified indirectly (most of them by Kepler)
- ~ **10% stars have potentially habitable planets** (rocky, in hab. zone)

In the coming decade, NASA will be preparing a large (~10m) telescope aimed at taking spectra of habitable exoplanets orbiting nearby stars. This large telescope **will be segmented**, and most likely centrally obscured.

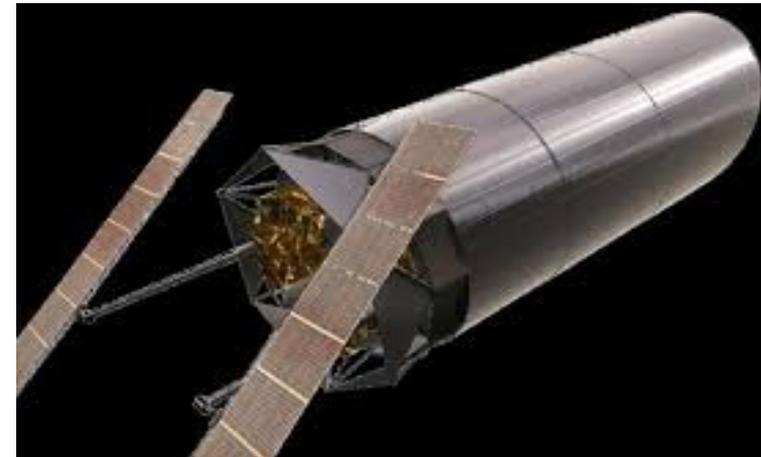
- See: *“Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades”*: Large UV/Optical/IR Surveyor (LUVOIR)

## Current Potentially Habitable Exoplanets

Ranked by the Earth Similarity Index (ESI)



## ATLAST telescope concept



CREDIT: PHL @ UPR Arecibo (phl.upr.edu) September 2, 2014

# Research Overview: Goals



- We are addressing key fundamental challenges associated with ***high contrast imaging on segmented apertures***:
  - coronagraph design for segmented mirrors
  - ultra-high-precision segment cophasing / calibration.  
Both prior and during observations
- Small university team: two senior researchers (Guyon and Codona) with >15yr experience in high-contrast imaging technology development, two PhD students (Miller, Knight), and one undergraduate student (Rodack).
- Our activity provides innovative technical solutions that help enable NASA's greatest astrophysics challenge: finding evidence of life outside our solar system

# Overview of Technologies developed



Our activity is focused on two connected themes:

## Coronagraph design

We have explored two approaches:

**PIAACMC** concept: high performance option

**Pupil phase apodization**: low hardware impact, flexible

## Wavefront control / segment cophasing

We have developed new ways to make very efficient use of starlight for wavefront sensing

Initial “rough” cophasing: **Differential OTF**

Fine cophasing: **Low-order wavefront sensor**

Ultra-high precision: **Linear Dark Field Control**

The following slides describe these concepts and their impact on NASA goals.

**Some of these concepts are also highly relevant to near-term NASA missions (JWST, WFIRST).**

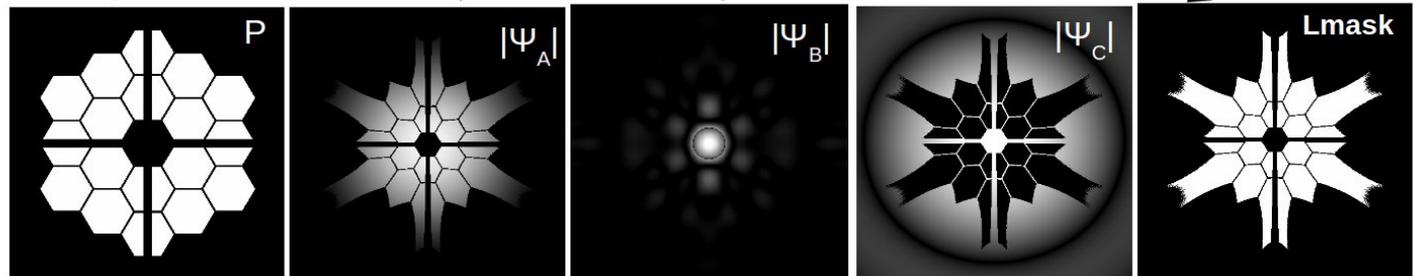
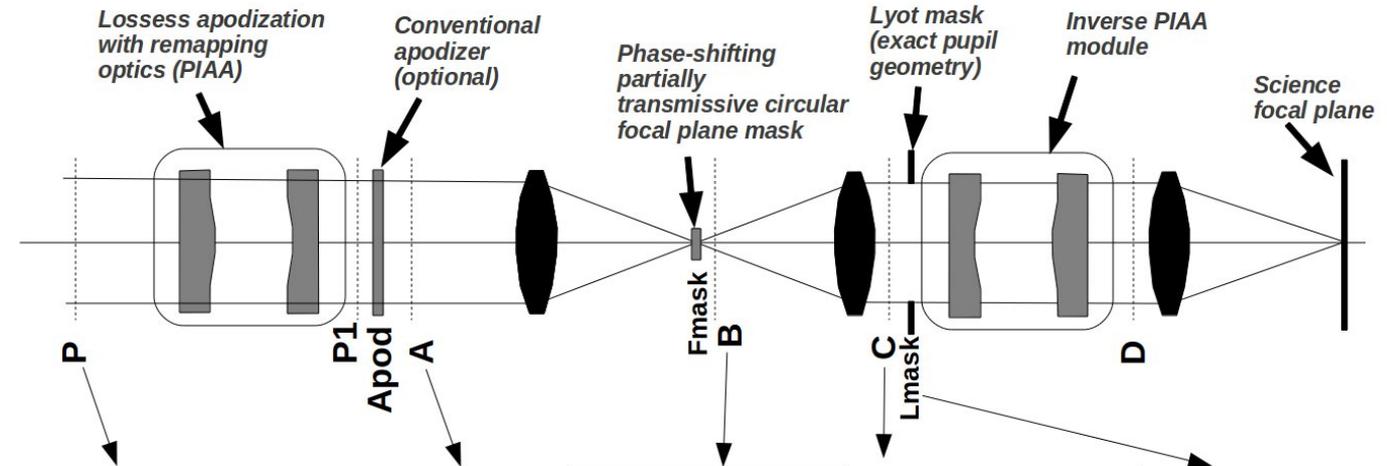
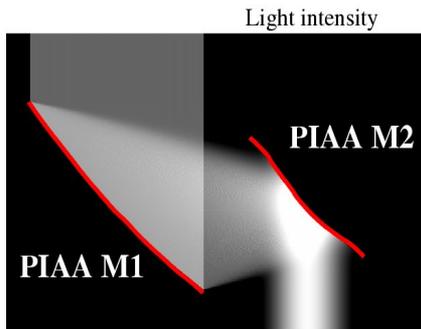
# Coronagraph design: PIAACMC



We have merged the PIAA concept (left) with a diffractive focal plane mask to create a coronagraph design that is compatible with segmented apertures: PIAACMC

This offers sub- $2\lambda/D$  inner working angles, providing ultra high contrast in broadband light thanks to multi-zone mask design → **proof that high-performance coronagraphy is not fundamentally incompatible with segmented apertures.**

## Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

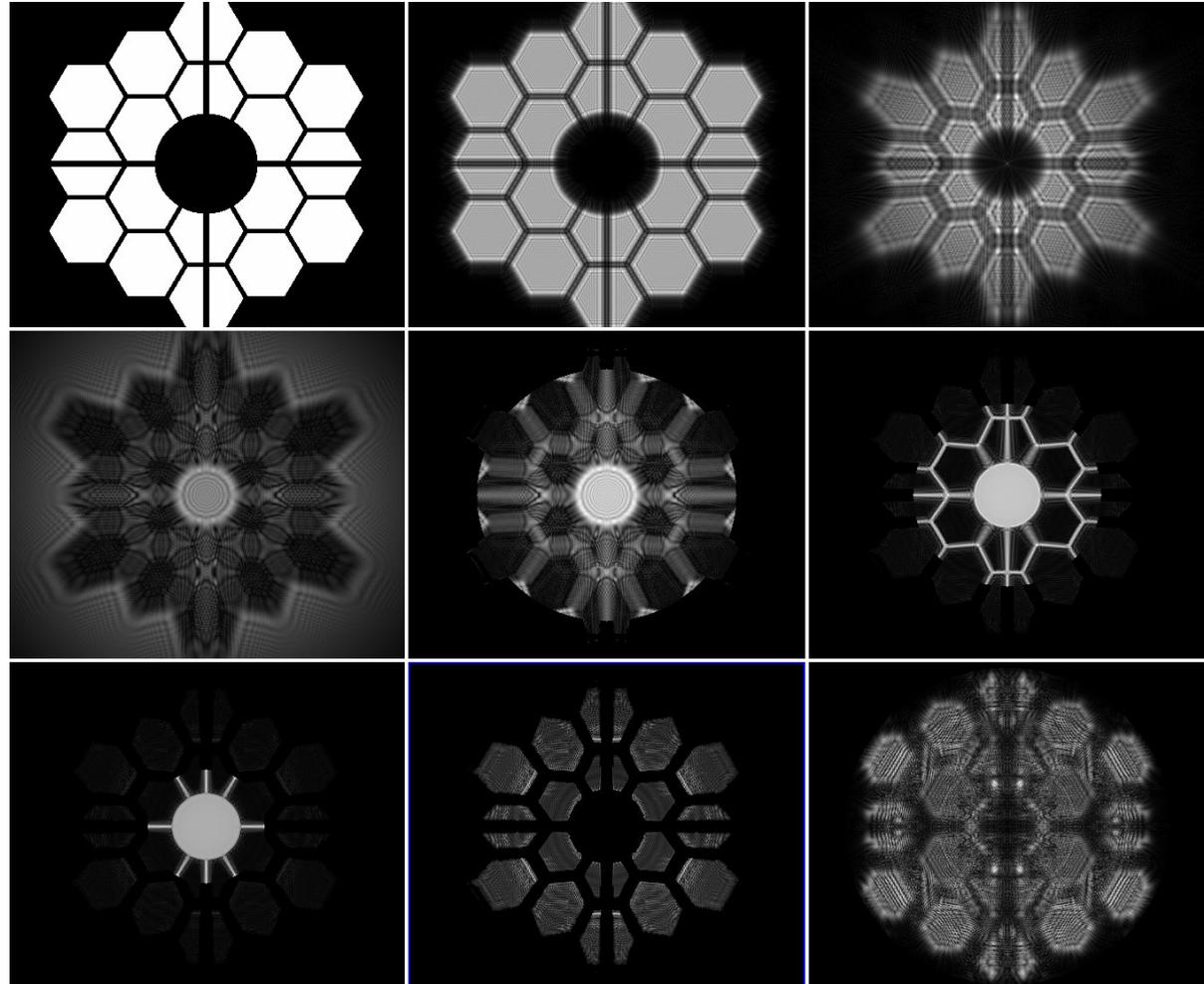


# Coronagraph design: PIAACMC



A significant challenge for the coronagraph design is to handle gaps between segments

We have shown that starlight can be diffracted INSIDE the gaps and then blocked by adequately designed Lyot stops that are conjugated where the gaps are sharp



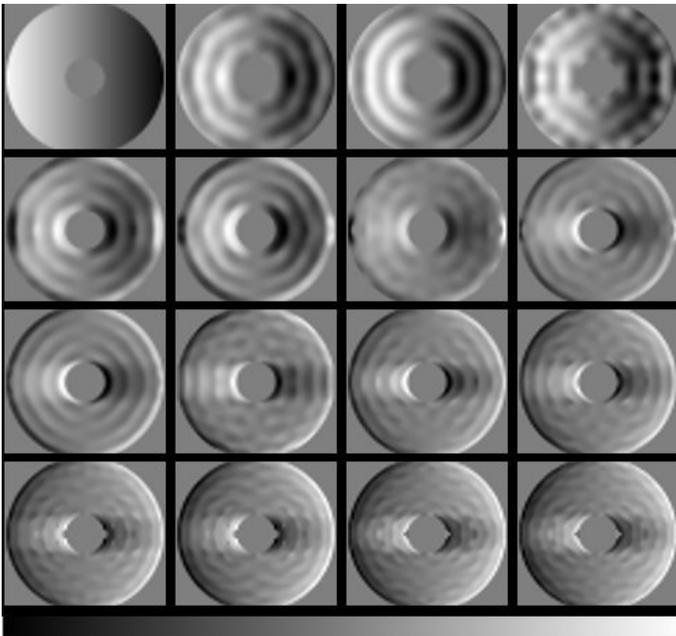
***This figure shows how 4 Lyot stops (images #5, 6, 7, 8), when properly conjugated, block light***

# Phase Apodization Coronagraphy (PAC)

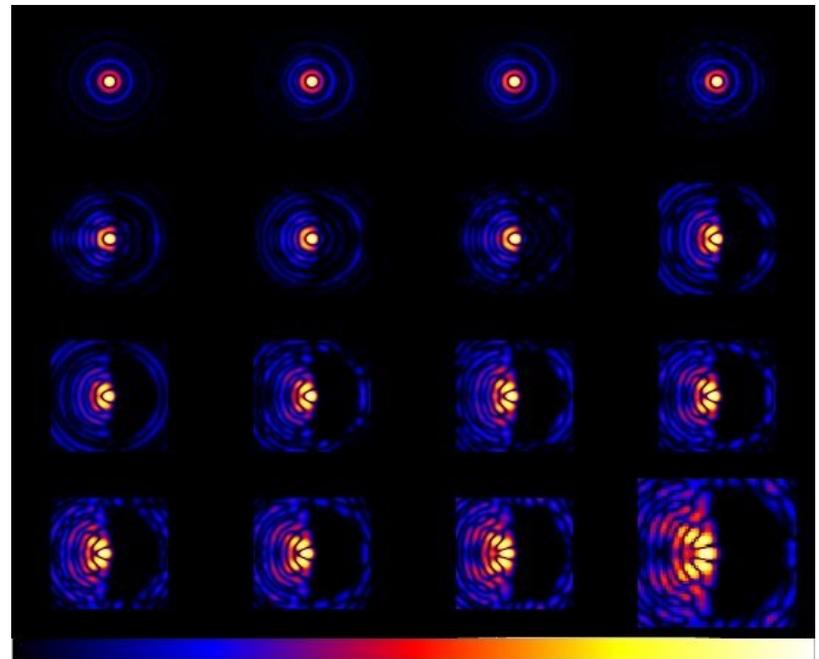


A special phase mask in the pupil plane can suppress the diffraction halo without using a focal plane mask or a Lyot stop. A PAC does not need to be carefully aimed at a star, and works on all stars and extended objects within the field of view. It is very compact and **applicable to small satellites.**

