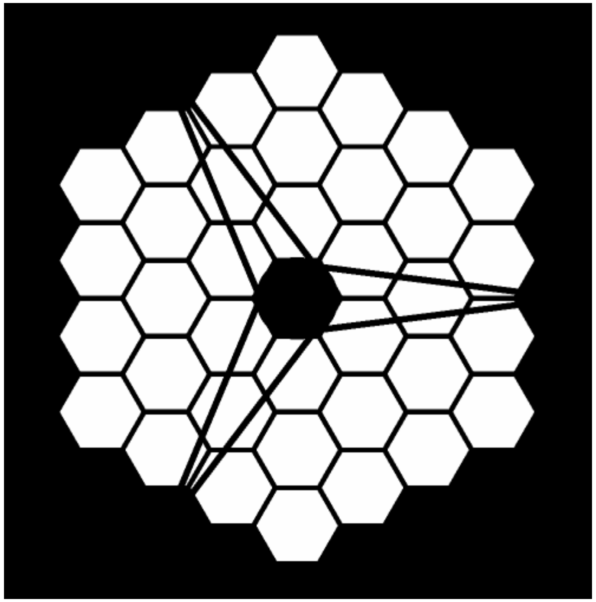
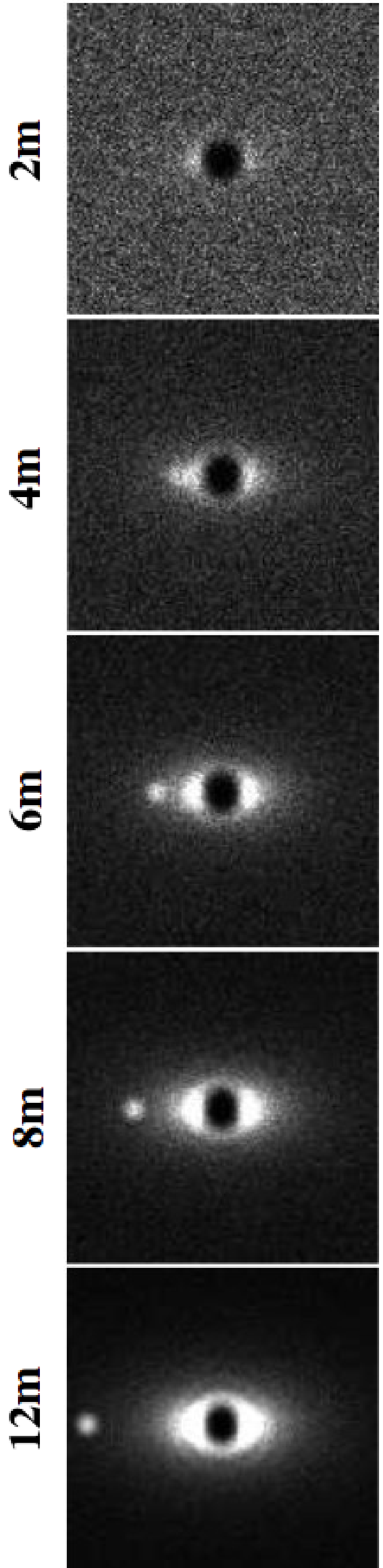
Internal Coronagraphs for Large Space Telescopes: Scientific Opportunities and Technical Challenges



Olivier Guyon

University of Arizona
Subaru Telescope / NAOJ
JPL

Why big apertures ?



Exoplanet imaging mission science return increases <u>very quickly</u> with aperture

<u>Efficiency & Yield (see C. Stark presentation)</u>

- Number of IWA-accessible planets goes as D^3
- Exposure time required to reach given SNR goes as D^{-4} for most low-mass planets (zodi+exozodi → background-limited detection)

<u>Characterization</u>

- Access to longer wavelength spectroscopy, $\lambda_{max} \sim D$
- Light can be sliced in multiple bins: spectral resolution, time domain, polarization
- Better astrometry → better orbits, dynamical masses
- Resolving (time-variable) structures in exozodi

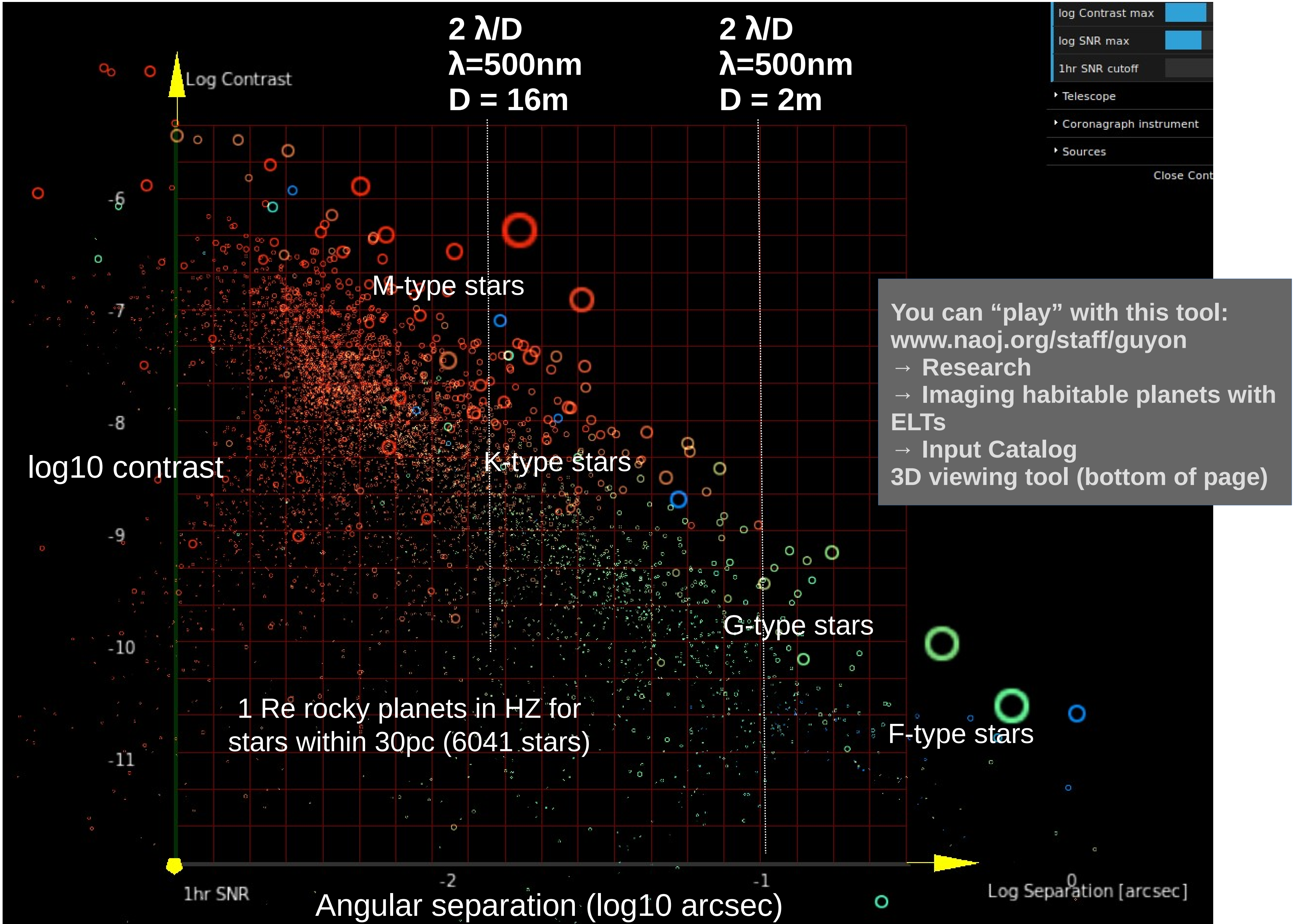
<u>Data quality</u>

- Higher angular resolution → less confusion between multiple planets, exozodi clumps
- More light → better PSF calibration

