



U.S. AIR FORCE



USSF

AFRL

LAsER guide Star Sensor Integrated Extreme adaptive optics (LASSIE) Project

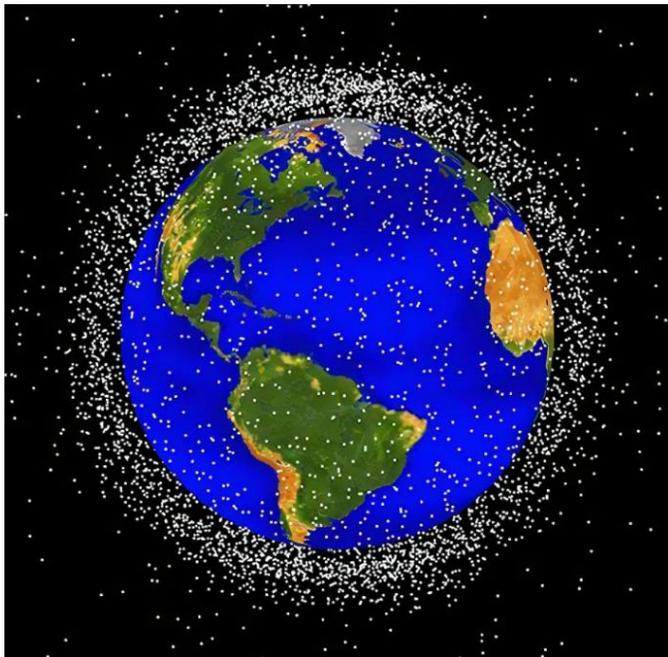
Dr. Lauren Schatz AFRL/RDSSE

Dr. Jeff Richey, Dr. Robert Johnson, Major Tod Laurvick, Dr. Colton Bigler,

Dr. Mala Mateen, Lt. Jeremiah Gauling, Ian Kingsolver

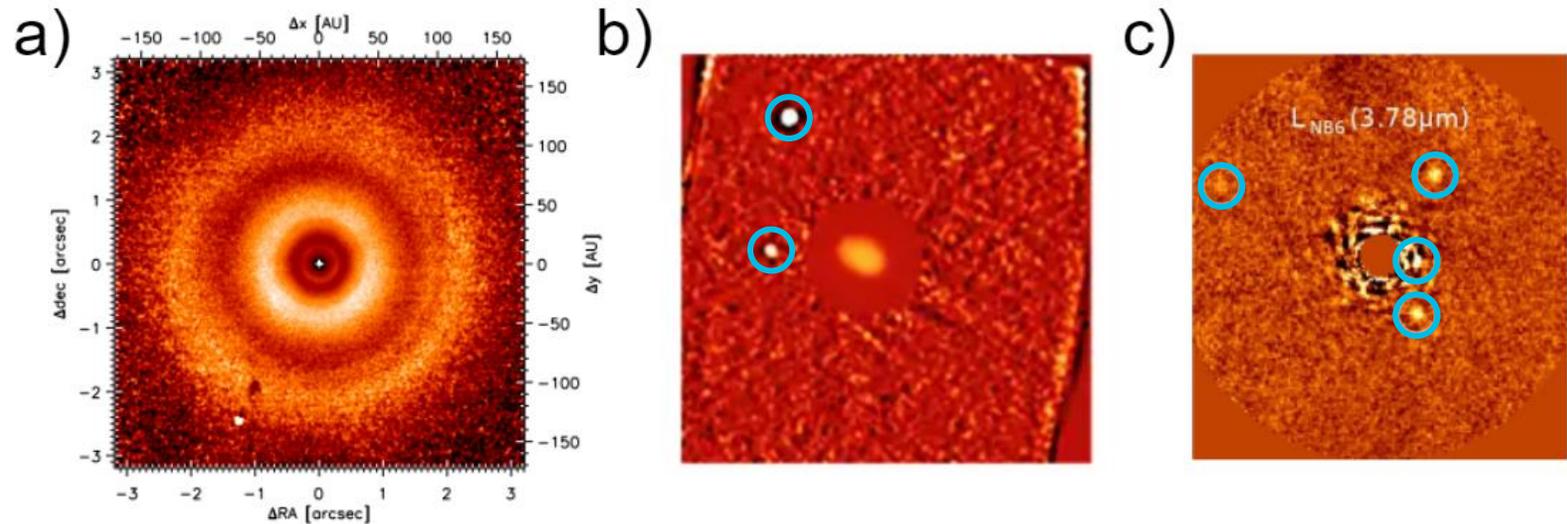
Motivation: High Contrast Imaging (HCI)

- Imaging faint companions around bright objects
- Closely Spaced Objects imaging at GEO similar to astronomical challenges



Space Domain Awareness
Closely Space Objects (CSO) mission

Real high contrast images taken in the infrared!



Circumstellar Disks

Van Boekel et. al

Asteroids + Moons

Yang, B, et. al

Exoplanets

Skemer, A



Problem One: Contrast

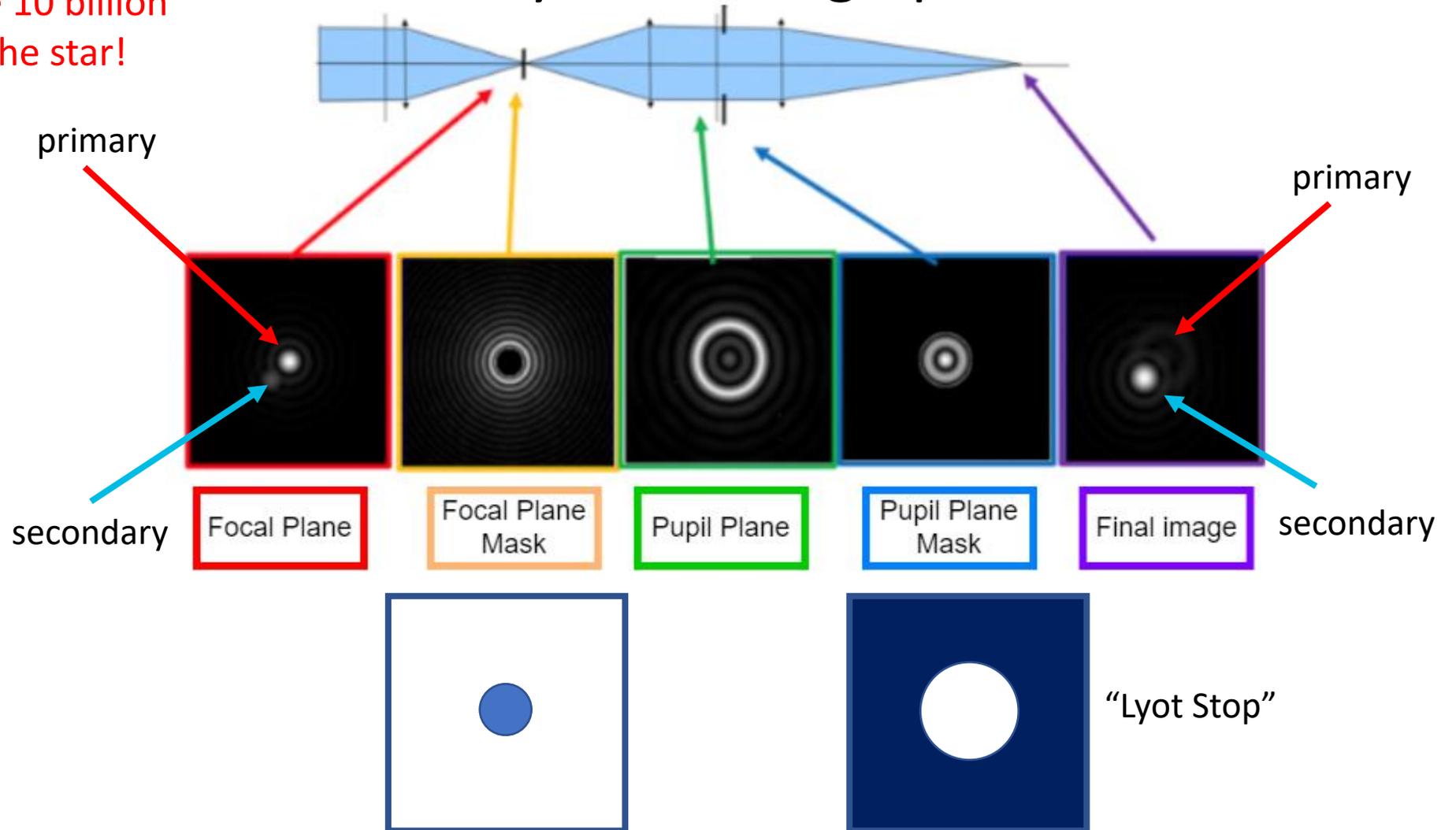
Companions can be 10 billion times fainter than the star!