Pupil Phase Patterns



Corresponding PSFs



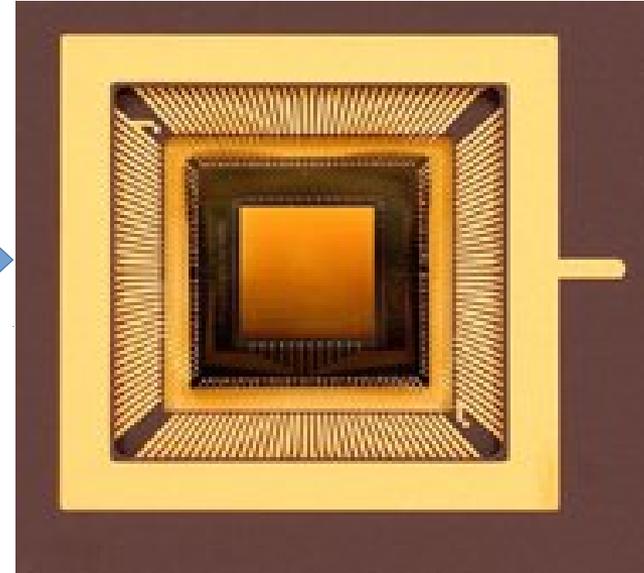
# Coronagraph design: Phase Apodization



Diamond-Turned ZnSe



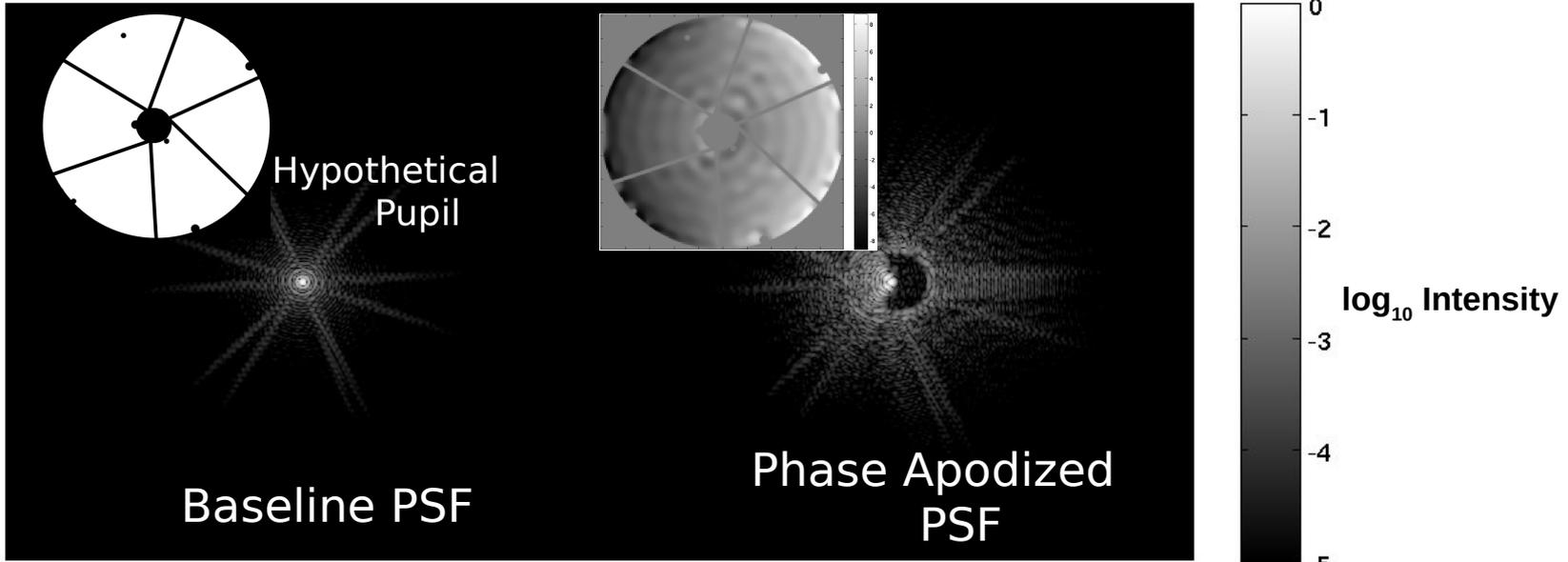
Deformable Mirror



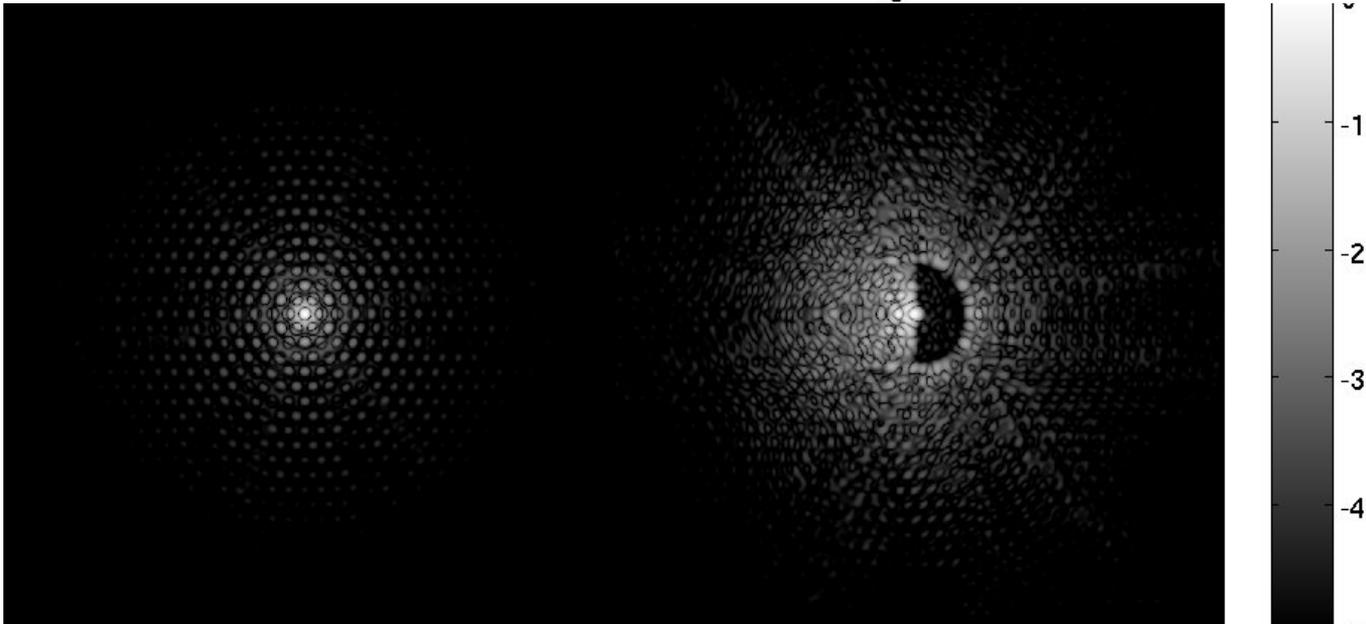
An “Apodizing Phase Plate” (APP) is an optical element manufactured to imprint a PAC phase pattern.

**We can implement a PAC using a deformable mirror (DM).** One single DM in a pupil plane would replace multiple manufactured APPs, providing a compact, programmable coronagraph.

# Coronagraph design: Phase Apodization



This technique can be applied to any segmented aperture geometry.



# Wavefront Control: Segment cophasing challenge



Wavefront sensing @  $\lambda=550\text{nm}$  with an effective spectral bandwidth  $\delta\lambda=0.1\mu\text{m}$ .

| Telescope diameter & wavelength | Number of segments | Contrast goal (raw) | Target brightness | Cophasing requirement | Stability timescale |
|---------------------------------|--------------------|---------------------|-------------------|-----------------------|---------------------|
| 4m, 0.55 $\mu\text{m}$          | 10                 | 1e-10               | V=8               | 2.8 pm                | 22 mn               |
| 8m, 0.55 $\mu\text{m}$          | 10                 | 1e-10               | V=8               | 2.8 pm                | 5.4 mn              |
| 8m, 0.55 $\mu\text{m}$          | 100                | 1e-10               | V=8               | 8.7 pm                | 5.4 mn              |

Vibration control is a significant challenge



Table above shows most challenging requirement

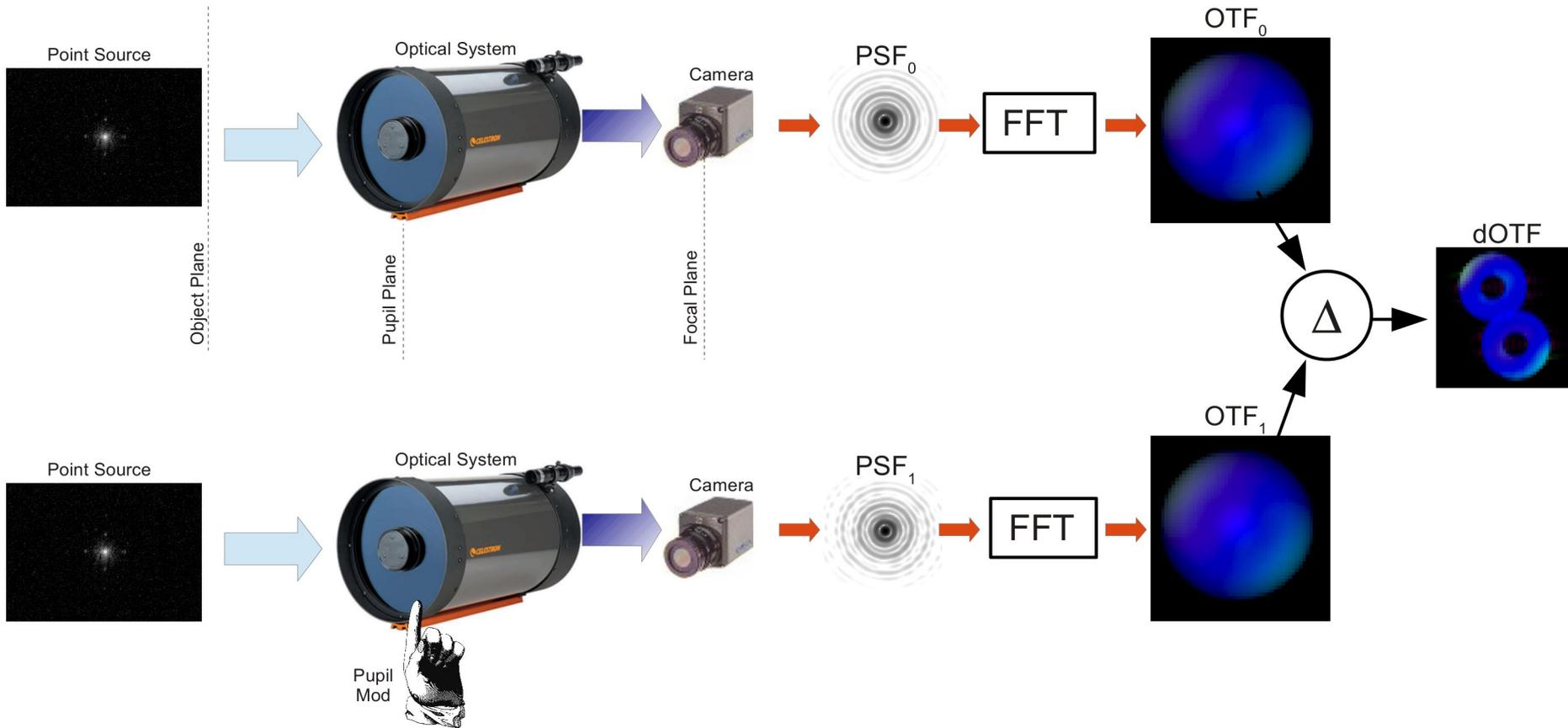
For  $m_v = 3$ , stability timescale is 100 times shorter (few seconds)

