High Contrast Imaging: Direct Detection of Extrasolar Planets

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and

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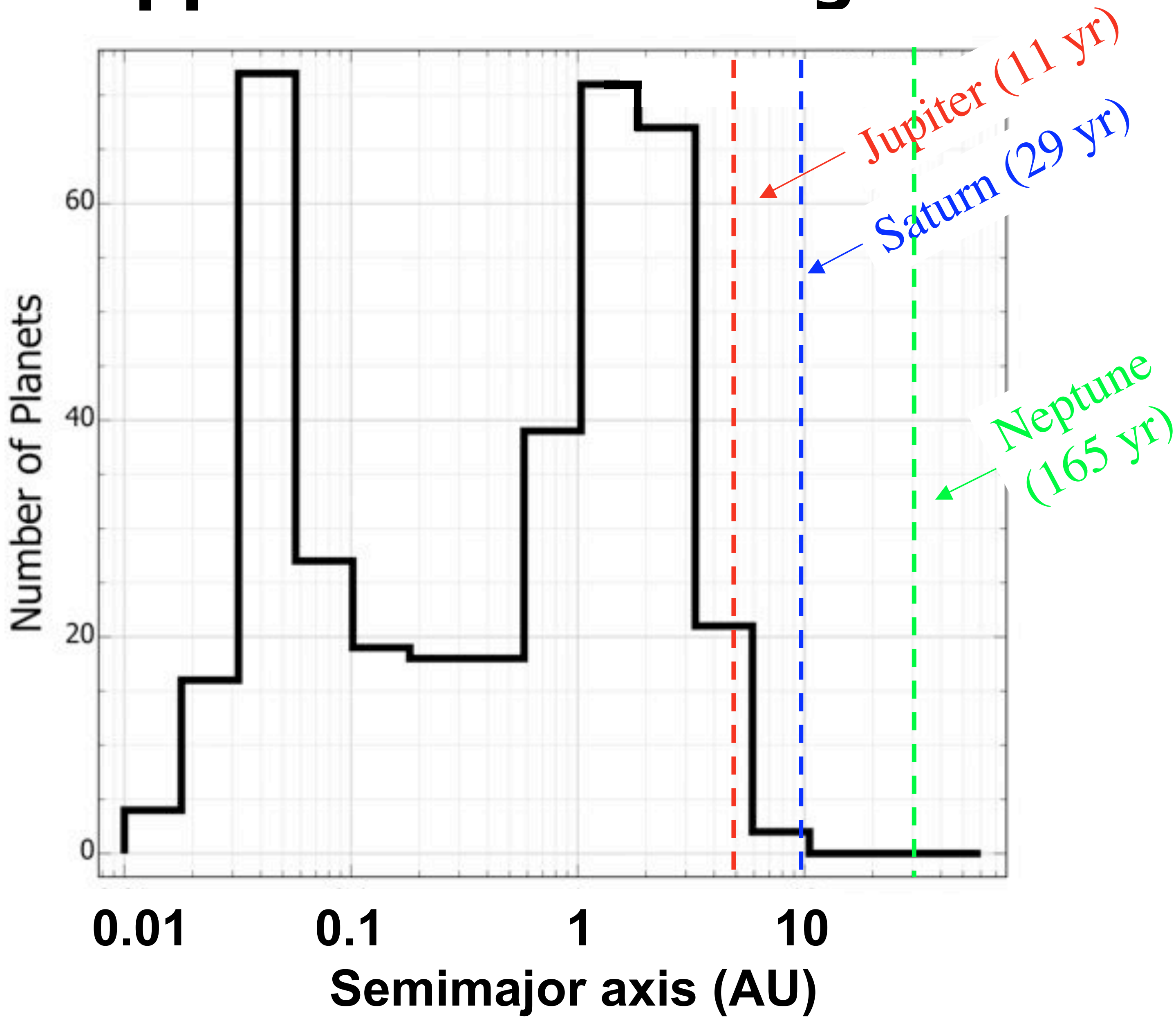
Exoplanet Science

- How and where to planets form?
  - Abundance of planets?
    - Is the solary system typical?
    - Are terrestrial planets common?
  - What type of stars have planetary systems?
- Physics of planets
  - Structure & evolution of planetary interiors
    - High pressure H/He equation of state (10^3–10^6 GPa)
  - Planetary atmospheres
    - Unexplored regime of 120 K < T < 600 K
      - Domain of H_2O and NH_3 clouds

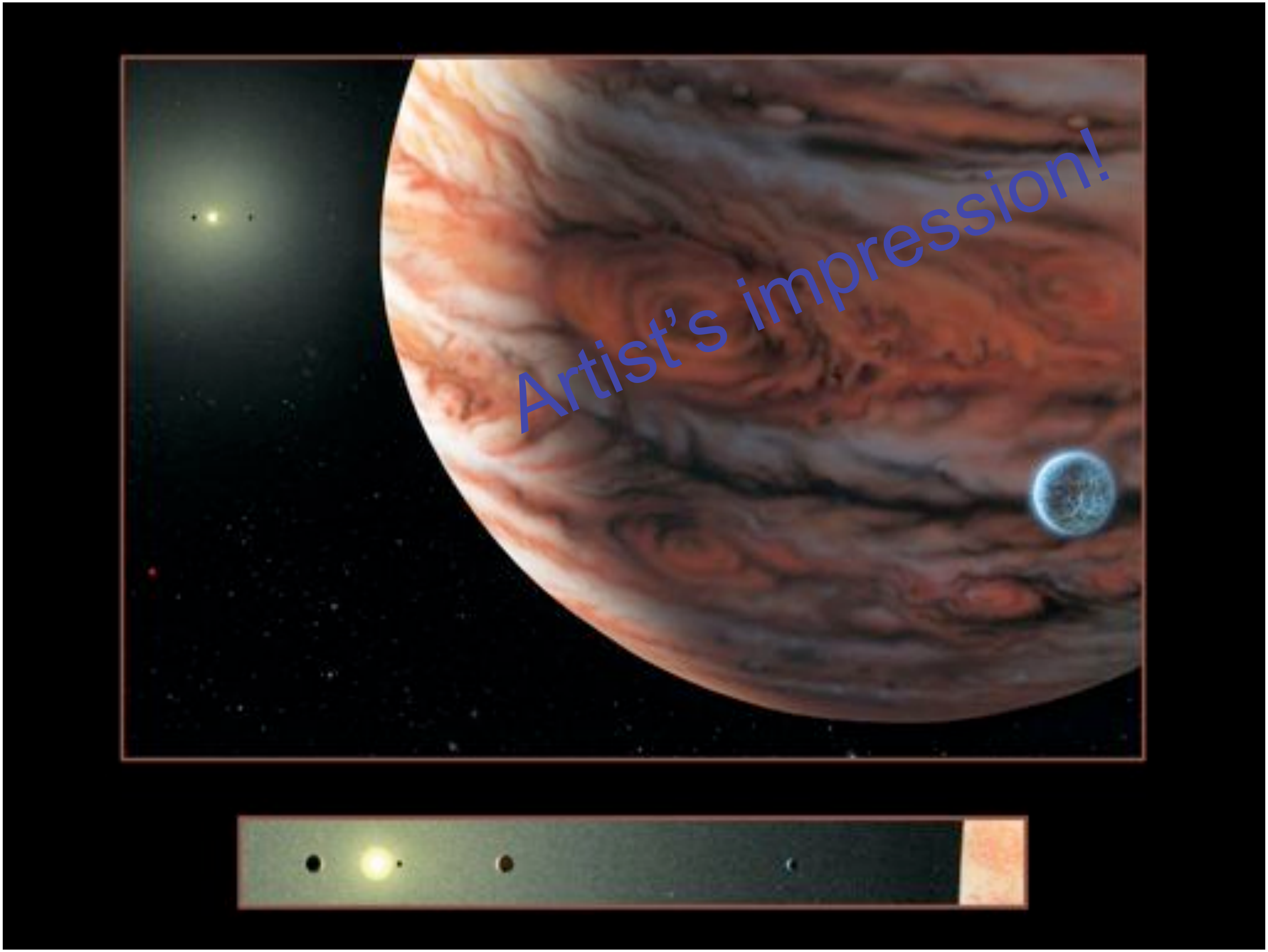
Doppler Planet Detection

Doppler Planet Histogram

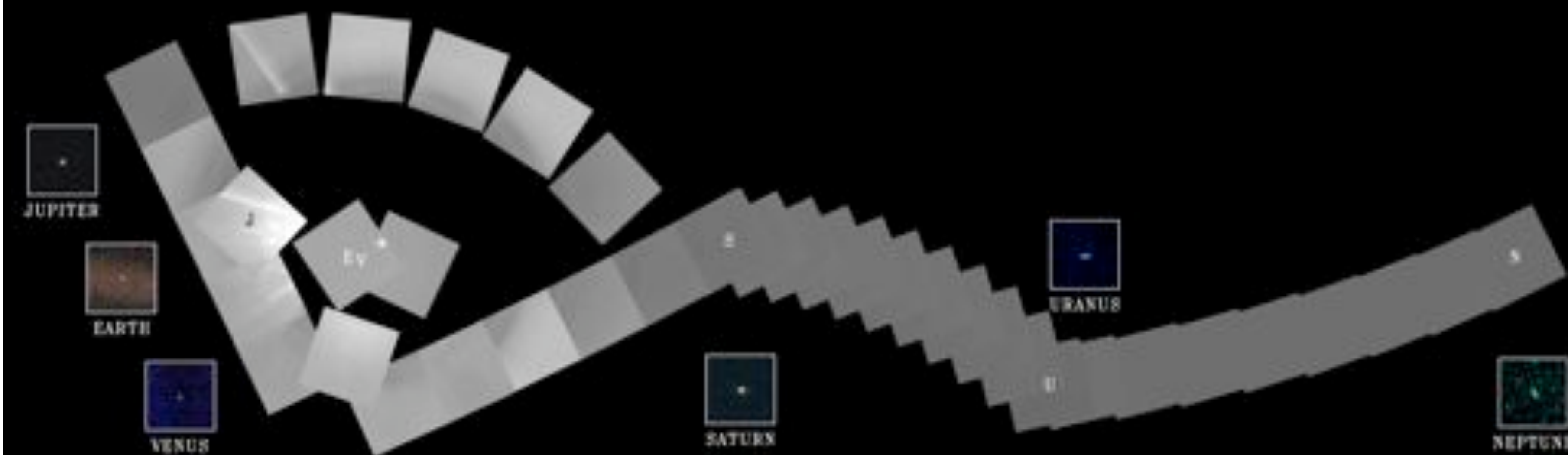


Indirect Detection Methods

- Doppler data yields a subset of orbital parameters
  - Period, semimajor axis, eccentricity
  - $M \sin i$ (if the star mass is known)
- Edge-on systems with star-planet eclipses give
  - Orbital inclination i
  - Planetary radius
    - Mean density


Artist's impression!

Voyager 1 “Family Portrait”



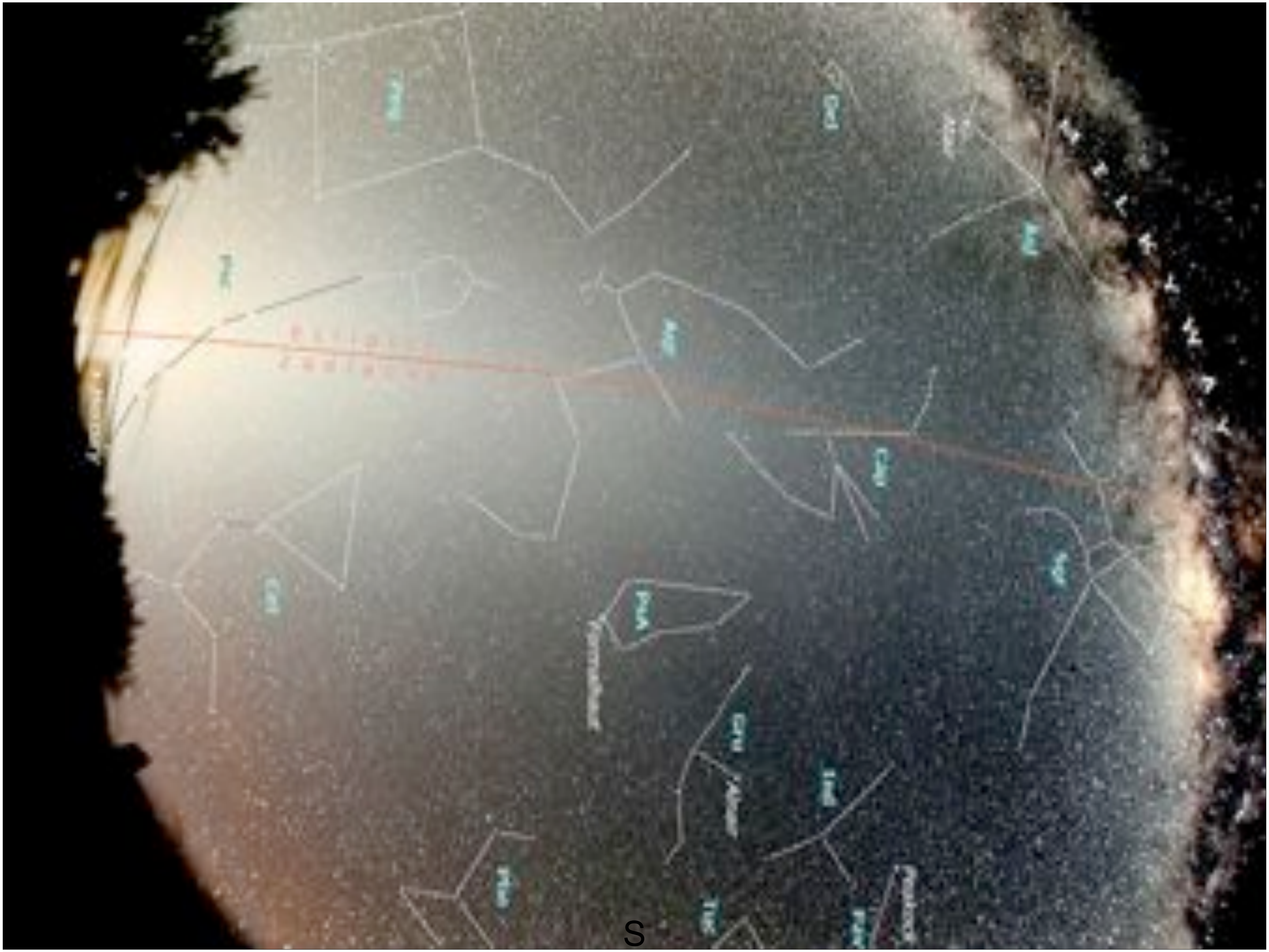
- Survey of the solar system 6×10^{12} m from Earth

