Coronagraphy Basics

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Eugene Higgins Prof. of Mechanical & Aerospace Engineering, Emeritus
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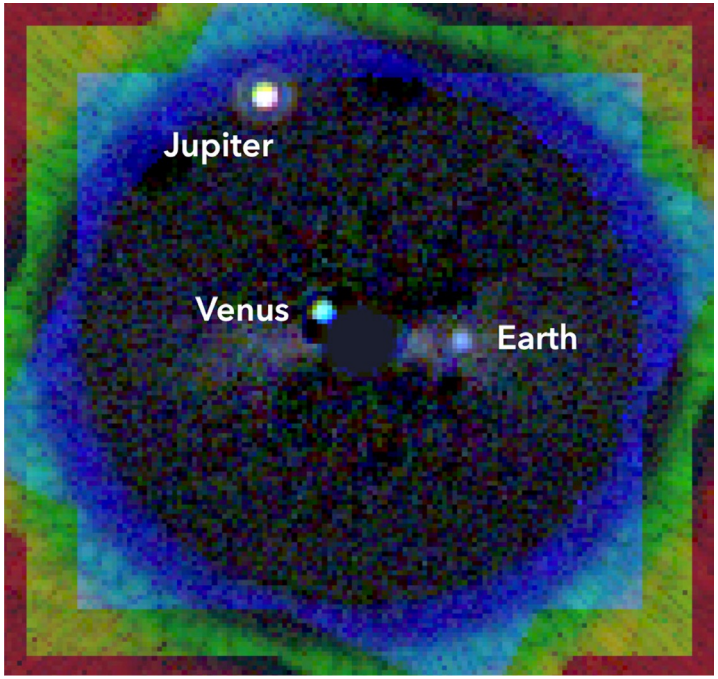
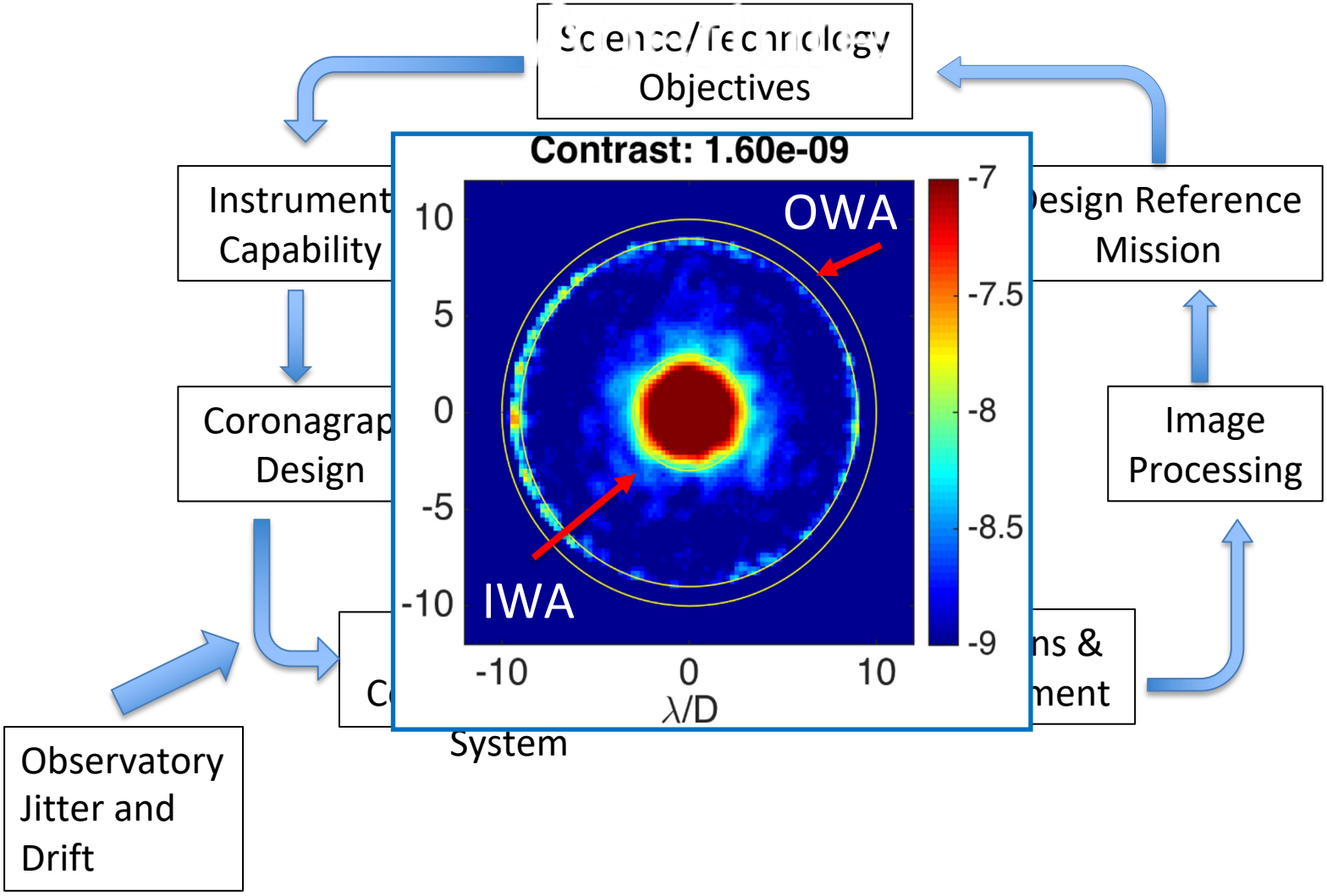
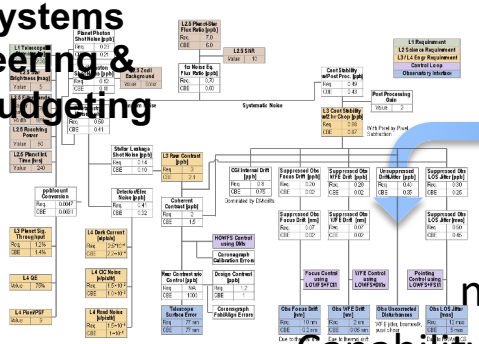


A Coronagraph is a System



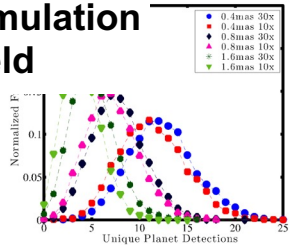
The Coronagraph on Roman as a Pathfinder

Full Systems Engineering & Error Budgeting



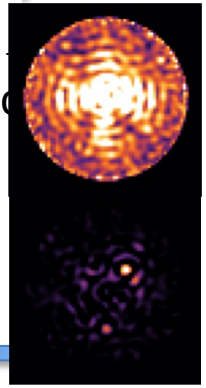
Science/Technology Objectives

Mission Simulation & Yield



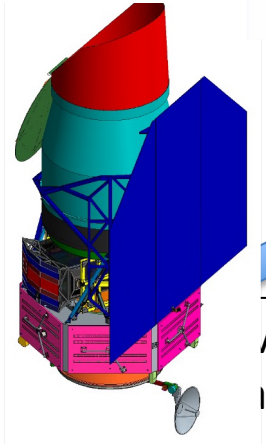
Design Reference Mission

Image Processing at Unprecedented Contrast Levels



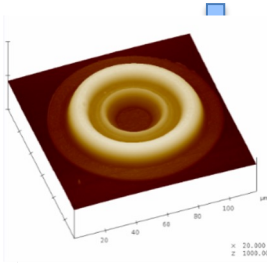
Proc

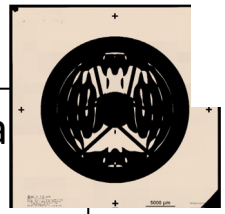
Stable Space Telescope &



Capability

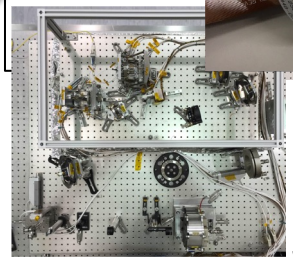
High Contrast Coronagraph Elements





First Use of Deformable

Wave



Autonomous Precision Wavefront Sensing & Control

Operations &

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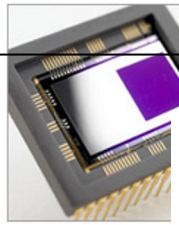


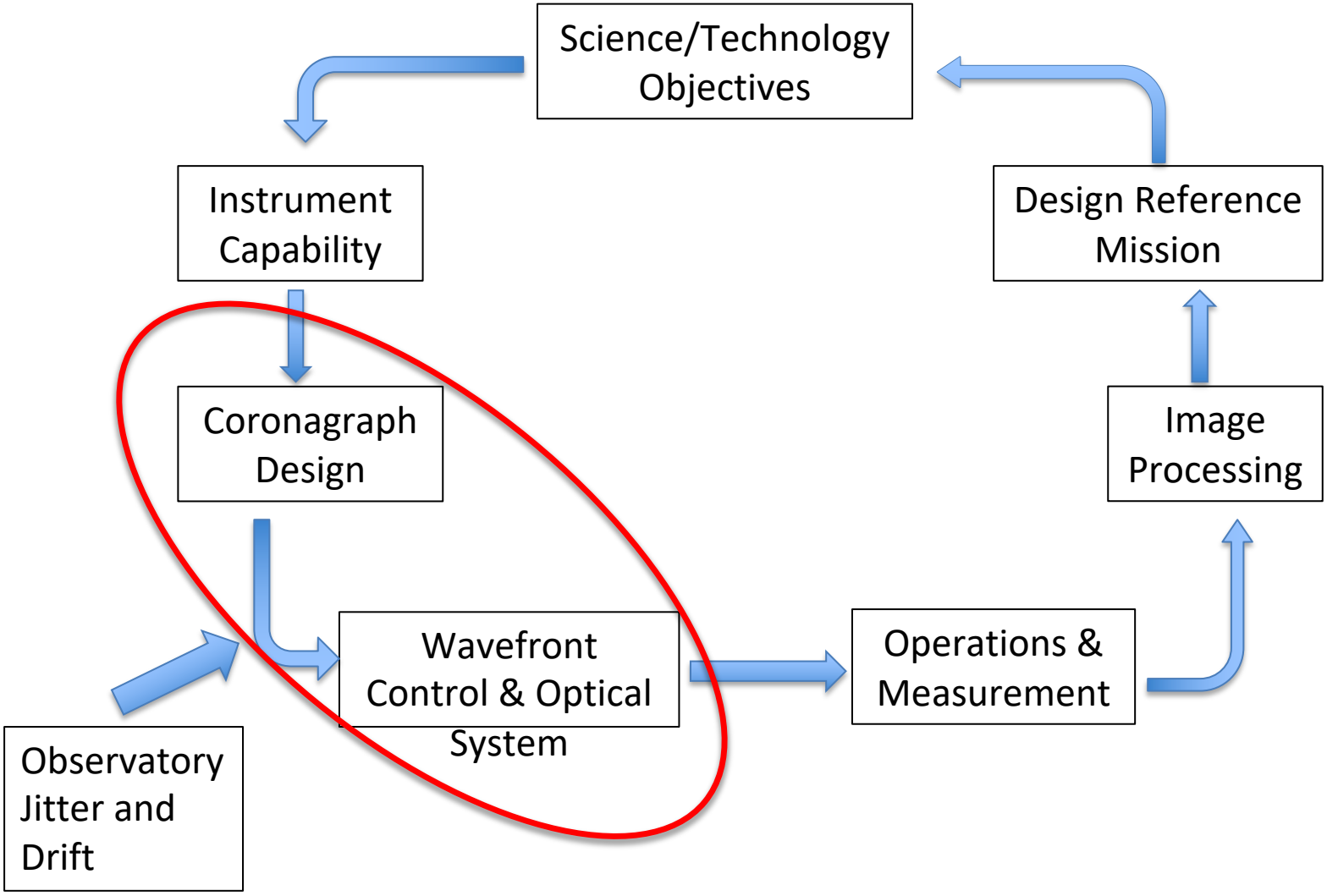
Ultra-low noise photon counting Visible Detectors