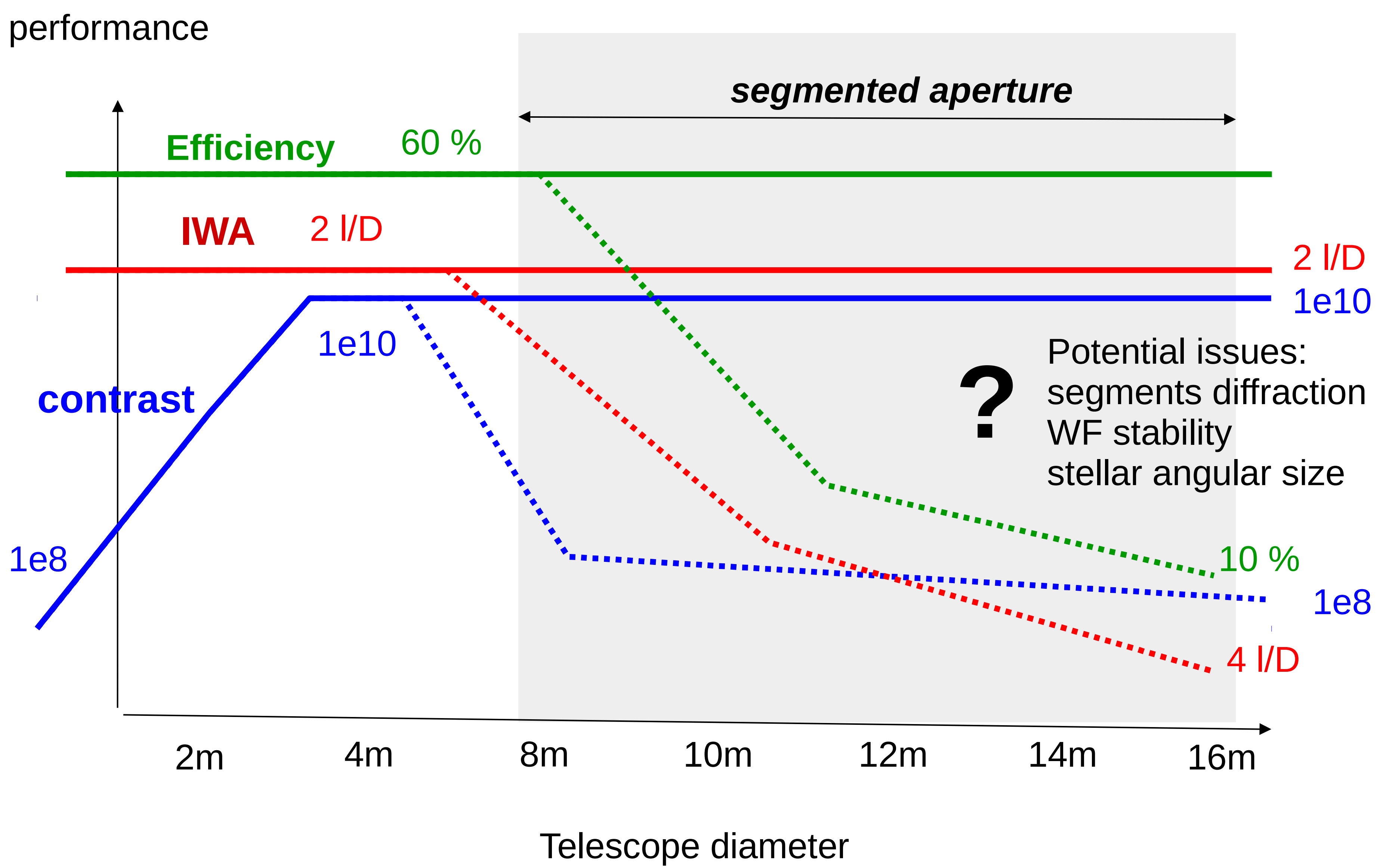
<u>Diversity</u>

- Larger aperture allows habitable planets to be observed around a wider range of stellar types

Large aperture + high contrast → habitable planets can be imaged around a wide range of spectral types



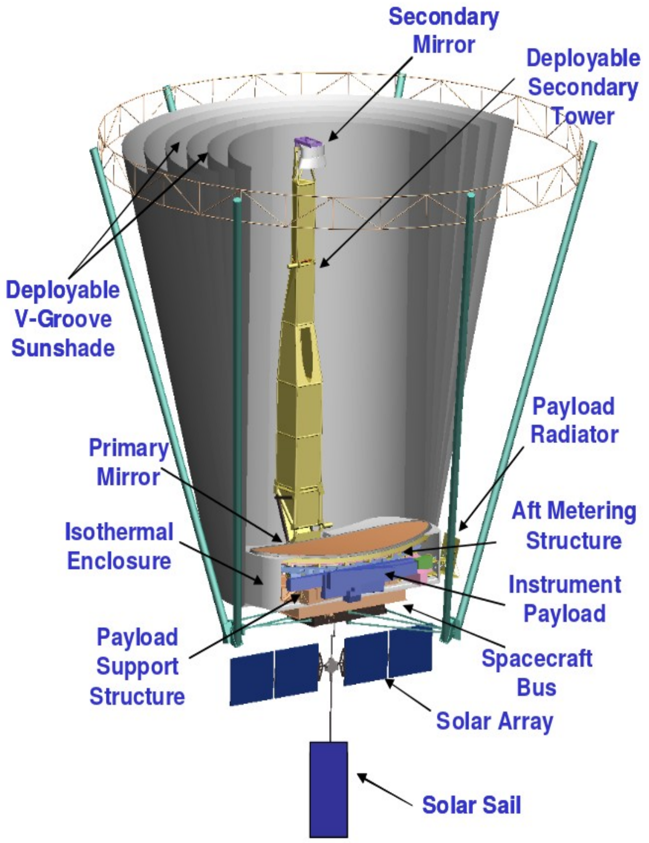
Science vs. aperture: how does performance scale with aperture ?