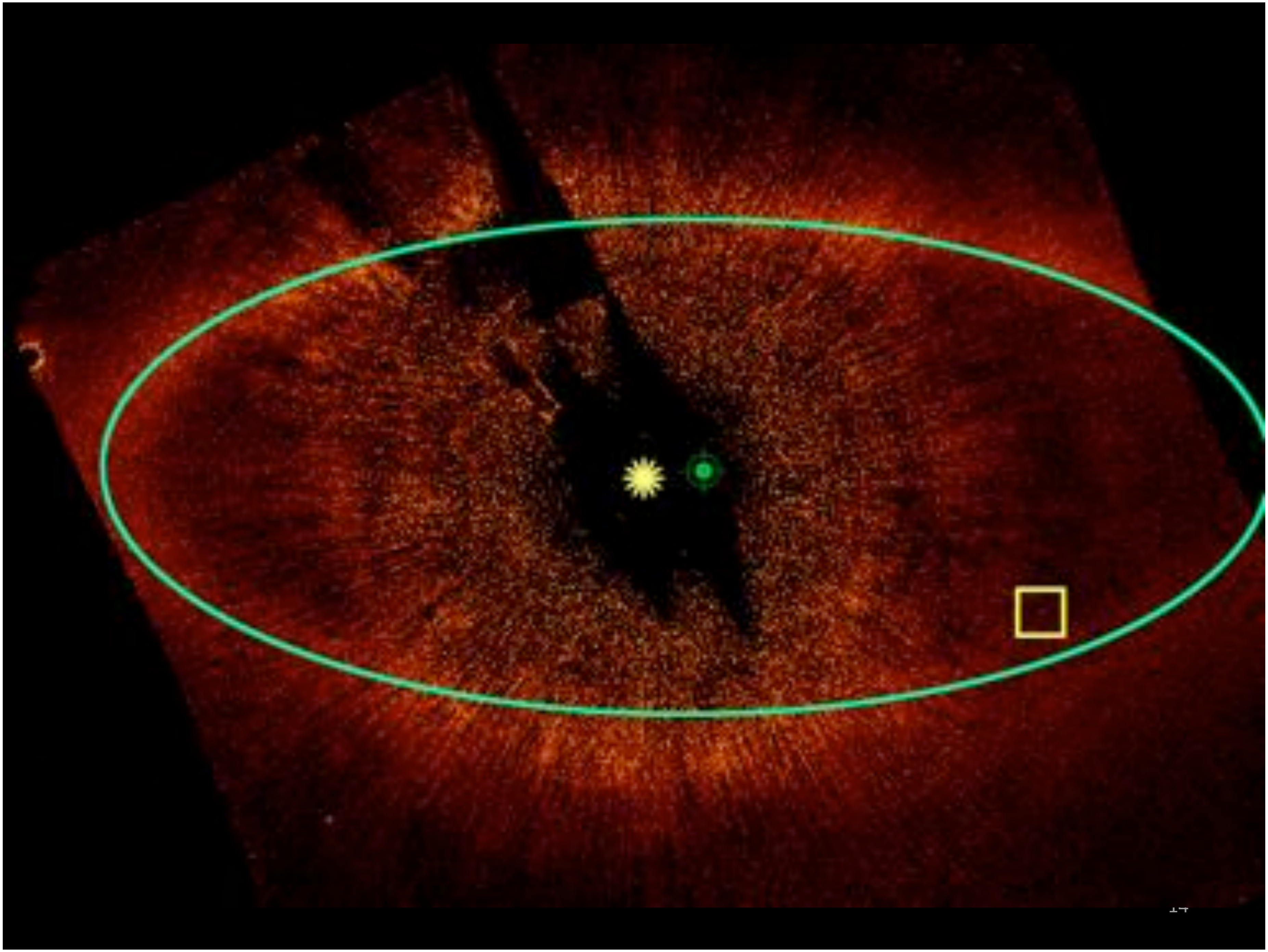

http://apod.nasa.gov


http://apod.nasa.gov

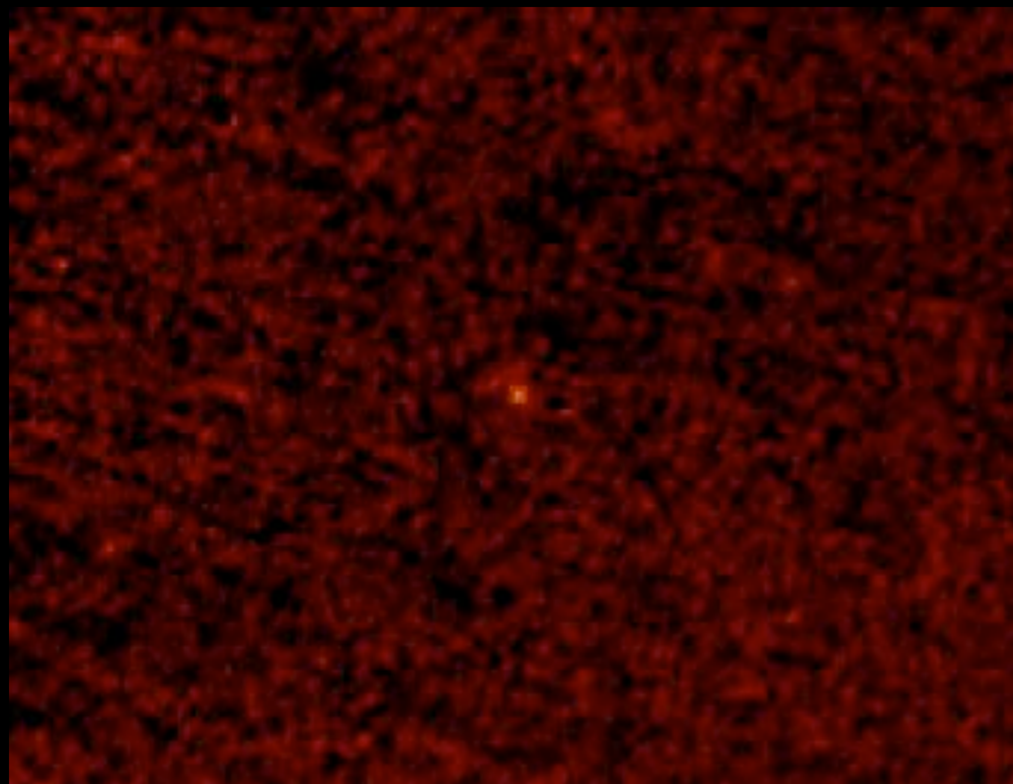
Finding Planets with the Hubble Telescope

- March 2002 Hubble is upgraded with a new camera
  - Advanced Camera for Surveys (ACS)
  - Coronagraphic with occulting spots to block the light of bright stars

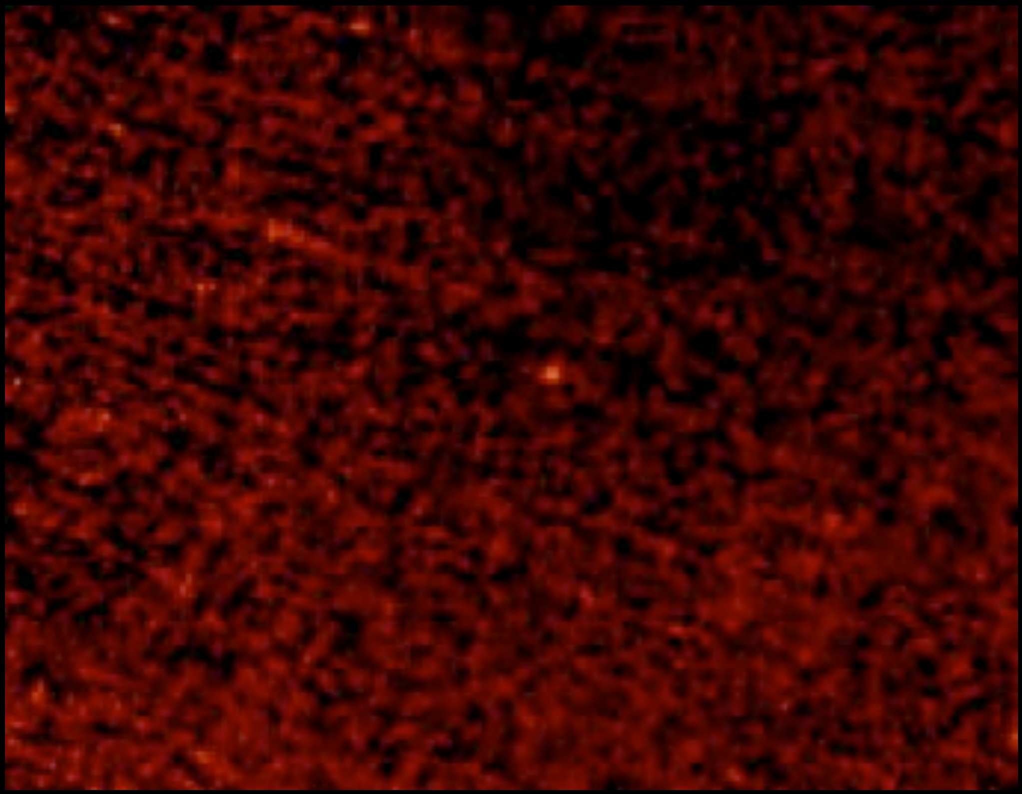

S

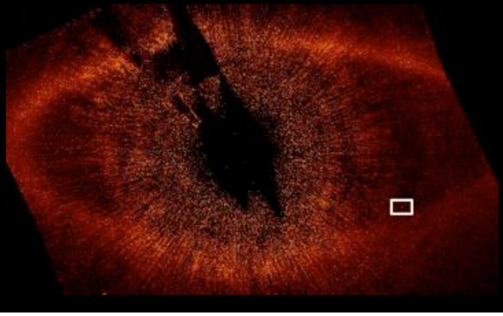


2004



2006

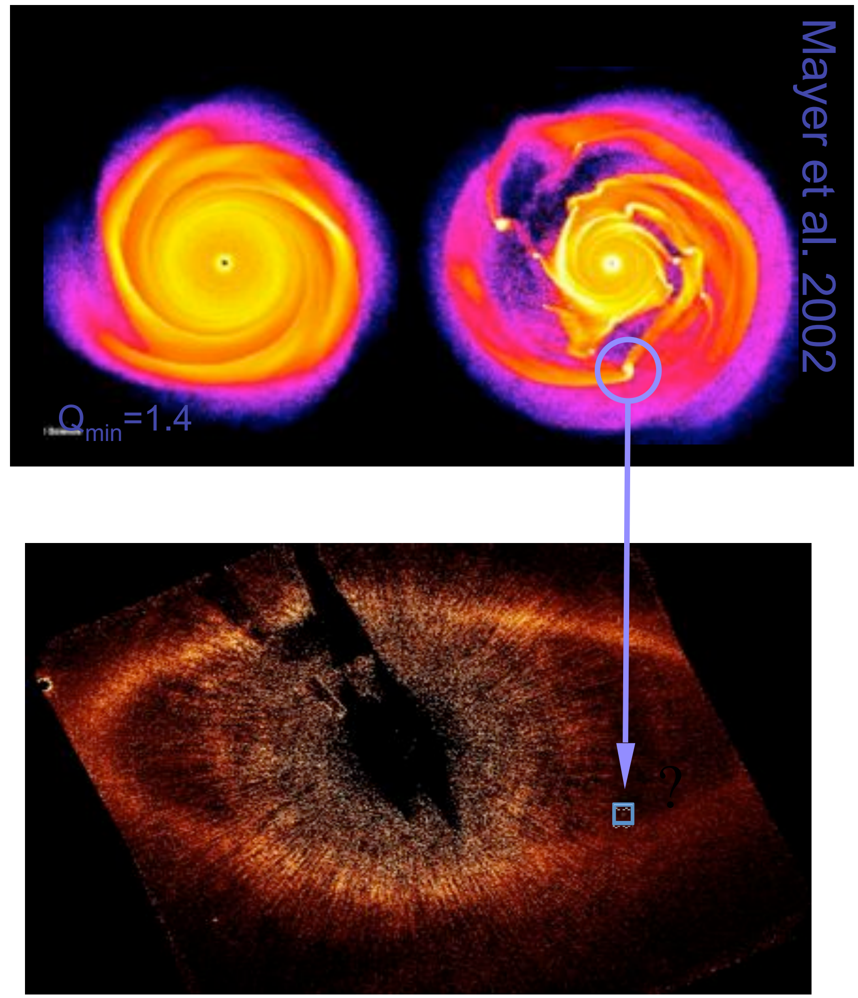




Science Motivation

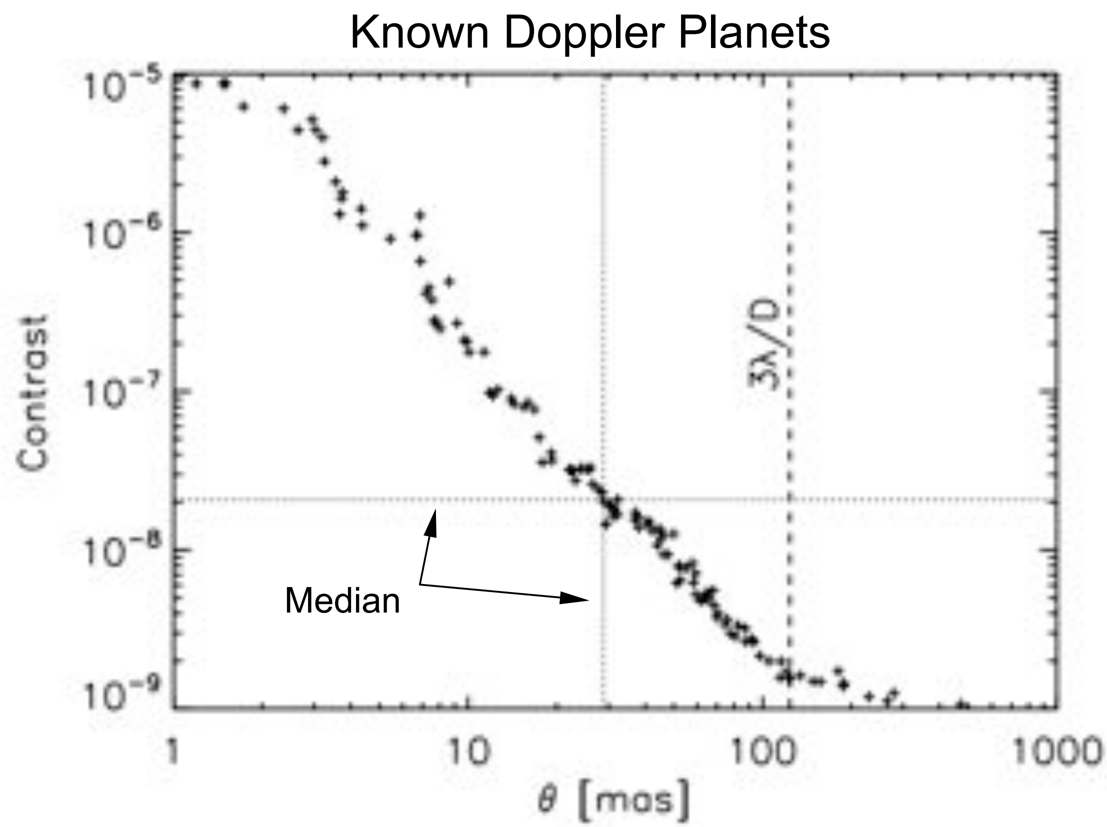
Solar System Imaging

- Fast alternative do Doppler
  - Improved statistics
    - 4–40 AU *vs*. 0.4–4 AU
- Search for exoplanets > 4 AU
  - Uniqueness of solar system?
  - Sample beyond the snow line & explore outer disks
    - Protostar disk radii are 50-80 AU
  - Do planets form by gravitational instability (30–100 AU)?
  - Traces of planetary migration
- Relation to debris disks
- Resolve *M* sin *i* ambiguity