vatory

nd

Drift

A Coronagraph is a System

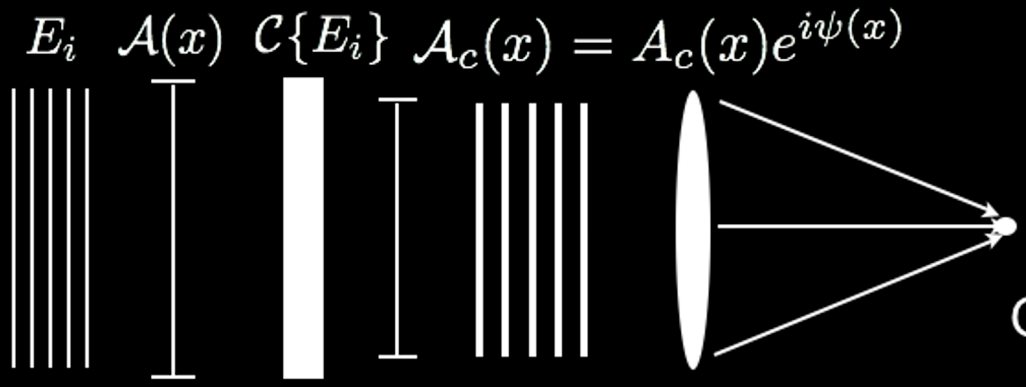


Coronagraph Metrics

- 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 light in the planet PSF to the nominal telescope PSF 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 aberrations.

Coronagraph performance also differs depending upon aperture (monolith vs. segmented, off-axis vs. on-axis)

Coronagraph Contrast



$$P_c(\omega) = \left|\mathcal{F}\left\{A_c(x)e^{i\psi(x)}\right\}\right|^2$$

On-Axis Point Spread Function

The Instrument Contrast Ratio (at a specific wavelength)

$$C_i = \frac{\int_{\Delta\Omega} P_c(\omega)d\omega}{\Delta\Omega P_o(0)} = \frac{\int_S |\mathcal{A}_c(x)|^2 dx}{\Delta\Omega A_o^2}\left[1 - \frac{\int_{\Delta C} P_c(\omega)d\omega}{\int_{-\infty}^{\infty} P_c(\omega)d\omega}\right]$$

Reduce the exit amplitude

Shift the energy (uncertainty principal)

Coronagraph Families

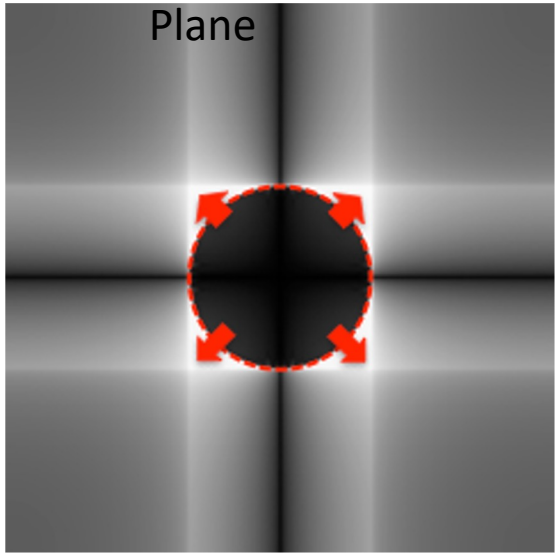
Image Plane

- Lyot & Bandlimited Lyot (Gemini, Keck, Hubble, Subaru, Palomar, VLT, JWST NICI, WFIRST)
- 4 Quadrant Phase Mask (JWST MIRI, VLT, LBT)
- Optical Vortex (Palomar, VLT, LBT), AIC, VNC and other nullers

Pupil Plane

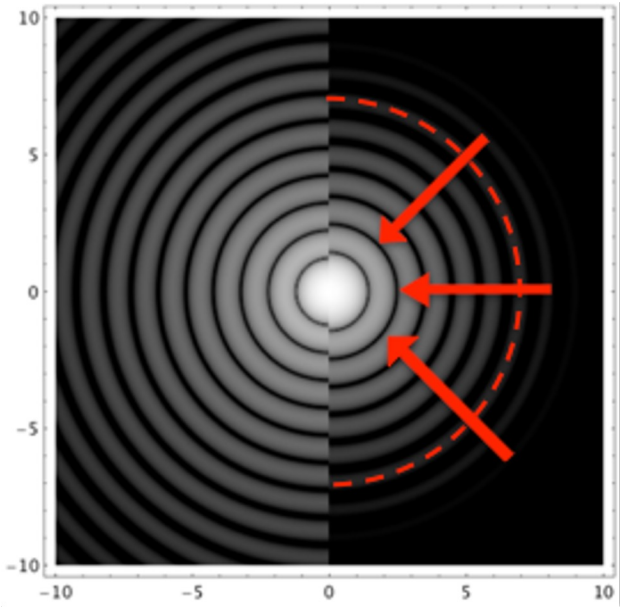
- Apodized pupils(VLT)
- Shaped pupils (Subaru, Roman)
- Pupil remappers (PIAA) (Subaru)
- Apodized phase plate (MMT, Magellan, VLT)

Lyot Plane

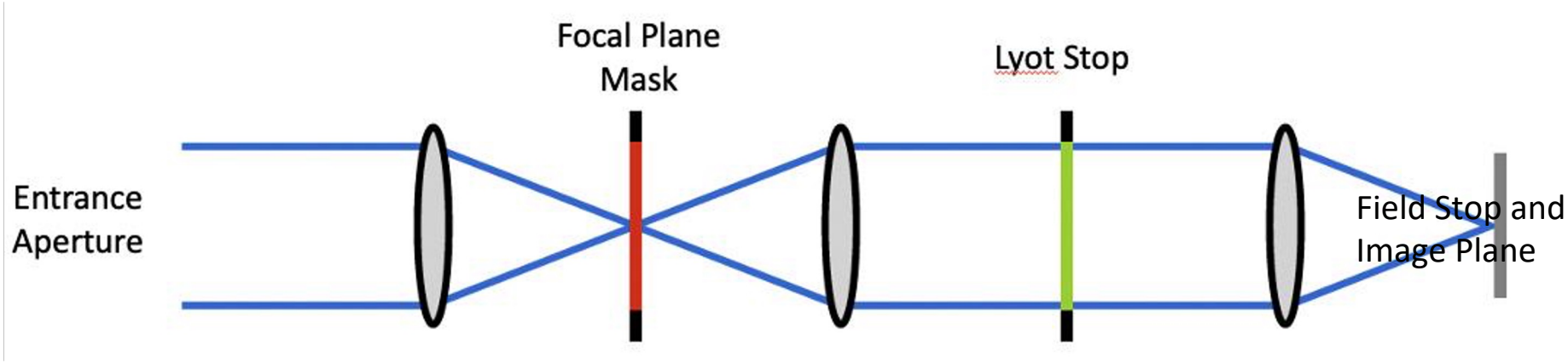


APLC, SPLC (GPI, VLT/SPHERE, Palomar)

