Lecture 16

Extreme Adaptive Optics: Exoplanets and Protoplanetary Disks

Claire Max

AY 289

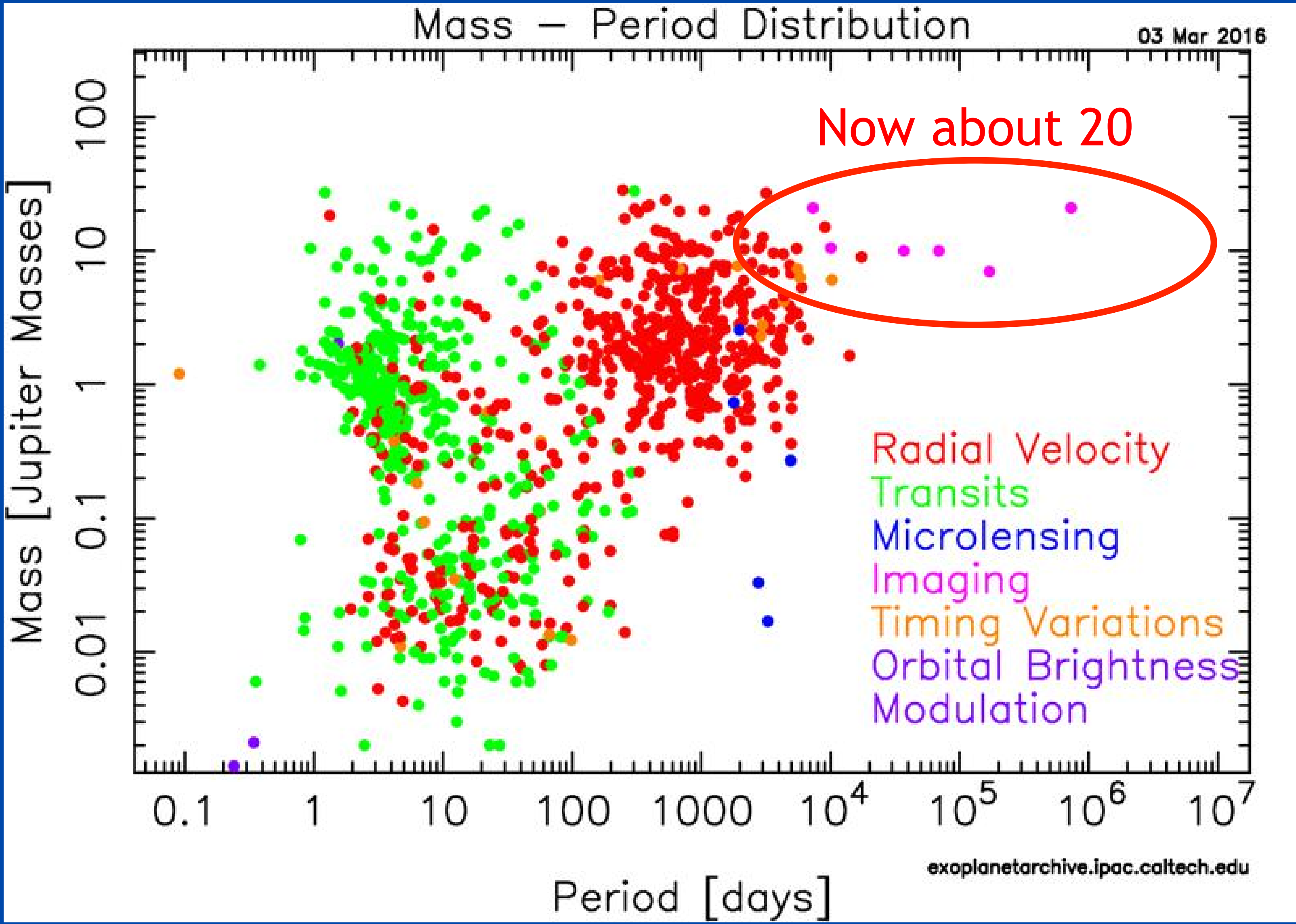
March 7, 2016

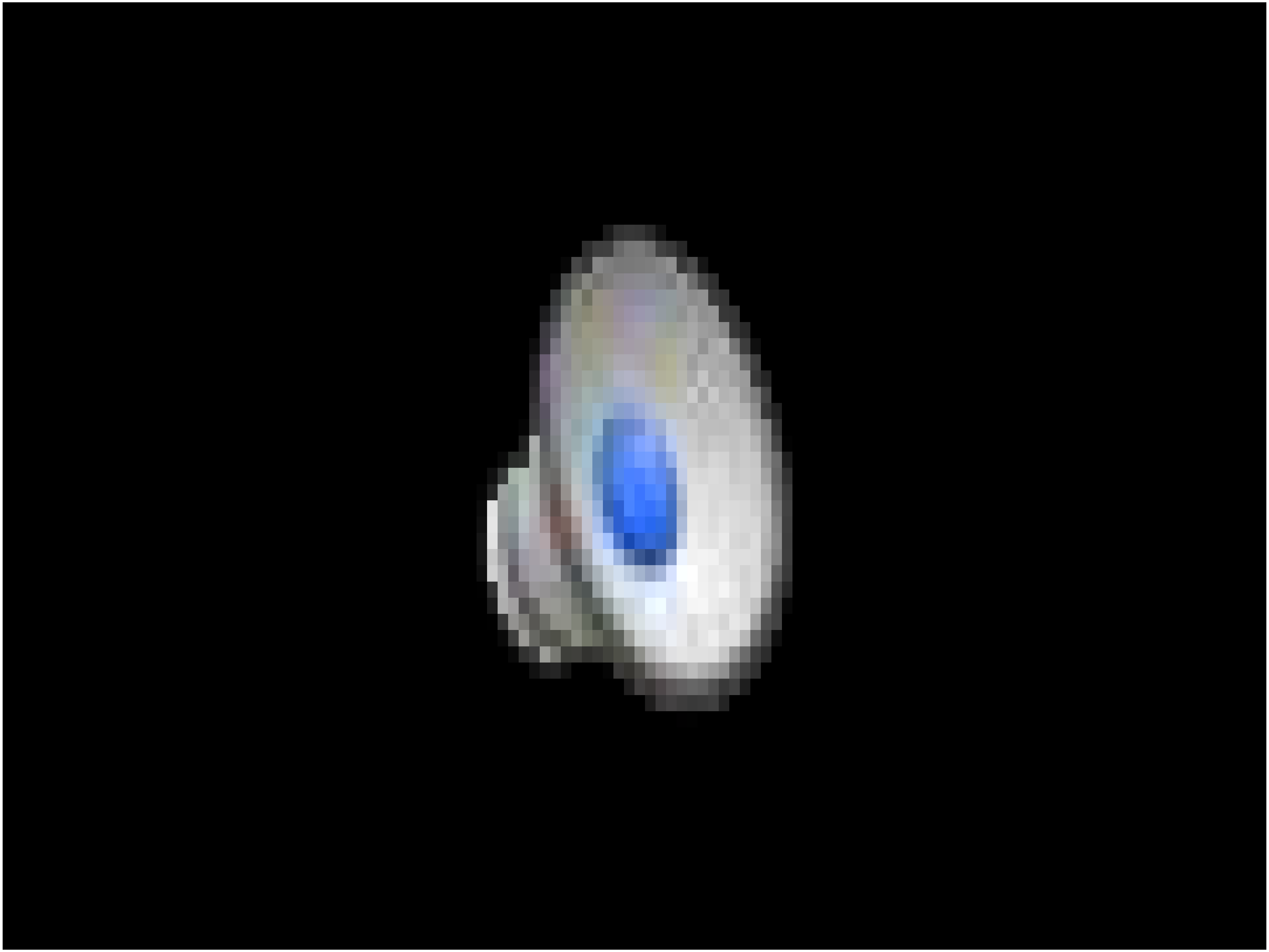
Based in part on slides from Bruce Macintosh and Sandrine Thomas

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 2015





Direct Imaging
Main Engineering Requirements

- Contrast
  - ~10^{10} for Earth-like planets
  - ~10^{7} for young hot planets and disks
- Inner Working Angle
  - The smaller the better!
  - Typically 1-3 λ/D required on missions

