Lecture 14

Extreme Adaptive Optics

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AY 289

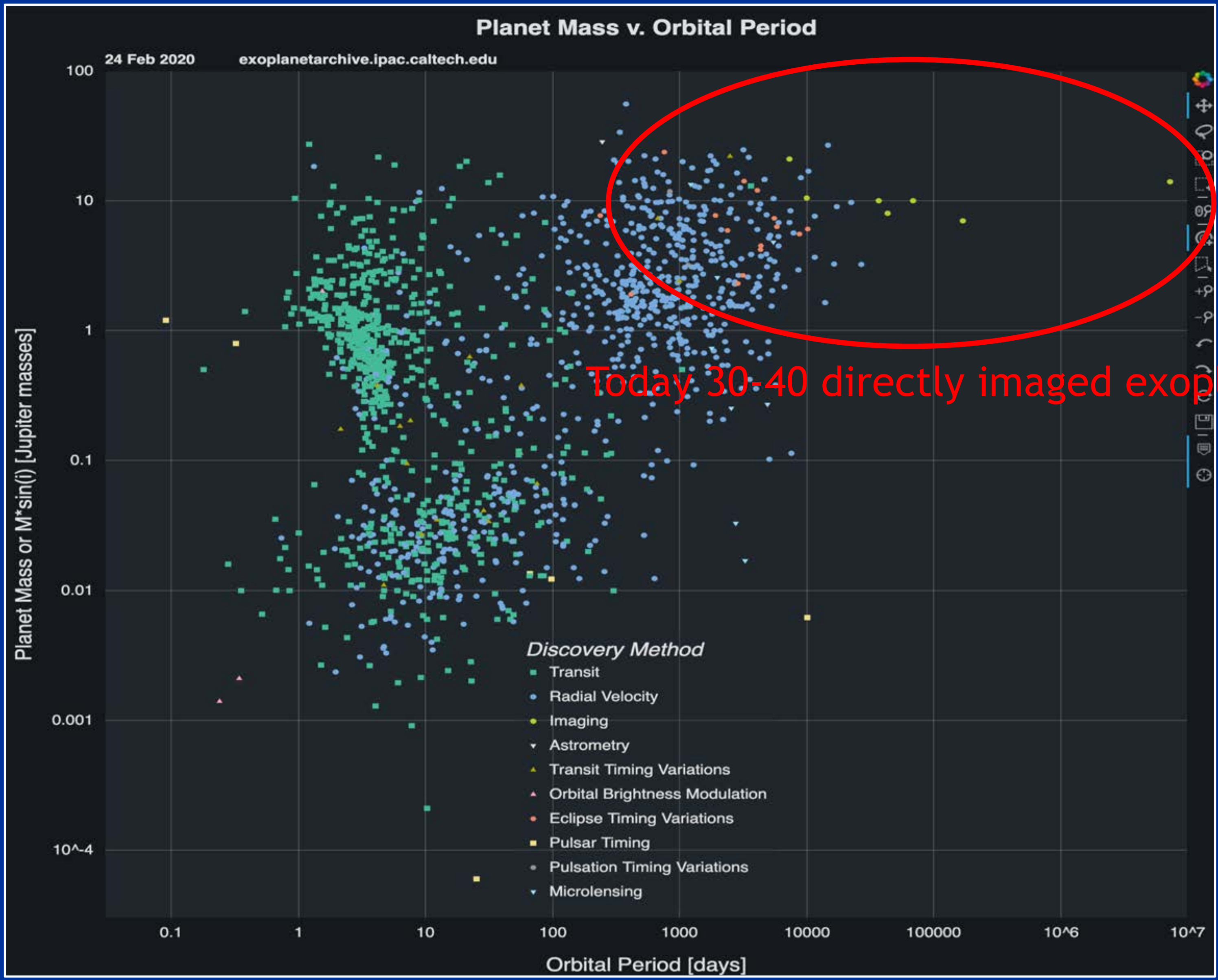
February 26, 2020

Based in part on slides from
Bruce Macintosh and Sandrine Thomas

Outline

- Science parameter space for Exoplanet systems
- Direct imaging of exoplanets with ground-based AO
- Approaches to high-contrast imaging with current telescopes: Angular Differential Imaging
- Coronagraphs to block light from host star
- Gemini Planet Imager: one example of the current state of the art
- Recent scientific results: directly imaged planets and disks

Exoplanets as of 2020



Working requirements for direct imaging

- **Contrast between flux from host star and planet**
  - Depends on wavelength, type of planet, type of star, distance of planet from star, etc.

- **Order of magnitude for sun-like star**
  - Earth: visible 10^{-9} to 10^{-10}
    mid-IR 10^{-7}
  - Required contrast ratios for gas giants and for M dwarf host starts are not so stringent (10^{-6} ?)

- **Inner Working Angle typically a few λ / D**

Ground based Instruments: Exoplanet direct imaging instruments

GPI

Macintosh et al, 14

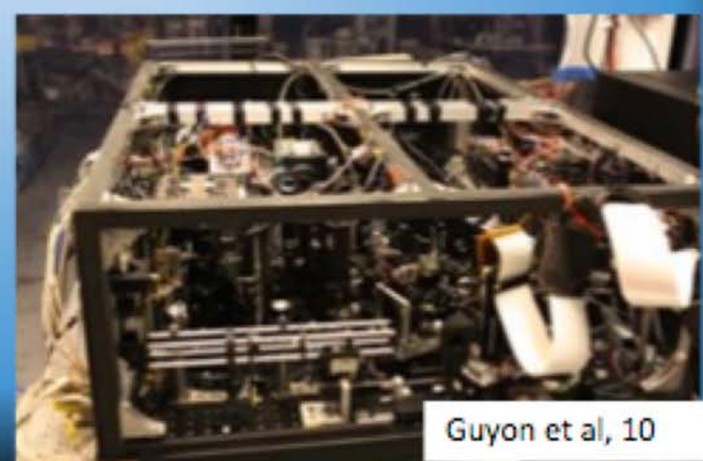
SPHERE

Beuzit et al, 14

P1640

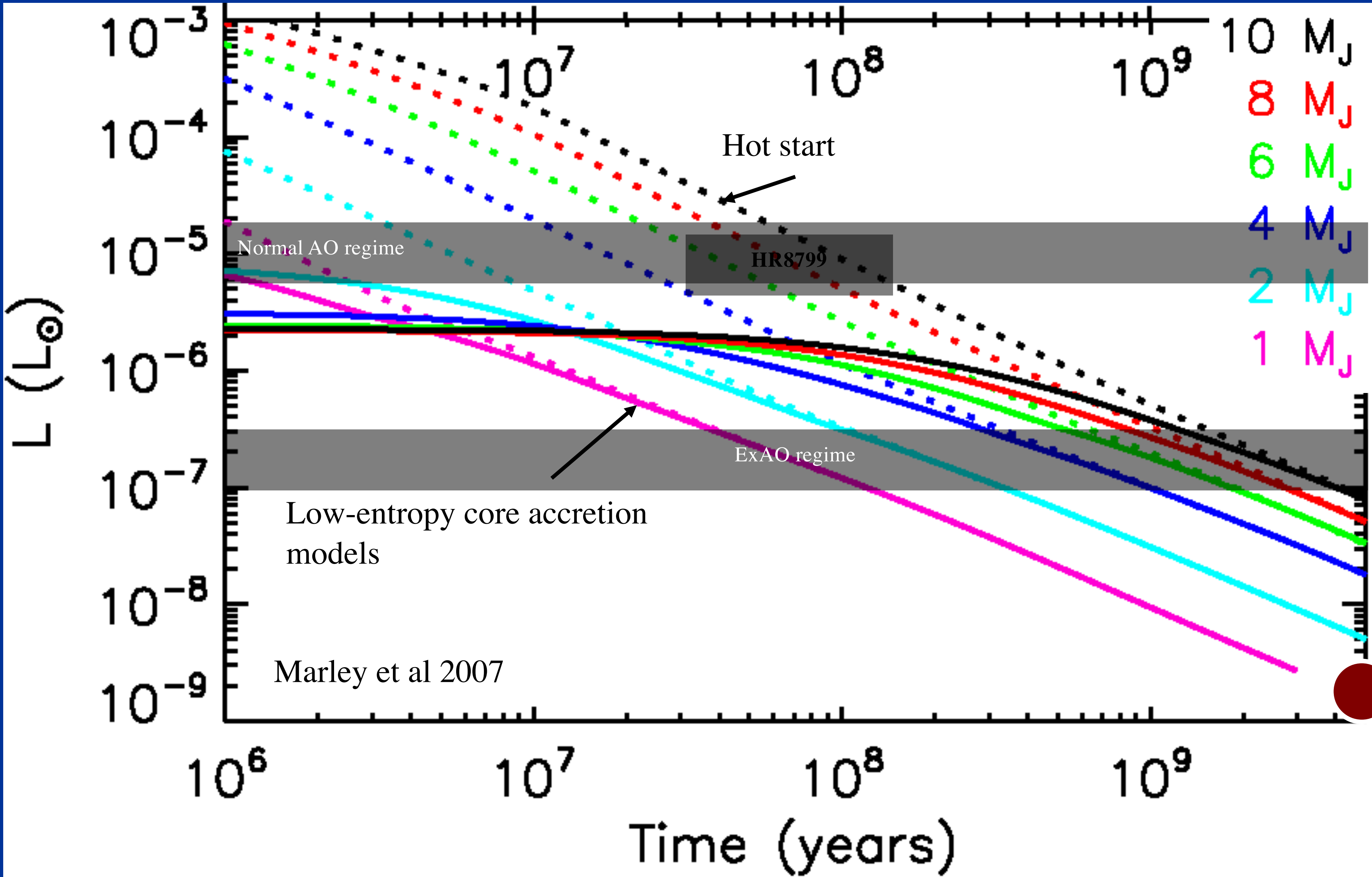
Hinkley et al, 08

SCExAO

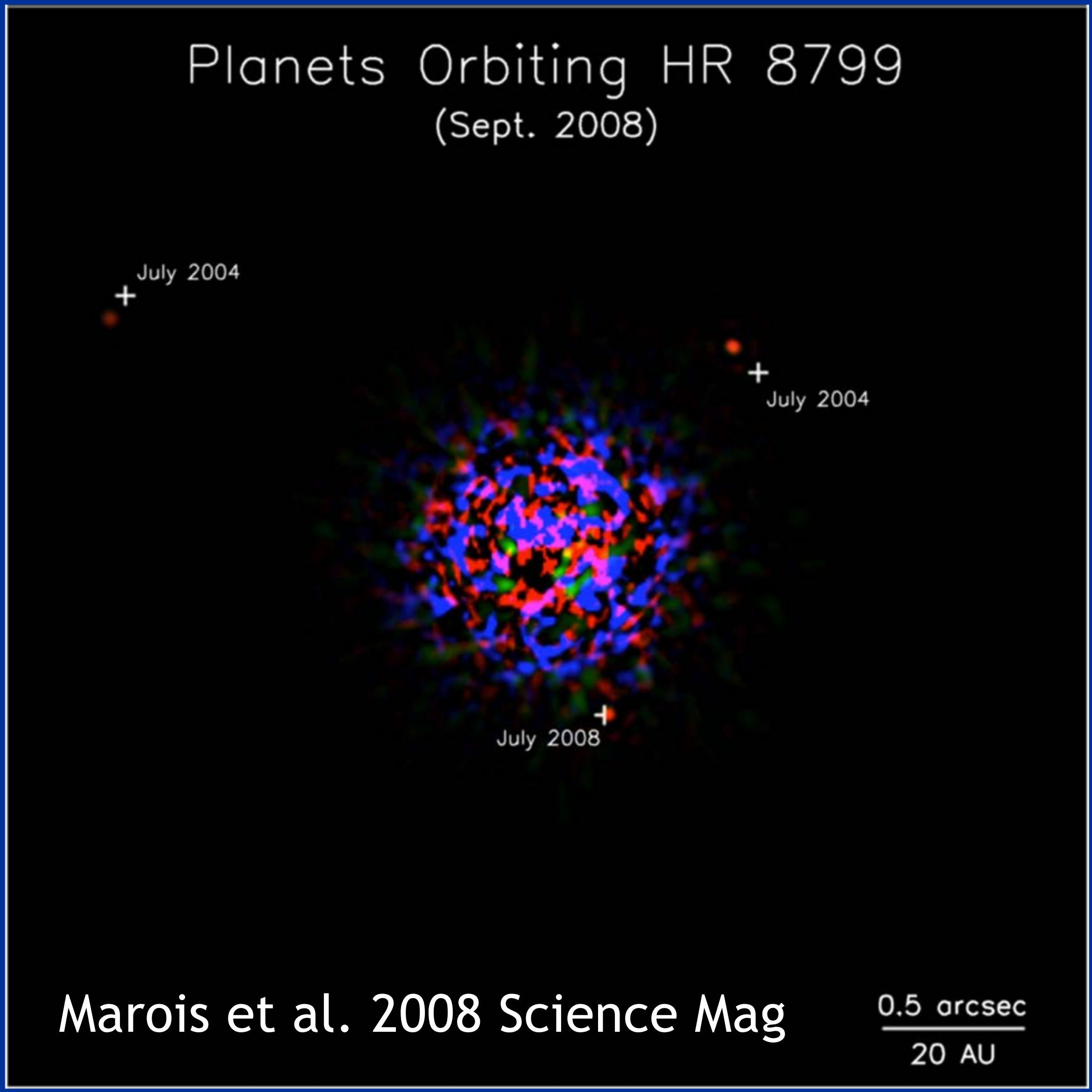


Guyon et al, 10

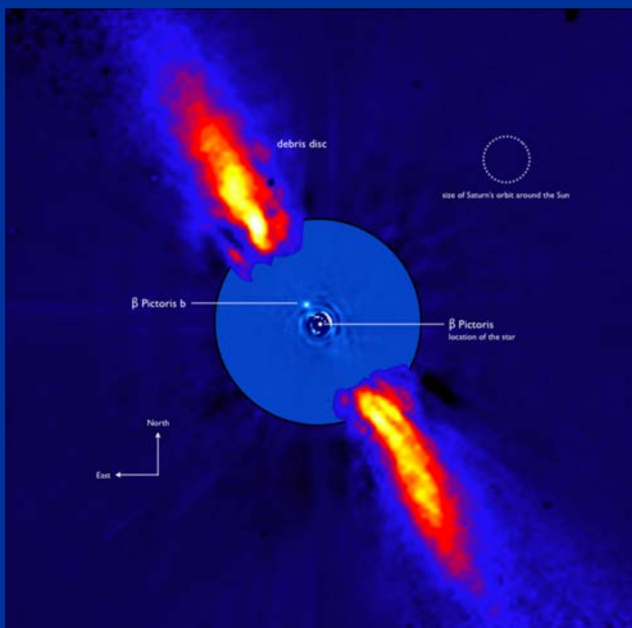
Brightness of ExAO targets: Gas Giants

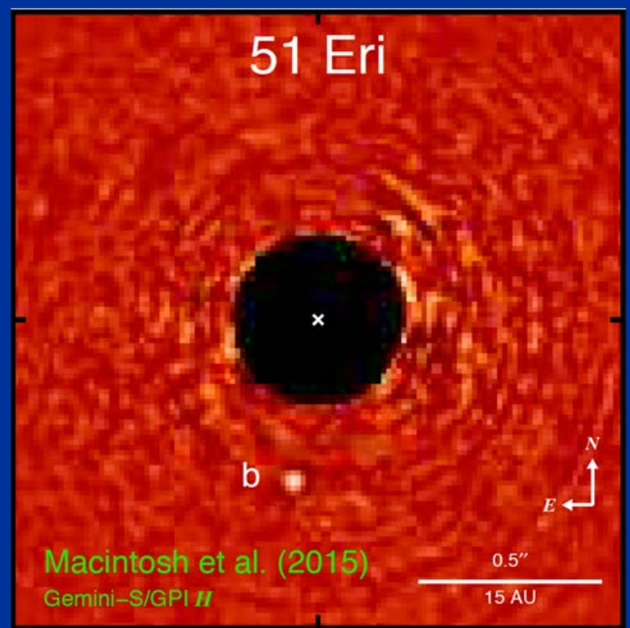


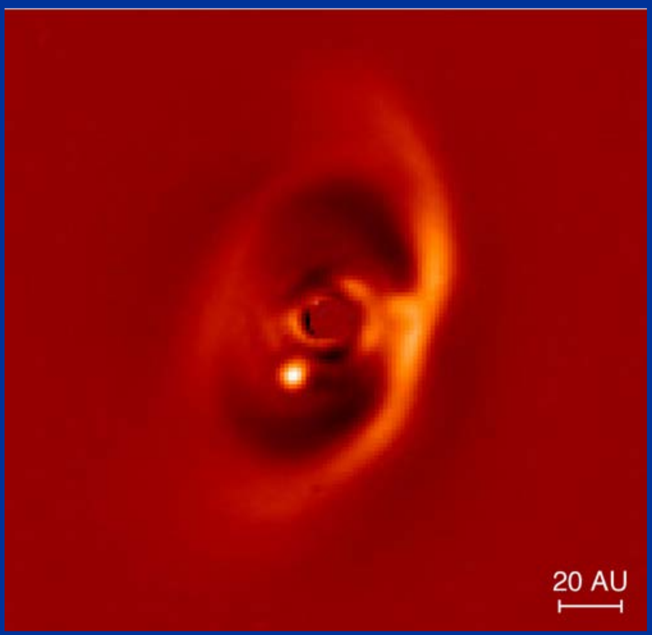
First images of an extrasolar planetary system (Keck and Gemini AO)