Image Plane



A Generic Coronagraph

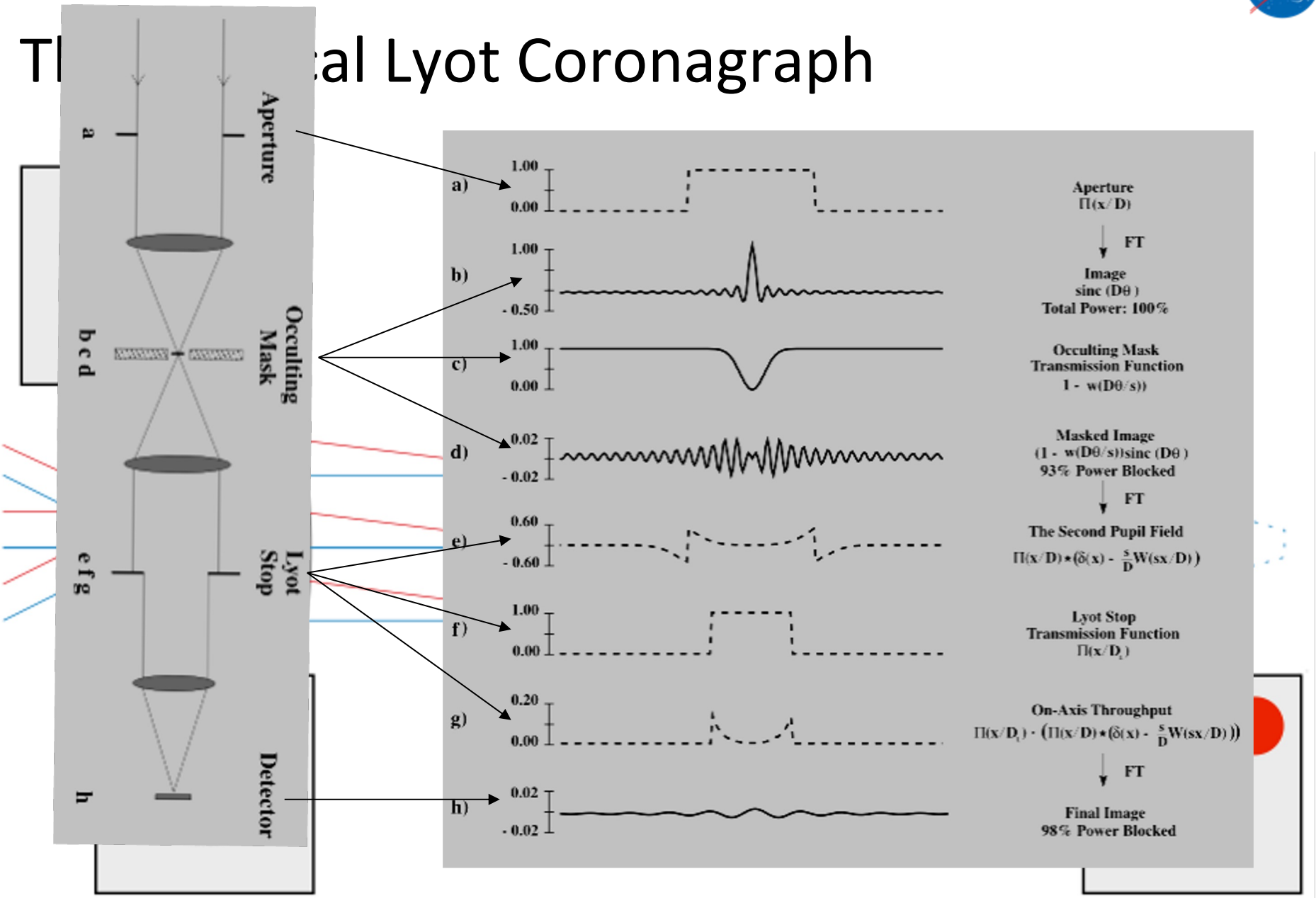


All coronagraphs work by modifying amplitude or phase at the entrance aperture, amplitude or phase at the first focal plane, amplitude or phase at the Lyot plane, or some combination of them.

All are based on using properties of the Fourier Transform.

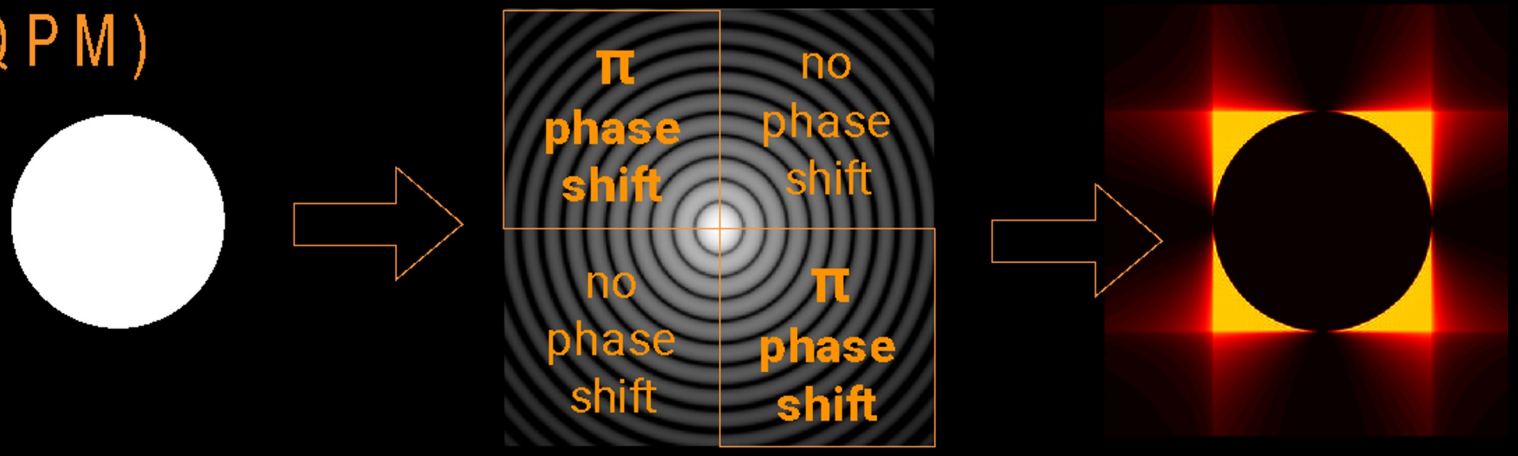
Mennesson et al.

Th cal Lyot Coronagraph

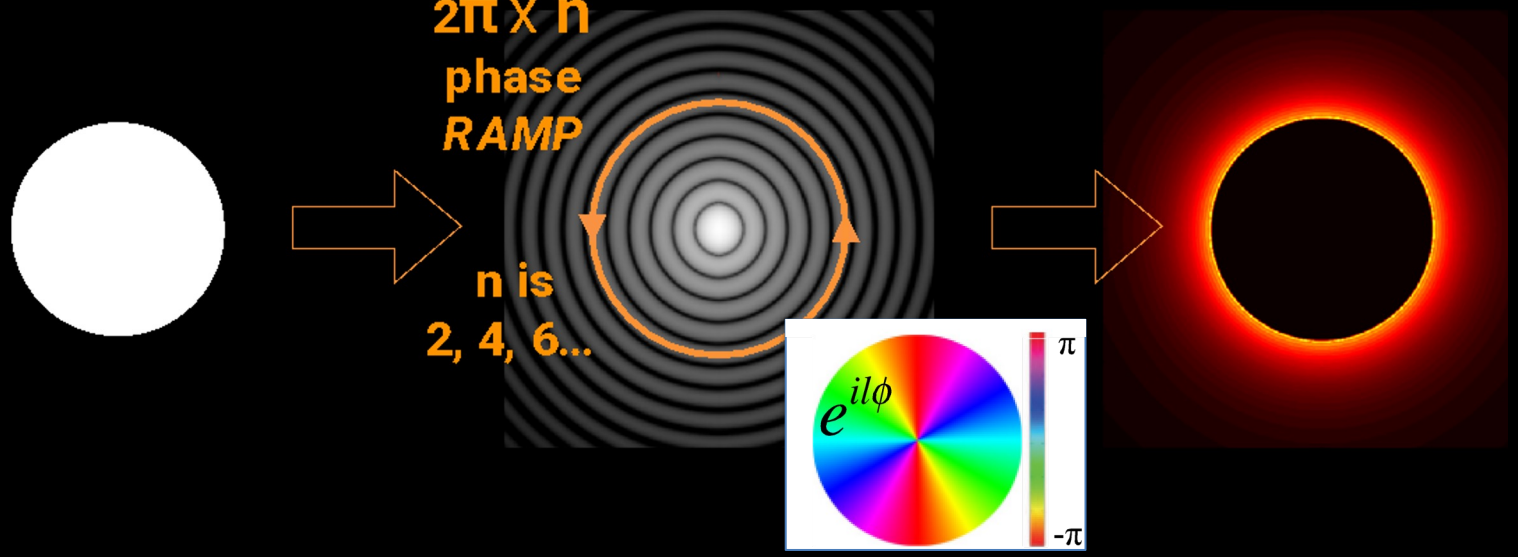


Courtesy Matt Kenworthy,University of Leiden

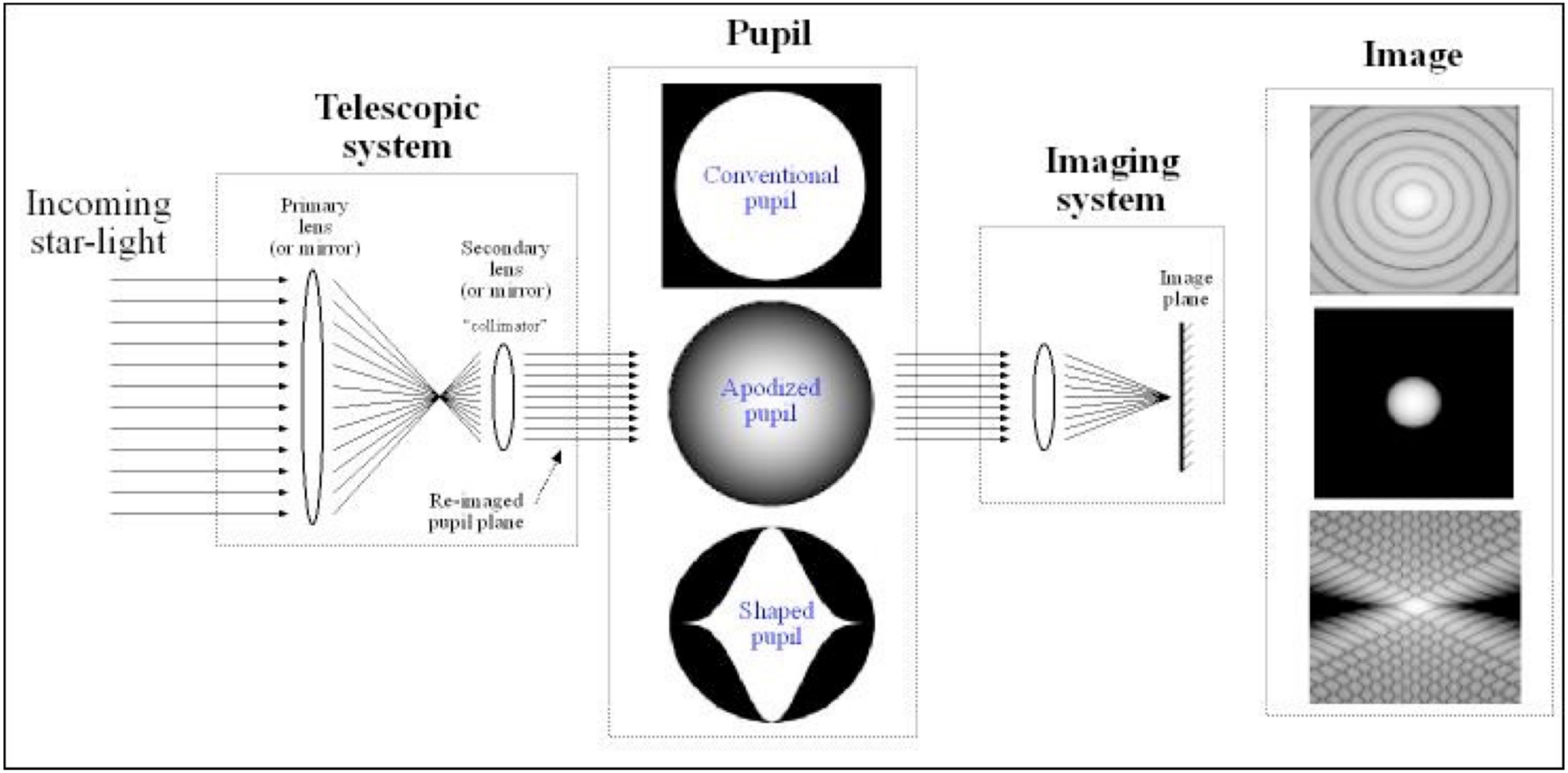
Four-Quadrant Phase Mask coronagraph (Rouan) (4QPM)



Vector vortex coronagraph (Mawet)



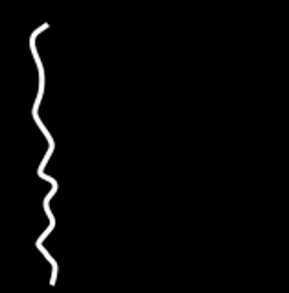
A Shaped Pupil



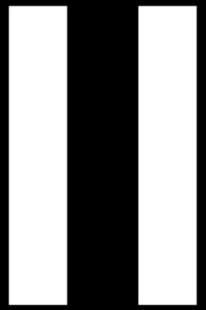
But . . .