Ground based Instruments: Exoplanet direct imaging instruments

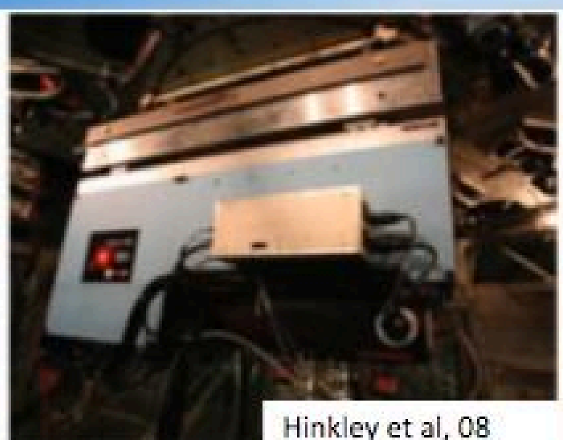
GPI

Macintosh et al, 14

SPHERE

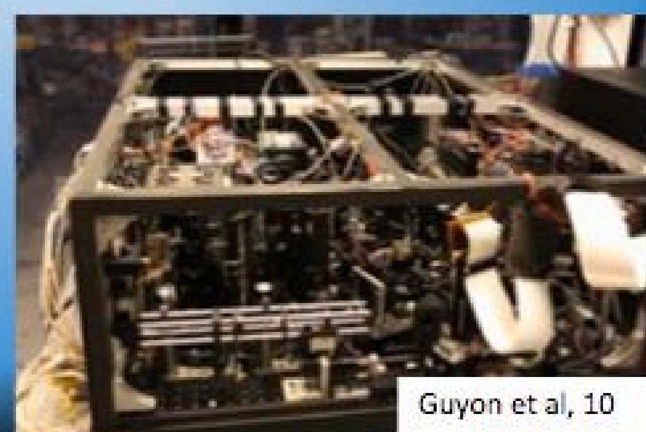
Beuzit et al, 14

P1640



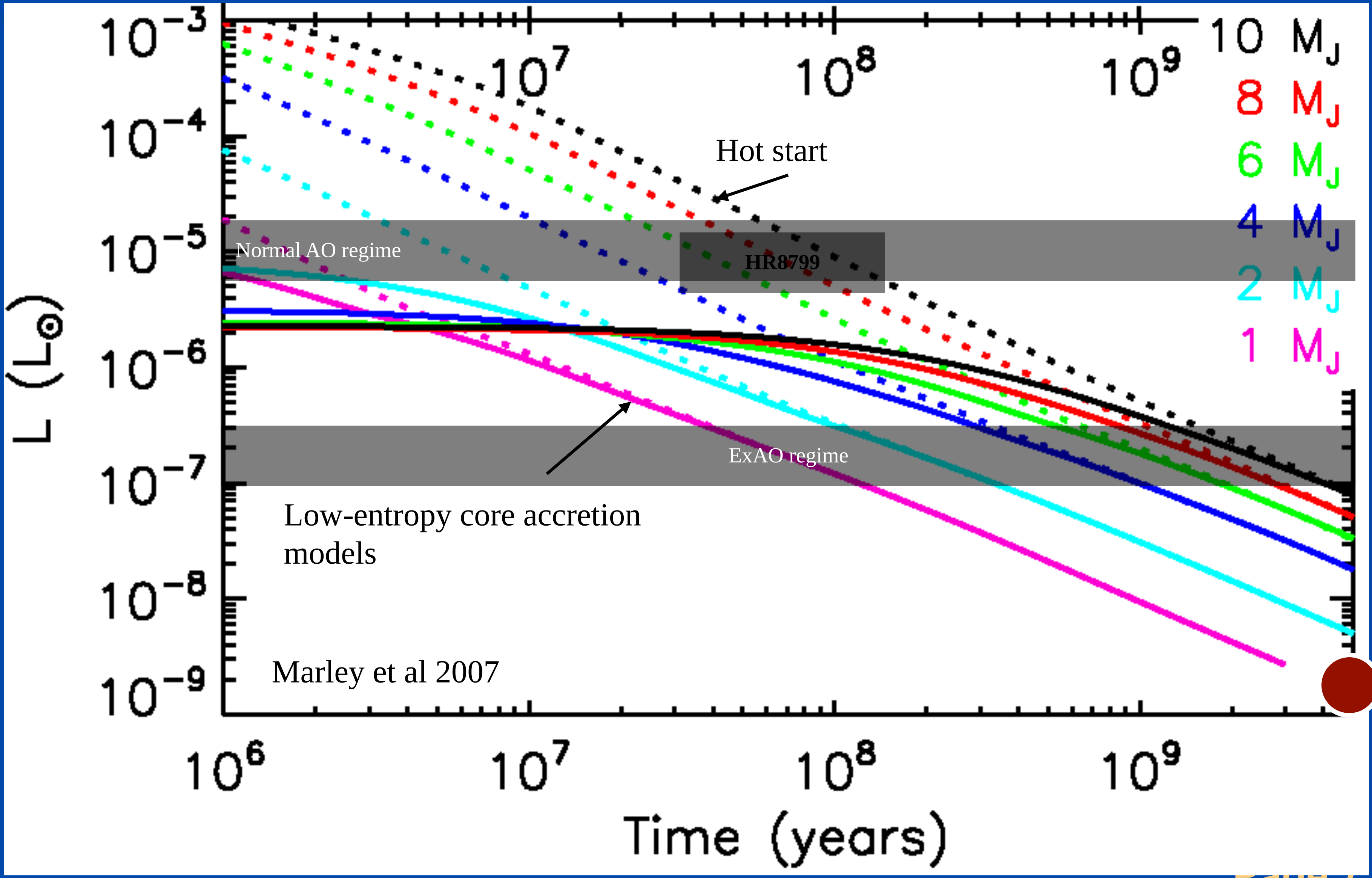
Hinkley et al, 08

SCExAO

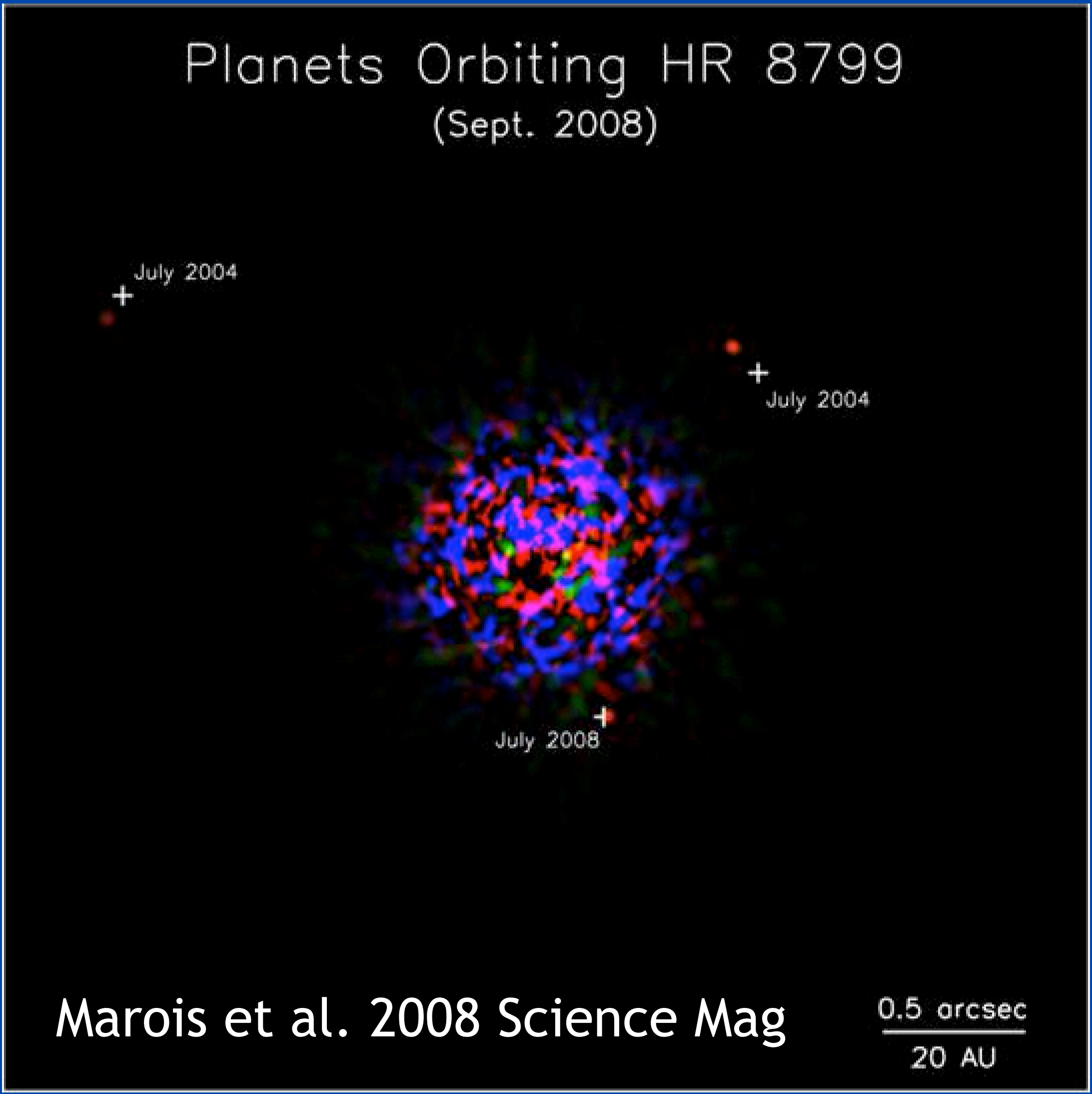


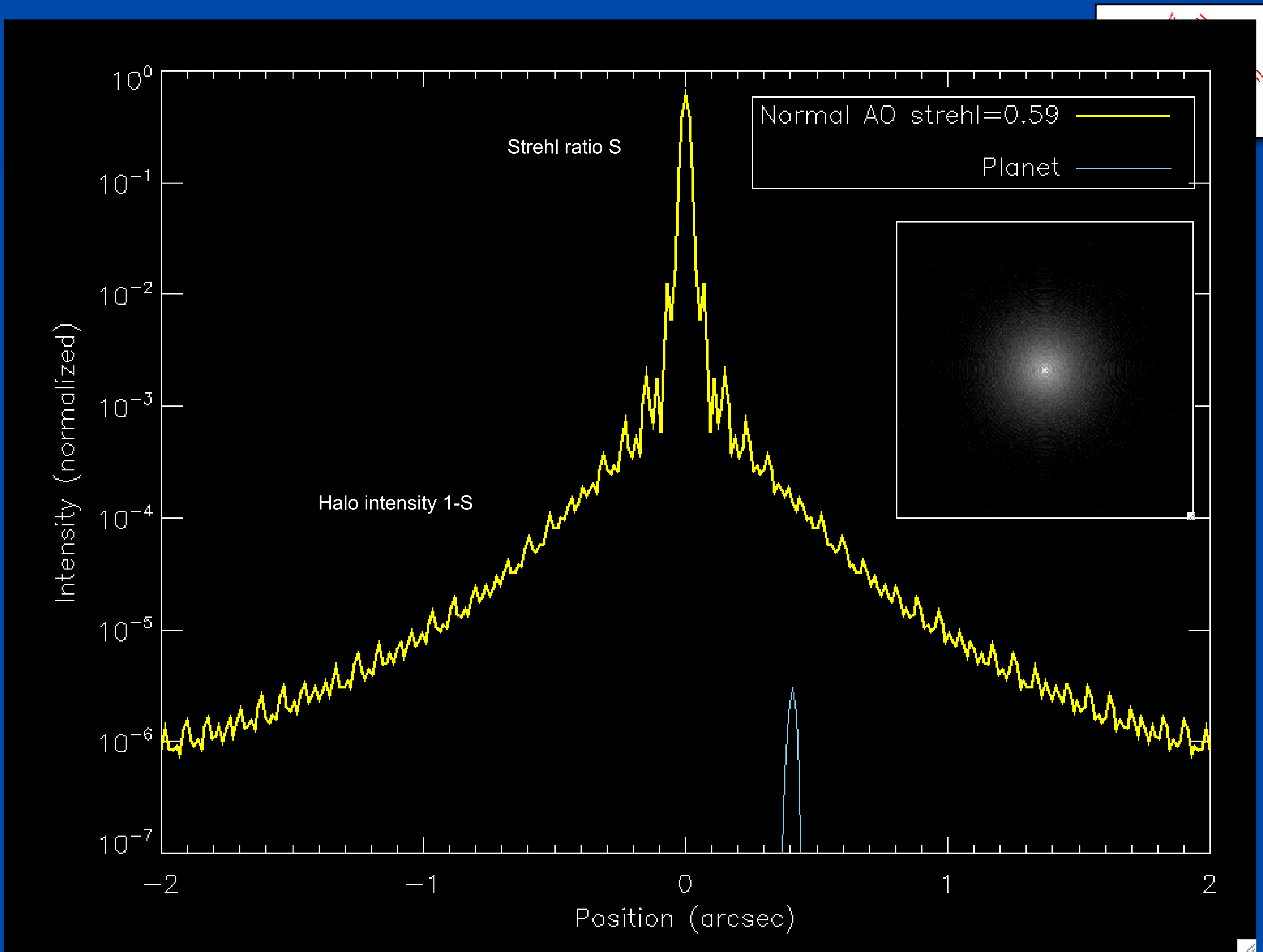
Guyon et al, 10

Brightness of ExAO targets

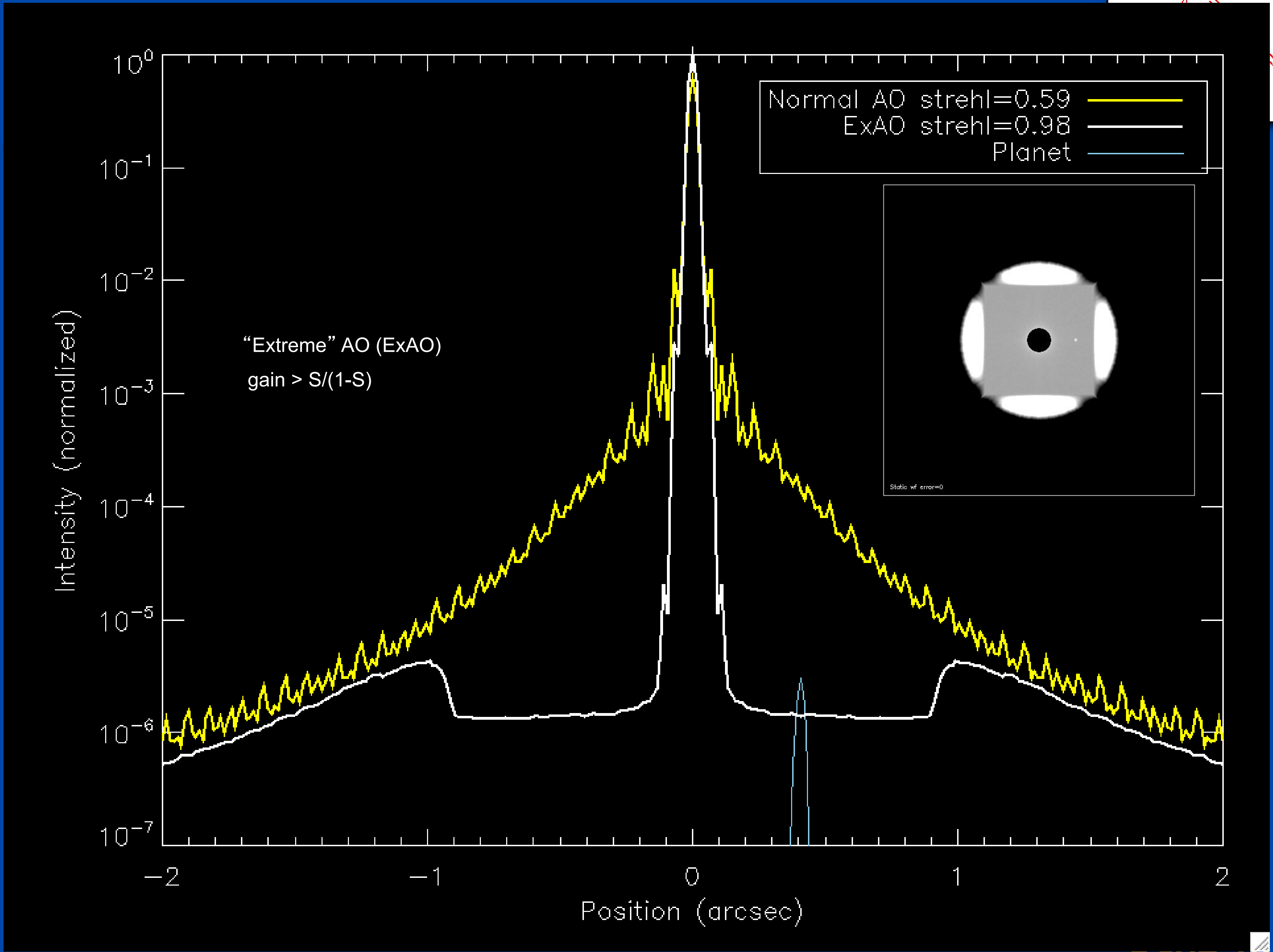


First images of an extrasolar planetary system (Keck and Gemini AO)



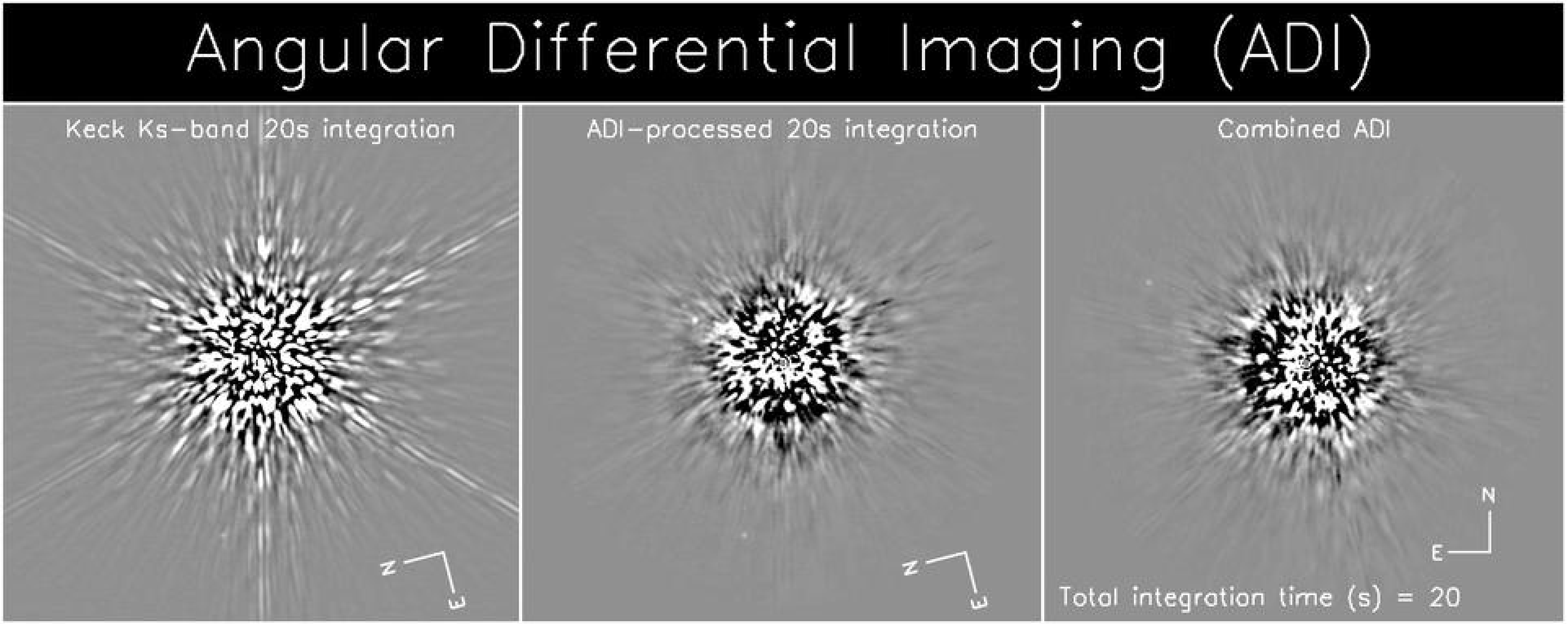


Strehl ratio S
Halo intensity 1-S
Normal AO strehl=0.59
Planet
Intensity (normalized)
Position (arcsec)
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
−2
−1
0
1
2



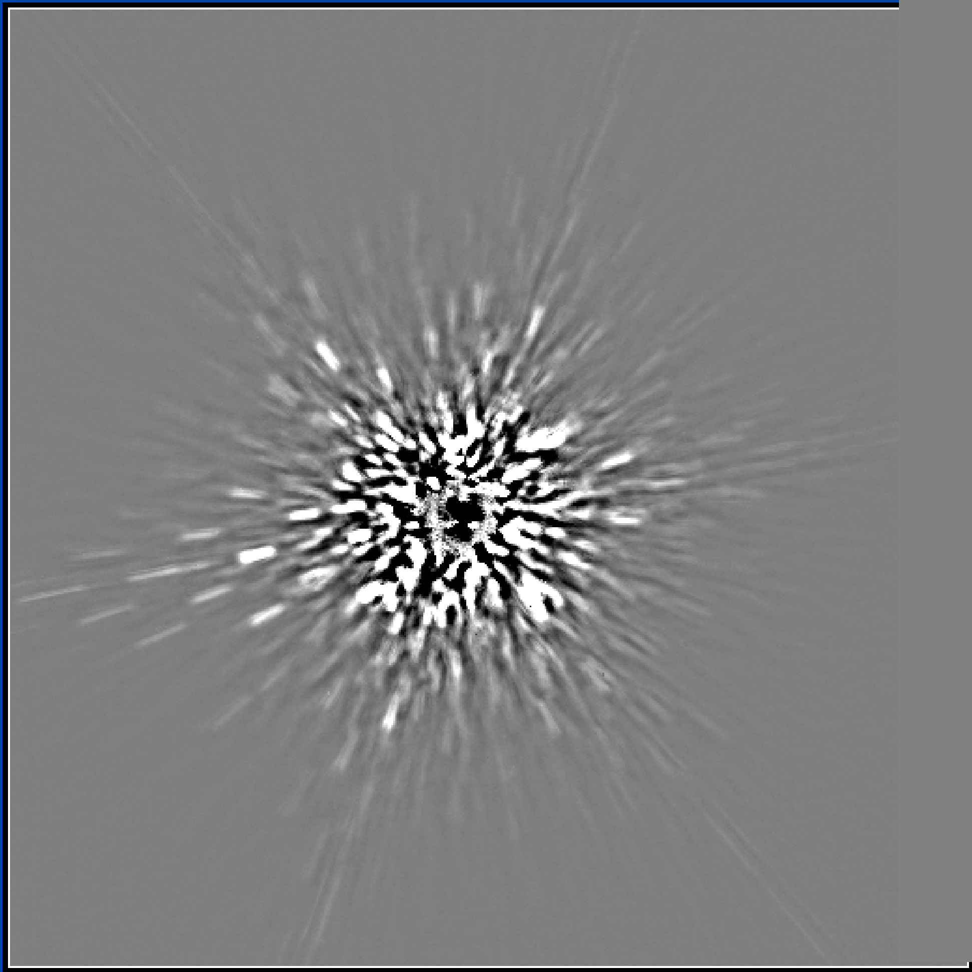
Normal AO strehl=0.59
ExAO strehl=0.98
Planet
"Extreme" AO (ExAO)
gain > S/(1-S)
Intensity (normalized)
Position (arcsec)

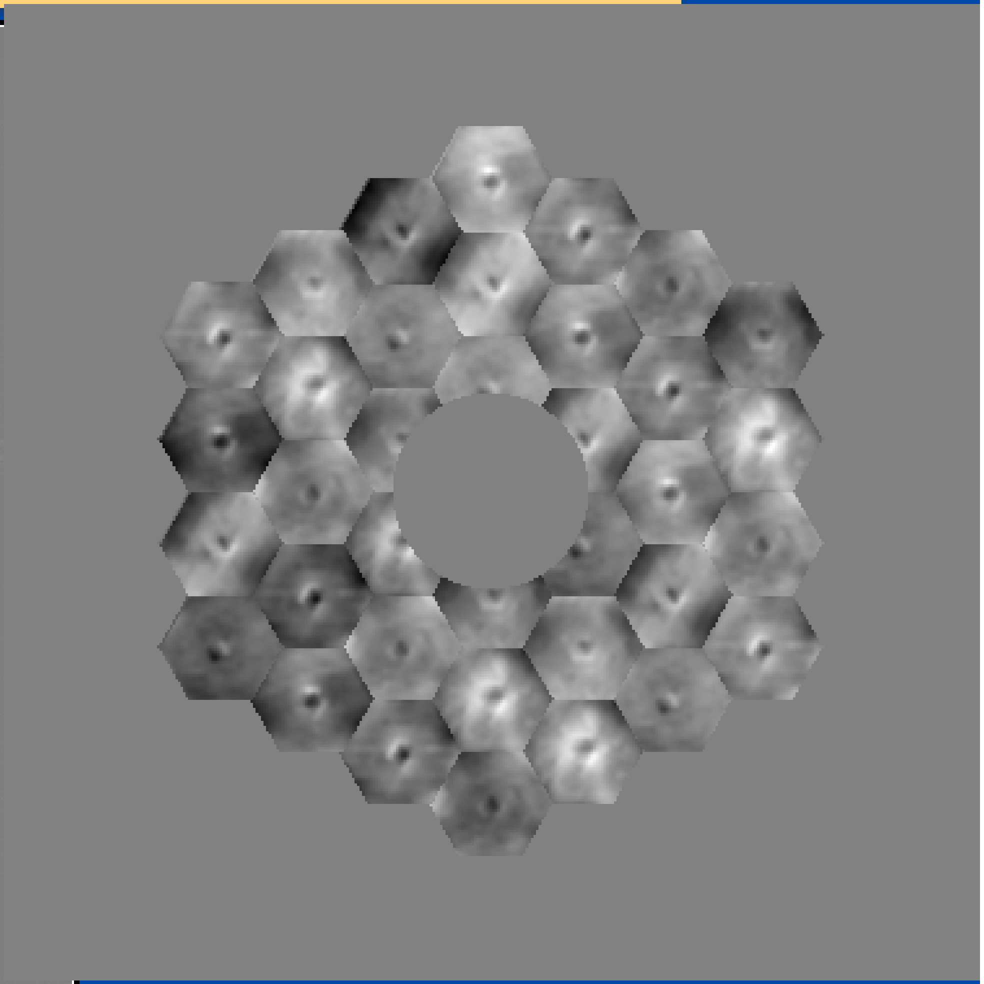
Image processing to suppress light from host star



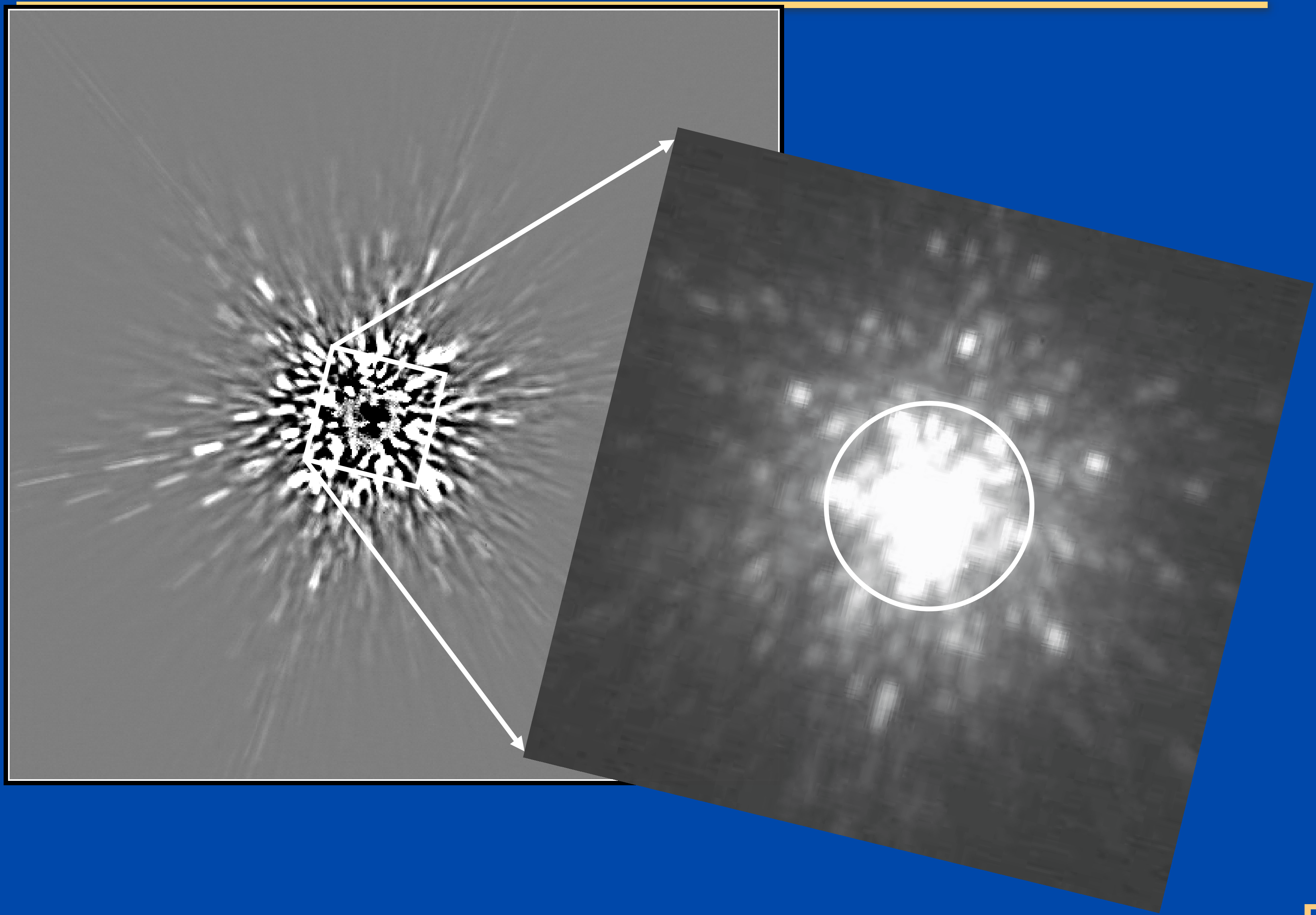
Marois et al.

