



# Phase and Pupil Amplitude Recovery for JWST Space-Optics Control

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OSA Frontiers in Optics, Oct. 27, 2010



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# Introduction

- The James Webb Space Telescope (JWST) is the successor to the HST (launch in 2014)
- JWST will operate in a manner similar to HST: enabling a range of science investigations proposed by astronomers world-wide
- General Observer community will drive science investigations

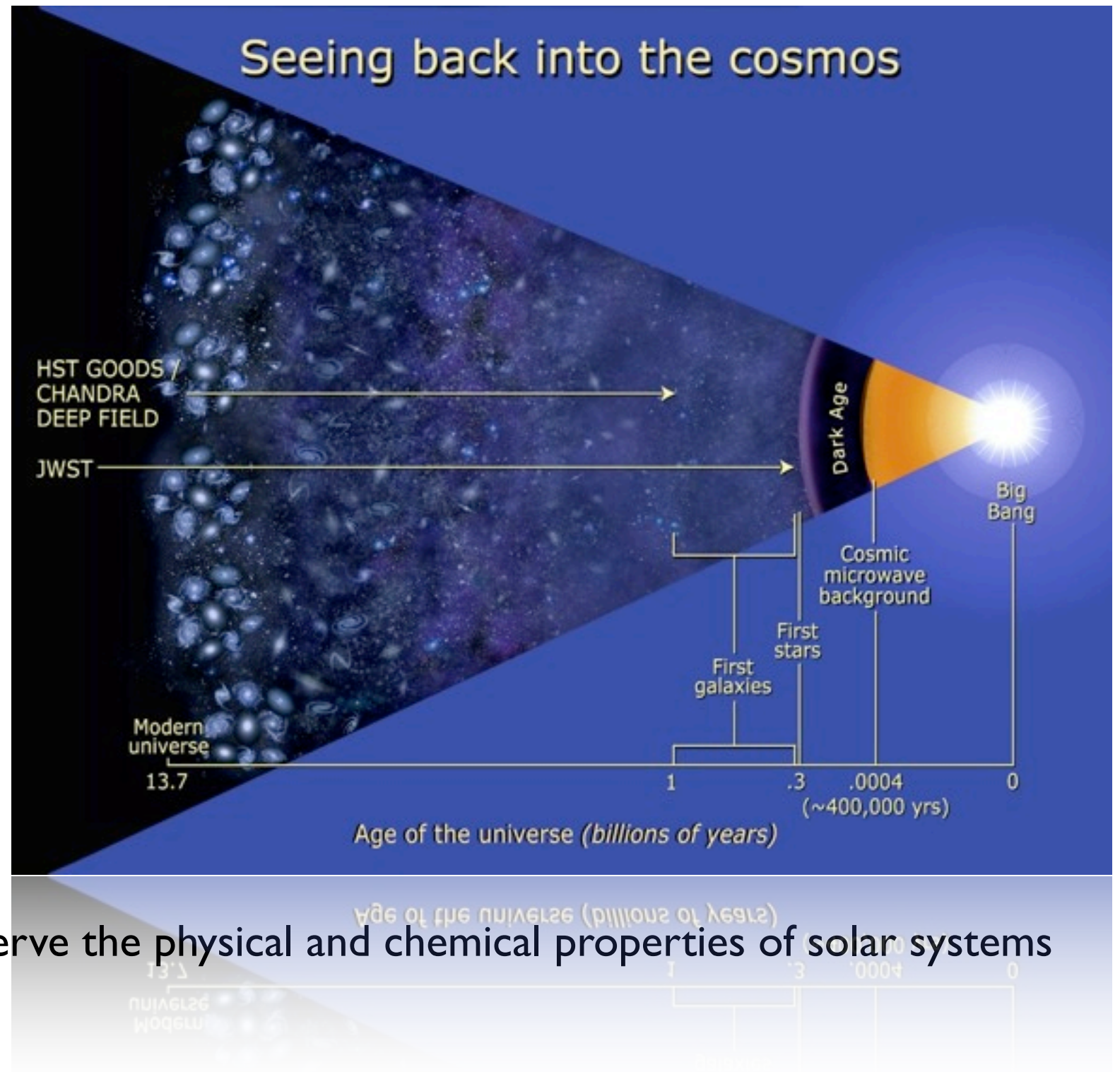




# JWST is an Astrophysics Mission

The development of technical requirements for JWST is driven by:

- **First-light and re-ionization:** Identify the first bright objects in the early Universe and follow ionization history
- **Galaxy formation and Evolution:** Shed light on how galaxies and dark matter evolved to present
- **Star formation in our galaxy:** Study the birth and early development of stars
- **Planetary systems:** Observe the physical and chemical properties of solar systems



# Optical Systems Engineering

- Verification of Requirements:
- Optical Performance Requirements Group 6 (OPRG6): summary of requirements and Performance Characterization Flows (PCFs)
- General goals of PCFs:  
Verify requirements formally assigned to the group by ISIM (40 requirements: 2 ISIM, 22 NIRCcam, 16 IOS, ALL 40 are related to NIRCcam)



Integrated Science Instrument Module = ISIM

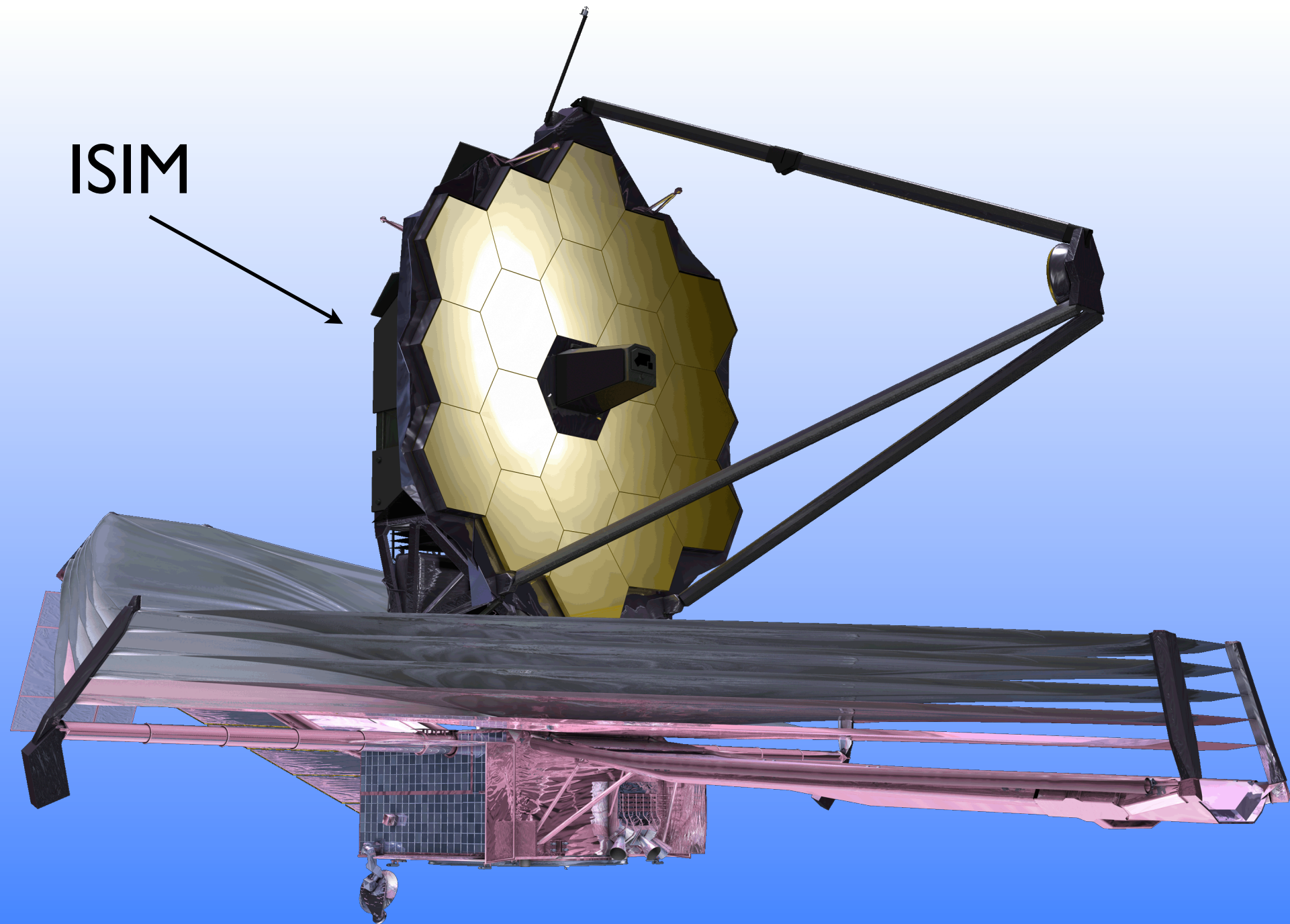


# Goals of Performance Requirements

- Verify the requirements assigned to ISIM
- Include the “ISIM Testing with OSIM” section of the Wavefront Sensing and Control Test Plan (Ball Aerospace)
- Provide a thorough demonstration/verification of the ISIM wavefront sensing capabilities testable by OSIM
- Coarse-Phasing, Fine-Phasing, MIMF: To emphasize high-level WFS performance metrics over low-level requirements