Wavefront Aberrations

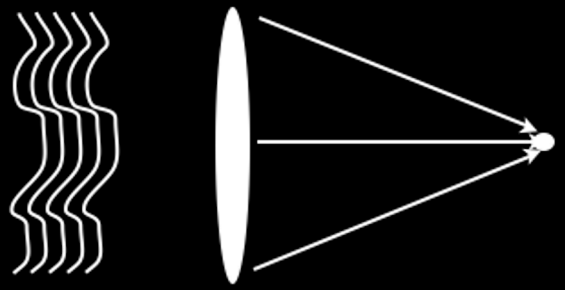
Atmospheric distortions and imperfect optics degrade contrast



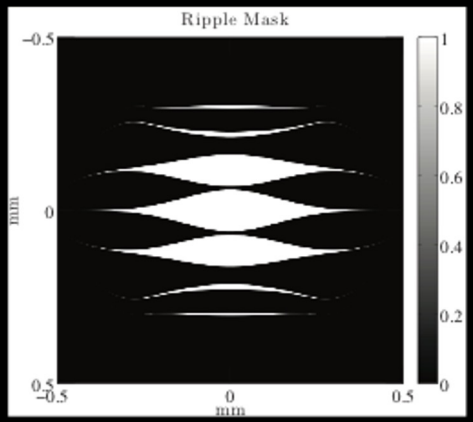
$E_i(1+\epsilon(x))e^{i\phi_a(x)}$

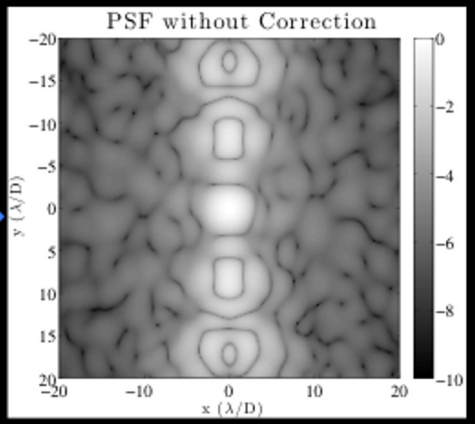


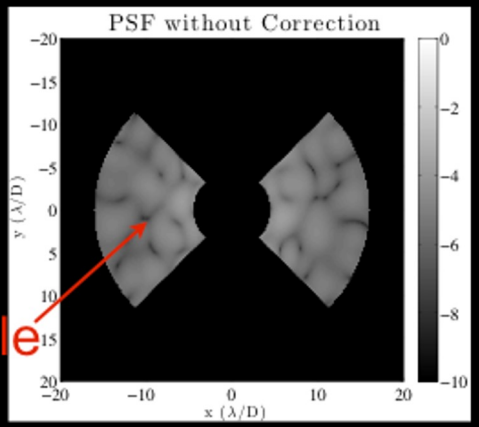
Coronagraph



$A_o(x)e^{i\phi(x)}$

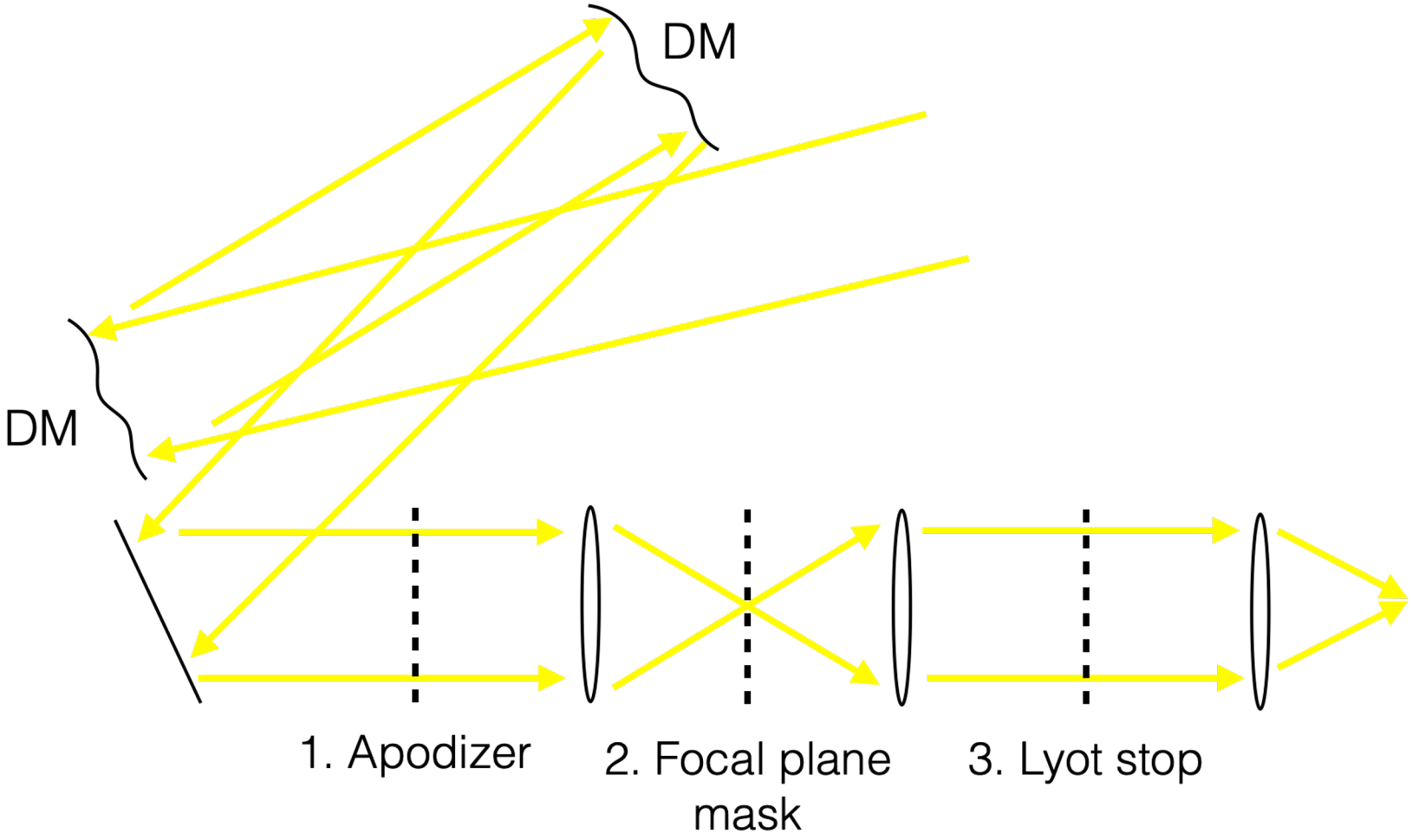






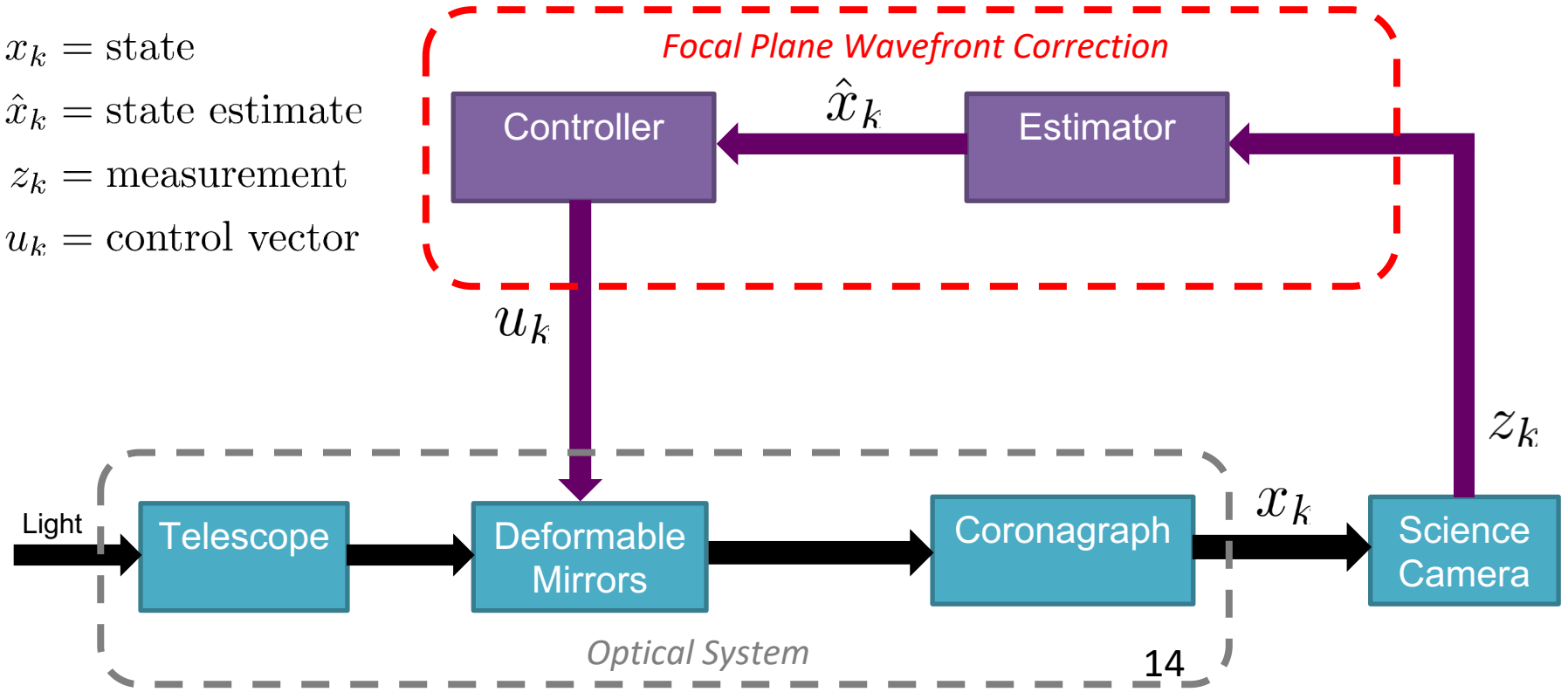
Aberrations significantly degrade contrast: 10^{10} ~10^5