Keck AO Image of a bright star

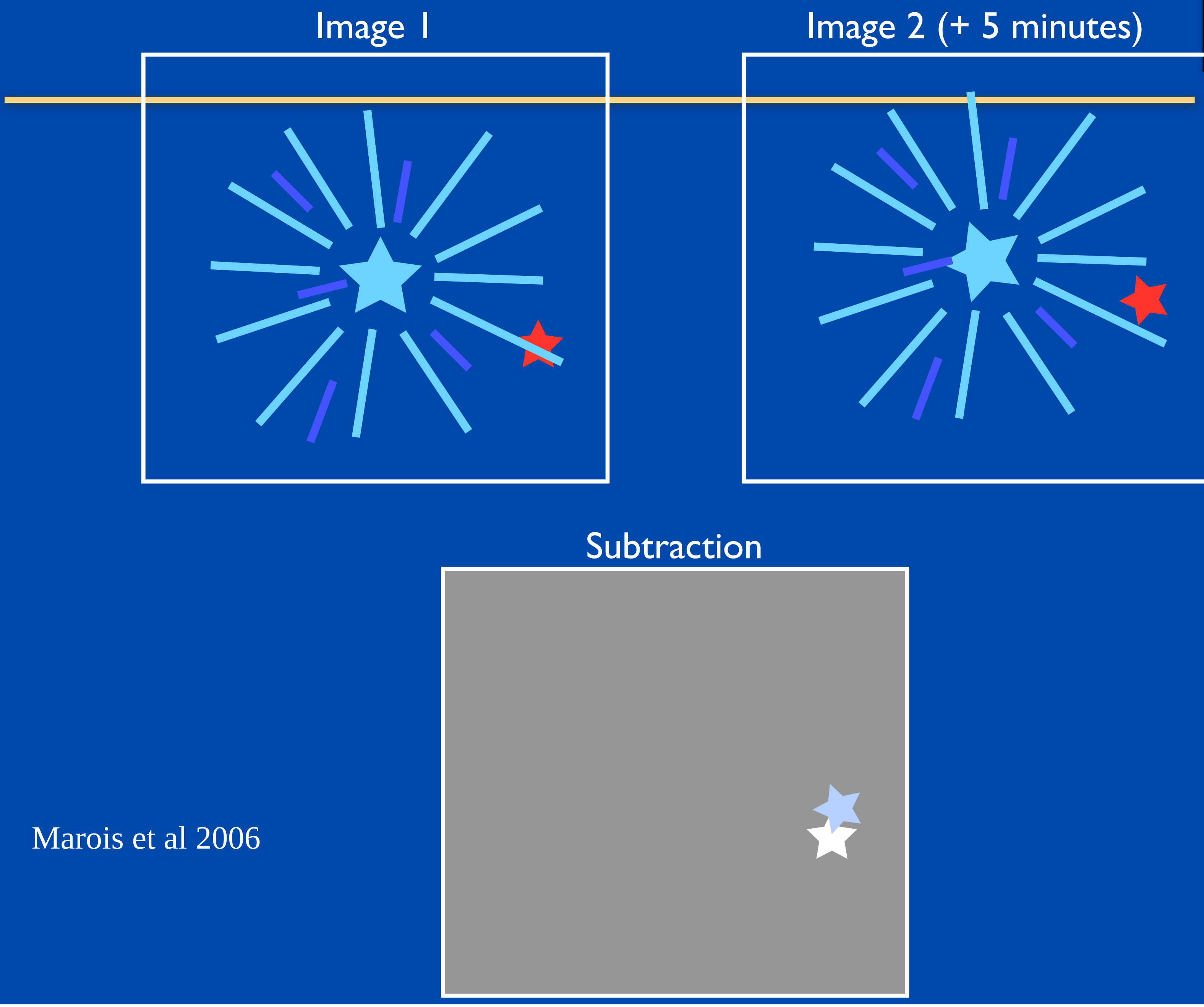




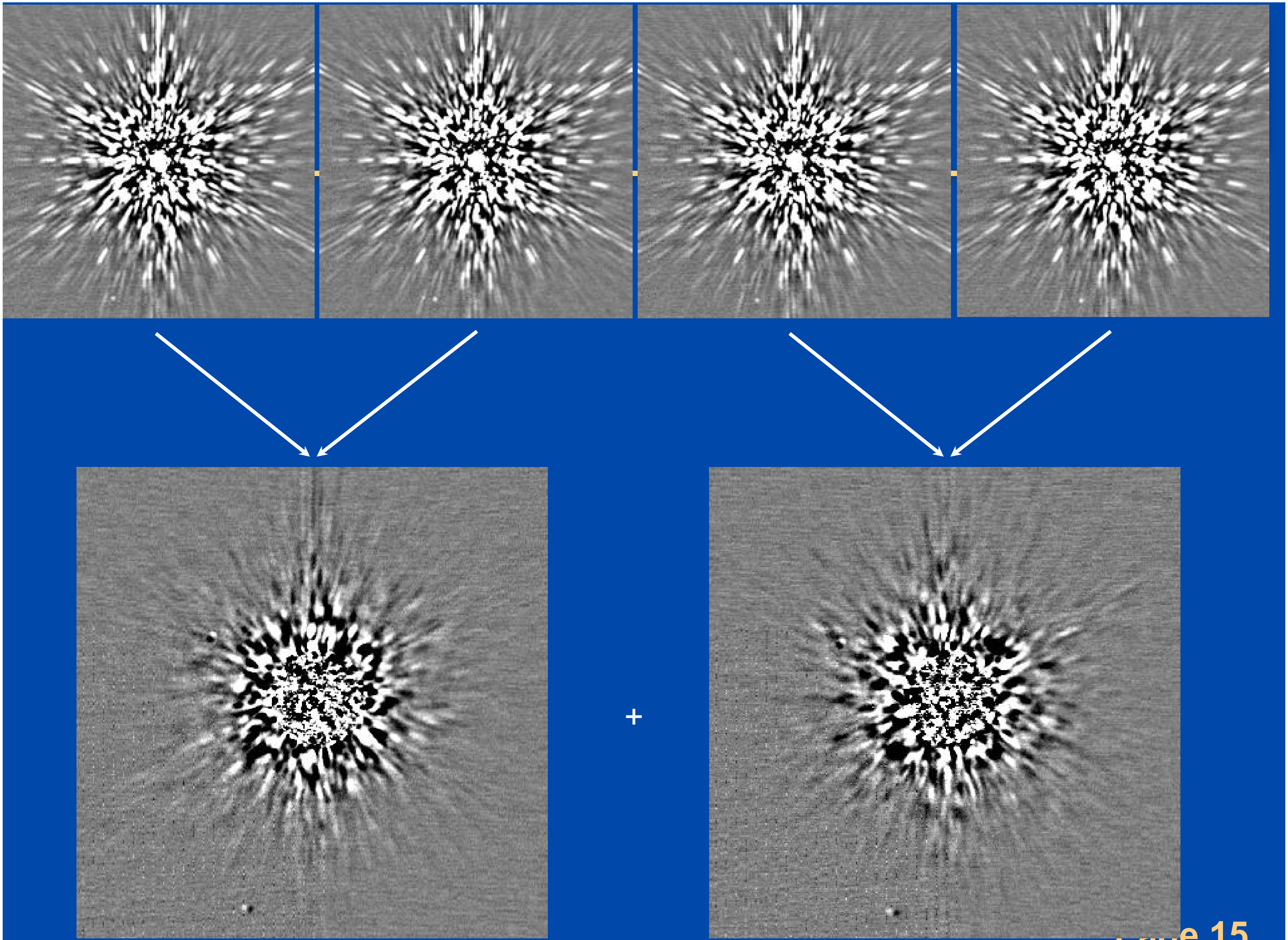
Inner part of image - artifacts due to AO optics

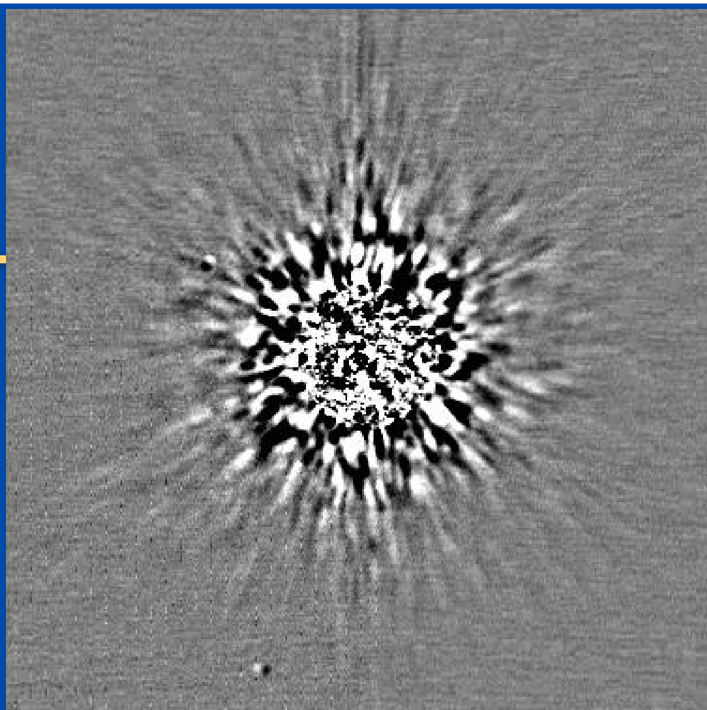


Angular Differential Imaging

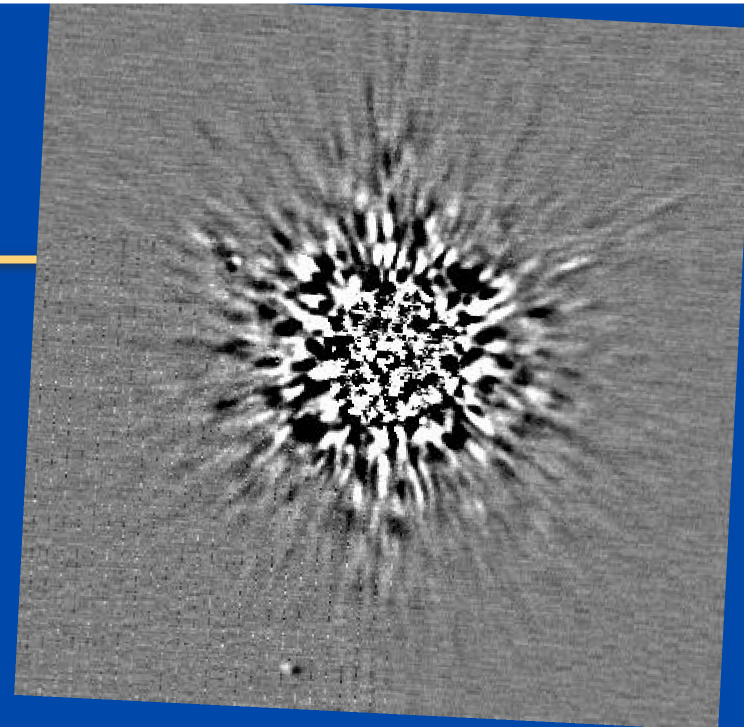


Marois et al 2006

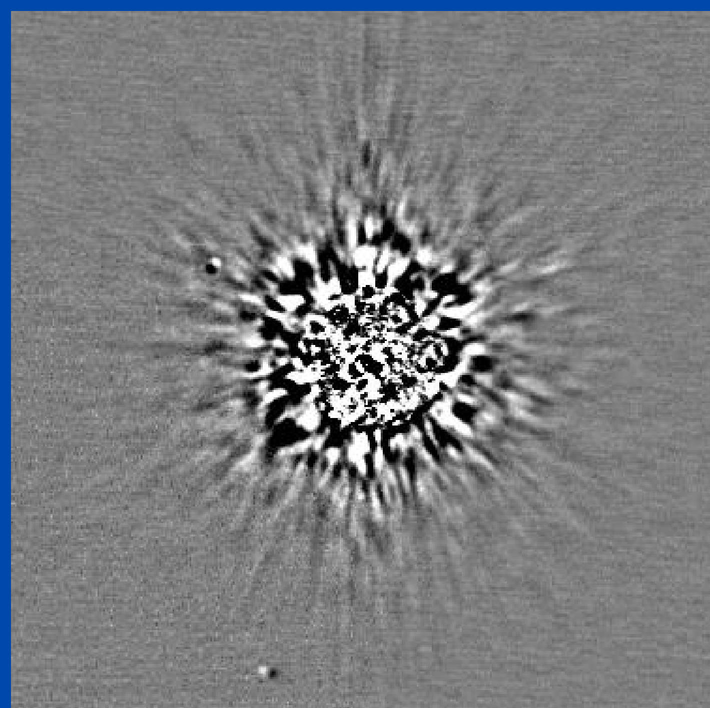




+



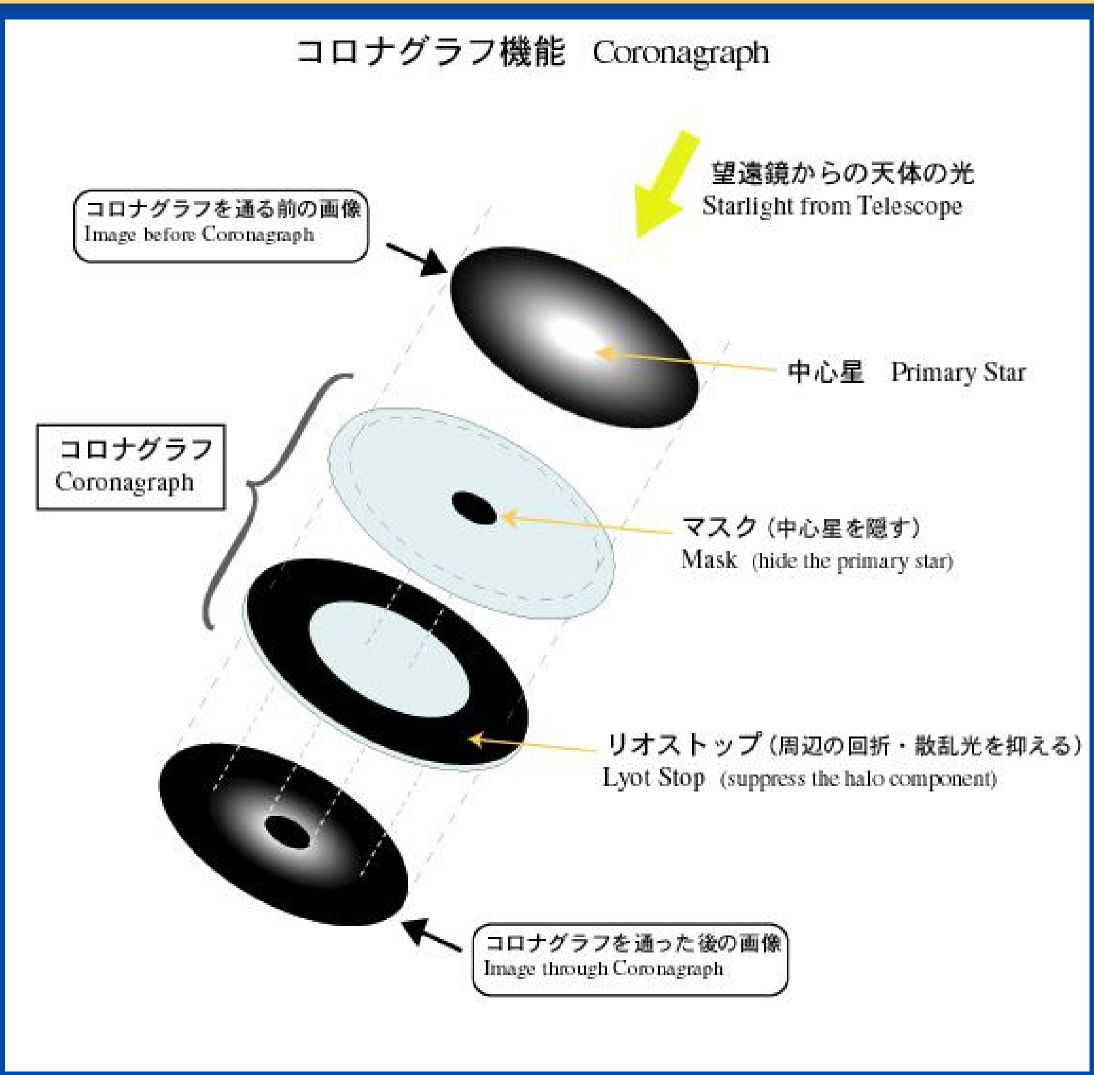
=



Coronagraphs

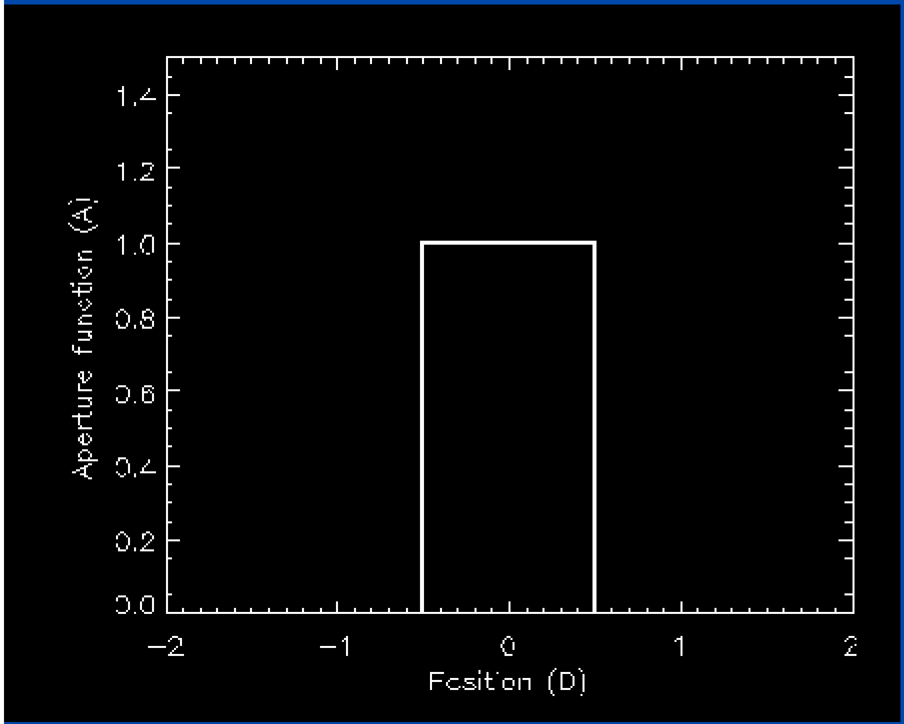
- Invented by Bernard Lyot in 1930 for studying the corona of the sun without waiting for an eclipse
- Block the sun's light with a circular mask in the focal plane
- Problem: diffraction from the sharp edges of the mask

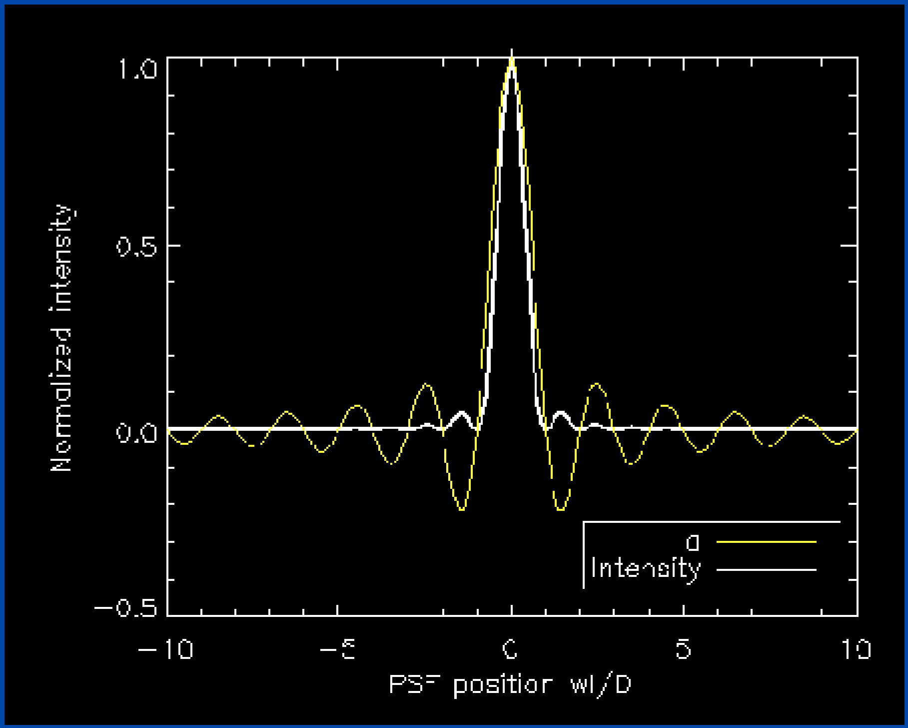
Cartoon of Lyot Coronagraph

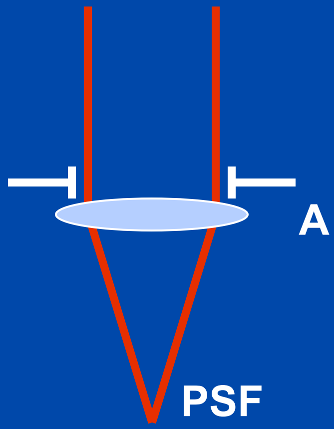


Credit: Subaru website

How can we control diffraction?