HDST study (report coming soon) highest priority tech challenges

Challenge	Current Status	Goal 2019 (pre decadal)	Goal 2024 (phase A)
Starlight suppression	Developing	TRL 4	TRL 5-6
Coronagraphy w/ segmented apertures	Developing	TRL 4	TRL 5-6
Ultra-stability and Wavefront Control	TRL 3-4	TRL 5	TRL 5-6
Mirrors	Substrate: TRL 4, System: TRL 3	TRL 5	TRL 5-6
Starshade	Developing	TRL 3-4	TRL 4-5
Detectors	TRL 4-6	TRL 6	TRL 6-7

History of coronagraphs on “unfriendly” apertures

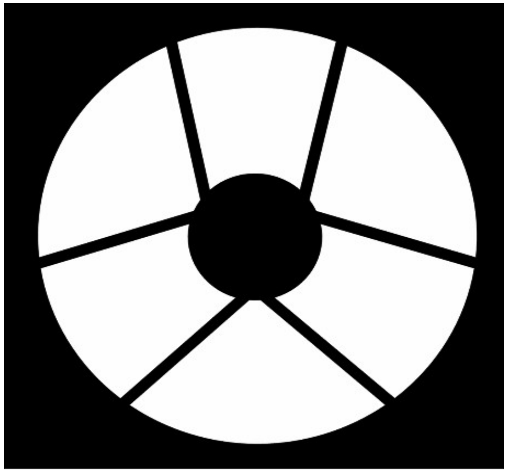


The dark ages (~ 2000 → 2012)
“Directly imaging habitable planets REQUIRES a monolithic unobstructed telescope”
→ TPF-C and smaller mission concept studies use off-axis telescopes
A few ideas for use of centrally obscured apertures emerge, but receive little attention

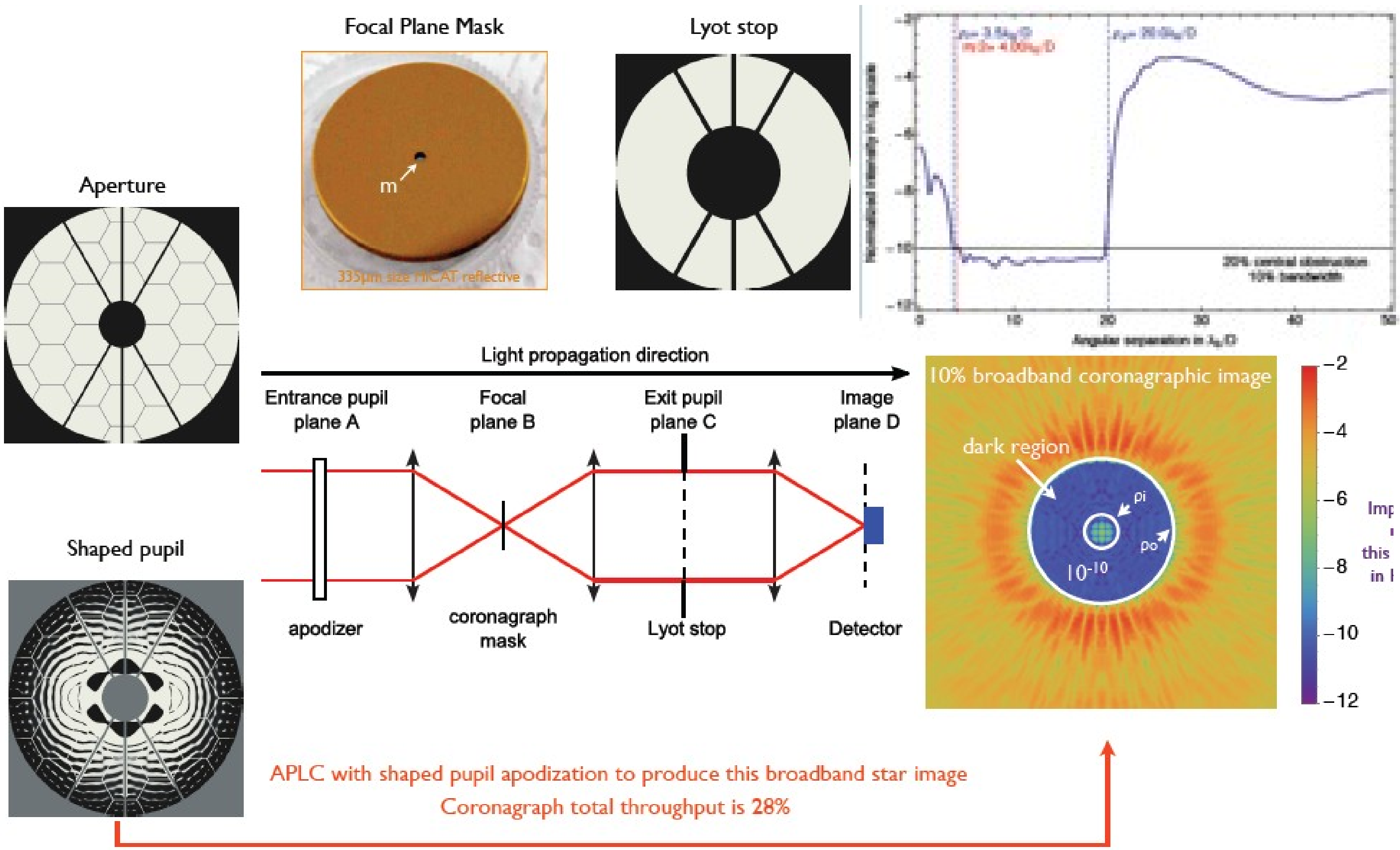
2012, The AFTA challenge: Designing a coronagraph for a centrally obscured aperture becomes a survival issue
→ within a very short time, 3 credible options emerge (SPC, HLC, PIAACMC)

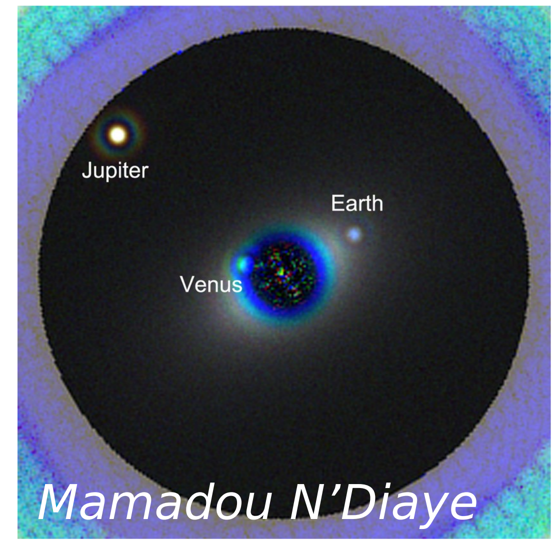
BUT, it appears that adapting coronagraphs to centrally obscured aperture comes at a high performance cost:
- SPC further looses throughput due to spiders and central obscuration
- HLC requires large DM stroke and undersized Lyot stop to cancel light diffracted by spiders → efficiency loss

→ risk of poor performance on segmented apertures ?