2 DMs for Full Dark Hole Correction

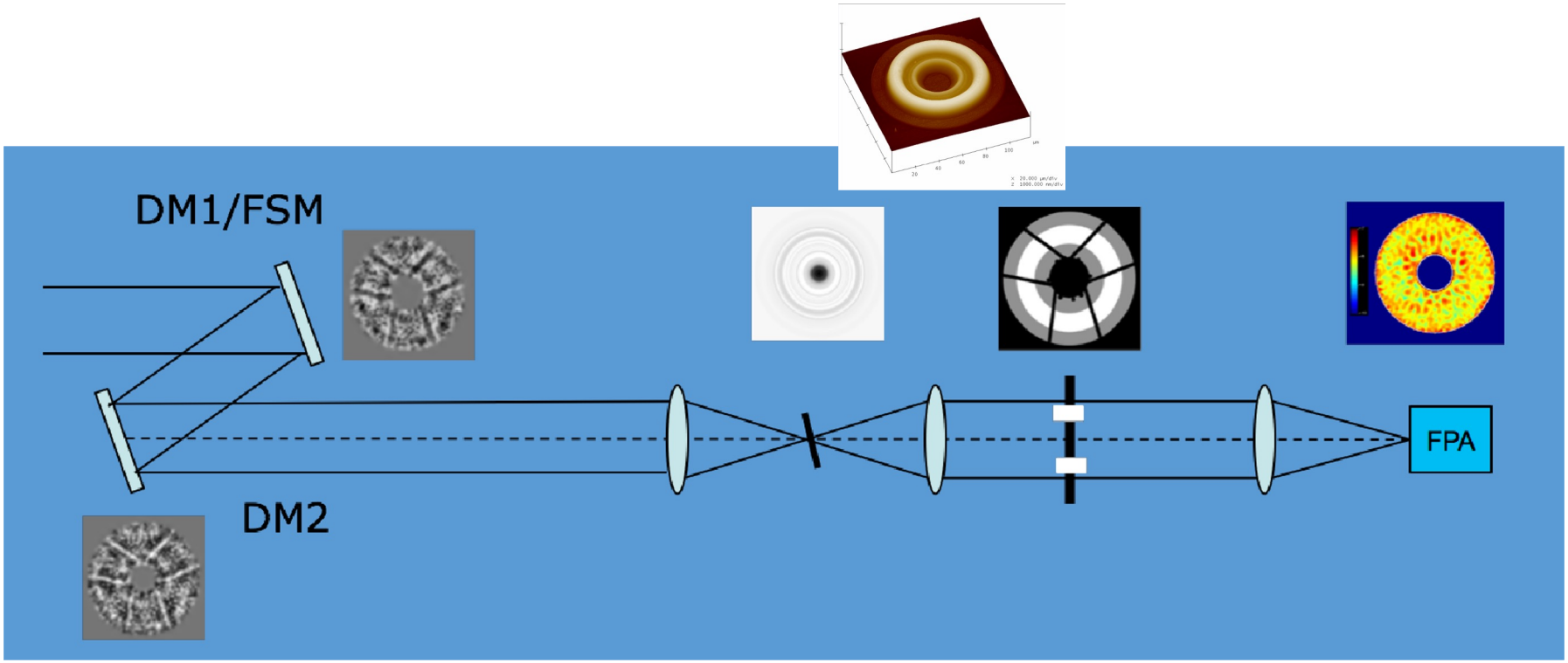


High-Order Wavefront Sensing and Control (HOWFS)

- To correct quasi-static speckles:
  - Estimate and control starlight directly in **focal plane.**
  - Use **science camera as WFS** to estimate all aberrations.
- **Estimation + Control** (= Correction) is **iterative:**
  - Model errors, estimation errors, nonlinearities



Hybrid Lyot (Roman Coronagraph)

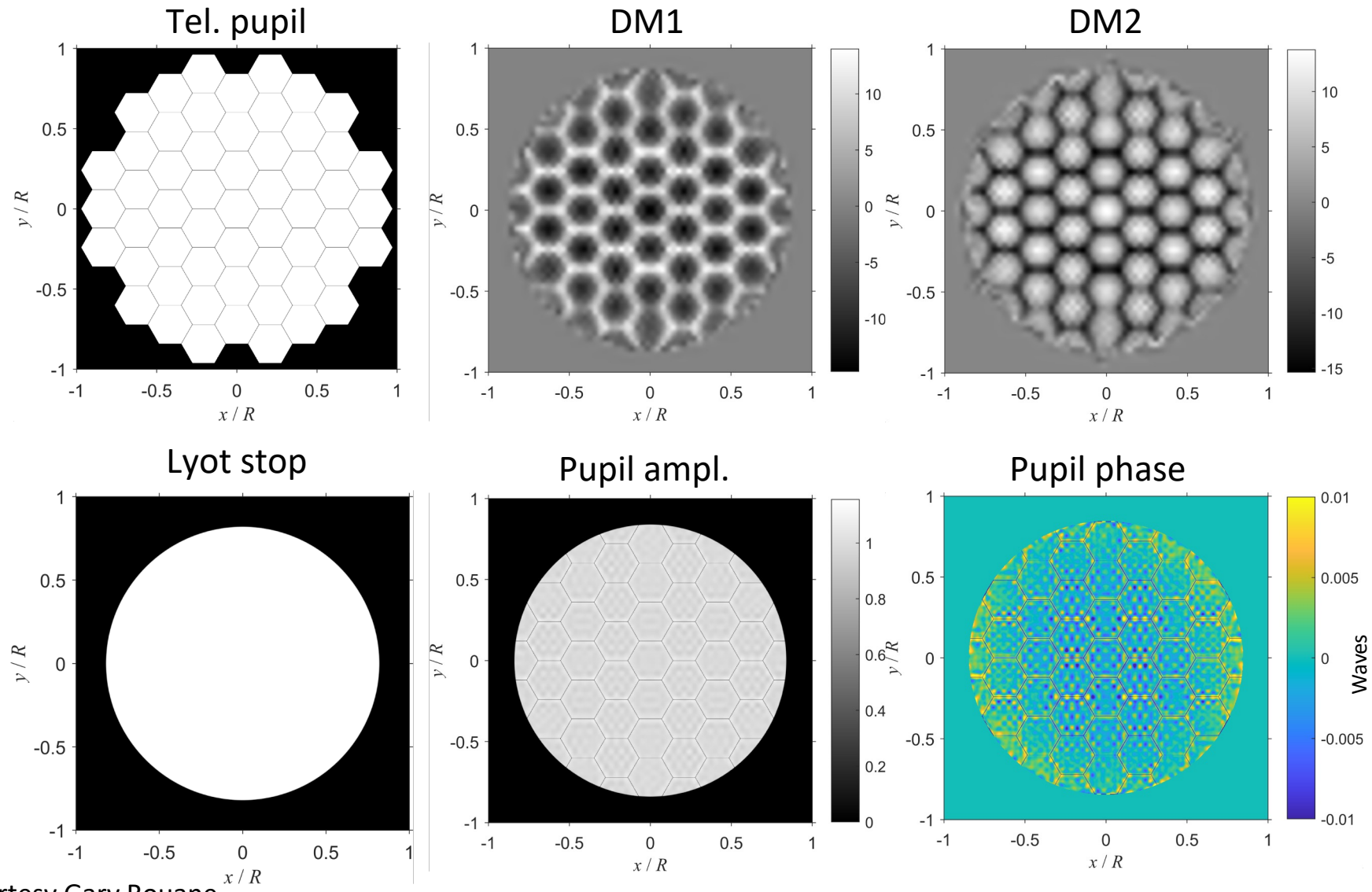


Increases throughput, maps out obstructions, and broadens bandwidth from classical Lyot.

Shaped Pupil Lyot Coronagraph for Roman

From Neil Zimmerman

Segmented Pupil
DM Apodized Vortex Coronagraph



Courtesy Gary Rouane.