More directly imaged exoplanets







Beta Pic b

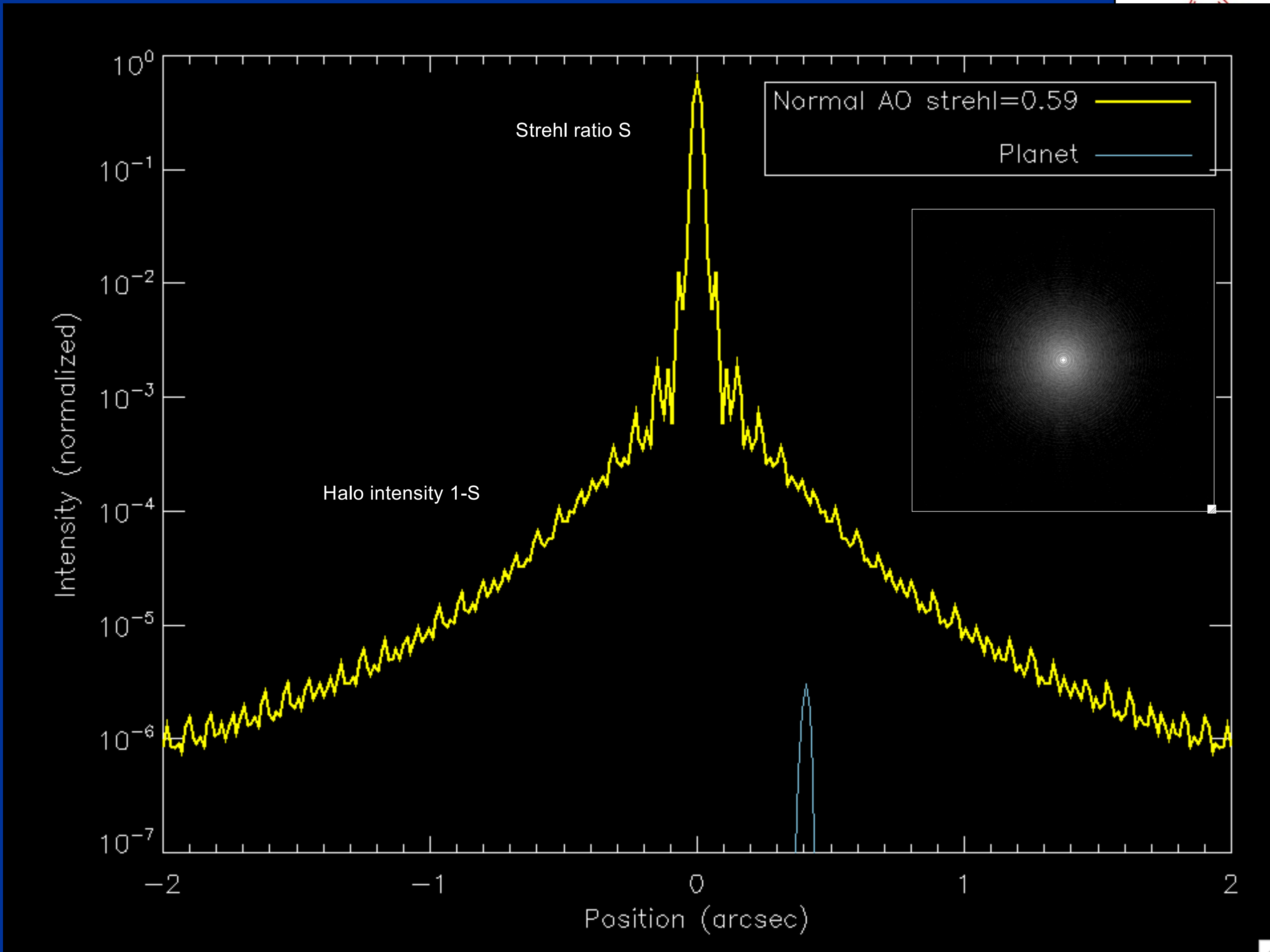
VLT NACO

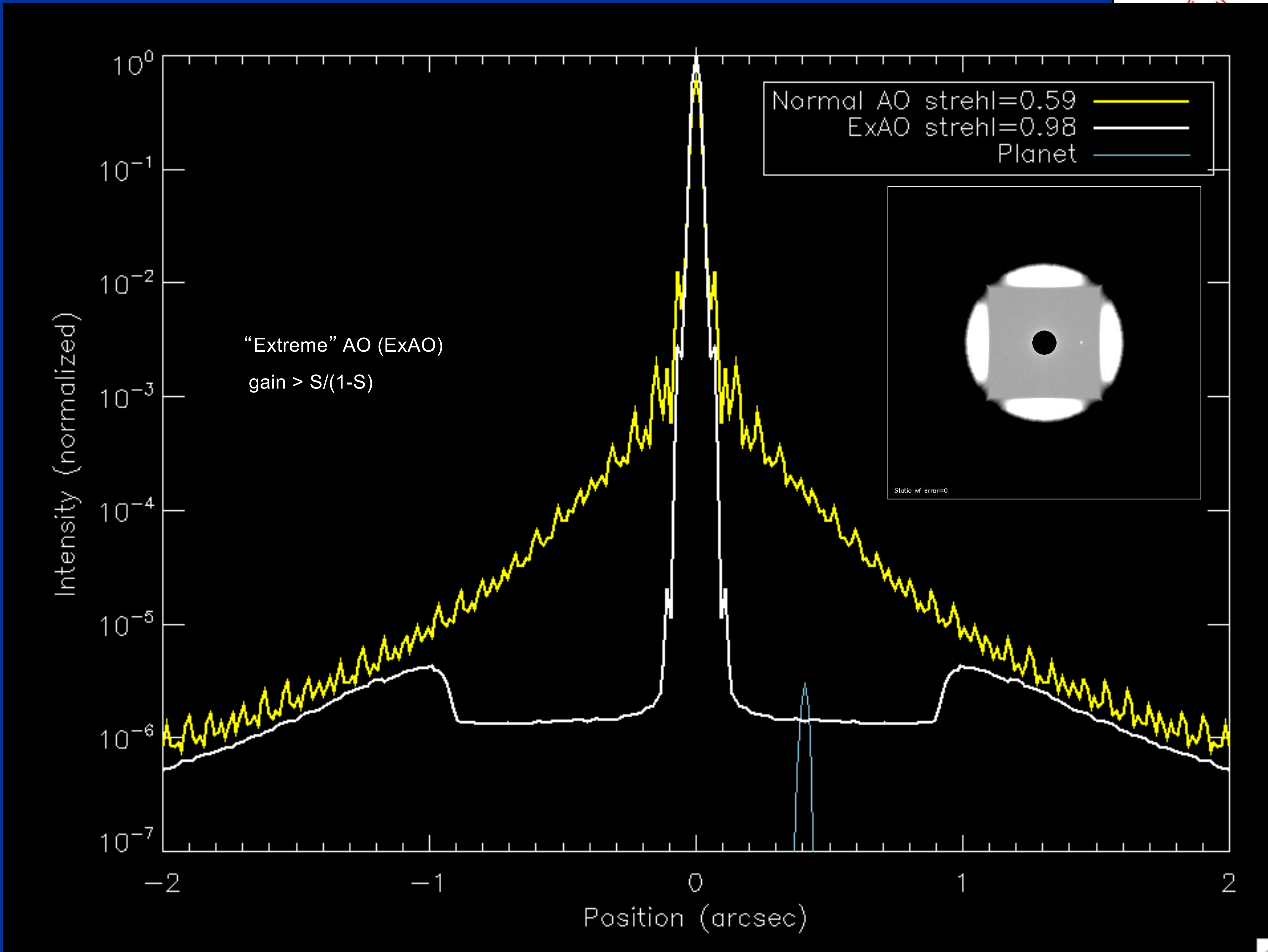
51 Eri b

GPI

PDS 70

SPHERE

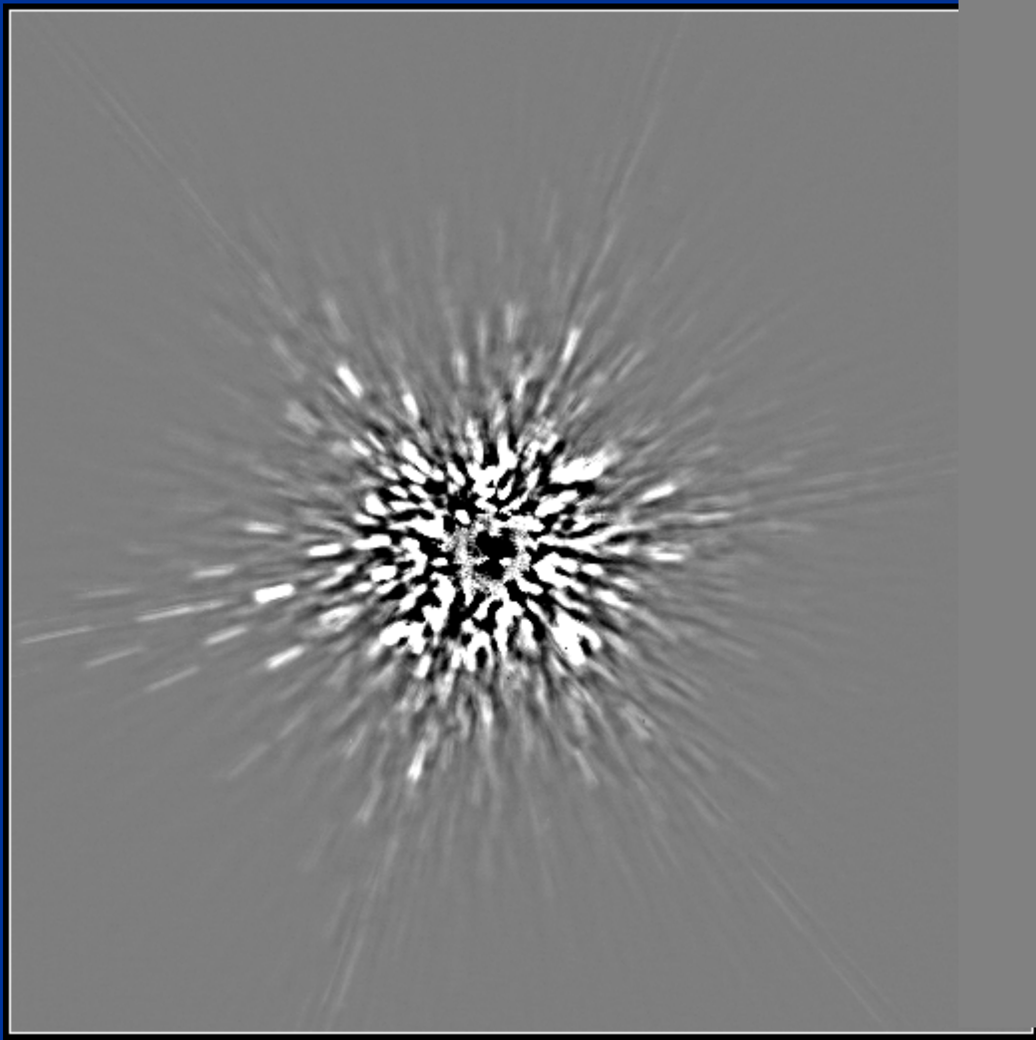

Normal AO strehl=0.59
Planet
Strehl ratio S
Halo intensity 1-S
Intensity (normalized)
Position (arcsec)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
−2
−1
0
1
2

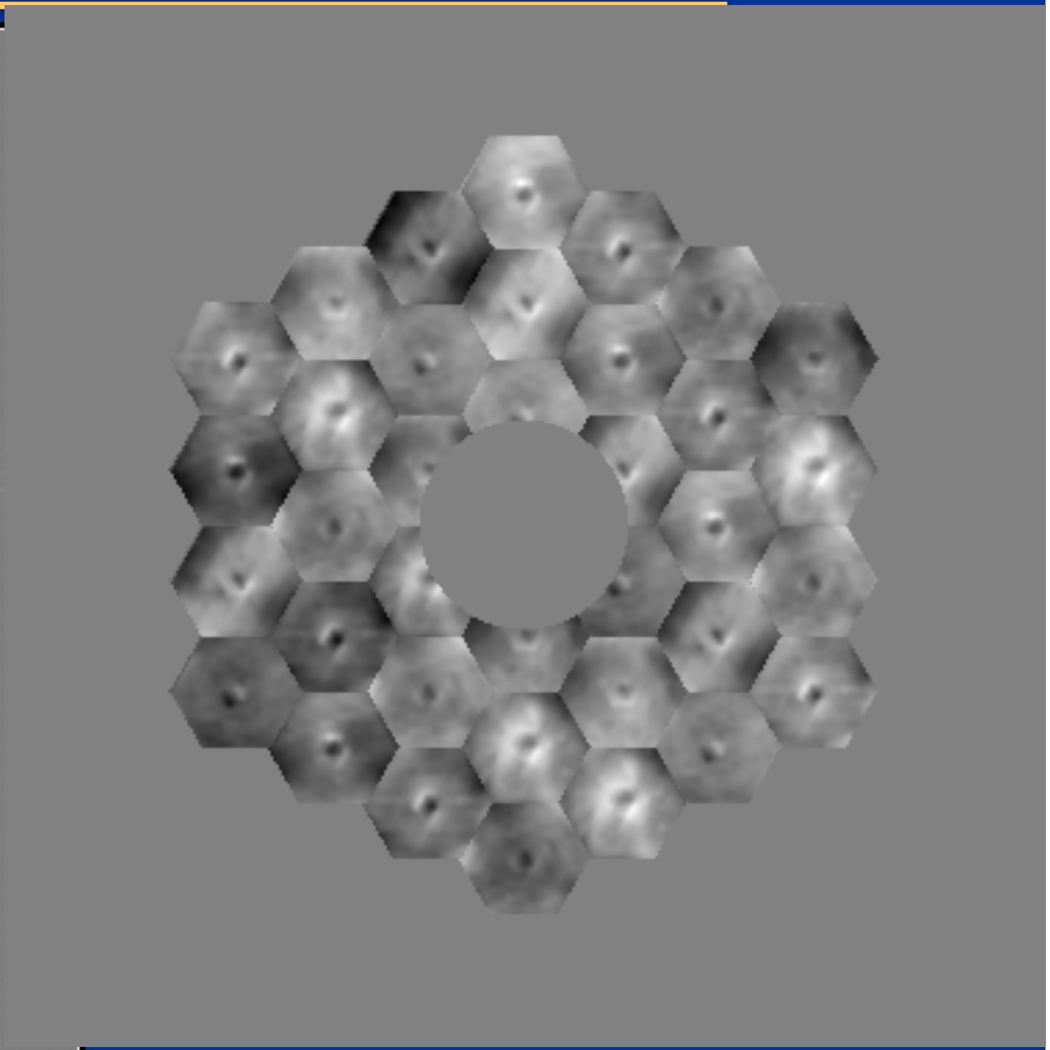


Normal AO strehl=0.59
ExAO strehl=0.98
Planet
Static wf error=0
"Extreme" AO (ExAO)
gain > S/(1-S)
Intensity (normalized)
Position (arcsec)

