High-Contrast Imaging and Exoplanet Applications

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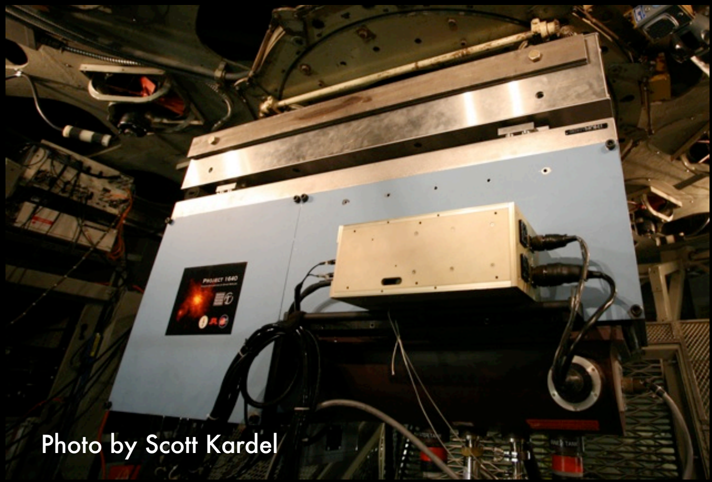
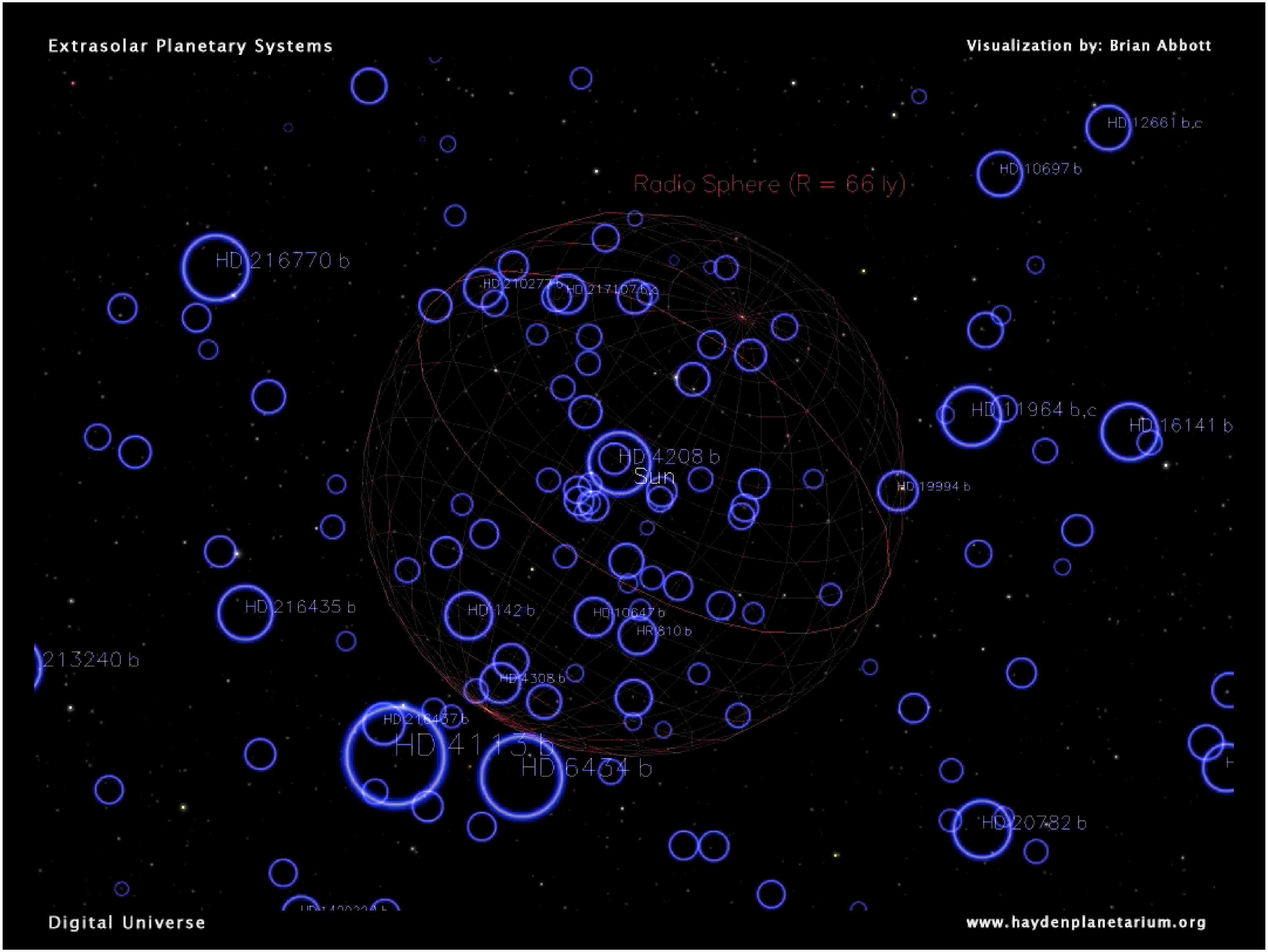


Photo by Scott Kardel


Extrasolar Planetary Systems
Visualization by: Brian Abbott
HD 12661 b,c
HD 10697 b
Radio Sphere (R = 66 ly)
HD 216770 b
HD 210277 b
HD 11964 b,c
HD 16141 b
HD 4208 b
Sun
HD 19994 b
HD 216435 b
HD 142 b
HD 10647 b
HR 810 b
213240 b
HD 4308 b
HD 216437 b
HD 4113 b
HD 6434 b
HD 20782 b
Digital Universe
www.haydenplanetarium.org

Status of Exoplanetary Science

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Nearly 400 exoplanets now known.
Many more not yet announced.

Highlights:

- Most of the planets are nothing like Earth.
- Usually many times the mass of Jupiter.
- Starting to find super earths.
- Many systems with multiple planets.

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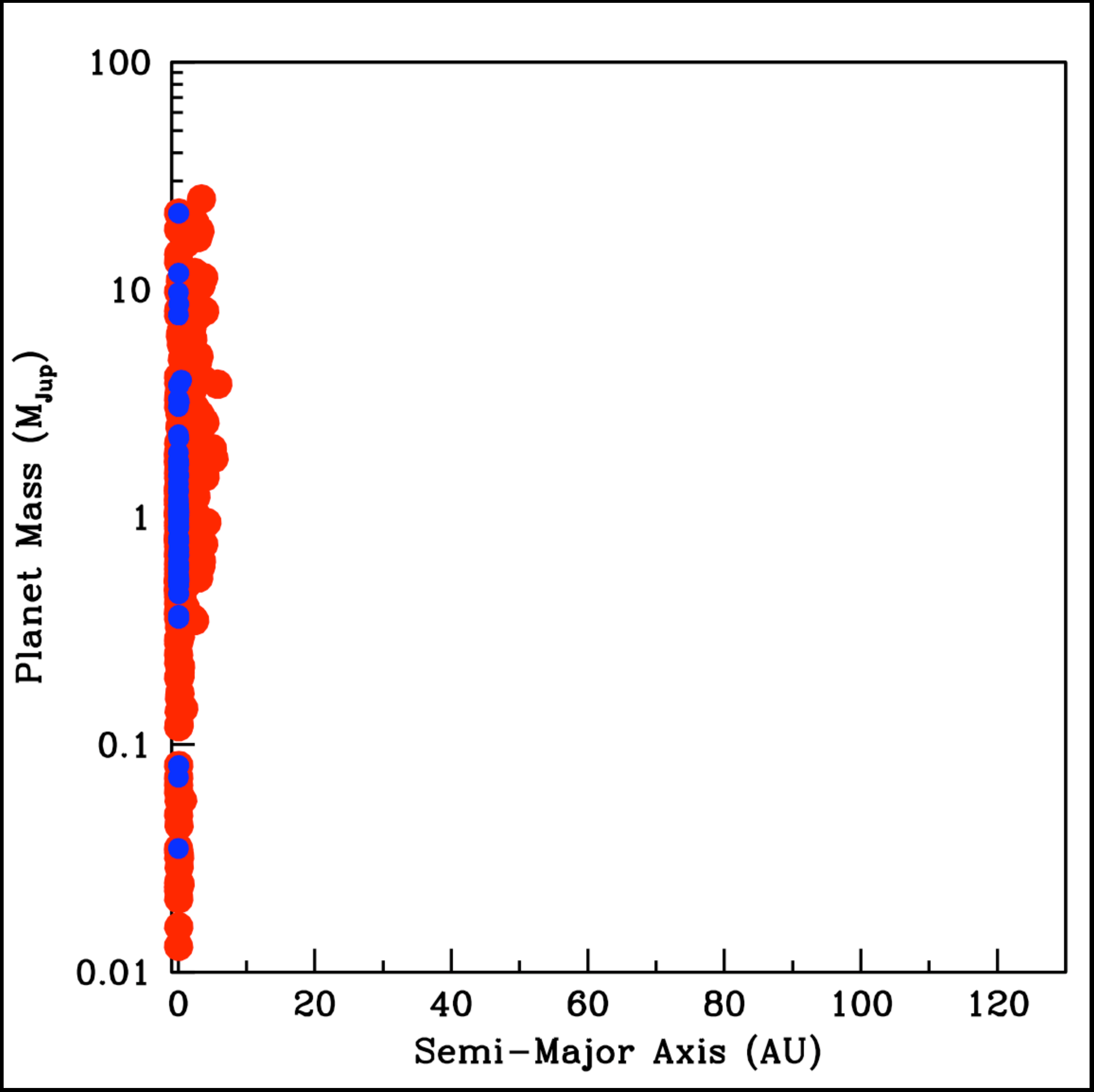
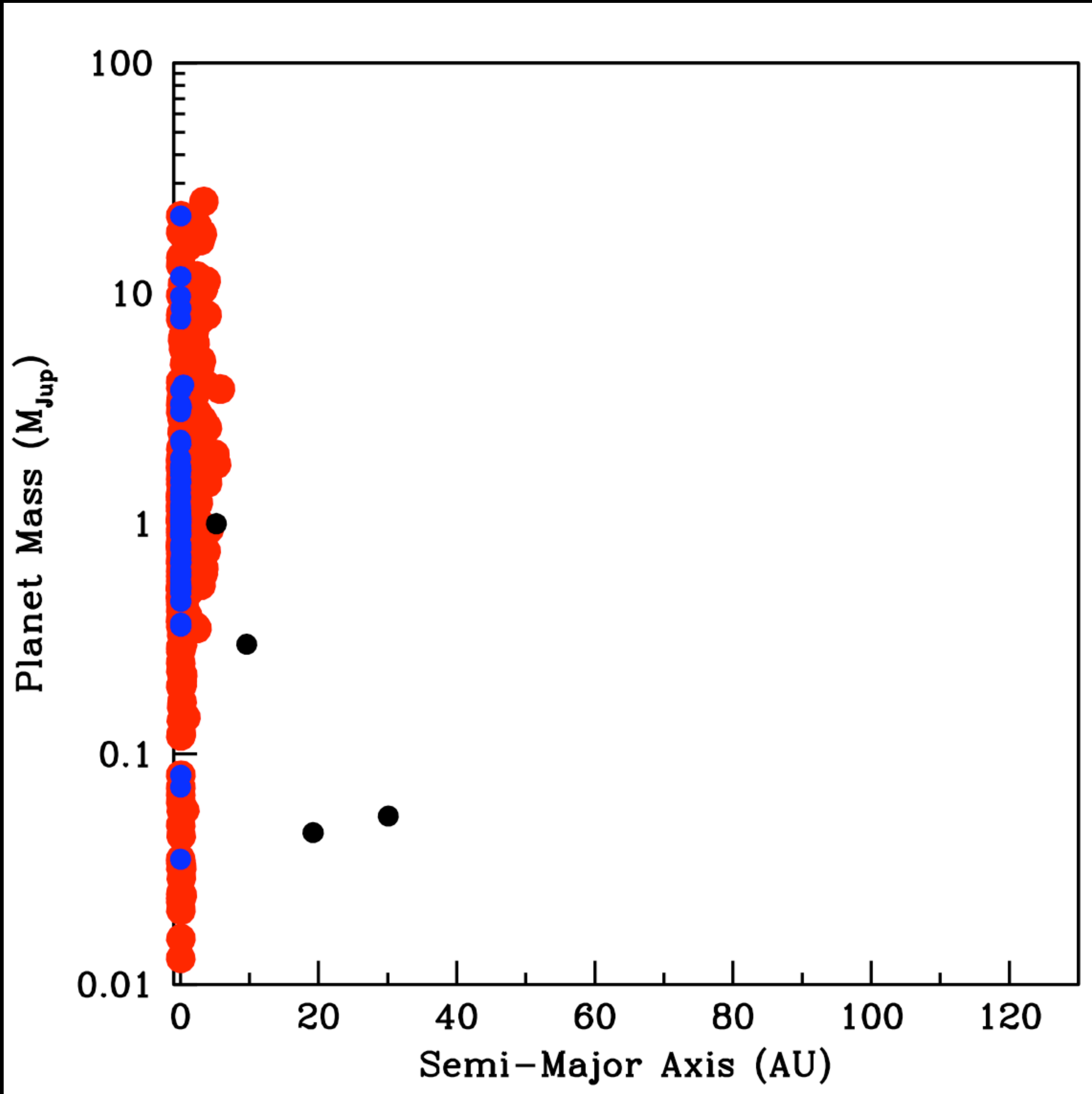
How do we detect these planets?

A majority have been detected indirectly: by measuring the planets' effect on their host star's light.