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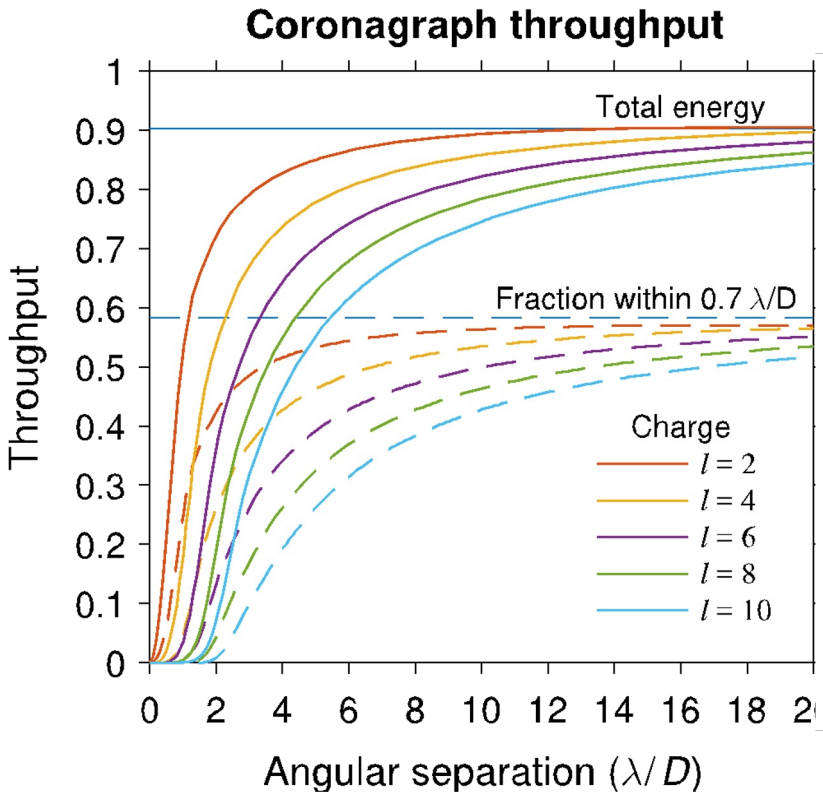
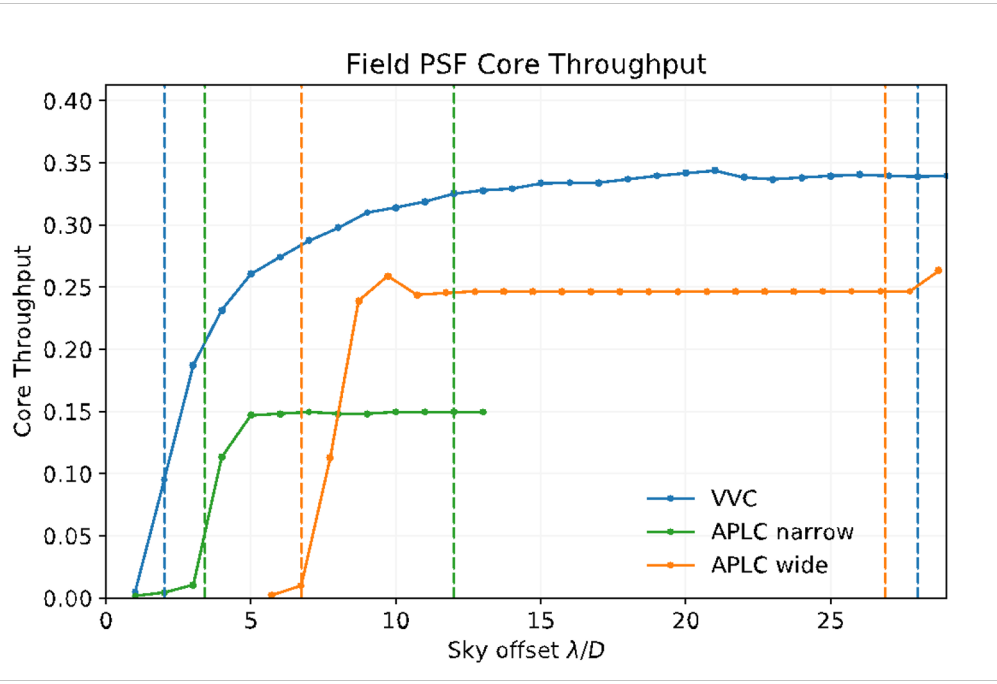
- Bandwidth: The wavelengths at which high contrast is achieved.
- Sensitivity: The degree to which contrast is degraded in the presence of aberrations.

Coronagraph performance also differs depending upon aperture (monolith vs. segmented, off-axis vs. on-axis)

Ex.: VVC and APLC Throughput



Ruane et al.



Juanola-Parramon et al.

Performance – Sensitivity

Coronagraphs differ in their sensitivity to optical aberrations and stellar diameter

Dynamic aberrations

Fast low-order variations (e.g., tip/tilt, jitter)

Low-order wavefront sensing and control (LOWFS)

Slow, quasi-static aberrations (actuator drift, thermal creep)

ements on observatory

See Laurent Pueyo's Talk

Static aberration

1. Low-order aberrations – **global** Zernikes

1. Segment-level aberrations – **segment** Zernikes
   a) Uniform segments
   b) Randomized segments

1. Mid-spatial frequency aberrations - **PSD** errors

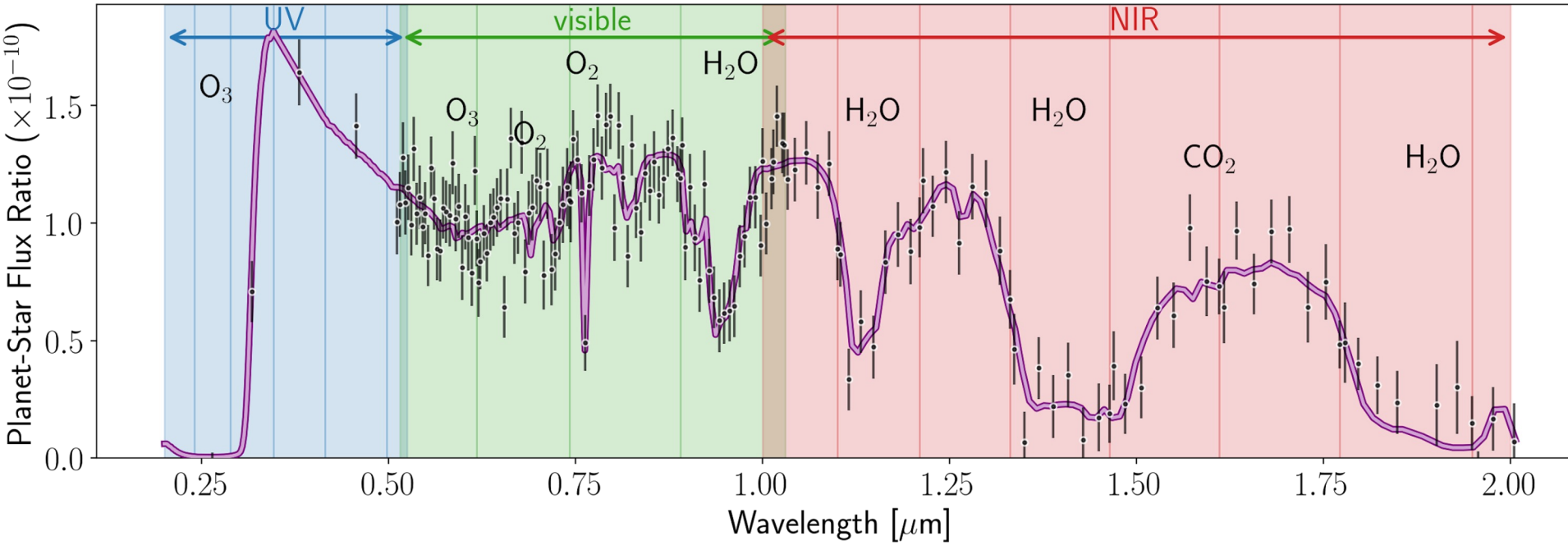
1. Lateral beam shear

1. Stellar diameter

Juanola-Parramon et al.

Performance – Bandwidth

The LUVOIR Report



Coronagraph must suppress starlight over bands from 10% to 20% for efficient spectroscopy at varying resolution.

Spectral resolution possible is determined by throughput and properties of detector (read noise, dark current, cosmic rays, stability) and type of spectrometer (IFS vs. Pointed).

Performance – Bandwidth

Coronagraphs differ in degradation with bandwidth.

Pupil based coronagraphs generally insensitive to bandwidth but lose iwa.

Focal plane coronagraphs generally have limited bandwidth due to spot size, though can be optimized via phase and amplitude variation. (e.g., HLC)

Focal plane phase varying coronagraphs are wavelength independent if broadband spot can be manufactured. (e.g., VVC)

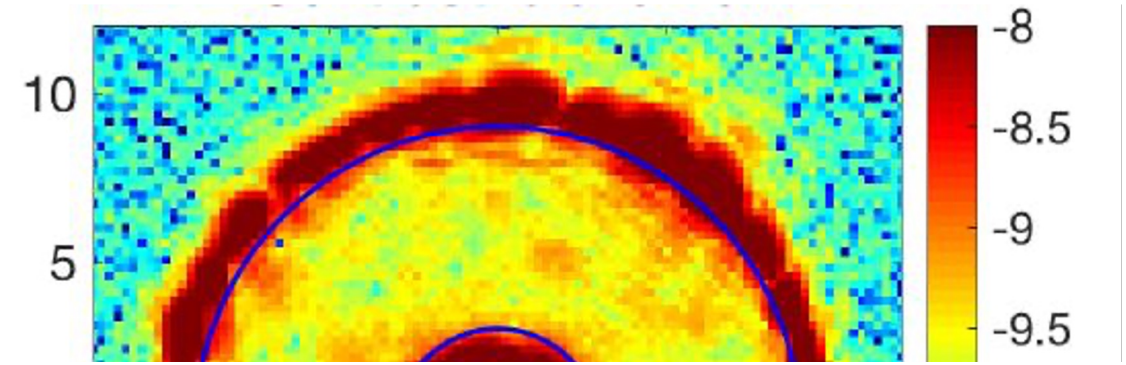
Main limiter of bandwidth is wavefront control via DMs.

Pueyo et al. 2007 show that in a multi-optic system, phase and amplitude errors can be written in a power series in $1/\lambda$. A single DM corrects $1/\lambda$ phase. Two DMs correct for lambda independent amplitude and $1/\lambda$ phase. The remaining terms set the bandwidth of the correction.

Closed Loop Laboratory Example

Classical Lyot Coronagraph

10% band centered at 550 nm



IWA (3 λ/D) set by coronagraph design, OWA (8 λ/D) set by actuators on DM.

See Bertrand Mennesson's and Garreth Ruane's talks

Average Contrast is 3.8e-10.