Table above ignores potential PSF calibration (segment cophasing errors can produce recognizable PSF features different from exoplanet)

# Wavefront Control: Differential OTF

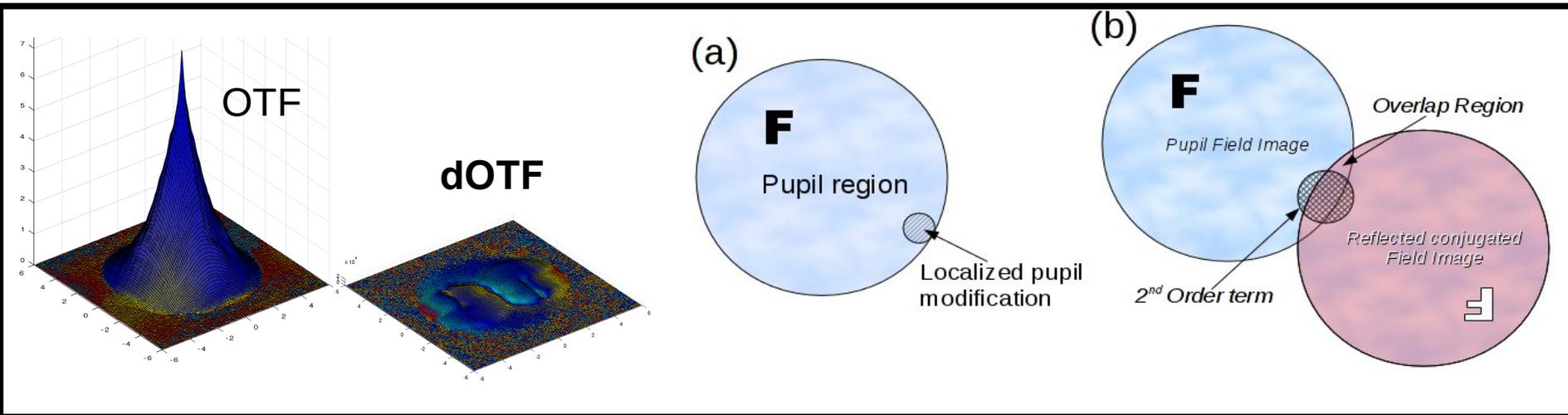


Differential Optical Transfer Function (dOTF) measures the wavefront using a change in the pupil illumination (or phase, with DM actuator)



Codona JL; Differential optical transfer function wavefront sensing. Opt. Eng. 0001;52(9):097105-097105. doi:10.1117/1.OE.52.9.097105.

# Wavefront Control: Differential OTF



**No refocusing of the camera or change in the mirror segments is required:**  
dOTF is a low hardware impact, high sensitivity **alternative to phase diversity techniques.**

A single DM actuator can be used for dOTF → zero impact on telescope/instrument design.

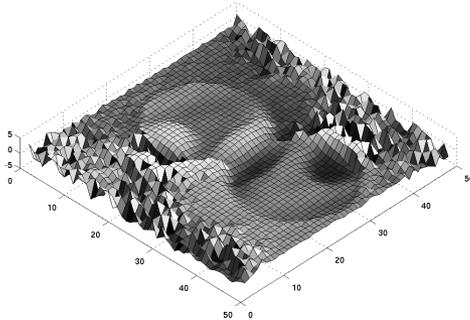
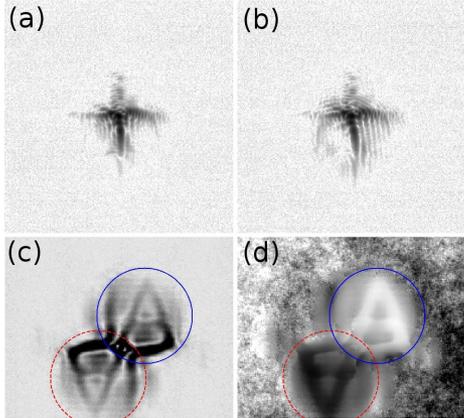
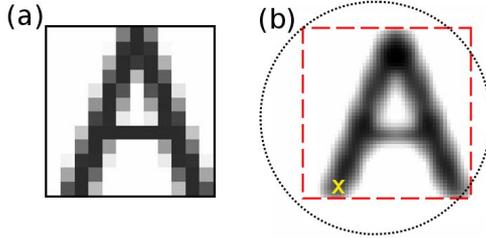
Works in broadband light for low-order aberrations such as segment cophasing errors. Multi-color images allow wide capture range ( $\gg 1 \lambda$ ).

***The dOTF technique is an excellent candidate to precision cophasing of a large space telescope designed for high-contrast imaging***

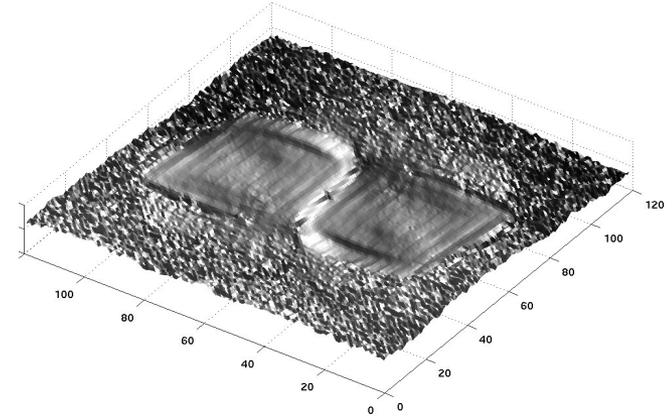
# Wavefront Control: dOTF Lab demonstrations



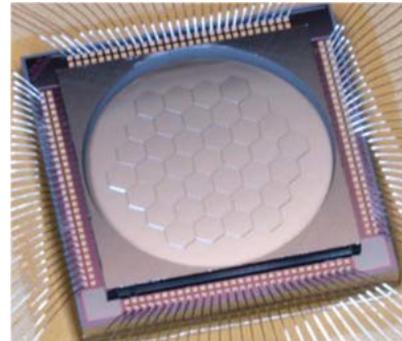
Reconstructing the first letter of the alphabet



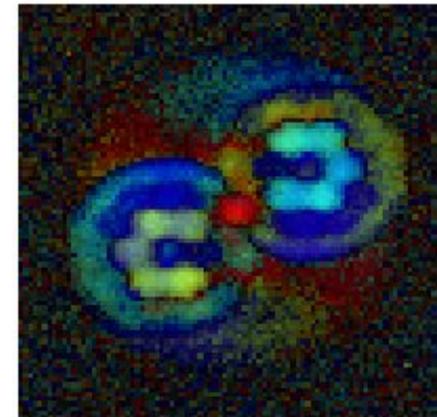
A Boston Micromachines 12x12 MEMS DM measured itself using dOTF. The result shows a low-order Zernike test pattern, as well as actuator print-through.