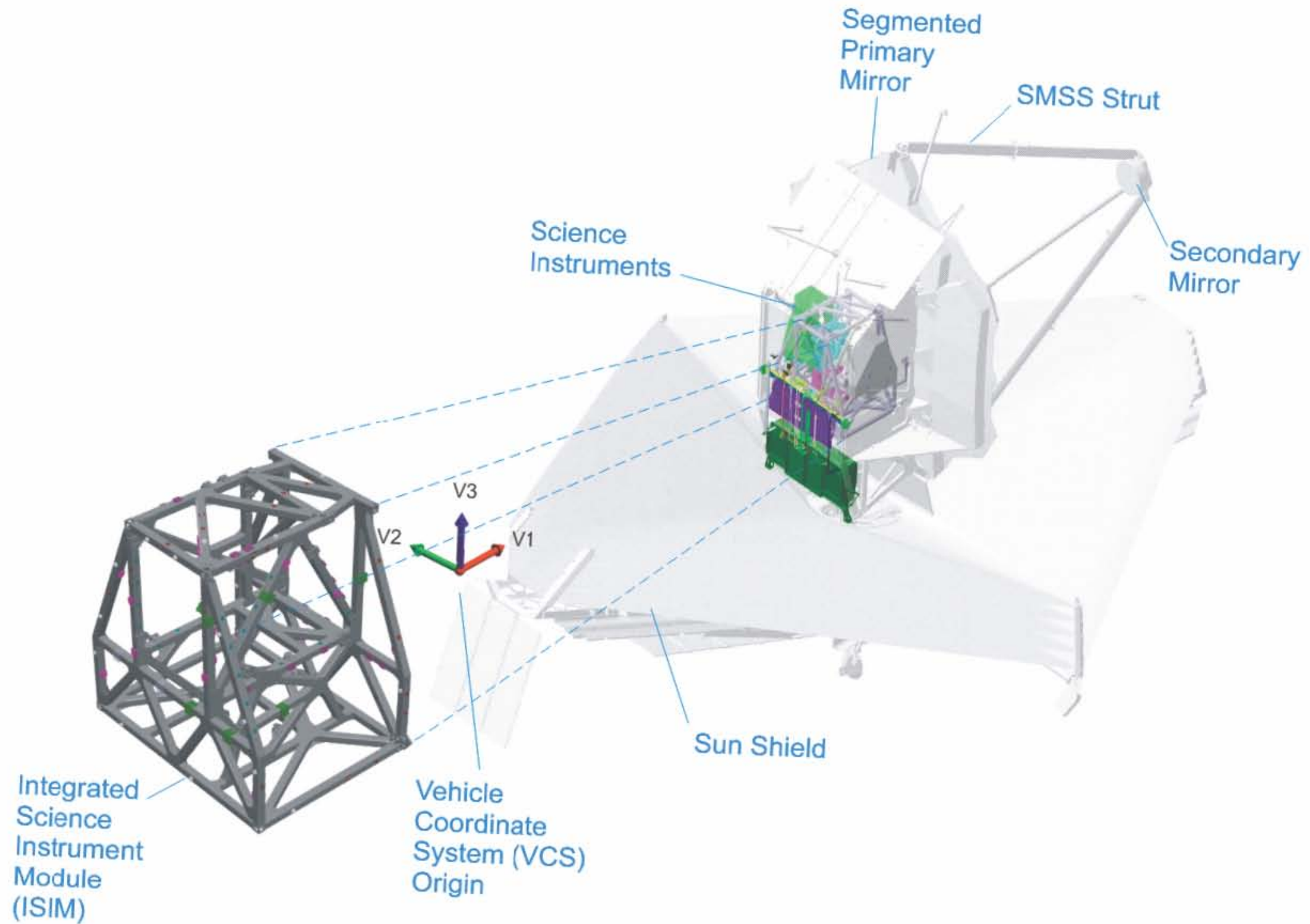


# Integrated Science Instrument Module (ISIM)



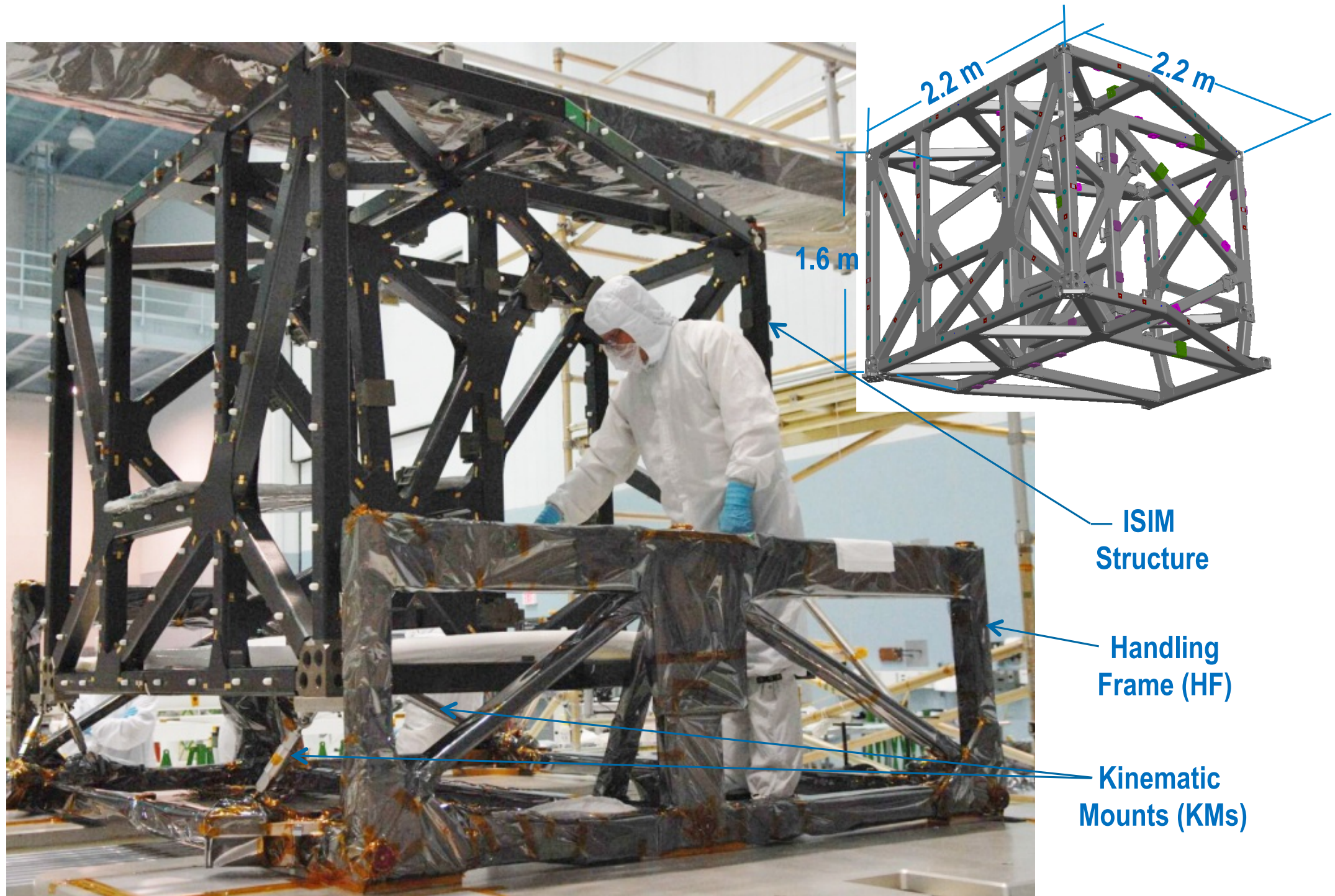


# ISIM (Component Form)



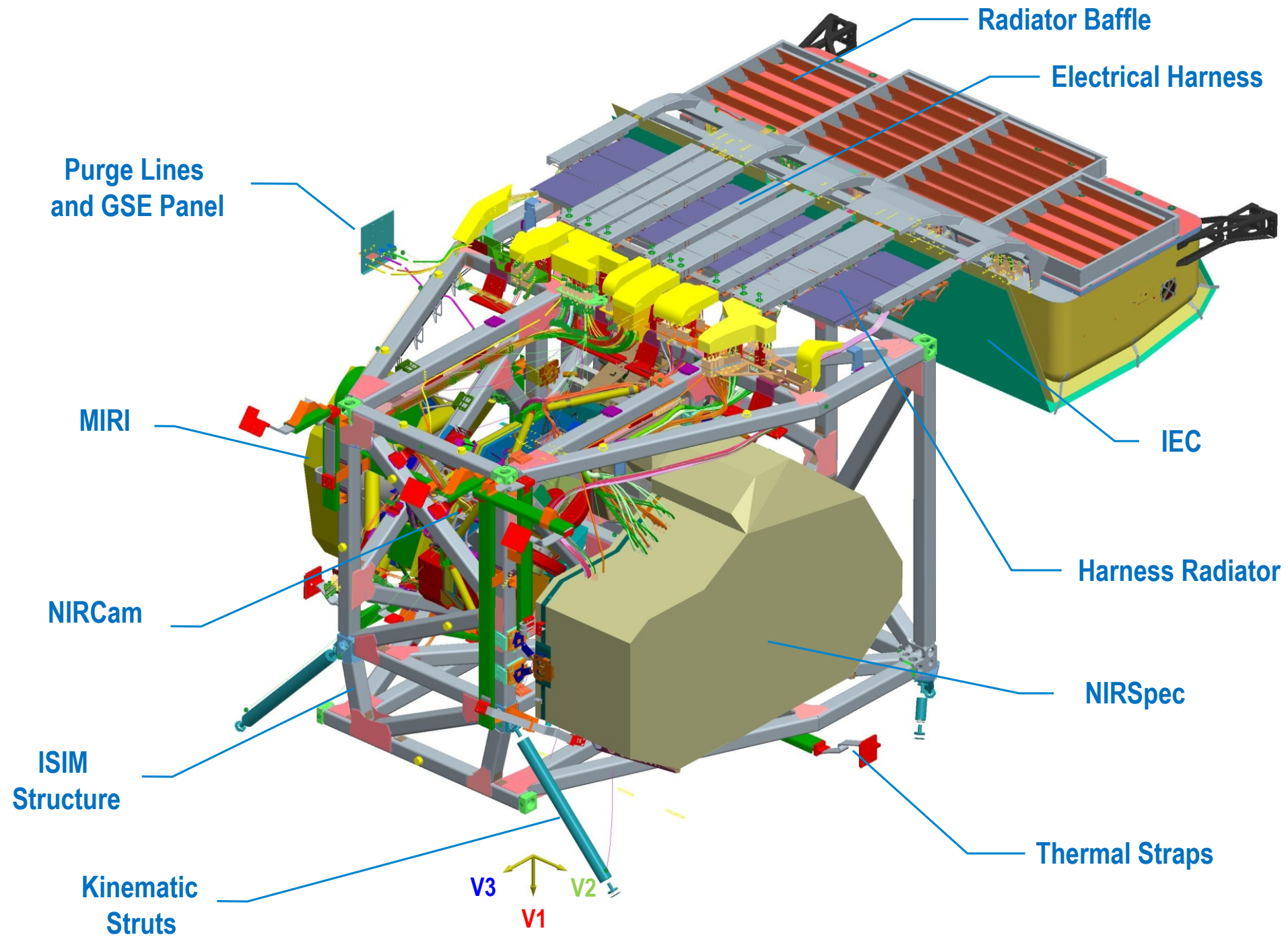


# Integrated Science Instrument Module (ISIM)





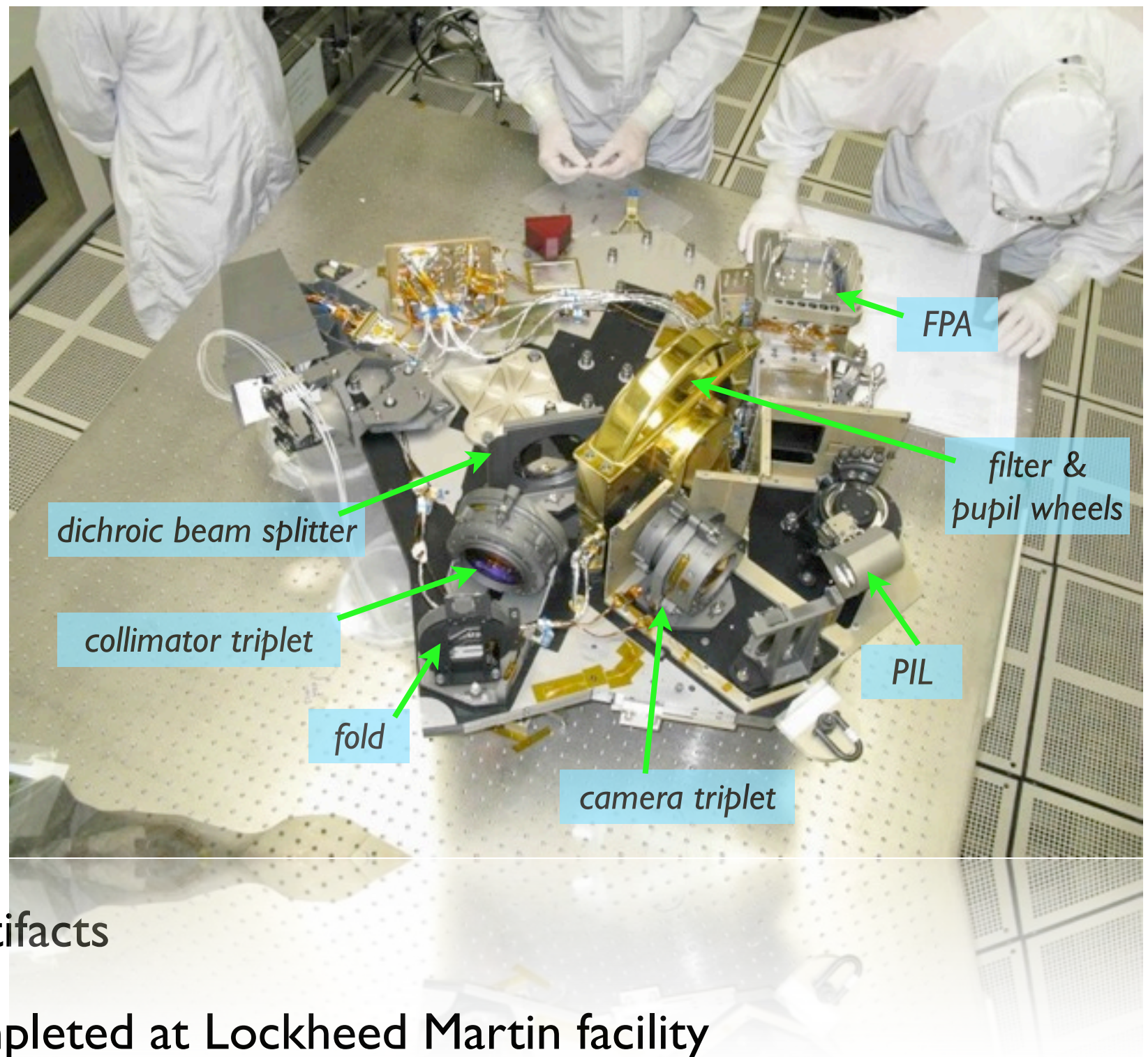
# Integrated Science Instrument Module (ISIM)





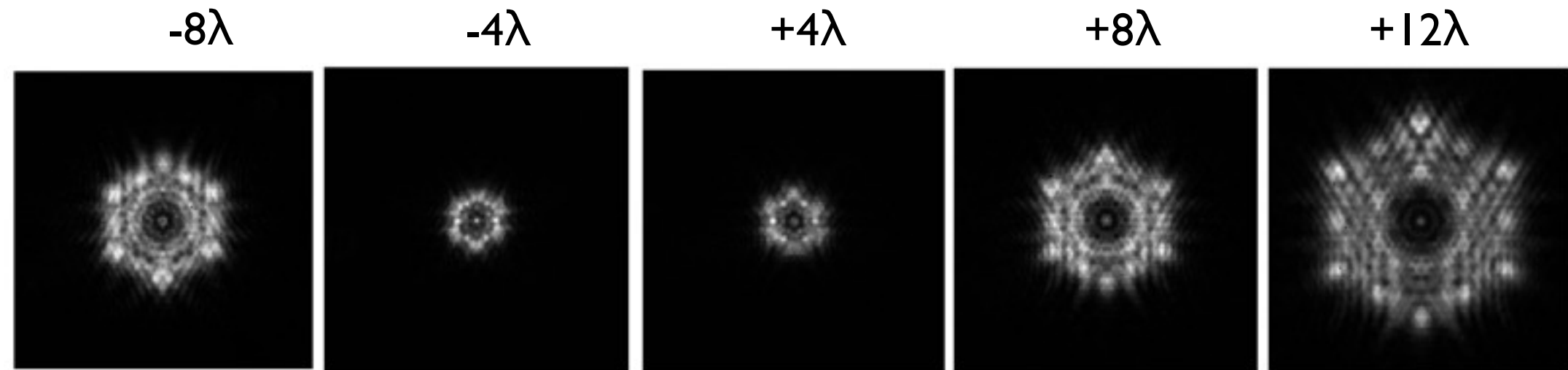
# NIRCam ETU Cryo Verification

- NIRCam: the primary JWST science camera, also used for WFSC
- Verification of WFSC Functions:
  - ─ phase retrieval performance,
  - ─ coarse phasing performance,
  - ─ ghost images,
  - ─ diamond turning artifacts
- April 2010, testing completed at Lockheed Martin facility