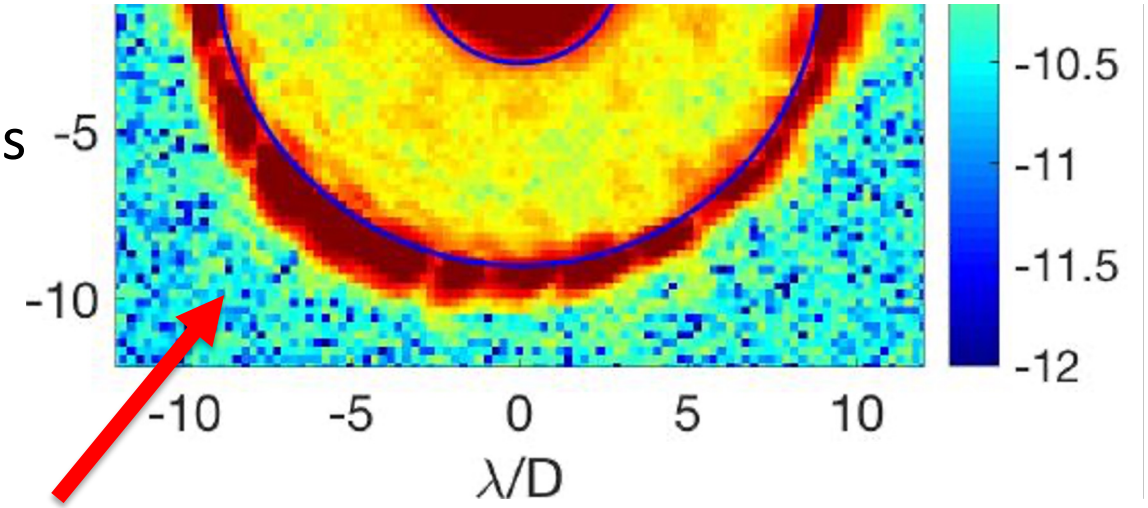
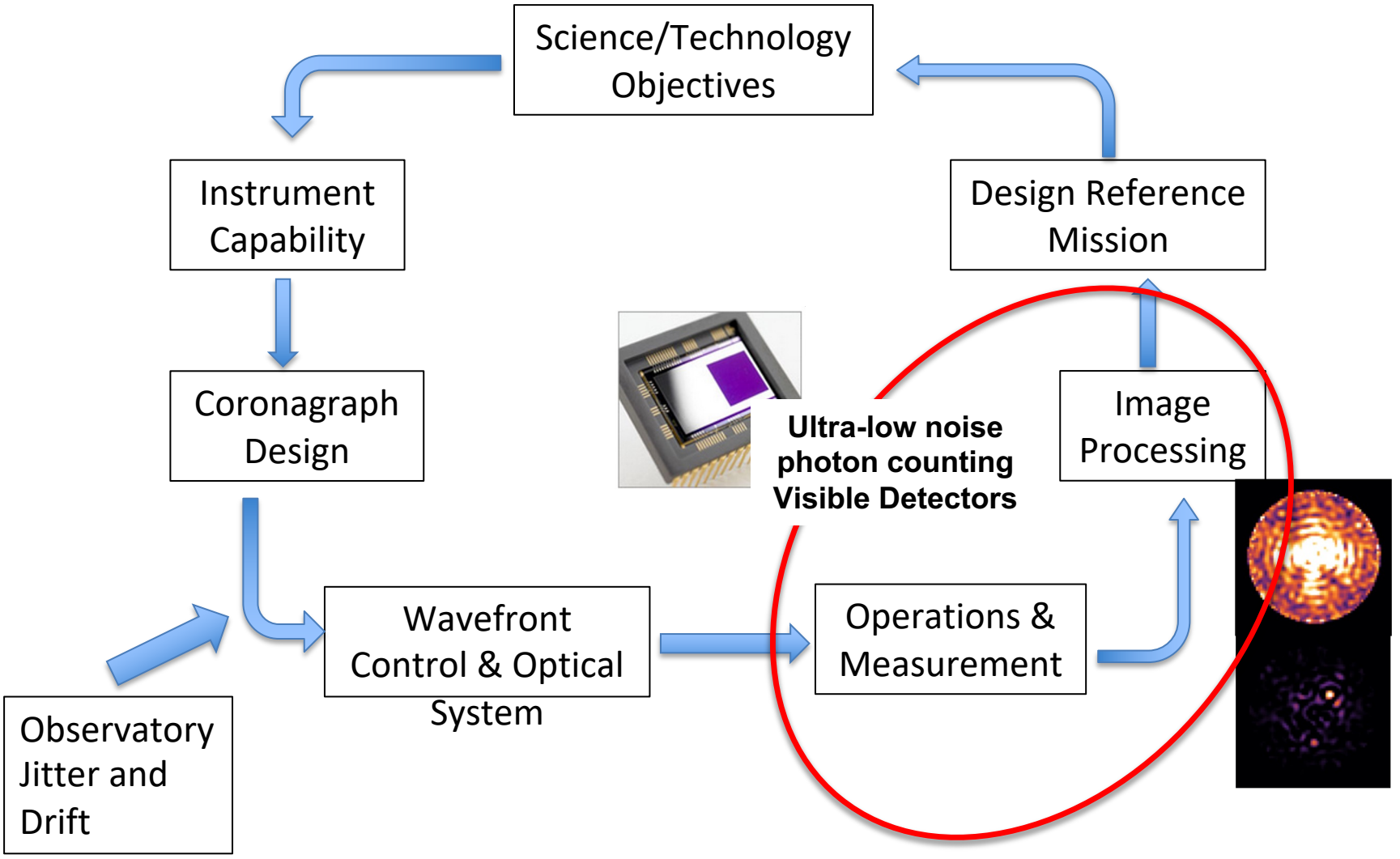


Image is blocked by a focal plane stop outside the OWA.

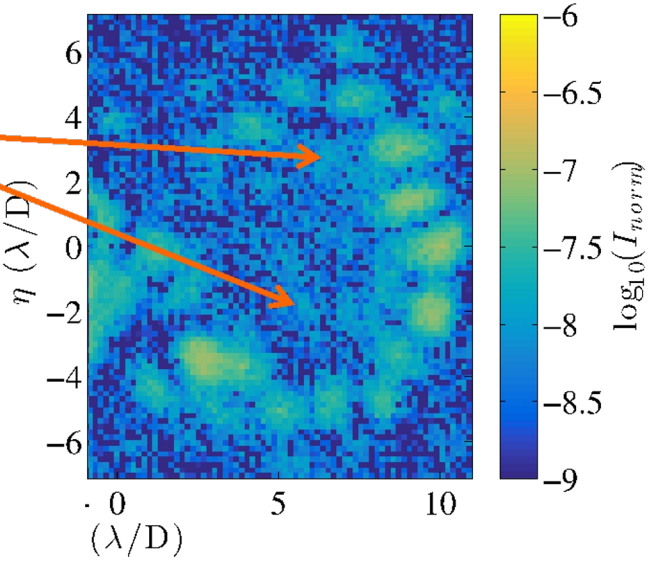
Seo, B-J. et al. 2019



See my colloquium from last week and Chris Stark's talk.

How is planet differentiated from residual speckles?

Planets or speckles?



JPL HCIT lab data

Subtract the remaining PSF to remove speckles and reveal planet:

1. Reference Differential Imaging (RDI and KLIP)
2. Angular Differential Imaging (ADI)
3. Spectral Differential Imaging (SDI)
4. Coherent Differential Imaging (CDI)