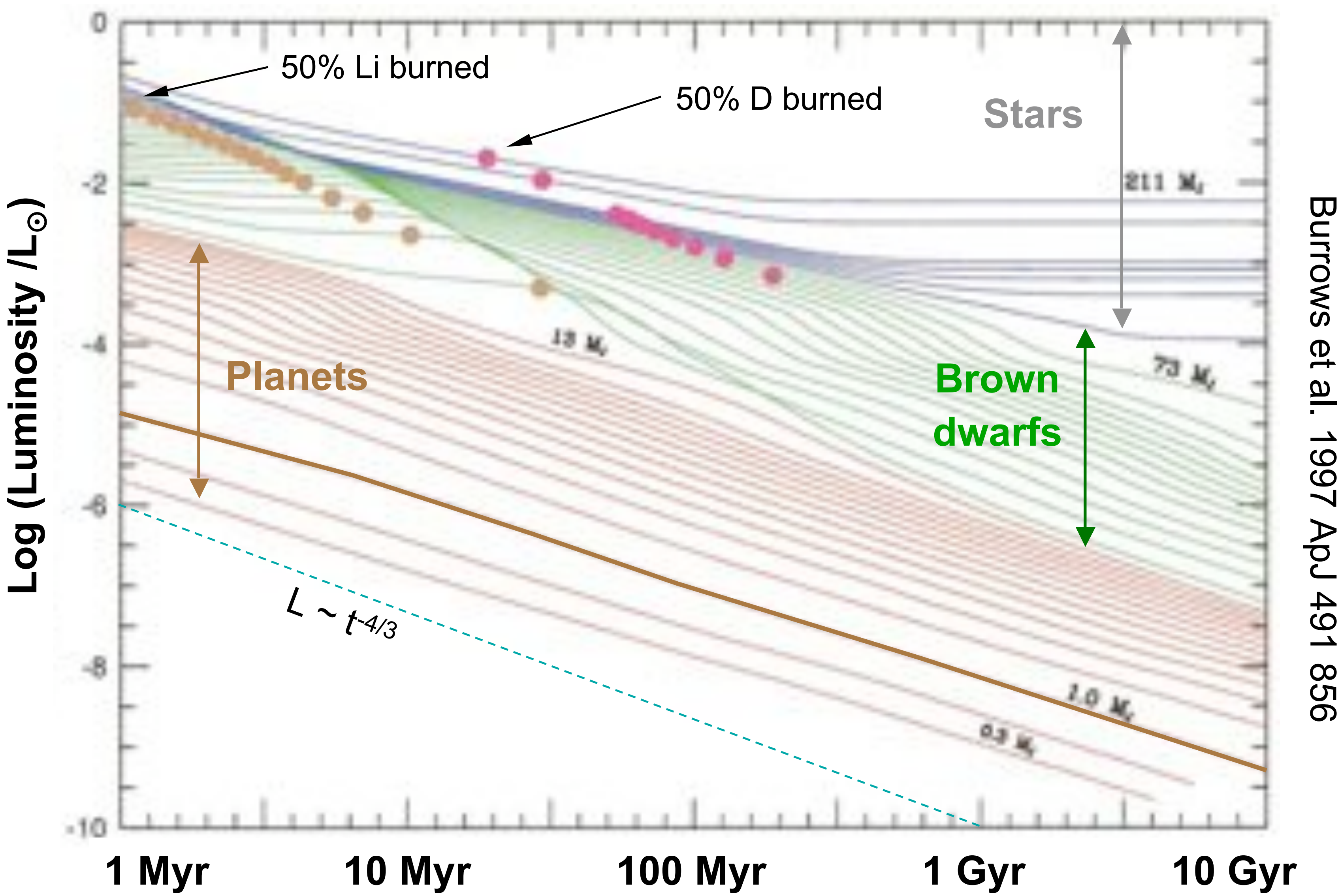
Detect Reflected Starlight?

- Predicted median contrast & angular separation for cataloged Doppler planets is 2×10^{-8} at 30 mas
  - $3\lambda/D$ = 130 mas @ 1.6 µm on a 8-m telescope



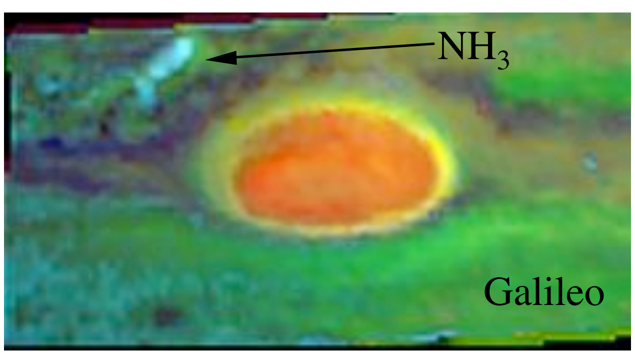
From the ground—target self-luminous planets between 4–40 AU

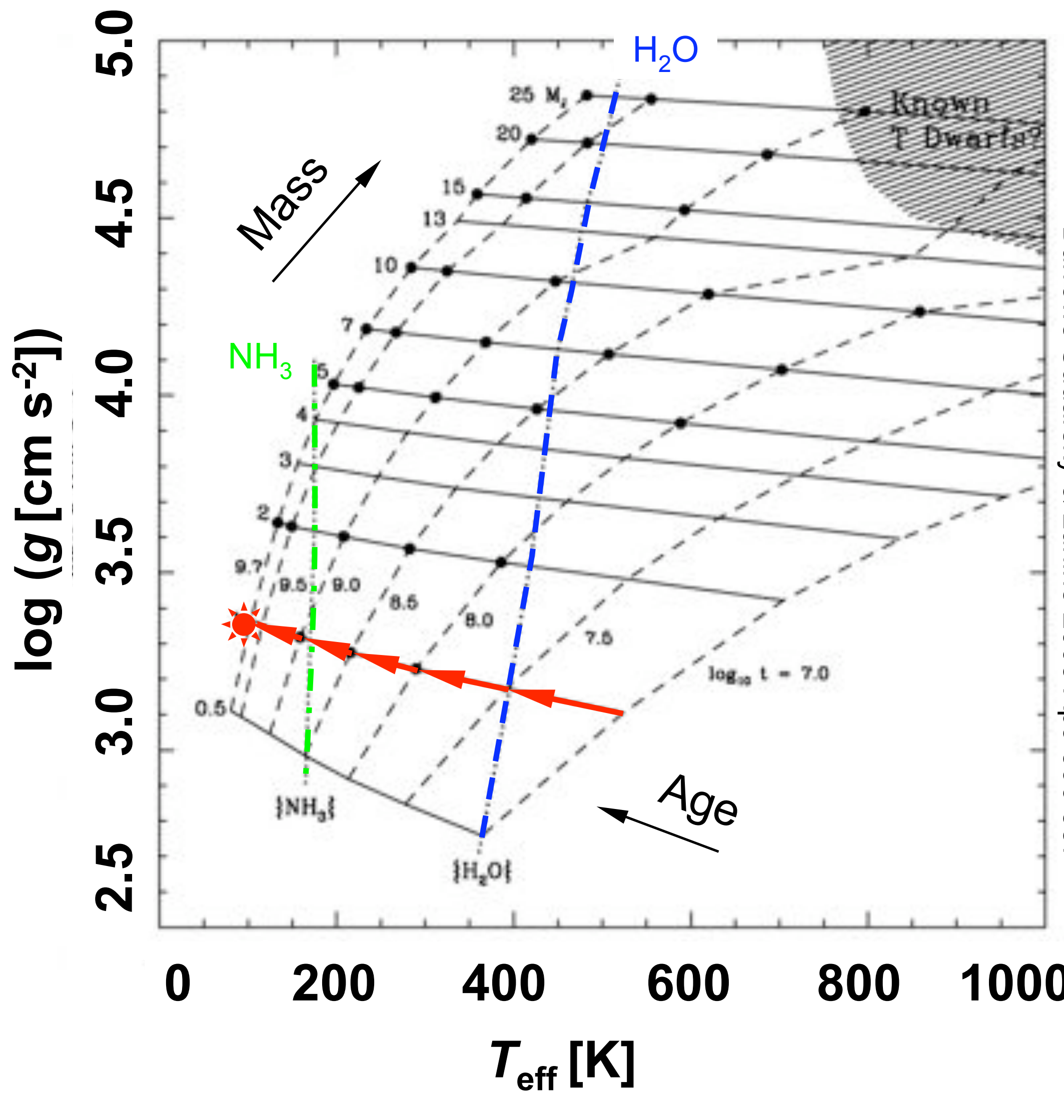
Young Planets are Luminous



Exoplanet Atmospheres

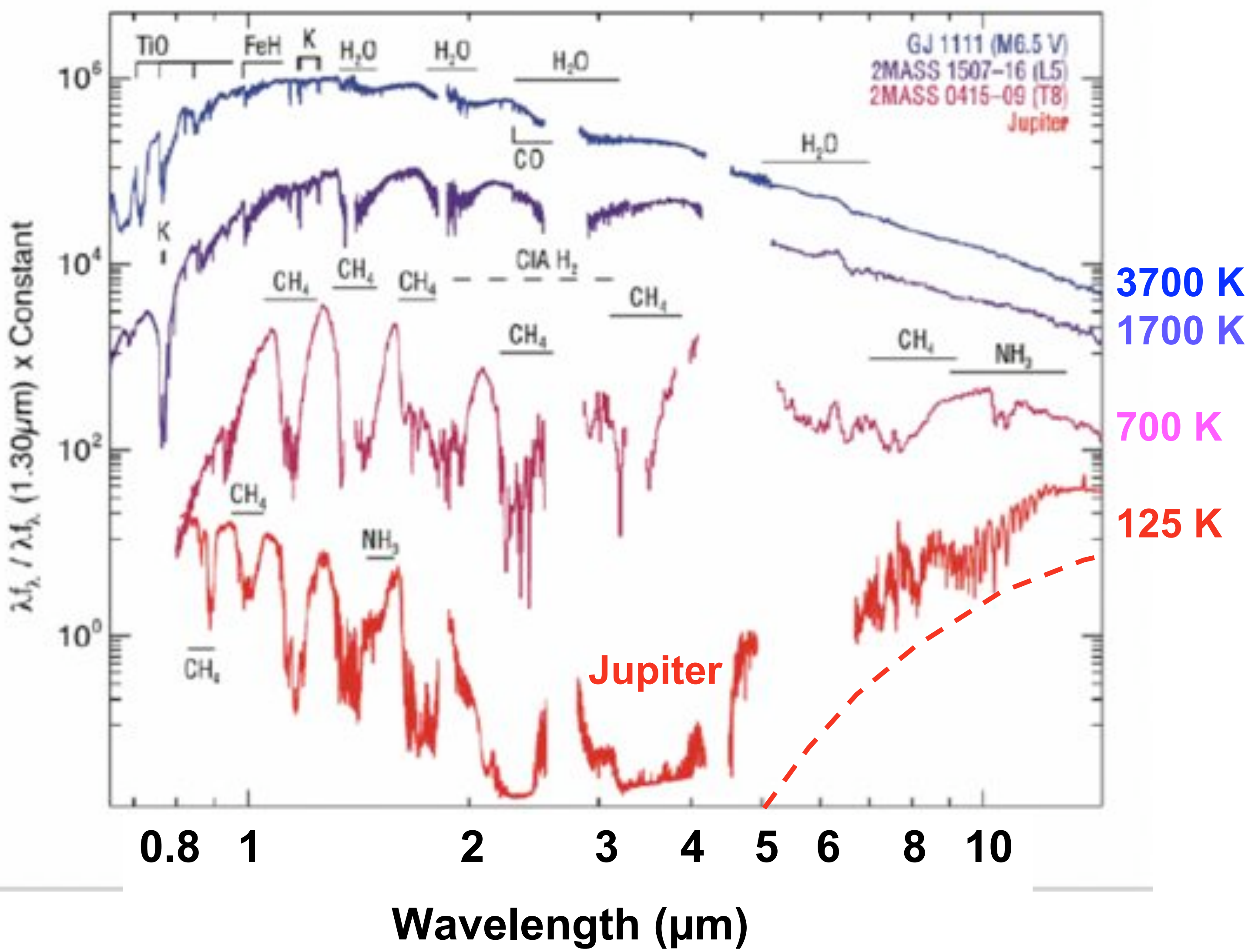
- Exoplanets will occupy a unique location in (log g, T_{eff}) phase space
  - Over 4.5 Gyr a Jovian mass exoplanet traverses the locus of H_2O & NH_3 cloud condensation
- Last frontier of classical stellar atmospheres





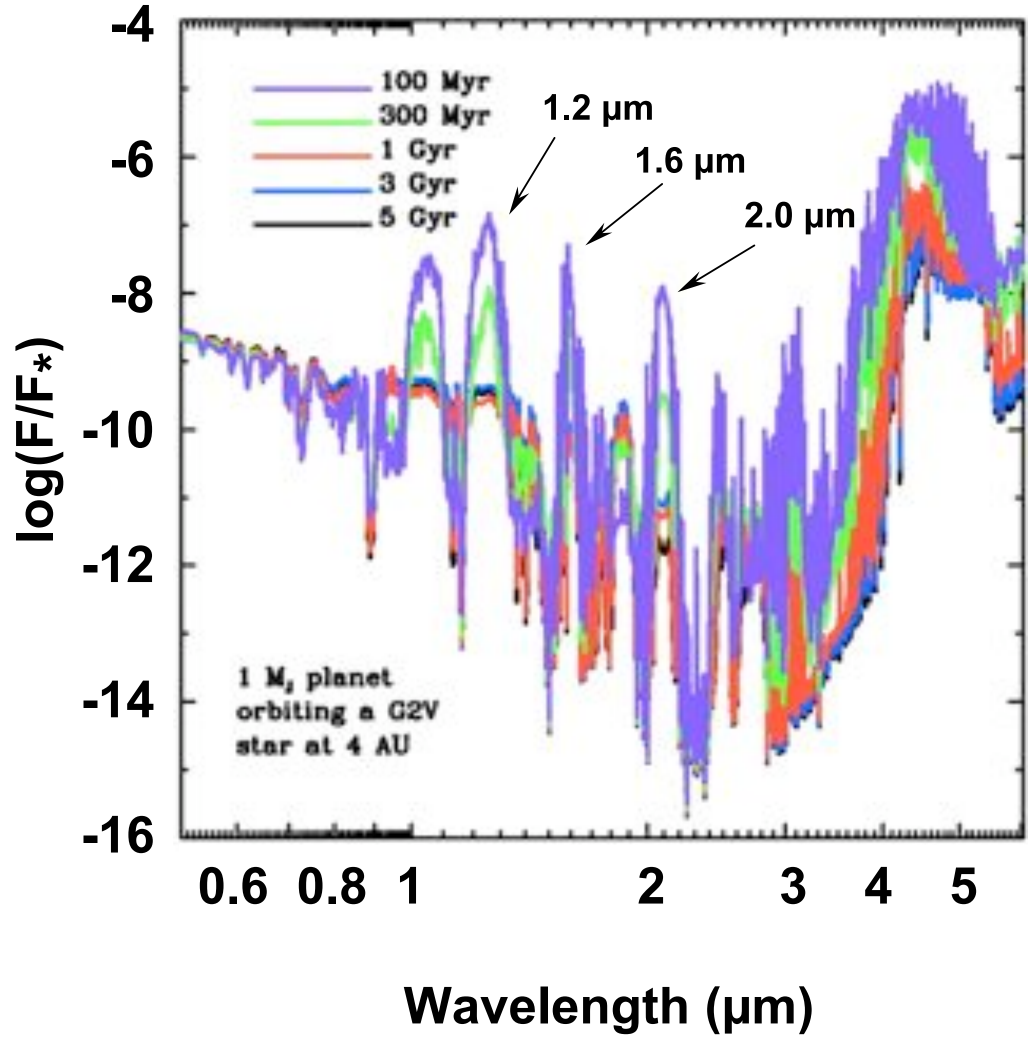
Burrows Sudarsky & Lunine 2003 ApJ 596 587