Apodized Pupil Lyot Coronagraph (APLC) is compatible with segmented apertures

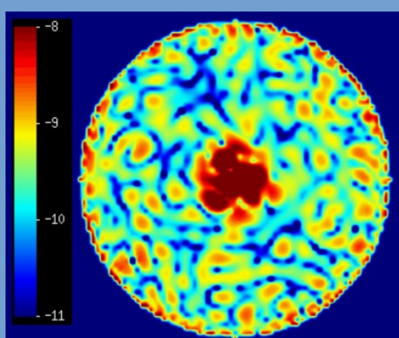




Simulated visible light image of a solar system twin at 13 pc

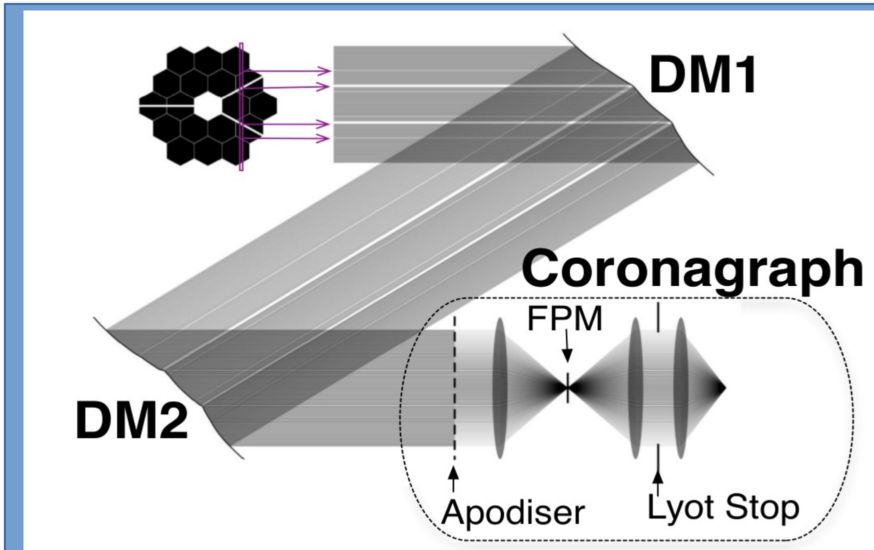
Combines pupil binary apodization and opaque focal plane mask
IWA = 3.6 l/D, contrast ~1e-10 in broadband
28% throughput is similar to WFIRST-AFTA

Wavefront control mitigates diffracted light by segments



WFIRST-AFTA HLC simulated image (J. Krist, JPL)

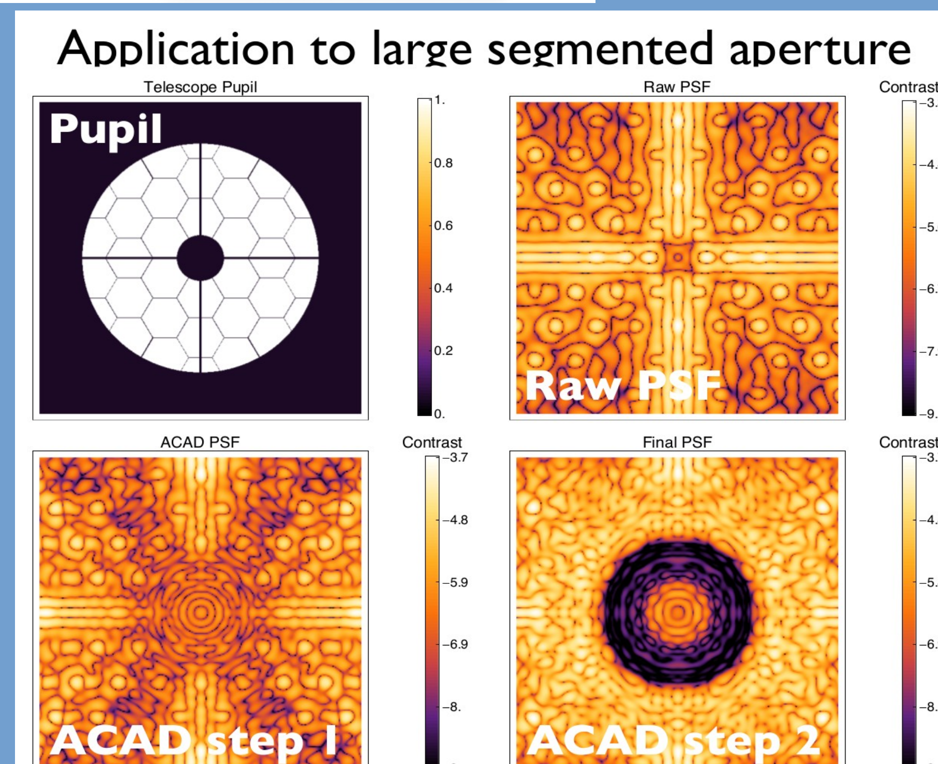
HLC uses two deformable mirrors to cancel diffraction by WFIRST telescope spiders by several orders of magnitude