Transits

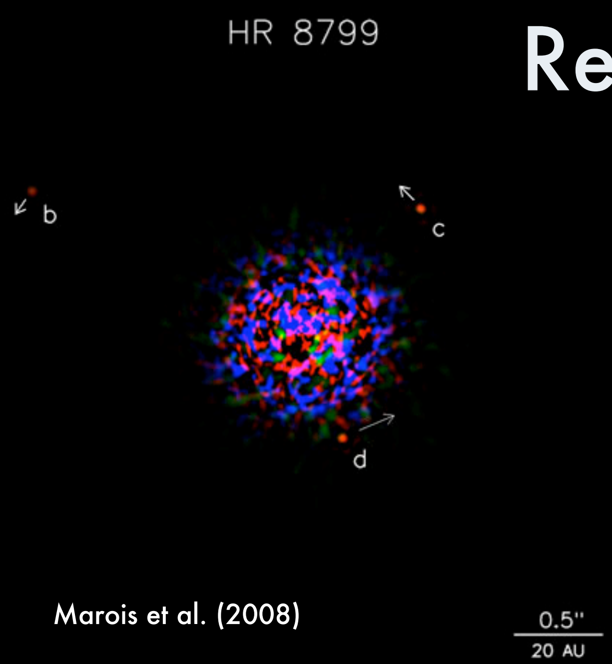
Radial Velocity



Transits

Radial Velocity

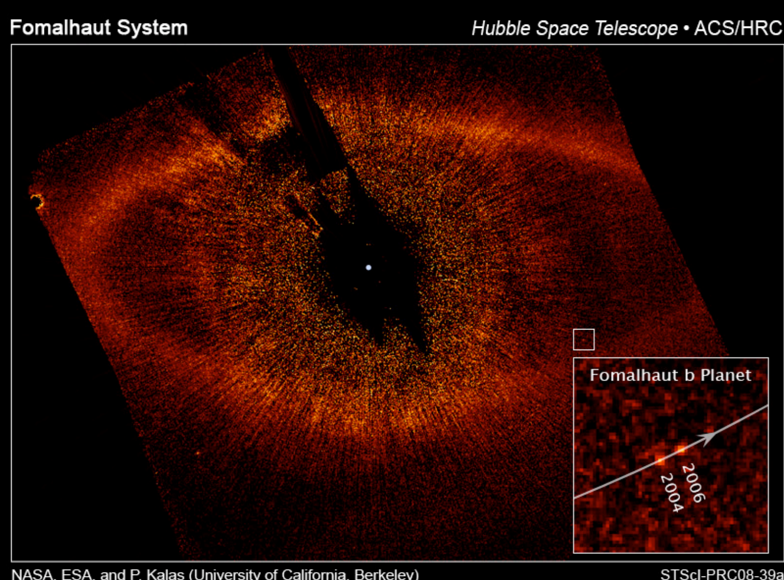
Recent Direct Imaging



Marois et al. (2008)

HR 8799 b, c, d:

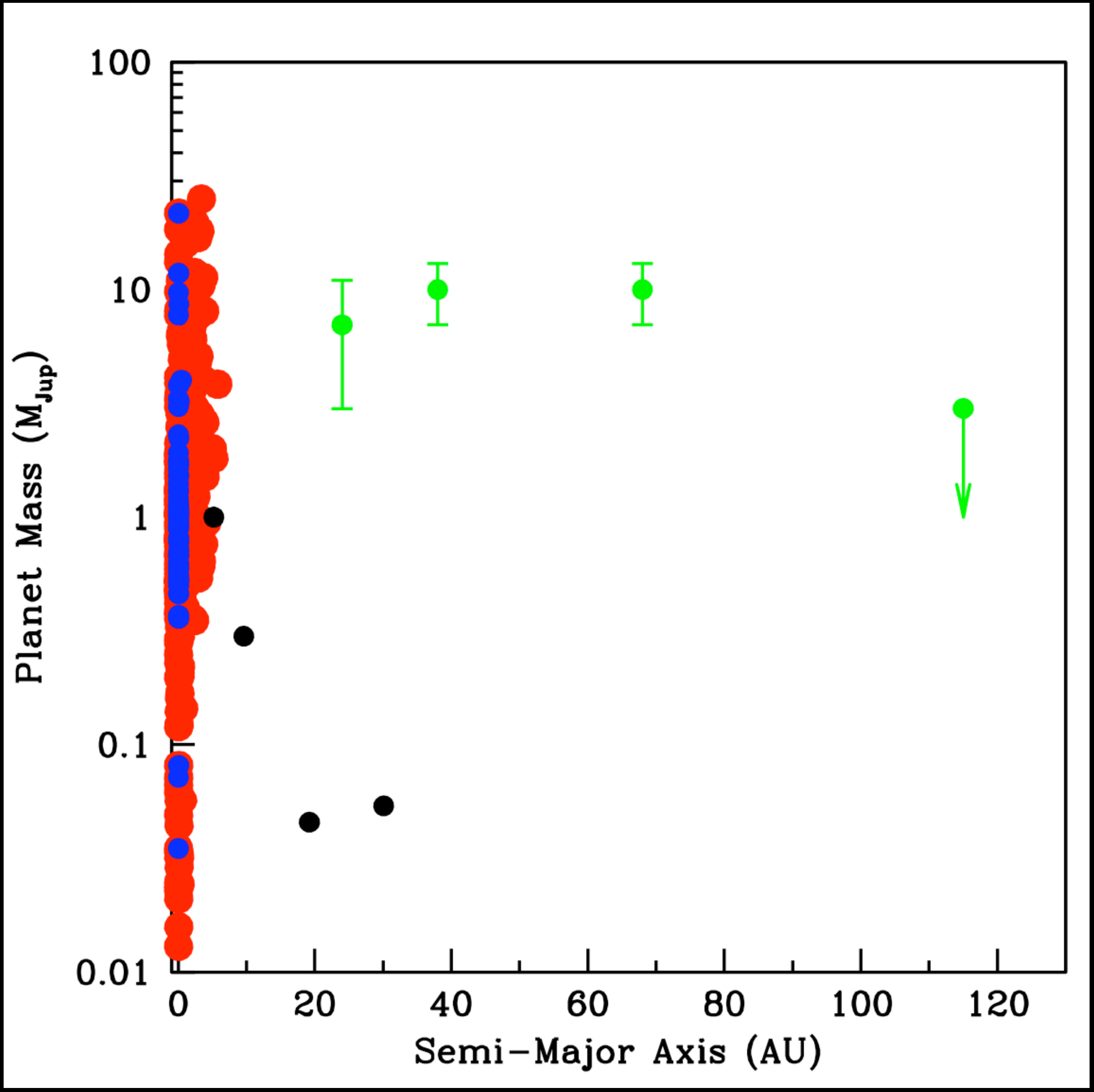
- 68, 38, 24 AU
- 7, 10, 10 M_{Jup}
- 60 Myr system



Kalas et al. (2008)

Fomalhaut b:

- 119 AU
- Few M_{Jup}

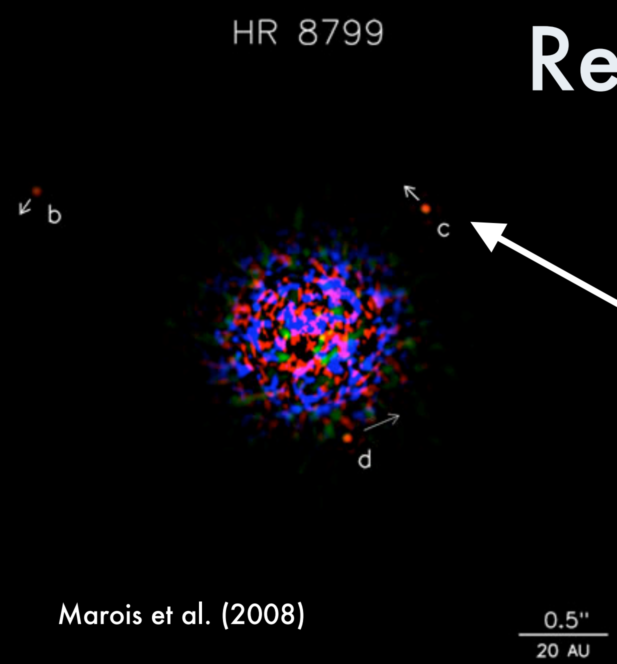


Transits

Radial Velocity

Direct Imaging

Recent Direct Imaging



Marois et al. (2008)

HR 8799 b, c, d:

- 68, 38, 24 AU
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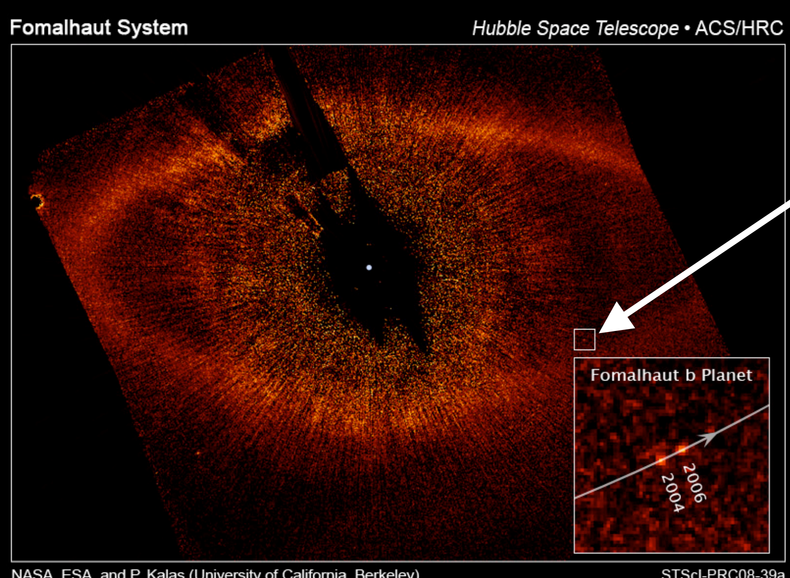
Get Spectra



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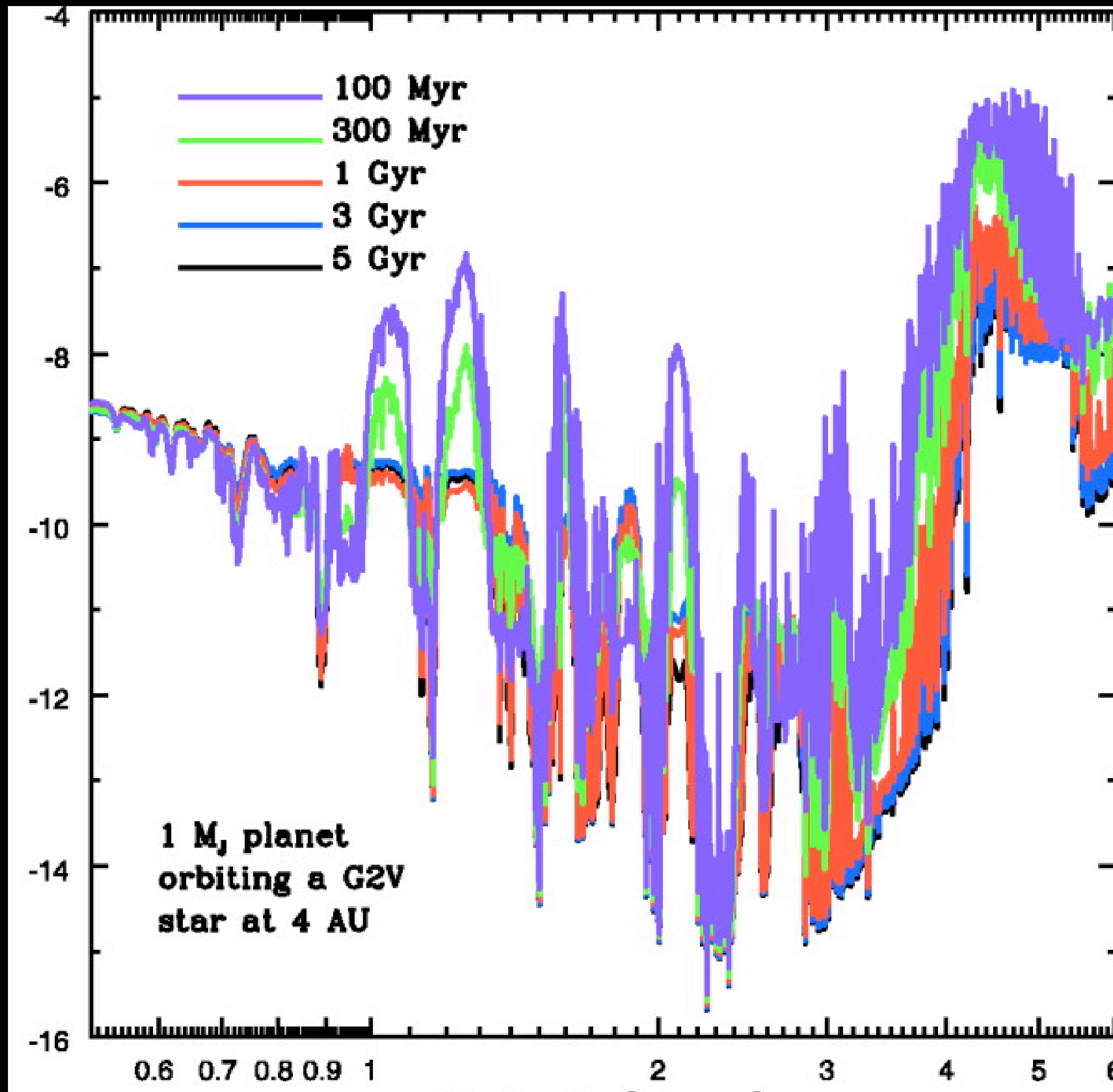
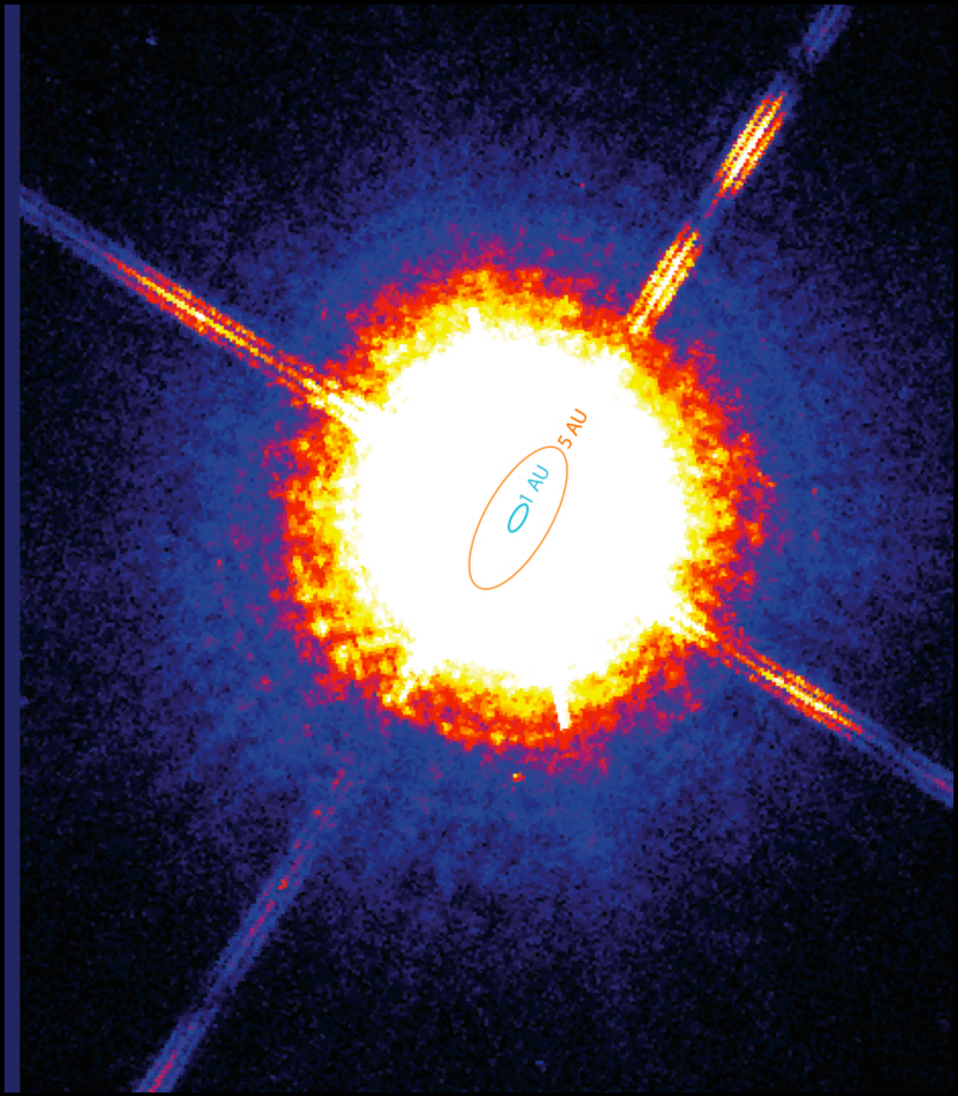