Segmented mirror experiment using an Iris AO MEMS DM to measure itself.



Iris AO MEMS DM.

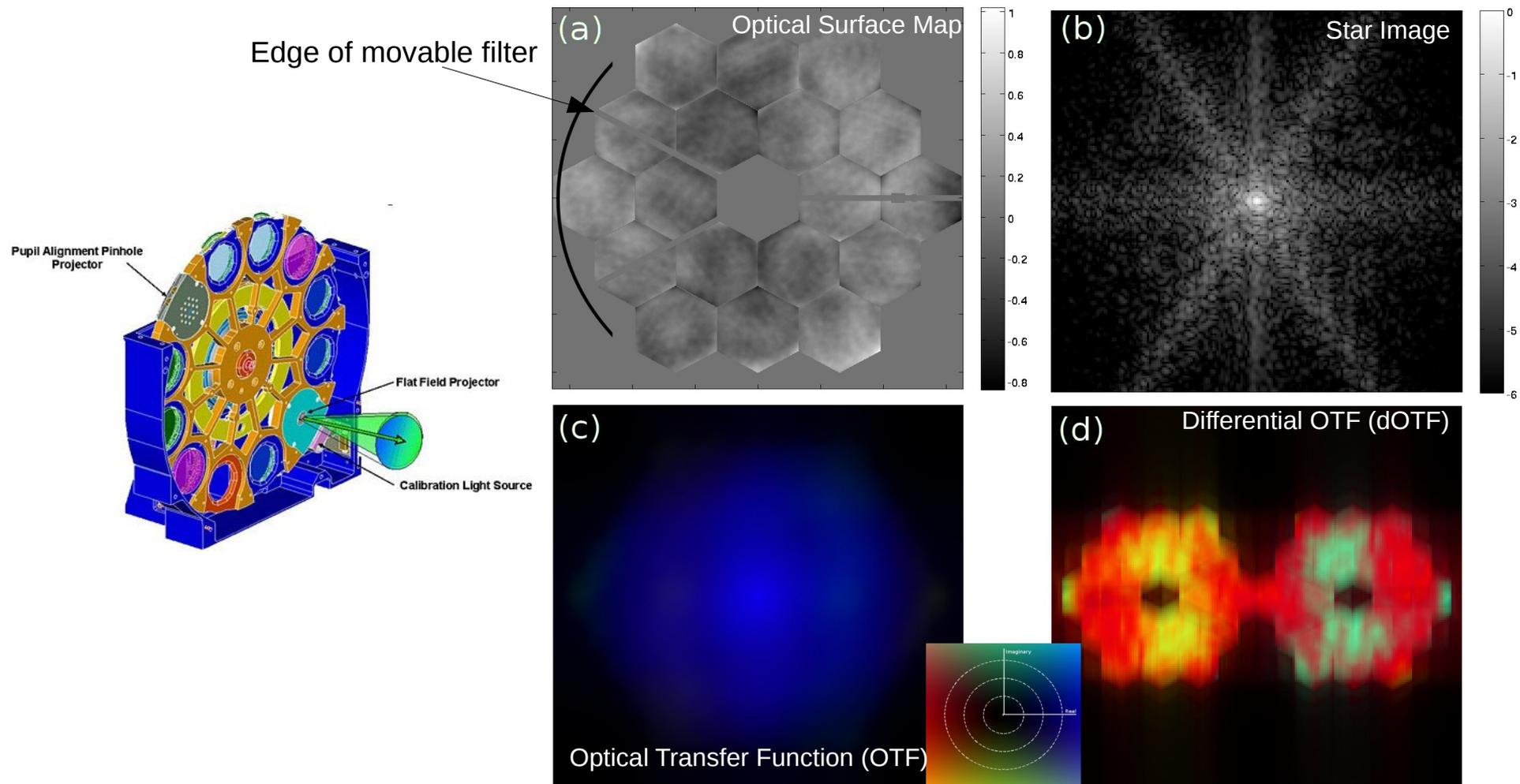


Resulting complex pupil field image

# Wavefront Control: dOTF for JWST



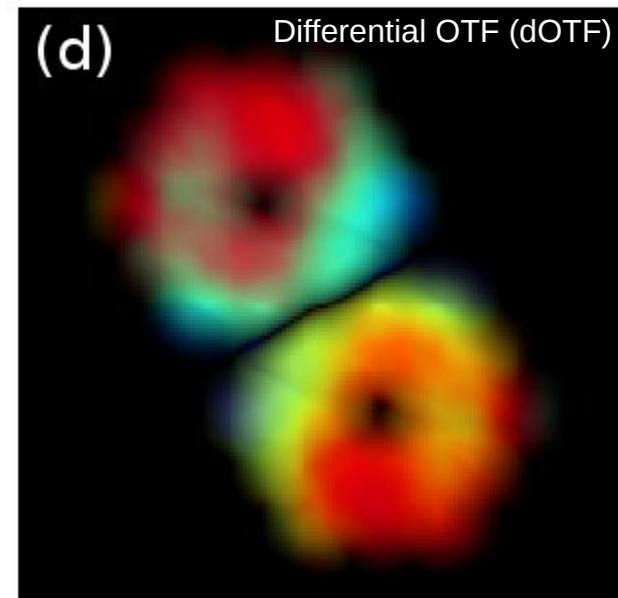
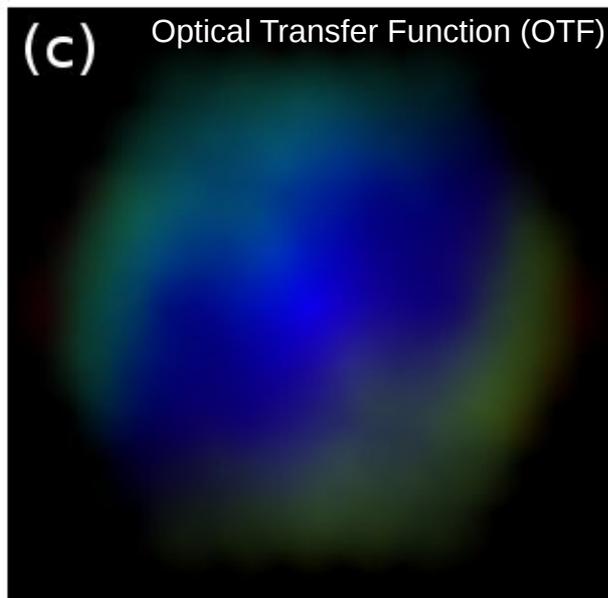
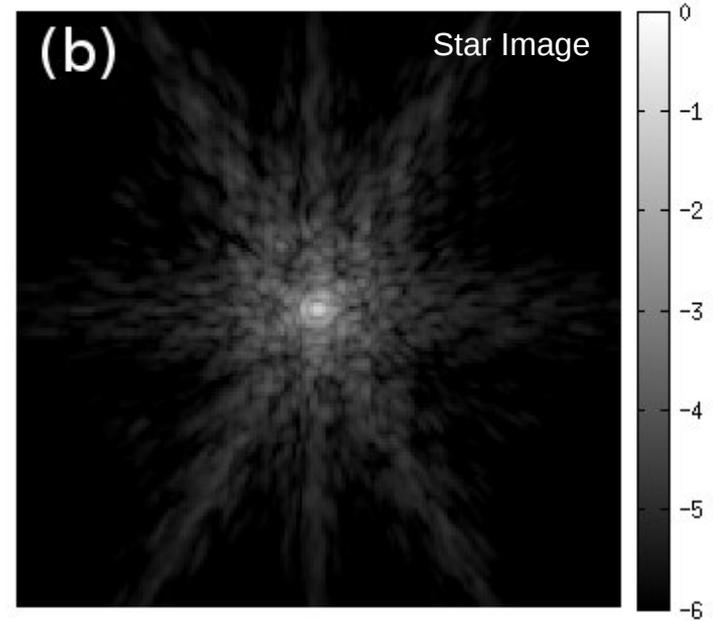
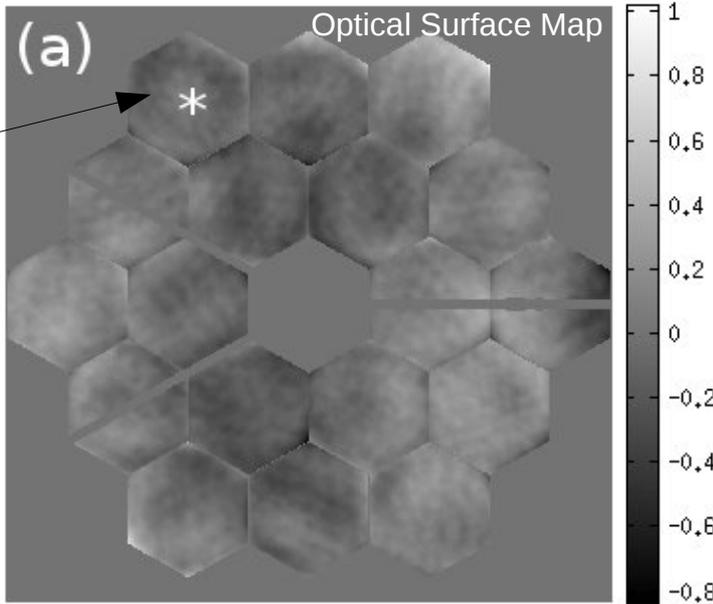
## JWST dOTF using a Misaligned Filter Wheel