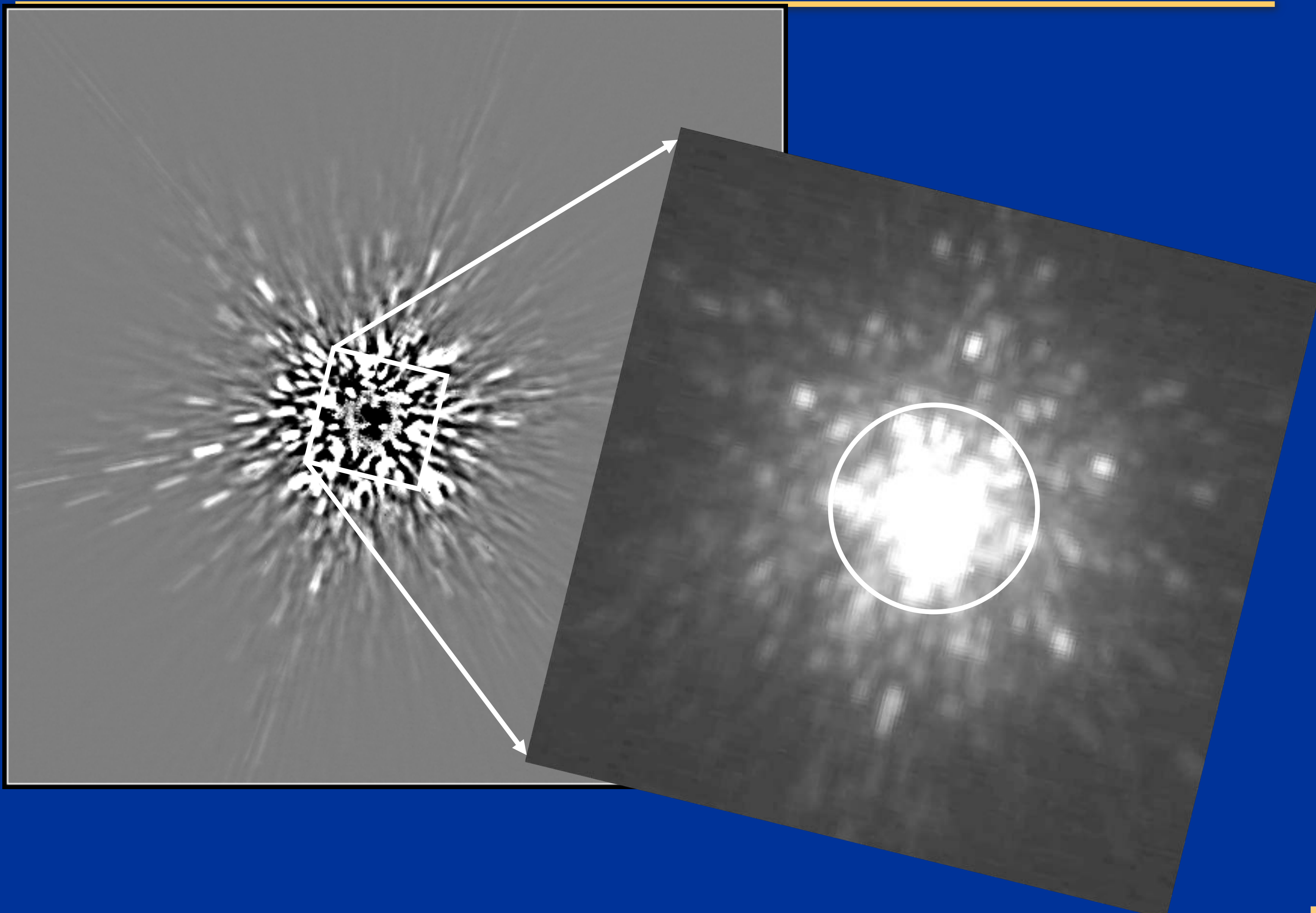
But - this assumes no non-common path errors and no AO artifacts

Keck AO Image of a bright star





Inner part of image - artifacts due to AO optics



Angular Differential Imaging

Image 1

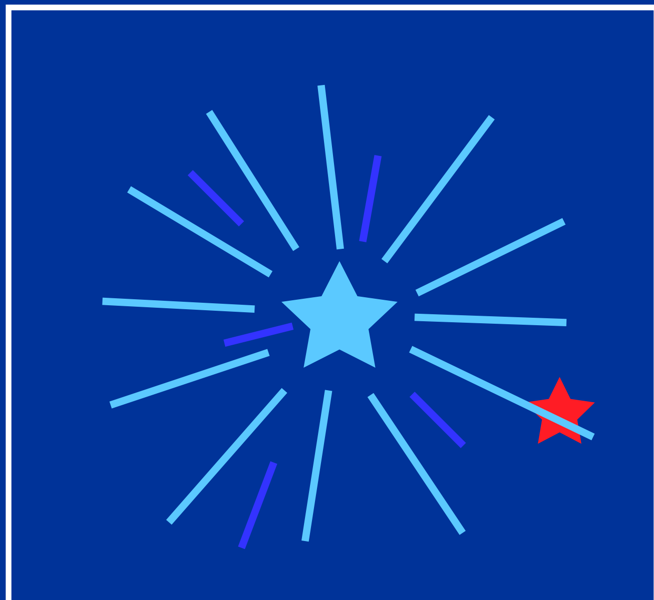
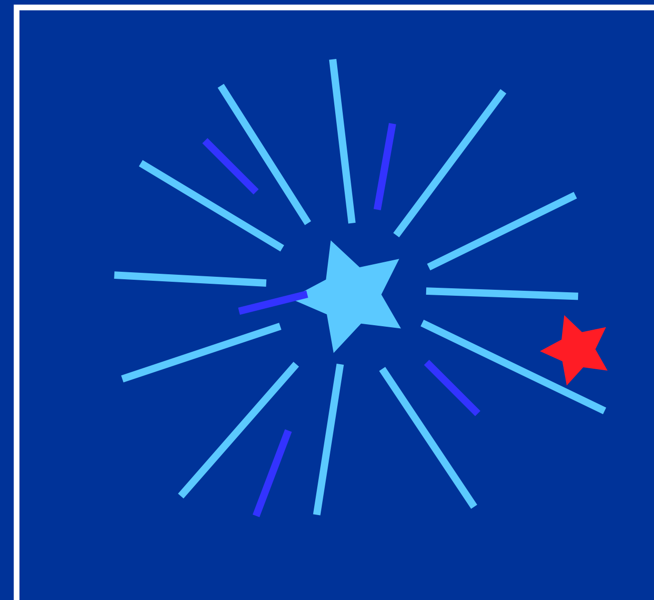
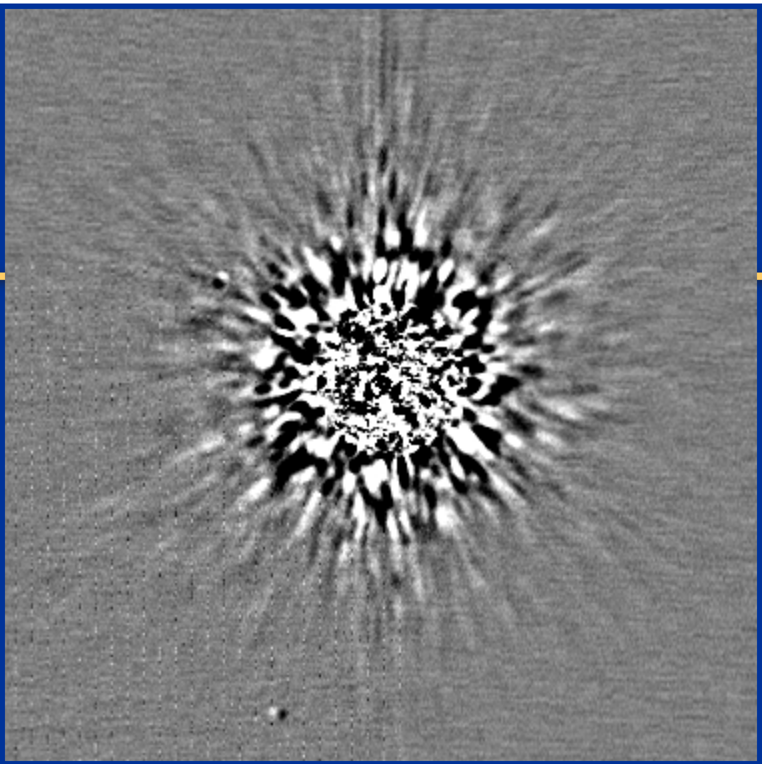


Image 2 (+ 5 minutes)



Subtraction

Marois et al 2006



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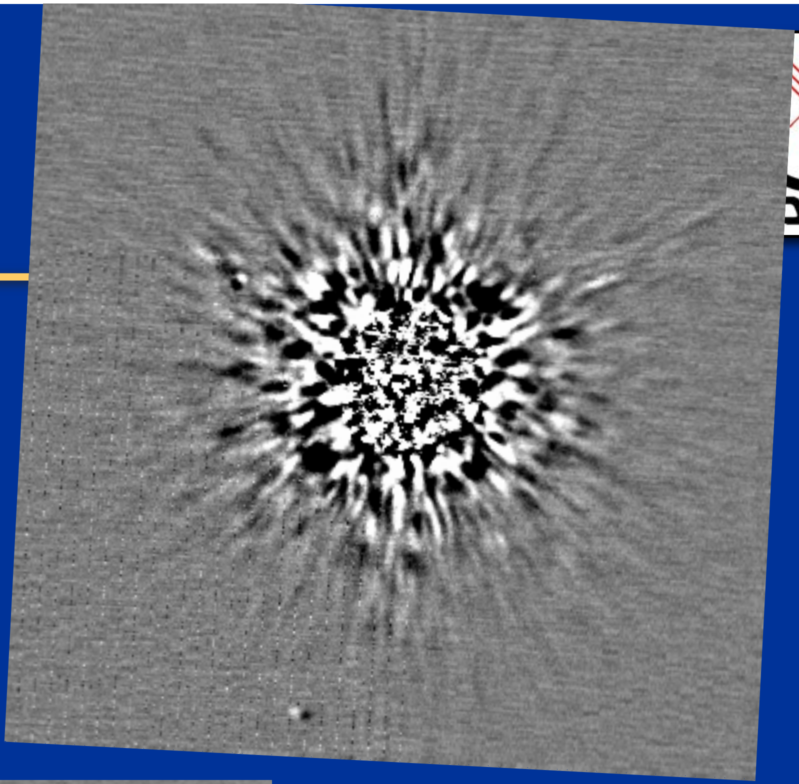

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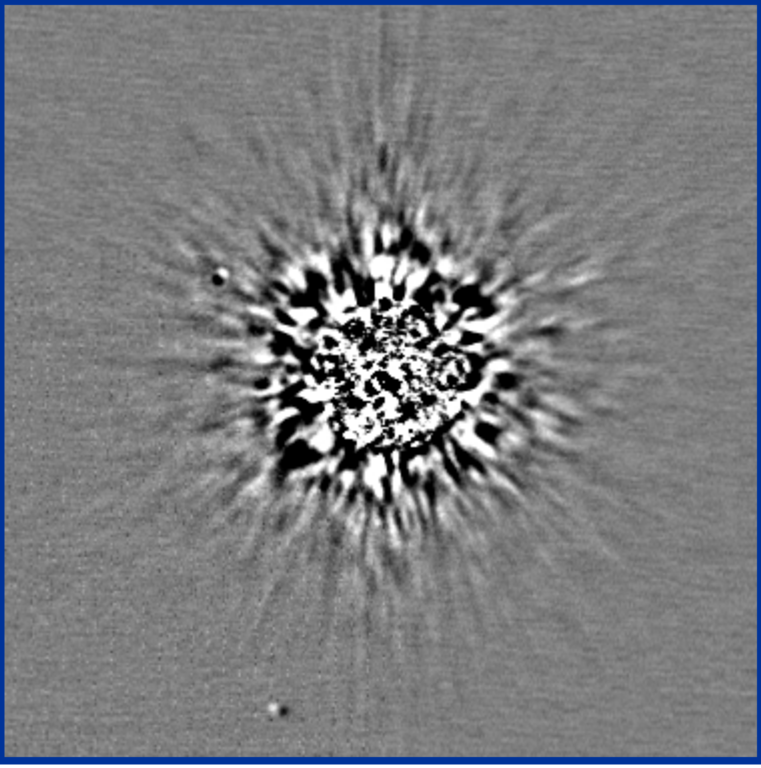
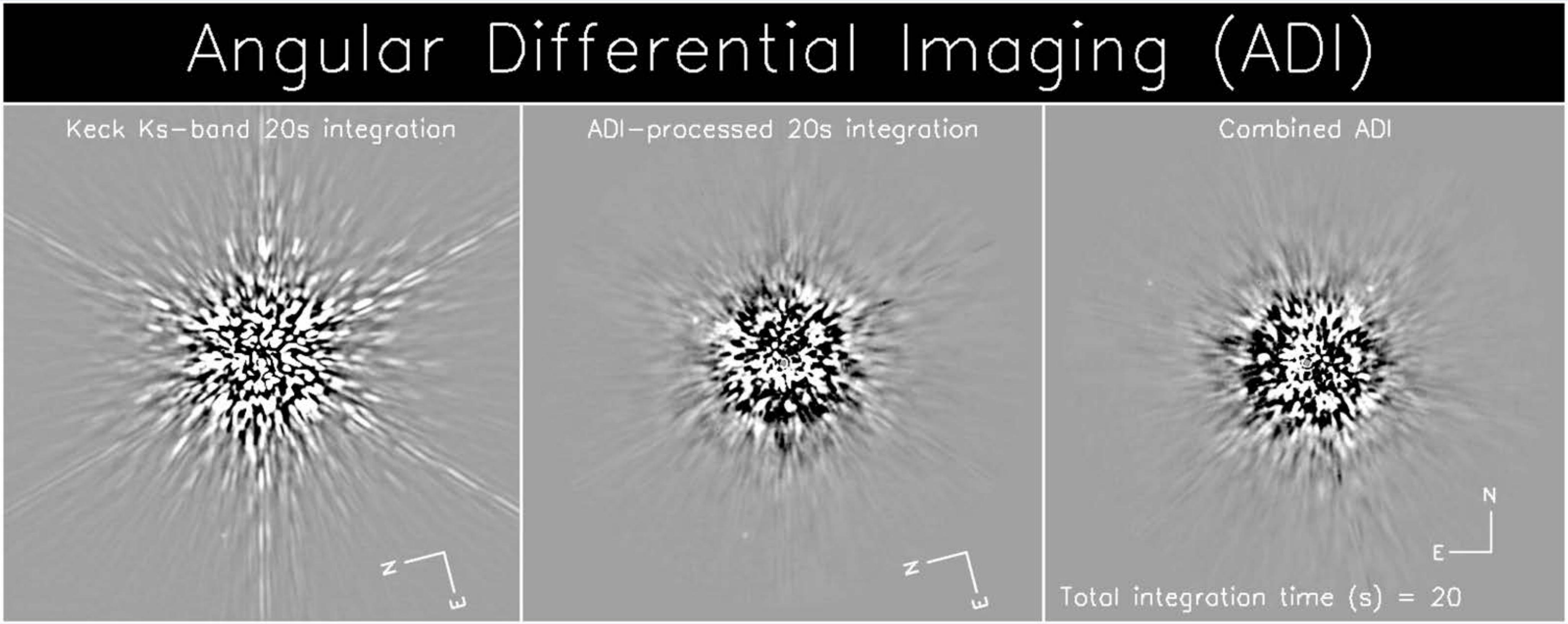


Image processing to suppress light from host star



Marois et al.