Log(Planet/Star Brightness Ratio)

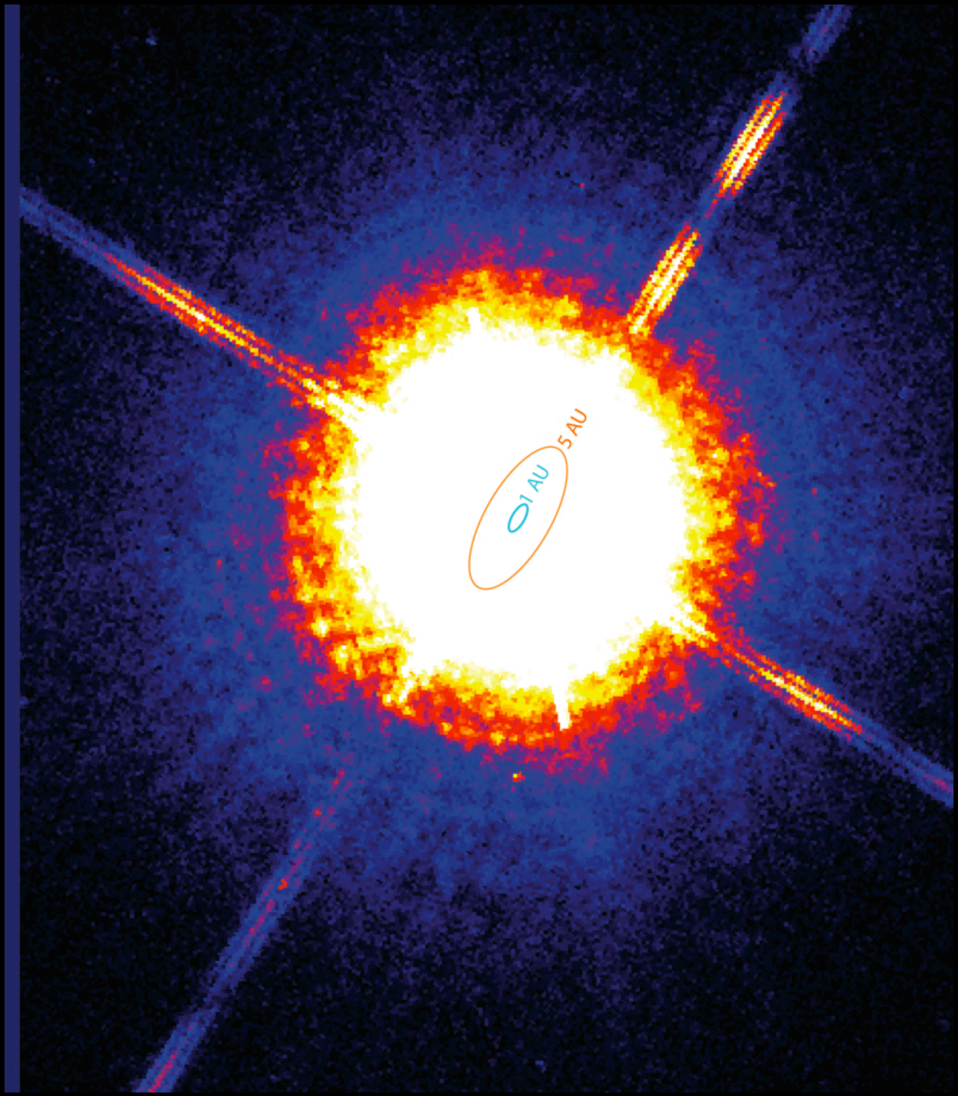
Wavelength (microns)