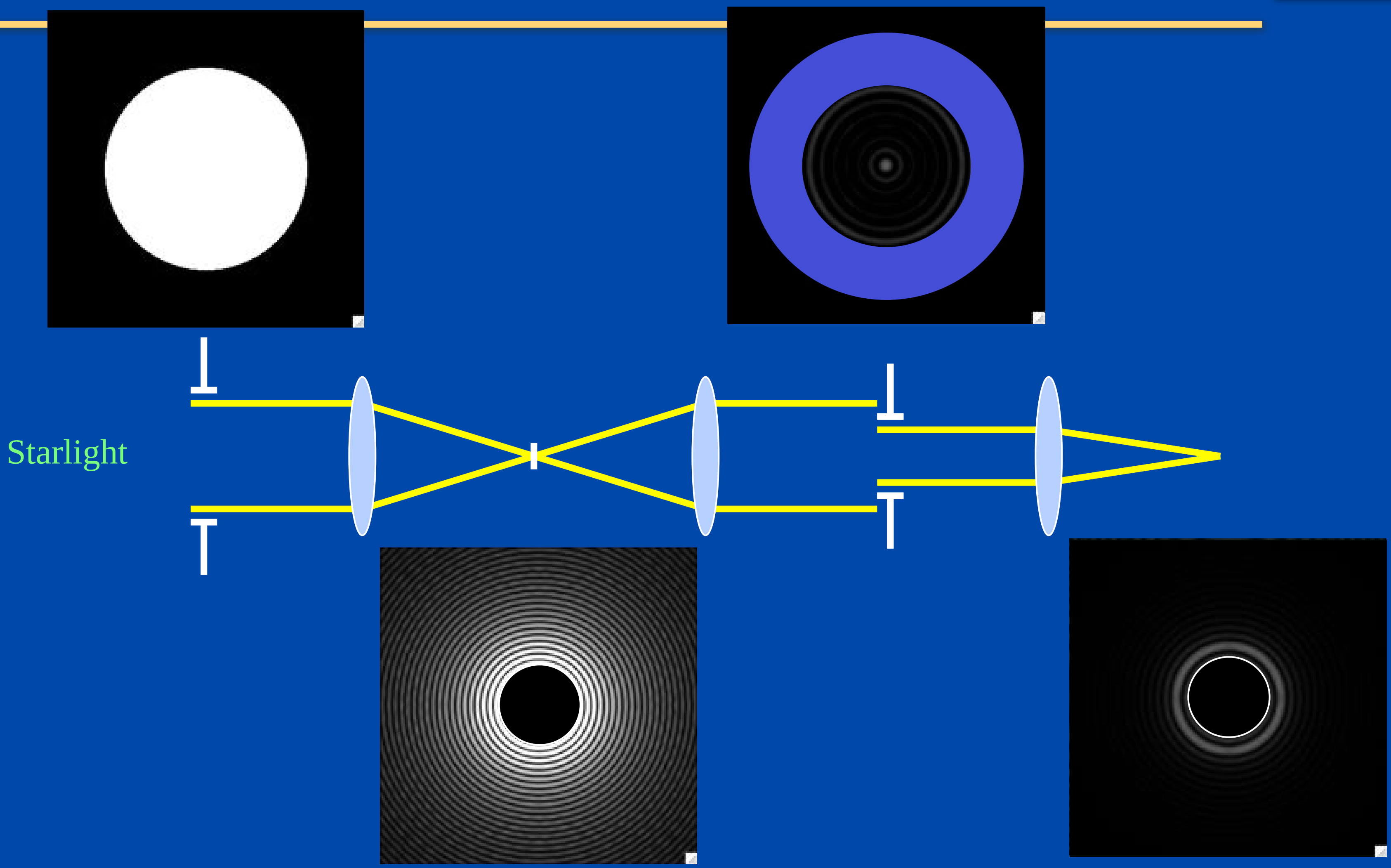




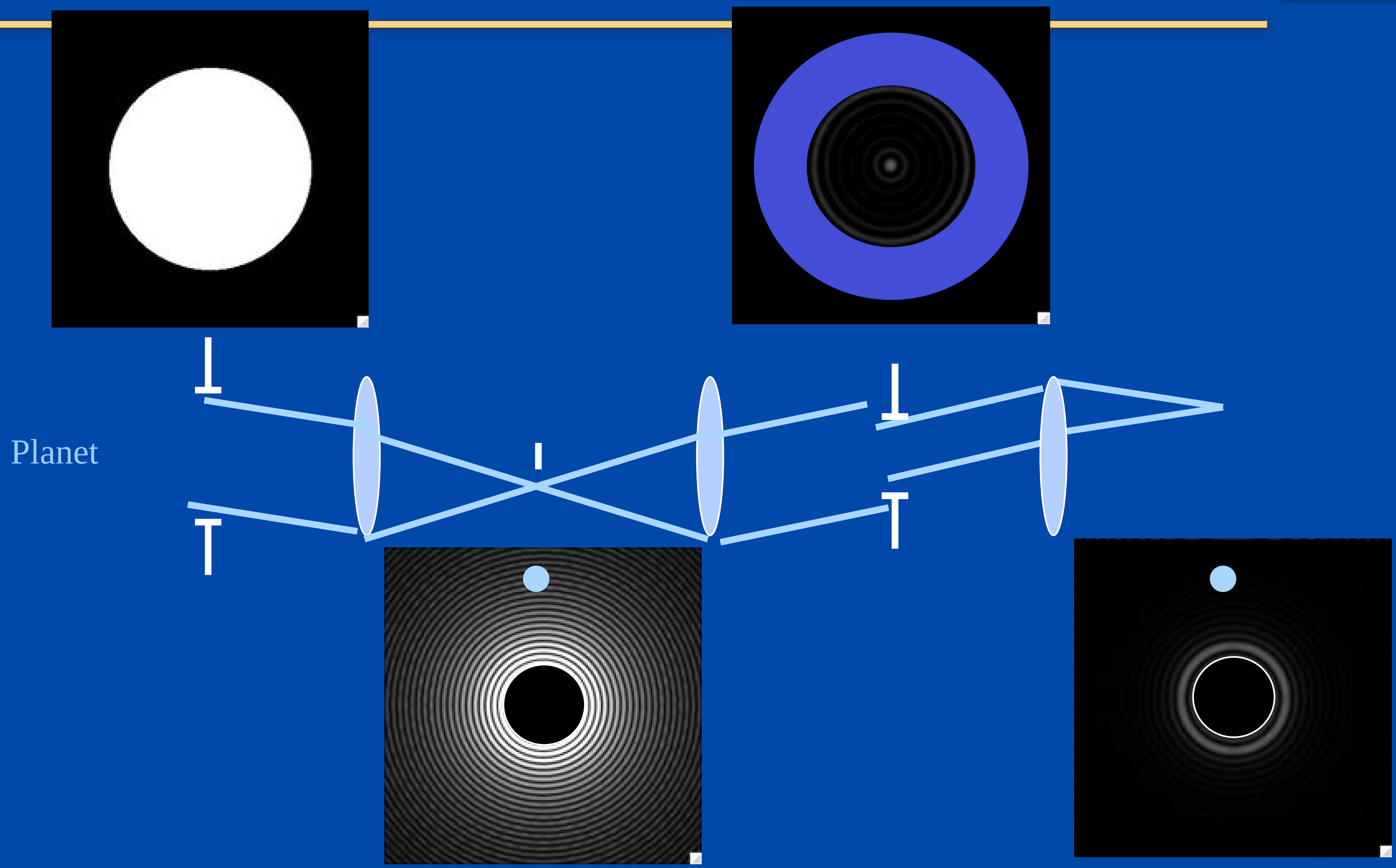


$$PSF = |FT(A)|^2$$

Lyot coronagraph (Lyot, 1933)



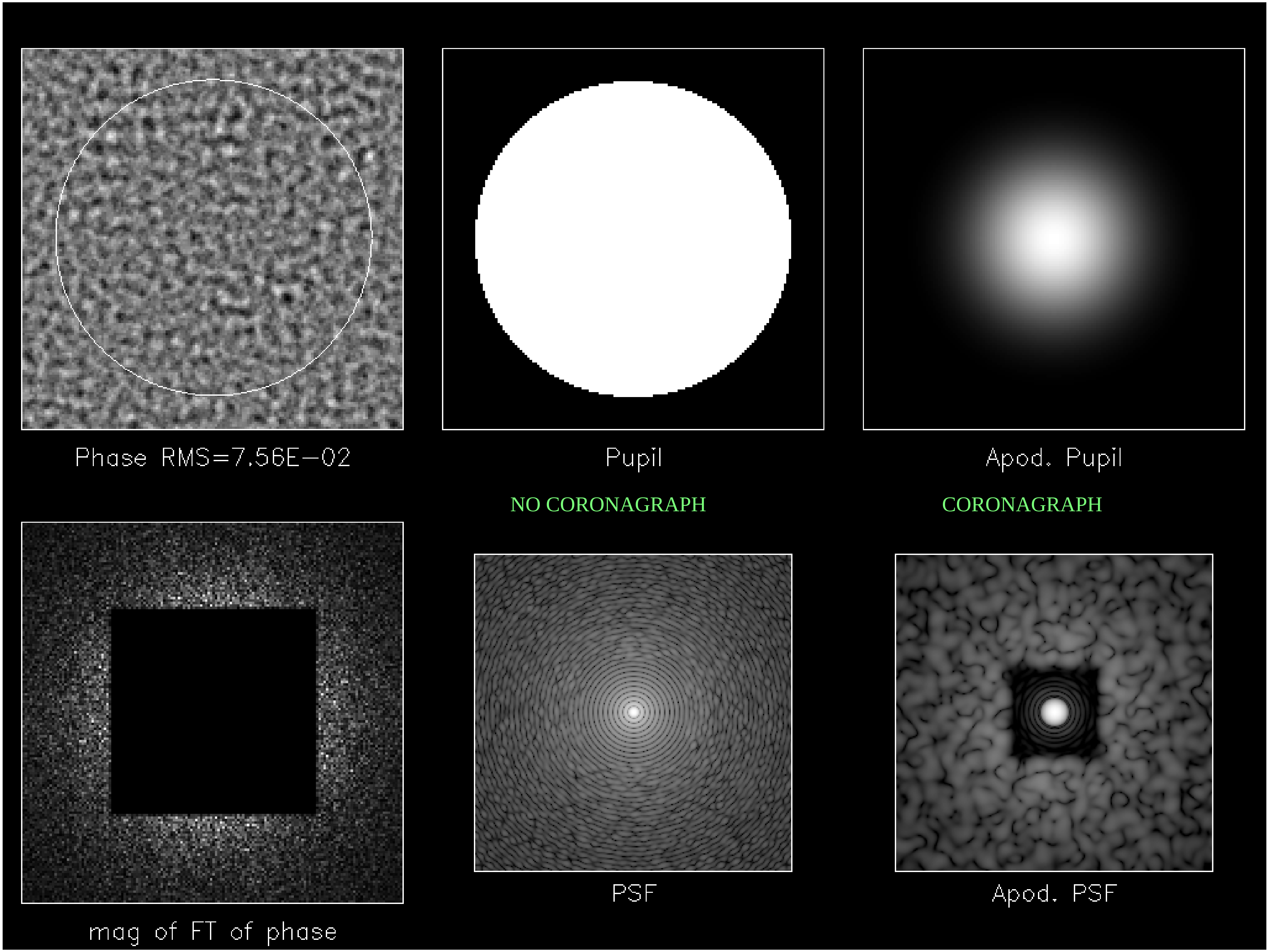
Lyot coronagraph (Lyot, 1933)



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

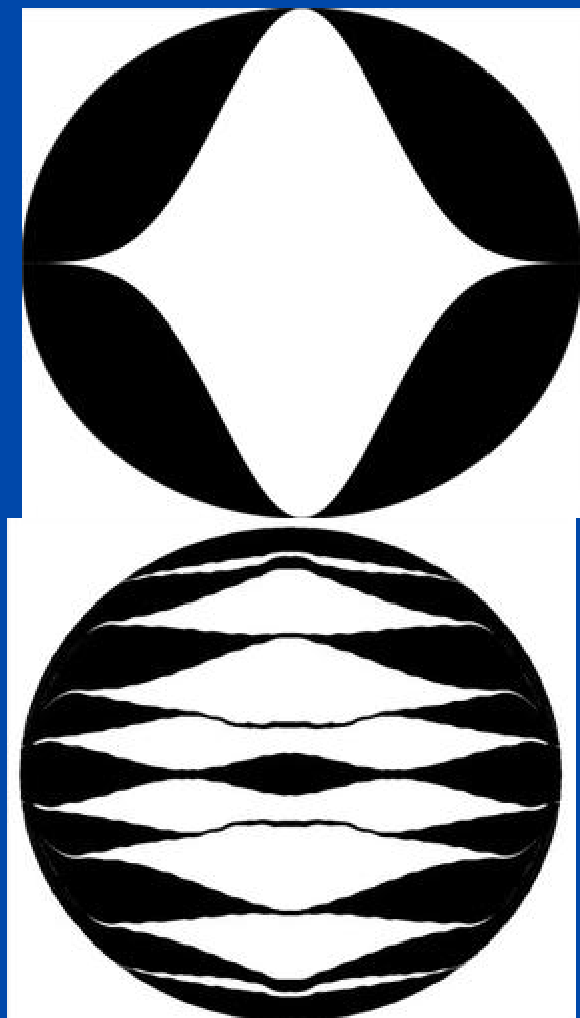
Explosion of new coronagraph ideas in recent years

- 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

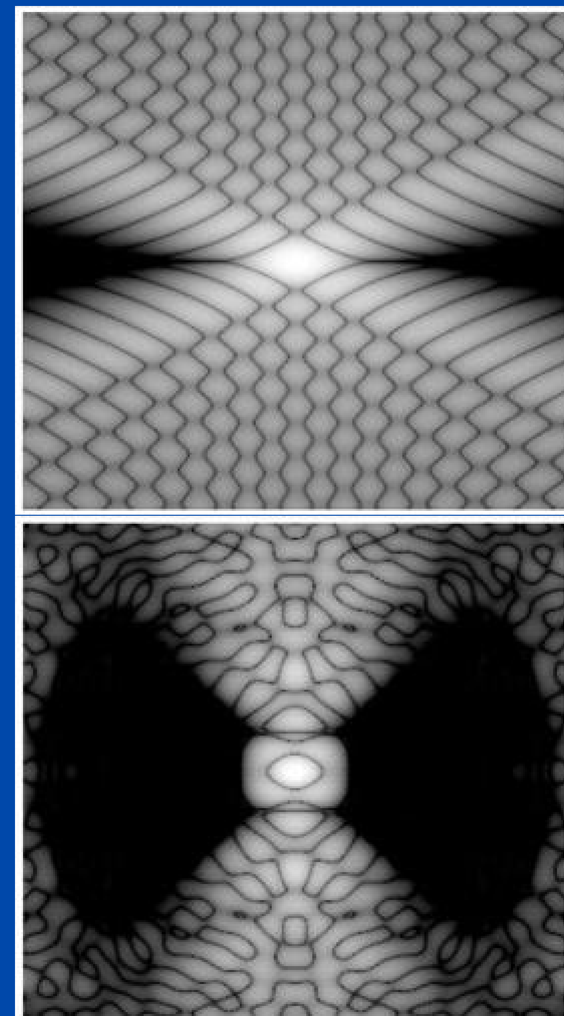

Phase RMS=7.56E−02
Pupil
Apod. Pupil
NO CORONAGRAPH
CORONAGRAPH
mag of FT of phase
PSF
Apod. PSF

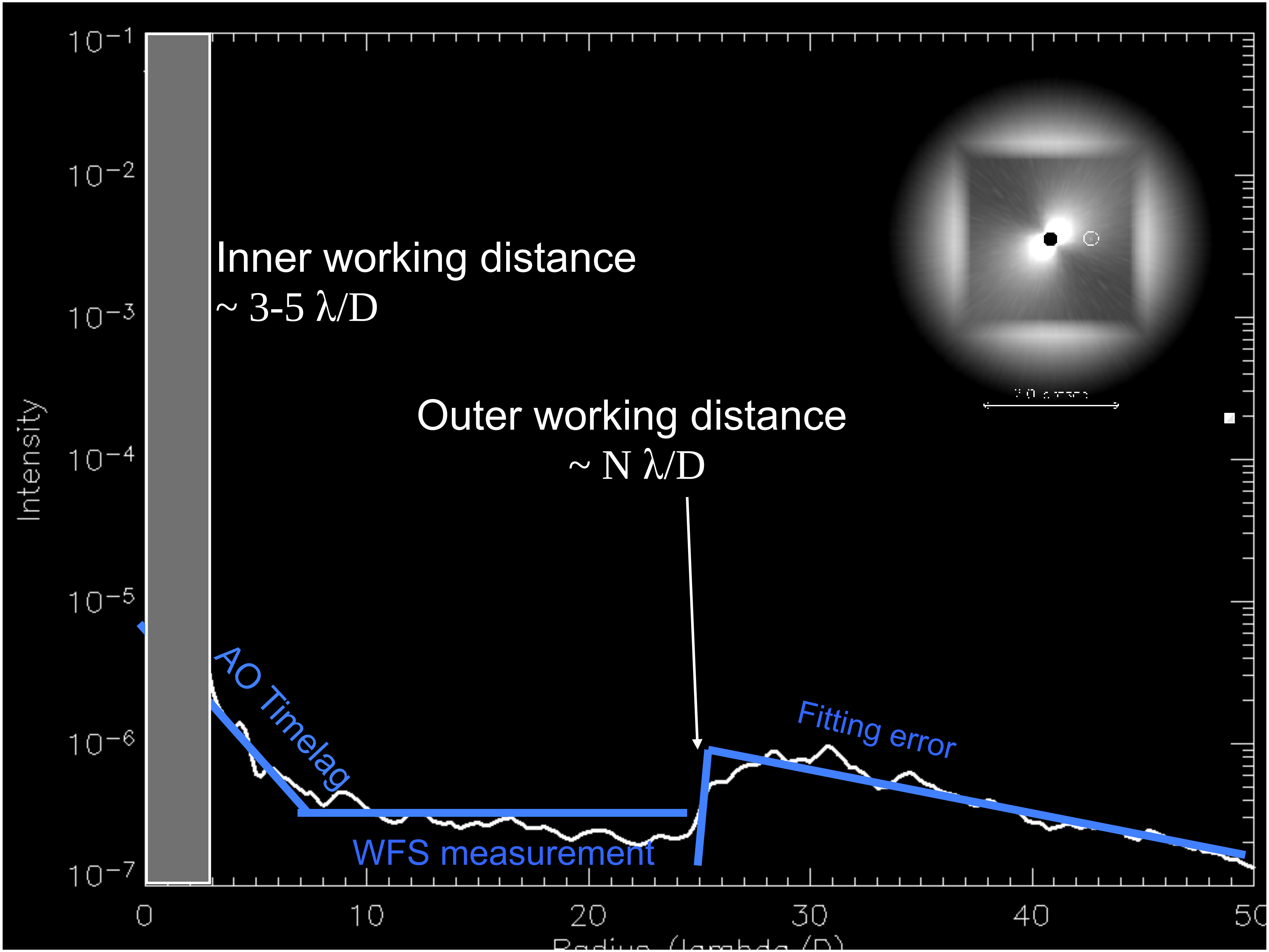
Shaped-pupil coronagraphs (Kasdin et al. 2003)