Spectra: Stars, Brown Dwarfs, & Planets



Warm Planets are not Black Bodies

- Contrast of an exo-Jupiter in a 5 AU orbit at 500 nm is ~ 2×10^{-9}
- Warm exoplanets are not black bodies
  - Contrast is 2-3 orders of magnitude more favorable in the IR
  - Radiation escapes in gaps between the CH_4 & H_2O opacity at 0.9, 1.2, 1.6, & 2.0 μm

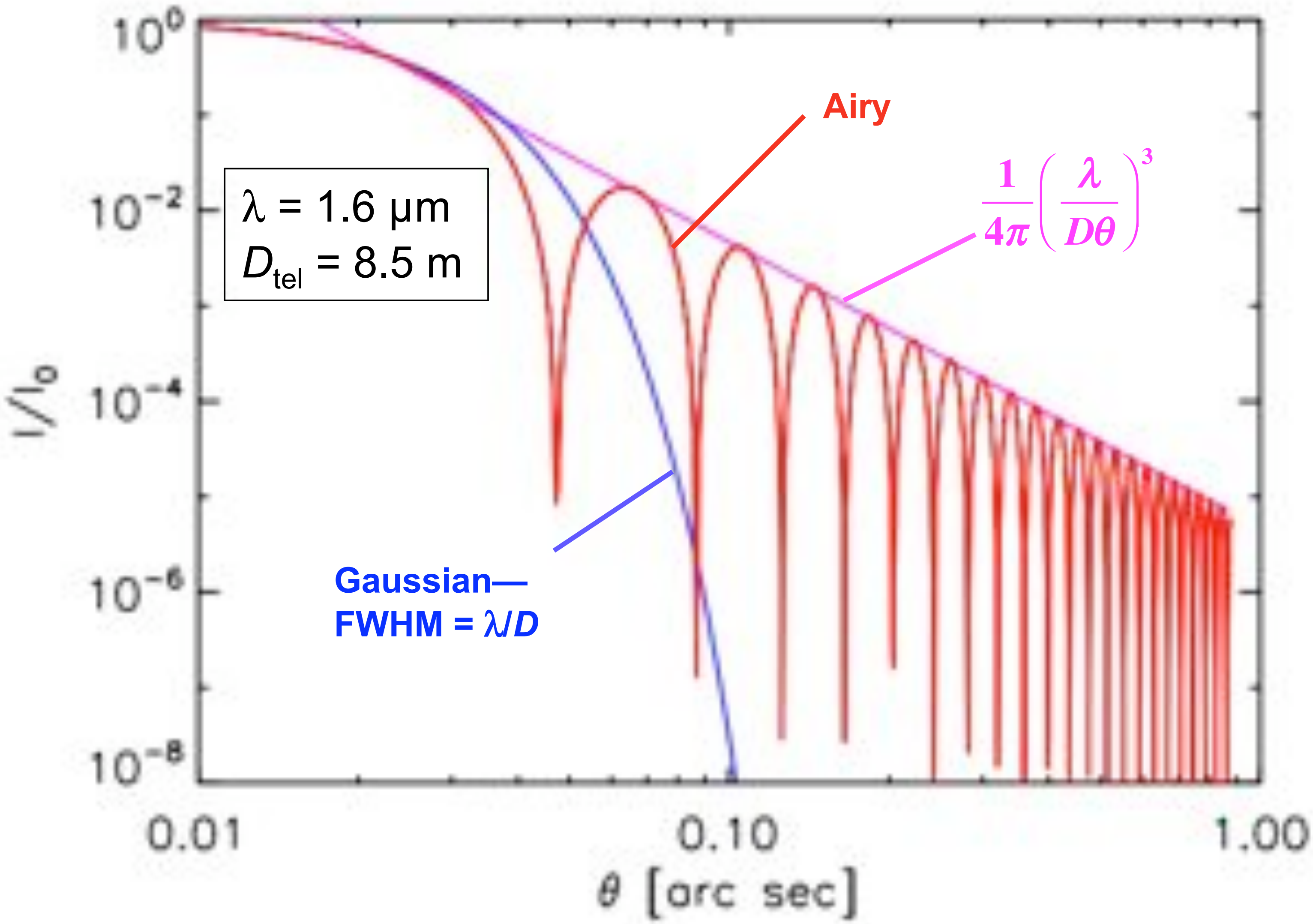


Burrows Sudarsky & Hubeny 2004 ApJ 609 407

How to Detect Exoplanets: Problems…

Diffraction

Diffraction: Circular Pupil



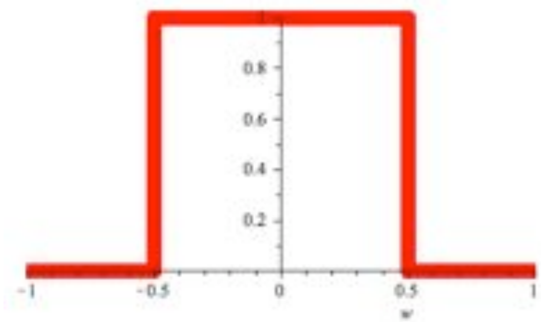
Diffraction & Pupil Shape

- Point spread function fades slowly with angle for a hard edged pupil
  - Asymptotically, the Airy function for a circular pupil falls ~ θ^{-3}
- Consequence of Fourier optics
  - Smooth pupil functions have compact PSFs
- If $f(x)$ and its first n-1 derivatives are continuous, then

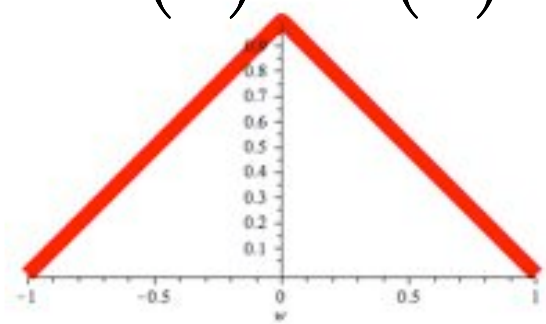
$$\mathrm{FT}[\ f(x)\ ] \sim 1/k^{(n+1)} \quad \text{for } k >> 1$$

  - Top hat $\Pi(x)$
    - Discontinuous $\rightarrow n = 0$,
    - FT[Π(x)] = sinc(k) ~ 1/k as k >> 1
  - Triangle $\Lambda(x) = \Pi(x) * \Pi(x)$
    - Continuous, but its first derivative is discontinuous $\rightarrow n$=1
    - FT[$\Lambda(x)$] = $\mathrm{sinc}^2(k) \sim 1/k^2$ as k >>1

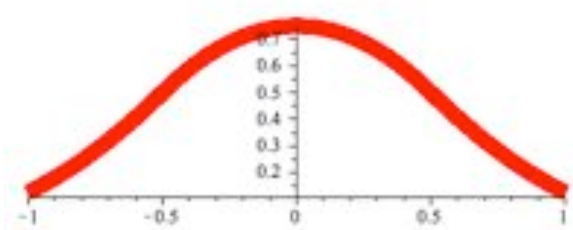
$$\Pi(x)$$

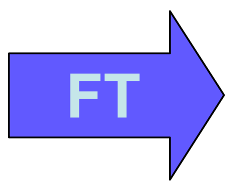


$$\Pi(x) * \Pi(x)$$

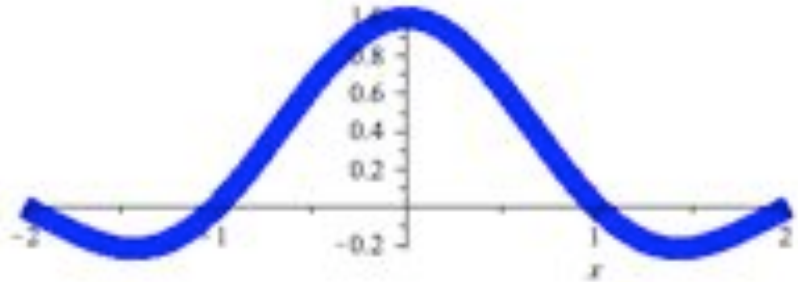


$$\Pi(x) * \Pi(x) * \Pi(x)$$

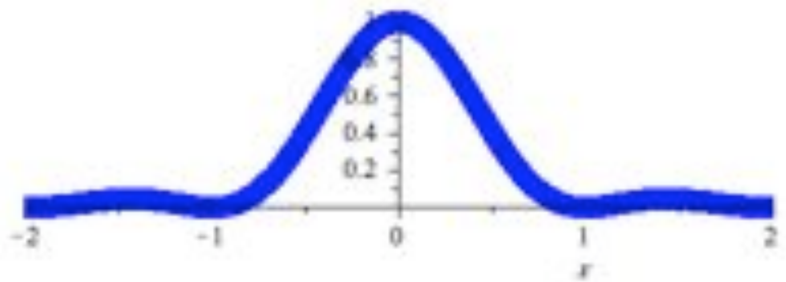




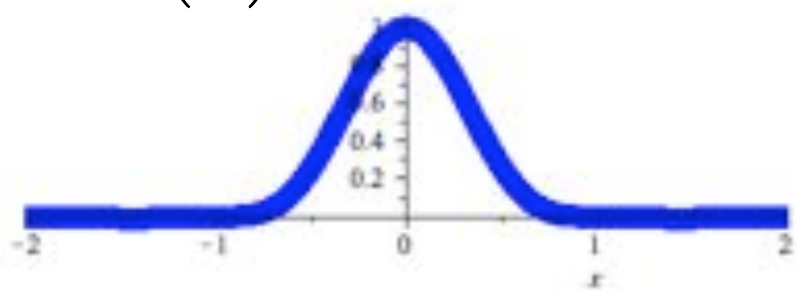
$$\operatorname{sinc}(k) \sim k^{-1} \quad k \to \infty$$



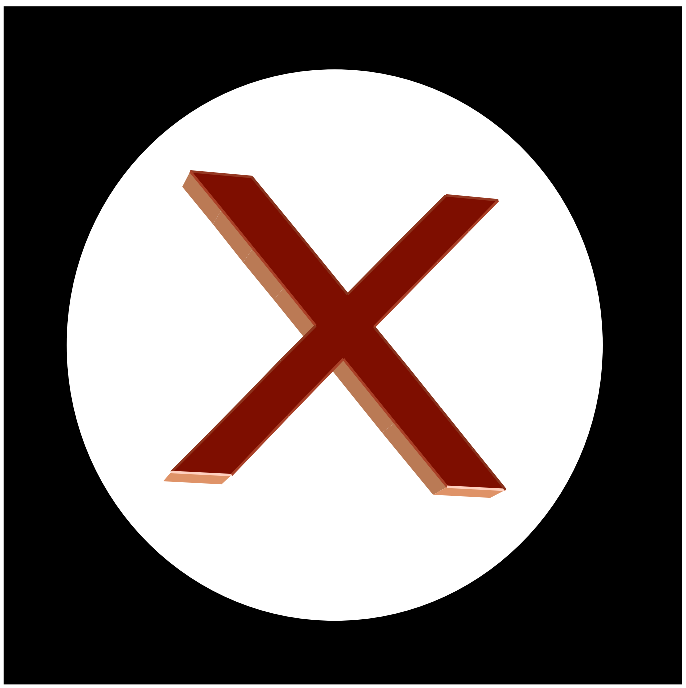
$$\operatorname{sinc}^2(k) \sim k^{-2} \quad k \to \infty$$



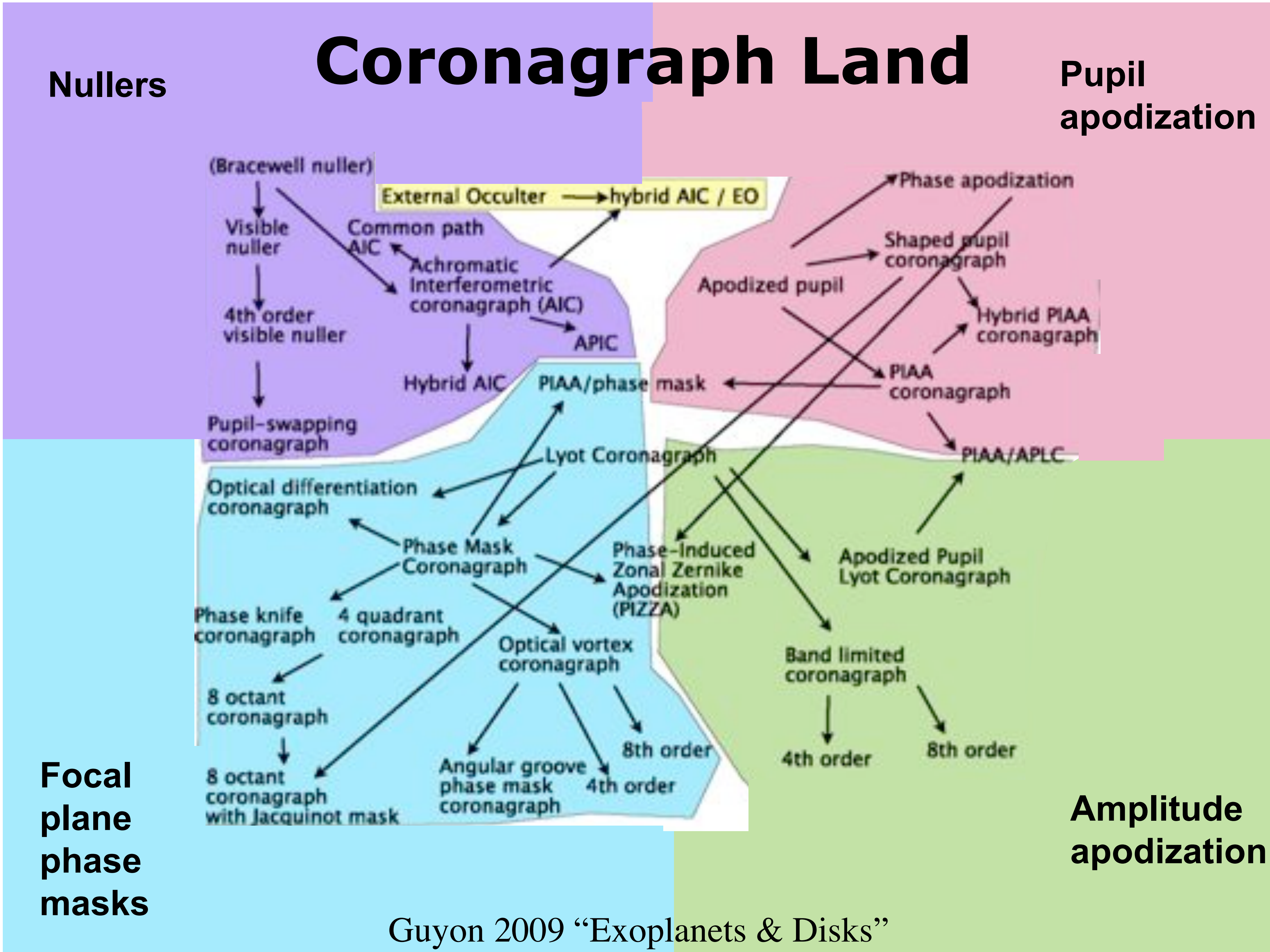
$$\operatorname{sinc}^3(k) \sim k^{-3} \quad k \to \infty$$