Burrows et al. 2004

Challenges to High Contrast Imaging

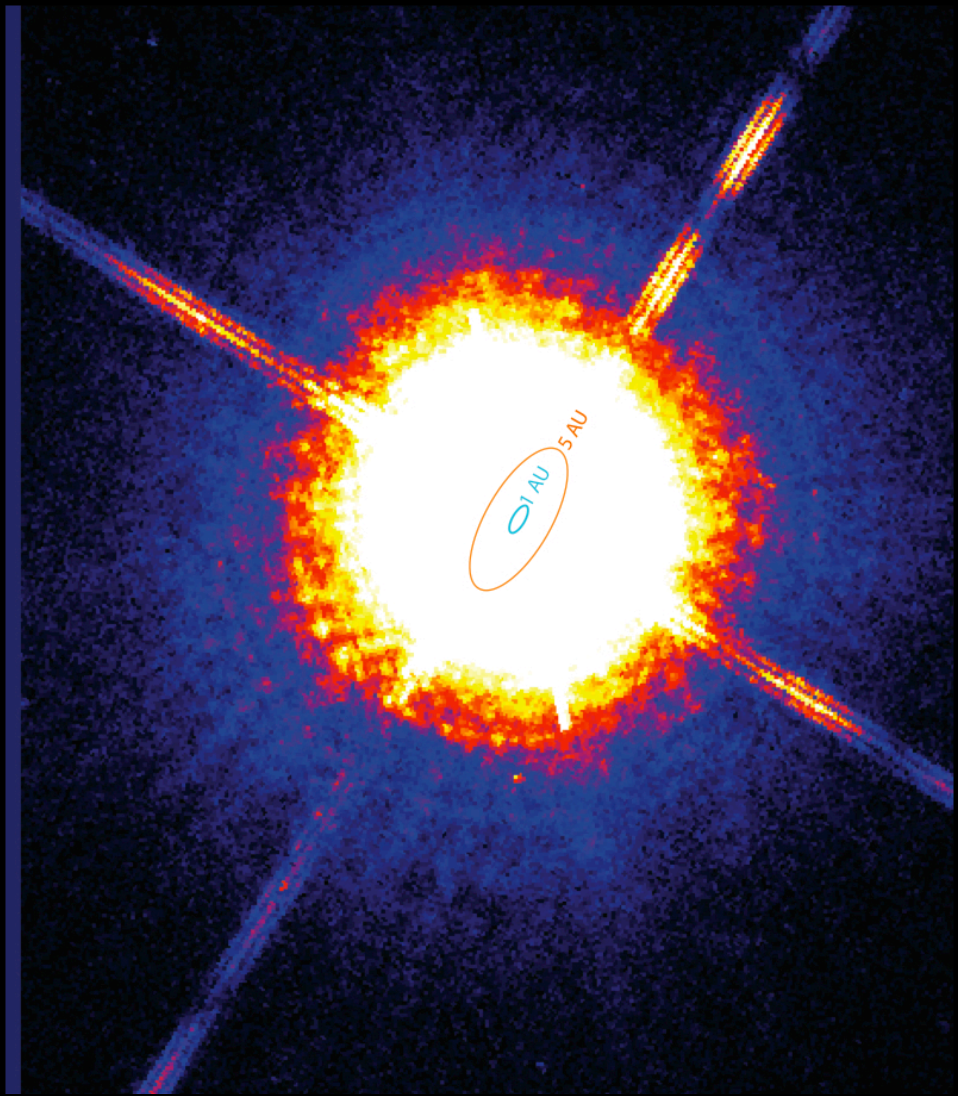


Challenges to High Contrast Imaging



1. Use <u>Adaptive Optics</u> for starlight control.

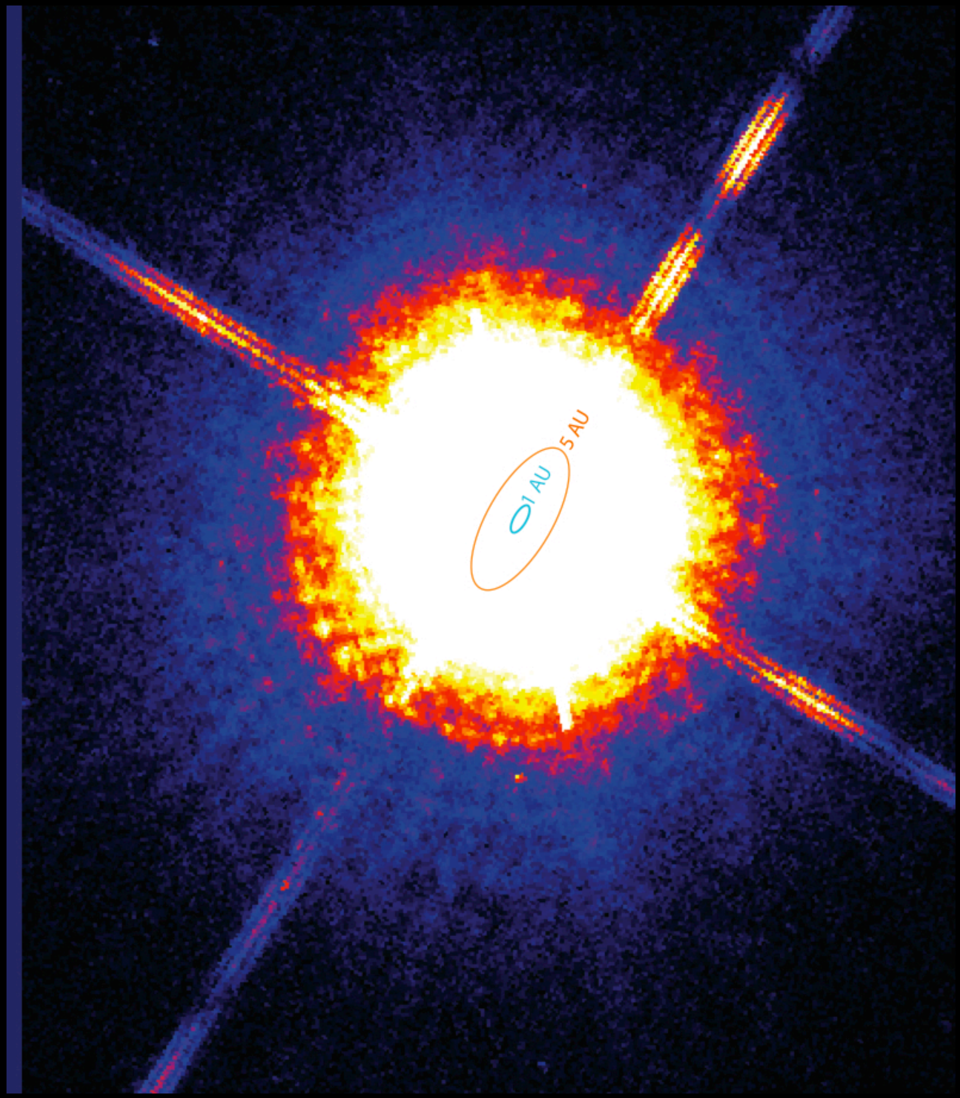
Challenges to High Contrast Imaging



1. Use Adaptive Optics for starlight control.

2. Block out this stable image with a coronagraph.

Challenges to High Contrast Imaging

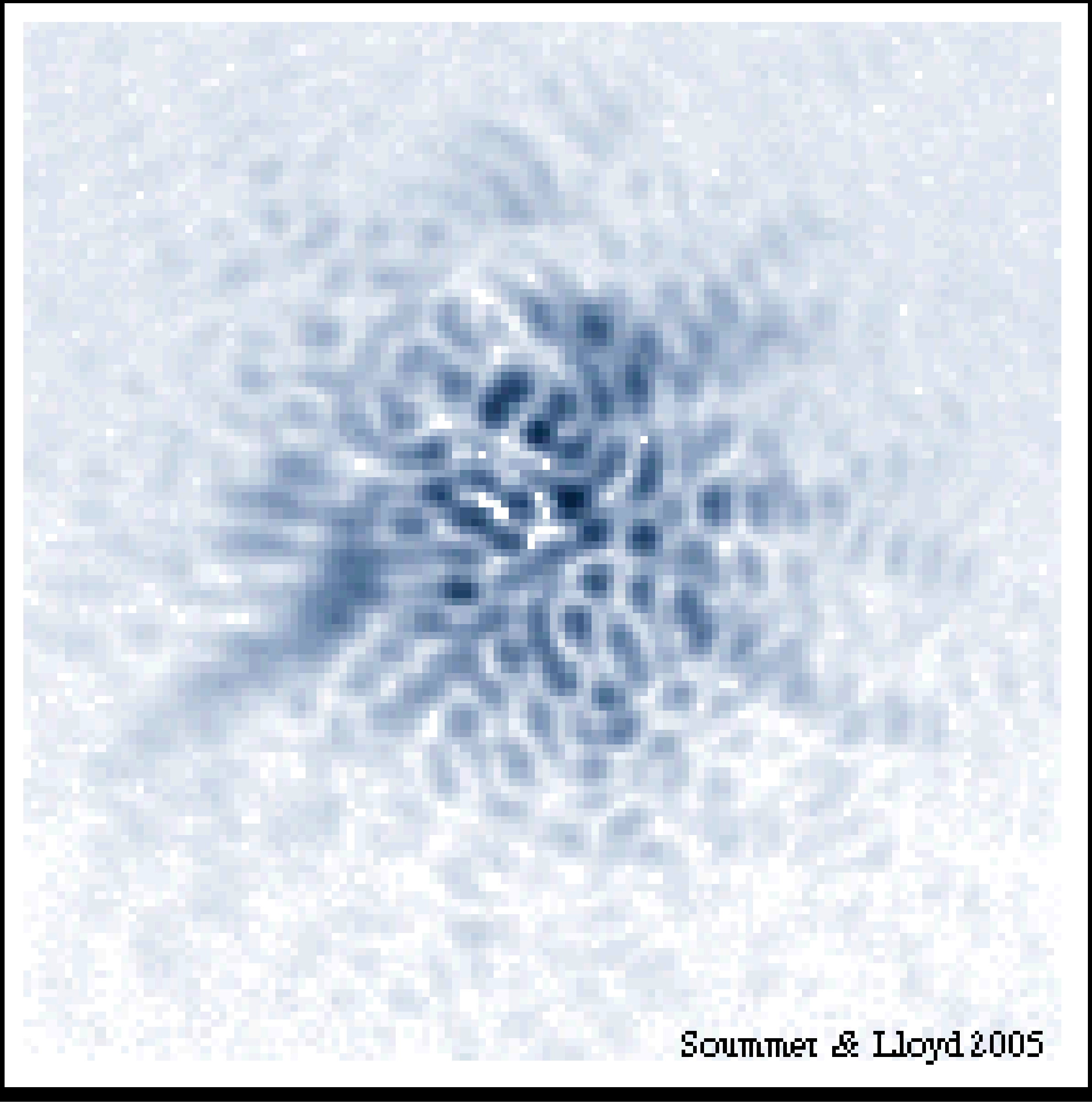


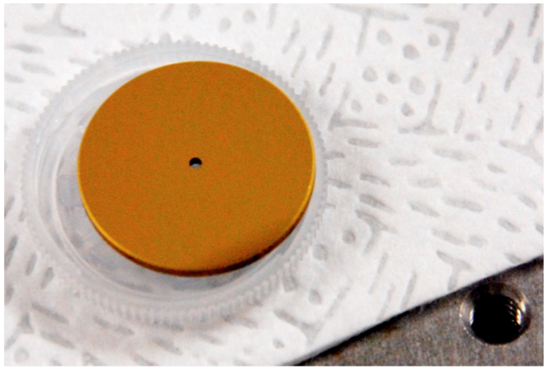
1. Use Adaptive Optics for starlight control.

2. Block out this stable image with a coronagraph.

3. Correct Any residual uncorrected starlight.

Step 1: Starlight Stabilization with Adaptive Optics





Step 2: Coronagraphy

Focal Plane Mask:

5.37λ/D at 1.65 μm,
.37 arcsec on sky:
hole diameter 1332 microns

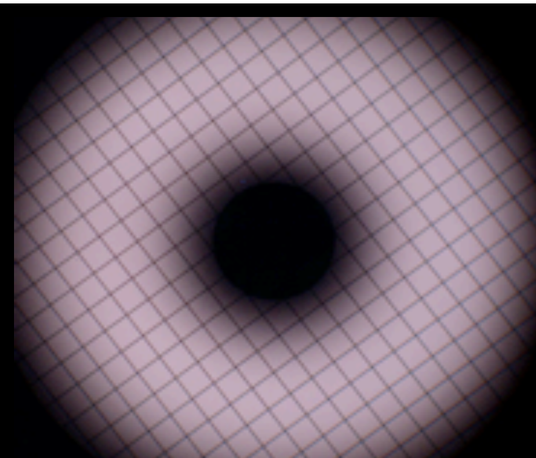
Lyot stop:

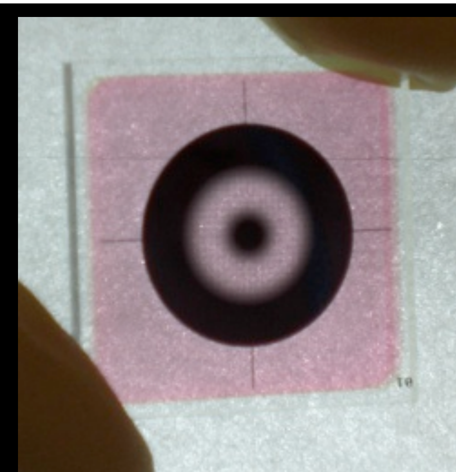
2% downsized from primary
Beam size at stop 3.8mm

Apodizing mask:

Chromium microdots
(1μm) on glass

Soummer et al. (2005)

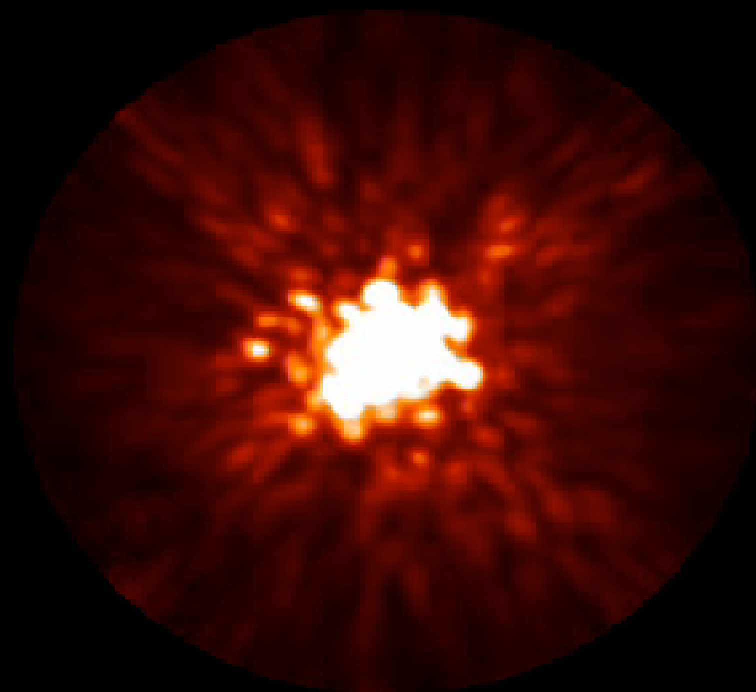




Correlated Speckle Noise Limits Sensitivity

40-minute H-band image sequence:

- AO on
- Coronagraphically-occulted



Hinkley et al. (2007)

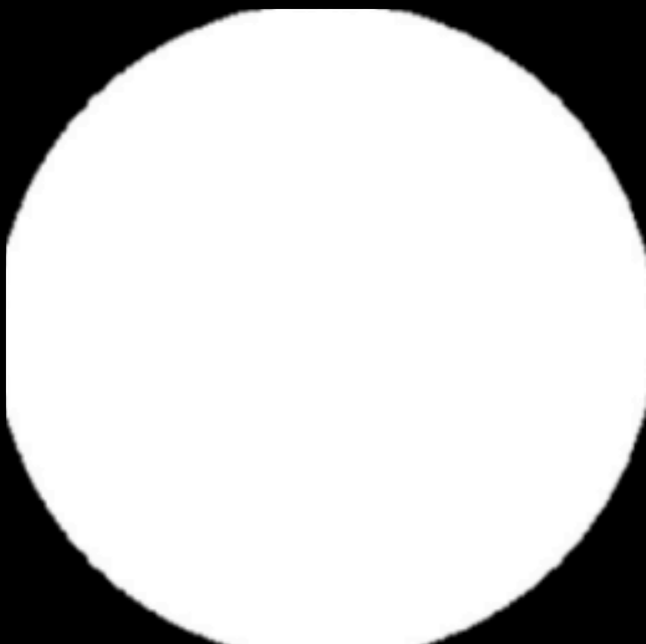
Correlated speckle noise: the greatest obstacle to ground-based exoplanet detection.

Averaging does not work

Highly Static Wave Front Aberrations in Pupil → ***Highly Static Speckles in Image***

Highly Static Wave Front Aberrations in Pupil

Highly Static Speckles in Image



Pupil: No Phase Errors

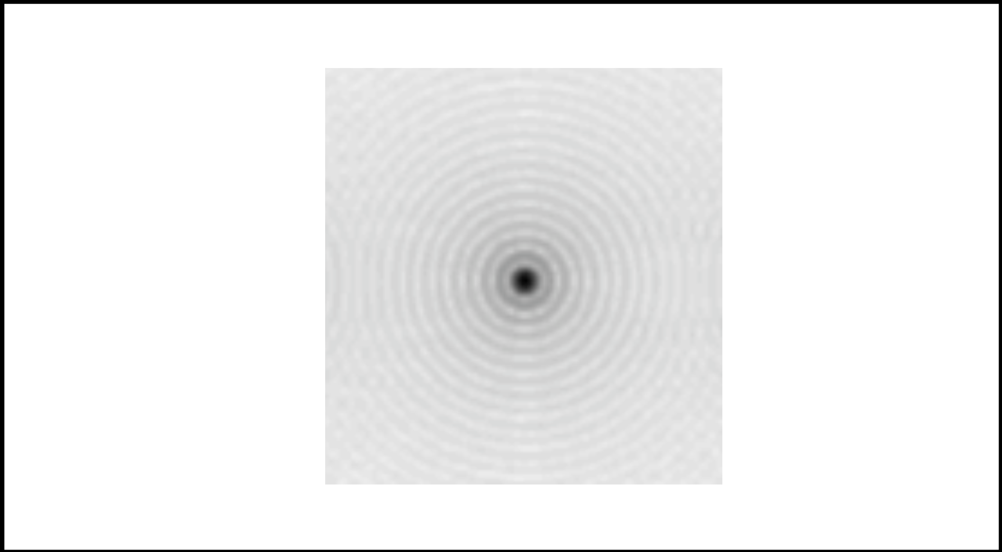
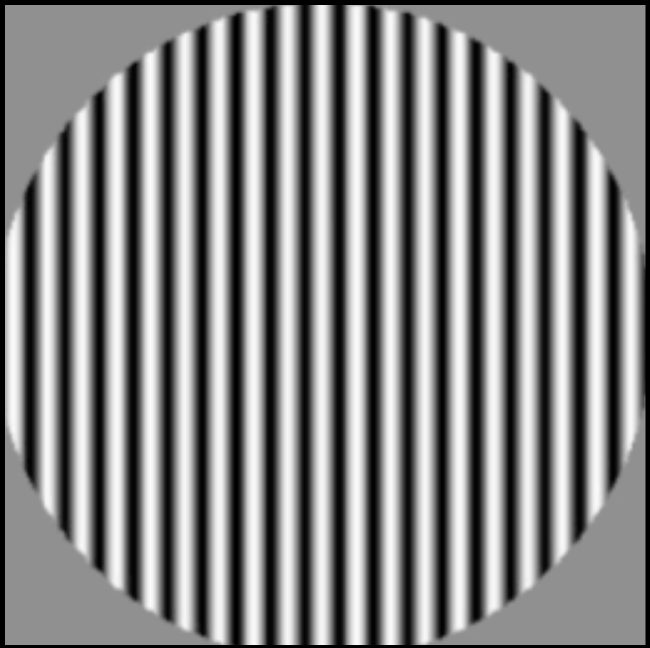


Image Plane: Point Spread Function

Highly Static Wave Front Aberrations in Pupil → **Highly Static Speckles in Image**