From Olivier Guyon's Annual Reviews paper

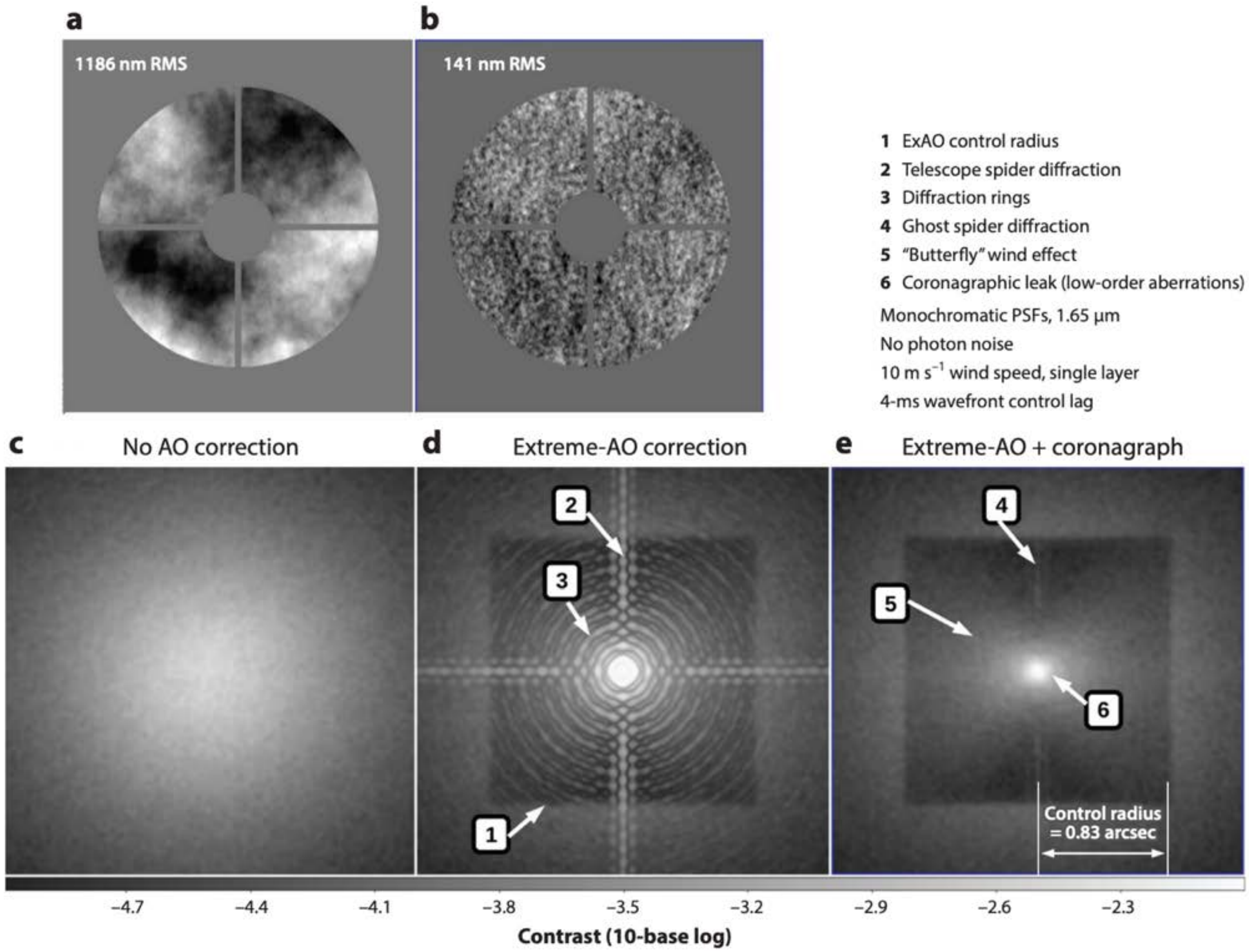
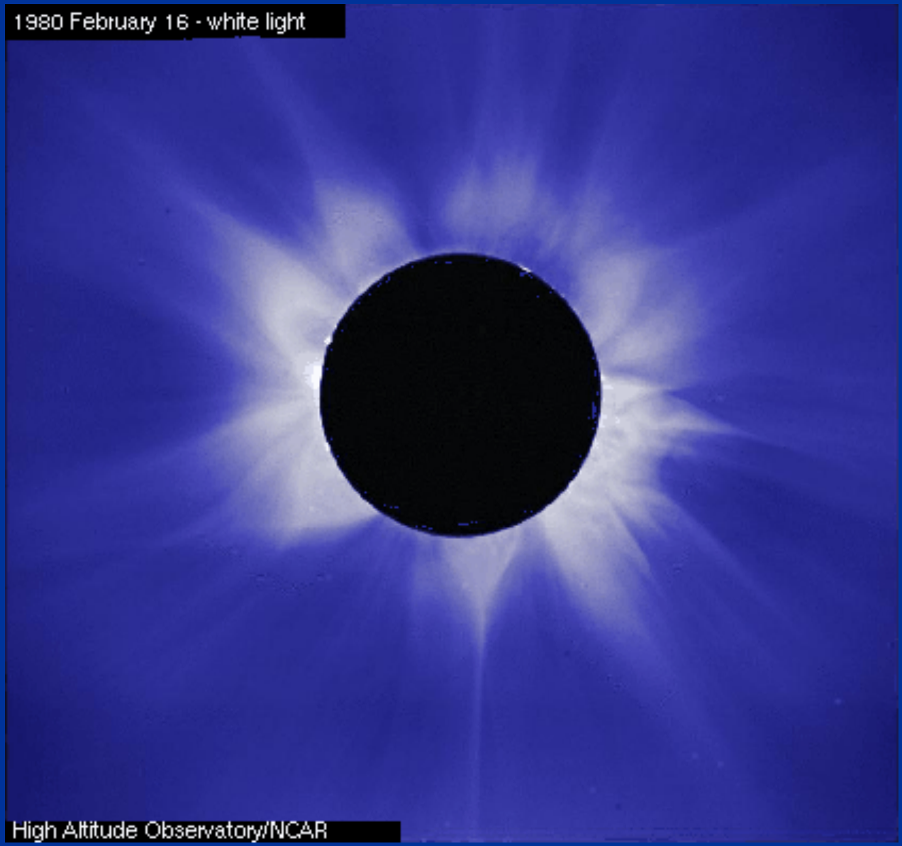


Figure 7

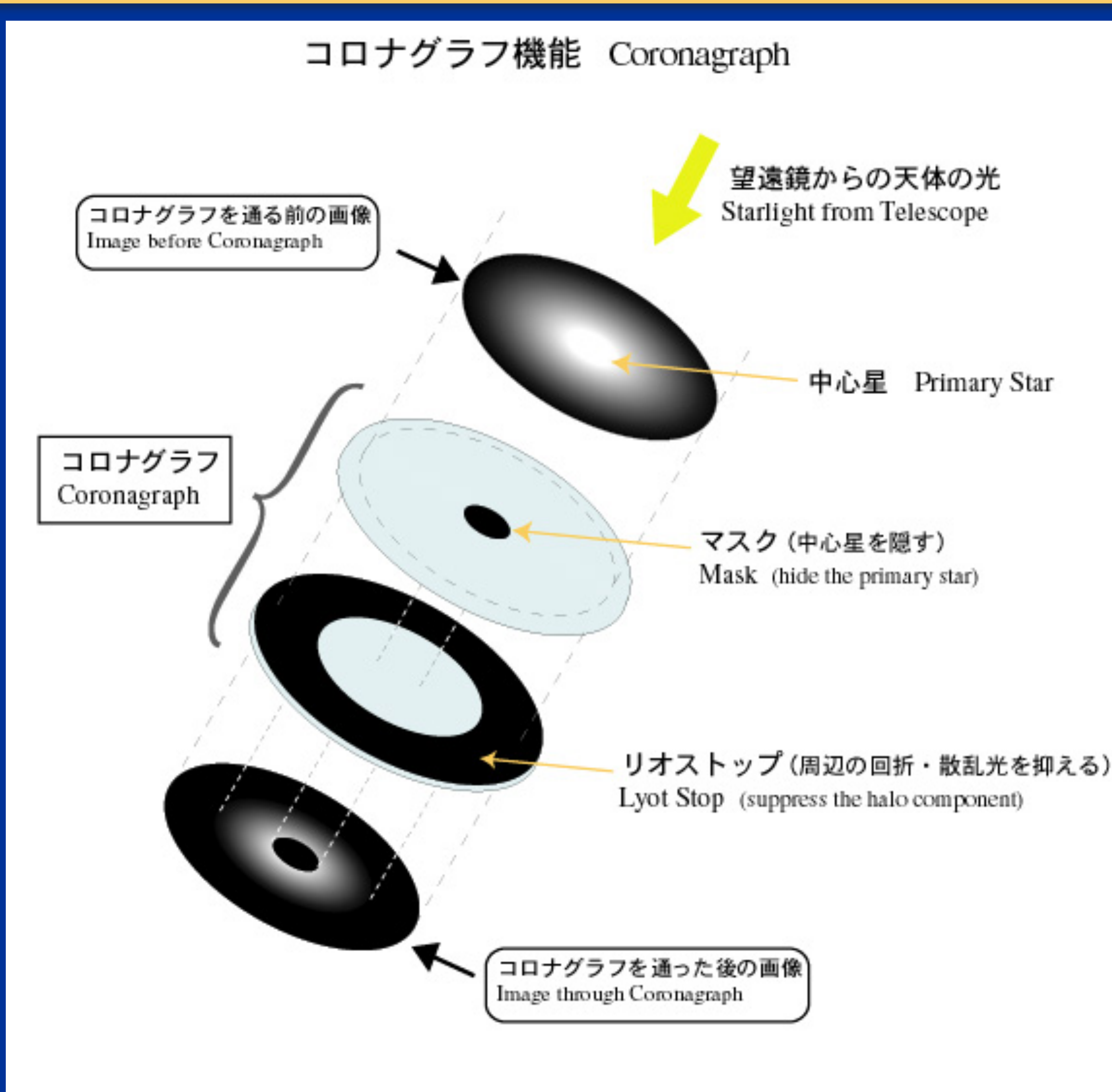
Image formation in an ExAO system. (*a*) Uncorrected atmospheric wavefront. (*b*) ExAO correction reduces the RMS aberration level from 1186 nm to 141 nm. Without correction, the PSF is an arcsecond-large cloud of speckles (*c*). The ExAO correction carves out a high-contrast region where telescope diffraction is the main source of flux (*d*). This diffraction term is removed by adding a coronagraph (*e*). Abbreviations: AO, adaptive optics; PSF, point spread function; RMS, root mean square.

Coronagraphs

- Invented by Bernard Lyot in 1930 for studying the corona of the sun without waiting for an eclipse
- Block the sun's light with a circular mask in the focal plane
- Problem: diffraction from the sharp edges of the mask

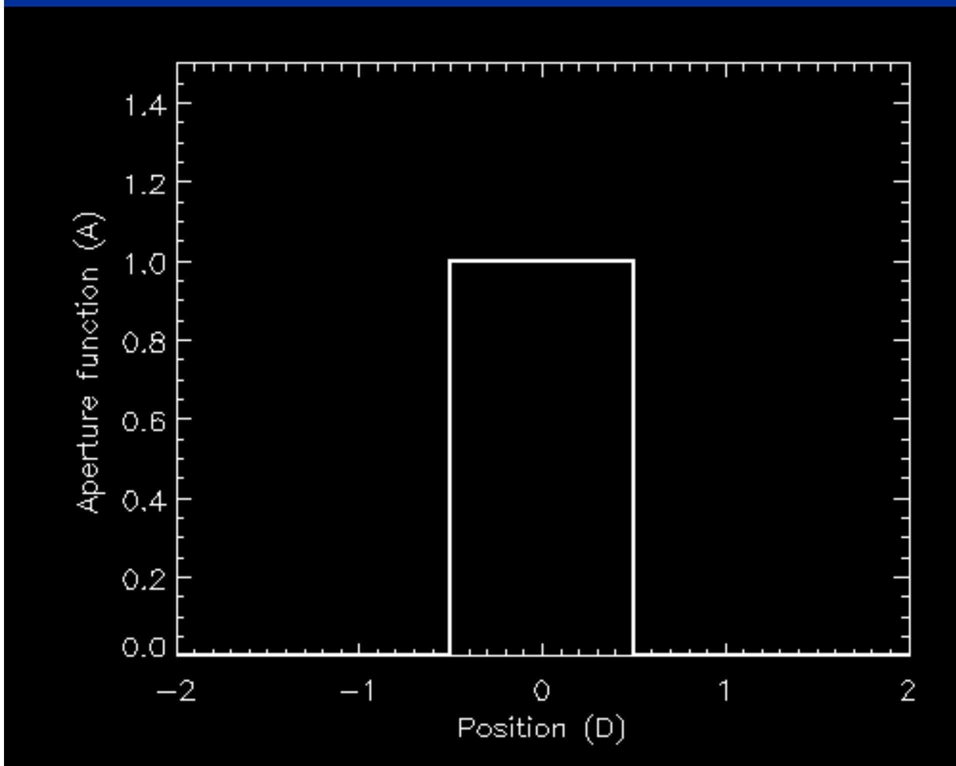


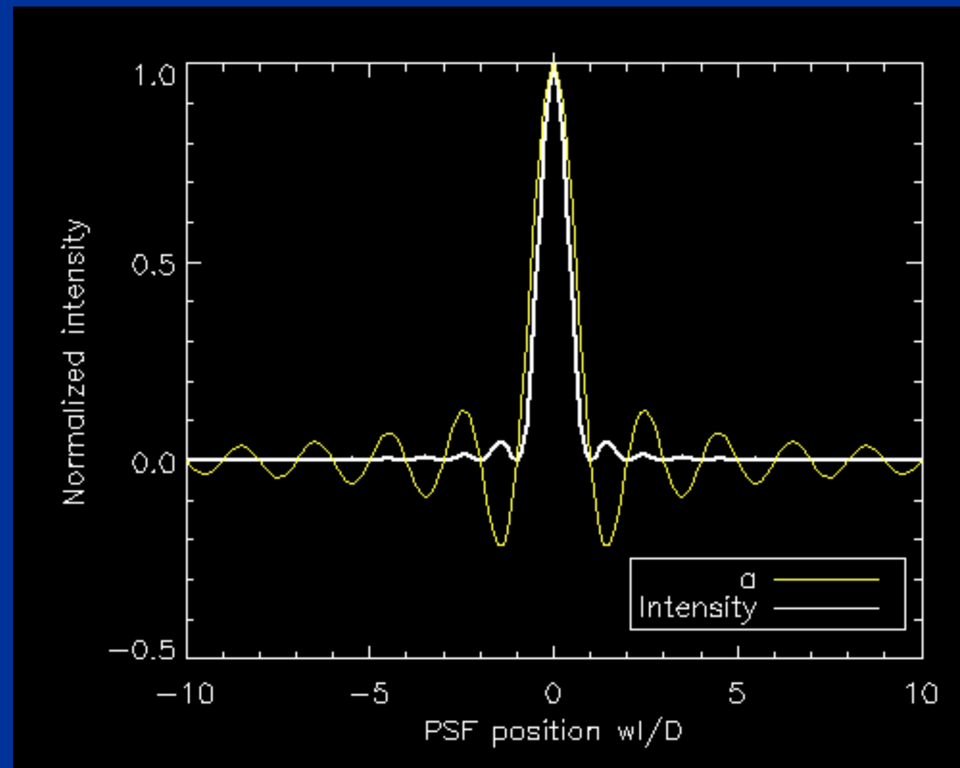
Cartoon of Lyot Coronagraph

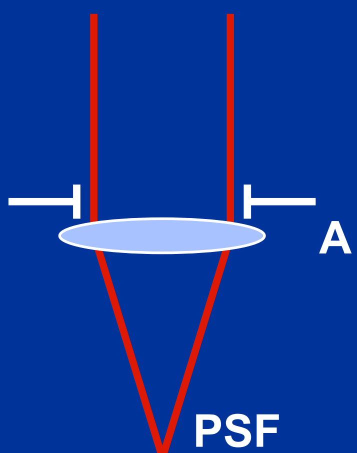


Credit: Subaru website

How can we control diffraction?