Pupil Apodization



Coronagraph Land

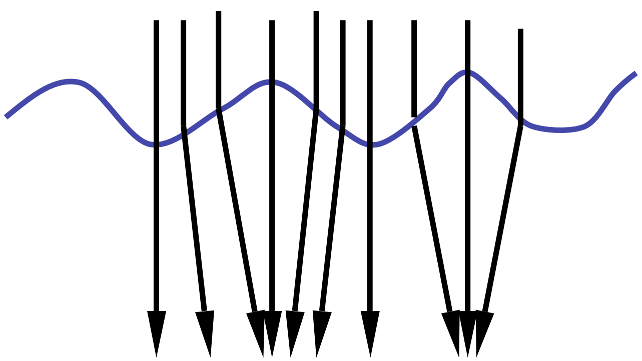


Guyon 2009 "Exoplanets & Disks"

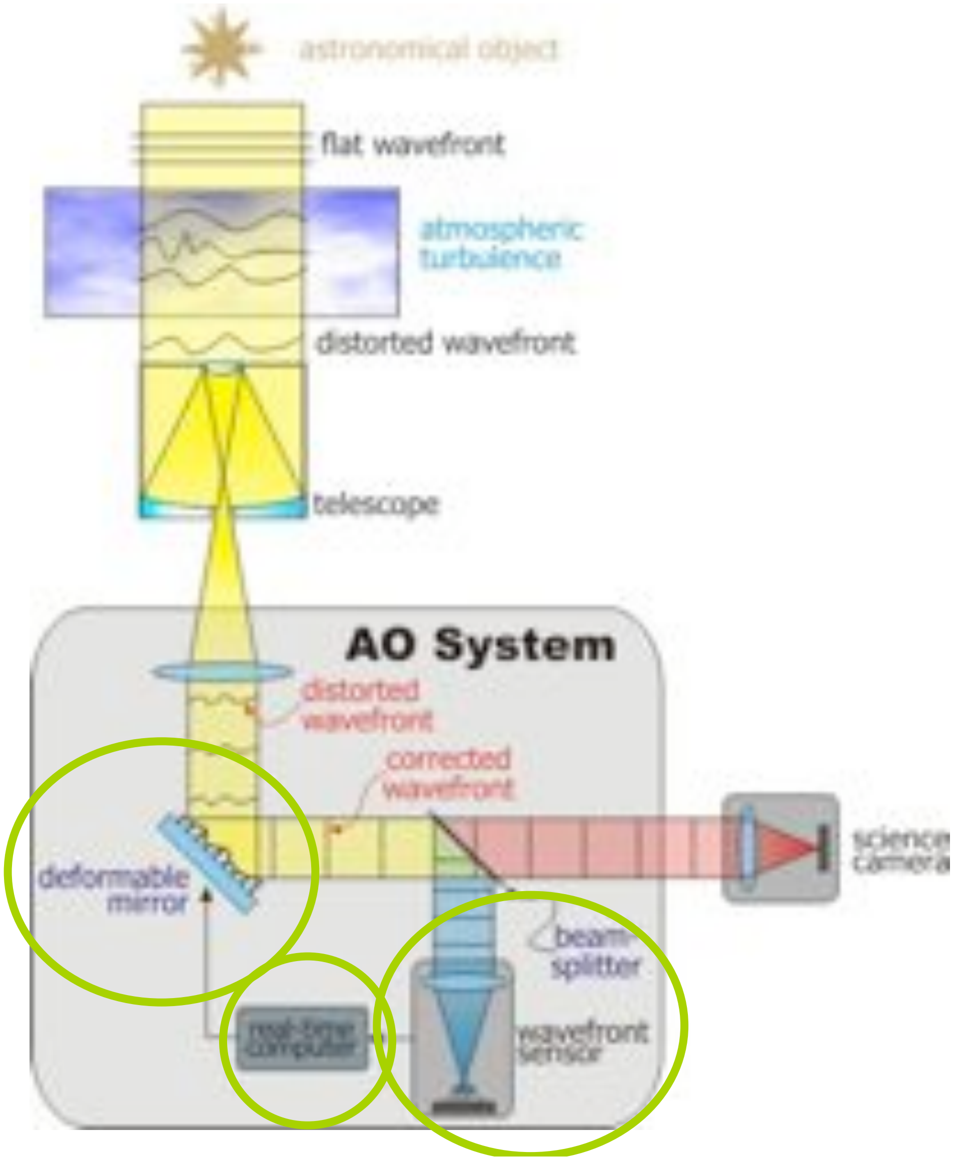
Wavefront Errors

Wavefront errors

- A wavefront error, spatial frequency *k,* diffracts light according to the condition for constructive interference $\theta = k\lambda/2\pi$

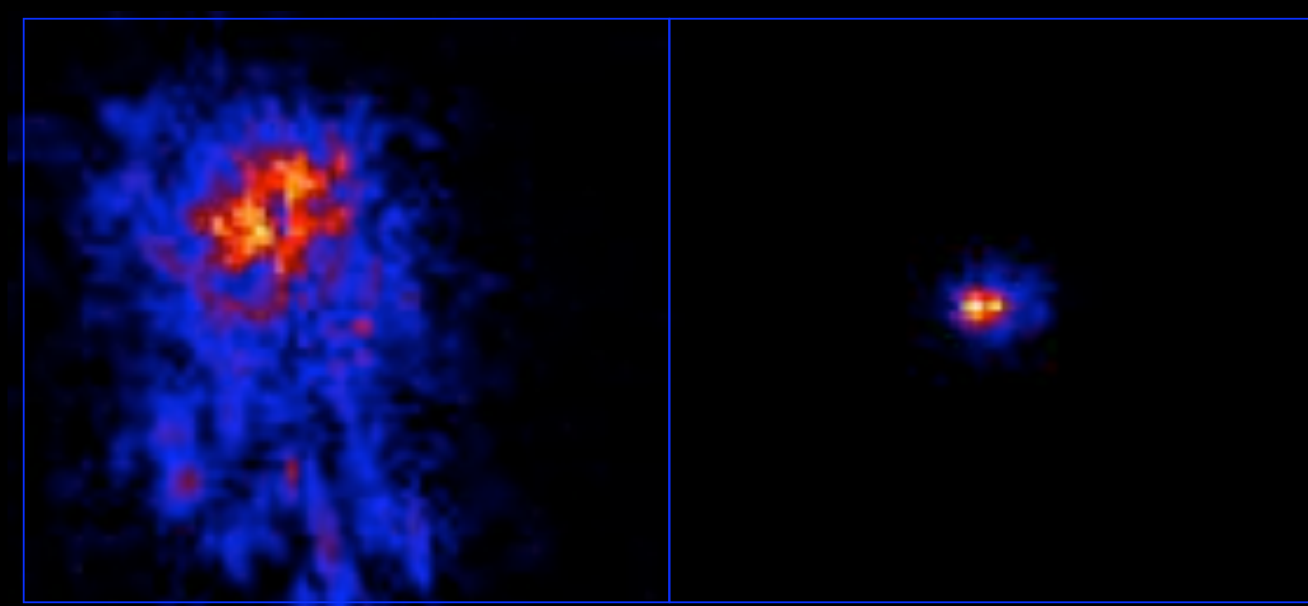


Adaptive Optics



No wavefront control

Adaptive optics



Dynamic & Static Phase Errors

PSF = dynamic atmosphere PSF (smooth) + static PSF (speckles)

$$p = \left| FT(A\Phi) \right|^2 \quad \text{where} \quad \Phi = \overbrace{\underbrace{\Phi_0}_{\text{Static}} + \underbrace{\Phi(t)}_{\text{Dynamic}}}^{\text{Phase error}}$$

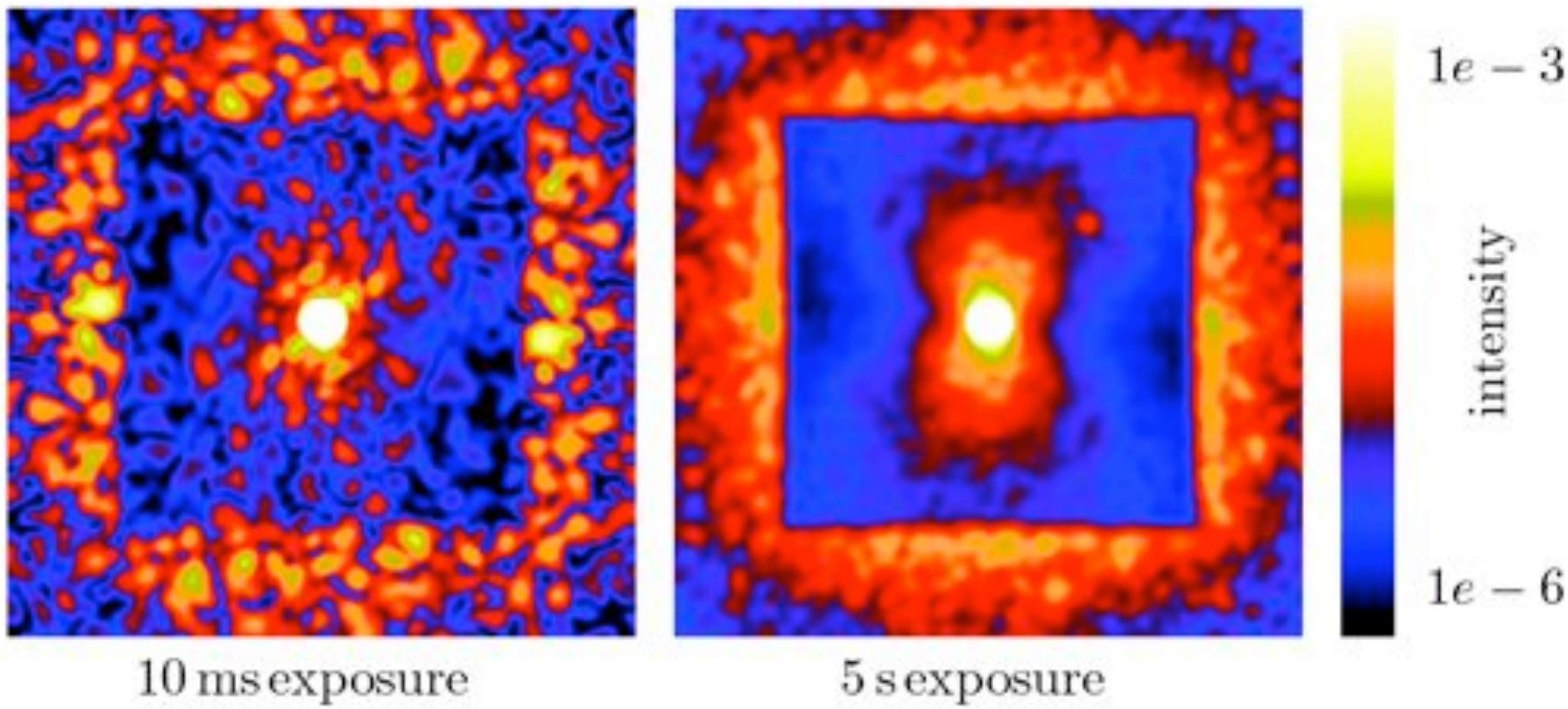
$$p = \left\langle \left| FT(A\Phi(t)) \right|^2 \right\rangle_t + \left| FT(A\Phi_0) \right|^2$$