Pupil: Sinusoidal Phase error

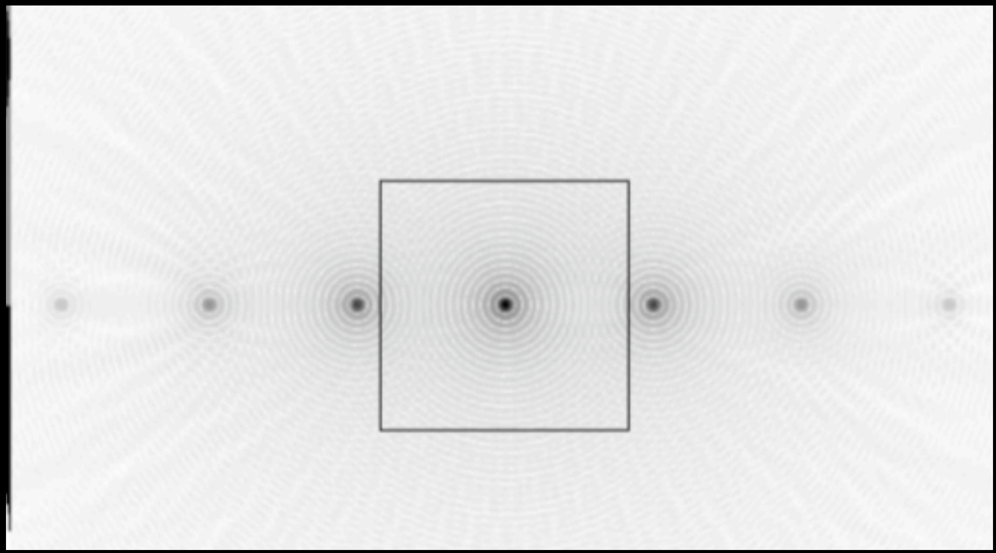
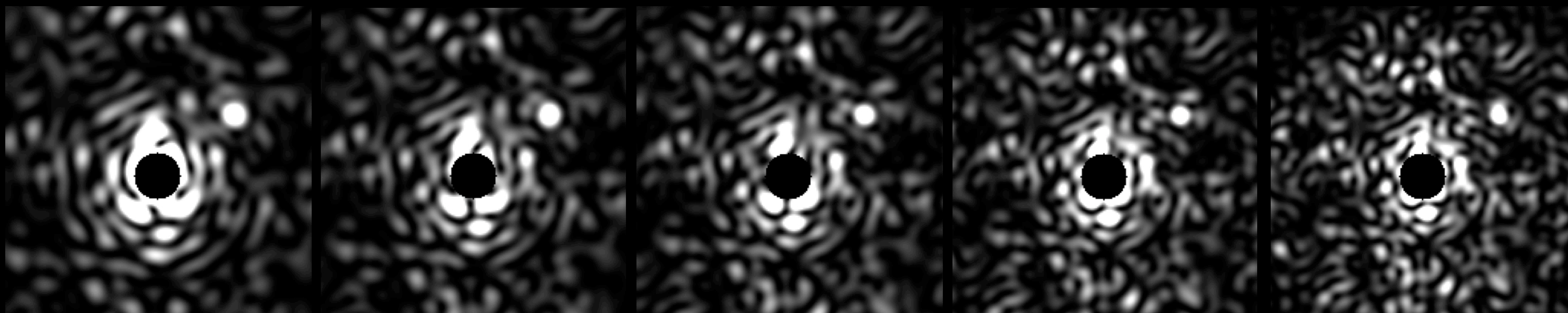
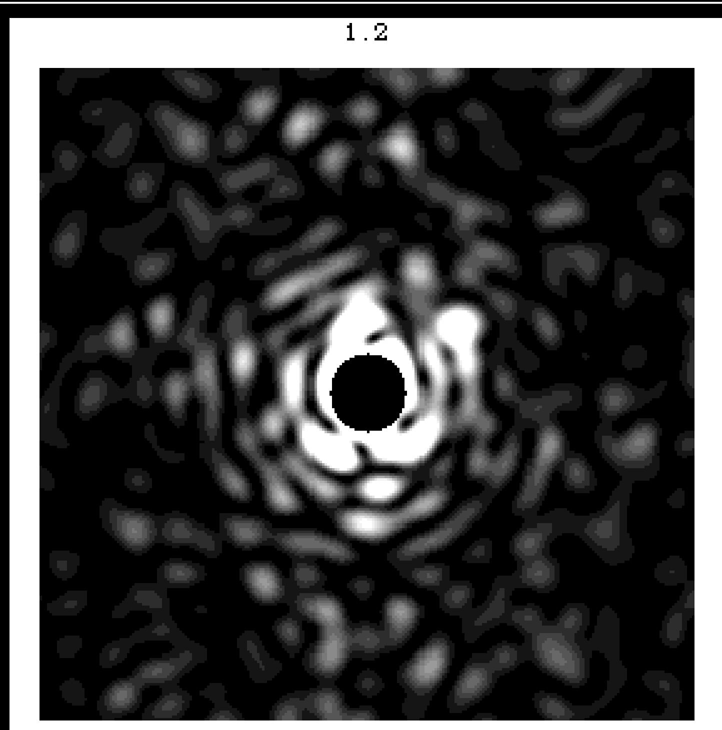


Image Plane: Speckles

Step 3: Speckle Suppression Through Chromaticity



RED (1.8 μm) ⟷ BLUE (1.0 μm)



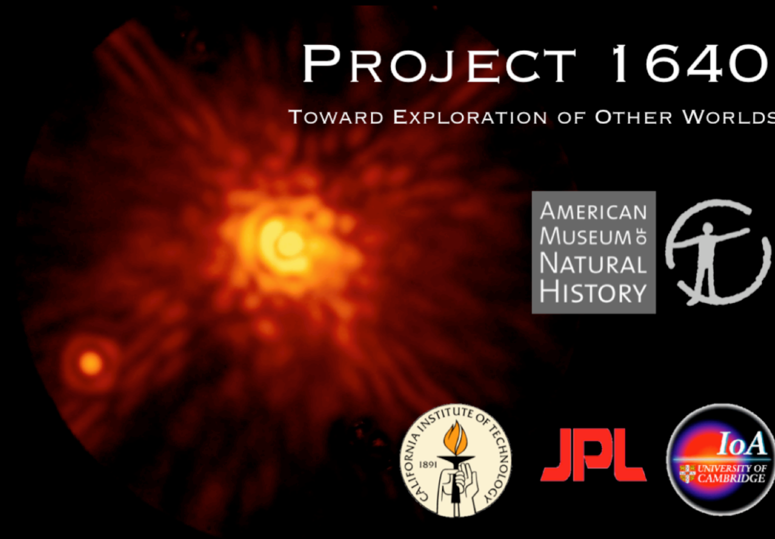
Plan: Utilize the chromatic nature of speckles with a IFS.

Enables differentiation between speckles and companions

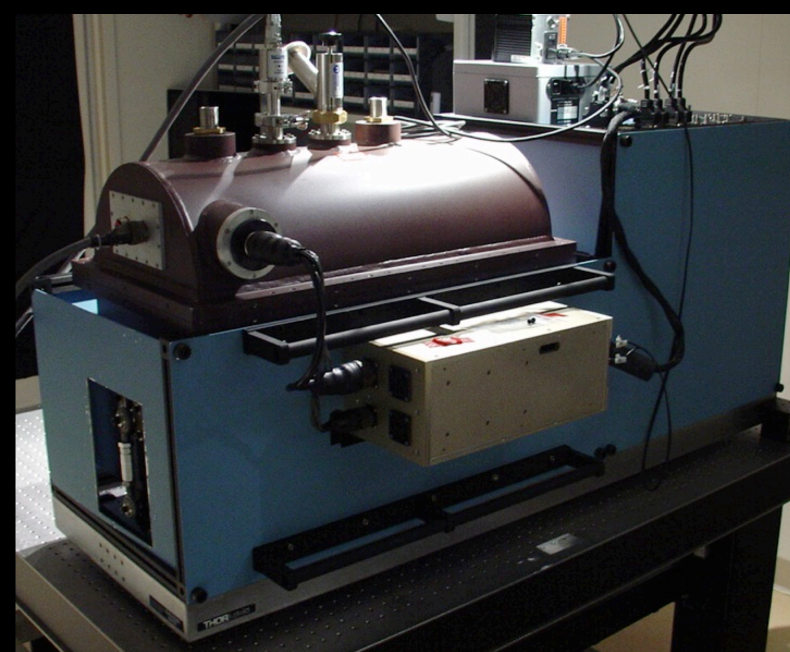
Automatically provides spectra of any companions.

Simulation courtesy of Remi Soummer & James Lloyd

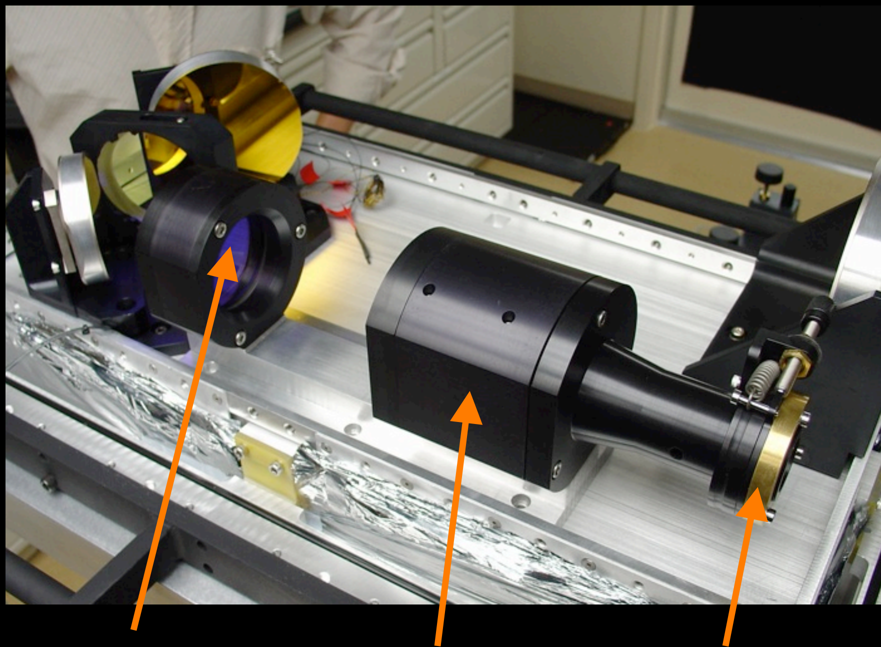
Project 1640: IFU+Coronagraph at Palomar



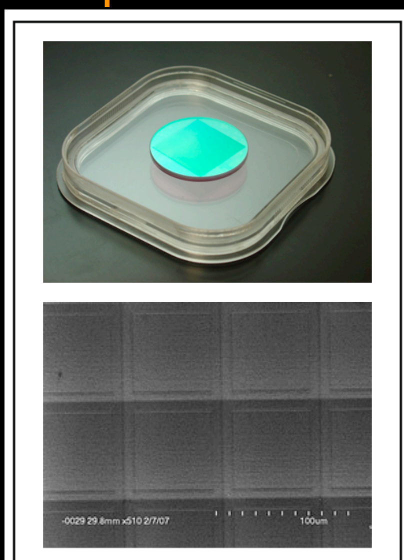
- Science Camera: IFU covering $\lambda = 1.05 - 1.75 \mu m$ (J to H bands)
- Diffraction-limited Apodized Pupil Lyot Coronagraph (APLC)
- Separate (2nd Stage) IR fine guidance system
- Designed to interface with the Palomar AO system (PALAO)
- Only project like it in the Northern Hemisphere.