# JWST dOTF by moving a single segment



Tilt this segment slightly ( $\sim\lambda/4$ )



# Wavefront Control: Coronagraphic LOWFS



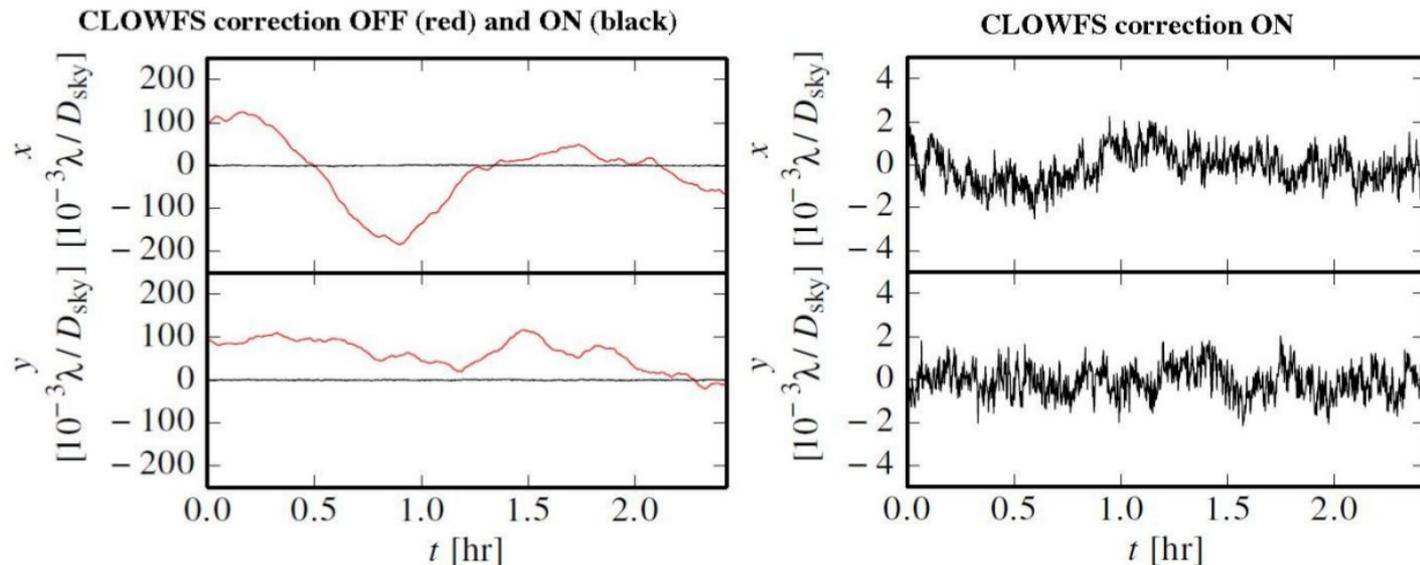
The Coronagraphic Low-Order Wavefront Sensor (LOWFS) **uses starlight rejected by the coronagraph masks to measure low-order wavefront errors.**

*Key advantages:*

- integrated within coronagraph → measures aberrations with no non-common path errors.
- highly sensitive, uses abundant starlight that would otherwise be discarded.

LOWFS development prior to this award has been very successful, with  $10^{-3} \lambda/D$  control demonstrated (TDEM milestone at JPL's HCIT)

## ***LOWFS validation at JPL (note that scale is 50x finer on the right)***

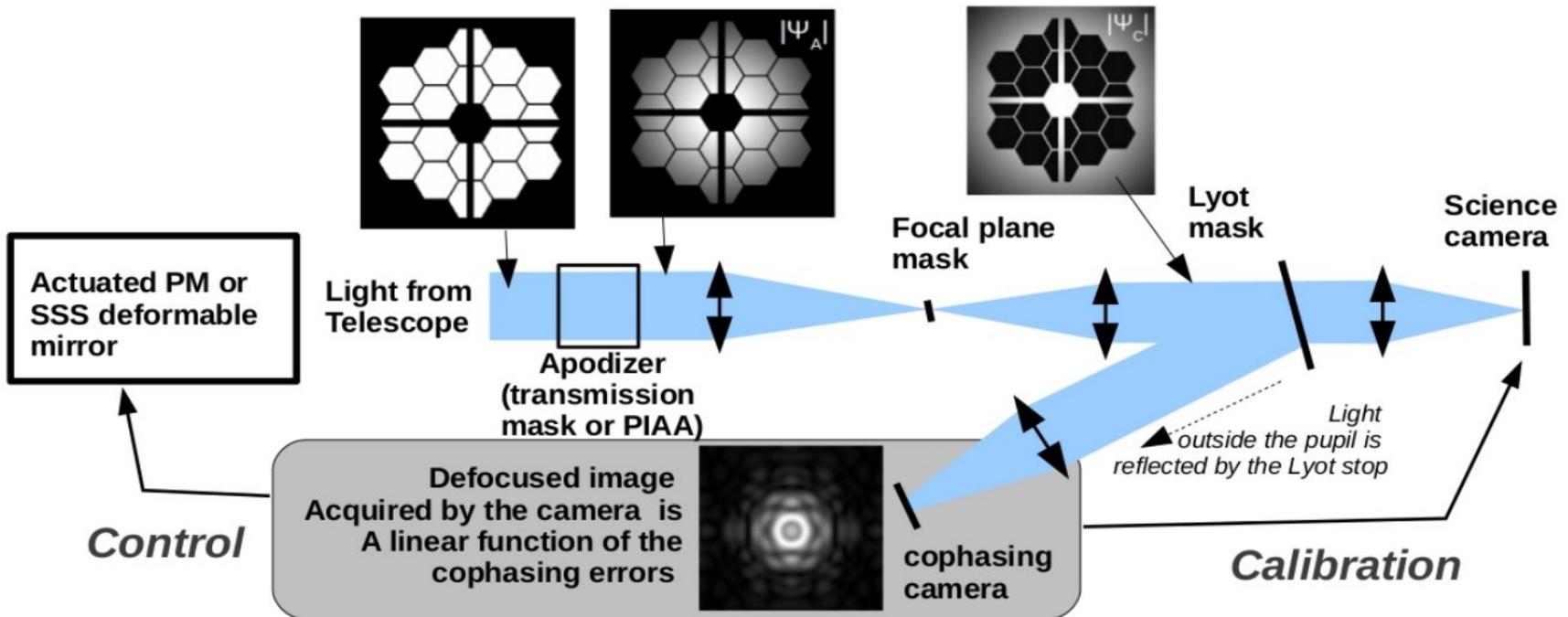


# Wavefront Control: Coronagraphic LOWFS



We have extended the LOWFS technique to segmented apertures → high efficiency measurement of cophasing errors at the 0.1 nm level