Averages to a smooth "halo" over the decorrelation time

"Static" speckles

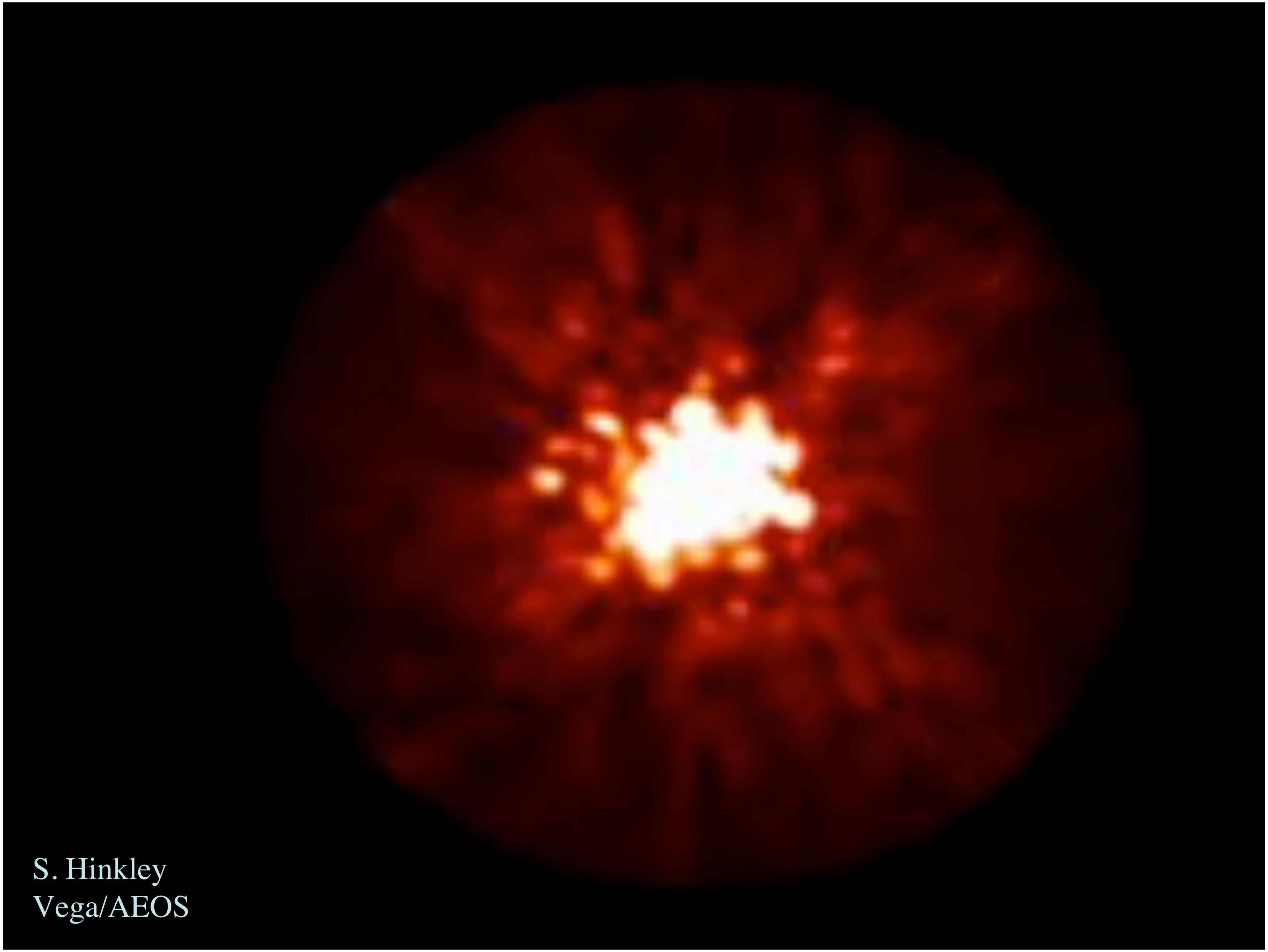
Sivaramakrishnan et al 2002

Atmospheric Speckles Smooth Out

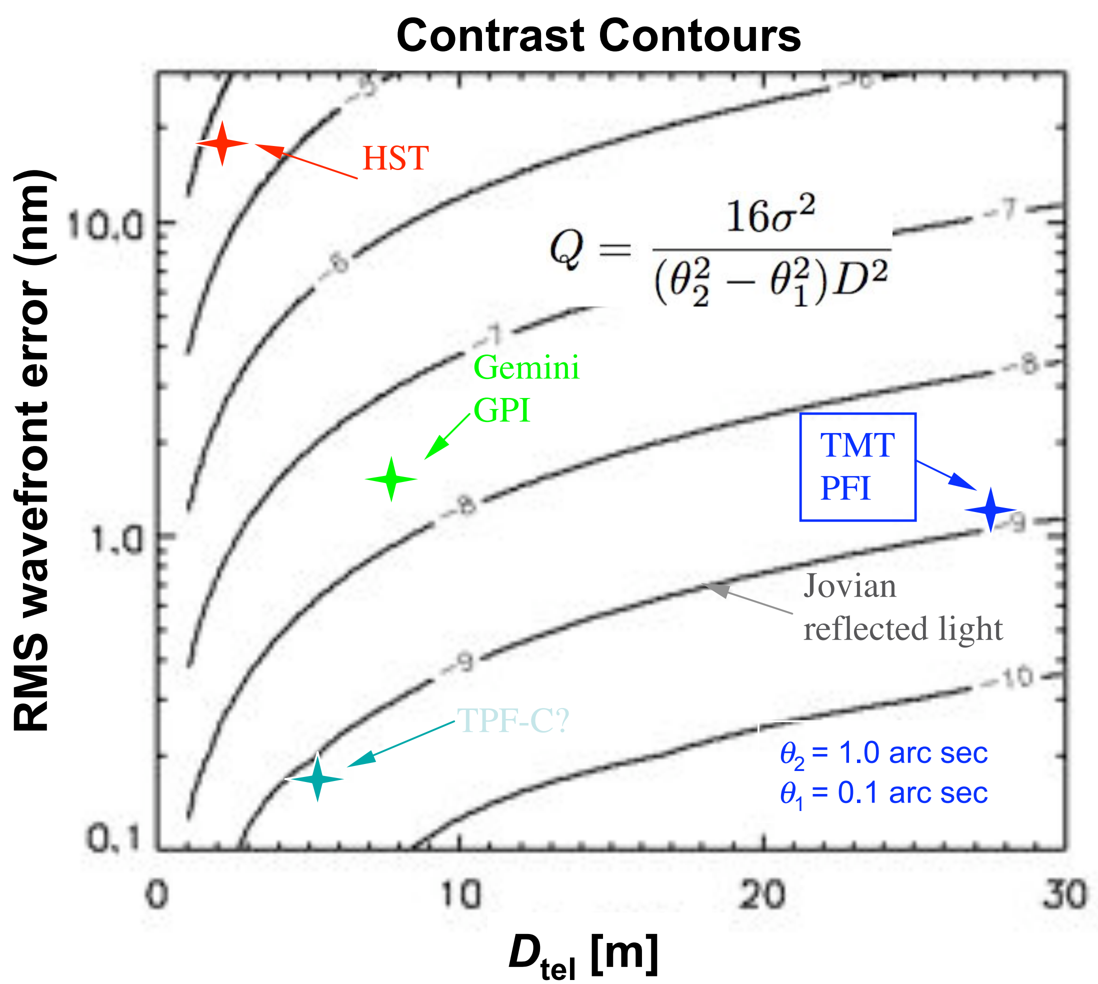


(Macintosh et al 2005 Proc. SPIE)

- Atmospheric speckle lifetime ~0.5 D_{tel}/v_{wind}
- AO control does not modify this (even predictive…)
- WFS measurement speckles and pinned speckles have shorter lives but atmosphere speckles provide floor


S. Hinkley
Vega/AEOS

Wavefront Errors & Contrast



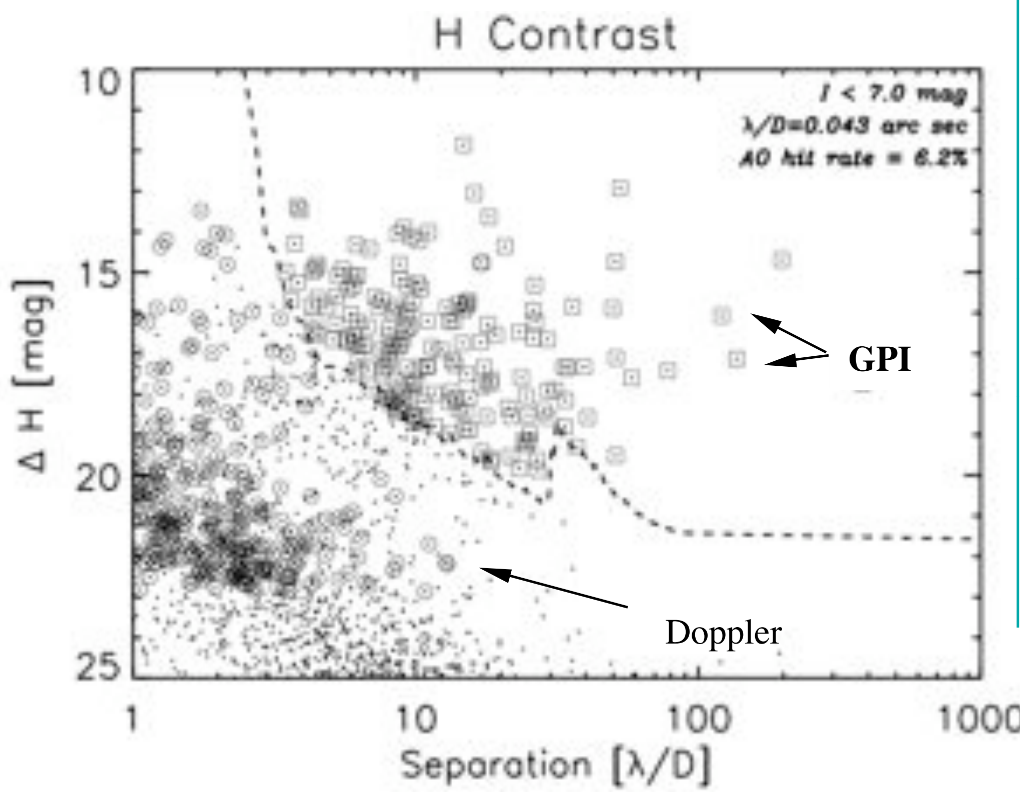
$$Q = \frac{16\sigma^2}{(\theta_2^2 - \theta_1^2)D^2}$$

Recipe for High Contrast Imaging

- Precise & accurate wavefront control
  - Advanced AO to control of dynamic (atmosphere) external static (telescope) aberrations
    - Few nm rms to reach contrast of 10^{-8}
    - Need a few x 10^3 degrees of freedom & kHz bandwidth to keep up with atmosphere
  - Amplitude errors must be small or controlled
- Control of diffraction to target contrast level
  - Pupil apodization to reduce side-lobes at angles of a few λ/D
- Stable to enable differential imaging
  - Field rotation: Cassegrain focus on Alt/Az telescope
  - Spectral differencing: integral field spectrograph

Monte Carlo Simulations

- AO
  - r_0 = 100 cm
  - 2.5 kHz update rate
  - 13 cm sub-apertures
    - *R* = 7 mag. limit
- Coronagraph
  - Ideal apodization
- Science camera
  - Broad band *H*
  - No speckle suppression
- Target sample
  - *R* < 7 mag.
  - 1703 field stars (< 50 pc)



Graham et al. arXiv:0704.1454

- Results
  - 110 exoplanets (~ 6% detection rate)
  - Semimajor axis distribution is complementary to Doppler exoplanets

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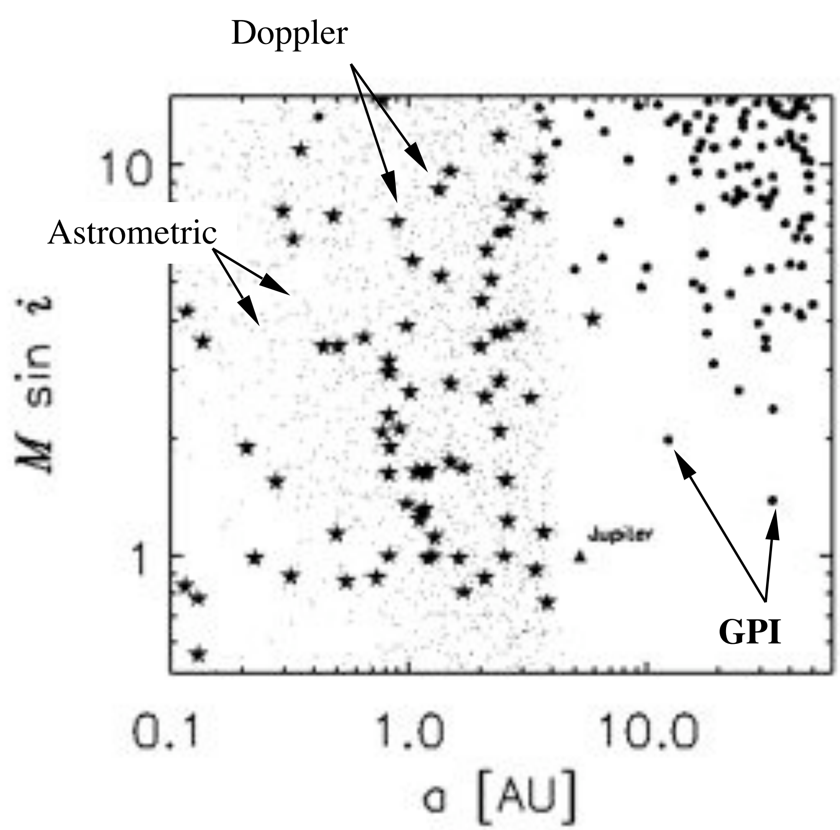

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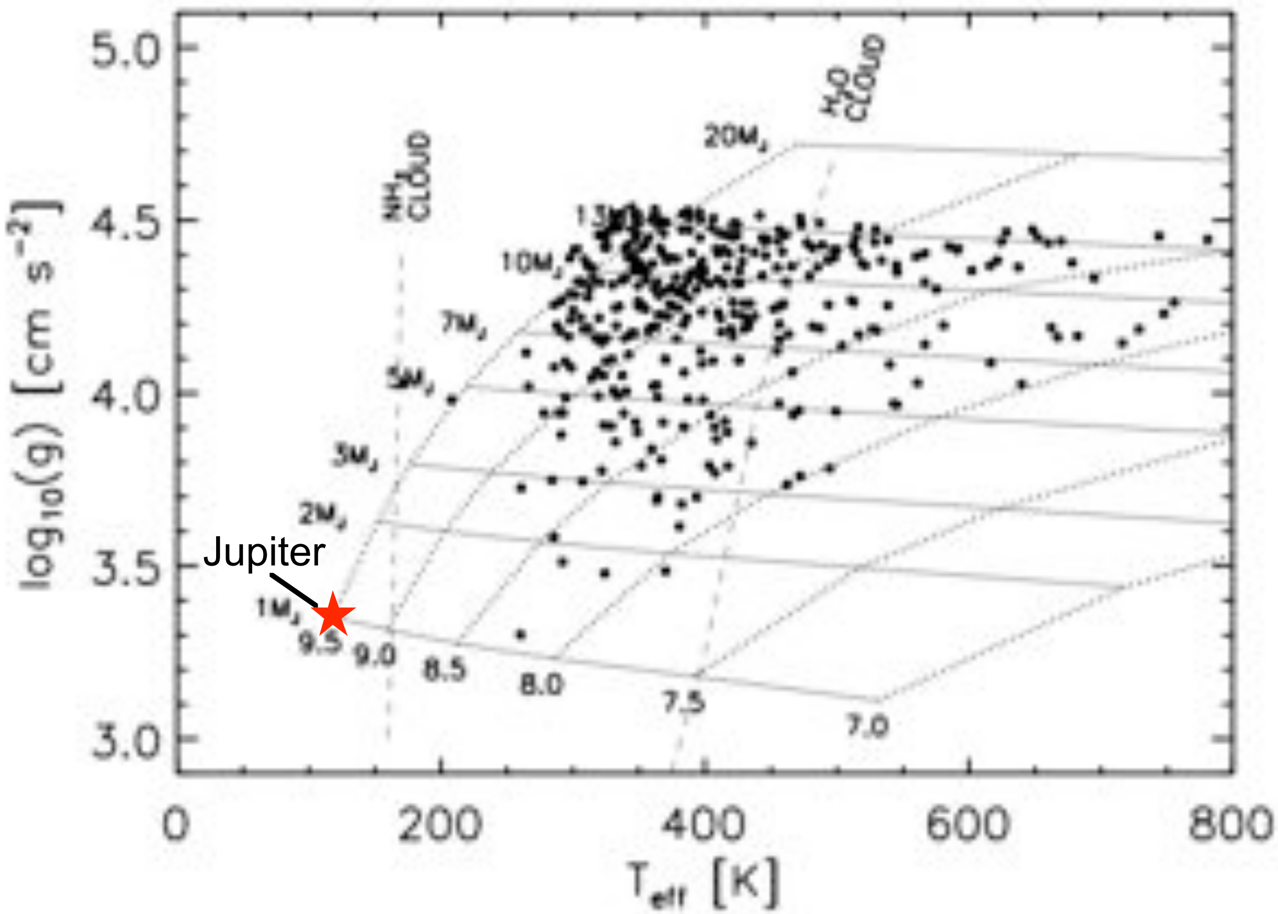
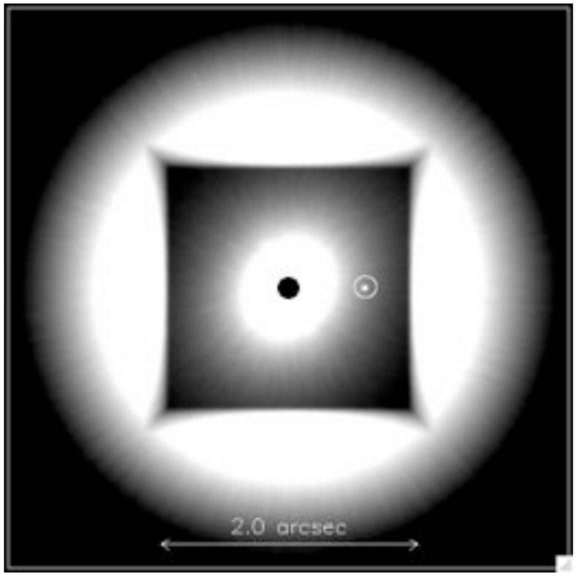