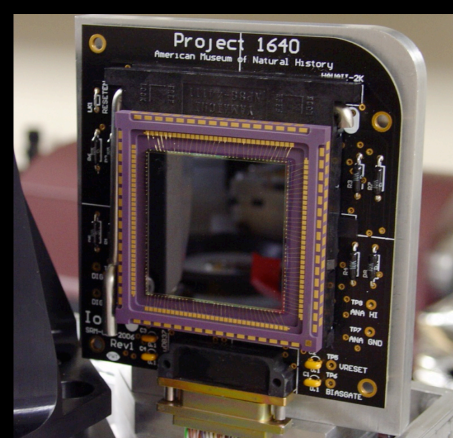
Integral Field Spectrograph

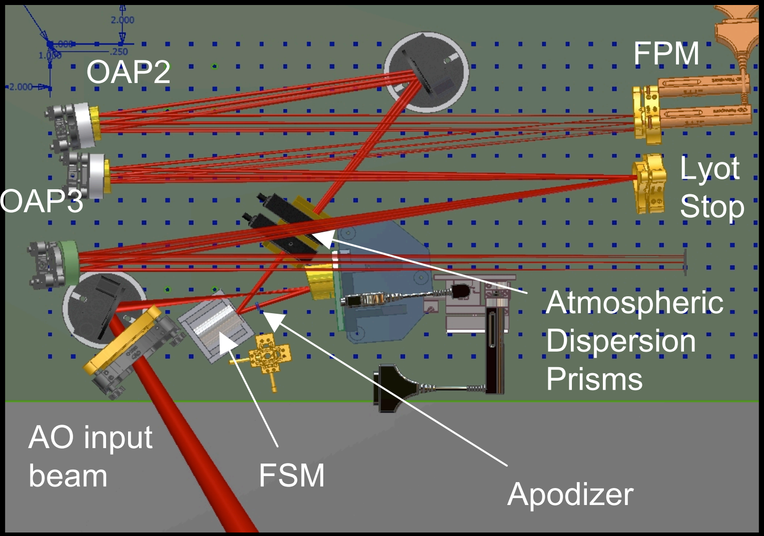


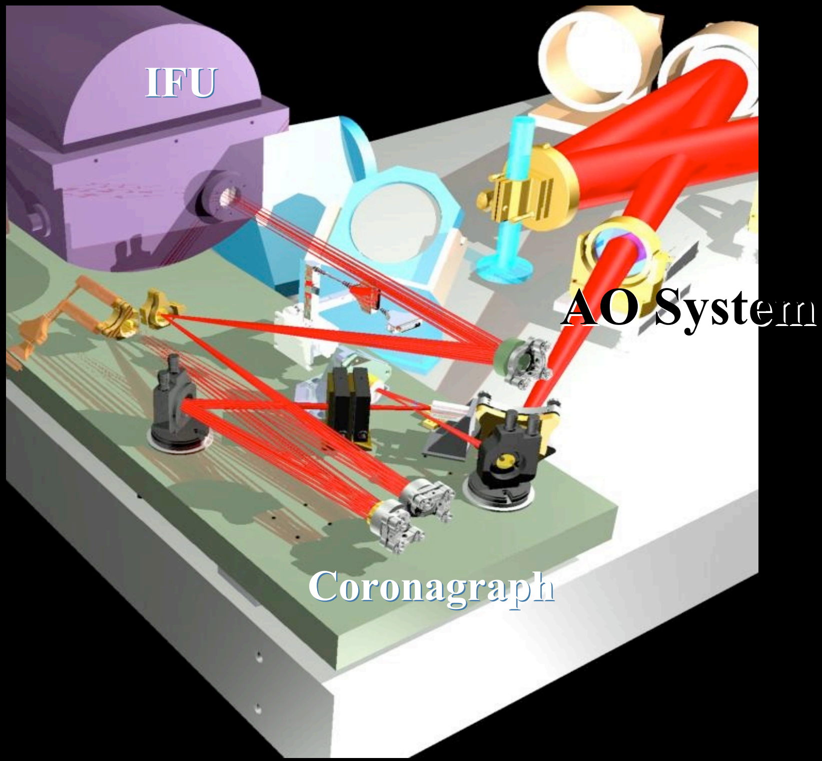
Property	Project 1640 IFU + Coronagraph
Wavelength coverage	1.05- 1.75 µm, Δλ = 0.7 µm
Central wavelength	1.403 µm
IFU FOV	4200 mas
Platescale	21 mas/lenslet
Total spectra	200 x 200 = 40,000
Pixels per spectrum	3.2768 x 32
Δλ per 2 pixels	.044 (.7µm/32 pix)
R = λ/Δλ	32
Lenslet Pitch	75 um (chosen for manufacturing issues)
Input f/ratio from coronagraph for λ/2D Spaxels at 1.0 µm	f = 143.21
Focal Plane Mask size	5.6 λ/d
Optimal coronagraph wavelength	1.65 µm
Apodizer throughput	51%



- Array of 270 x 270 microlenses 75µm pitch. Two powered faces.
- Rockwell Hawaii-II 2048x2048 pixel HgCdTe array

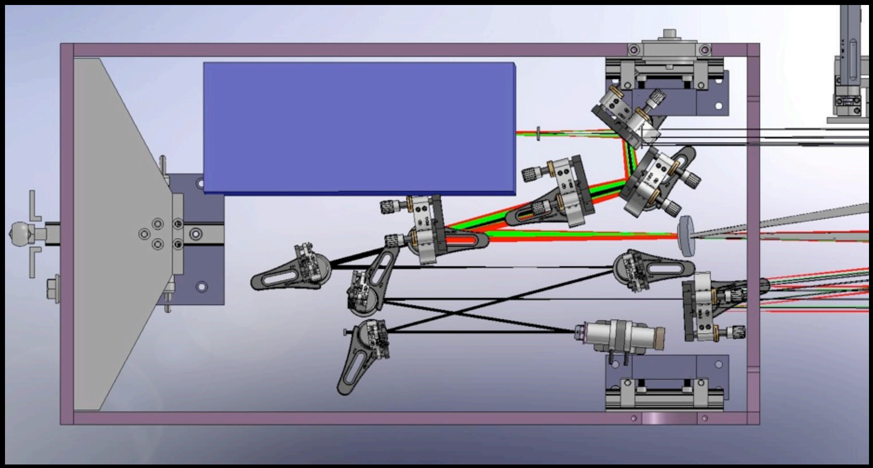






P1640 Coronagraph & Wave Front Calibration System

Wave Front Calibration system (2010):

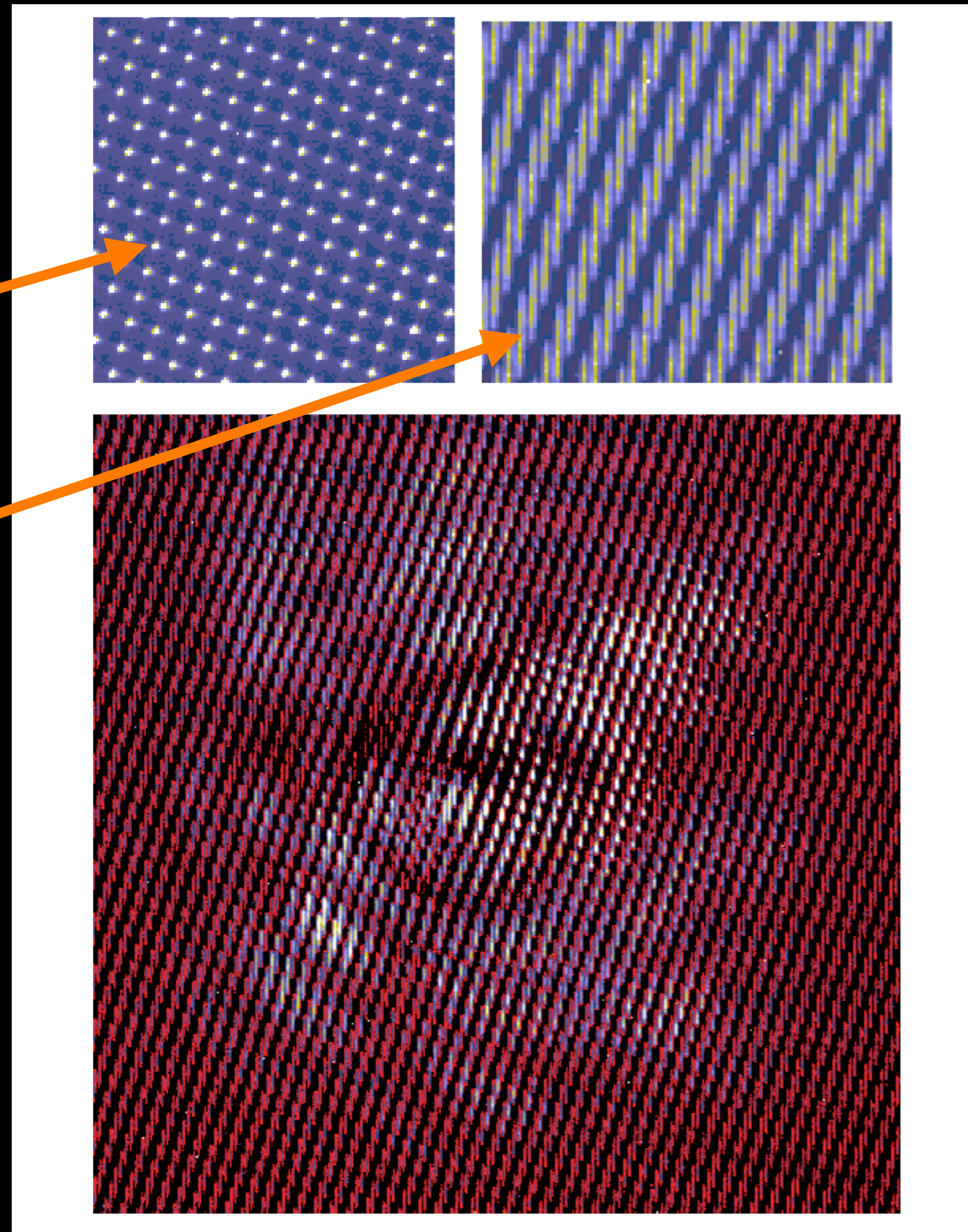


- Interferometer nearly identical to GPI
- Designed to achieve 1nm RMS wave front error measurement at 1Hz
- Dynamic Control of wave front errors.

Laboratory Data

Monochromatic 1330 nm light source

Broadband white light source



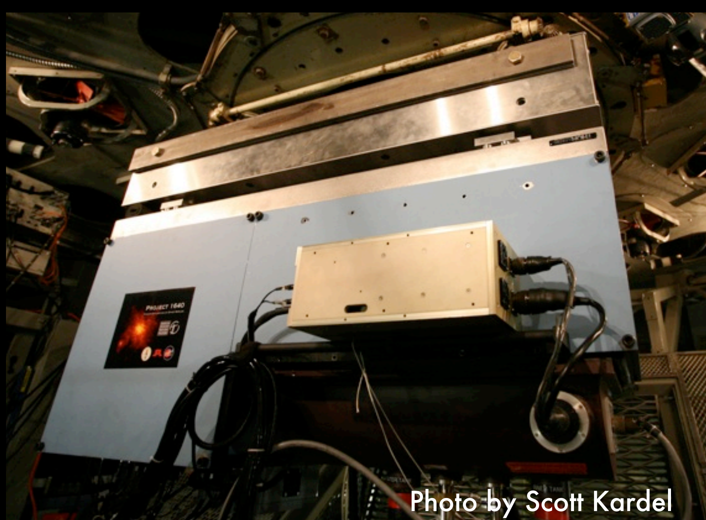
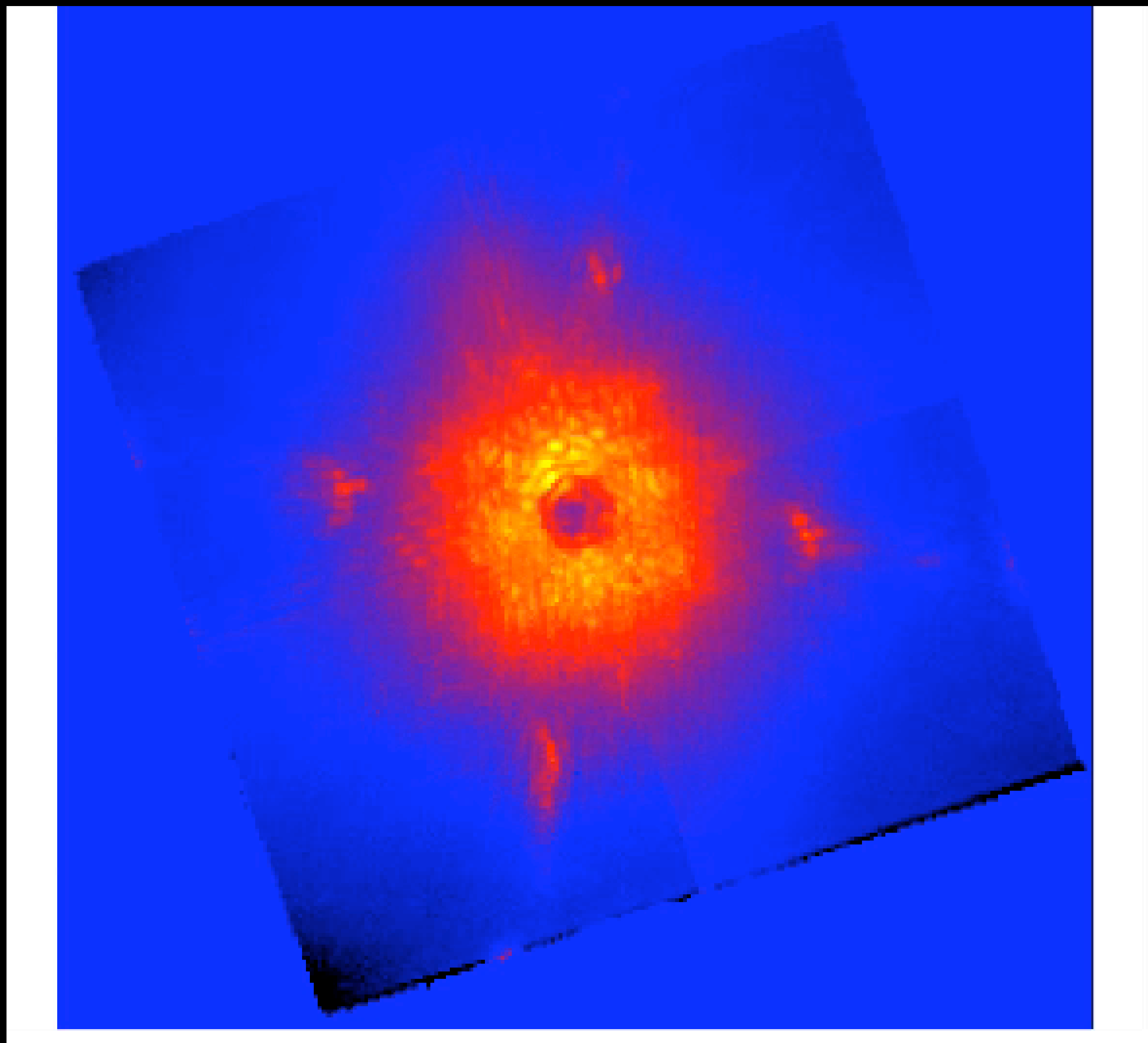


Photo by Scott Kardel

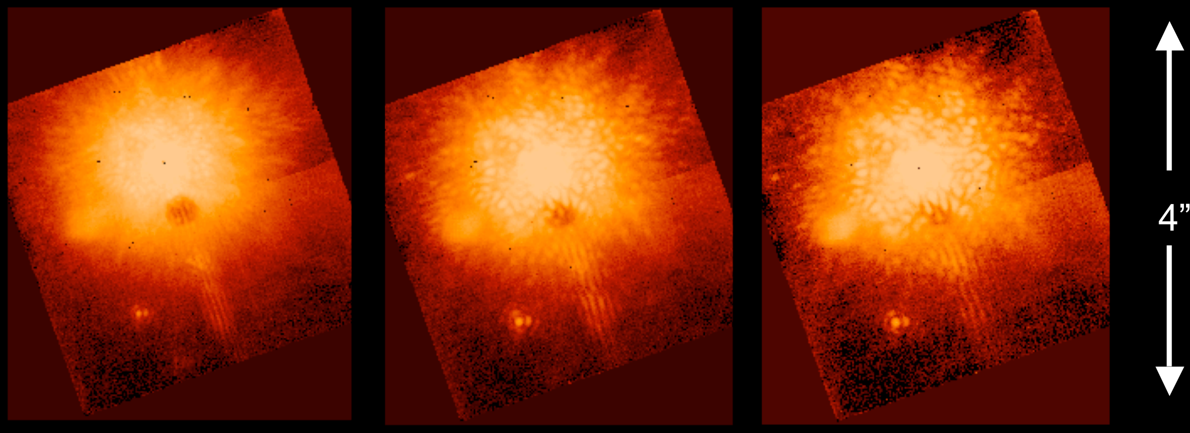
Data

Data cube spans 1.05 - 1.75 μm.