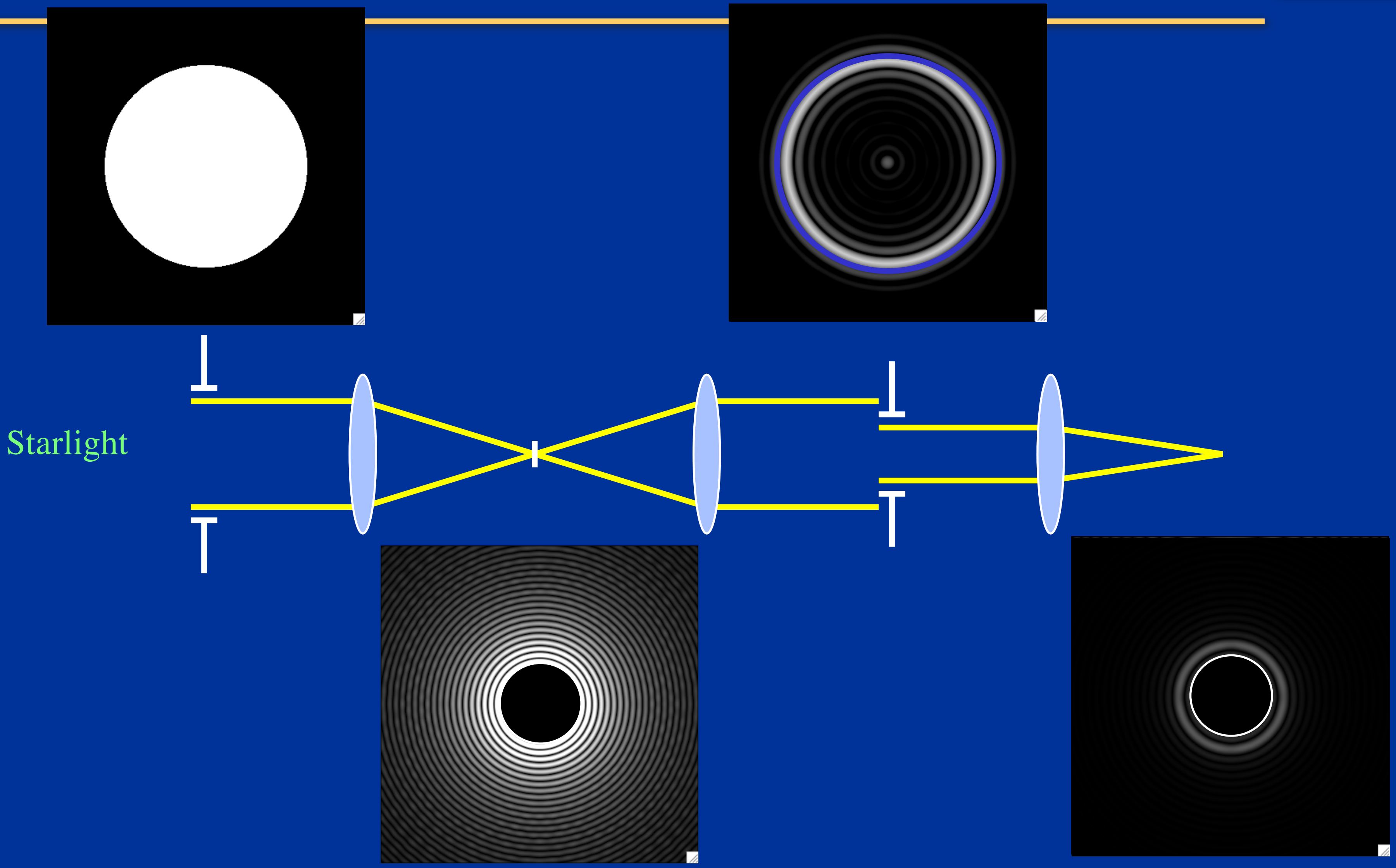




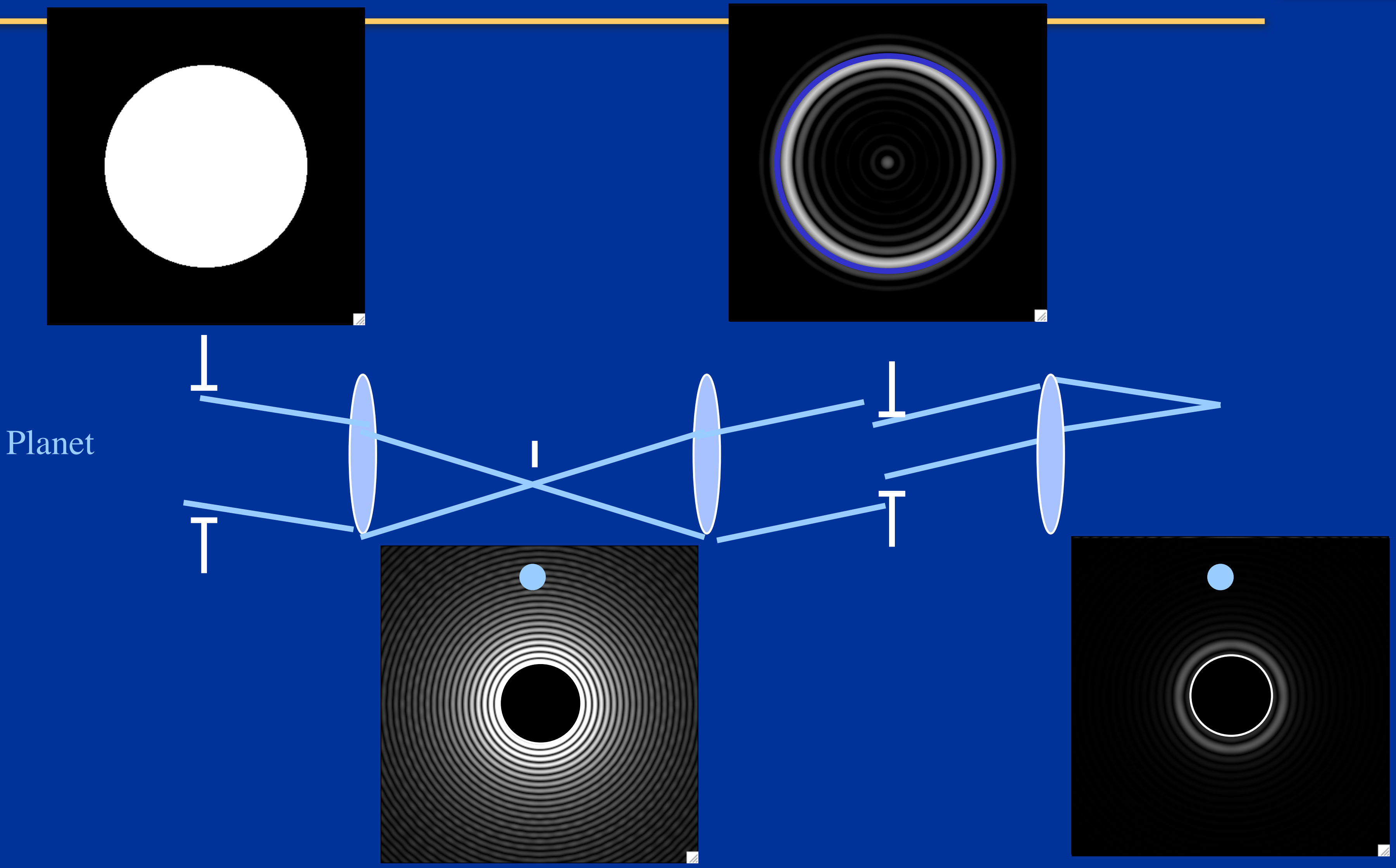


$$PSF=|FT(A)|^2$$

Lyot coronagraph (Lyot, 1933)



Lyot coronagraph (Lyot, 1933)



Sivaramakrishnan et al 2001 has a nice 1-d analysis of how this works

Large variety of coronagraph ideas

- Lyot family:
  - Basic: Lyot 1939 MNRAS 99, 538; Sivaramakrishnan et al 2001
  - Band-limited: Kuchner & Traub 2003
  - Apodized: Soummer 2005 Ap.J. 618, L161
- Apodizers:
  - Shaped-pupil: Kasdin et al 2003, Kasdin et al 2005 Applied Optics 44 1177, etc.
  - Phase-induced apodizer: Guyon et al 2005 Ap.J. 622, 744
- Interference / wave-optics
  - 4-quadrant phase mask: Rouan et al 2000 PASP 777 1479
  - Nulling interferometer/coronagraphs: Mennesson et al. 2004 Proc. SPIE 4860, 32
- Optical Vortex Coronagraphs
- Most practical coronagraphs only work at > 3-5 λ/D
- Control of phase errors is as important as controlling diffraction

Coronagraph also improves stability

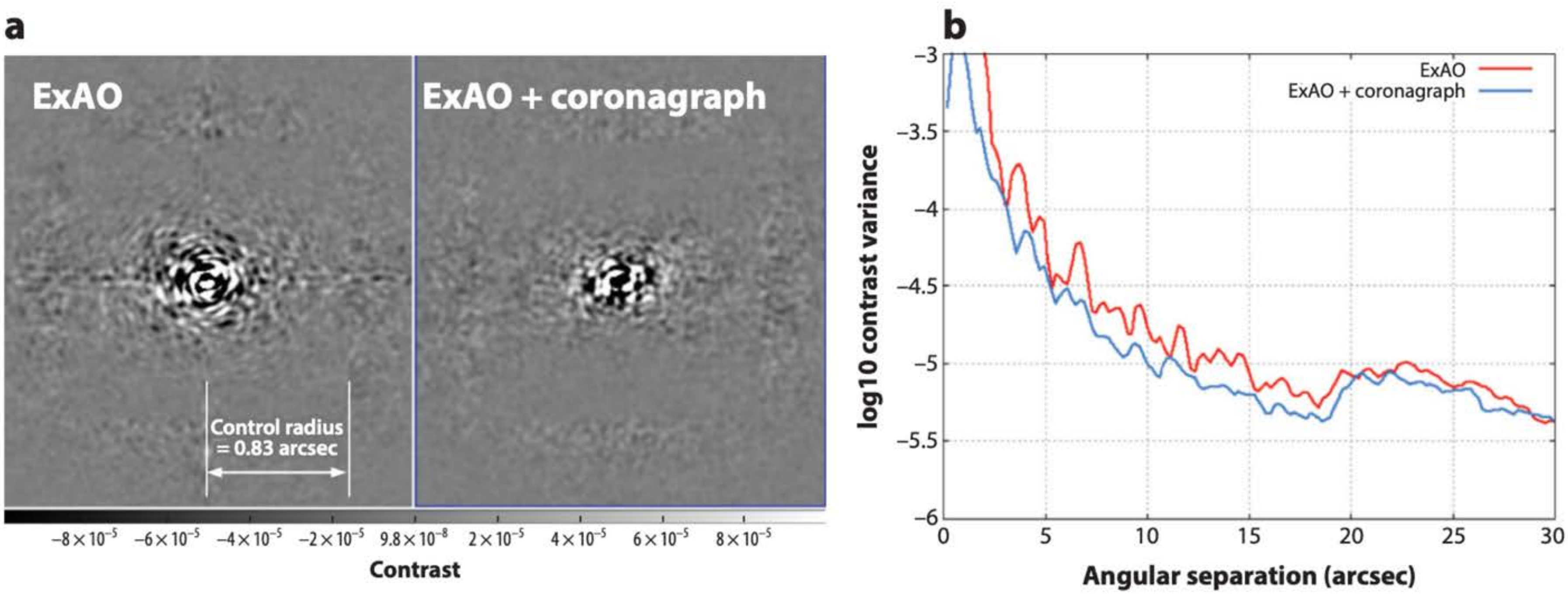


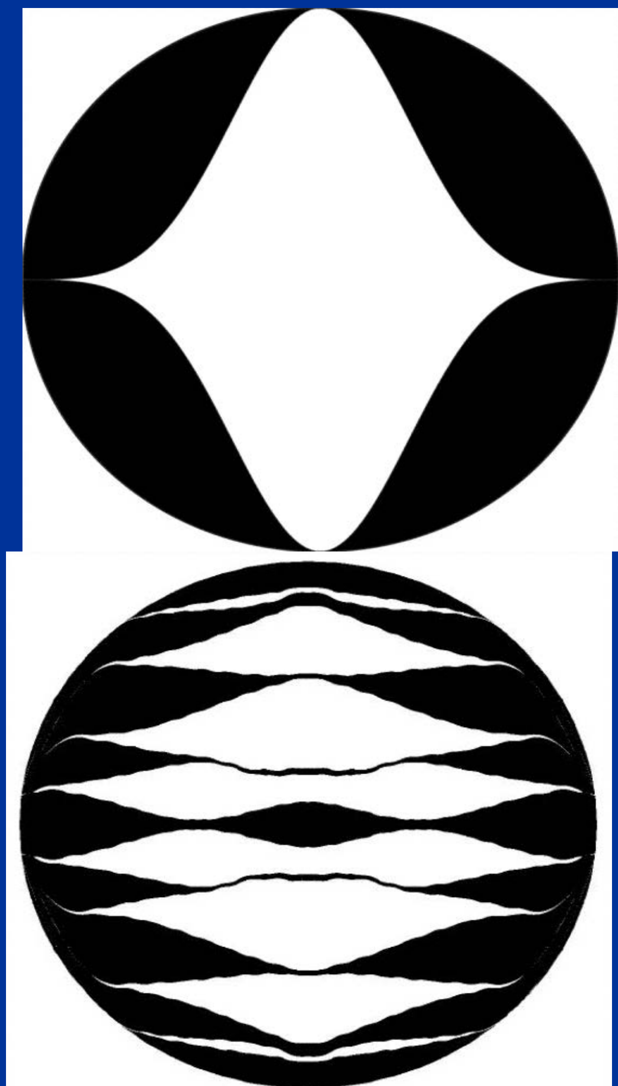
Figure 9

(*a*) ExAO PSF stability without and with coronagraph (exposure time per PSF = 100 coherence times) and (*b*) numerical simulation without photon noise. PSF stability is improved by adding a coronagraph to the ExAO system. See **Table 3** for simulation details. Abbreviation: PSF, point spread function.