Pupil



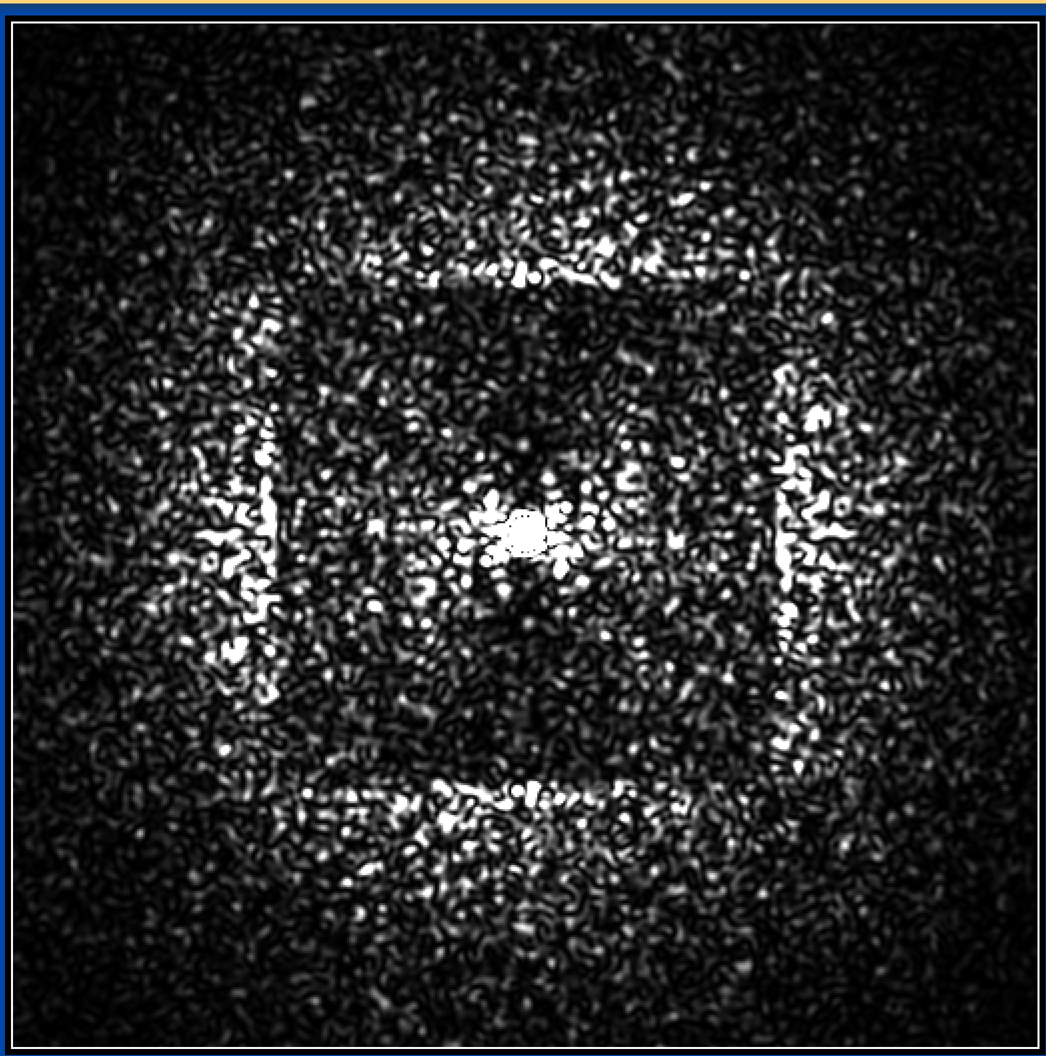
PSF



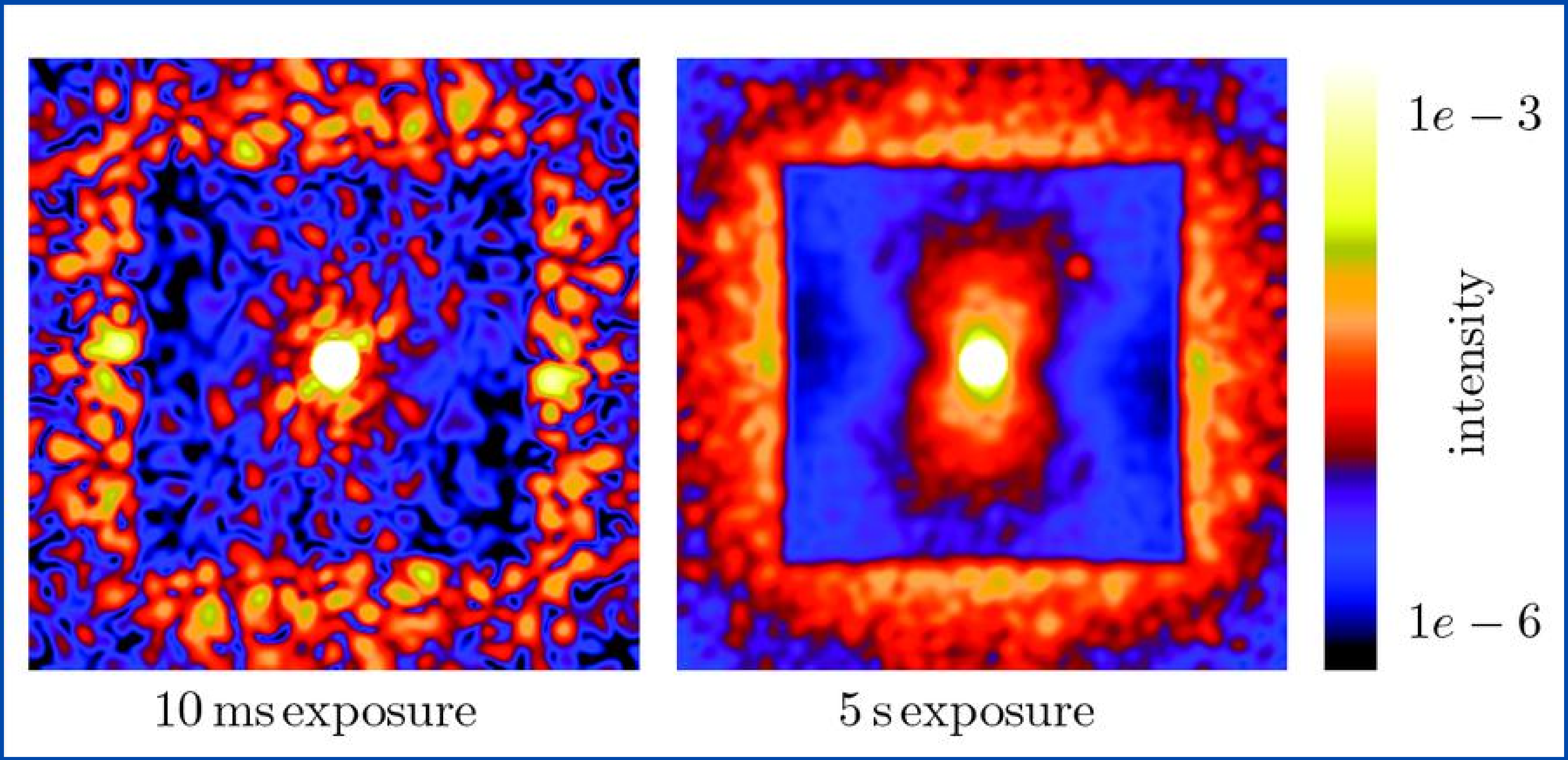


Inner working distance
~ 3-5 λ/D
Outer working distance
~ N λ/D
AO Timelag
WFS measurement
Fitting error
Intensity
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0
10
20
30
40
50

Random intensity of all the Fourier components produces speckles

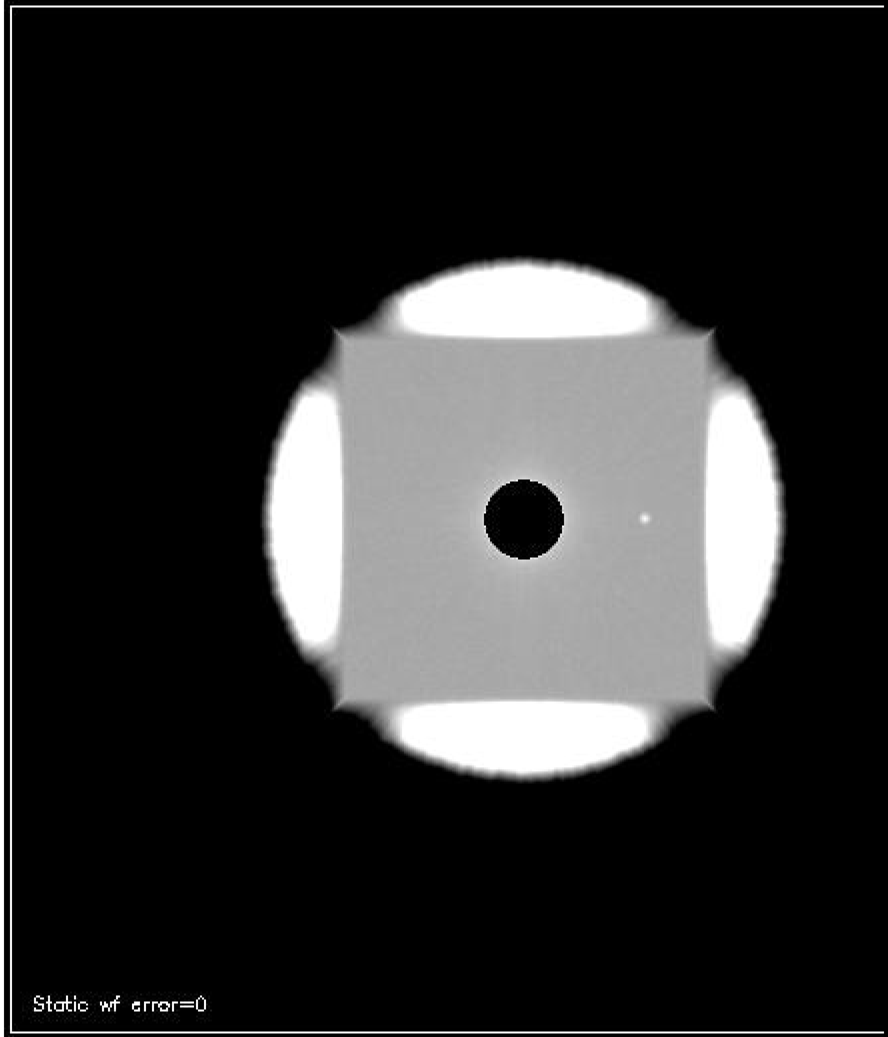


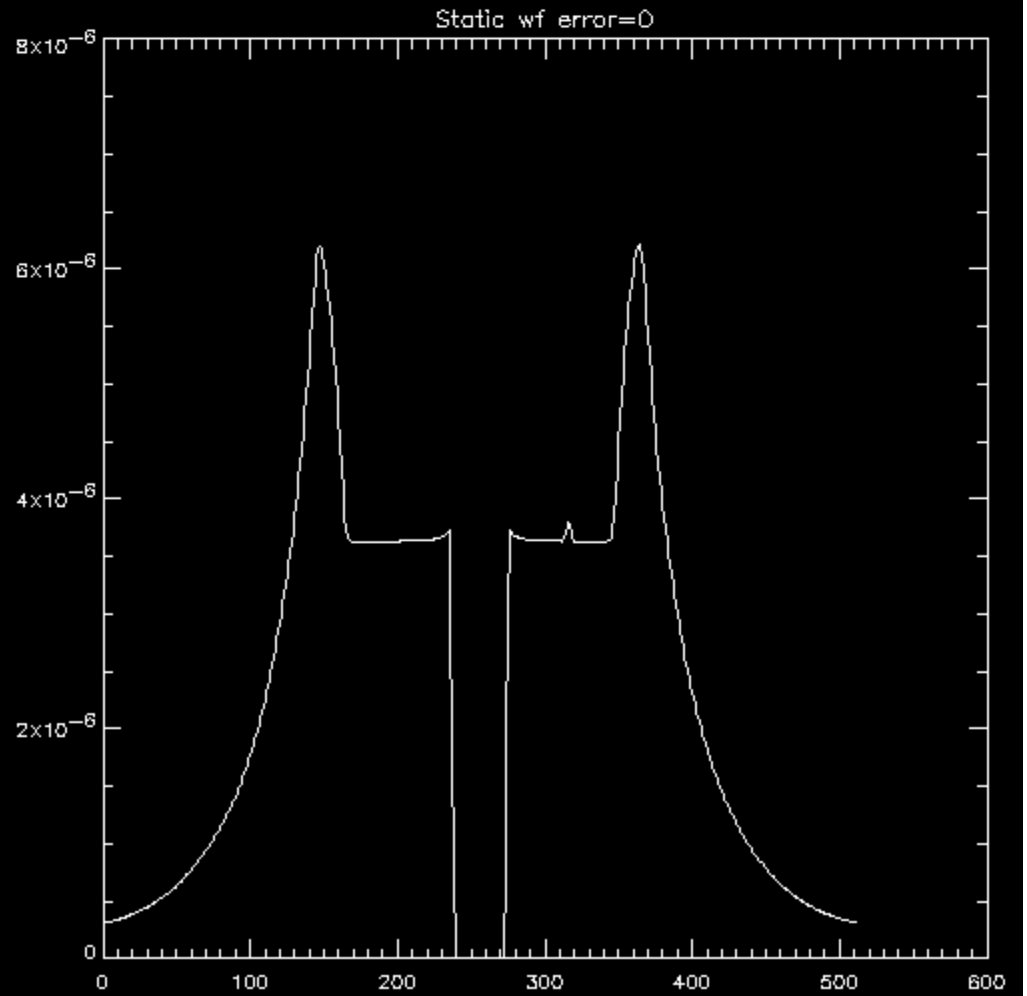
As speckles average out ($t \sim D/v_{wind}$) planets can be detected



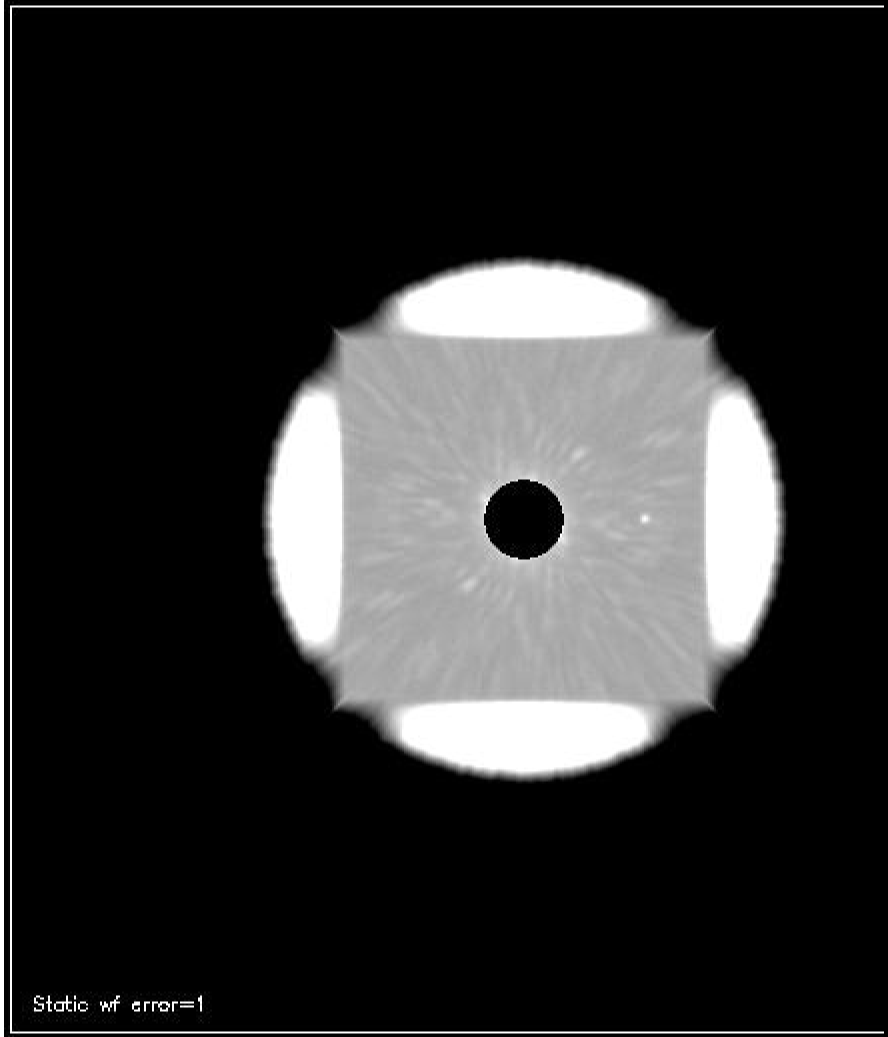
Must get rid of static errors as well

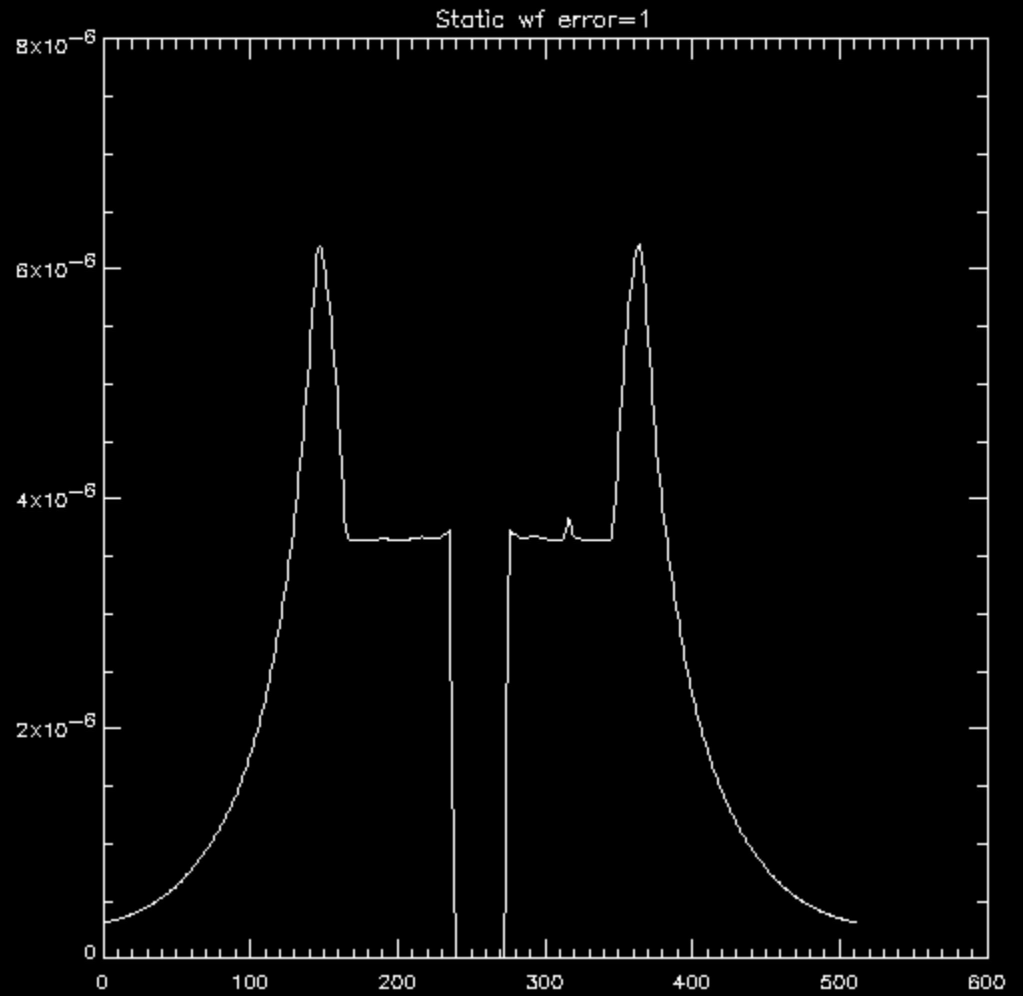
ExAO 0 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