Contrast



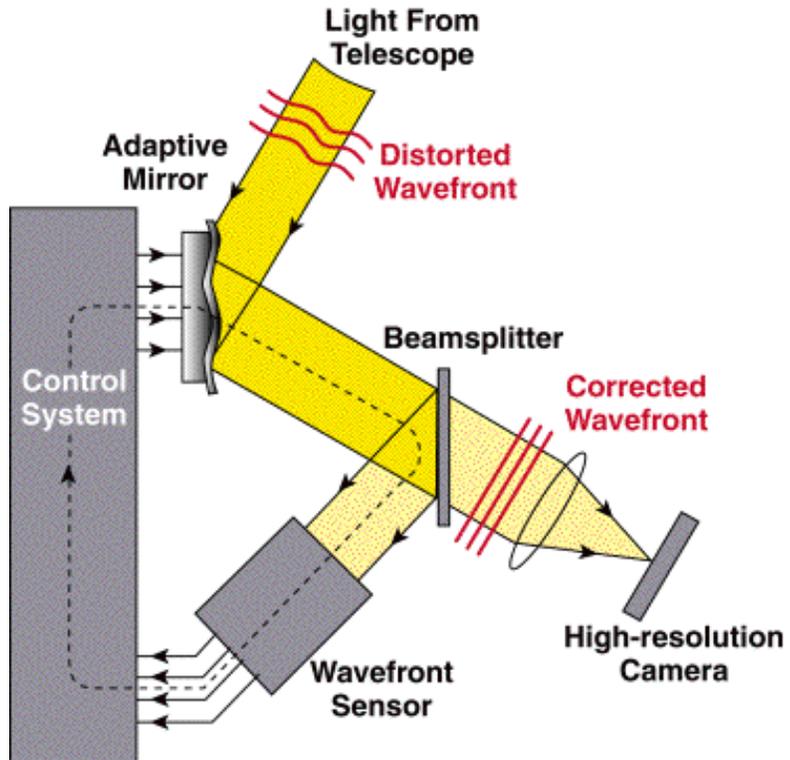
Photo Credit:
NASA Hubble Space
Telescope

Lyot Coronagraph



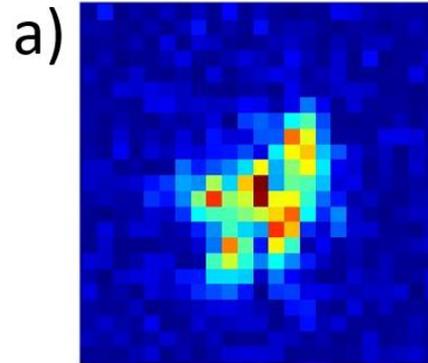
Problem Two: Atmospheric Turbulence

- Adaptive optics (AO) systems correct distortions of starlight wavefronts caused by atmospheric turbulence.

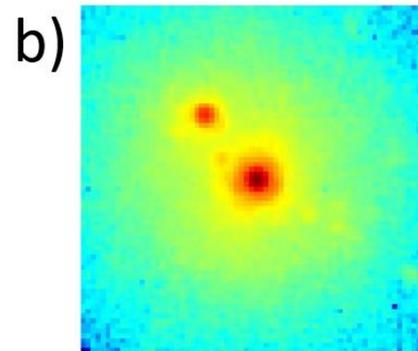


[4] Suárez-Gómez et al., 2017

Binary Star System

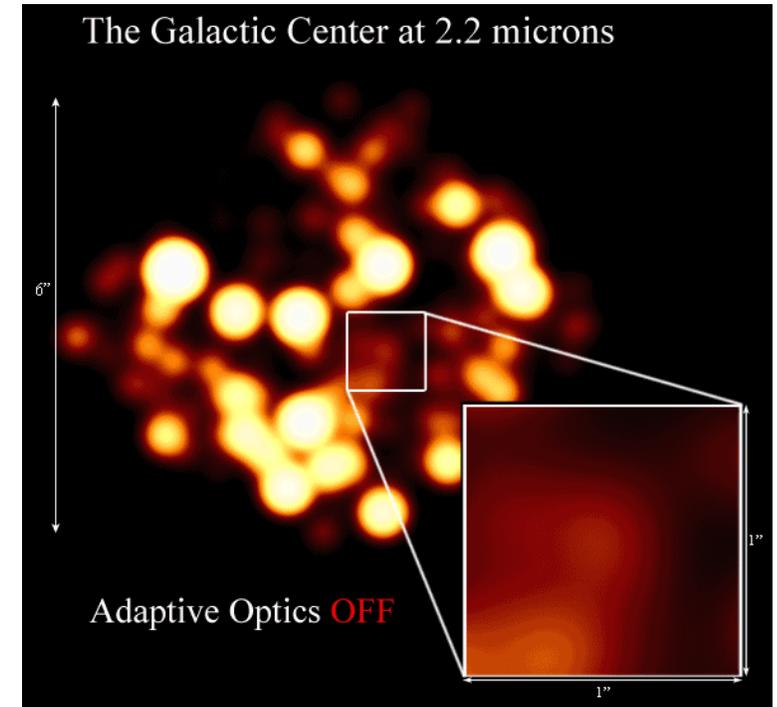


Adaptive Optics OFF



Adaptive Optics ON

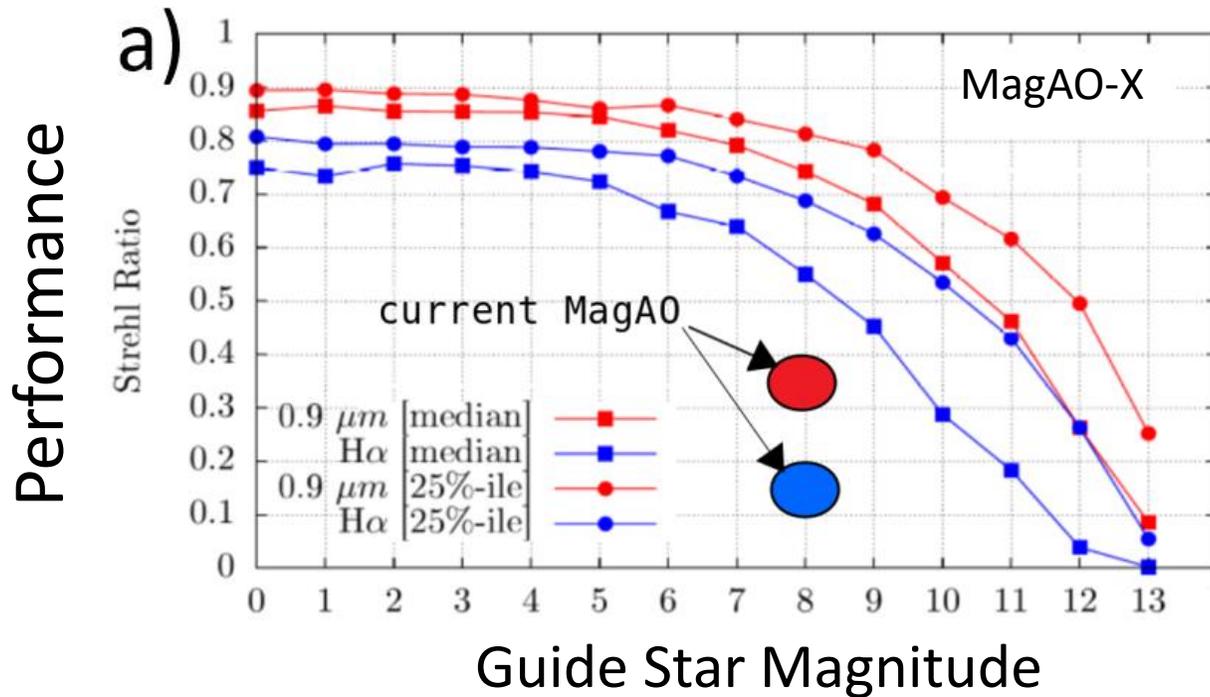
[5] Tavenner et al. (2021)



UCLA Galactic Center Group / W. M. Keck Observatory Laser Team

Problem Three: AO only works on bright stars

- Results in about 1% sky-coverage for AO observations
- Laser Guide Stars (LGS) are artificial beacons to allow AO systems to work if there are no bright guide stars
- Extreme adaptive optics (ExAO) are systems optimized for coronagraphy and HCI
- **LGS has never been applied to ExAO systems**



But most stars are fainter!

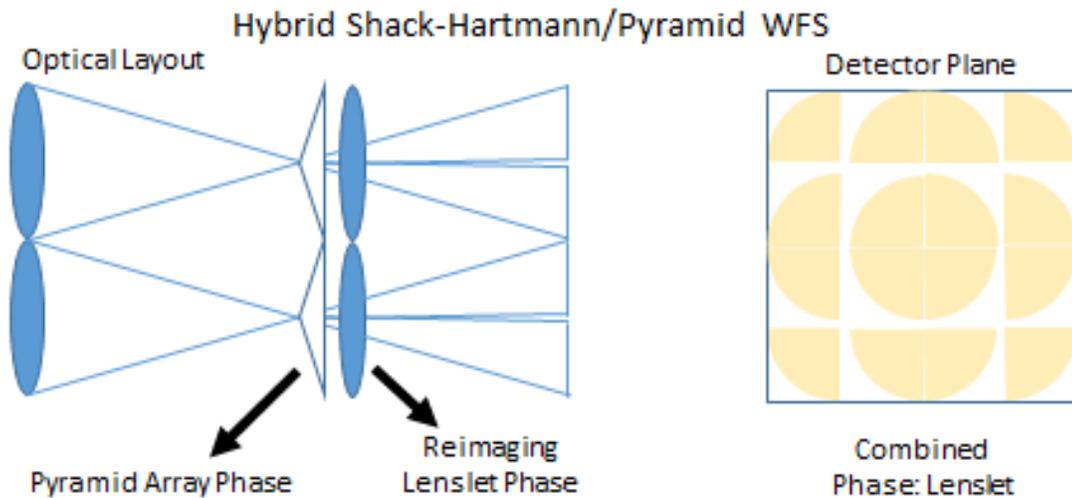


Laser Guide Stars

LASer guide Star Sensor Integrated Extreme adaptive optics (LASSIE) project

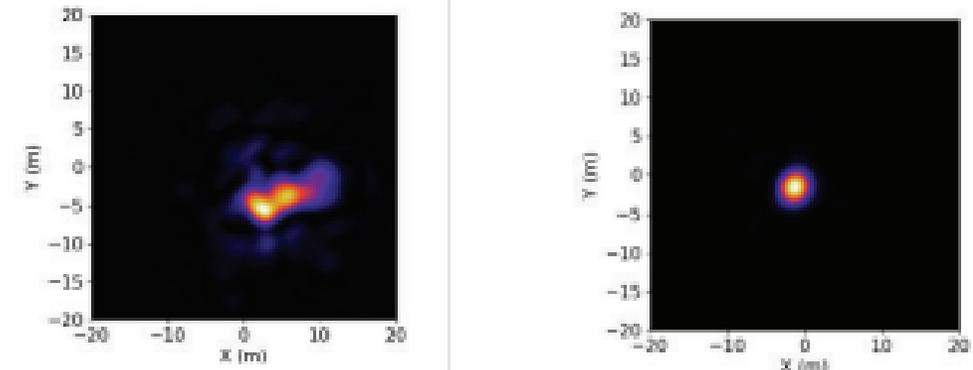
- GEO satellites are very faint and therefore we need an LGS System
- Explore advances in laser guide stars, wavefront sensors, and coronagraphy to build a new LGS ExAO