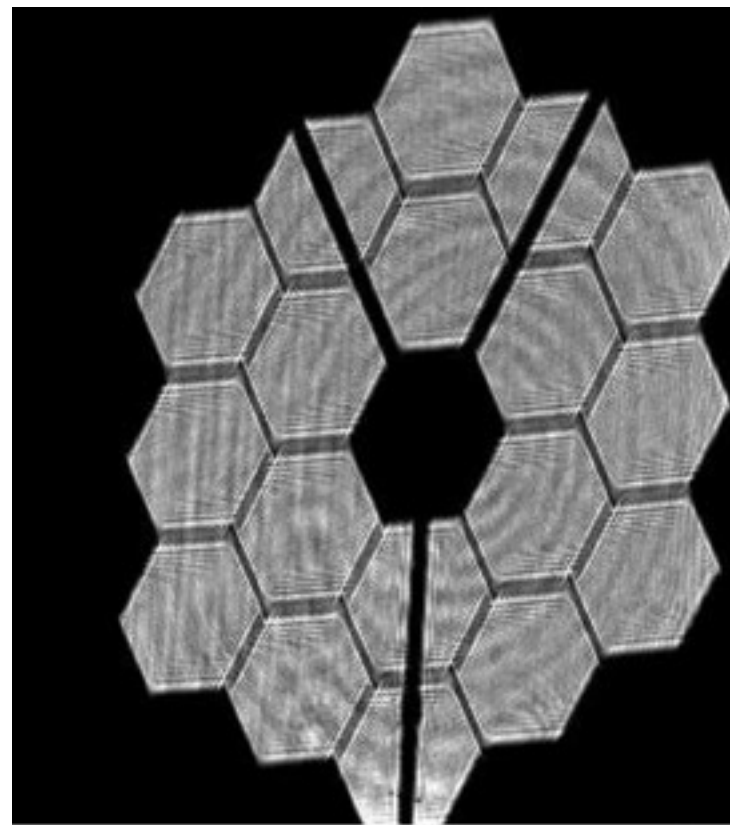




# Example Phase Retrieval Data

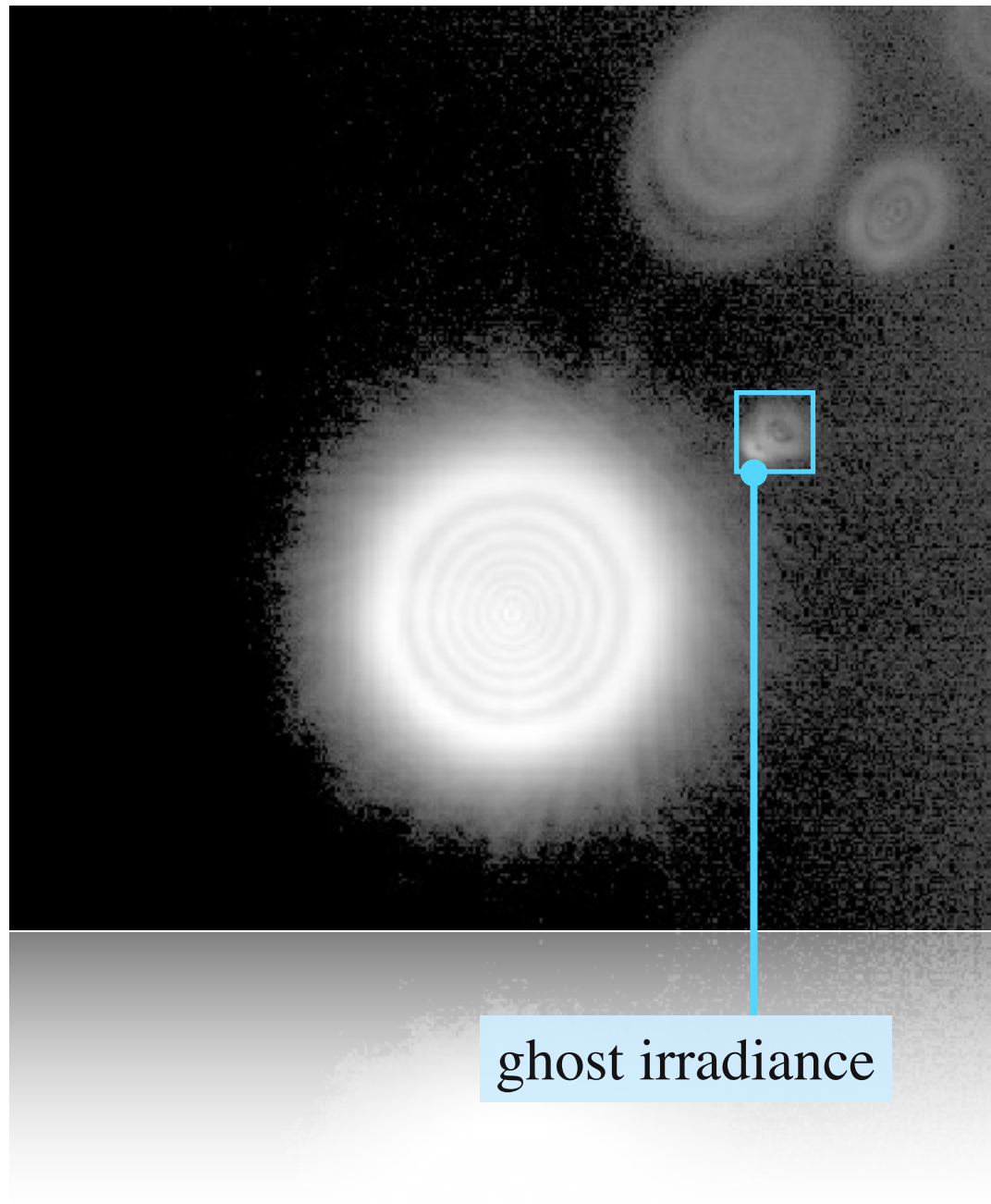


pupil data:

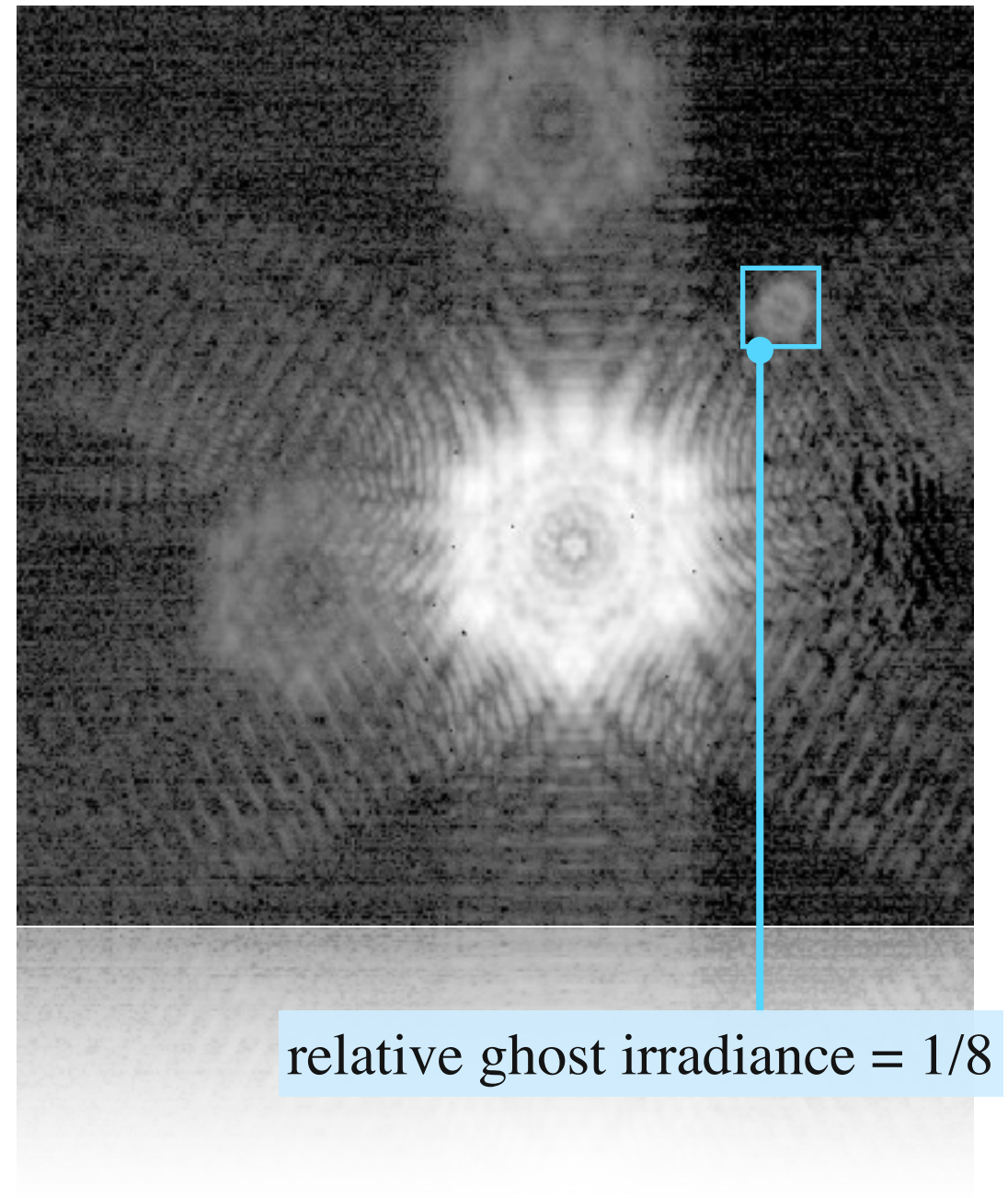


# Ghost Irradiance

Older NIRCams Pathfinder



NIRCams ETU





# Phase Retrieval Approach

- Non-Linear Optimization (NLO):

- J. R. Fienup, “Phase-retrieval algorithms for a complicated optical system.” *Applied Optics*, Vol. 32, Issue 10, pp. 1737-1746 (1993)

$$\hat{E} = \left[ \frac{1}{N} \sum_n \frac{\sum_x^{pixels} w_n(x) |I_n(x) - I'_n(x)|^2}{\sum_x^{pixels} w_n(x) |I_n(x)|^2} \right]^{1/2}$$

- Incorporating variable sampling and pupil-amplitude reconstruction:

- B. Dean, “Gradient Calculations for the NLO Approach to Phase Retrieval,” Code 551; Doc # 20100405BHDVer1a, April 5, 2010

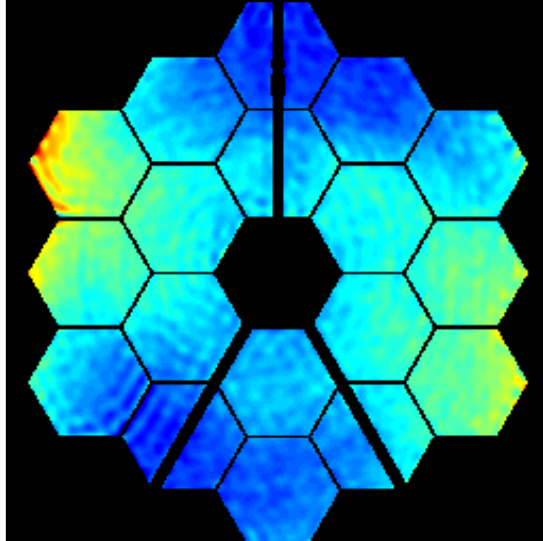
- Iterative Transform:

- B. Dean, D. Aronstein, J. Smith, R. Shiri, and D. Acton, “Phase Retrieval Algorithm for JWST Flight and Testbed Telescope,” *SPIE 6265* 11-1 - 17 (2005)
- J. Smith, B. Dean, D. Aronstein, S. Acton, “Broadband and Under-sampled Phase Retrieval Results for the JWST Testbed Telescope,” *SPIE 7436*-13 (2009)