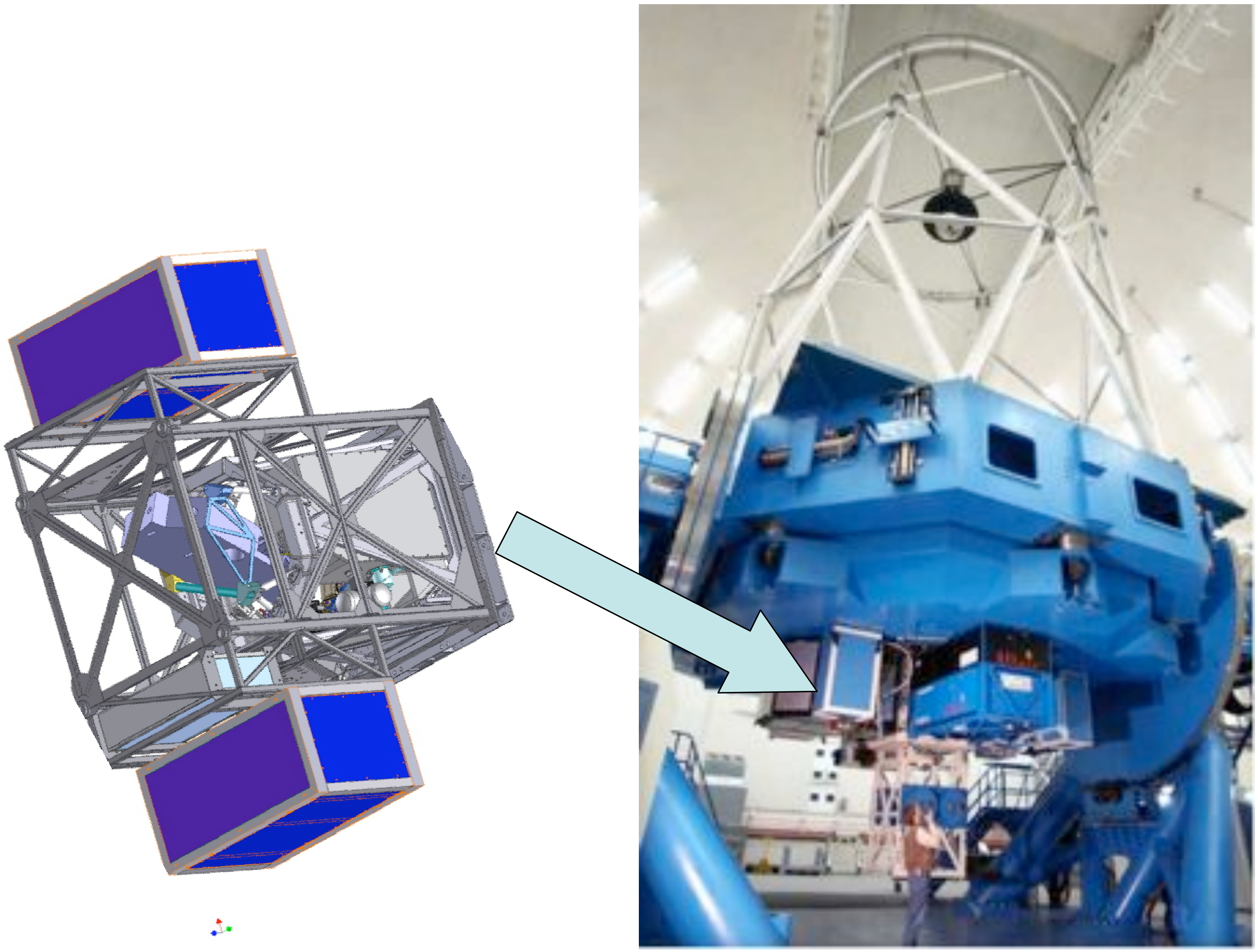
Graham et al. arXiv:0704.1454

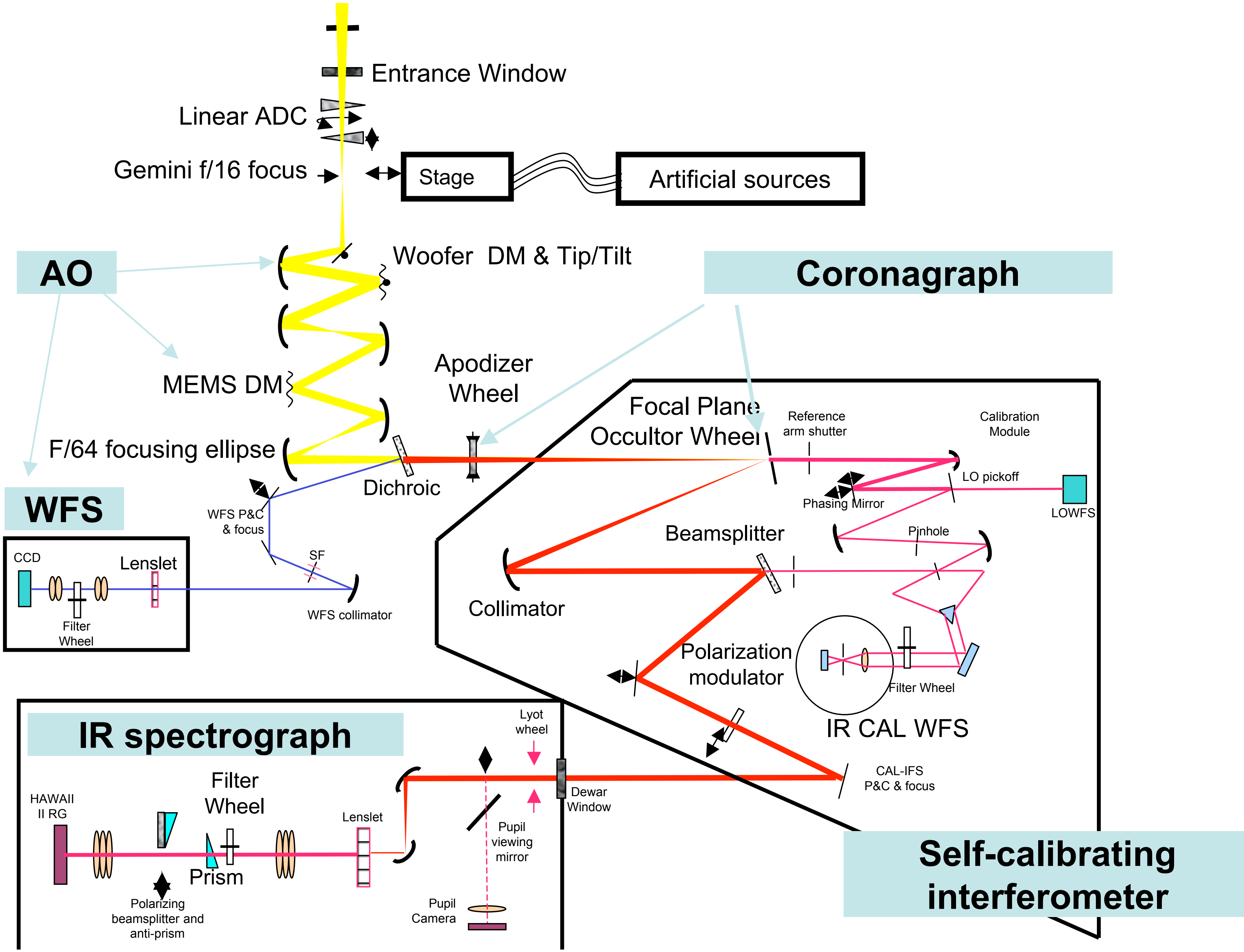
Gemini Planet Imager



- 1800-actuator AO system
- Strehl ratio ~ 0.9 at *H* for the Gemini 8-m telescope
- Super-polished optics & precision calibration
- APLC coronagraph
- Integral field spectropolarimeter

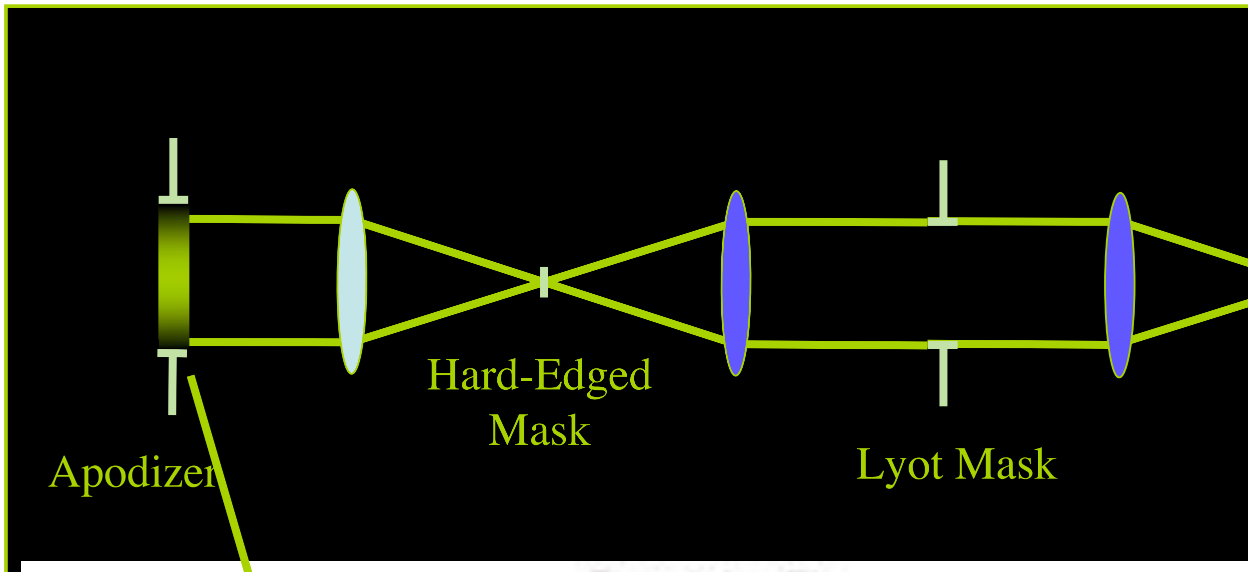
LLNL: Macintosh-PI/management/ AO
AMNH:Oppenheimer-Coronagraph masks
HIA: Saddlemyer-Optomechanical/software
JPL: Wallace-Interferometer
UofT: Graham-Project scientist
UCLA: Larkin-IR spectrograph
UdM: Doyon-Data pipeline
UCSC: Gavel-Final integration & test

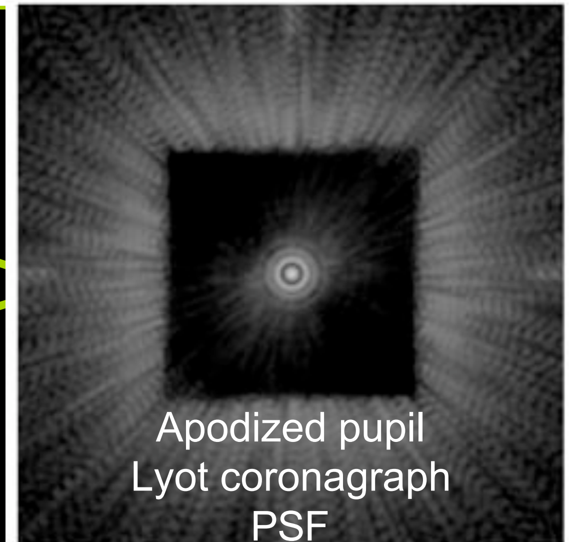


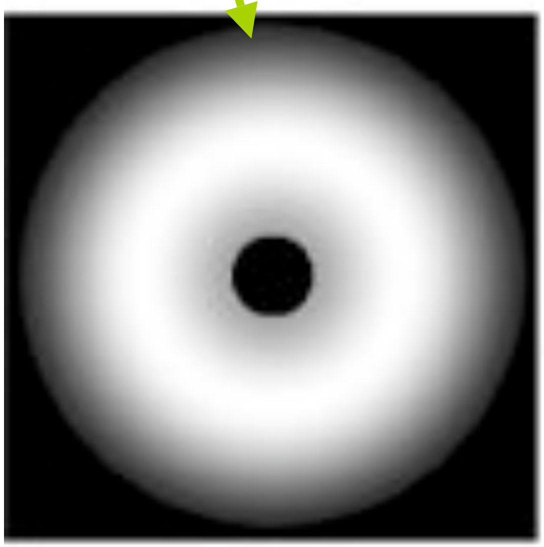


Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
AO
Woofer DM & Tip/Tilt
Coronagraph
MEMS DM
Apodizer Wheel
F/64 focusing ellipse
Focal Plane Occultor Wheel
Reference arm shutter
Calibration Module
LO pickoff
LOWFS
Phasing Mirror
Dichroic
WFS
WFS P&C & focus
SF
CCD
Lenslet
Filter Wheel
WFS collimator
Beamsplitter
Pinhole
Collimator
Polarization modulator
IR CAL WFS
CAL-IFS P&C & focus
IR spectrograph
Lyot wheel
Dewar Window
HAWAII II RG
Filter Wheel
Lenslet
Prism
Polarizing beamsplitter and anti-prism
Pupil viewing mirror
Pupil Camera
Self-calibrating interferometer