New LGS Wavefront Sensor Developed at SOR



Richey (2022)

New uplink corrected Laser Guide Star Technology (Simulation). *Calia et al. (2021)*



Uncorrected

Full LGS AO,
tip-tilt from satellite

Calia et al. (2021)

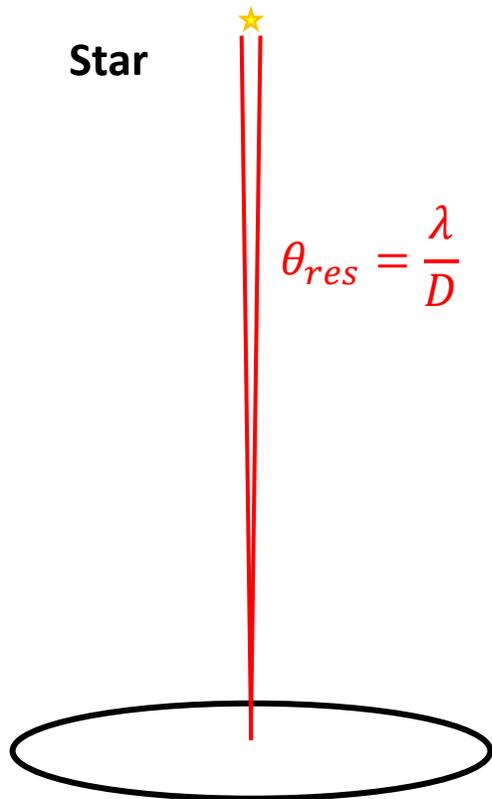


Partially Coherent Beacons

Richey (2022)

Coherent Beacon

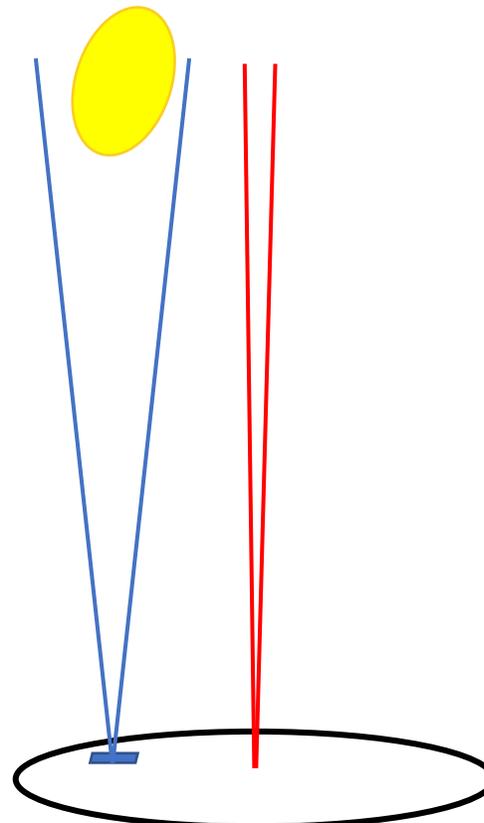
$$\theta_{beacon} < \frac{\lambda}{D}$$



Partially Coherent Beacon

$$\frac{\lambda}{D} < \theta_{beacon} < \frac{\lambda}{D_s}$$

Uplink Corrected / Pulsed Sodium Beacon

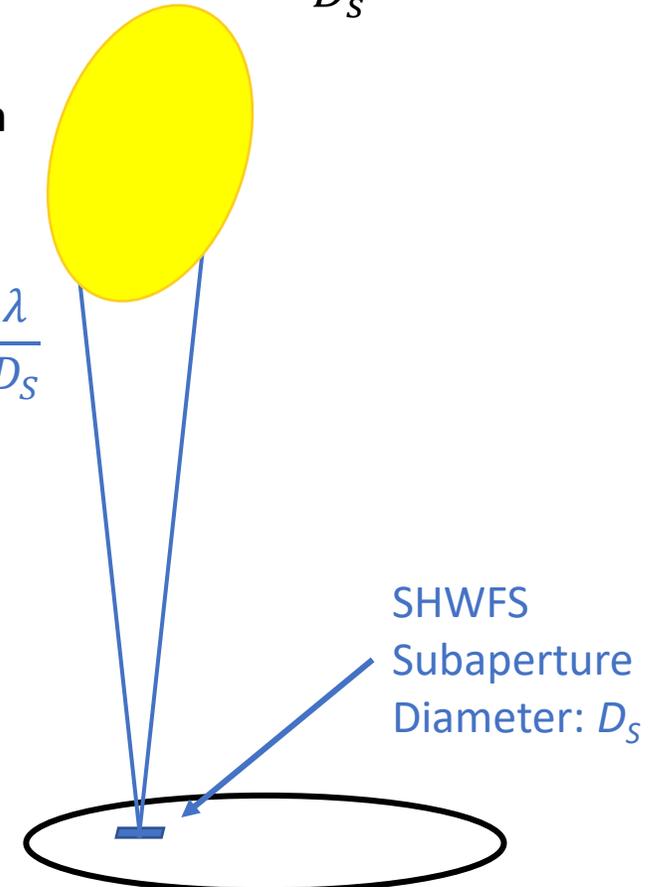


Incoherent Beacon

$$\theta_{beacon} > \frac{\lambda}{D_s}$$

Sodium Beacon

$$\theta_{res} = \frac{\lambda}{D_s}$$

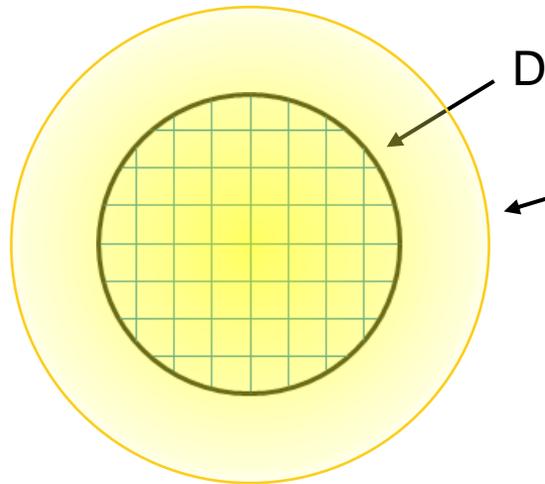




Partially Coherent Beacons *Richey (2022)*

Coherent Beacon

$$\theta_{beacon} < \frac{\lambda}{D}$$

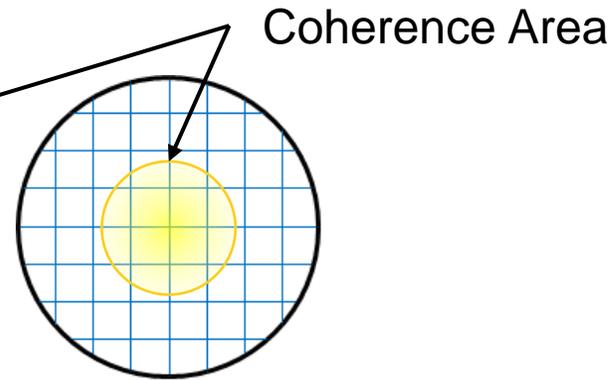


Approximation:

$$|\mu(\vec{r}_1, \vec{r}_2)| = 1$$

Partially Coherent Beacon

$$\frac{\lambda}{D} < \theta_{beacon} < \frac{\lambda}{D_s}$$

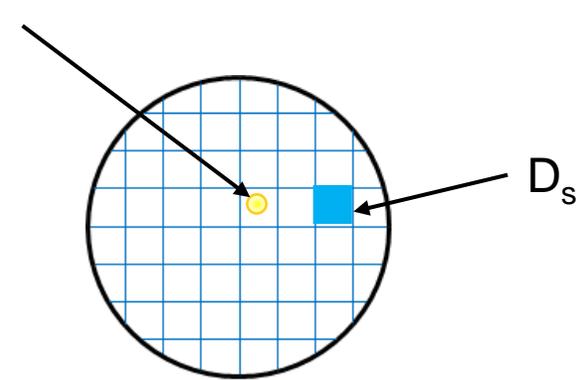


No Approximation:

$$0 < |\mu(\vec{r}_1, \vec{r}_2)| < 1$$

Incoherent Beacon

$$\theta_{beacon} > \frac{\lambda}{D_s}$$



Approximation:

$$|\mu(\vec{r}_1, \vec{r}_2 \neq \vec{r}_1)| = 0$$

- Coherence area: lower bound, spatial coherence magnitude: $|\mu(\vec{r}_1, \vec{r}_2)|$
- Mutual intensity: $J(\vec{r}_1, \vec{r}_2) = \langle u(\vec{r}_1)u^*(\vec{r}_2) \rangle = A_1A_2|\mu(\vec{r}_1, \vec{r}_2)|e^{i(\varphi_1 - \varphi_2)}$