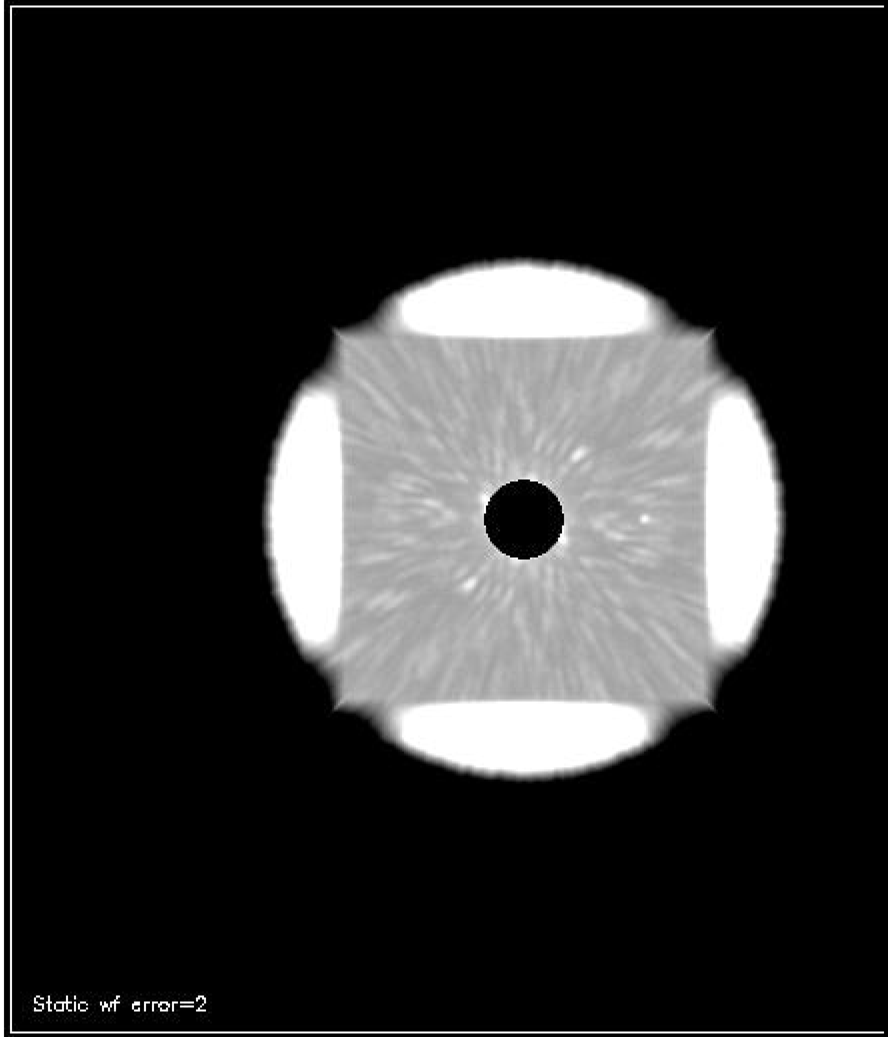


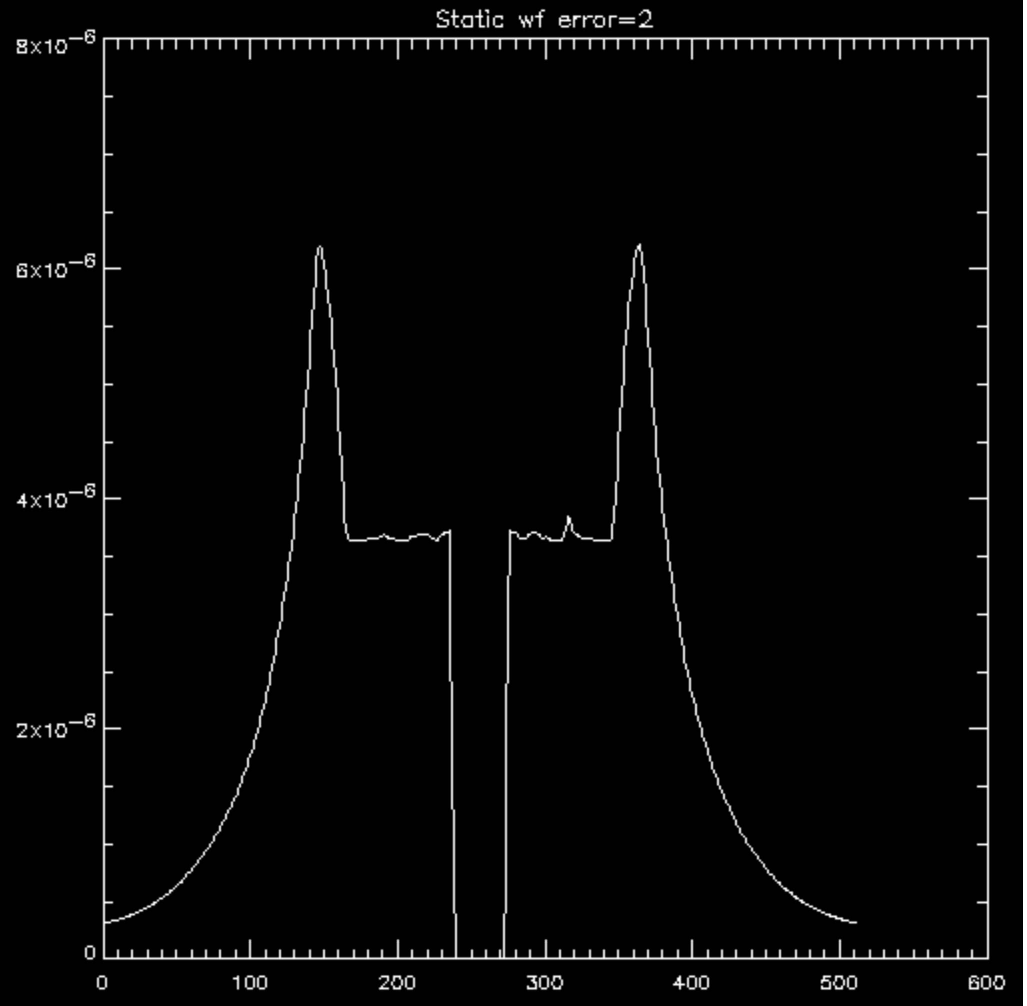
ExAO 1 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



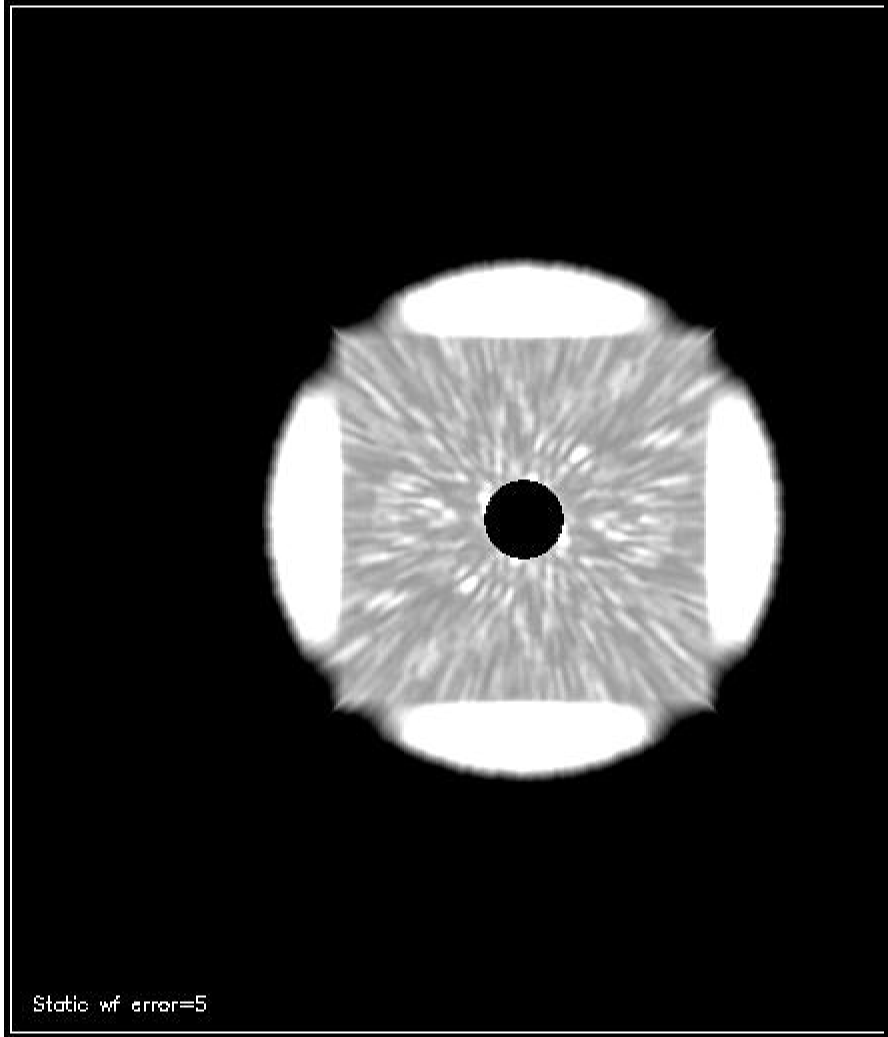


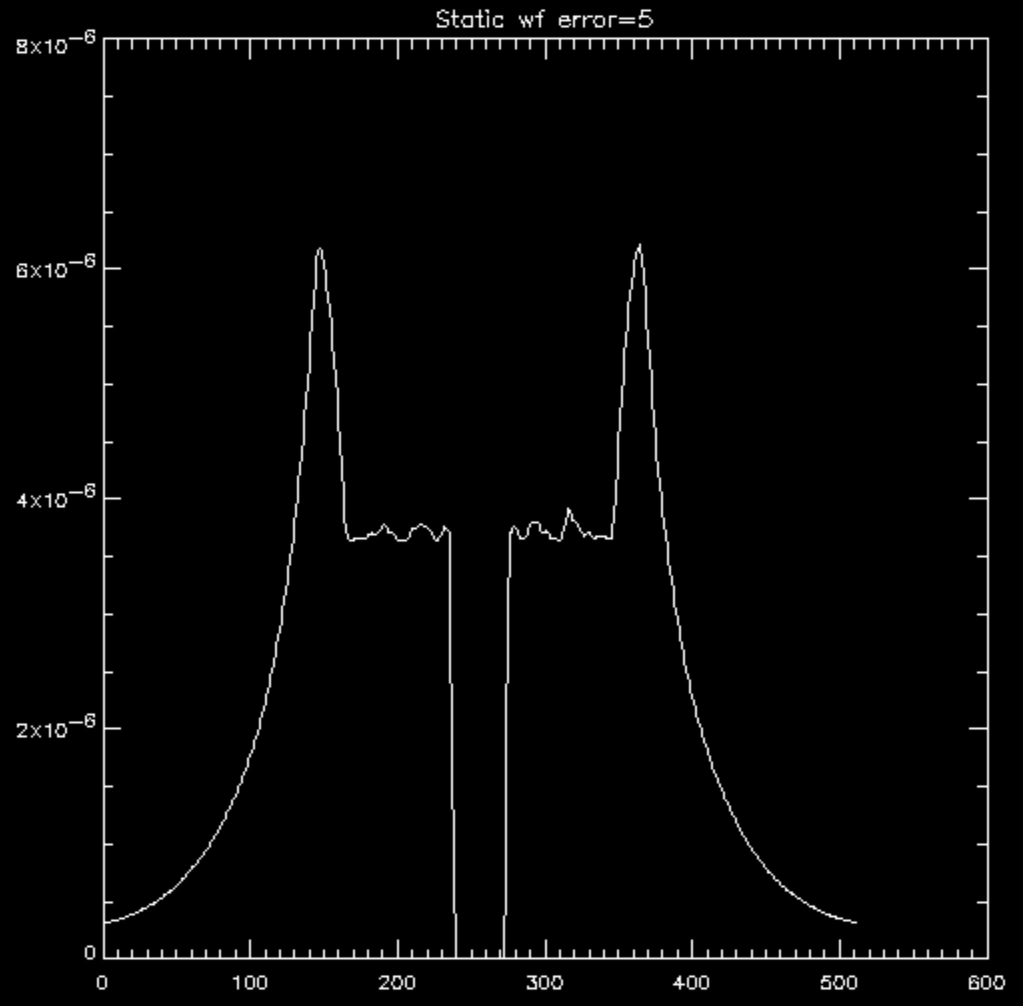
ExAO 2 nm static errors, 5 MJ/500 MYr planet, 15 minute integration



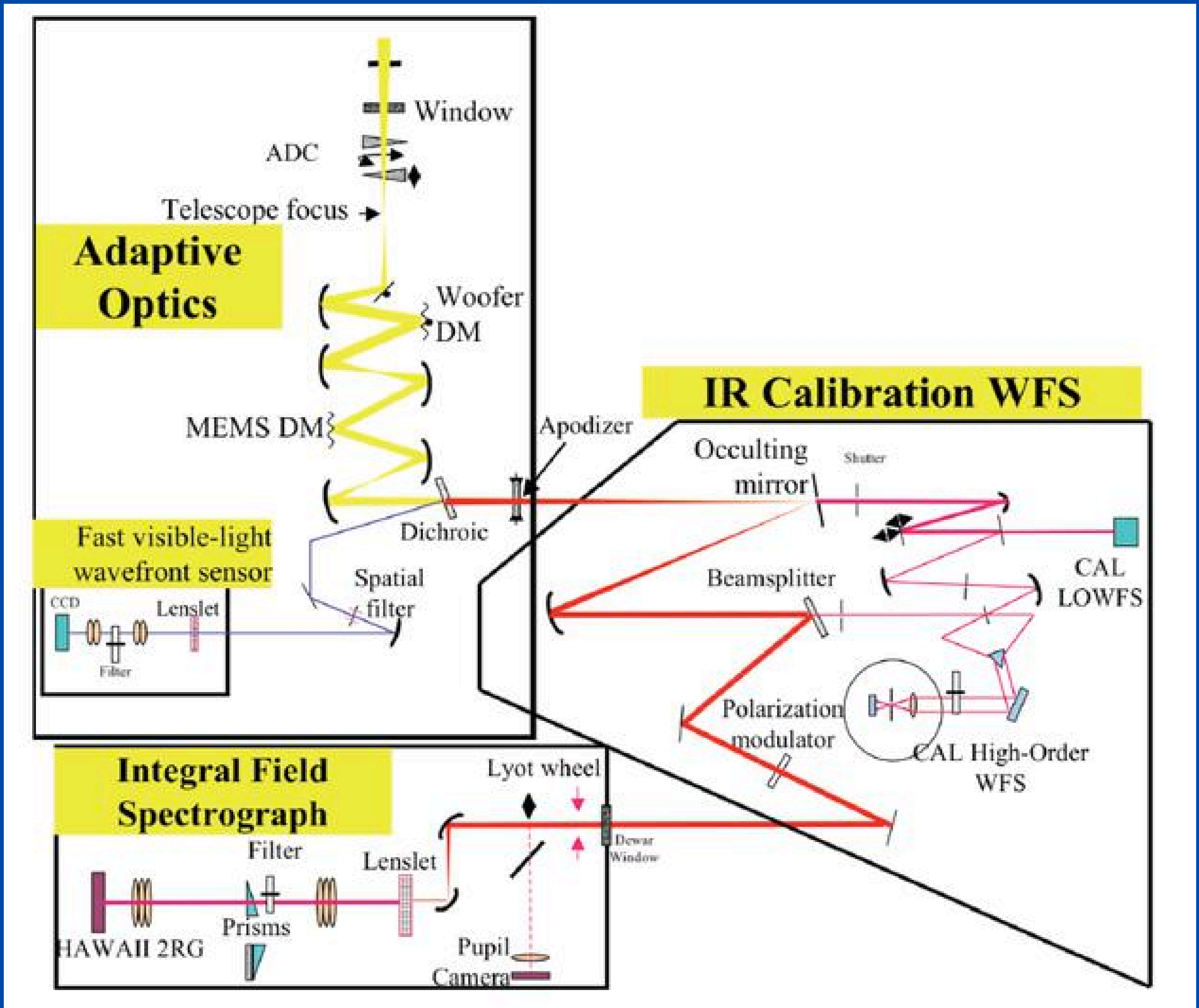


ExAO 5 nm static errors, 5 MJ/500 MYr planet, 15 minute integration





Schematic of Gemini Planet Imager

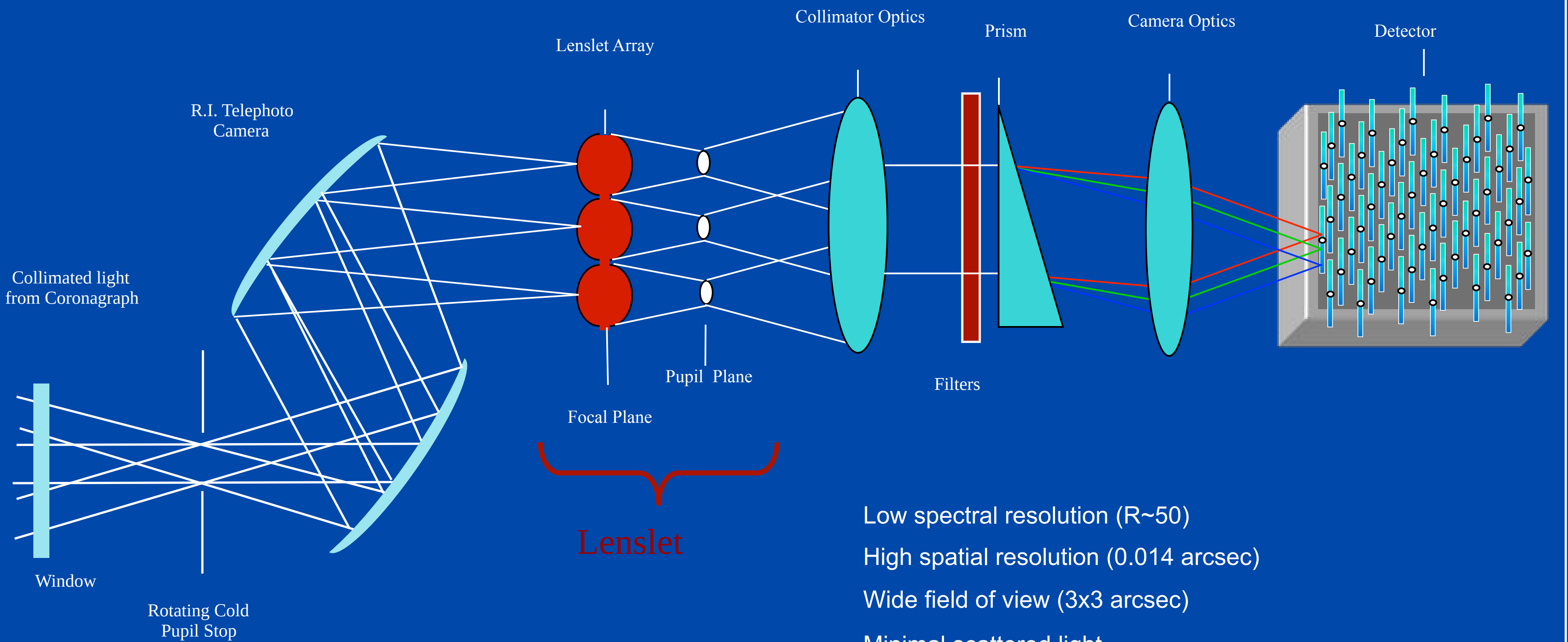


Comparison of original Keck AO and GPI AO parameters

	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 mm	40%	> 90%
Guide star mag (NGS only)	*R* < 13.5 mag.	*I* < *9* mag. (V < 11)