4 arcsec

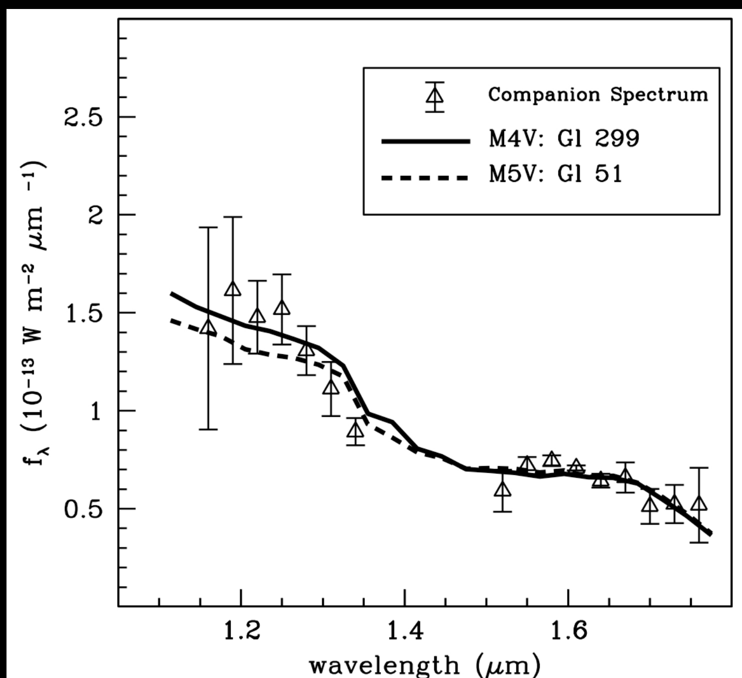


Stellar Companion to a Nearby A-star



1.25μm 1.58μm 1.73μm

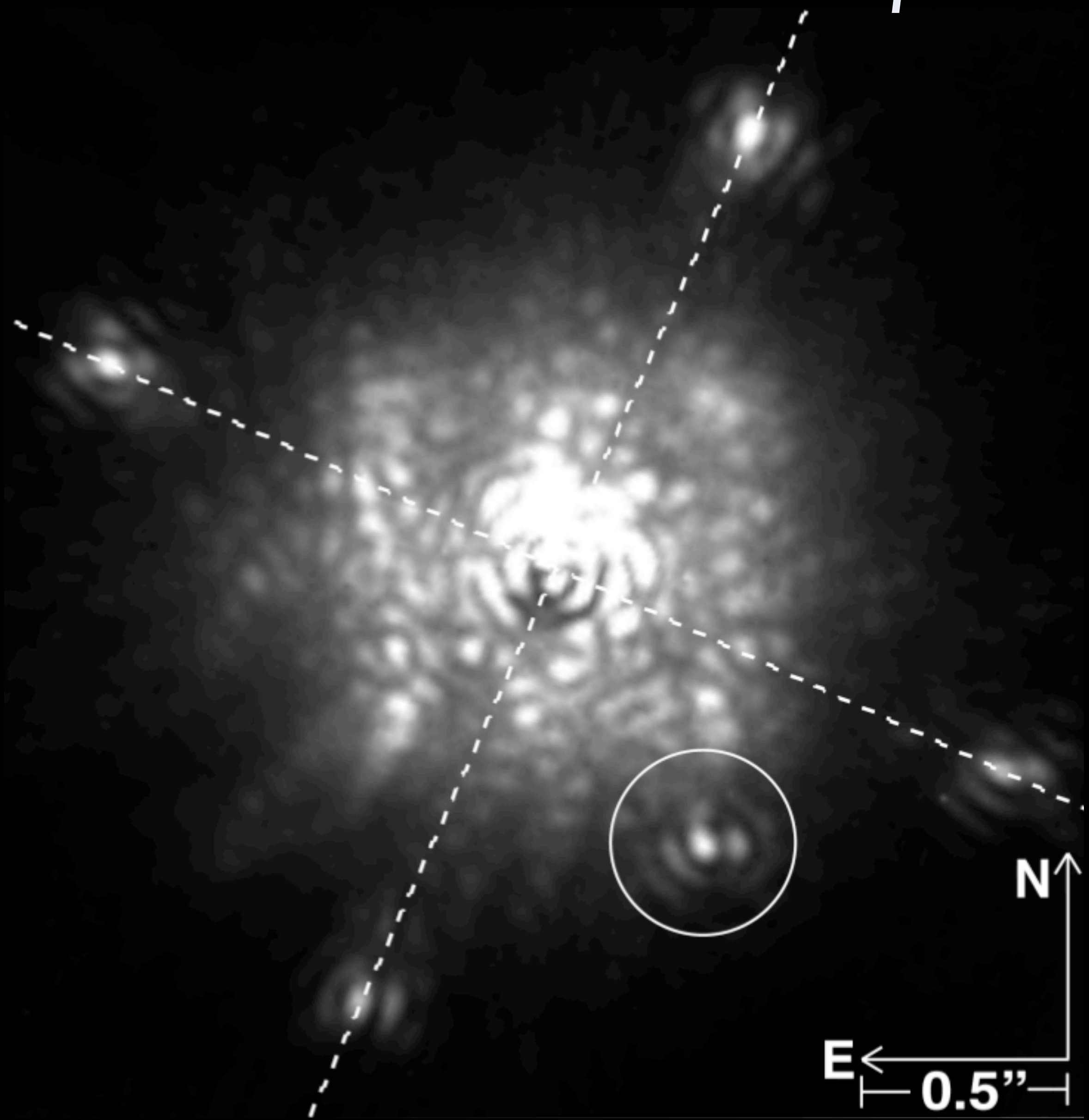
- Photometry
- Astrometry
- CPM
- Orbital motion
- Spectrum



- Photometry suggests ~0.16 solar masses.
- Mass ratio *q* ~ 0.07

Hinkley et al. (2009) submitted

Alcor B: A New Stellar companion in the Big Dipper

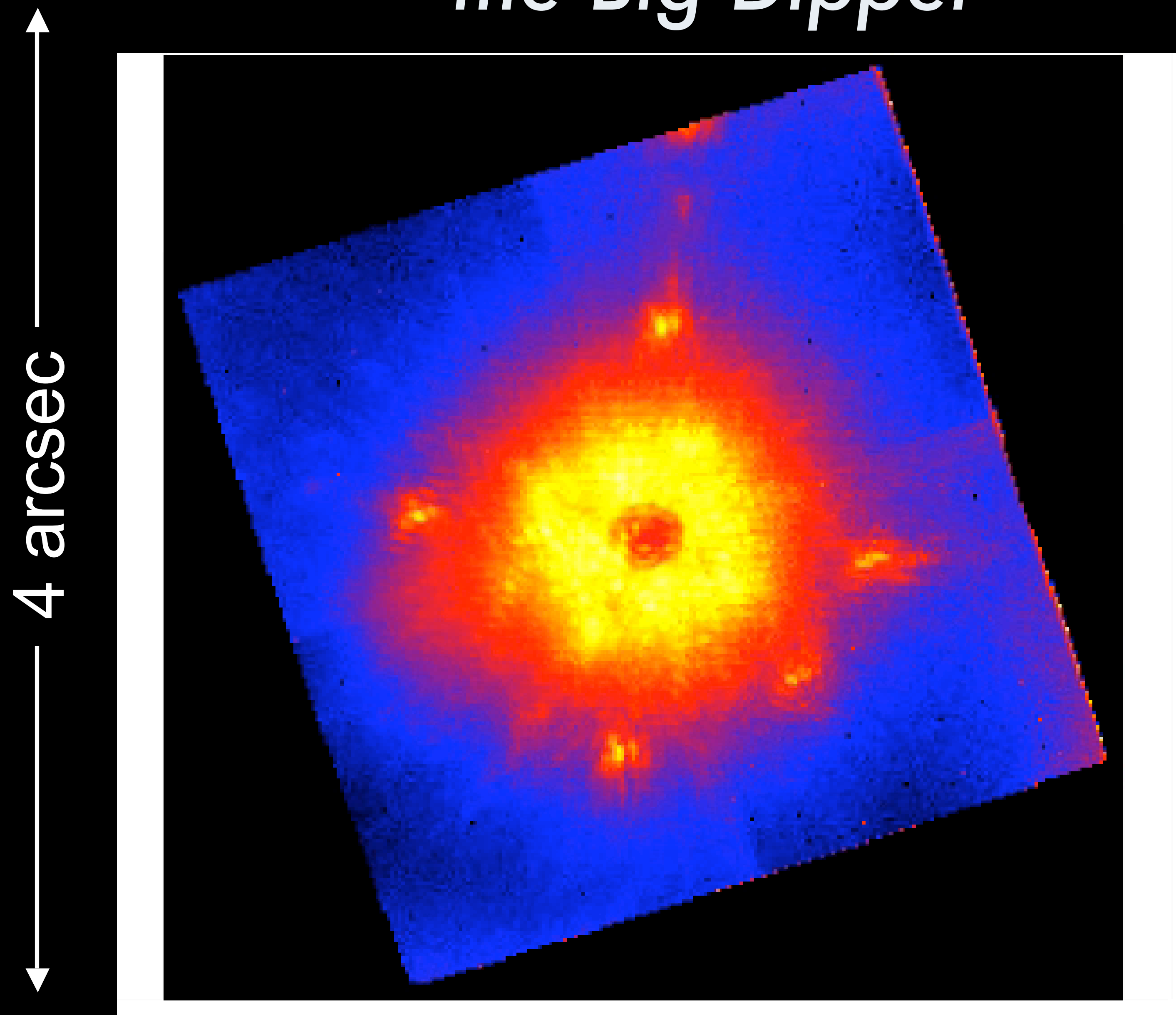


Zimmerman et al. (2010)

- Are unseen low mass companions the source of anomolously high X-ray counts from A-stars?

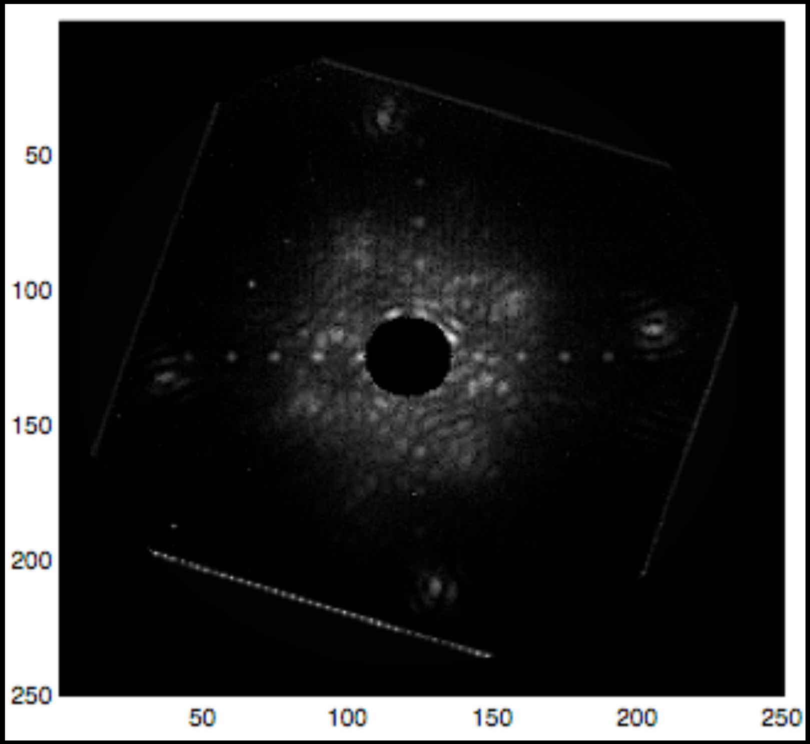
- Common parallax obtained
- Anomolously high ROSAT brightness
- M3-M4 companion

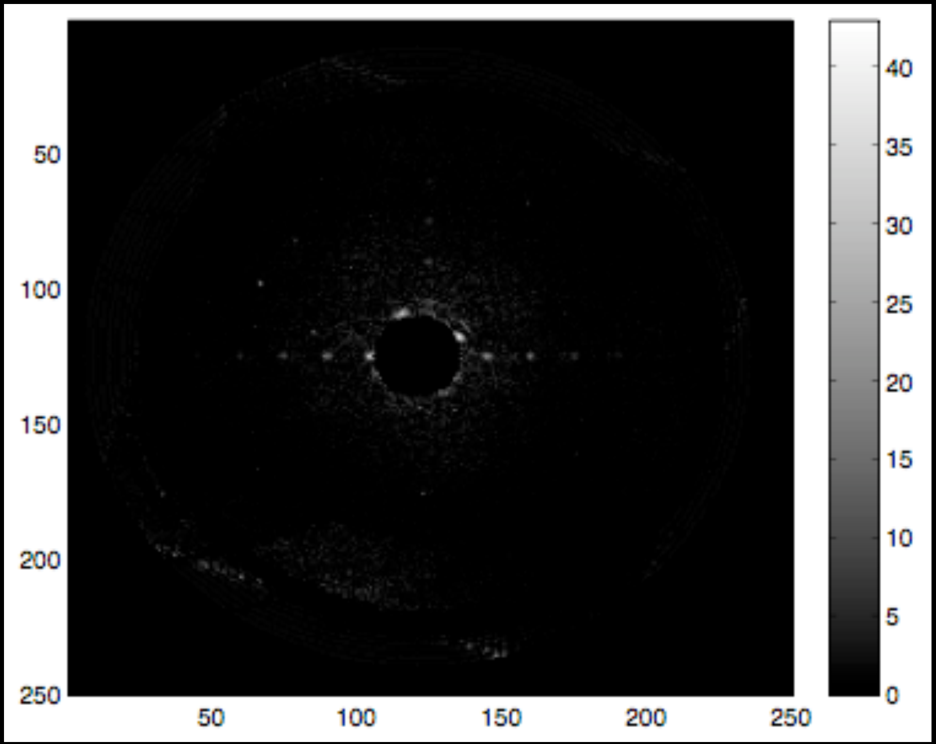
Alcor B: A New Stellar companion in the Big Dipper



Data cube spans 1.05 - 1.75 μm.