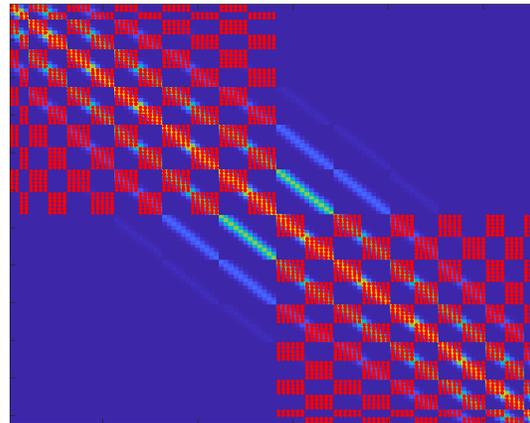
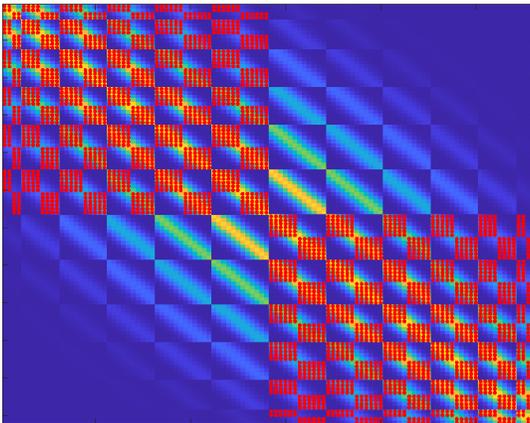
Optimizing WFS design for Partially Coherent Beacons

Pupil Segmentation – Hybrid WFS

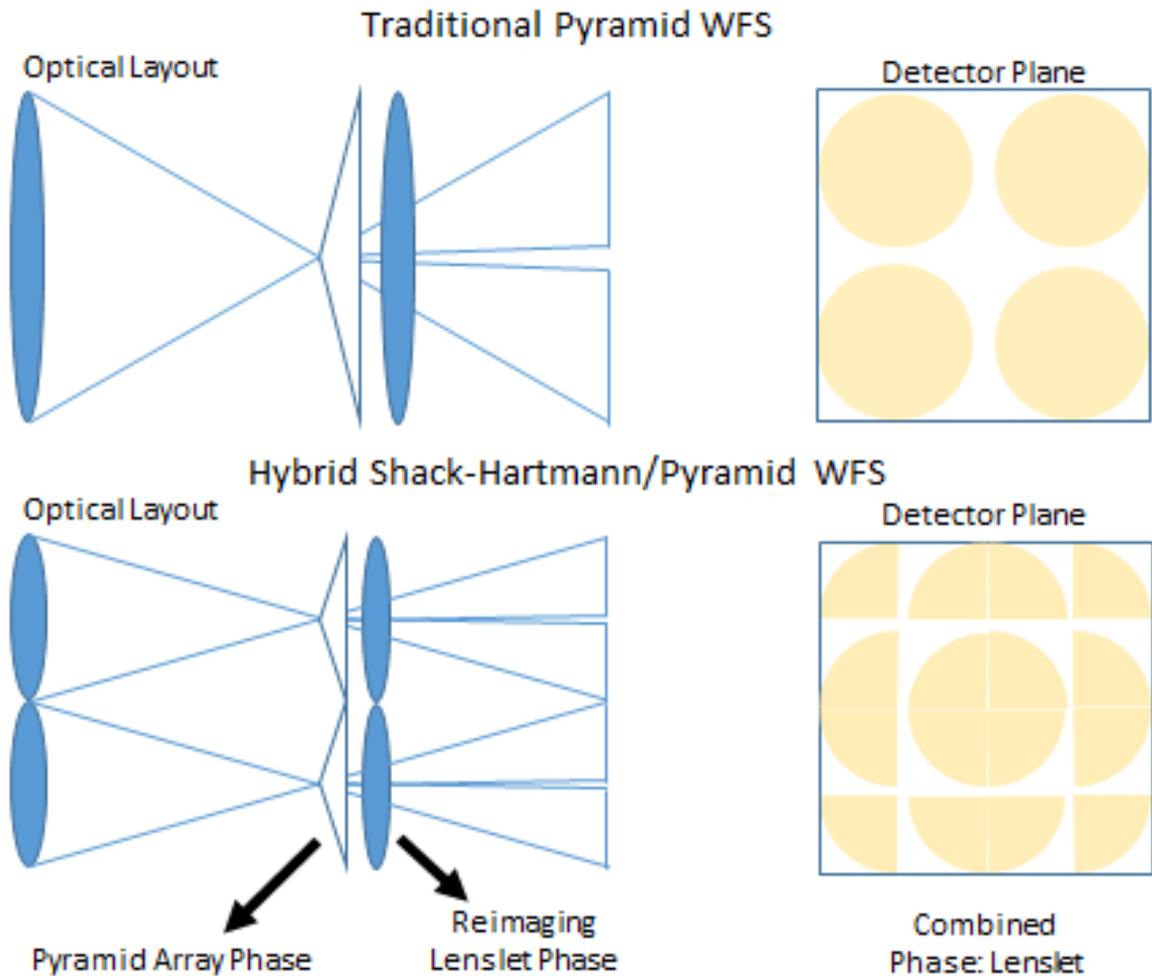
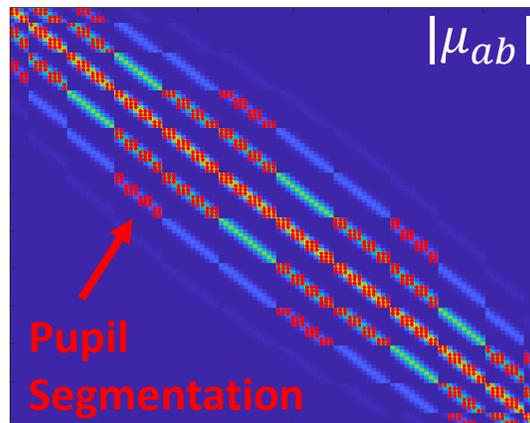
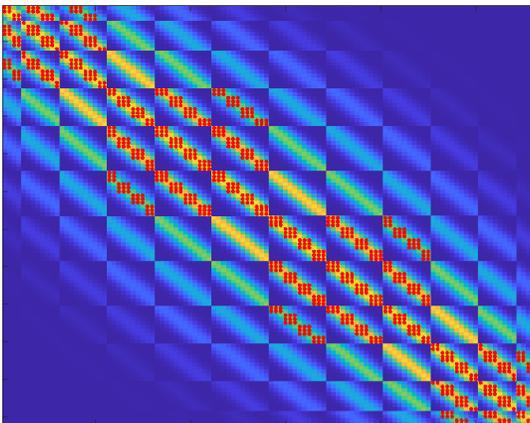
Source: 2 λ/D

Source: 4 λ/D

2x2



4x4

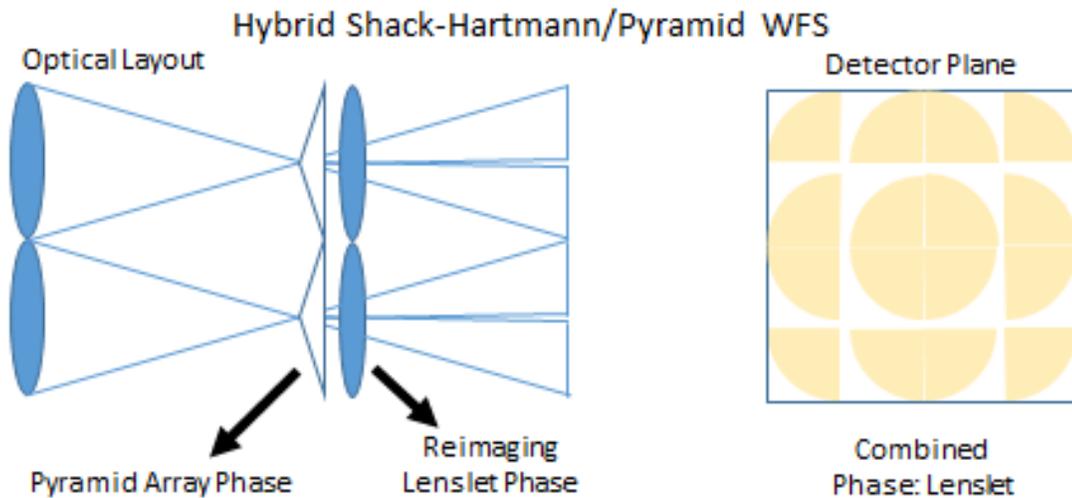


Richey (2022)