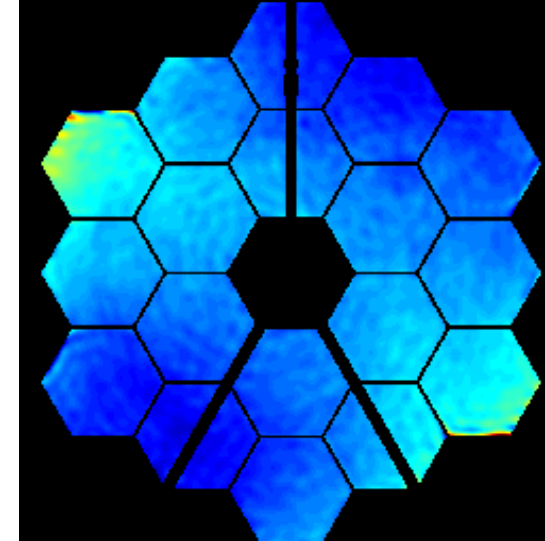
# Example Phase Retrieval Results

Across the FOV:

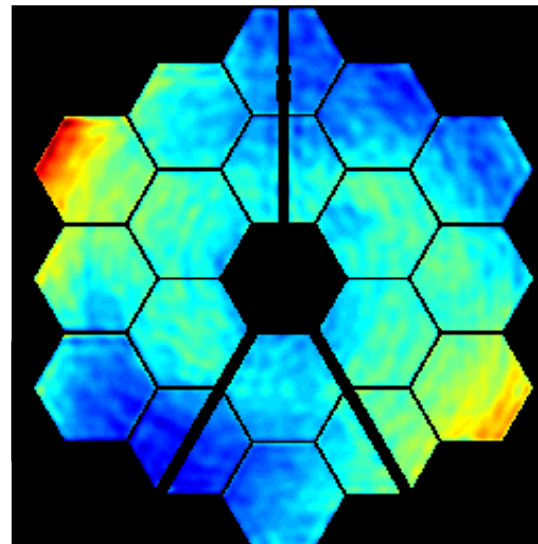
Complex Field Retrieval (Phase)  
4.5.11 ETU4 JWST



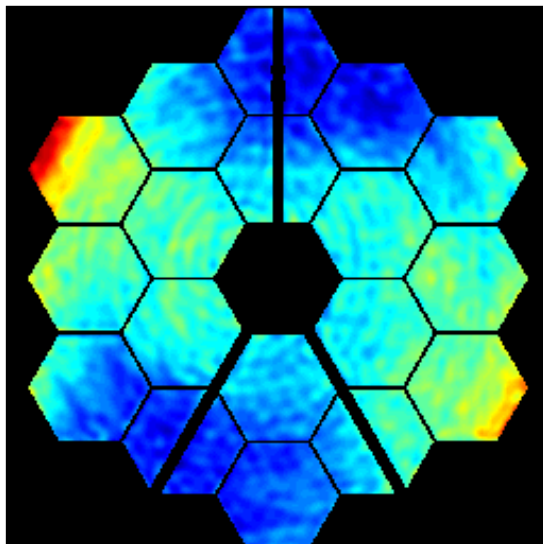
Complex Field Retrieval (Phase)  
4.5.10 ETU3 JWST



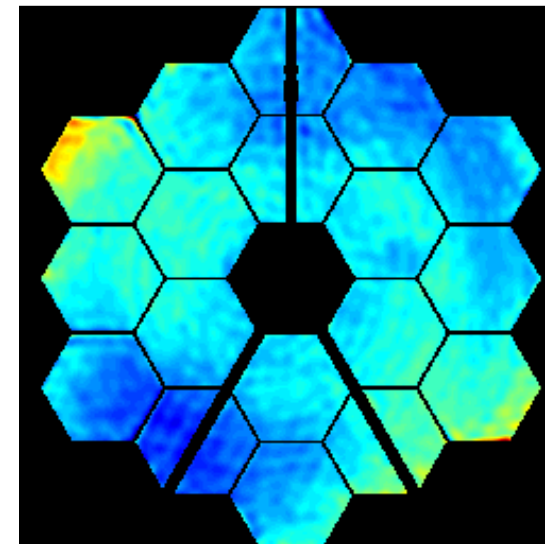
Complex Field Retrieval (Phase)  
4.5.8 ETU1 JWST



Complex Field Retrieval (Phase)  
4.5.9 ETU2 JWST



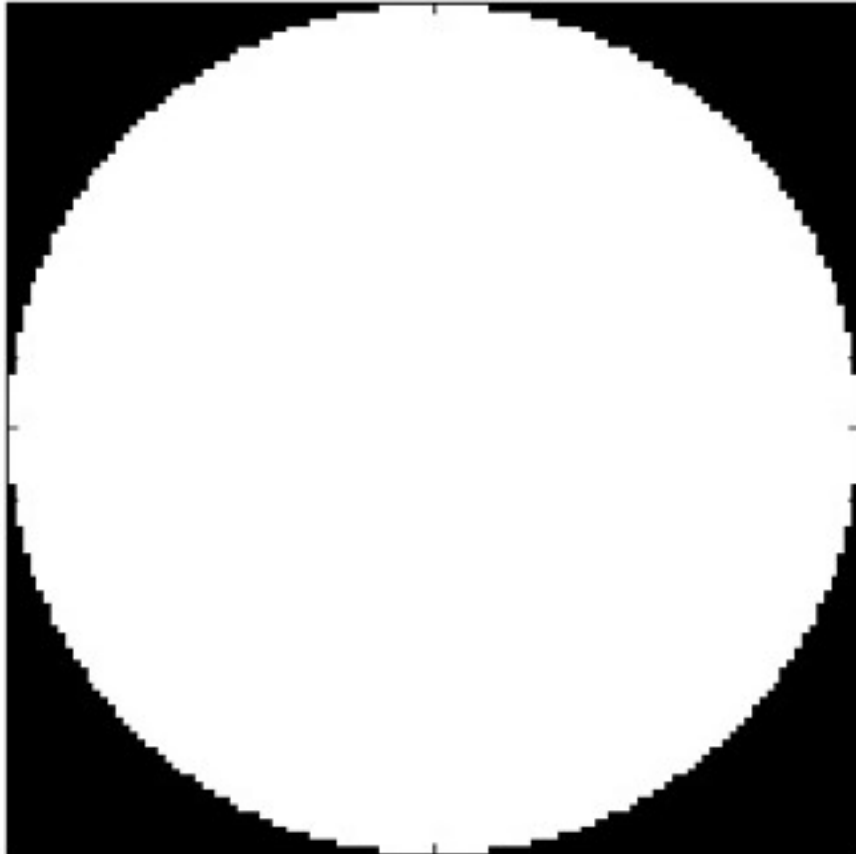
Complex Field Retrieval (Phase)  
4.5.12 ETU5 JWST



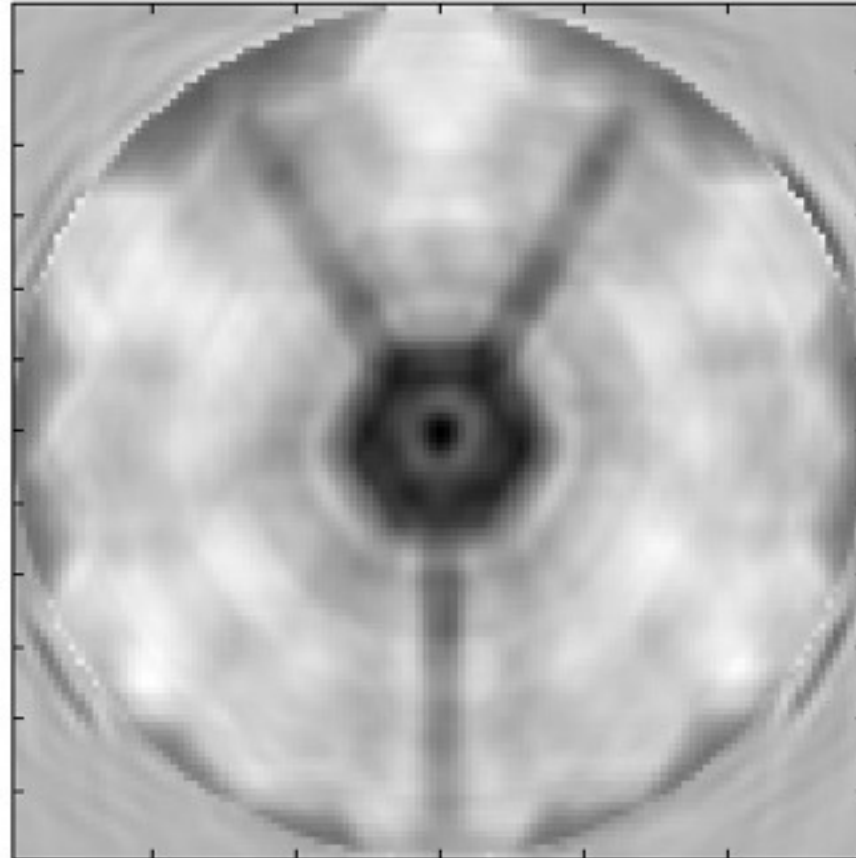


# Pupil Amplitude Estimation

Start:

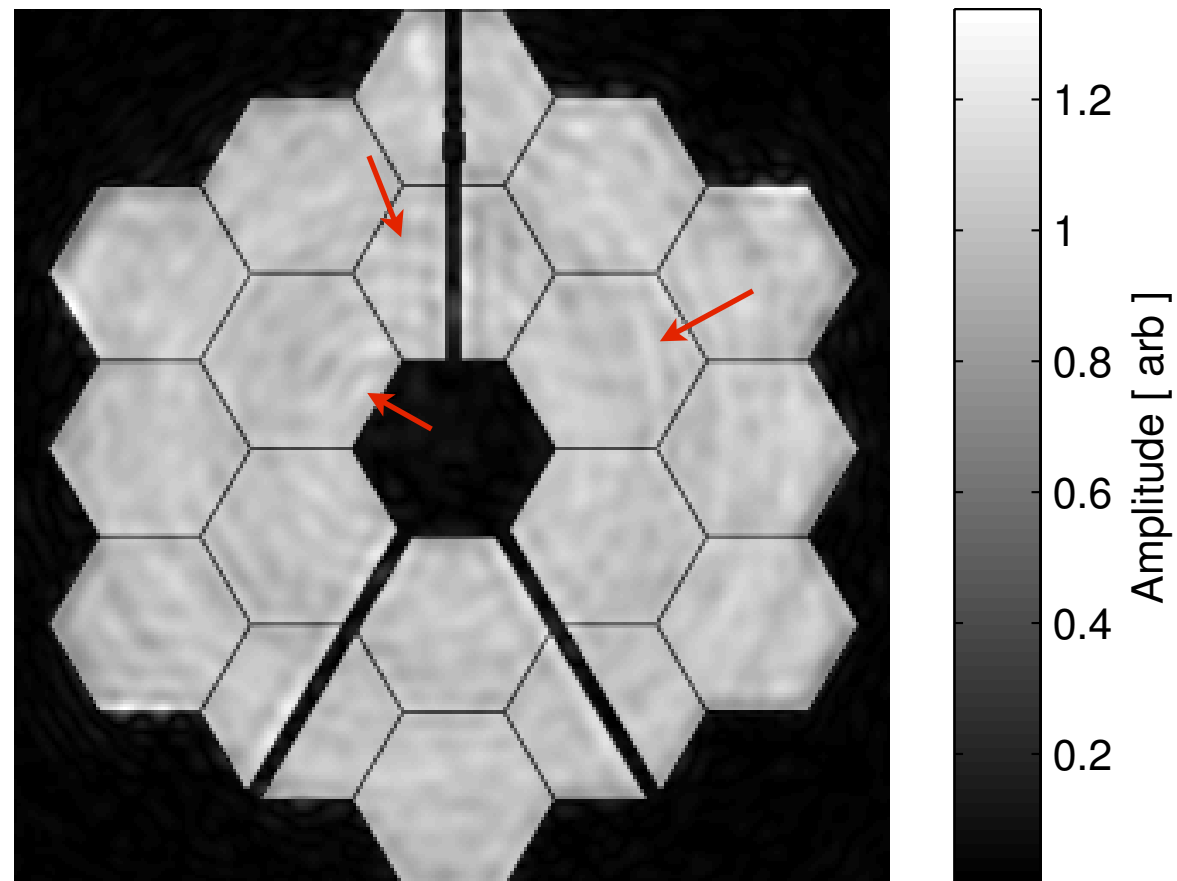


Initial Estimate:



# JWST-like Amplitude Retrieval

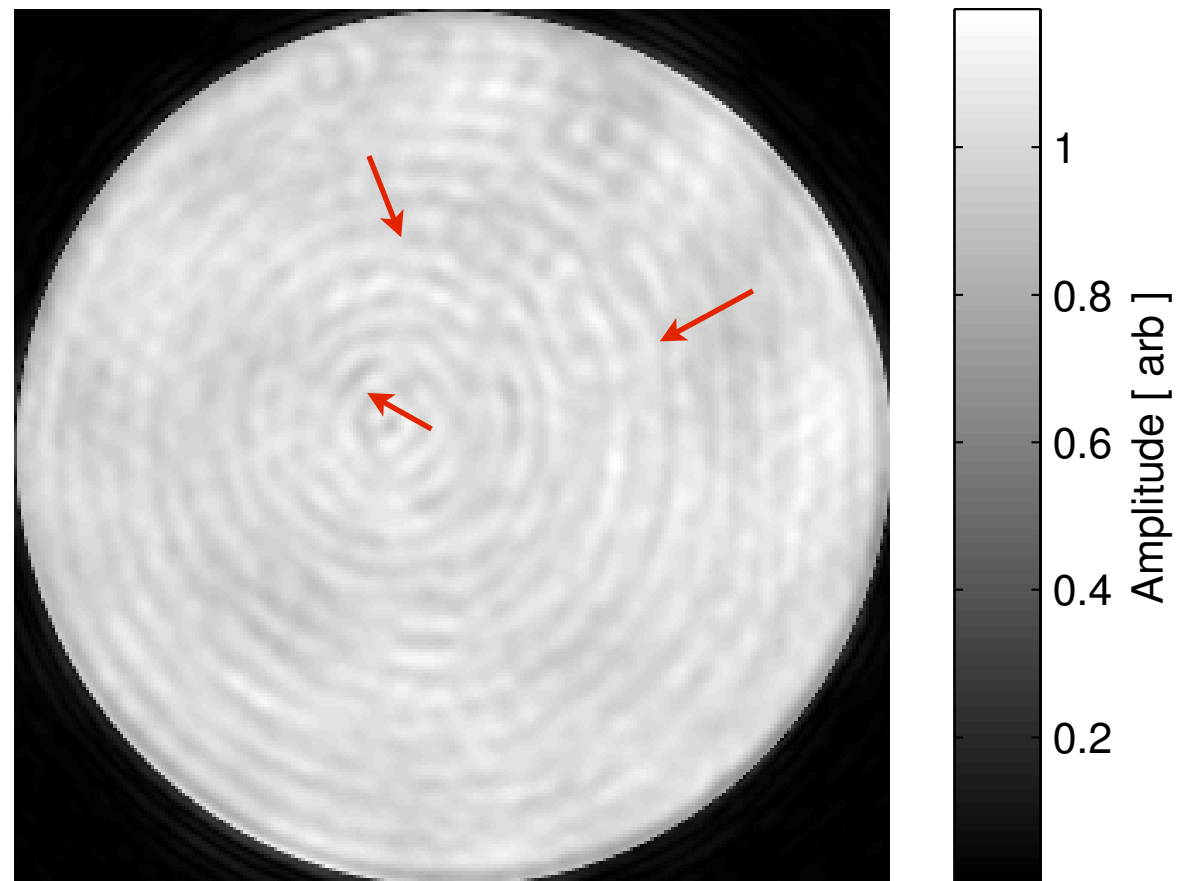
Complex Field Retrieval (Amplitude)  
4.5.8 ETU1 JWST





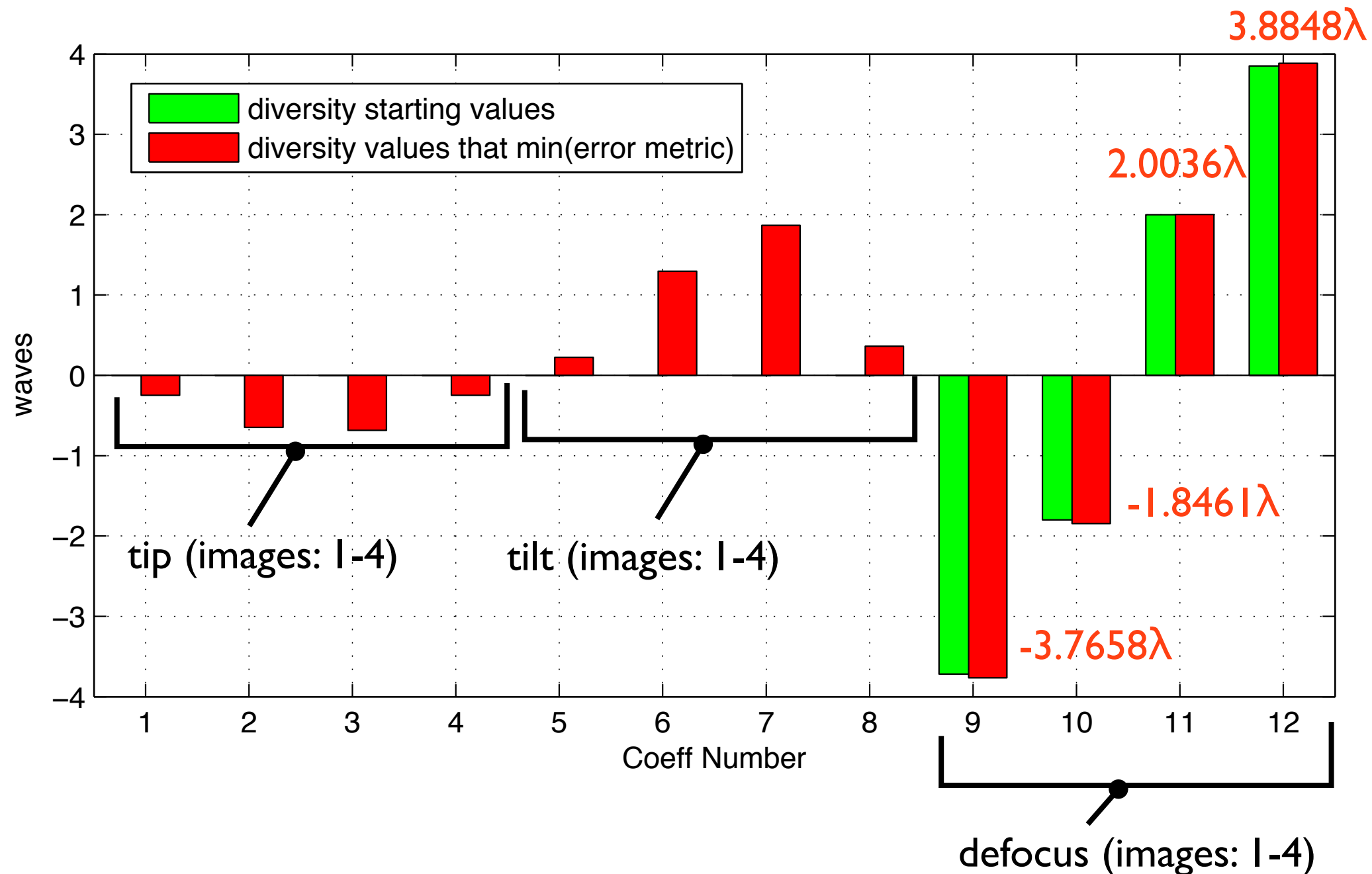
# Circular Amplitude Retrieval

Complex Field Retrieval (Amplitude)  
4.5.3 ETU1 F/20



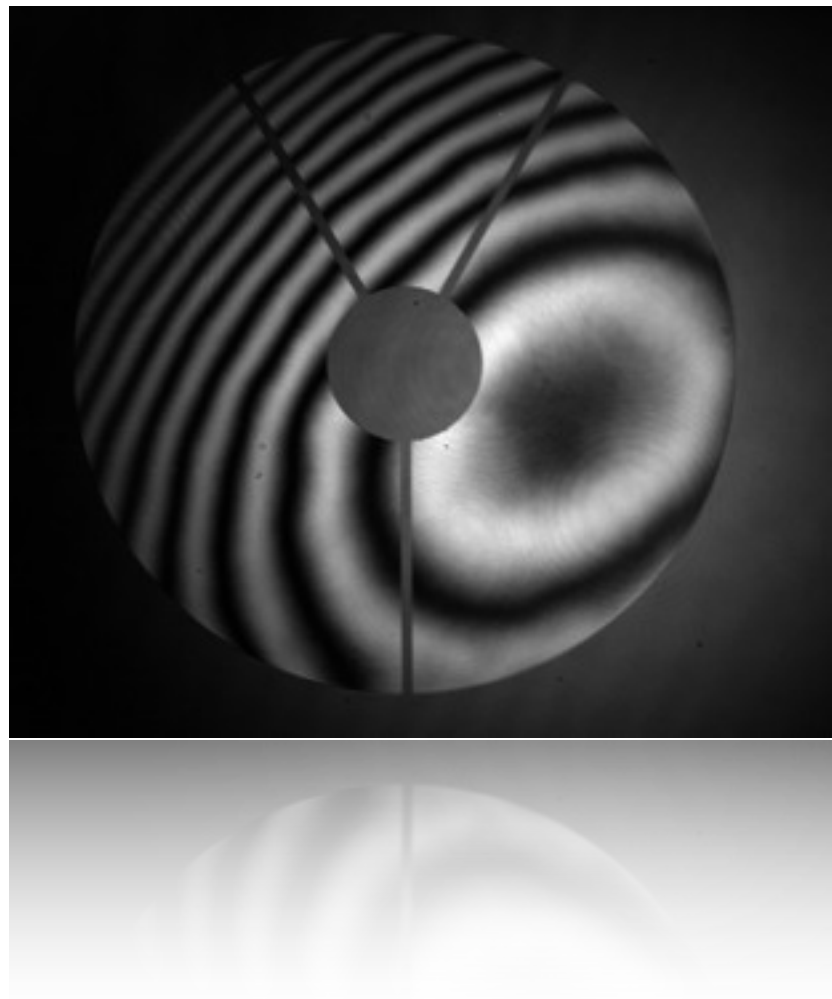
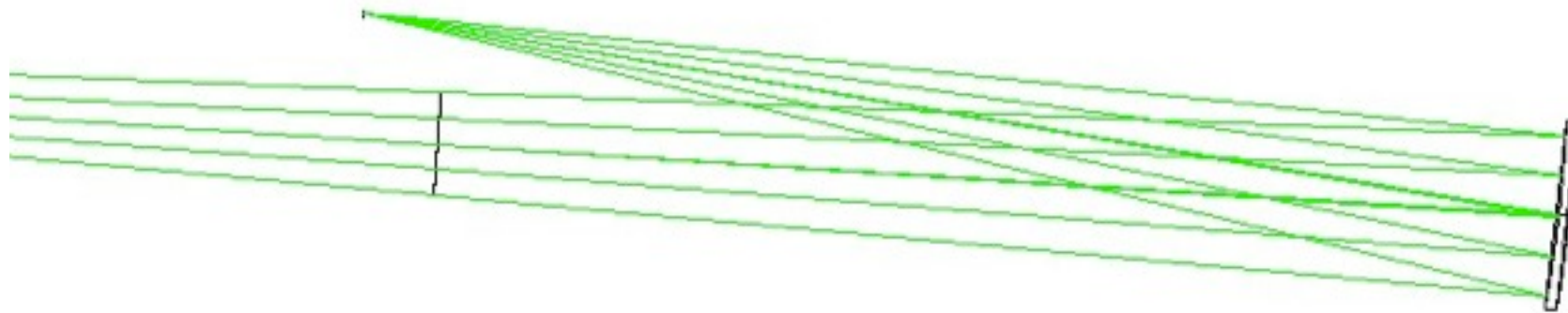
# NLO Optimized Diversity Functions

- Tip, tilt, and defocus are optimized to minimize the error metric
- In this approach, starting values only need to be approximate