Reference Differential Imaging

RDI: Remove starlight by subtracting a template PSF

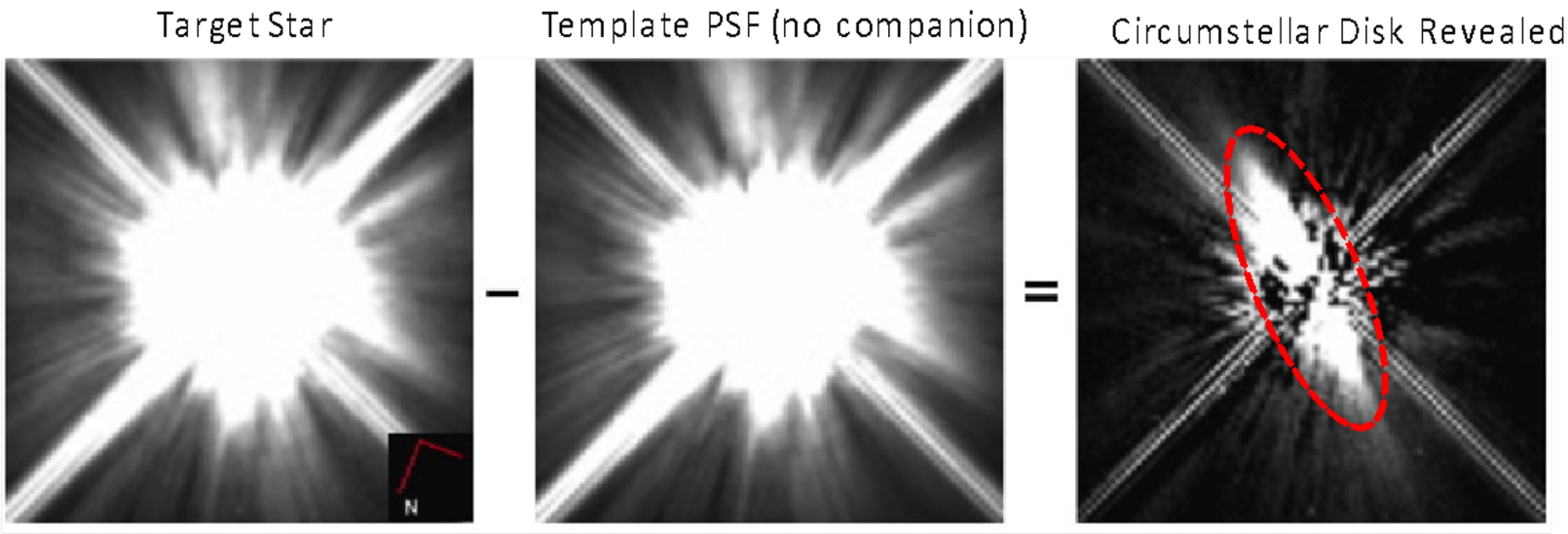


Image Credit: archive.stsci.edu/prepds/laplace/

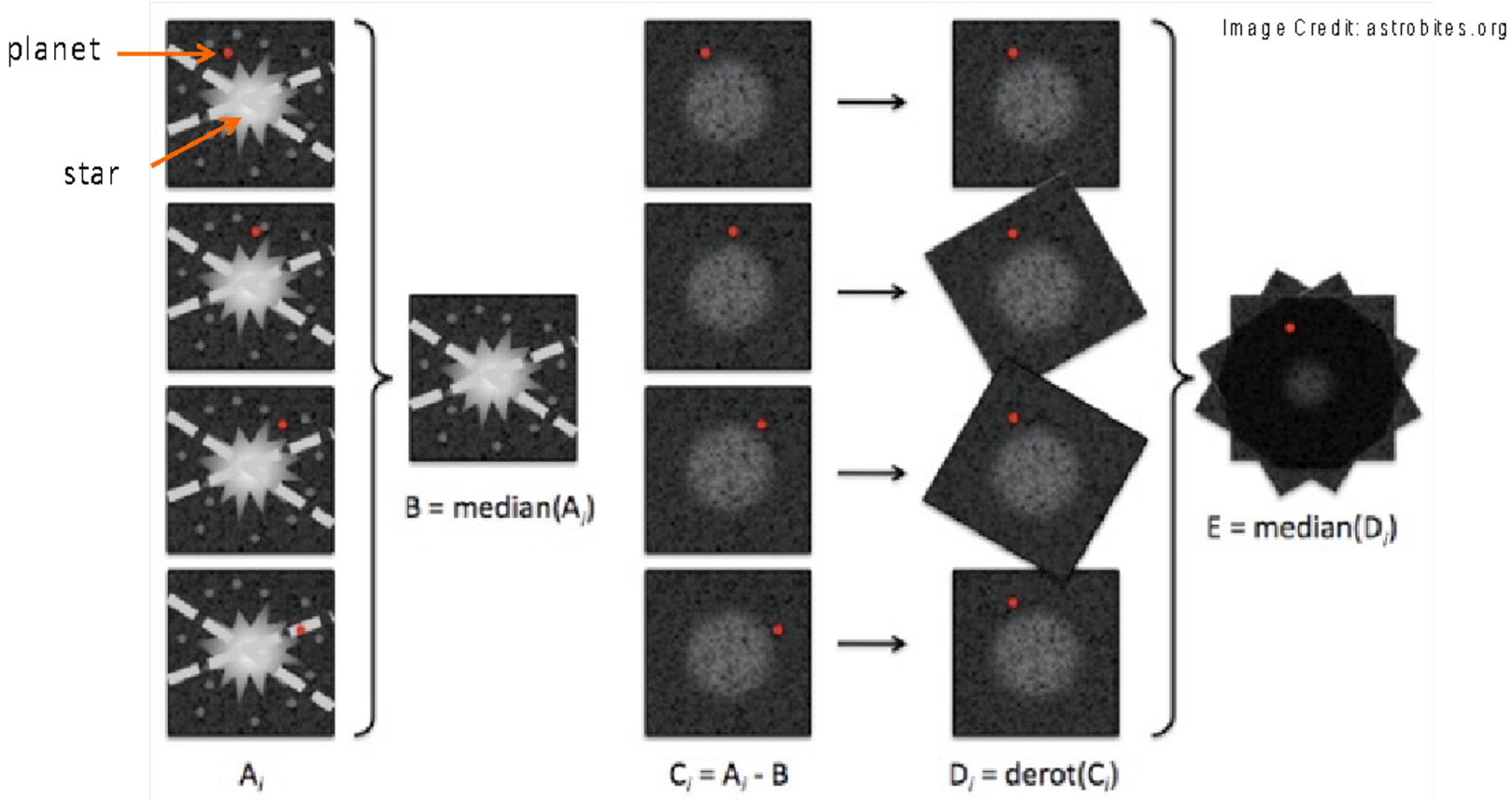
Two variations:

- **PSF Subtraction** (simplest case): Template PSF is directly measured from 1 star
- **Principle Component Analysis** (PCA): Template PSF is a "Franken-image" built from similar parts of many PSFs

Lafrenière + 2007
Soummer 2012

Angular Differential Imaging

ADI: Take advantage of planet moving w.r.t. stellar speckles during telescope/sky rotation.

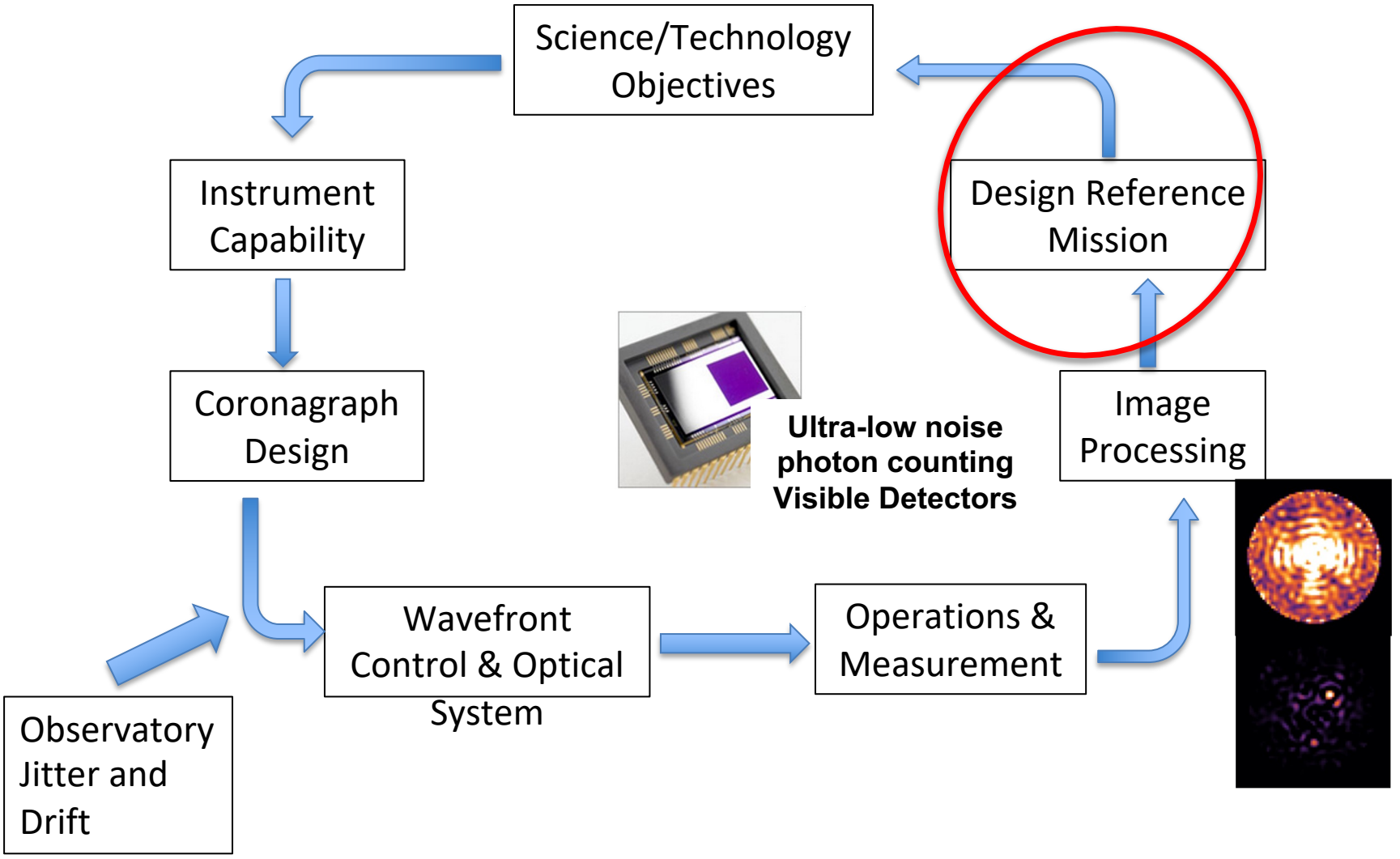


1. Take images at different orientations.

2. Subtract median from all images.

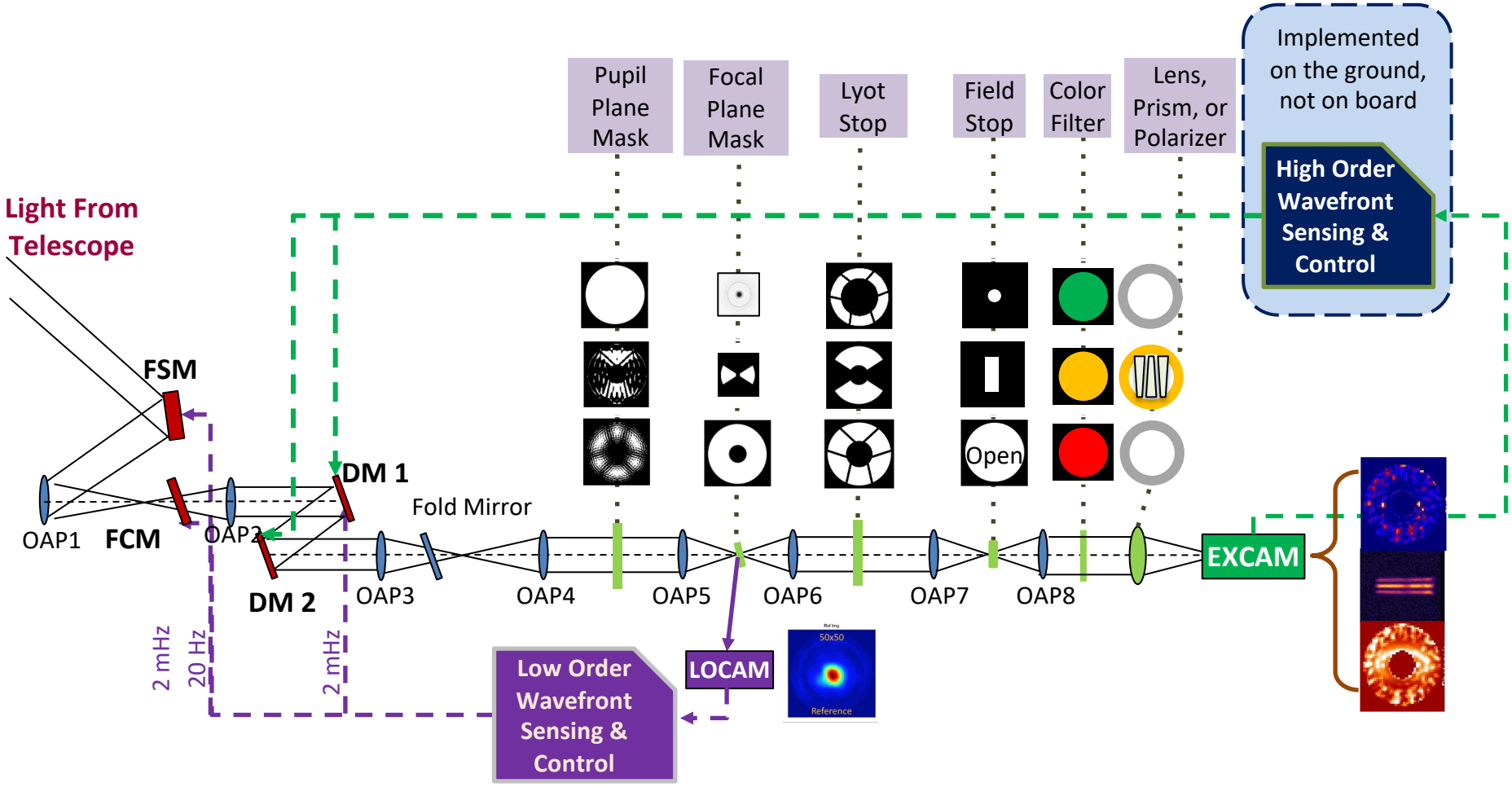
3. Derotate images.

4. Combine images.



See my colloquium from last week and Chris Stark's talk.

Putting it all together



The Roman Coronagraph System