Speckle Suppression with Wavelength (Energy) Diversity





Images courtesy of Laurent Pueyo

Gemini Planet Imager

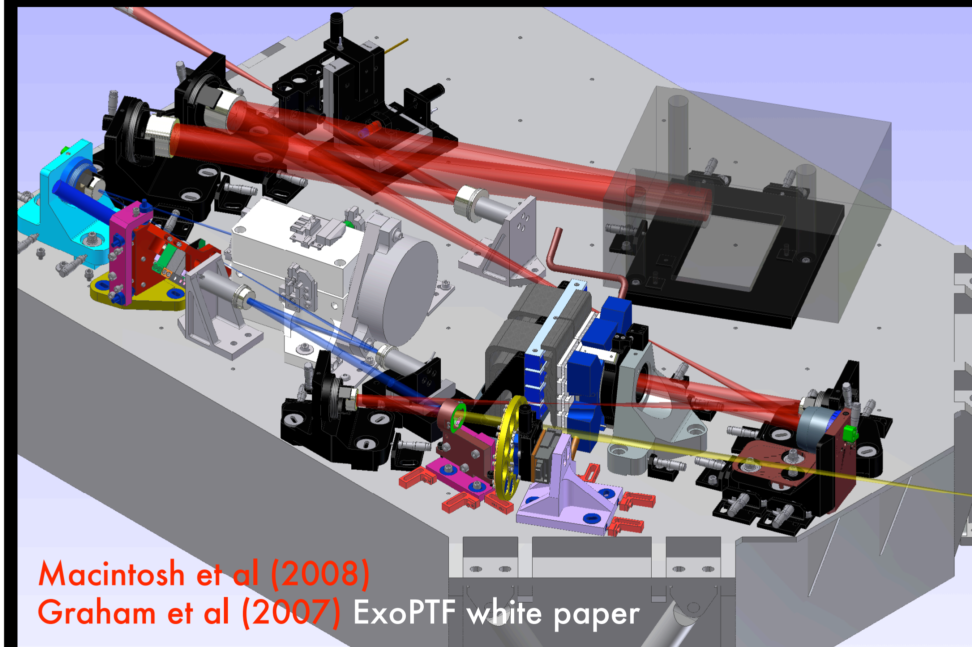
MEMS Extreme-AO +
apodized pupil coronagraph

IFS (1-2.4 μm), R=45,
2.8"x2.8" FOV

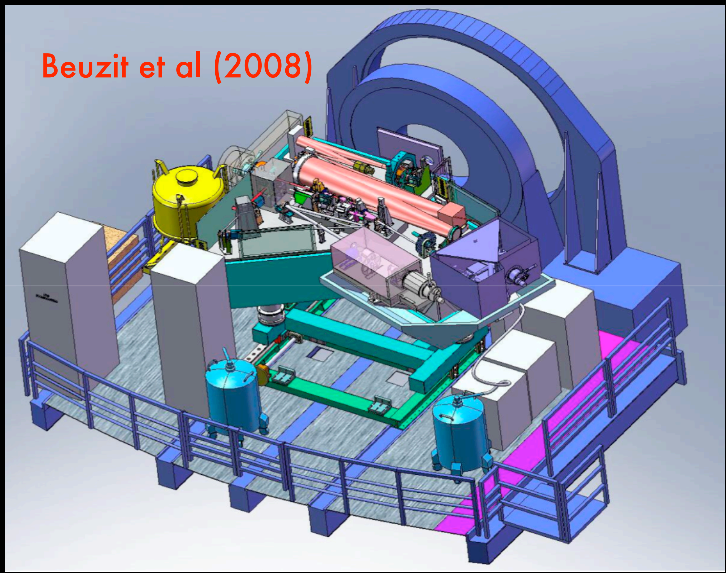
Dual channel polarimetry

Wave front calibration system

(southern hemisphere) First light: 2011



SPHERE (VLT)



Extreme-AO (41x41 actuator)
+ coronagraph

Differential imaging (Y, J, H, Ks)

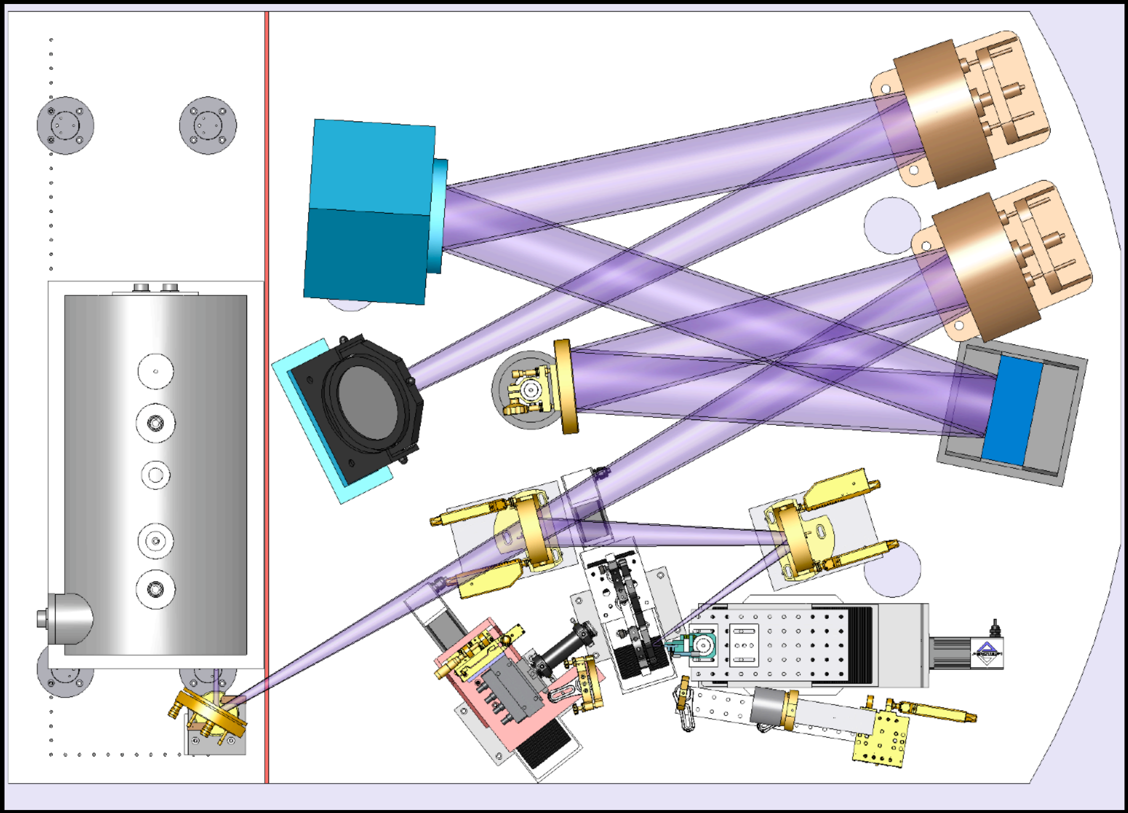
IFS (0.95-1.65 μm)
R=30, 1.8" x 1,8"FOV

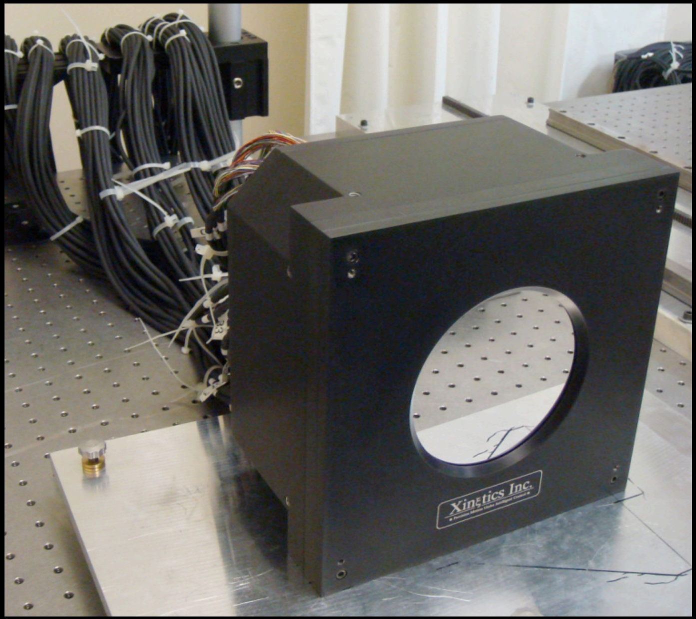
Visible Imaging Polarimeter

First light: 2011

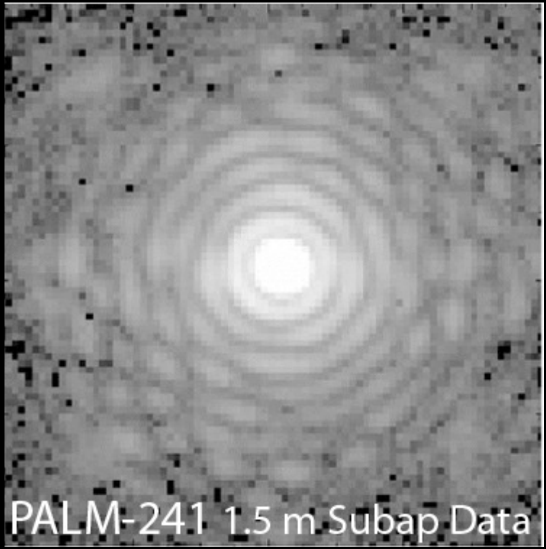
Palomar AO Upgrade: "PALM-3000" (2010)

- 3,388 Actuator Deformable Mirror.
- High-order Wave Front Sensor (62 x 62 Shack-Hartmann).





High Strehl Preview:

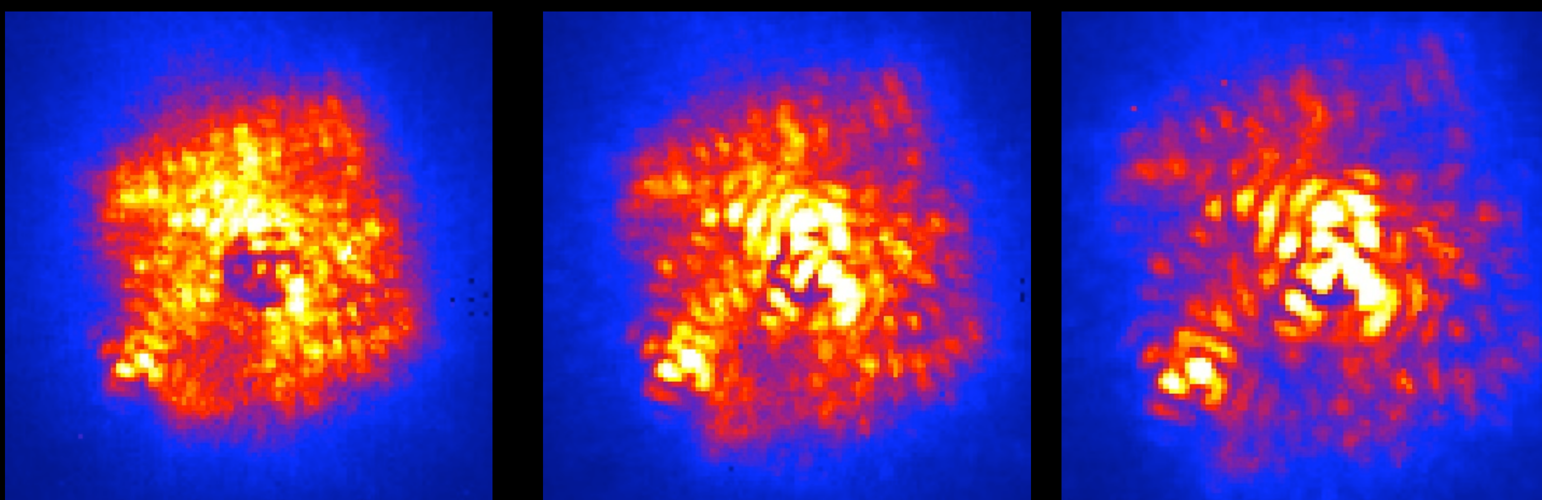


Serabyn et al. (2007)

Wavelength/Energy Resolution is a key for Higher contrast

Assigning an energy to each photon with single photon counting devices is akin to our wavelength diversity.

See also talks by Ben Mazin, Don Figer.



1.34μm 1.55μm 1.67μm