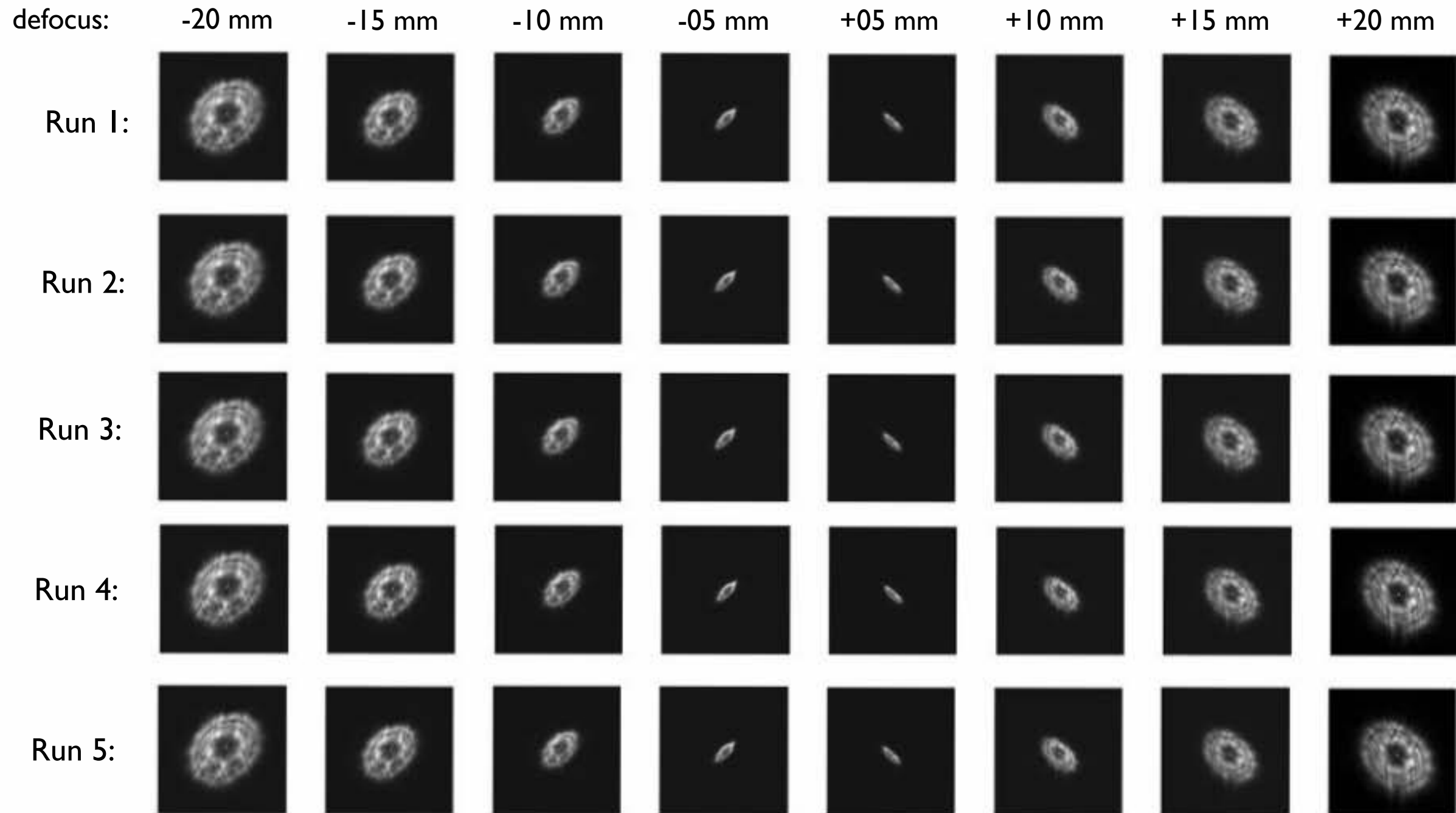


# Algorithms Tested Using Simple Testbeds



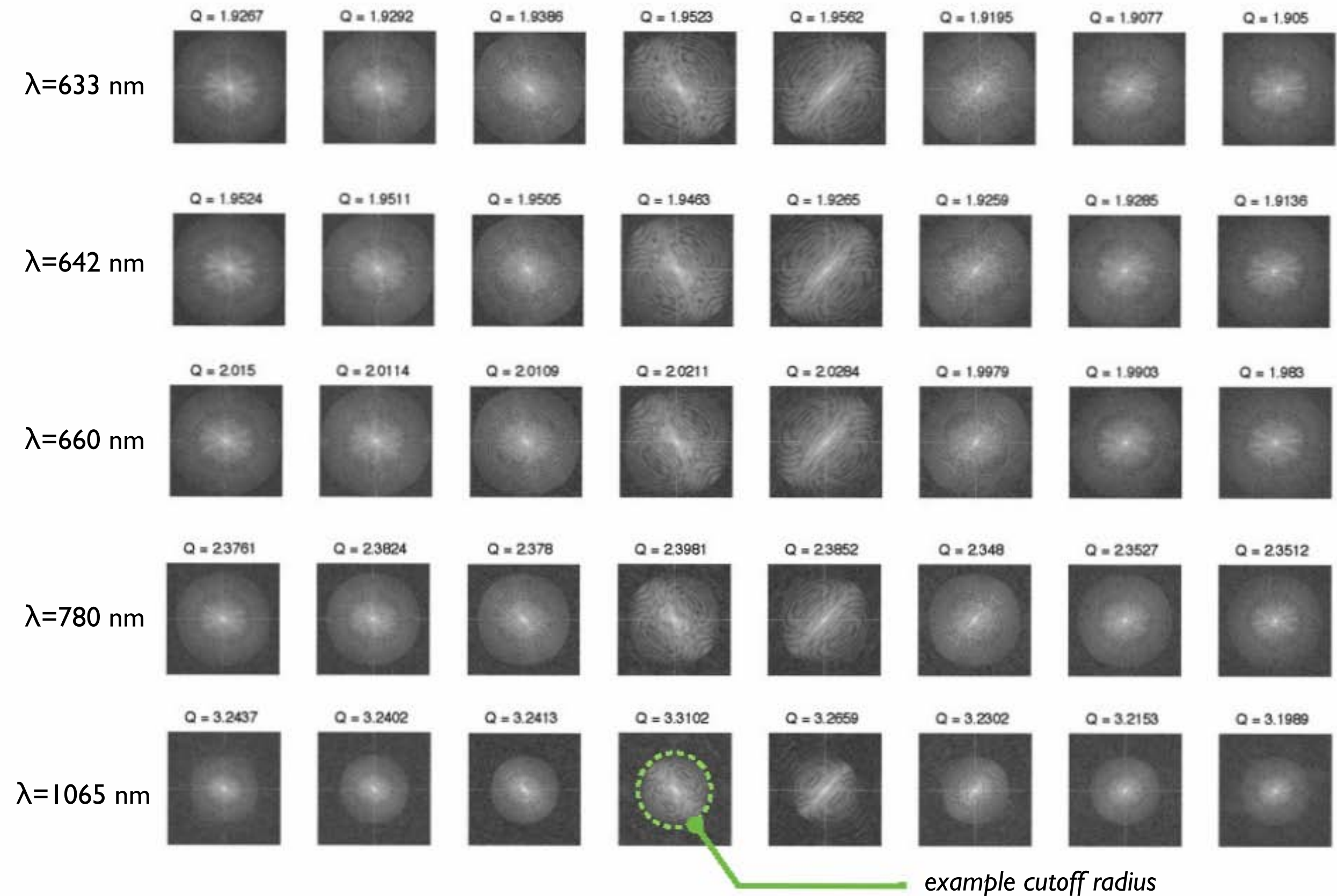
Results are correlated with PDI and alternative implementations of algorithms

# Example Testbed Data

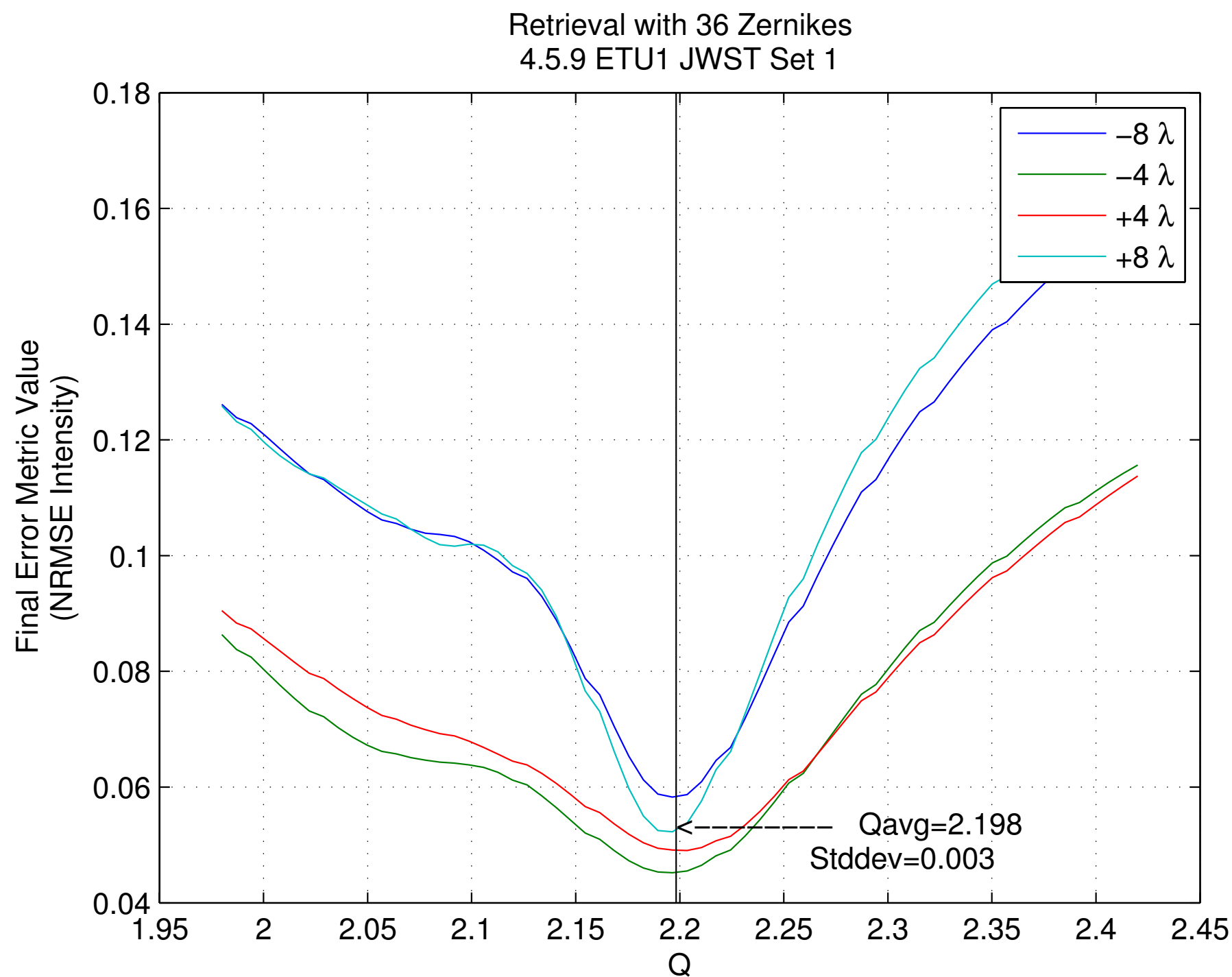




# Initial Plate Scale Estimation using the MTF



# Determining Q Values (initially: grid search)





# Theory: Data Parameters Estimated from the MTF

- Solve for these parameters directly from the data

- Diameter of the MTF defines the optical passband:

$$2 \times \nu_b$$

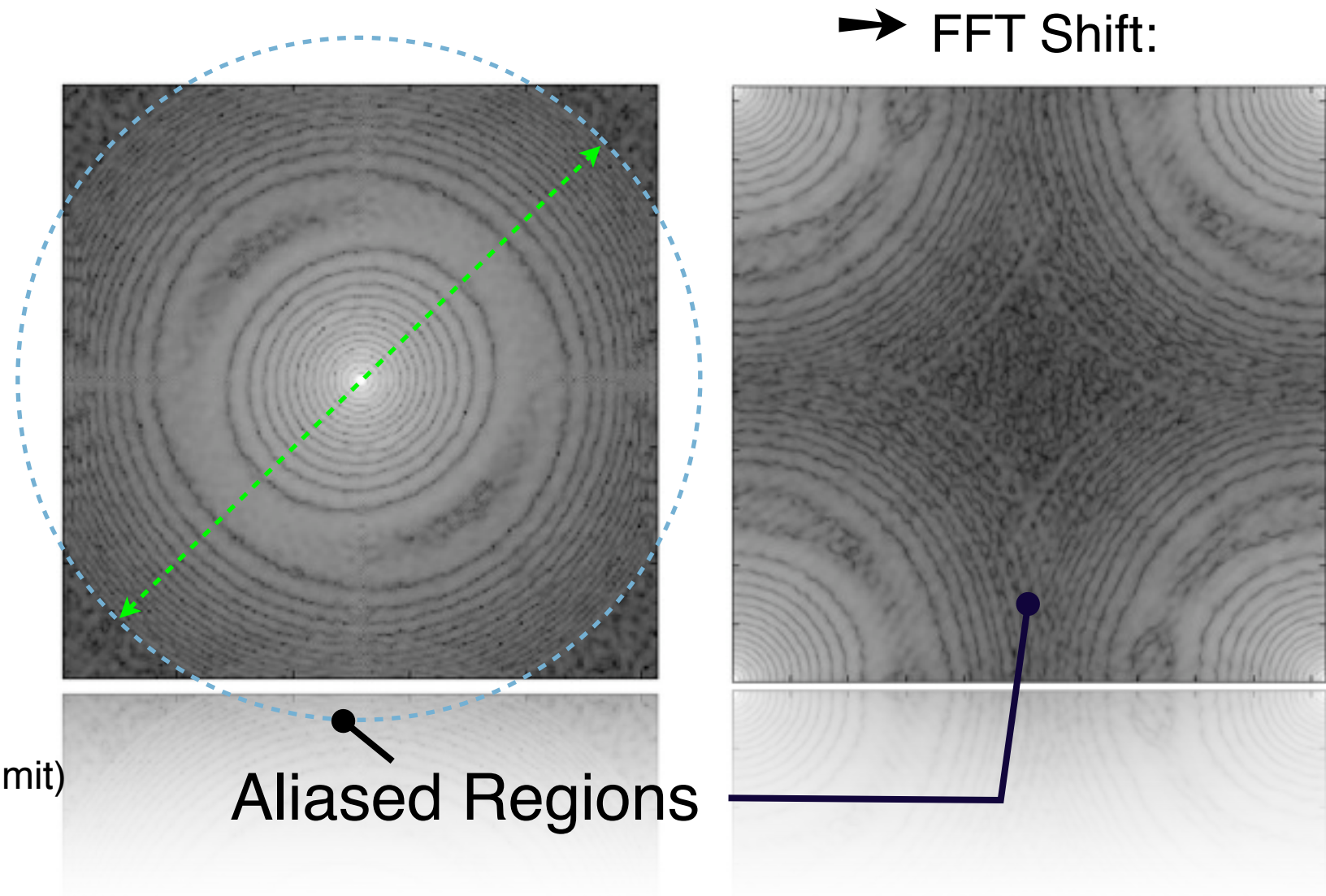
- Define:

$\nu_b \equiv$  cut-off frequency (band-limit)

$\nu_\Delta \equiv$  data sampling frequency

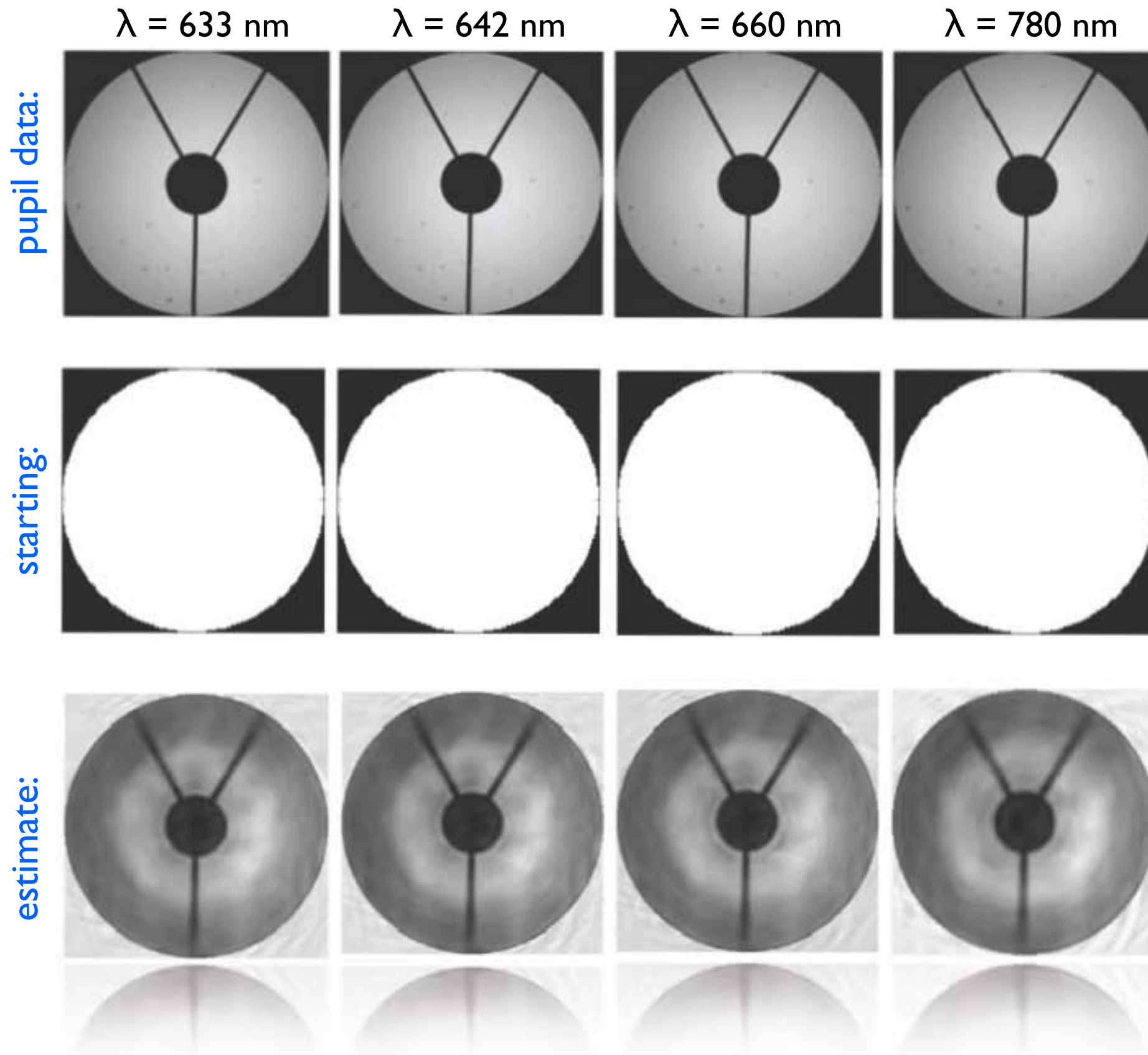
$p \equiv$  plate scale (radians)

$Q \equiv$  image sampling parameter



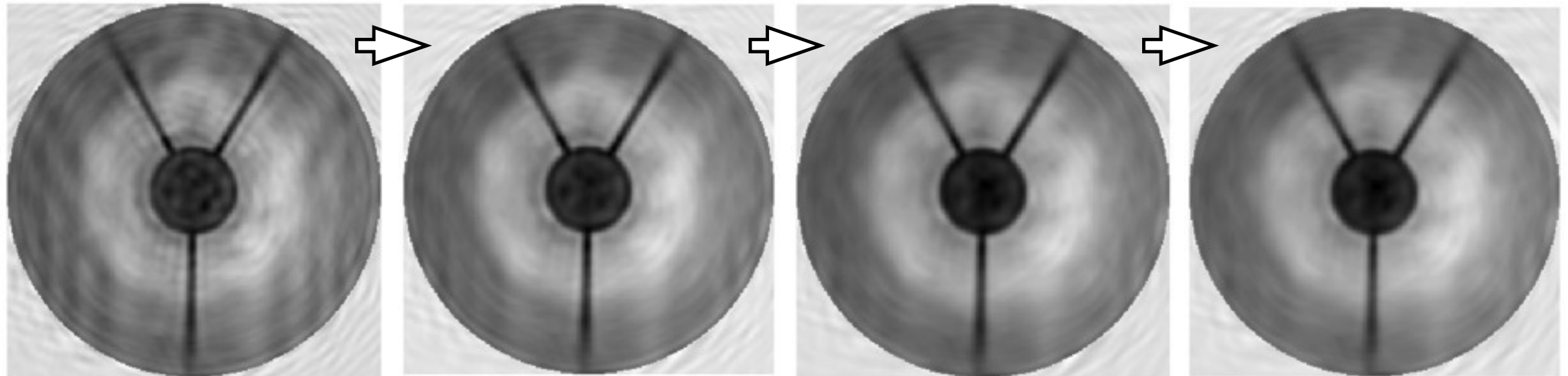
$$Q \equiv \frac{\nu_\Delta}{\nu_b} = \frac{\lambda f_\#}{\Delta x} = \frac{\lambda}{p \cdot D}$$

# Pupil Amplitude Estimation vs. $\lambda$

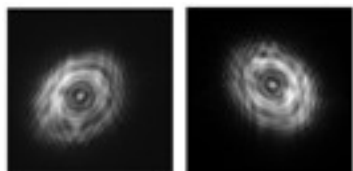




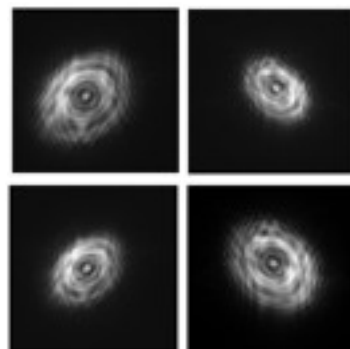
# Pupil Amplitude Estimation vs. # of Images