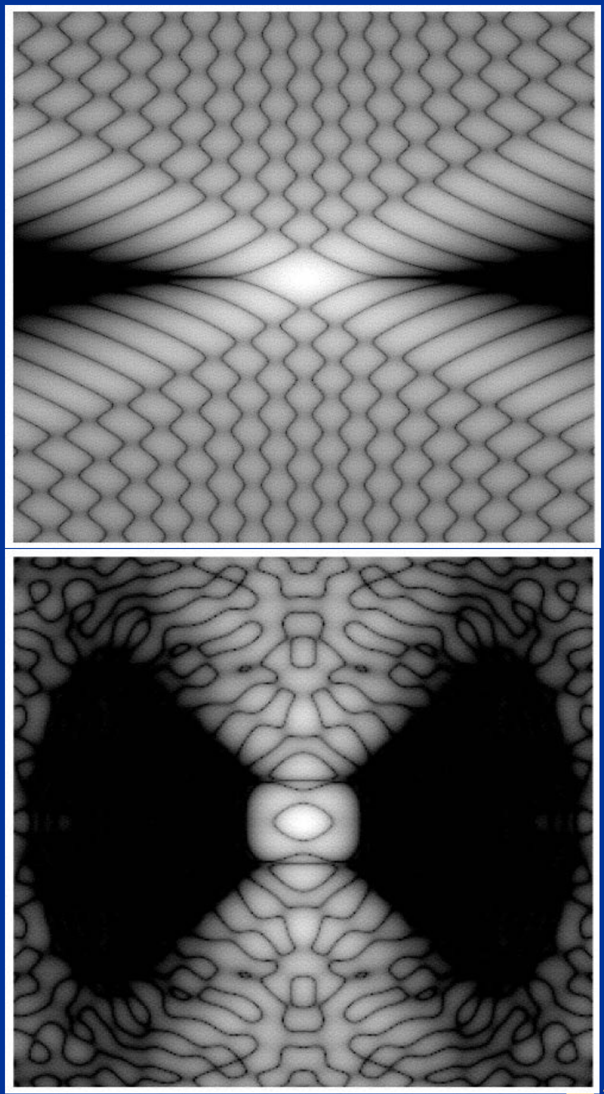
From Olivier Guyon Annual Reviews paper

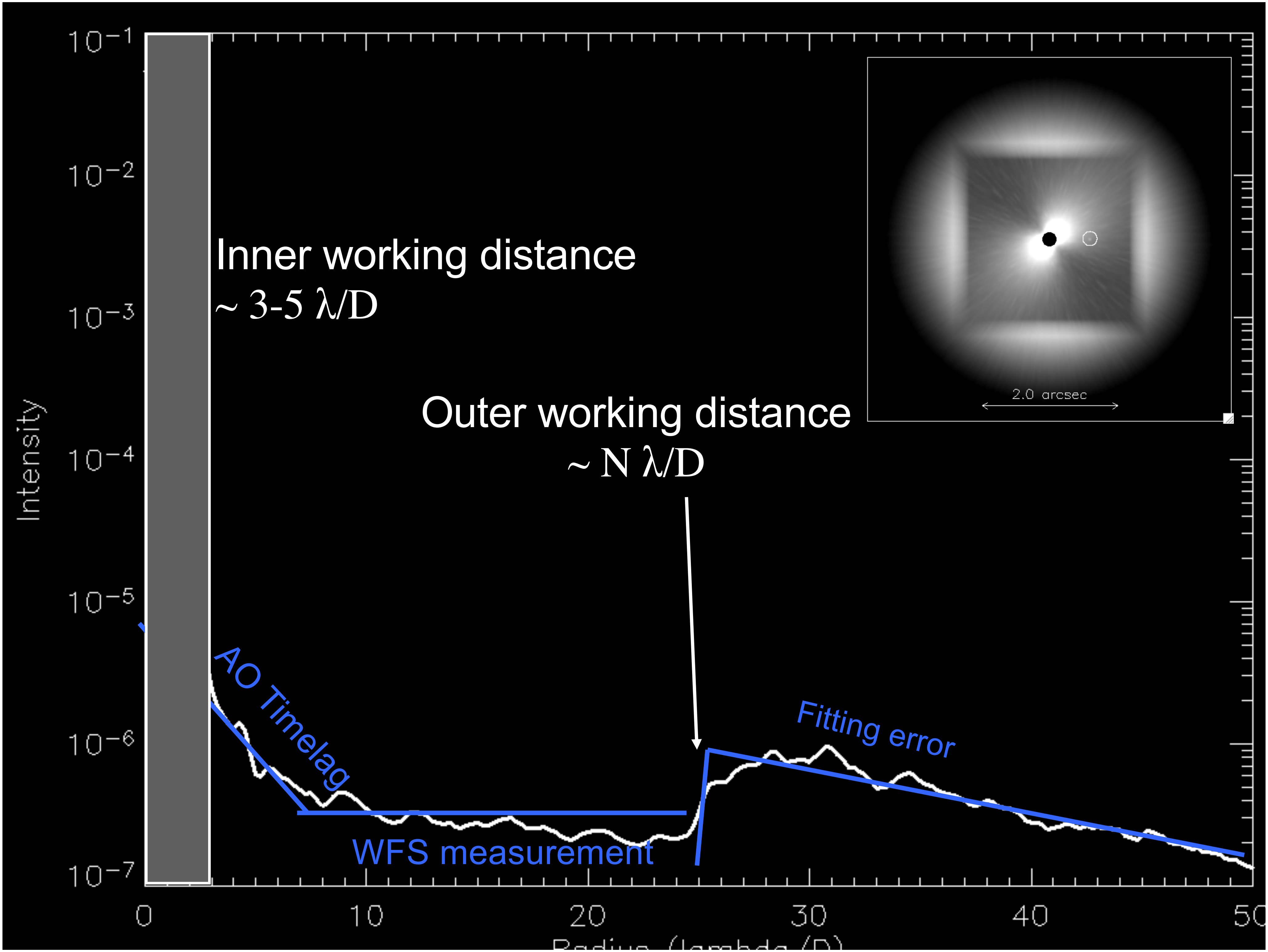
Shaped-pupil coronagraphs to make dark holes (Kasdin et al. 2003)

Pupil



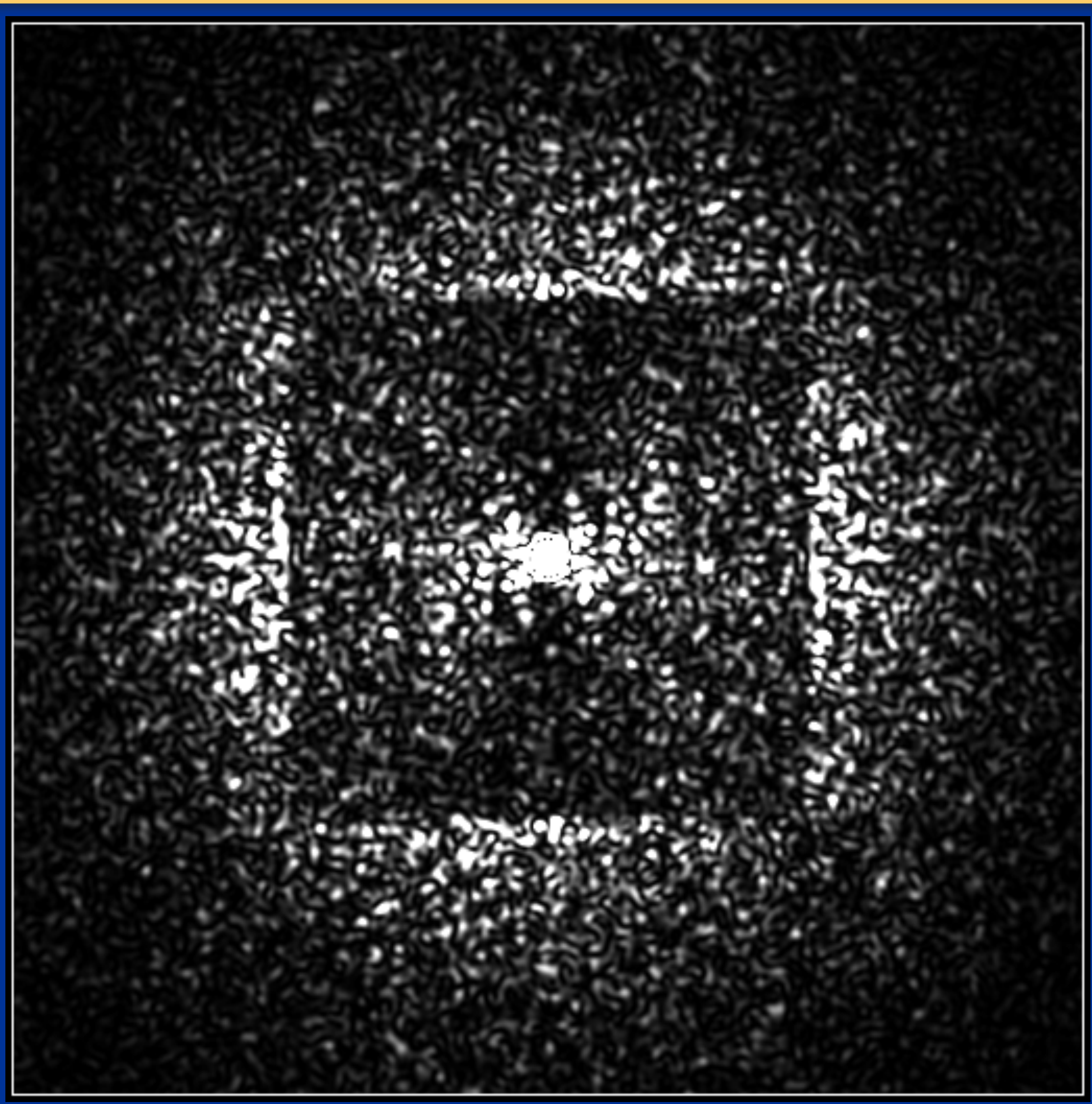
PSF



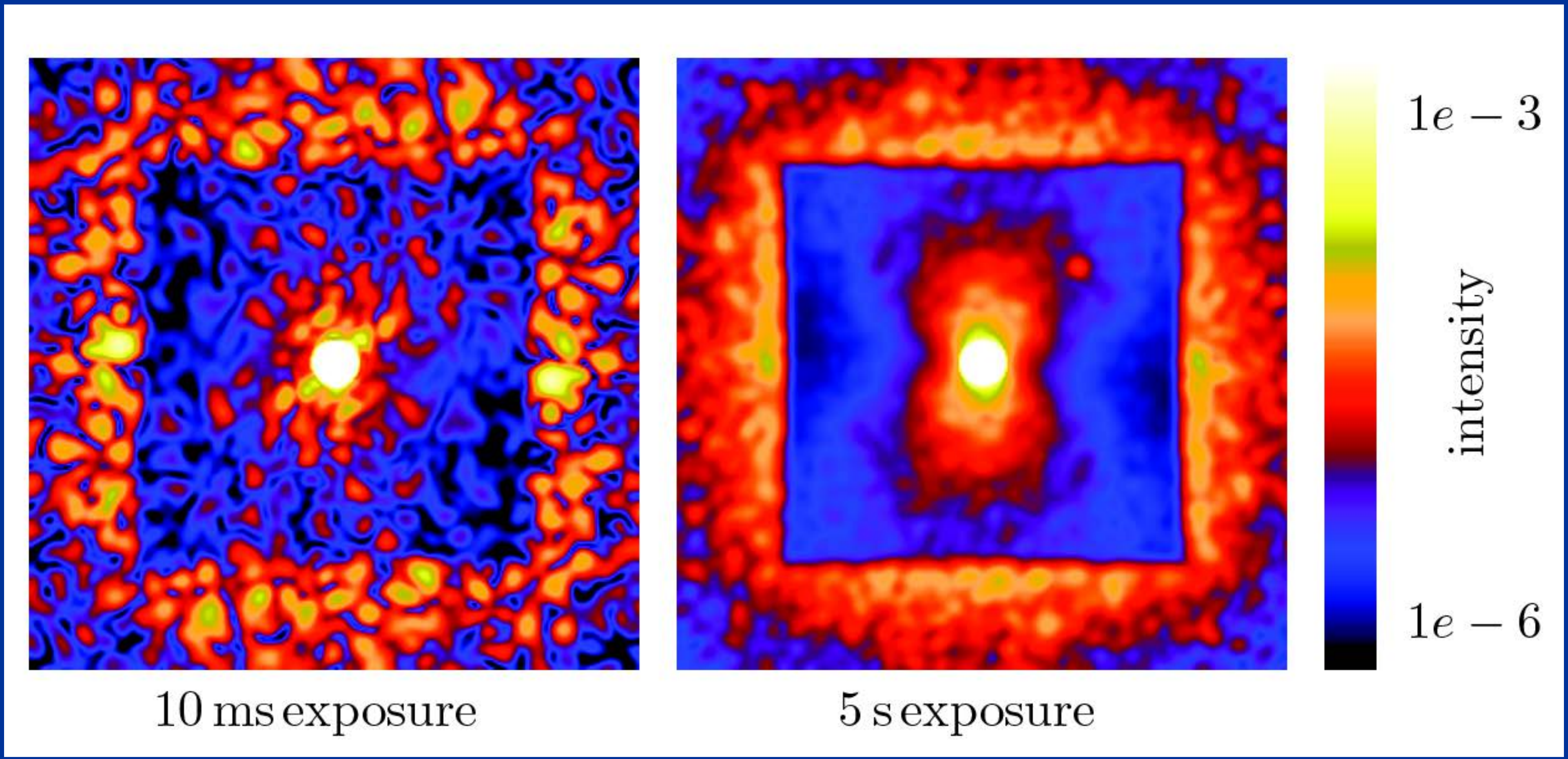


Inner working distance
~ 3-5 λ/D
Outer working distance
~ N λ/D
2.0 arcsec
AO Timelag
WFS measurement
Fitting error
Intensity
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0
10
20
30
40
50