**1** Phase-shifting mask diffracts starlight outside the pupil in the Lyot plane



**3** The camera image LINEARLY encodes cophasing errors

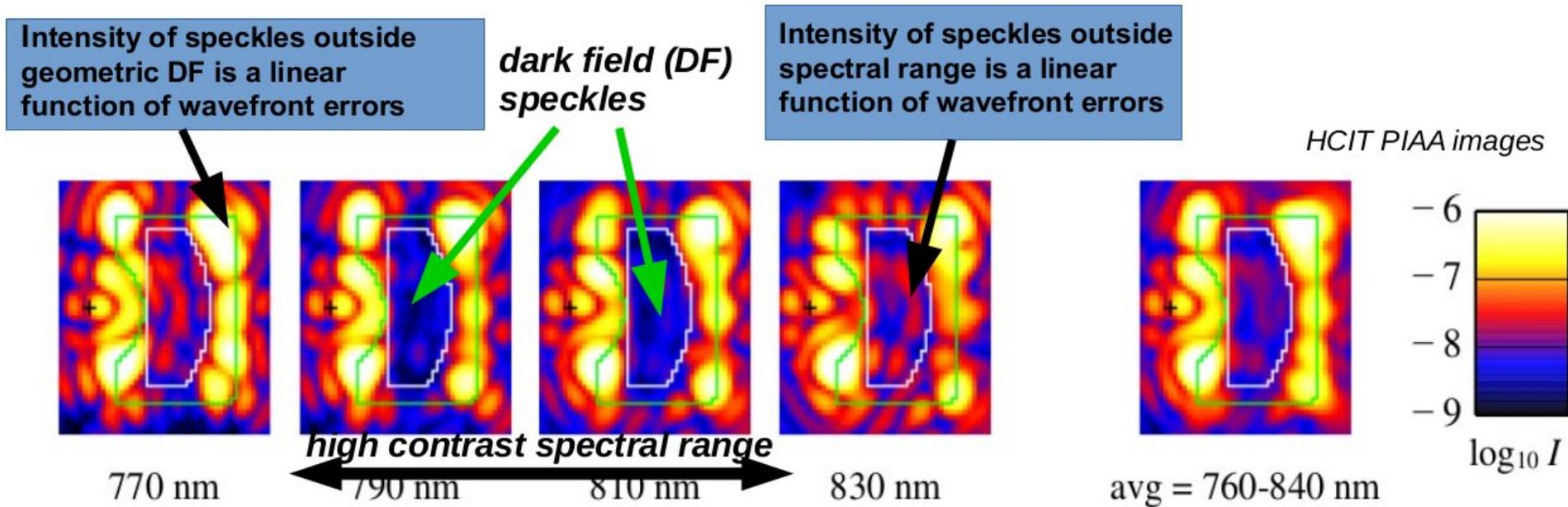
**2** Reflective Lyot stop redirects this light to the LOWFS camera

# Wavefront Control: LDFC



The series of images below shows intensity as a function of spatial coordinate (x,y) and wavelength ( $\lambda$ ) obtained with the PIAA coronagraph at the JPL high contrast imaging testbed.

The **DARK FIELD (DF)** is the area in (x,y, $\lambda$ ) space over which starlight is removed. The **BRIGHT FIELD (BF)** is the area outside the dark field.

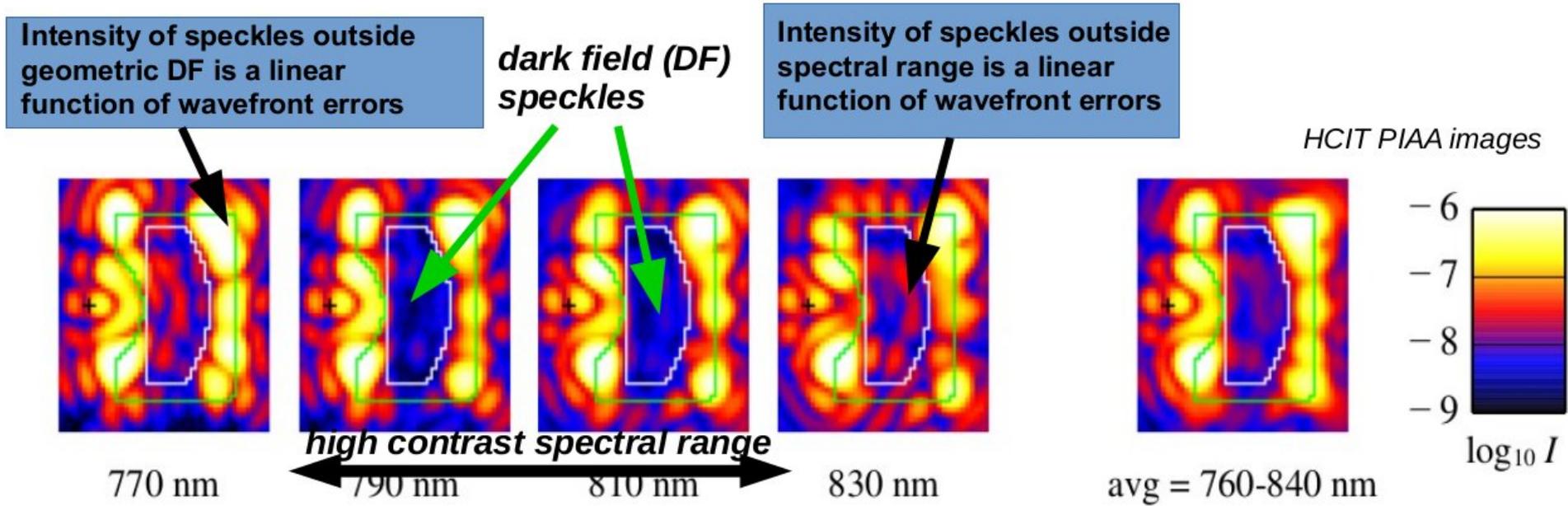


# Linear Dark Field Control (LDFC) principle

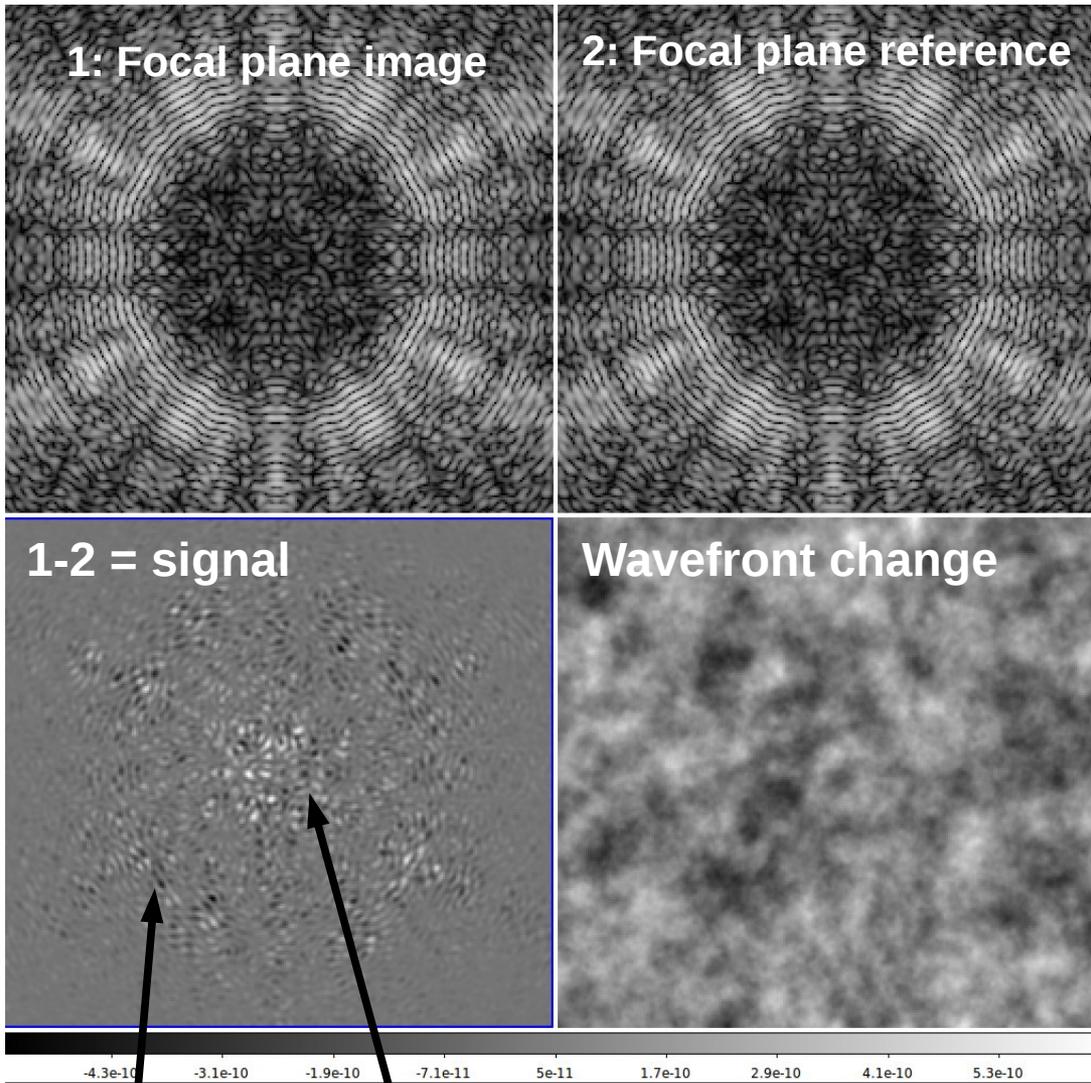
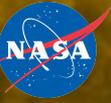