ACAD generalizes this approach to segmented apertures

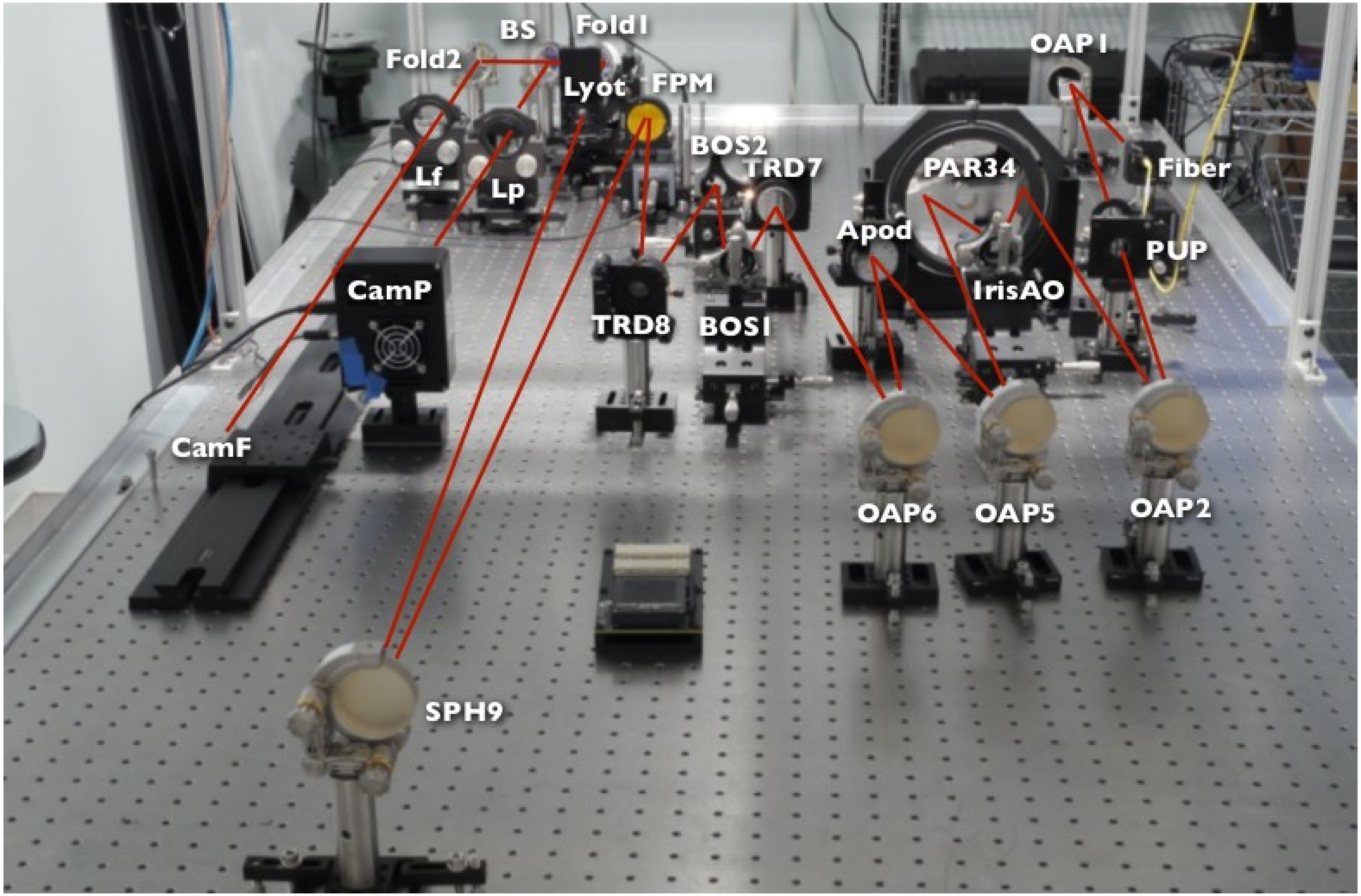
Several orders of magnitude gain in contrast

Pueyo & Norman 2013



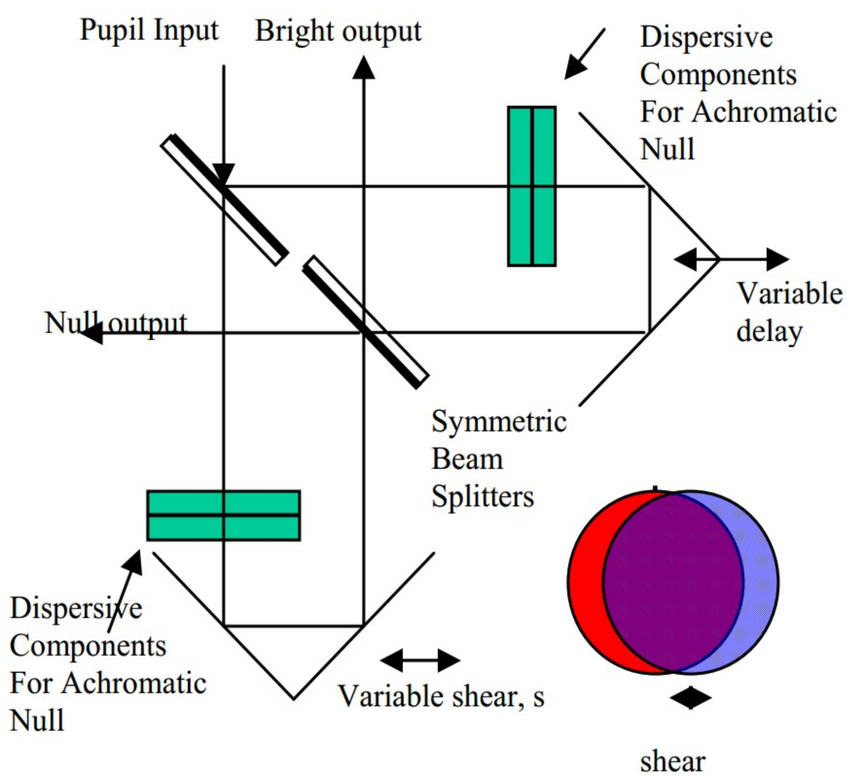
Limitations: DM stroke, some efficiency loss, limited wavelength coverage (10-20% ?)

Lab efforts for WFC/coronagraphy on segmented apertures at Univ. of Arizona and Space Telescope



Space Telescope Science Institute lab

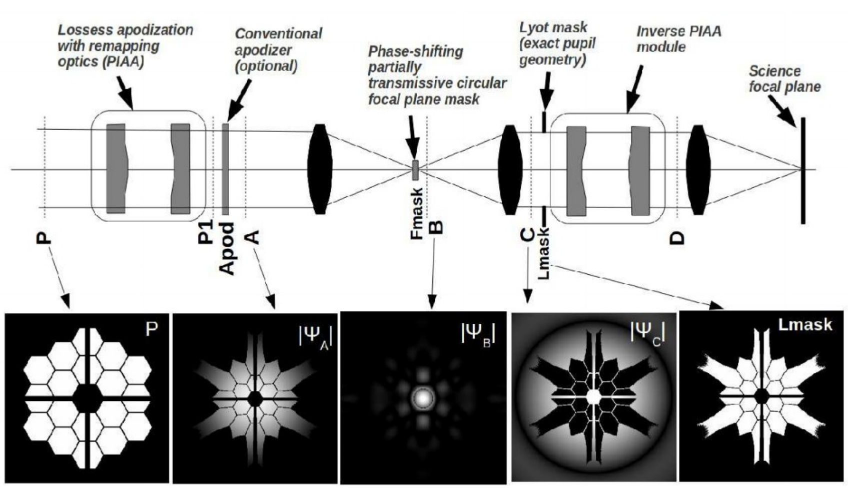
Approaches that are inherently insensitive to aperture geometry exit (no performance loss induced by segmentation)



Visible nulling coronagraph (VNC)

Destructive interference between shifted copies of the pupil

Shift can be integer multiple of segments



PIAACMC

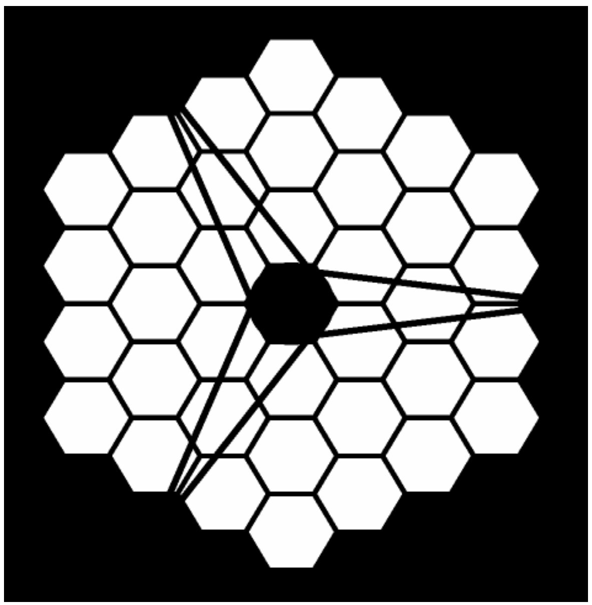
Uses lossless apodization (beam shaping) + diffractive focal plane mask