Random intensity of all the Fourier components produces speckles

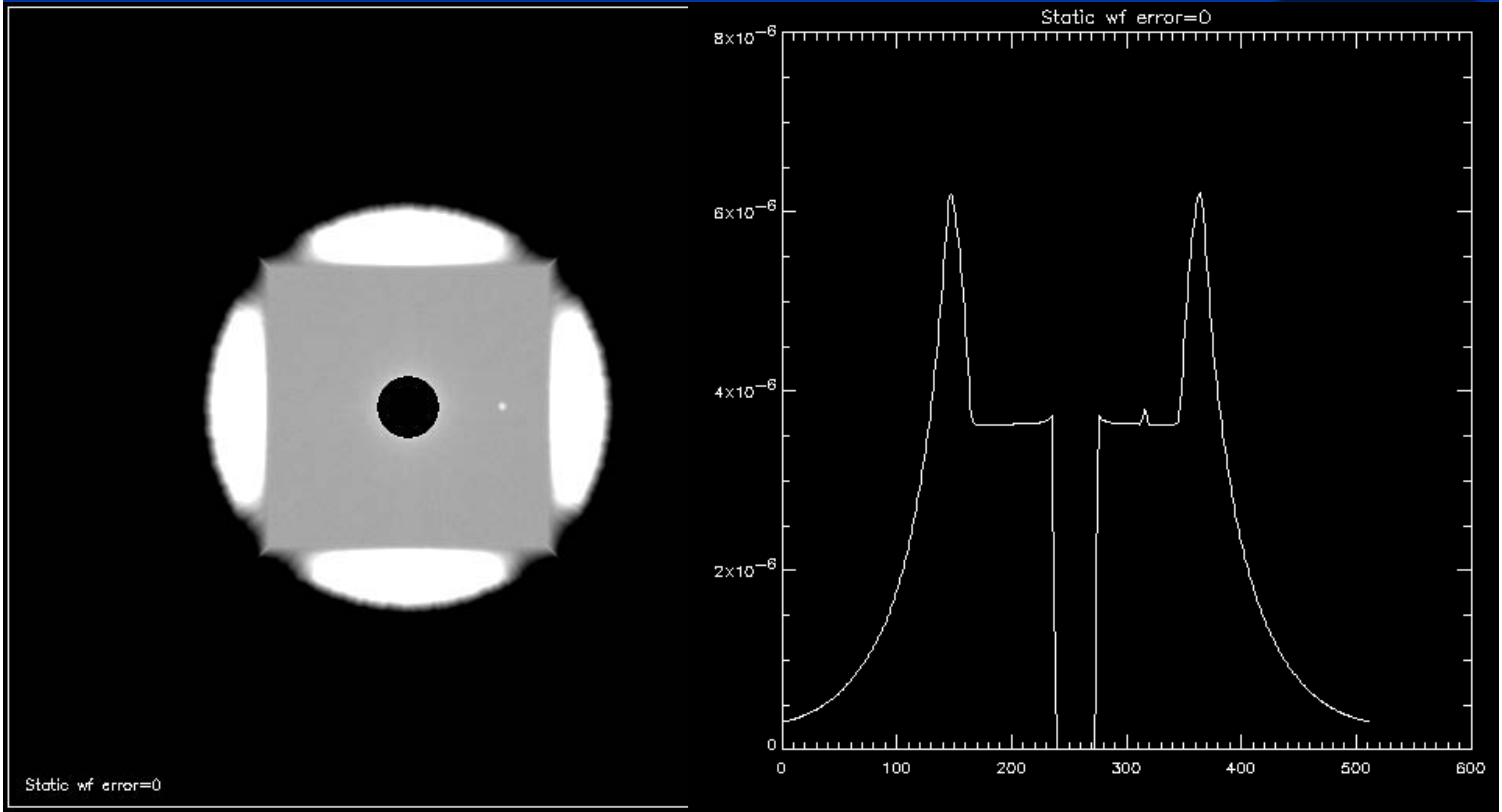


As speckles average out (τ ~ D/v_{wind}) planets can be detected

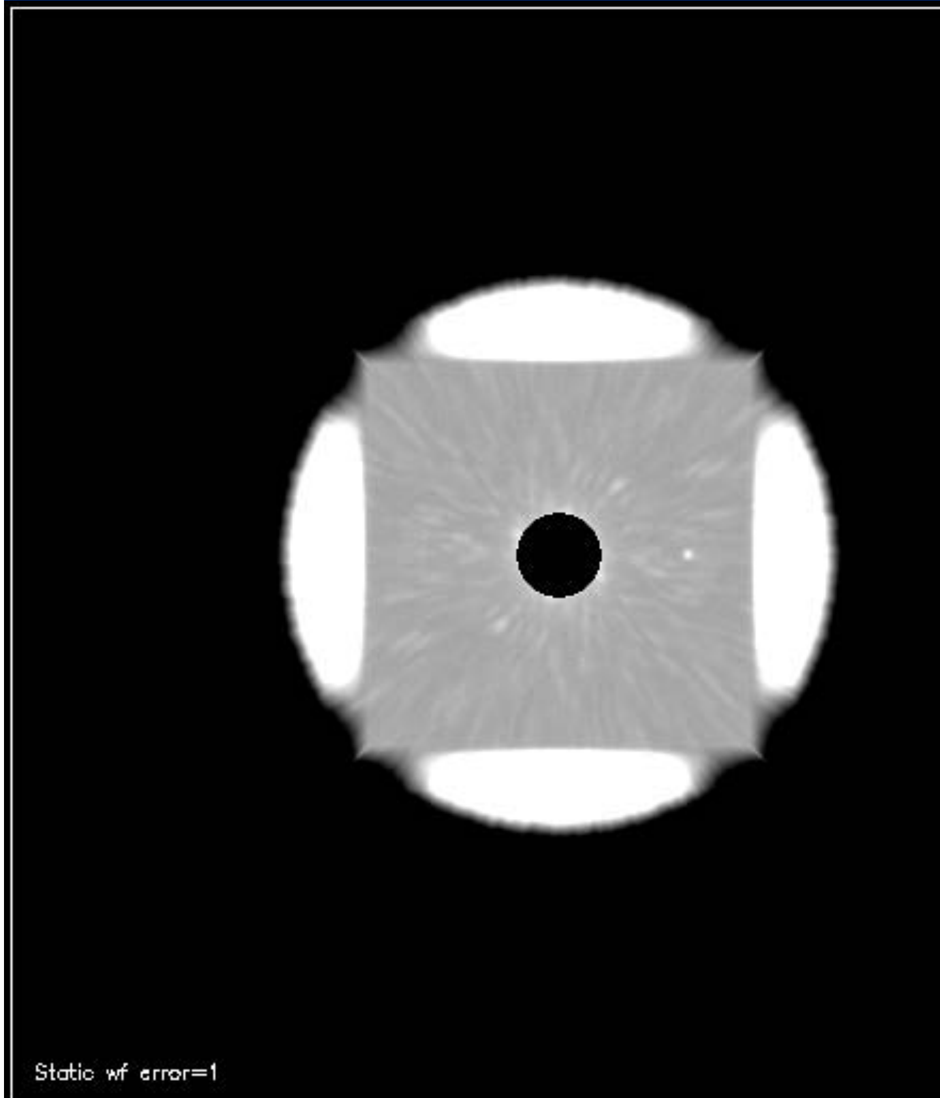


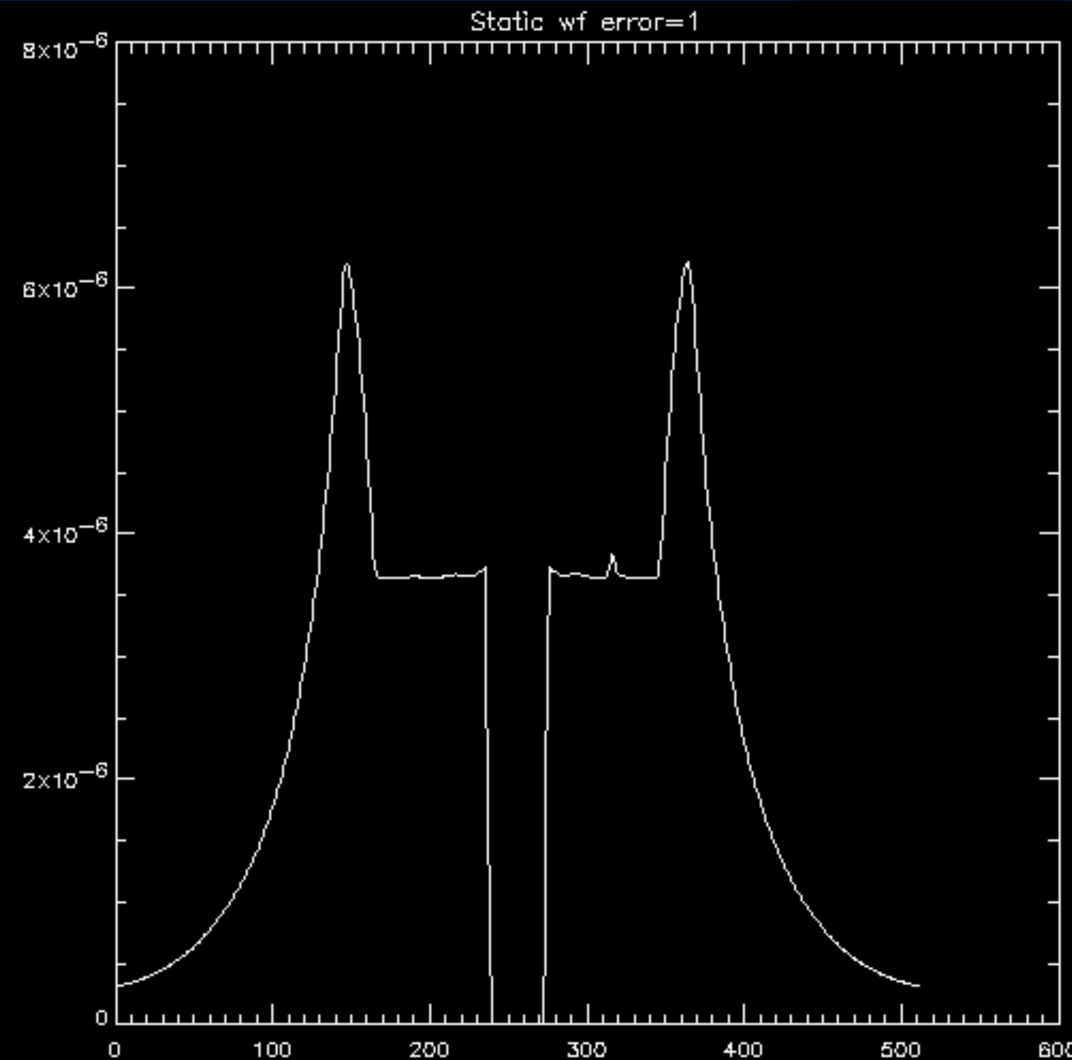
Must get rid of static errors as well

ExAO 0 nm static errors, 5 MJ/500 MYr planet, 15 minute integration

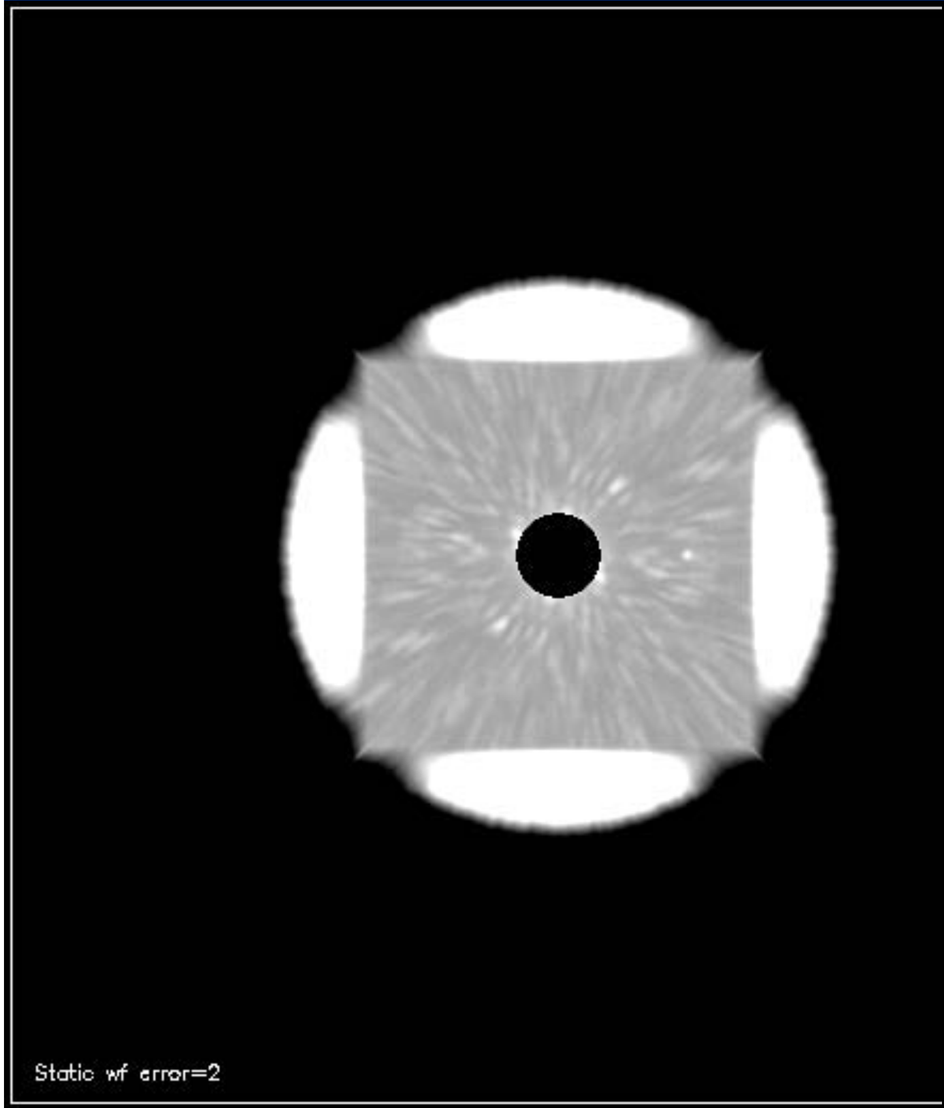


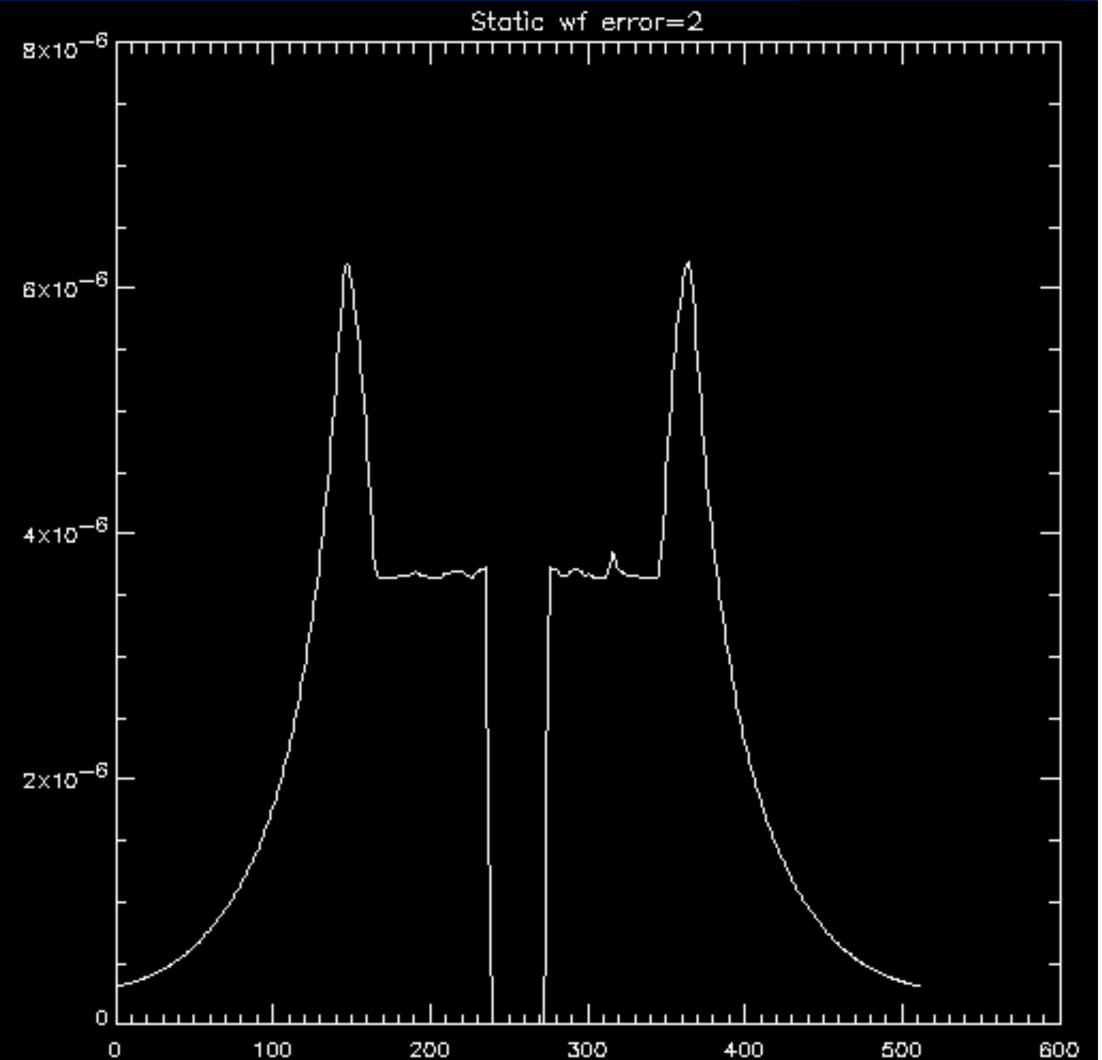
ExAO 1 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