LASer guide Star Sensor Integrated Extreme adaptive optics (LASSIE) project

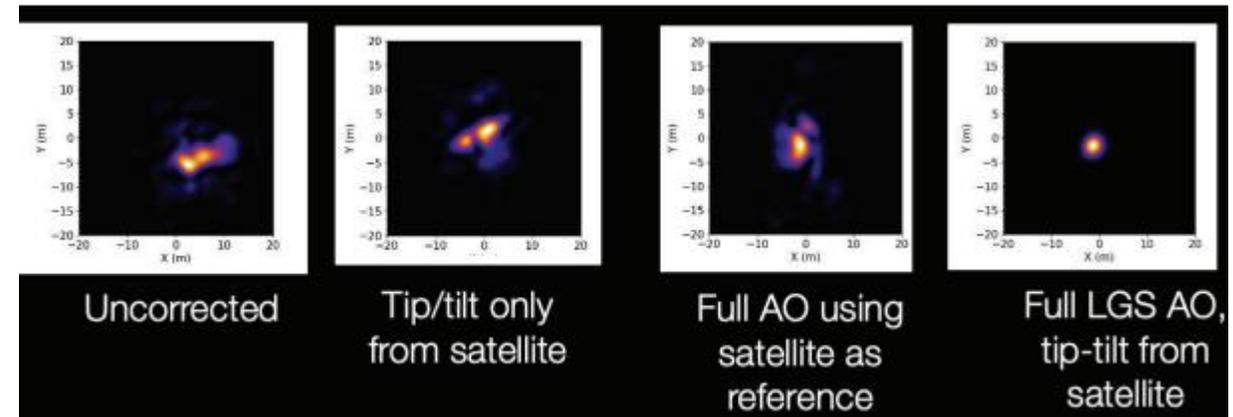
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New LGS Wavefront Sensor Developed at SOR



Richey (2022)

New uplink corrected Laser Guide Star Technology (Simulation)



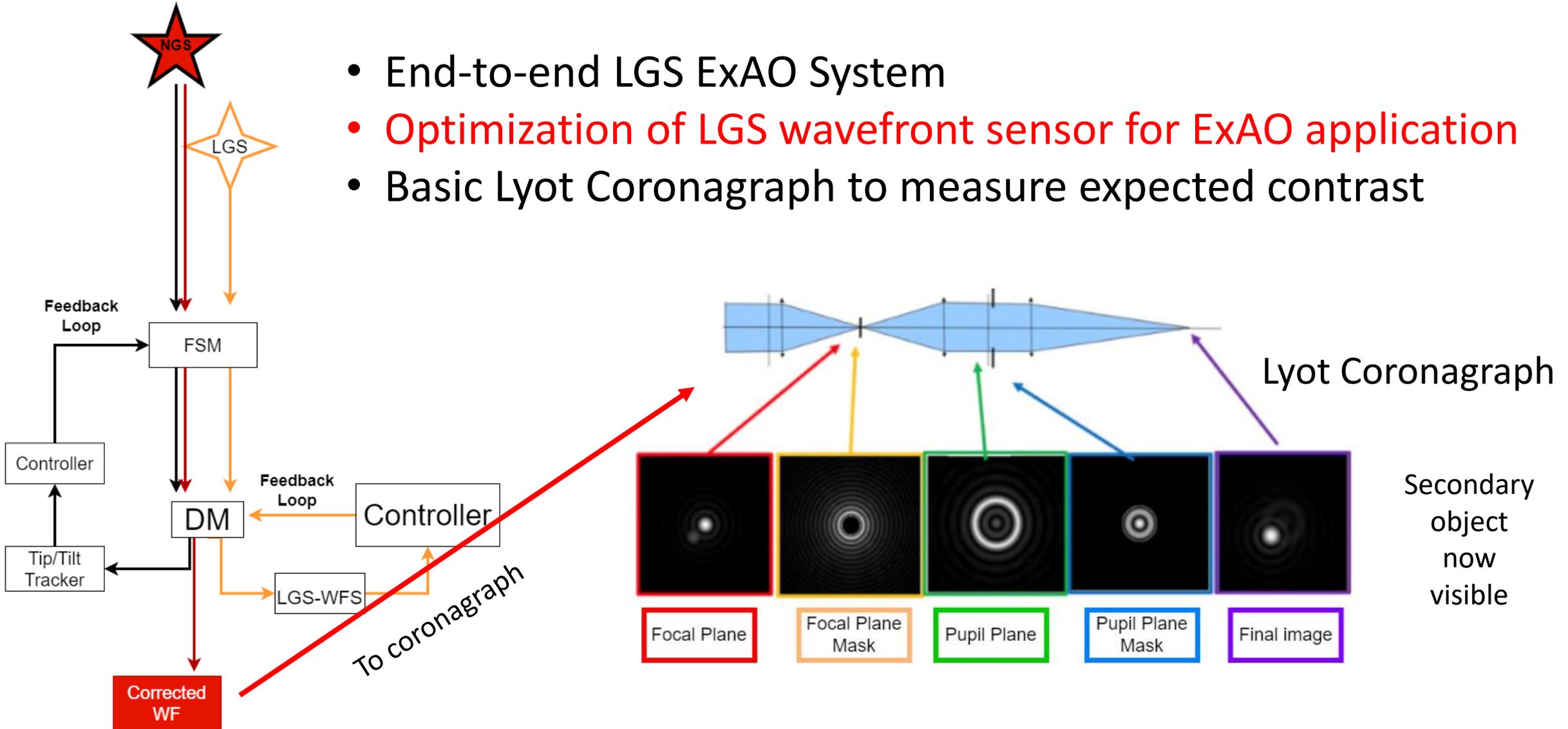
Calia et al. (2021)



Three Lab Tasks

Task 1: Task One: Simulations and Optimization

- End-to-end LGS ExAO System
- **Optimization of LGS wavefront sensor for ExAO application**
- Basic Lyot Coronagraph to measure expected contrast

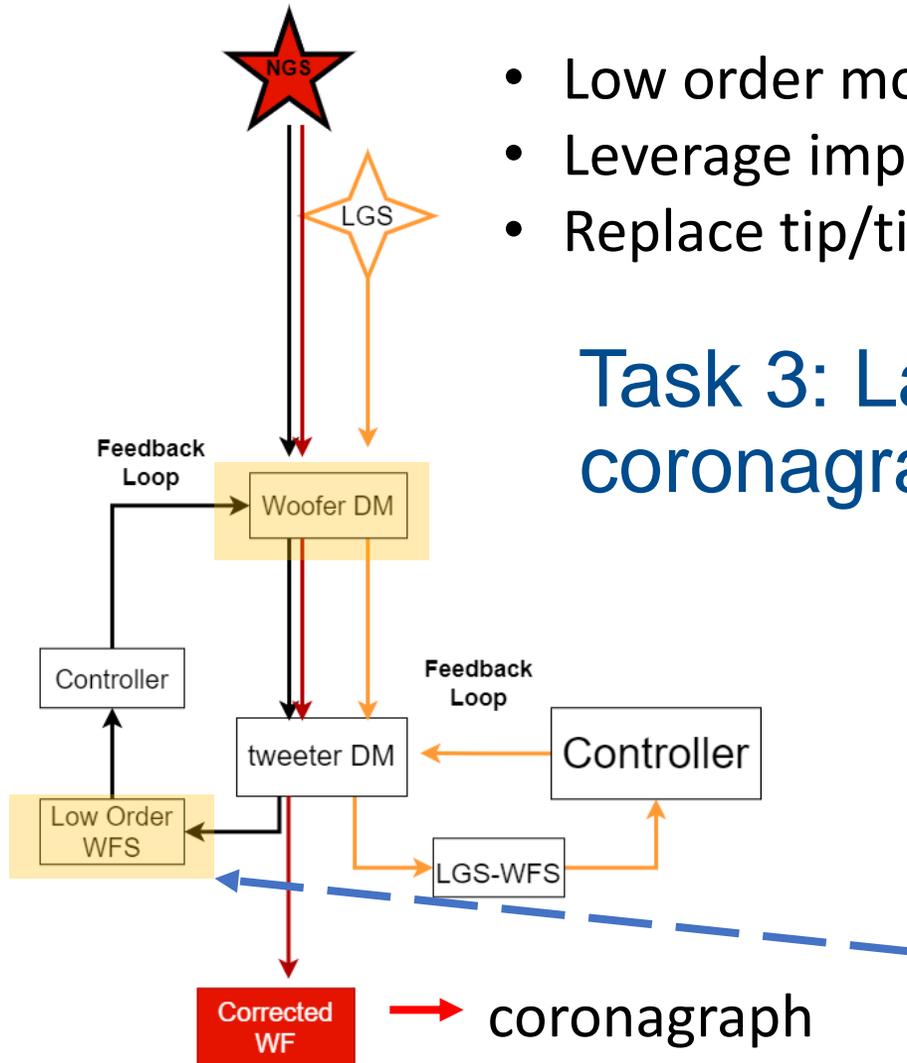


LGS+LOWFS Adaptive Optics

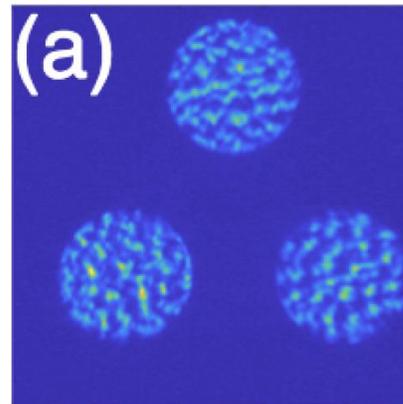
Task 2: Tip/Tilt Sensor Upgrade

- Low order modes bad for coronagraphy, not well encoded by LGS
- Leverage improvements to detectors
- Replace tip/tilt sensor with a 3PWFS

Task 3: Lab demo of LGS Wavefront sensor + coronagraph at Starfire Advanced Optics Lab