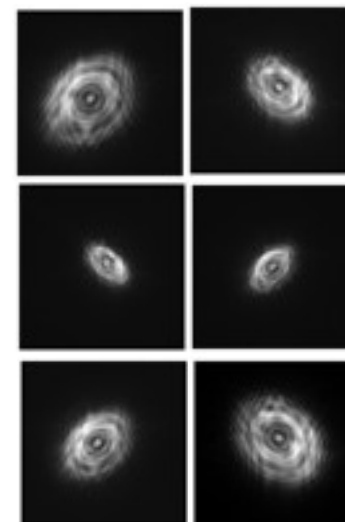
*2-images:*



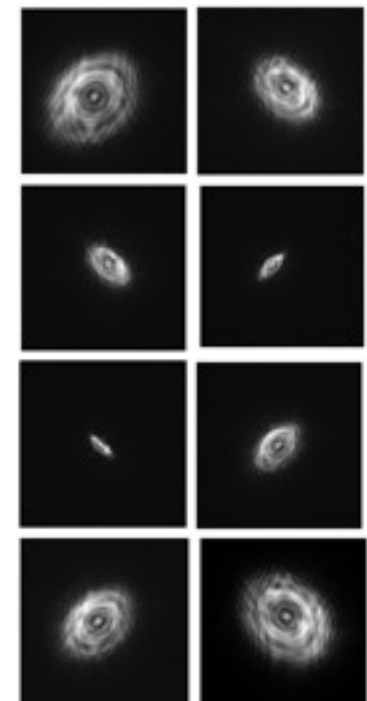
*4-images:*



*6-images:*

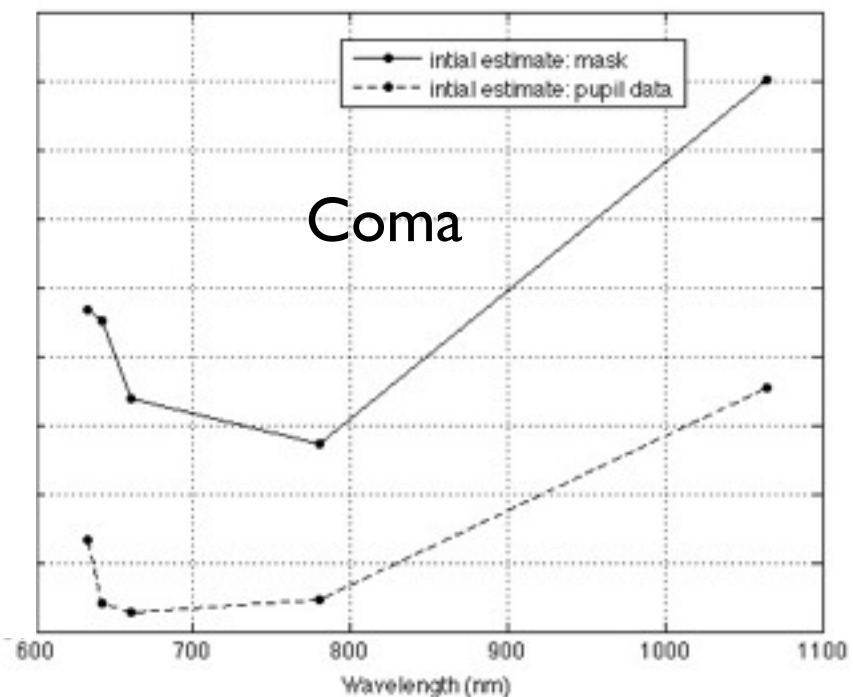
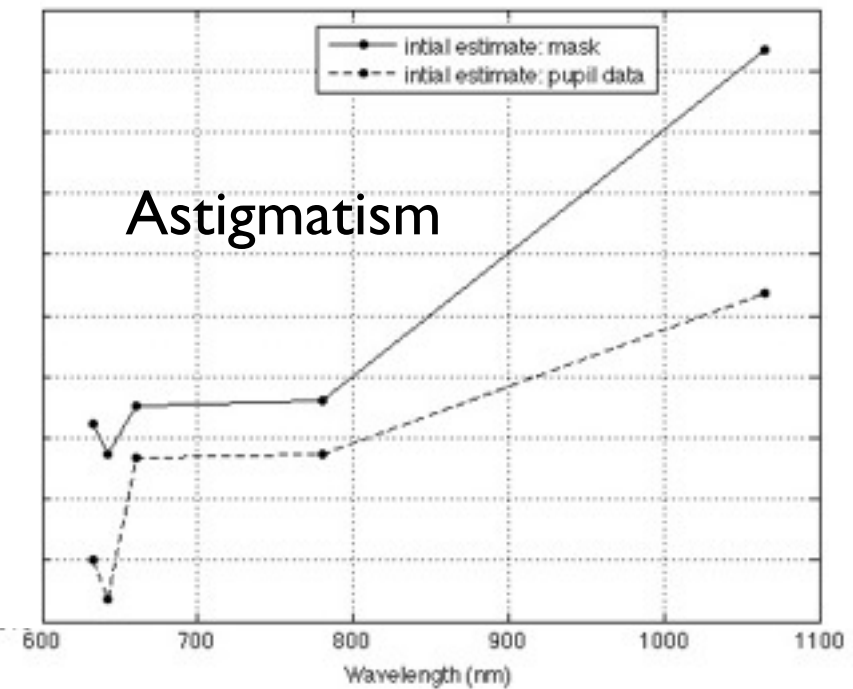
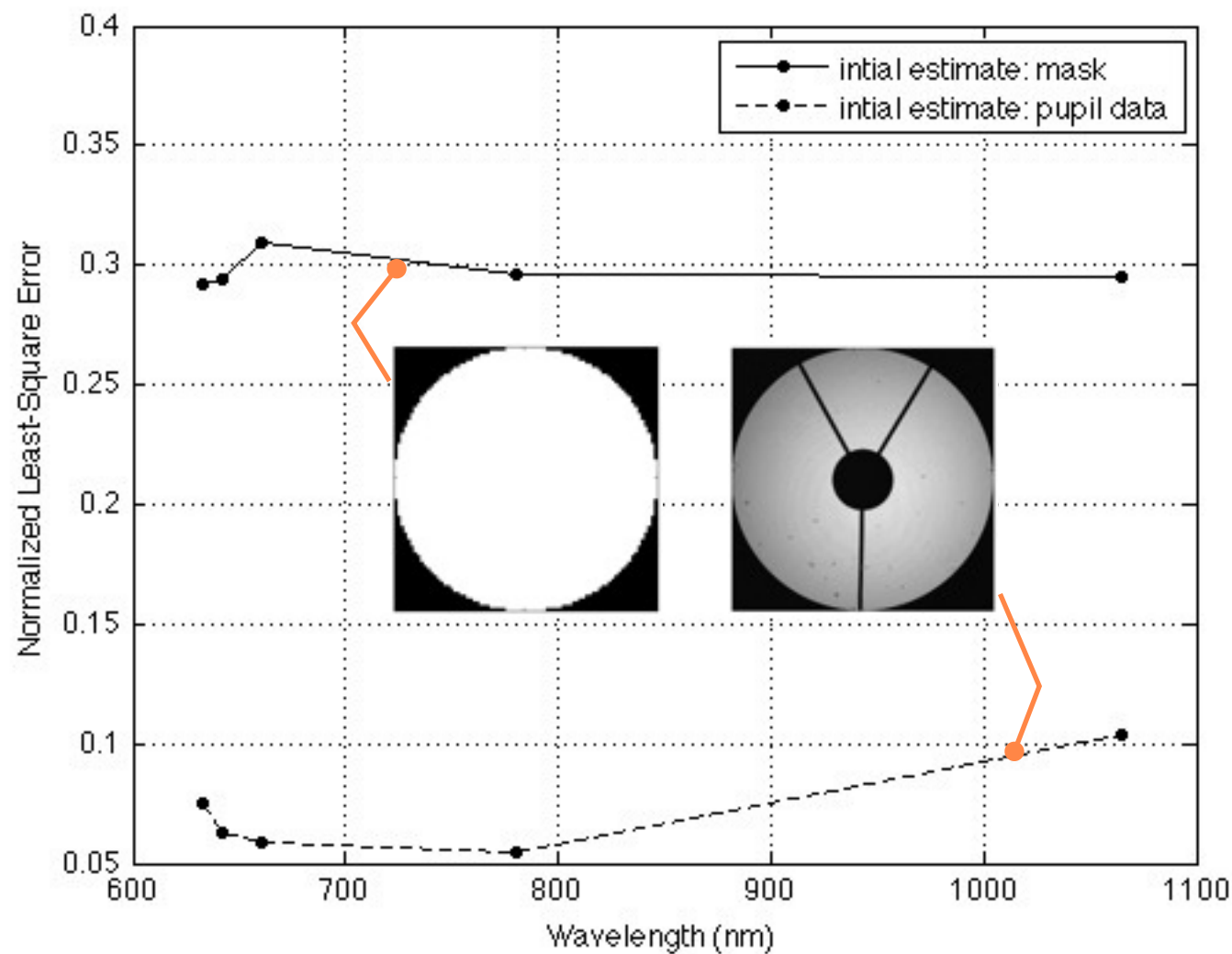


*8-images:*

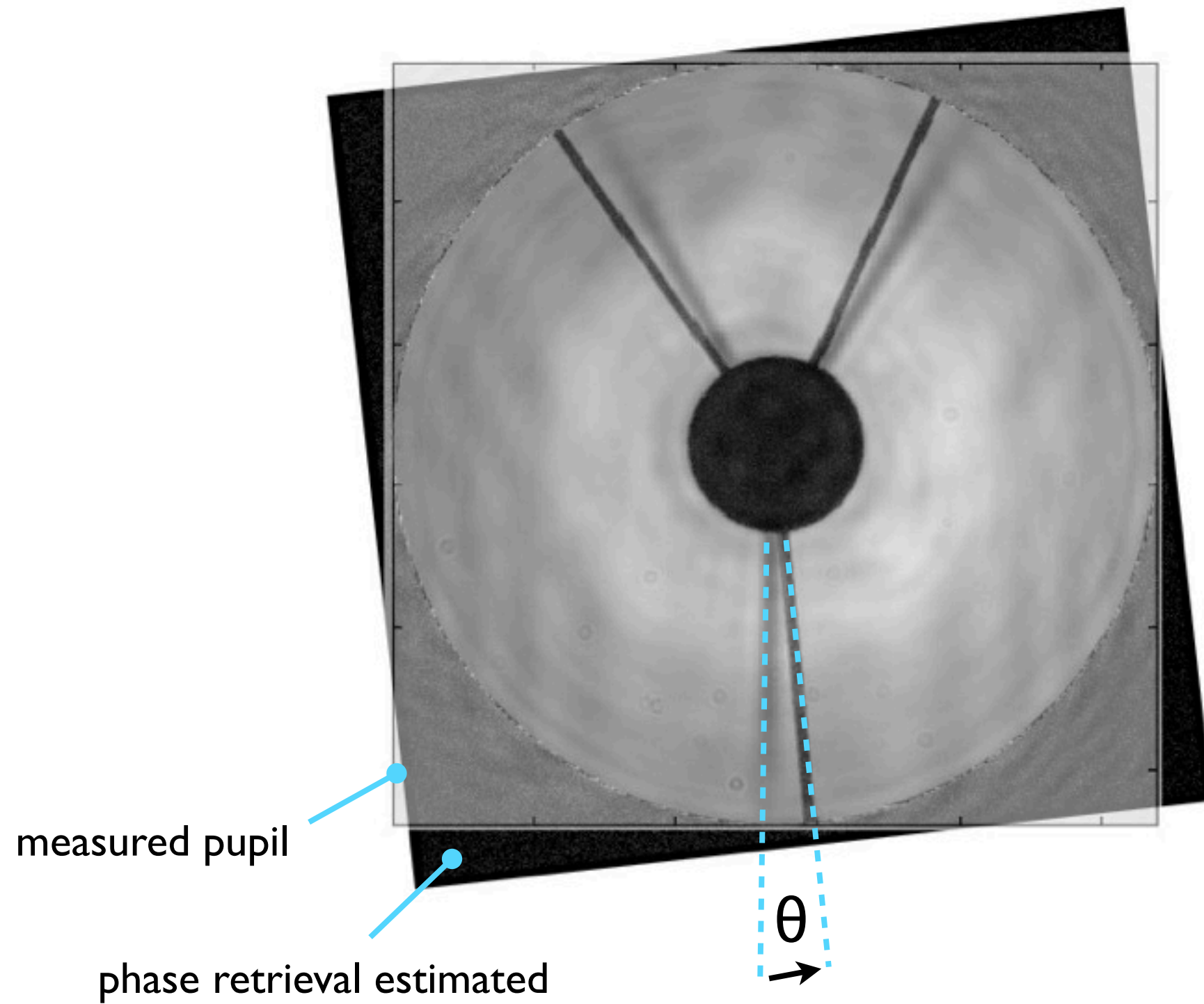


# Least Square Error vs. Starting Pupil Amplitude

$$\hat{E} = \left[ \frac{1}{N} \sum_n \frac{\sum_x^{pixels} w_n(x) |I_n(x) - I'_n(x)|^2}{\sum_x^{pixels} w_n(x) |I_n(x)|^2} \right]^{1/2}$$



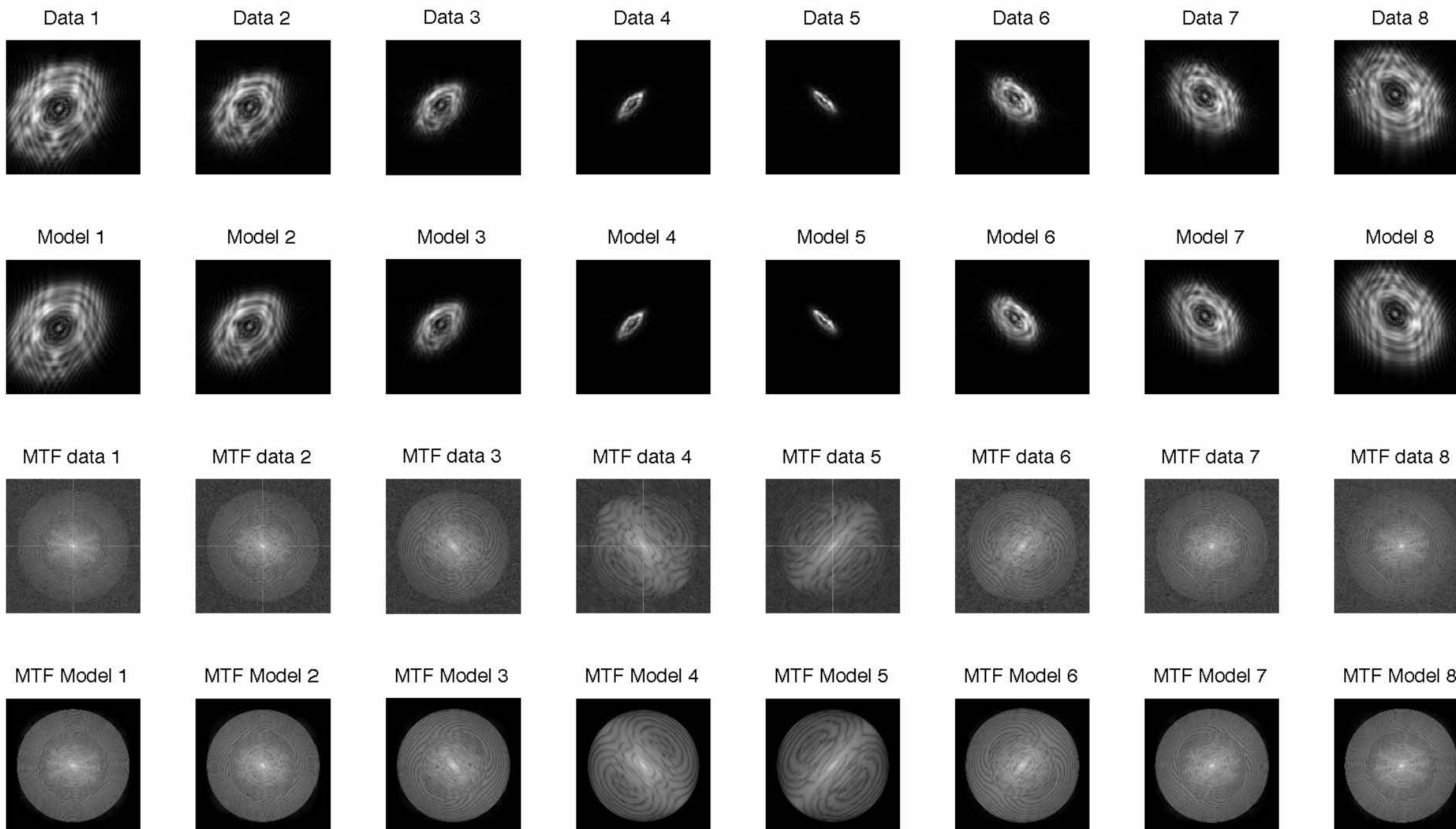
# Pupil Amplitude Estimation vs Rotation (clocking)





# Typical Phase Retrieval Results

-20 mm    -15 mm    -10 mm    -5 mm    +5 mm    +10 mm    +15 mm    +20 mm





# Summary

- A robust suite of algorithms have been developed for JWST sensing and control.
- NIRCam ETU instrument tests indicate that WFS will meet NIRCam specific OPRG-6 requirements.
- We consider pupil amplitude estimation to be a “standard” component of the analysis.
- Ground testing of JWST instruments indicate that accurate estimation of phase and pupil amplitude are expected, even with subsystem deployment anomalies.