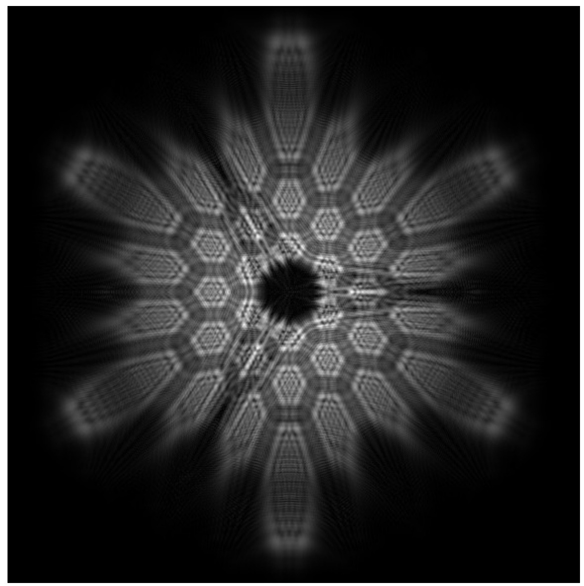
Near-full transmission and small IWA

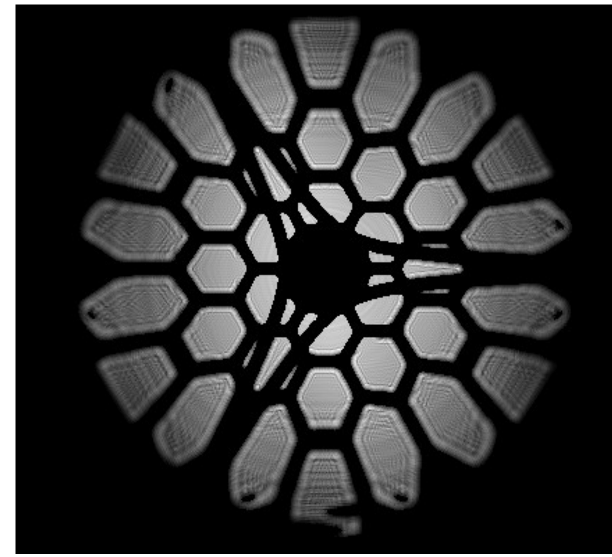
PIAACMC design for 12m segmented telescope
IWA = 1.2 l/D, throughput = 70% (similar to WFIRST-PIAACMC)

Polychromatic diffraction propagation in AFTA-C PIAACMC optical configuration
Reflective focal plane mask

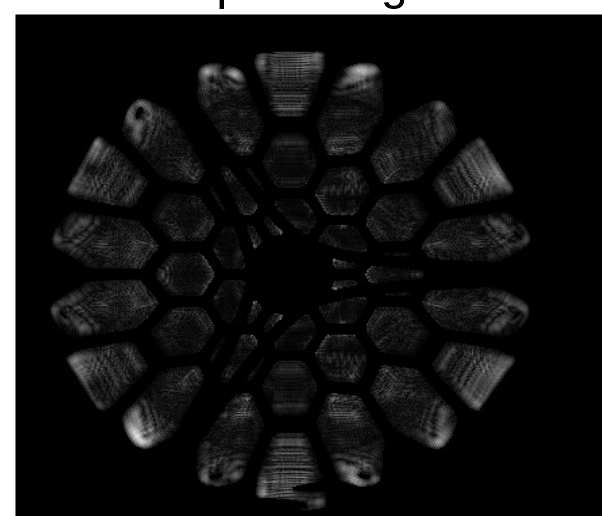
FLAT DEFORMABLE MIRRORS (no ACAD)







planet light

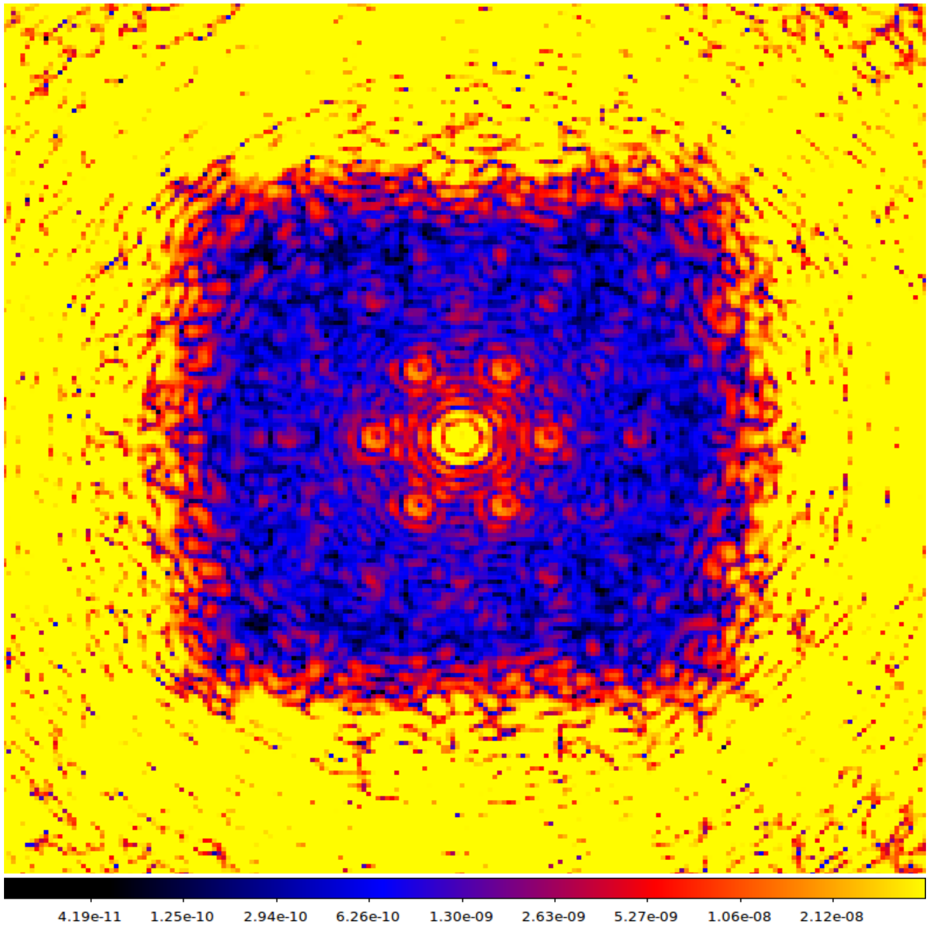


starlight (very faint)

Focal plane mask redirects starlight to
LOWFS (reflected by Lyot stop)
70% of planet light goes through Lyot stops
to science image

Stellar PSF dominated by stellar angular size

Further optimization of focal plane mask and WFC (ACAD ?) will reduce leaks due to stellar angular size. This process improved contrast by 15x between PIAACMC gen2 and PIAACMC gen3 on AFTA.