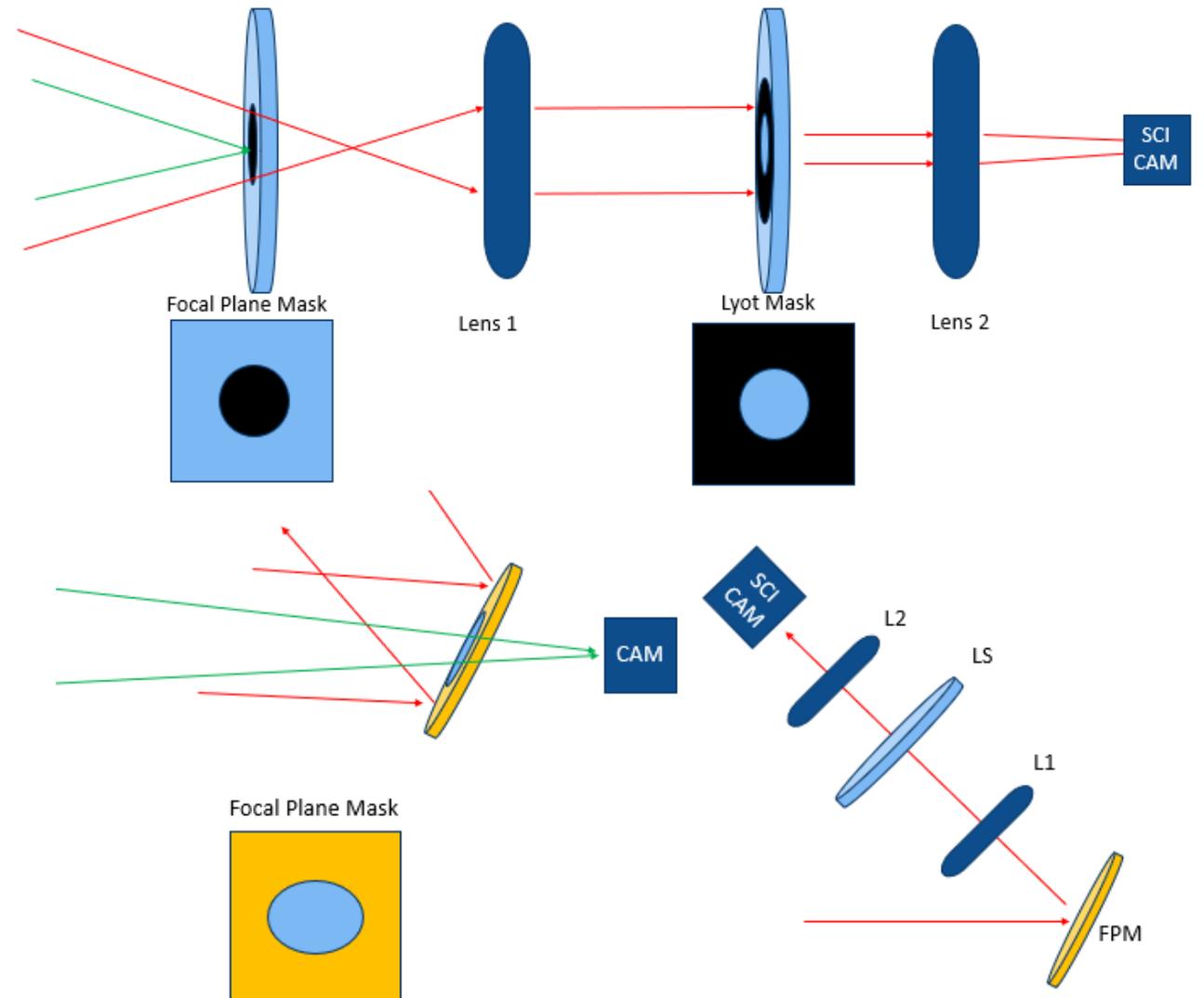
Three-sided pyramid wavefront sensor



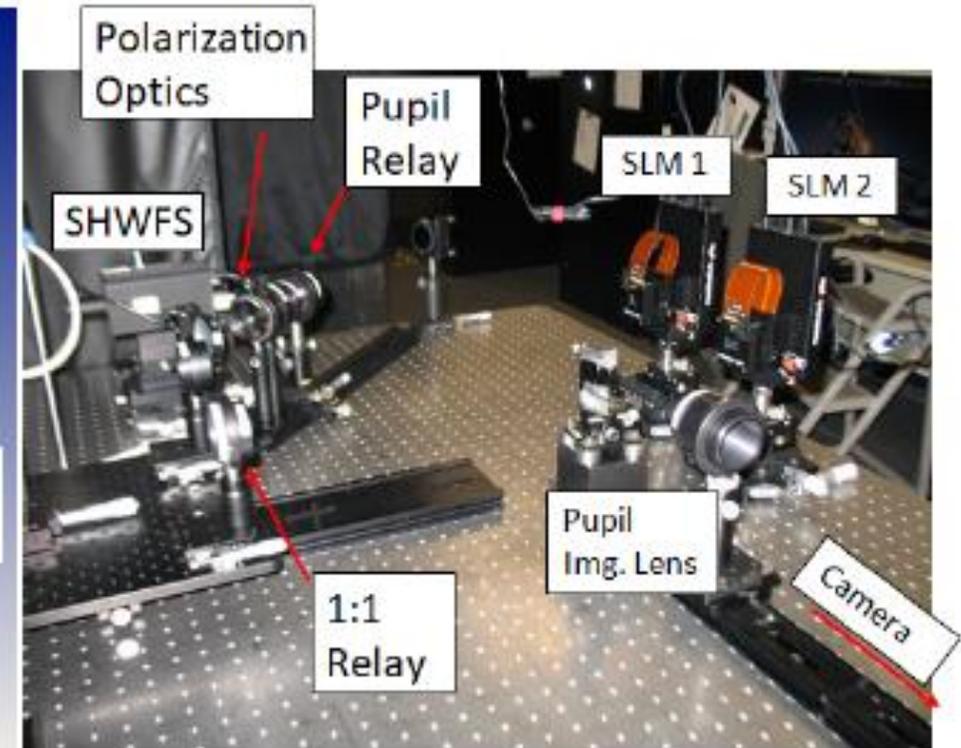
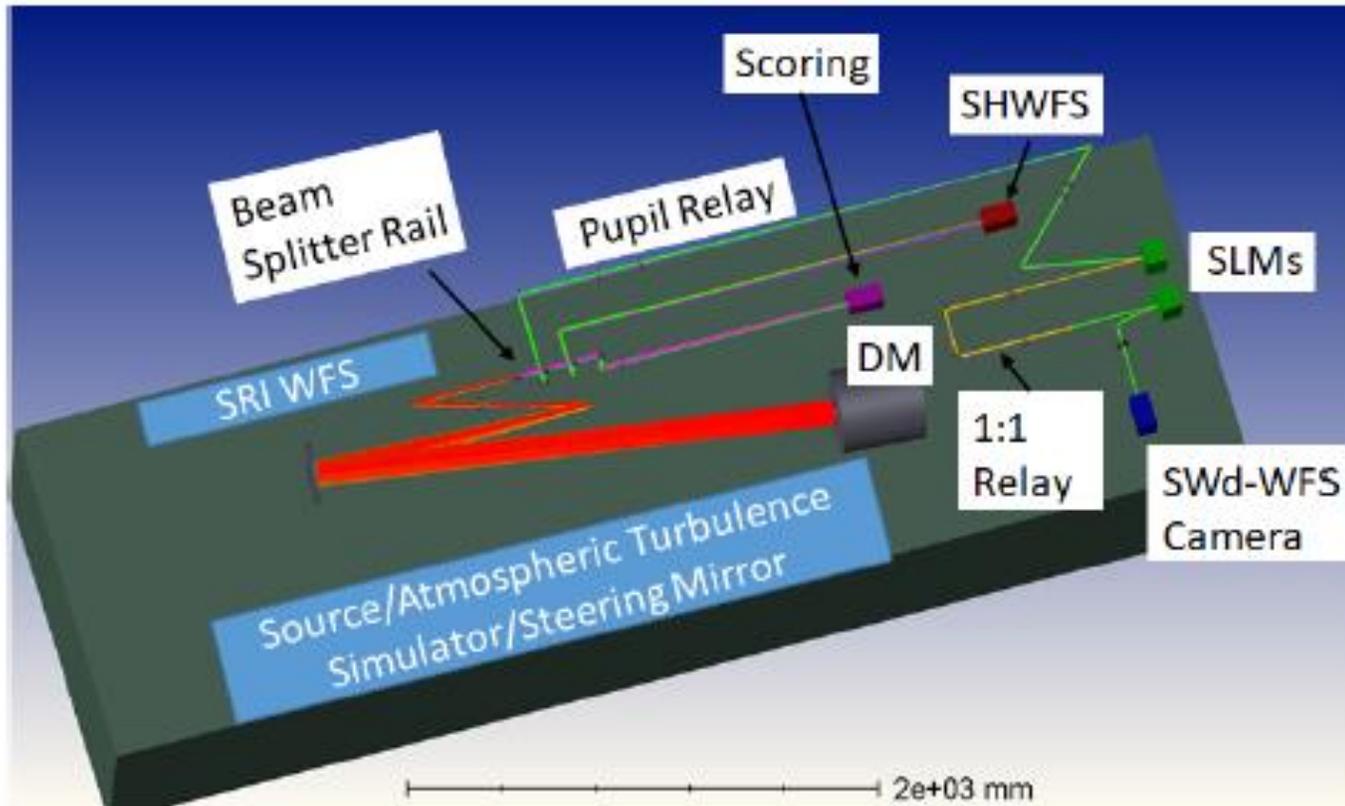
- More photon efficient than a Shack-Hartmann or 4PWFS
- Cheap and easy to make high quality pyramid optic
- Can rebin detector for hybrid NGS-LGS system