GPI Integral field spectrograph (James Larkin, UCLA)

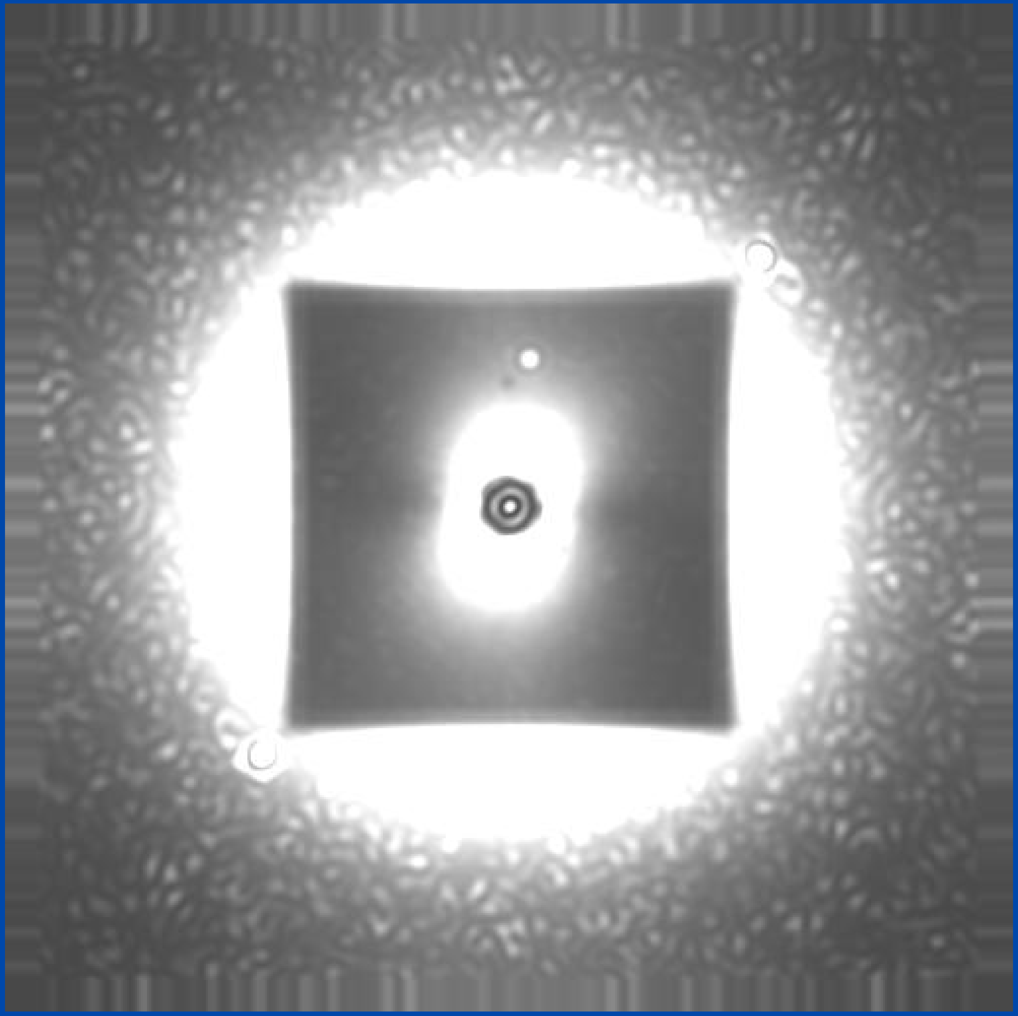
Spectrograph



Lenslet

- Low spectral resolution (R~50)
- High spatial resolution (0.014 arcsec)
- Wide field of view (3x3 arcsec)
- Minimal scattered light

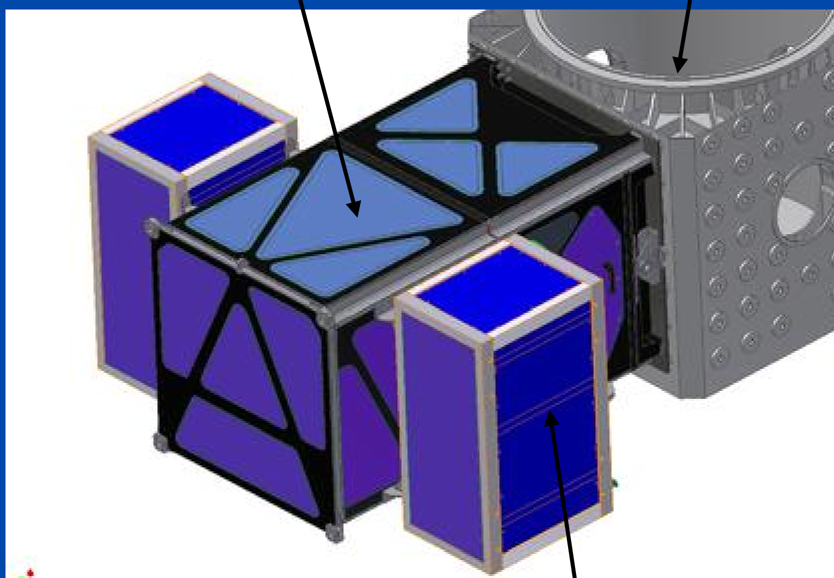
Data pipeline assembles cubes: image of planet as function of wavelength



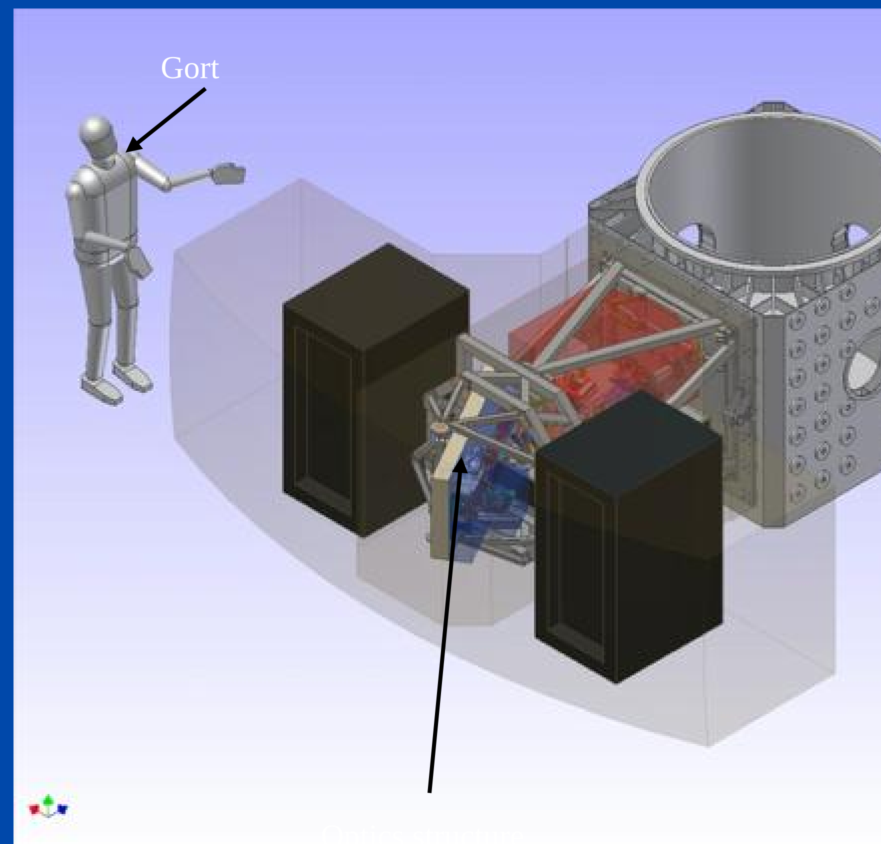
GPI mechanical design

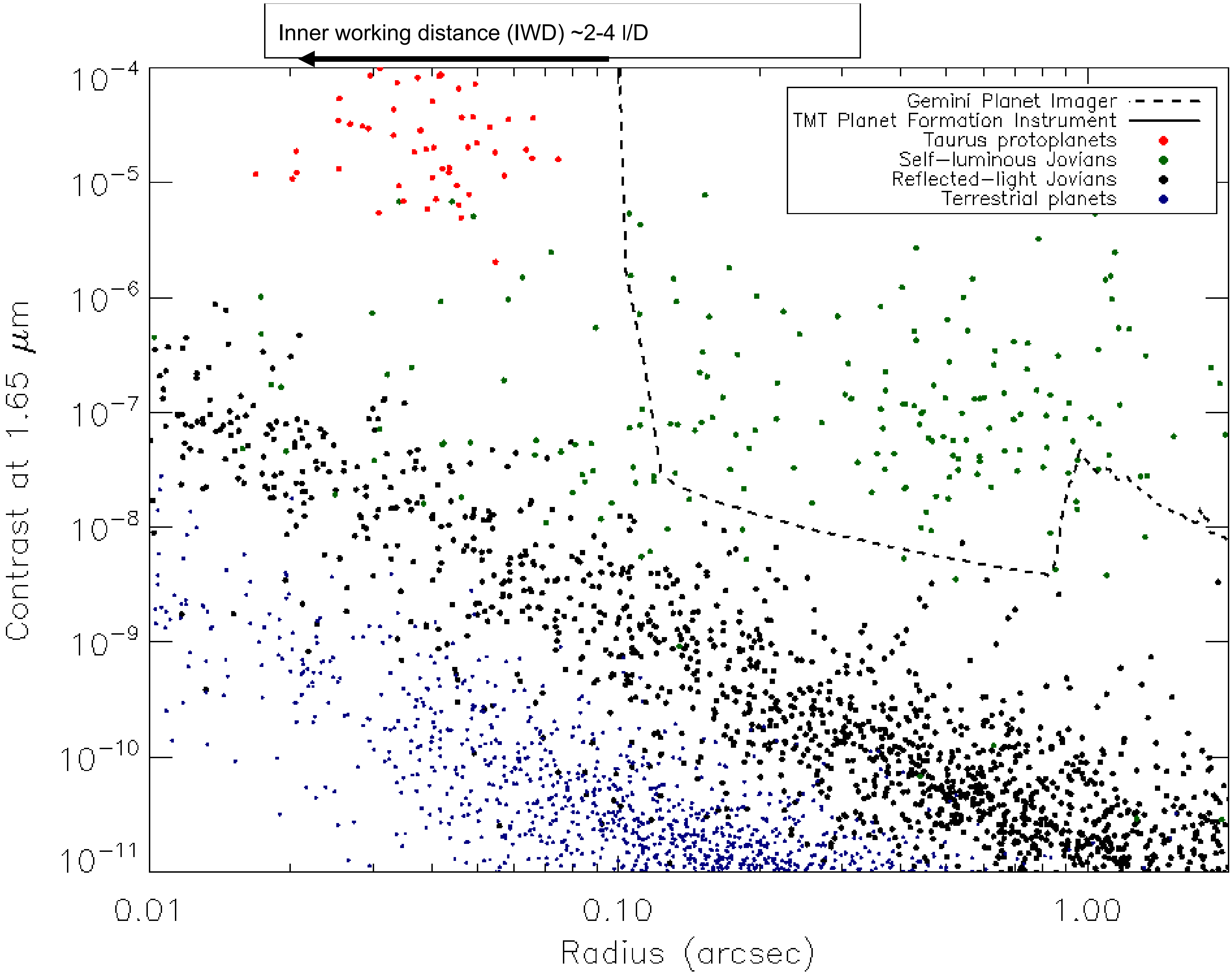
Gemini Cassegrain support structure

GPI enclosure

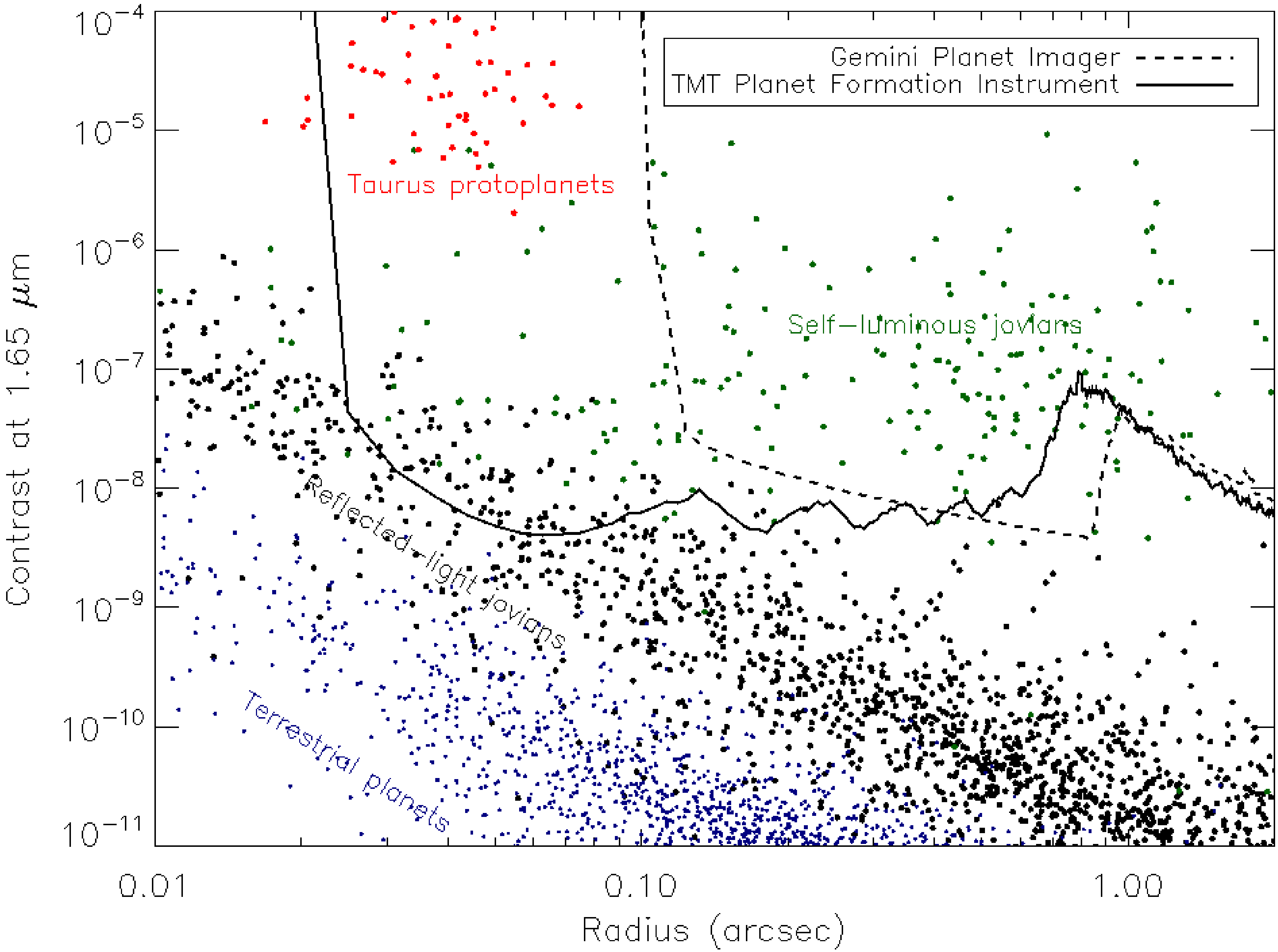


Electronics



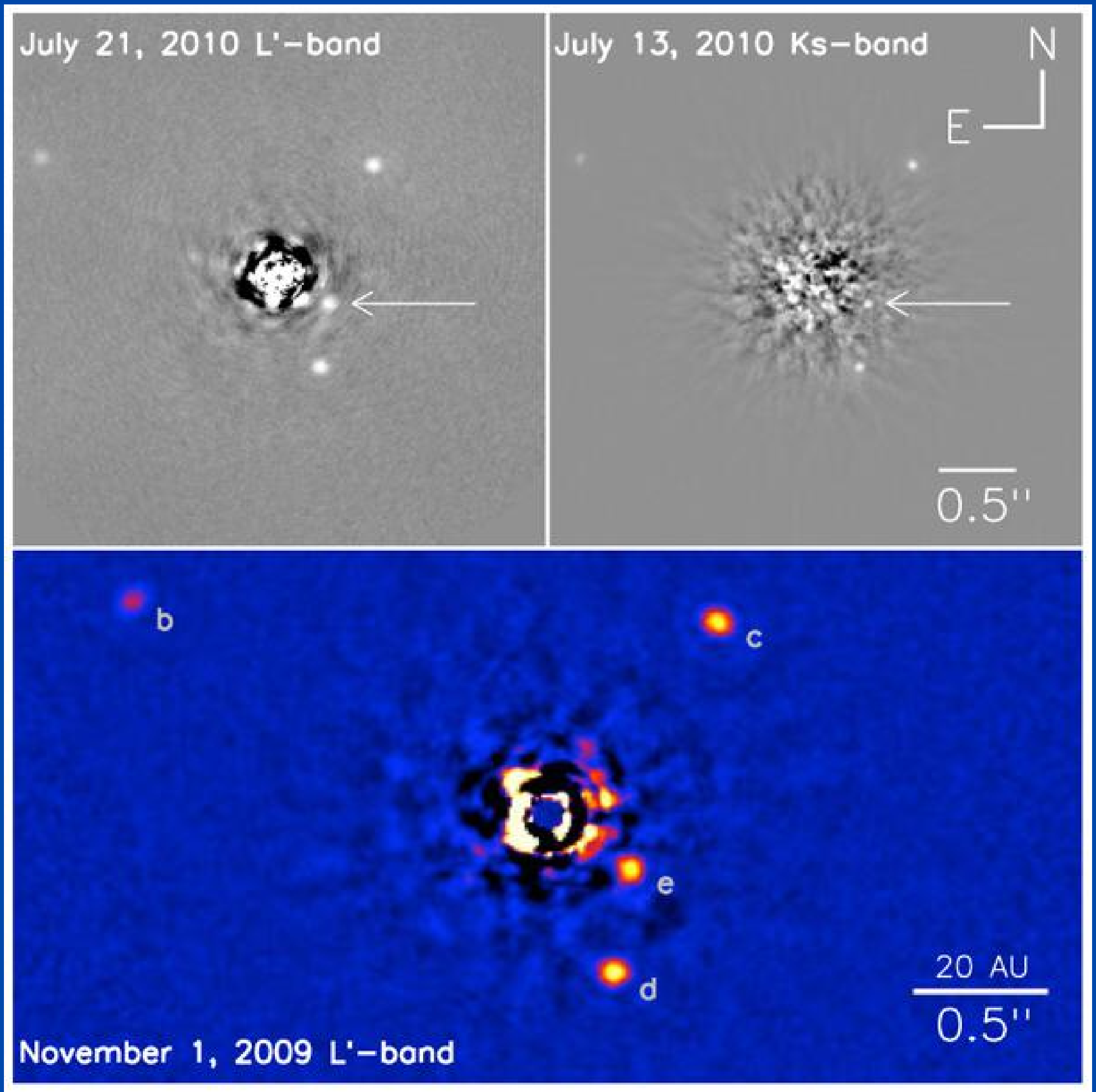


Inner working distance (IWD) ~2-4 l/D
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self–luminous Jovians
Reflected–light Jovians
Terrestrial planets
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Contrast at 1.65 μm
0.01
0.10
1.00
Radius (arcsec)