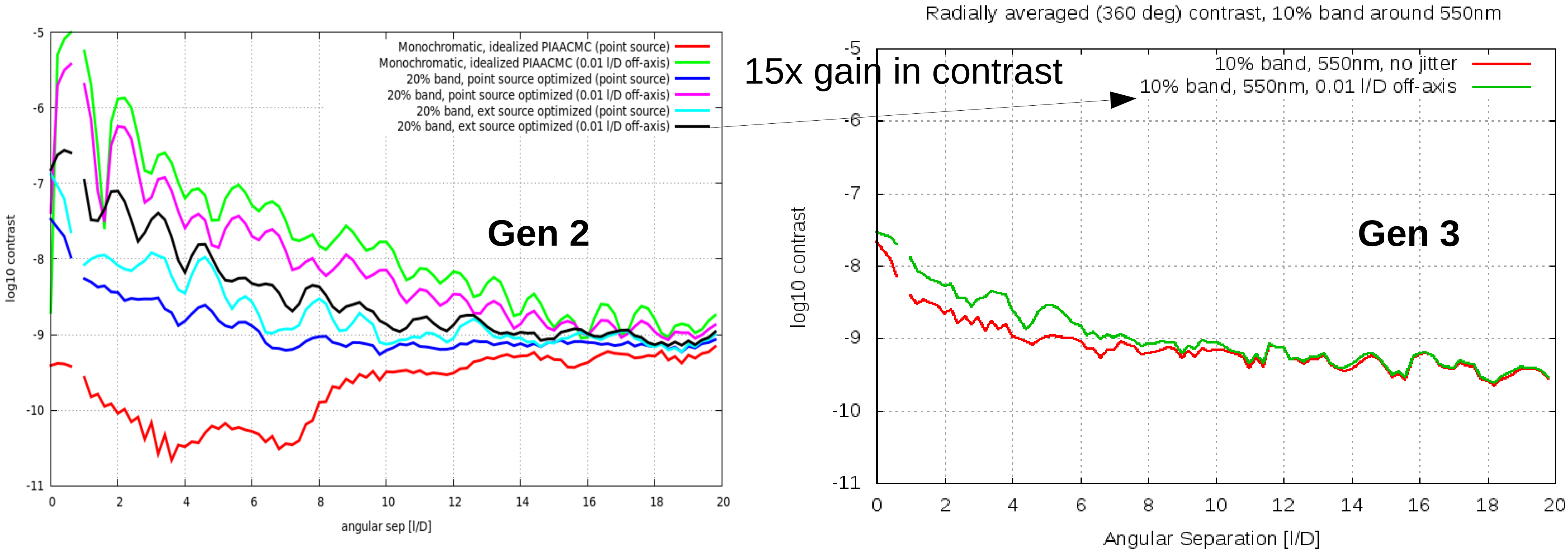


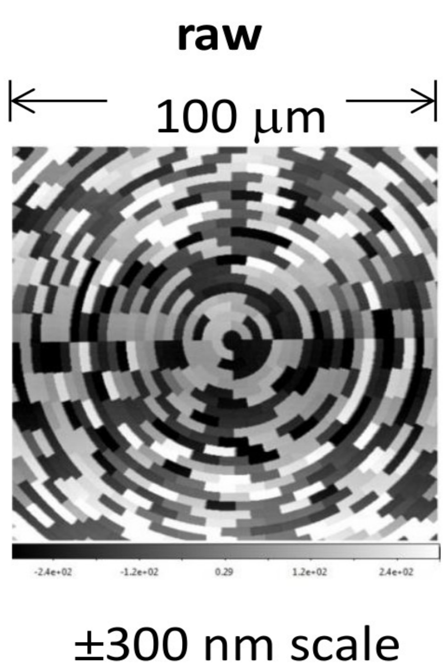
Inner spot+rings due to stellar angular size, at few 1e-9 contrast in 2-4 l/D range

6 small circular spots at 7 l/D due to aperture geometry (side lobes)

This component is subtracted from image in next slide, assuming photon-noise limit

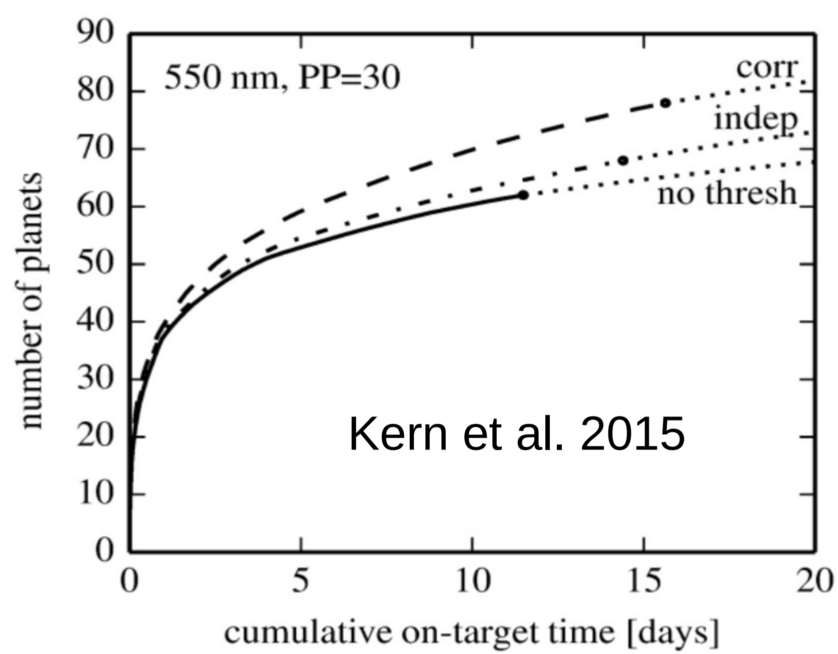
Stellar leak and focal plane mask design on AFTA