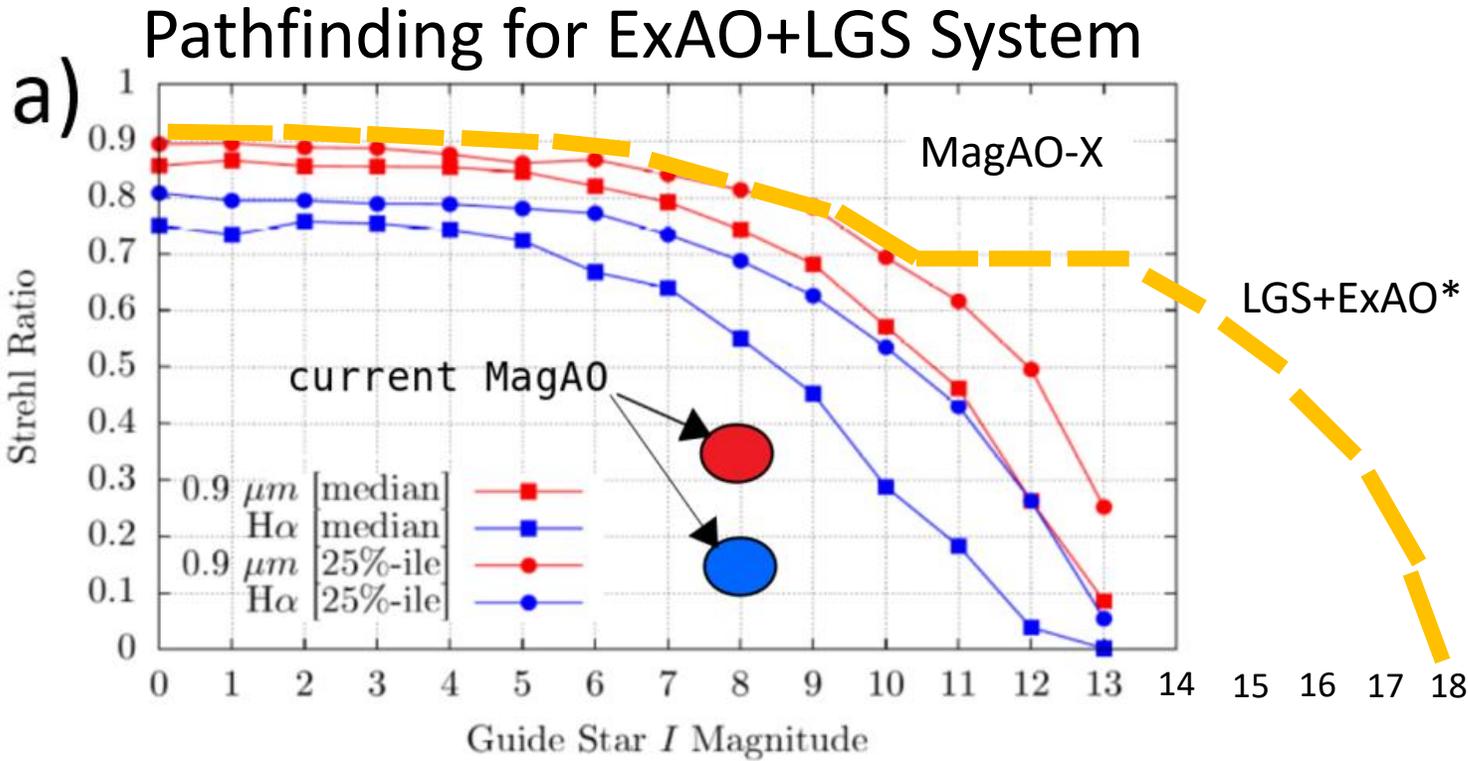
Coronagraph Preliminary Mask Designs

- We plan to fabricate these masks in collaboration with the Air Force Institute of Technology (AFIT).
- Metrics:
 - Surface quality,
 - Reflectivity/opacity
 - Ease of optical alignment
 - Chromaticity
- Examine how the deposition process effects surface quality of mirrors and preexisting AR coatings.



ASALT: Adaptive Optics Testbed at SOR





*Real performance to be determined

1. Apply and advance research by AFRL scientists:

- LGS Wavefront Sensor- Jeff Richey
- 3PWFS- Lauren Schatz and Mala Mateen
- LGS Beacon- Robert Johnson and Colton Bigler

2. Important for astronomical applications

- Decadal Survey Priority Area: Pathways to Habitable World with the goal of trying to discover worlds that could resemble Earth and answer the fundamental question: “Are we alone?”
- Pathfinding for next generation ExAO systems.

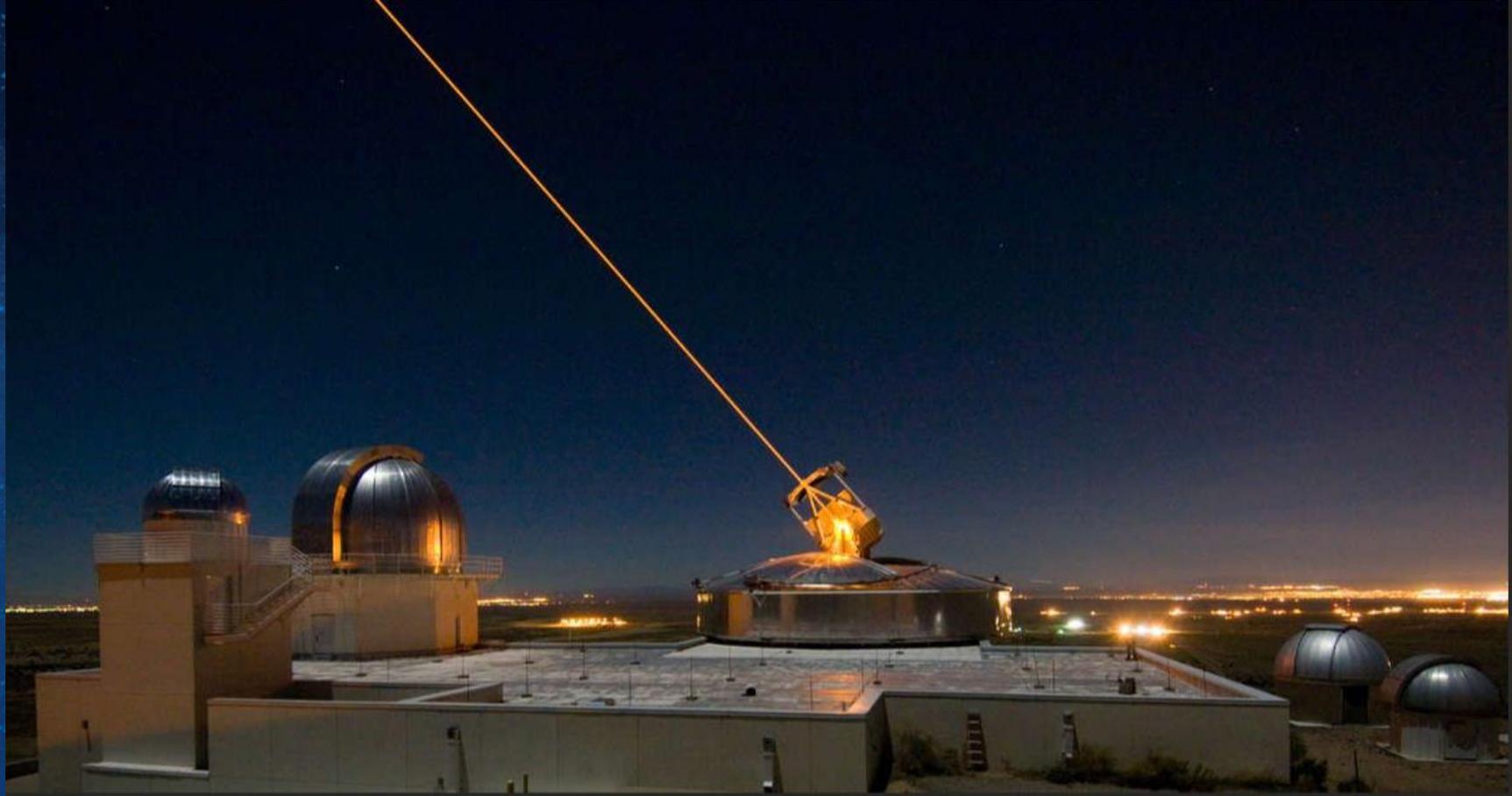


References

1. Van Boekel, R., Henning, T., Menu, J., De Boer, J., Langlois, M., Müller, A., Avenhaus, H., Boccaletti, A., Schmid, H. M., Thalmann, C., et al., "Three radial gaps in the disk of *tau* hydrae imaged with sphere," *The Astrophysical Journal* 837(2), 132 (2017).
2. Yang, B., Wahhaj, Z., Beauvalet, L., Marchis, F., Dumas, C., Marsset, M., Nielsen, E., and Vachier, F., "Extreme ao observations of two triple asteroid systems with sphere," *The Astrophysical Journal Letters* 820(2), L35 (2016).
3. Skemer, A. J., Marley, M. S., Hinz, P. M., Morzinski, K. M., Skrutskie, M. F., Leisenring, J. M., Close, L. M., Saumon, D., Bailey, V. P., Briguglio, R., et al., "Directly imaged hot transition exoplanets in the mid-infrared," *The Astrophysical Journal* 792(1), 17 (2014).
4. Suárez-Gómez, S. L., C. González-Gutiérrez, F. Sánchez-Lasheras, A. Basden, I Montilla, F. de Cos Juez, and M. Collados-Vera (2017). An approach using deep learning for tomographic reconstruction in solar observation. *Proceedings of the Adaptive Optics for Extremely Large Telescopes*, 5.
5. Tavenner, T., Drummond, J., Mateen, M., Wood, E., and Jenkins, O. R. E., "Speckle interferometry of binary stars with a 1m telescope, grounded with ao from a 1.5 m," (2021).
6. Schatz, Lauren, et al. "Three-sided pyramid wavefront sensor, part 1: simulations and analysis for astronomical adaptive optics." *Journal of Astronomical Telescopes, Instruments, and Systems* 7.4 (2021): 049001.
7. A. Tokovinin, "AO tutorial at CTIO" (2001).
8. Dalcanton, Julianne, et al. "From cosmic birth to living earths: the future of UVOIR space astronomy." *arXiv preprint arXiv:1507.04779* (2015).
9. Richey, Jeff, and Michael Hart. "Hybrid wave front sensor for partially coherent beacons." *Adaptive Optics Systems VII*. Vol. 11448. SPIE, 2020.
10. Calia, D. Bonaccini, et al. "CaNaPy: SatComm LGS-AO experimental platform with laser uplink pre-compensation." *International Conference on Space Optics—ICSO 2020*. Vol. 11852. SPIE, 2021.