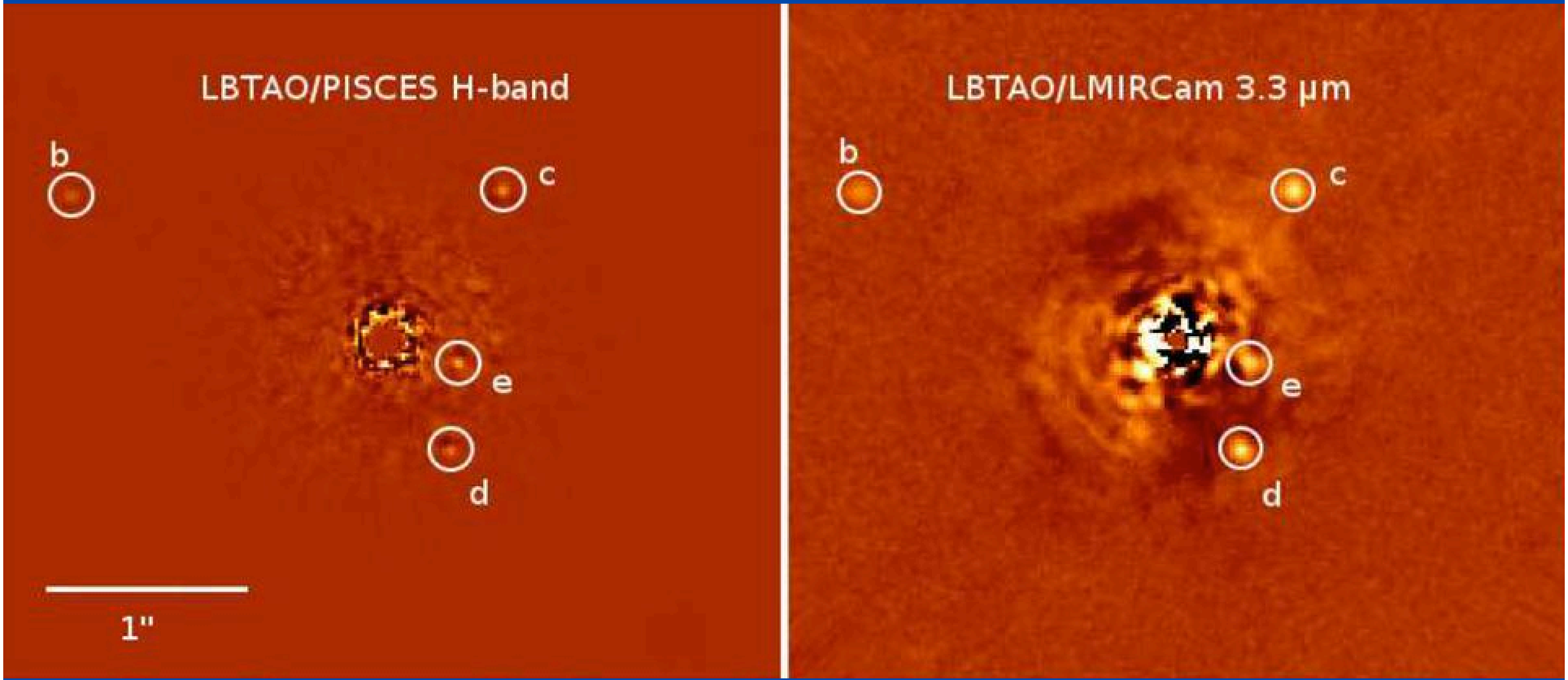
Gemini Planet Imager
TMT Planet Formation Instrument
Taurus protoplanets
Self−luminous jovians
Reflected−light jovians
Terrestrial planets
Contrast at 1.65 μm
Radius (arcsec)
10−4
10−5
10−6
10−7
10−8
10−9
10−10
10−11
0.01
0.10
1.00

Directly imaged planets: HR 8799 System



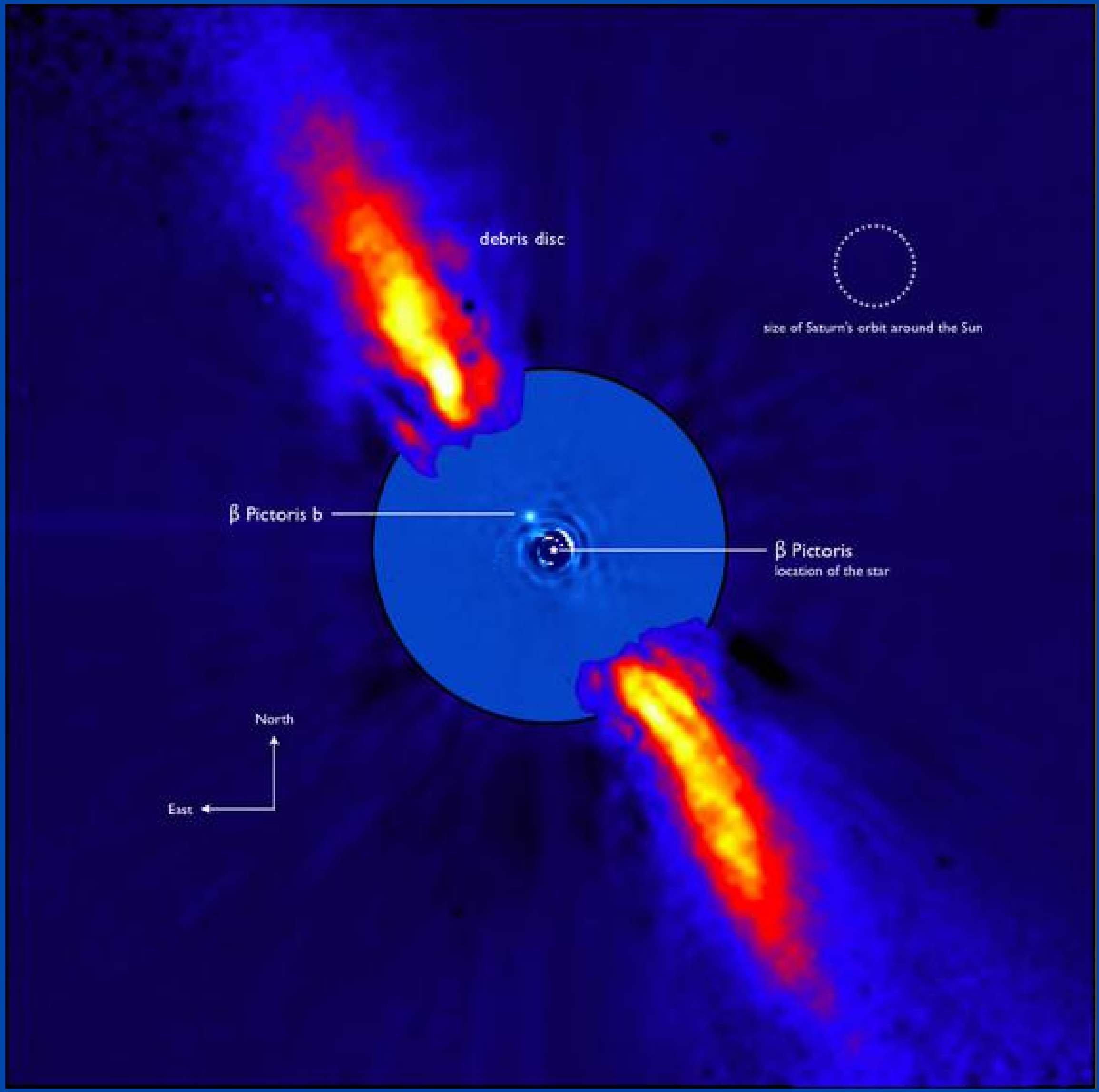
Marois and colleagues, Gemini and Keck

HR 8799: greater contrast with parent star at 3.3 microns

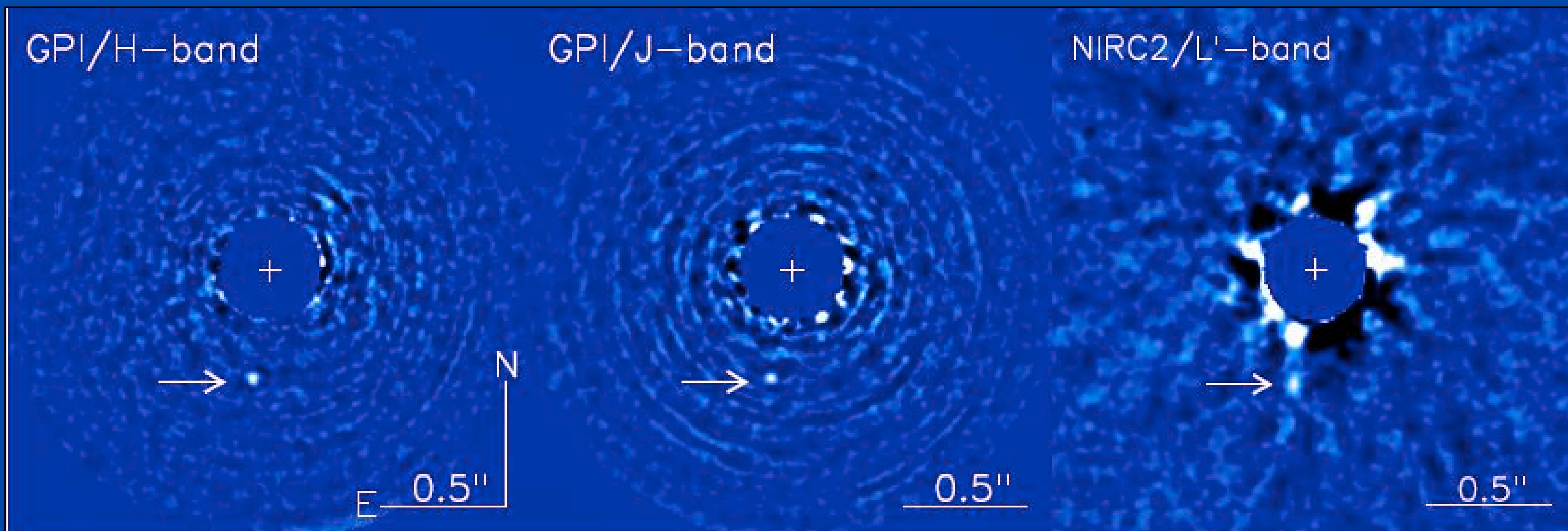


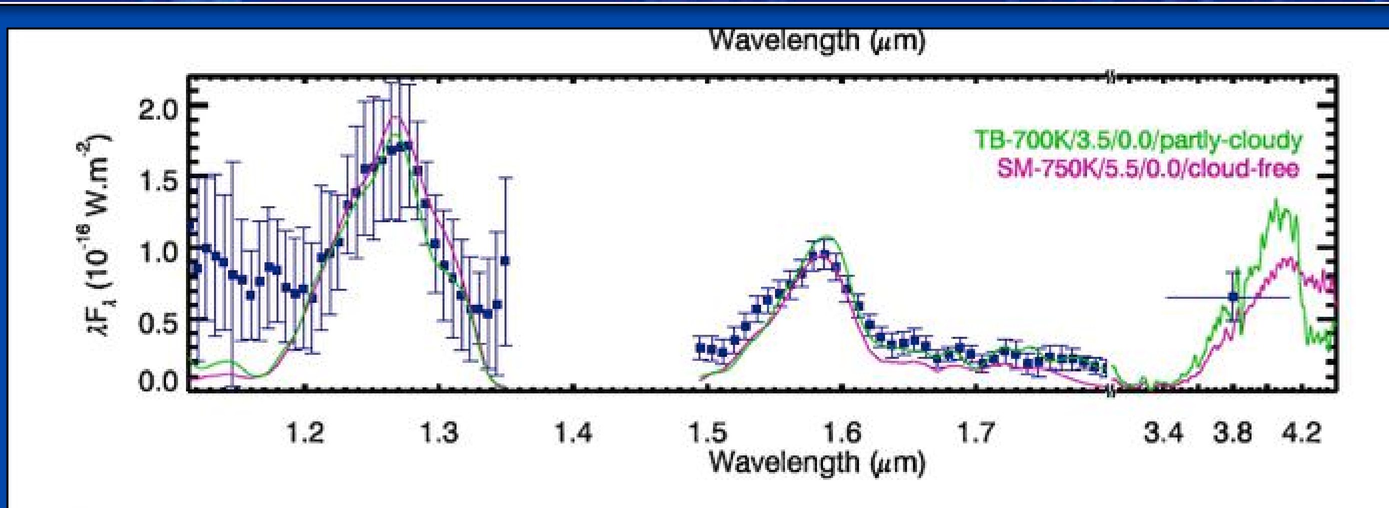
Hinz and colleagues, LBT

Beta Pictoris b: a planet within a disk

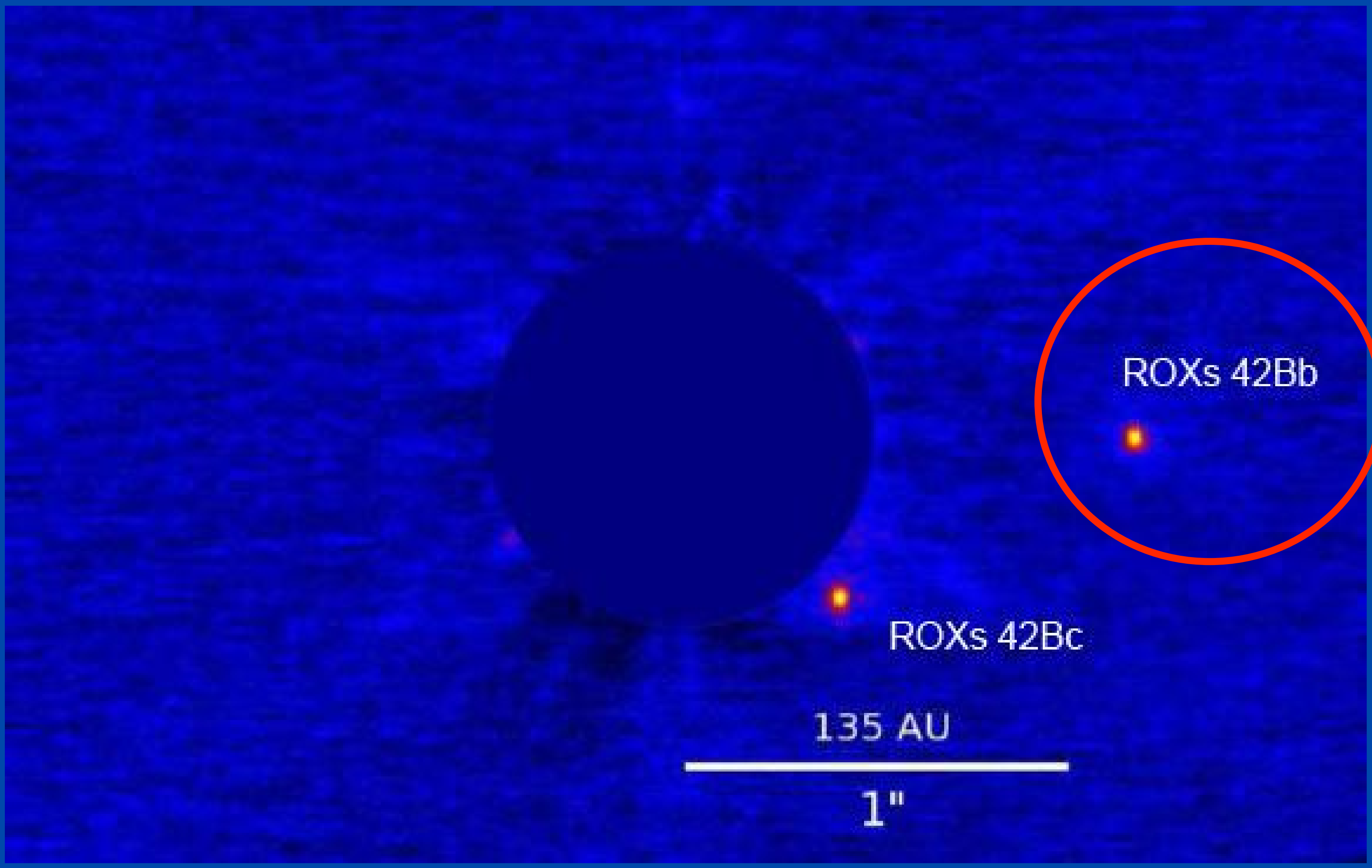


51 Eri b: from GPI (Macintosh et al. 2015)





ROXs 42b (Currie et al. 2015)



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 (2nd-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

Marois, C., et al., 2000, “Efficient Speckle Noise Attenuation in Faint Companion Imaging”, 2000 Proc. SPIE 767, 91

Marois, C., et al., 2006, “Angular Differential Imaging: A Powerful High-Contrast Technique”, 2006 Ap.J. 6541, 556

Marois, C., Macintosh, B., Barman, T., et al, “Direct Imaging of Multiple Planets Orbiting the Star HR8799”, 2008 Science 5906, 1348

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

Ground based Instruments: Exoplanet direct imaging instruments

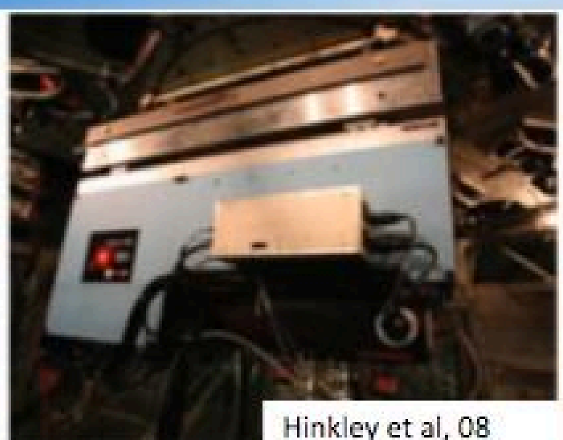
GPI

Macintosh et al, 14

SPHERE

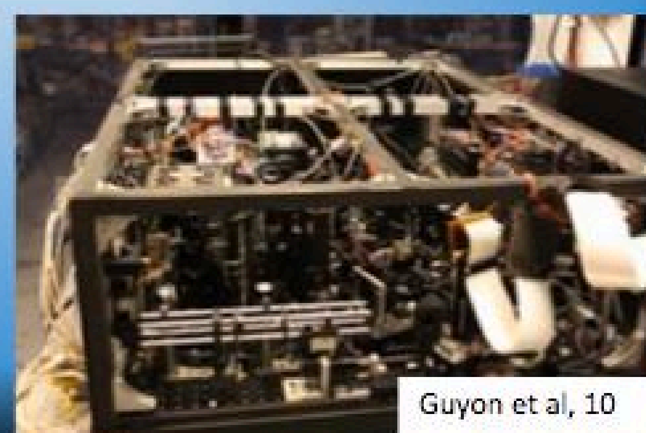
Beuzit et al, 14

P1640



Hinkley et al, 08

SCExAO



Guyon et al, 10