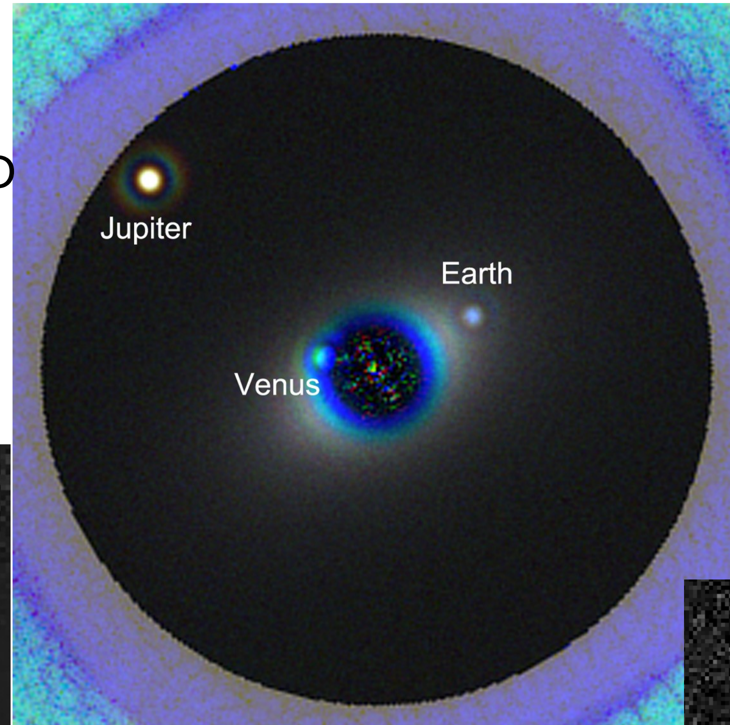
Focal plane mask consists of ~1000 zones

Zone height computer-optimized simultaneously for broadband operation and stellar angular size

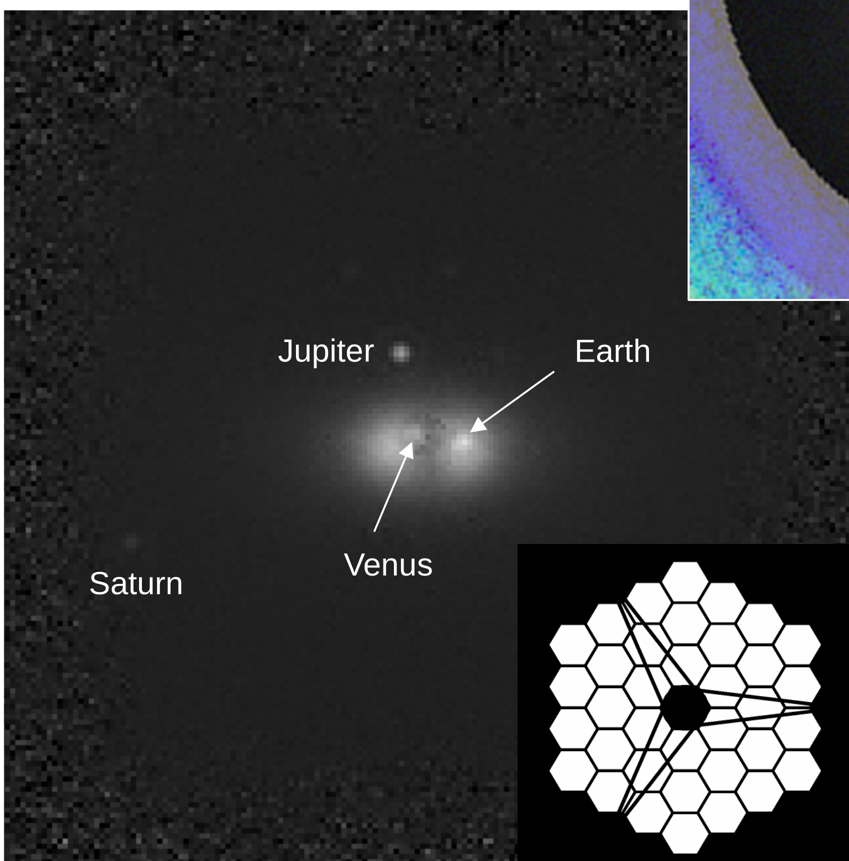


Simulated images of solar system twin – 12m telescope, 2 day exposure

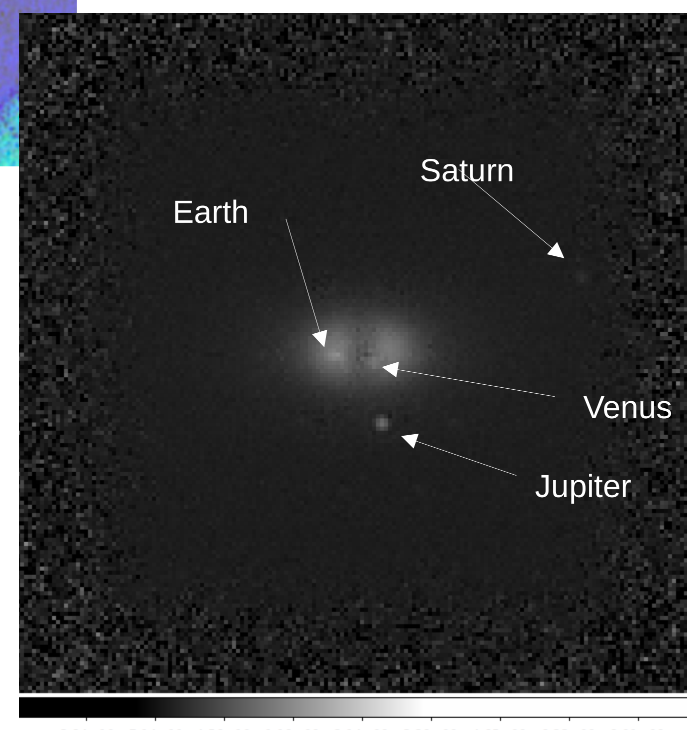
SS twin at 13pc
Visible light
APLC, IWA=3.6 l/D



SS twin at 13pc
near-IR (1600nm)
PIAACMC, IWA=1.2 l/D



SS twin at 40pc
Visible (550nm)
PIAACMC, IWA=1.2 l/D



Ultra-stability: limiting segment vibrations

Raw contrast in the 1e-9 to 1e-10 range requires ~10pm stability of combined telescope and WFC.

Continuous speckle control can compensate and calibrate slow thermal drifts, but vibration must be addressed separately (too fast for speckle control)

Vibration and fast WF changes can be addressed with multi-tiered approach, some combination of :

- Using bright starlight for fast sensing of a few modes ***[example: LOWFS concept on WFIRST and SCExAO]***
- Picometer laser metrology ***[SIM and non-NASA heritage]***
- Vibration suppression / isolation ***[industry-developed non-contact isolation]***

[More details in upcoming HDST report]

Conclusions, path forward

Exoplanet imaging science (yield and quality) increases steeply with aperture size. Large space telescope + coronagraph required for search of biomarkers on a sample of rocky planets in HZ of nearby stars

Two highest priority technologies:

Internal coronagraphs are compatible with segmented apertures. At least 2 concepts can be deployed on segmented aperture with little to no performance loss.
→ Need to continue / ramp up technology development effort for coronagraph and WFC on large space-based segmented apertures
→ Emulate/follow AFTA coronagraph process: simulation/science team evaluate designs, designers improve designs, lab demos with well-chosen milestones

A large segmented aperture for high contrast imaging requires a **stable ultra low-vibration primary mirror.**
→ Need engineering study + scaled lab demos

Check upcoming HDST report...