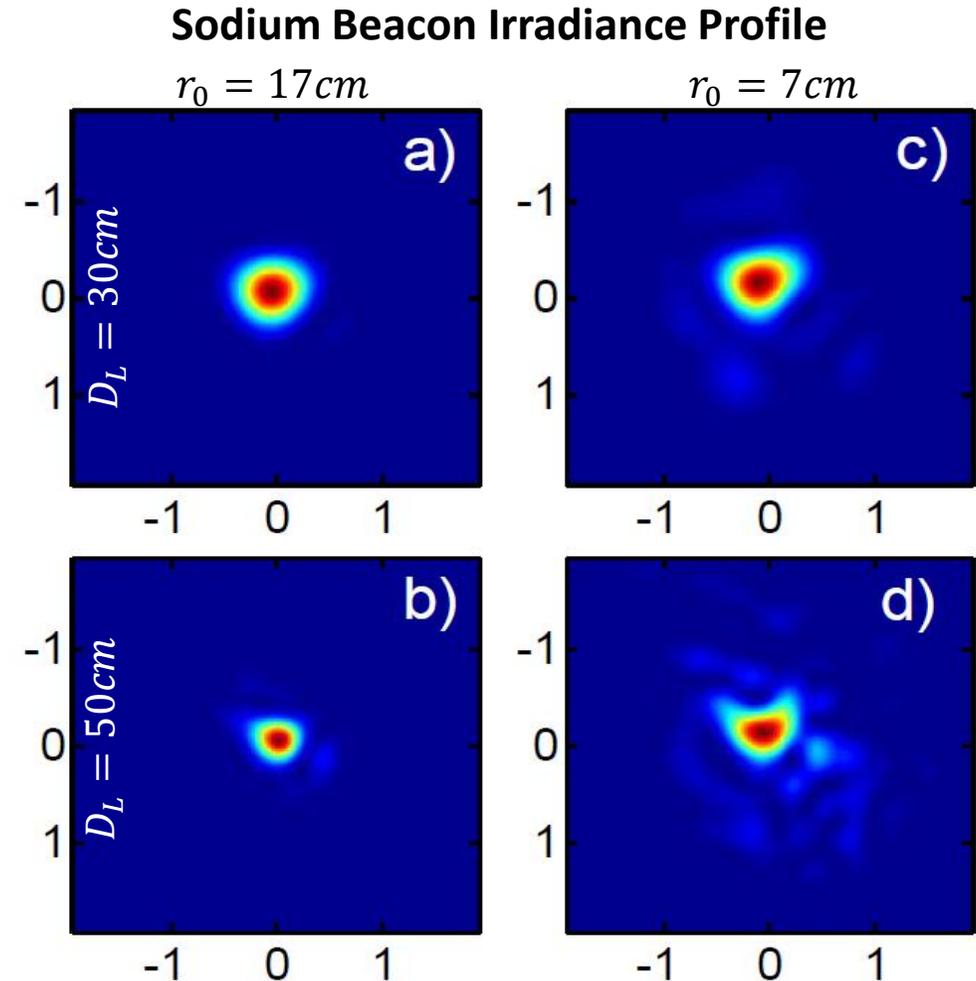
QUESTIONS?





Partially Coherent Laser Beacon

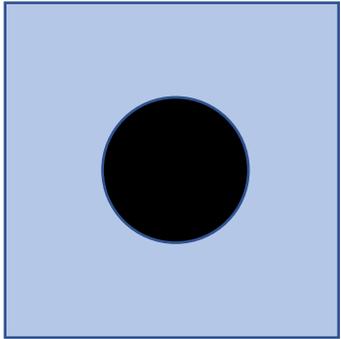
- Correct atmospheric turbulence on laser launch telescope
 - Uplink correction on 1st LGS AO system
 - Limited research into benefits:
 - Focus on SHWFS [4]
 - Limited aperture sizes [4]
- Benefits of uplink correction
 - WFS sensitivity vs. spatial coherence
 - Optimal WFS design vs. spatial coherence



(Holzlöhner, et al., 2008)



Opaque on glass



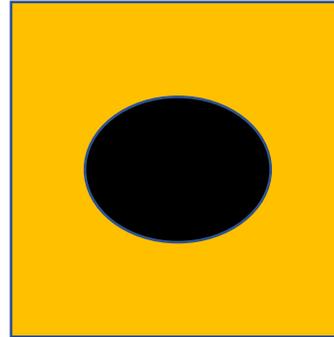
Pros:

- Surface quality should be good

Cons:

- Not chromatic

Opaque on Mirror



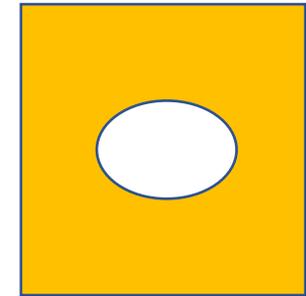
Pros:

- Chromatic

Cons:

- Unclear if coating process will effect surface quality

Hole Drilled in Mirror



Pros:

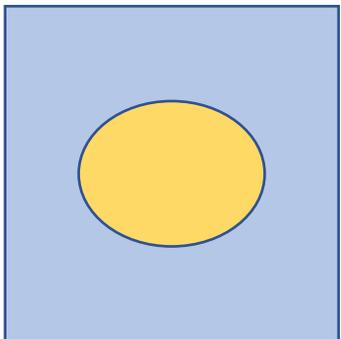
- Enables Focal Plane WFS

- Chromatic

Cons:

- Custom optic (could be expensive)
- Coring could cause surface defects

Mirror on glass v1



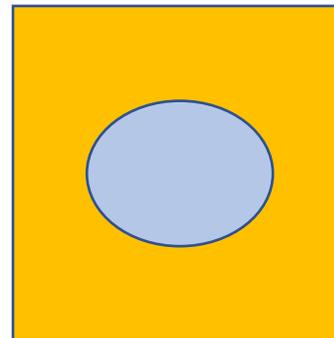
Pros:

- Enables Focal Plane WFS

Cons:

- Not fully chromatic
- Unclear surface quality of mirror deposition

Mirror on Glass v2



Pros:

- Enables Focal Plane WFS

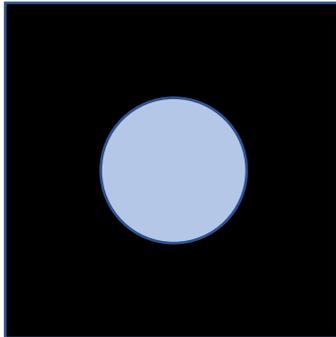
- Easiest alignment

Cons:

- Not fully chromatic
- Unclear surface quality of mirror deposition

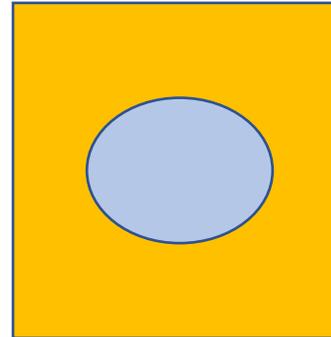


Opaque on Glass



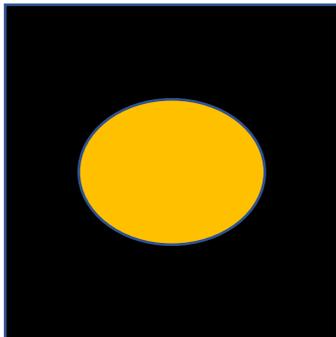
- Pros:
- Surface quality should be good
- Cons:
- Not chromatic

Mirror on Glass



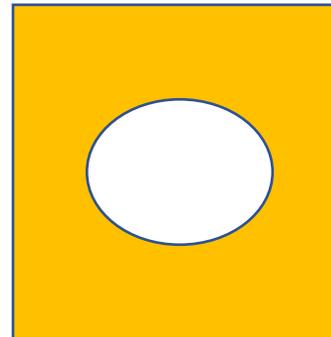
- Pros:
- Enables Pupil plane WFS
- Cons:
- Not fully chromatic
 - Unclear surface quality of mirror deposition

Opaque on Mirror



- Pros:
- Chromatic
- Cons:
- Unclear if coating process will effect surface quality

Hole in Mirror



- Pros:
- Enables Pupil plane WFS
 - Fully chromatic
- Cons:
- Unclear surface quality
 - Will we need complex mask shapes when considering spiders?