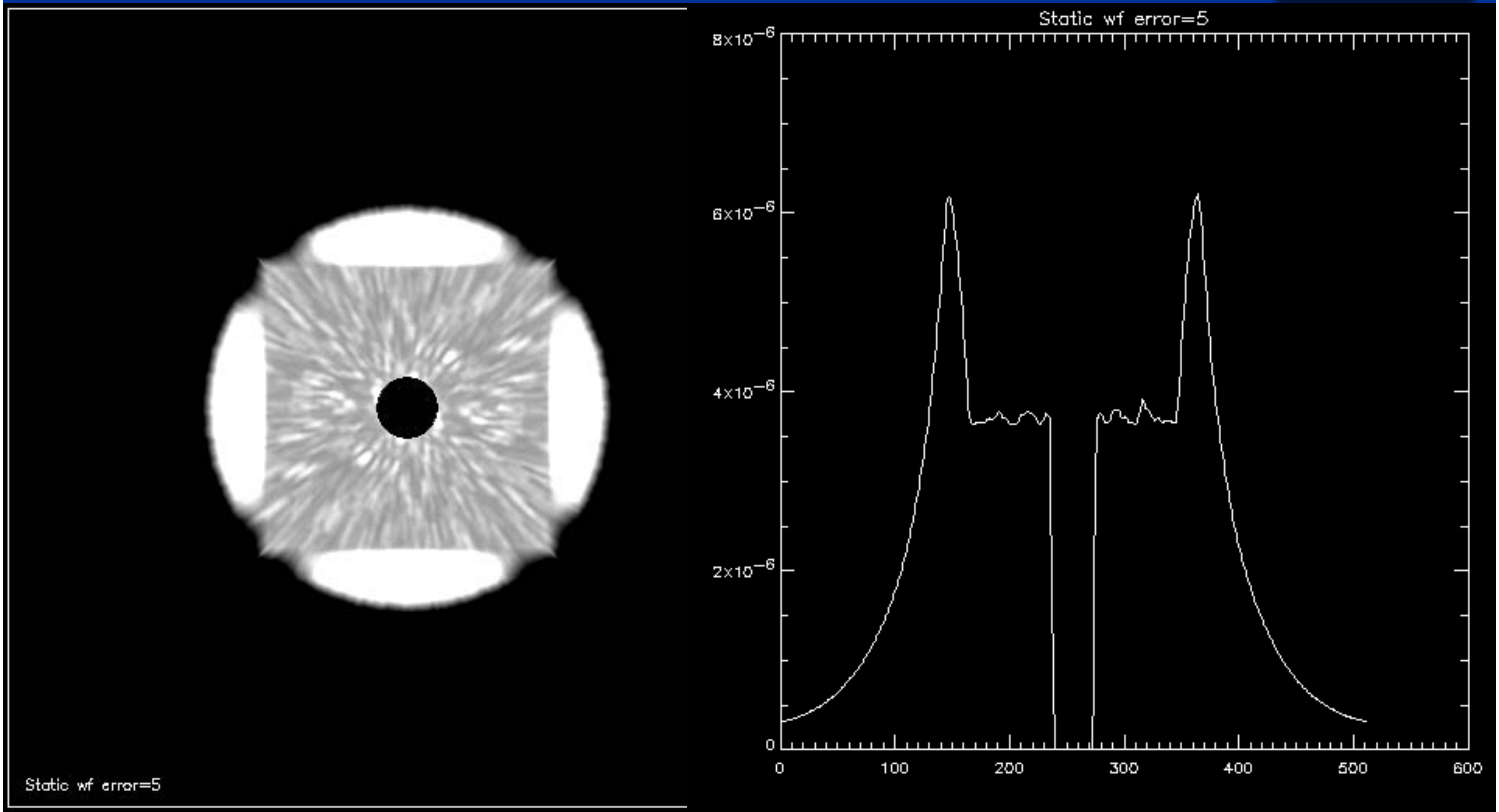


ExAO 2 nm static errors, 5 MJ/500 MYr planet, 15 minute integration





ExAO 5 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



Evolution of AO Systems

Table 2 Main instruments benefiting from AO and high-contrast imaging capabilities. This non exhaustive list groups the instruments by generation.

Instrument	Telescope	Wavelength (μm)	Operations[a]
ADONIS	La Silla 3.6	1-5	1996-?
PUEO	CFHT	0.7-2.5	1996-2013
NaCo	VLT	1-5	2002
Lyot Project	AEOS	0.8-2.5	2003-2007
ALTAIR-NIRI	Gemini N.	1.1-2.5	2003
NIRC2	Keck	1-5	2004
NICI	Gemini S.	1.1-2.5	2007
HiCIAO	Subaru	1.1-2.5	2009
PALM-3000/P1640	Palomar 200”	1.1-1.65	2009
FLAO/LMIRCam	LBT	3-5	2012
GPI	Gemini S.	1.0-2.3	2013
MagAO/VisAO	Clay	0.5-5	2014
SPHERE	VLT	0.5-2.3	2014
SCExAO	Subaru	0.5-2.2	2015

[a] Instruments without end date are still in operation.

Milli et al. 2017

Extreme AO Systems today

Table 4 ExAO systems: Primary ExAO wavefront control characteristics

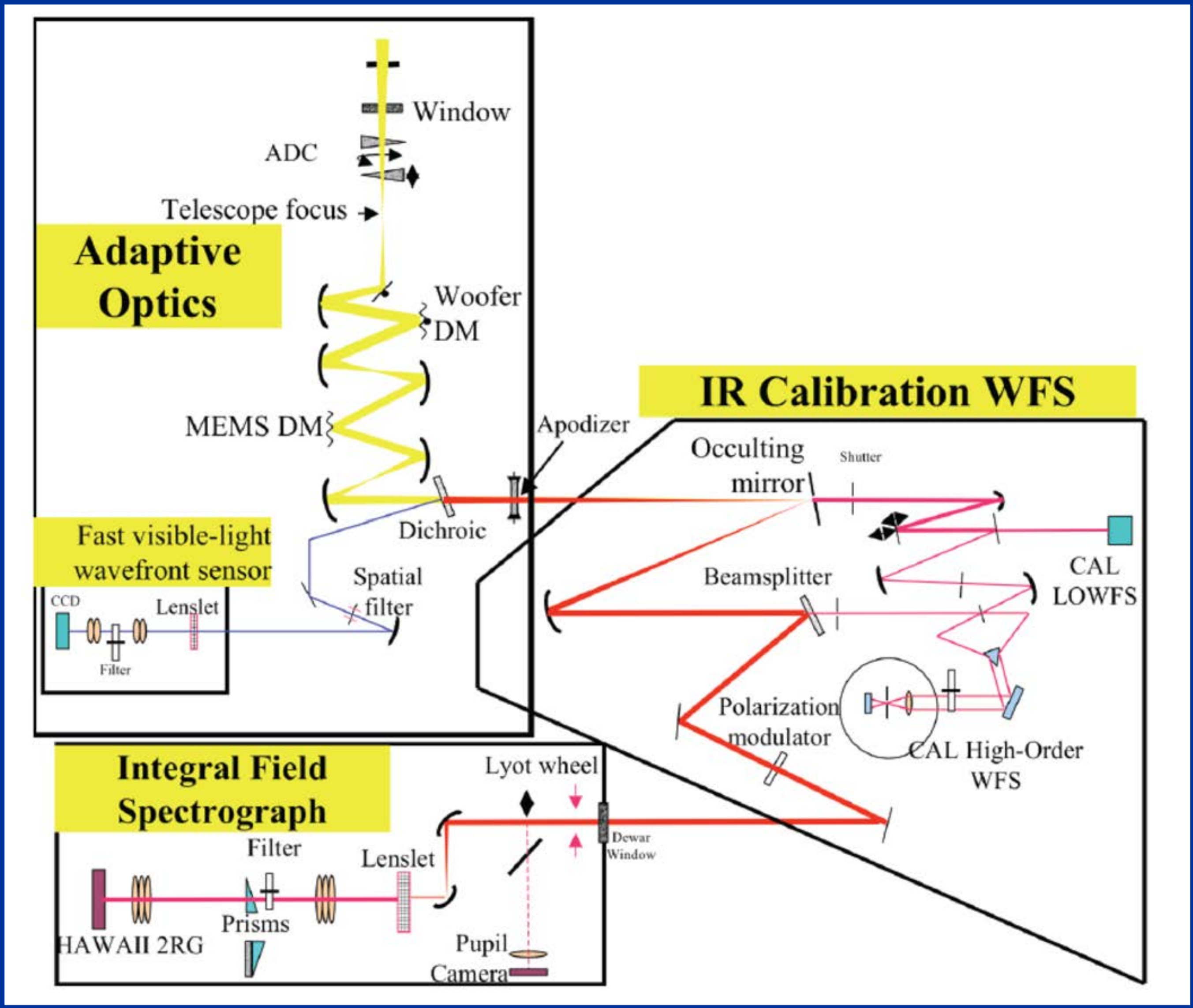
	Status	DM[a]	Primary WFS(s)[b]
Palm3000+P1640, Palomar (5 m)	Operation 2012–2017	66	SHWFS, 2 kHz
GPI, Gemini (8.2 m)	Operation 2014–present	50	SHWFS, 1 kHz
SPHERE, VLT (8.2 m)	Operation 2014–present	50	SHWFS, 1.2 kHz
SCExAO, Subaru (8.3 m)	Operation + development	48	Pyramid, 3.6 kHz
MagAO-X, Magellan (6.5 m)	Development	48	Pyramid, 3.6 kHz

[a]Number of actuators across the beam diameter.

[b]Highest speed supported by hardware and real-time computer. Systems can run slower on fainter stars to optimize correction. SCExAO's max speed (3.6 kHz) offers marginal performance gain over 2-kHz speed. Abbreviations: DM, deformable mirror; WFS, wavefront sensor; SHWFS, Shack–Hartmann wavefront sensor.

From Olivier Guyon Annual Reviews paper

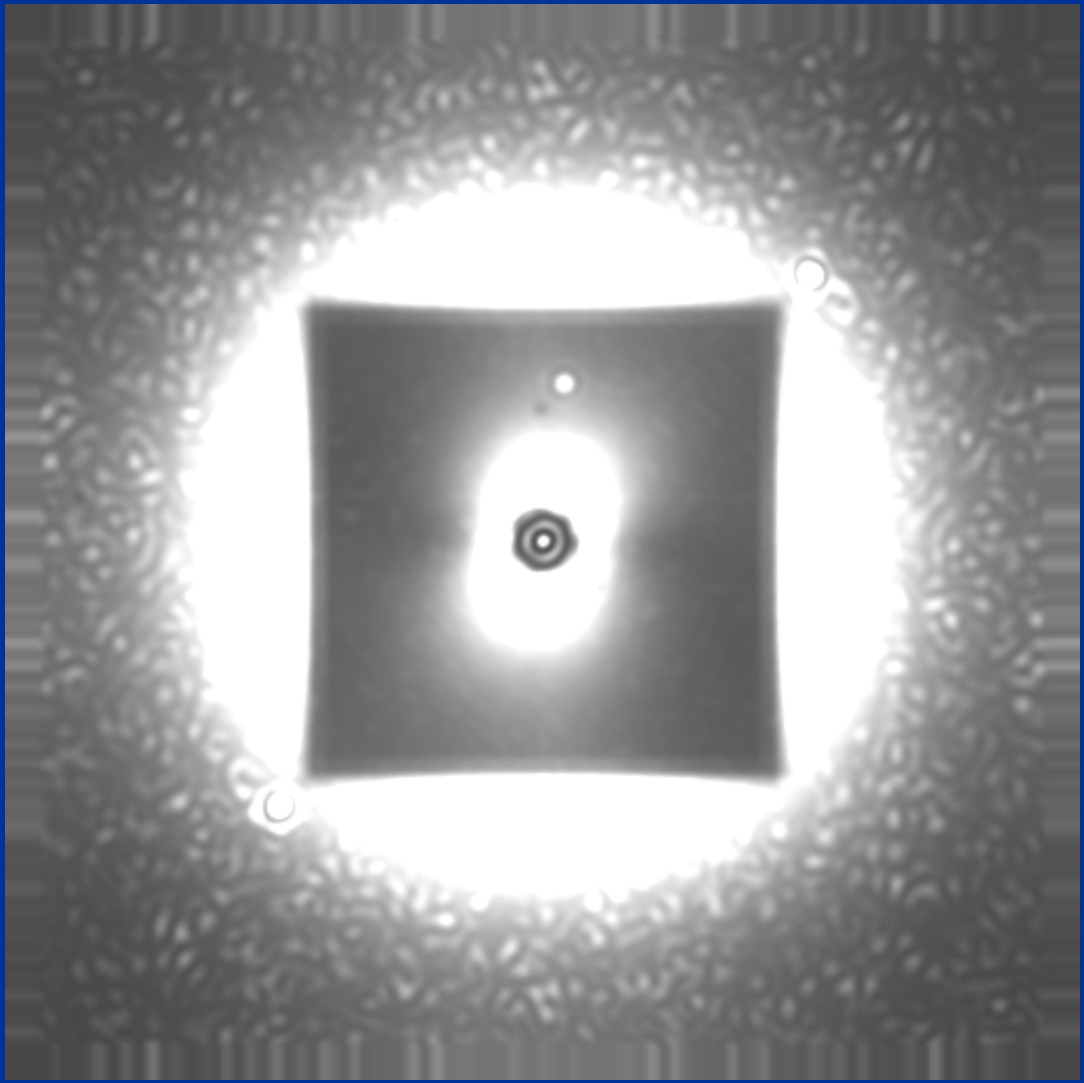
Schematic of Gemini Planet Imager



Comparison of original Keck AO and GPI AO parameters

	Keck AO (1999)	GPI (2010)
Deformable mirror	349 actuators (240 active)	4096 actuators (1809 active)
Subaperture	56 cm	18 cm
Control rate	670 Hz	2000 Hz
Wavefront sensor	Shack-Hartmann 400 – 1000 nm	Spatially-filtered Shack-Hartmann 700-900 nm
Strehl @ 1.65 μm	40%	> 90%
Guide star mag (NGS only)	$R < 13.5$ mag.	$I < 9$ mag. (V < 11)

Data pipeline assembles cubes: image of planet as function of wavelength



For Class Projects, how to calculate contrast ratio?

- Not a simple expression, as it depends on removing internal wavefront errors as well as atmospheric ones, coronagraph performance, etc

- One very rough guess (from Milli et al. 2017):

$$Contrast \approx \frac{1 - Strehl}{N_{actuators}}$$

- In real systems this is an under-estimate of the contrast

- For ExAO, want very high Strehl (>90%)

References, part 1

Angel, R, "Ground based imaging of extrasolar planets using adaptive optics', 1994 Nature 368, 203 (Original exoplanet paper)

Burrows, A., et al., "A nongray theory of extrasolar planets and brown dwarfs", 1997 Ap.J 491, 856 (Planet models)

Sivaramakrishnan, A., et al., "Ground-based coronagraphy with High-Order Adaptive optics", 2001 Ap.J. 552, 397 (Lyot coronagraphs)

Kasdin, N.J., et al, 2003, "Extrasolar planet finding via optimized apodized pupil and shaped pupil coronagraphs", Ap.J. 582, 1147

Kuchner, M, and Traub, W., "A Coronagraph with a Band-limited Mask for Finding Terrestrial Planets" 2002 Ap.J. 570, 200 (improved Lyot coronagraph)

Sivaramakrishnan, A., et al, "Speckle decorrelation and dynamic range in speckle noise limited imaging", 2002 Ap.J. 581, L59 (2^{nd}-order PSF expansion)

Perrin, M., et al. "The structure of the High Strehl Ratio Point-Spread Functions", 2003, Ap.J. 596, 702 (high-order PSF expansion)

Poyneer, L, and Macintosh, B., "Spatially-filtered wavefront sensor for high-order adaptive optics", 2004, JOSA A 21, 810 (aliasing + WFS)

Guyon, O., et al. "Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs", 2006 Ap.J.S. 167, 81

References, part 2

LaFreniere, D., et al., "A new algorithm for point-spread function subtraction for high-contrast imaging"

Macintosh, B., et al, "The Gemini Planet Imager: From Science to Design to Construction", 2008 Proc. SPIE 7015-18

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Poyneer, L., Macintosh, B., and Veran, J-P., "Fourier transform wavefront control with adaptive prediction of the atmosphere", 2007 JOSA A 24, 2645