Speckle intensity in the DF are a non-linear function of wavefront errors  
→ current wavefront control technique uses several images (each obtained with a different DM shape) and a non-linear reconstruction algorithm (for example, Electric Field Conjugation – EFC)

**Speckle intensity in the BF are linearly coupled to wavefront errors → we have developed a new control scheme using BF light to freeze the wavefront and therefore prevent light from appearing inside the DF**



# Wavefront Control: LDFC



## STEPS:

- Take an image
- Subtract reference: this is our signal
- Multiply signal by reconstruction (control) matrix
- Apply DM correction

Linear part (keep)

Non-linear part (ignore)

# LDFC vs. state of the art



**LDFC improves wavefront control loop speed by ~20x (because brighter parts of the starlight halo are used for the measurement) and does not require DM modulation.**

**The linear control loop is simpler, more robust than state-of-the-art methods.**

## EFC

- Requires  $\approx 4$  images
- Competes with science measurement: dark field needs to be broken
- Time aliasing effects and confusion between incoherent residual and time-variable coherent residual
- Sensitive to (exo)zodi unless probes are large
- Sensitive to dark current and readout noise unless probes are large
- Sensing relies on DM calibration and system model
- Difficult to measure/verify G-matrix
- Only uses  $\approx 15\%$  spectral band
- Only uses dark field area
- Single polarization
- Non-linear loop (convergence, computing power)

## LDFC

- Single image
- Maintains dark field during measurement: 100% duty cycle
- More robust against temporal effects: speckle variations have small negative effect on loop
- Insensitive to (exo)zodi
- Robust against dark current and readout noise (photon noise  $>$  readout noise)
- Sensing relies on camera calibration
- Response matrix obtained from linear measurements
- Can use  $\approx 100\%$  spectral band
- Can use whole focal plane (if combined with EFC)
- Dual polarization (if detector(s) allow)
- Linear loop: simple matrix multiplication

# LDFC: Application to NASA missions



We assume here:

- 2.4m telescope, 10% efficiency, 400nm-900nm LDFC bandwidth
- $1e-9$  contrast dark field speckle sensing,  $m_V = 5$  star
- $1e-8$  incoherent background (zodi + exozodi + detector)

0.2 ph/sec/speckle, 2ph/sec for background.

| Bright speckle level  | Relative modulation | Absolute change          | 1mn SNR | Camera dynamical range |
|-----------------------|---------------------|--------------------------|---------|------------------------|
| $1e-4$ (20000 ph/sec) | 0.6%                | $6.3e-7$ (127 ph/sec)    | 7.0     | $1e5$                  |
| $1e-5$ (2000 ph/sec)  | 2%                  | $2.01e-7$ (40.2 ph/sec)  | 7.0     | $1e4$                  |
| $1e-6$ (200 ph/sec)   | 6%                  | $6.43e-8$ (12.86 ph/sec) | 7.0     | 1000                   |
| $1e-7$ (20 ph/sec)    | 21%                 | $2.1e-8$ (4.2 ph/sec)    | 6.9     | 100                    |
| $1e-8$ (2 ph/sec)     | 73%                 | $7.3e-9$ (1.46 ph/sec)   | 5.65    | 10                     |
| $1e-9$ (0.2 ph/sec)   | 300%                | $3e-9$ (0.6 ph/sec)      | 3.13    | 1                      |

Case study for WFIRST:

LDFC correction update timescale is  $\sim 10$  min, compared to several hours for state-of-the-art EFC.

## Our team is working with WFIRST coronagraph group at JPL to implement LDFC:

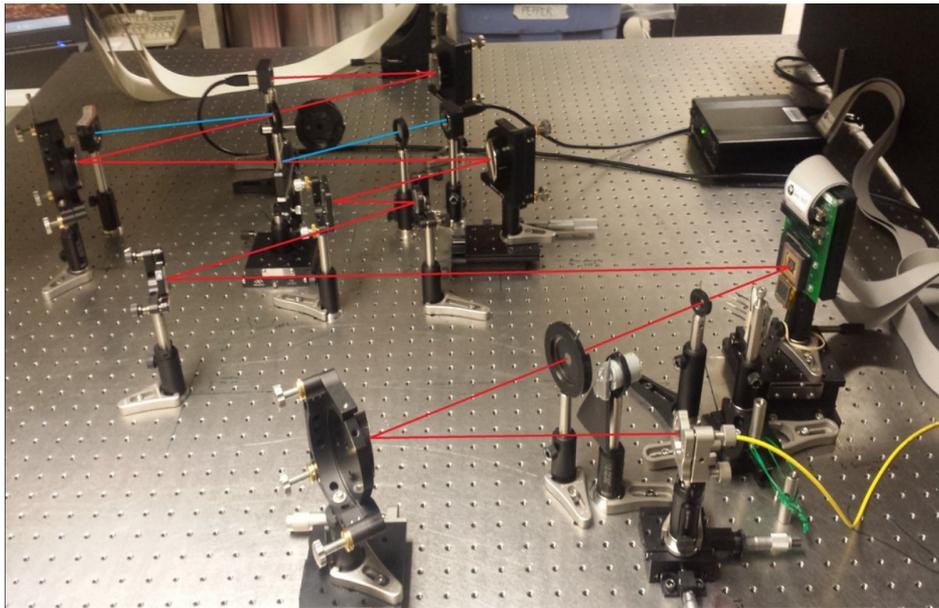
- LDFC enables close loop aberration control on science targets, as opposed to the current “set and forget” scheme  $\rightarrow$  deeper contrast can be maintained, and system can be more resilient to small wavefront changes.
- LDFC is also a powerful aid to PSF calibration. During science exposures, LDFC images provide live telemetry of wavefront changes.

**LDFC is particularly well suited to track cophasing errors on a segmented aperture, using diffraction features created by segments.**

Air testbed, flexible configuration, compatible with Lyot type coronagraphs + PIAA

Designed to explore high contrast approaches for segmented apertures:

- \* Segmented DM used to simulate telescope primary mirror.
- \* Continuous DM for on-instrument wavefront control.



Key features:

Two LOWFS channels (blue paths in figure) to use light rejected by coronagraph

Supercontinuum broadband laser source + selectable filter

Segmented and continuous DM in series, can be replaced by flats

Access to pupil plane before and after focal plane occulter

# Dissemination of results, next steps



We have held **two technical workshops** at JPL, each 2-day long, with ~50 attendees.

Our activity is providing **technical input to the AURA beyond-JWST study.**

Publications, talks:

**Presentations** at SPIE meetings (4 presentations at upcoming meeting)

**Refereed science papers:** one published (dOTF), 3 more expected this year (LDFC control, LDFC calibration, PIAACMC for segmented apertures)

We are **working with the WFIRST coronagraph group** to test the LDFC approach  
→ could greatly enhance the mission science return by contrast improvement and PSF calibration

We are now preparing a request, under a JPL-led TDEM proposal, for laboratory **validation of PIAACMC concept for segmented apertures**

# Summary of Key Points



- [1] We have created a **credible coronagraph architecture for segmented apertures** (work done jointly with TDEM grant), based on the PIAACMC concept  
→ first proof-of-concept that high-contrast imaging is compatible with large segmented apertures.
- [2] We have **quantified requirements for cophasing errors**. Vibration control is the main challenge.  
→ our findings will guide technology development essential to solving this challenge.
- [3] We have **extended the low-order wavefront sensor to segmented apertures**, showing that light rejected by the coronagraph can be used to measure cophasing errors.  
→ Very efficient approach that is free of non-common path errors.
- [4] We have **developed a new approach to cophasing using focal plane images: dOTF**  
→ this complements existing approaches (phase diversity) as it does not require defocus, or large segment motions → safer.
- [5] We have developed a **powerful new approach to wavefront control for high contrast imaging**, the LDFC concept.  
→ significant efficiency gain and risk reduction. This technique is also very well suited for cophasing errors