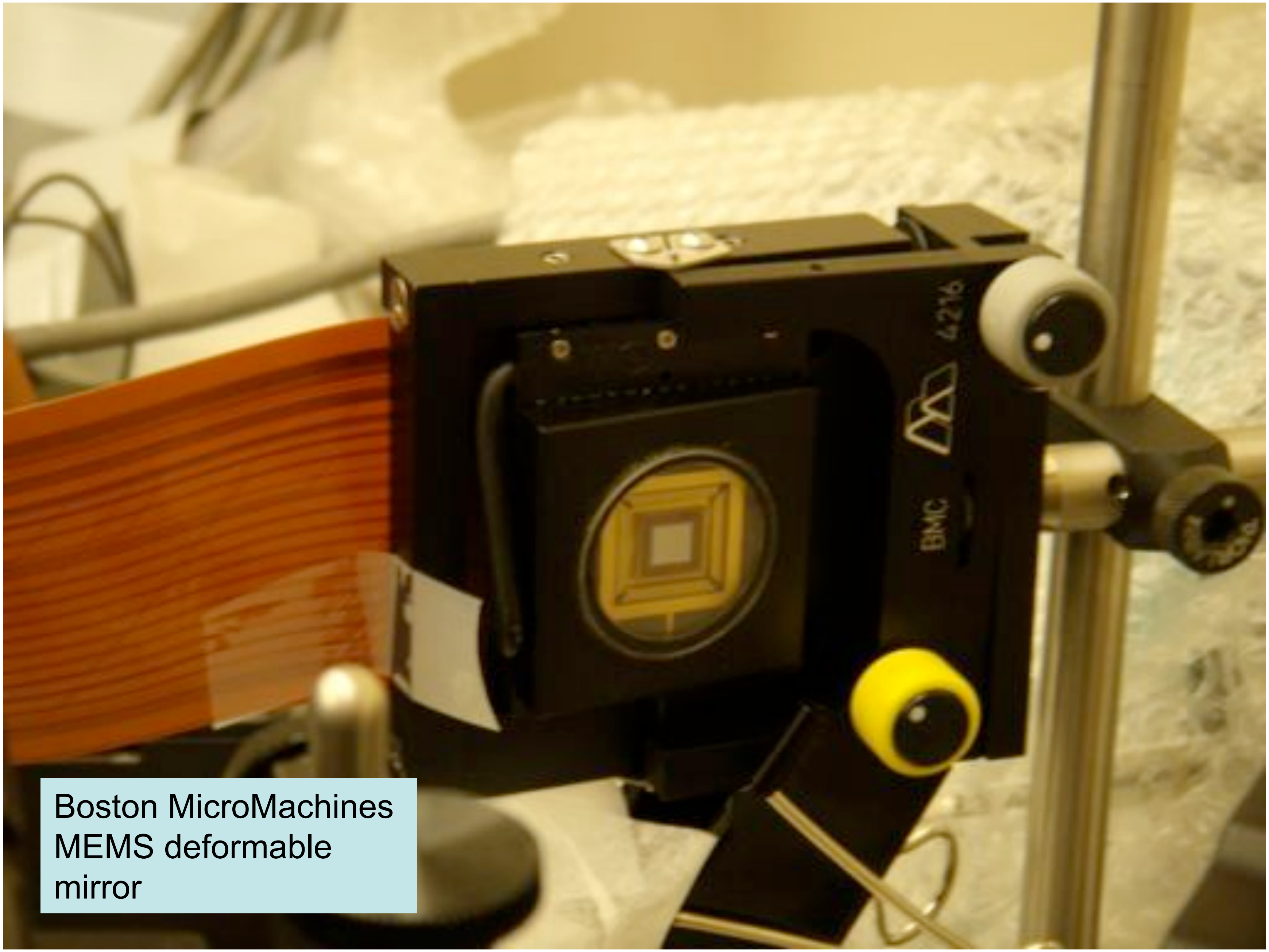
APLC Optimized for Obscured Pupil





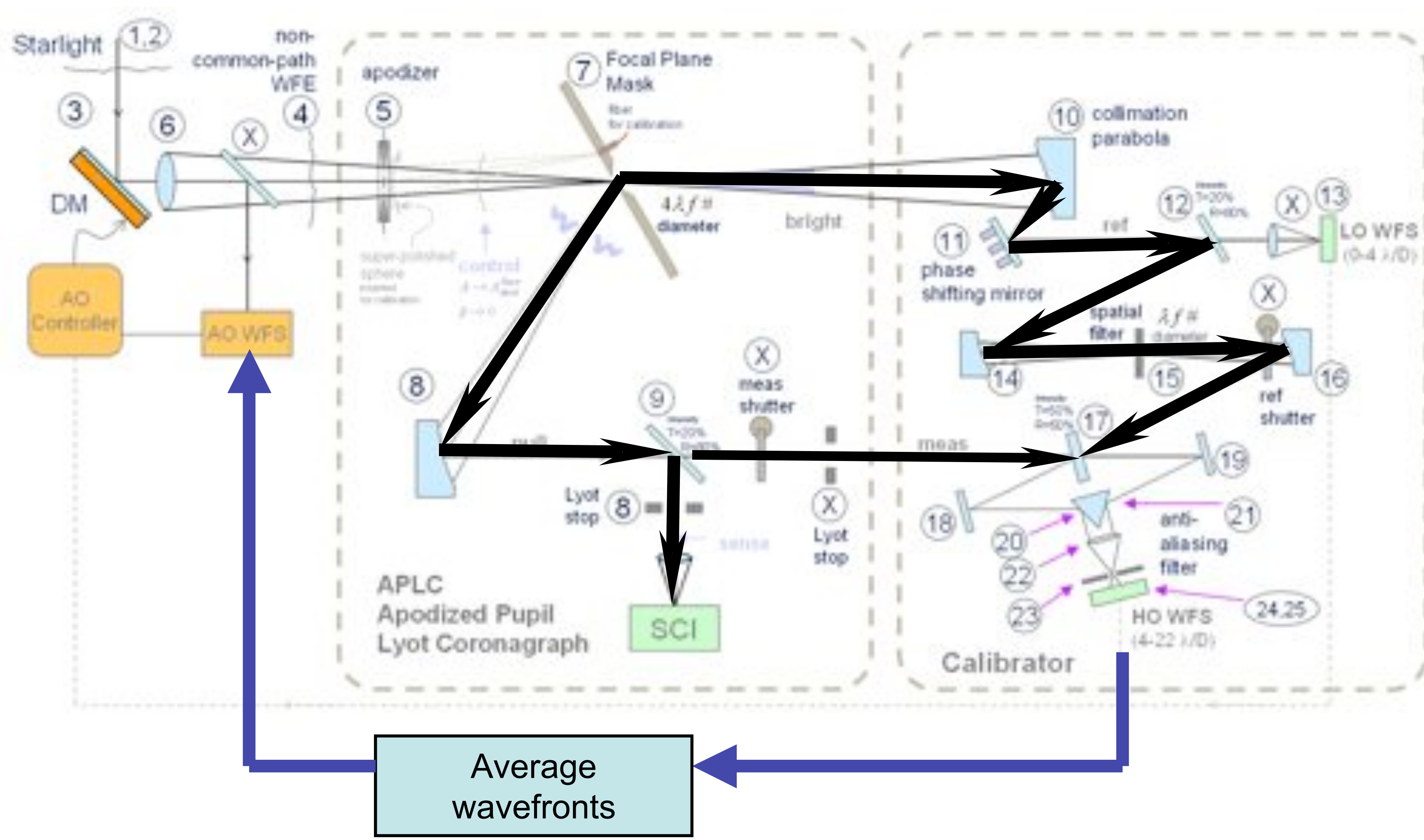


- *H*-band optimized
  - Additional mask for *Z, J, & K*
- Achromatic
  - Contrast < 10^{-7} for 1.5-1.8μm
- Inner working angle 0.2 arc sec



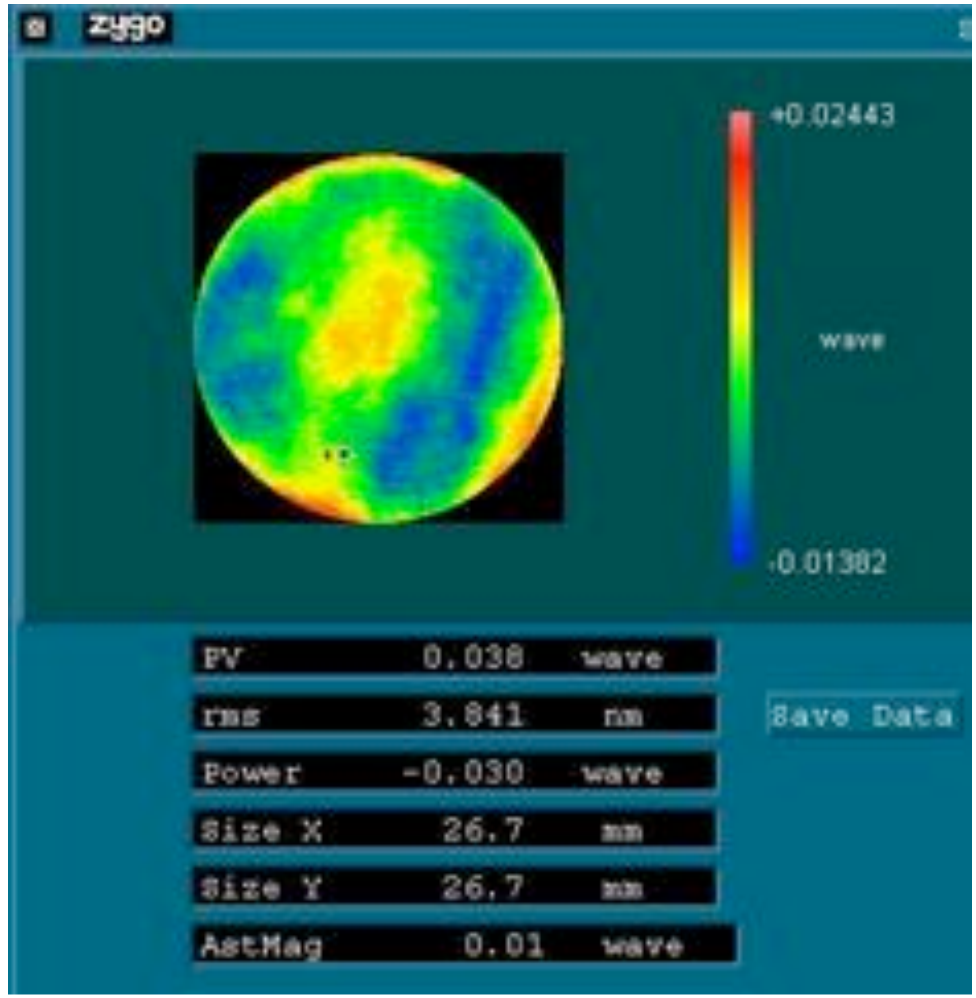
Boston MicroMachines MEMS deformable mirror

Interferometer Measures Science Wavefront



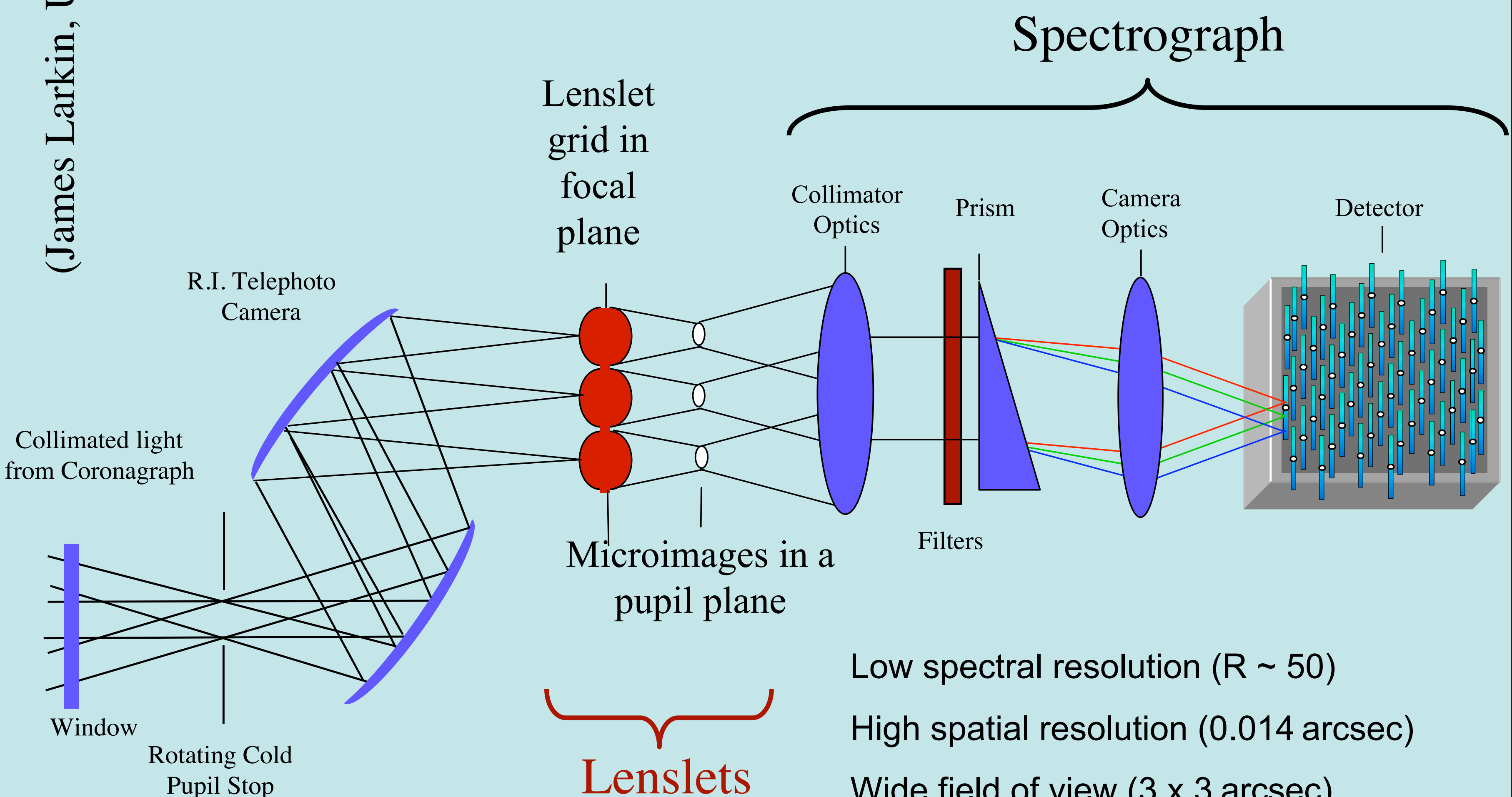
Chromaticity & scintillation

- Integral field spectrograph minimizes differential chromatic errors
- Super polished optics minimize internal beam-walk and Fresnel effects (4 nm RMS, 1 nm RMS mid frequency)
- Optics maintained to clean room 300 standards
- Transmissive optics minimized
- Atmospheric dispersion corrected early in the system



(James Larkin, UCLA)

Integral field spectrograph

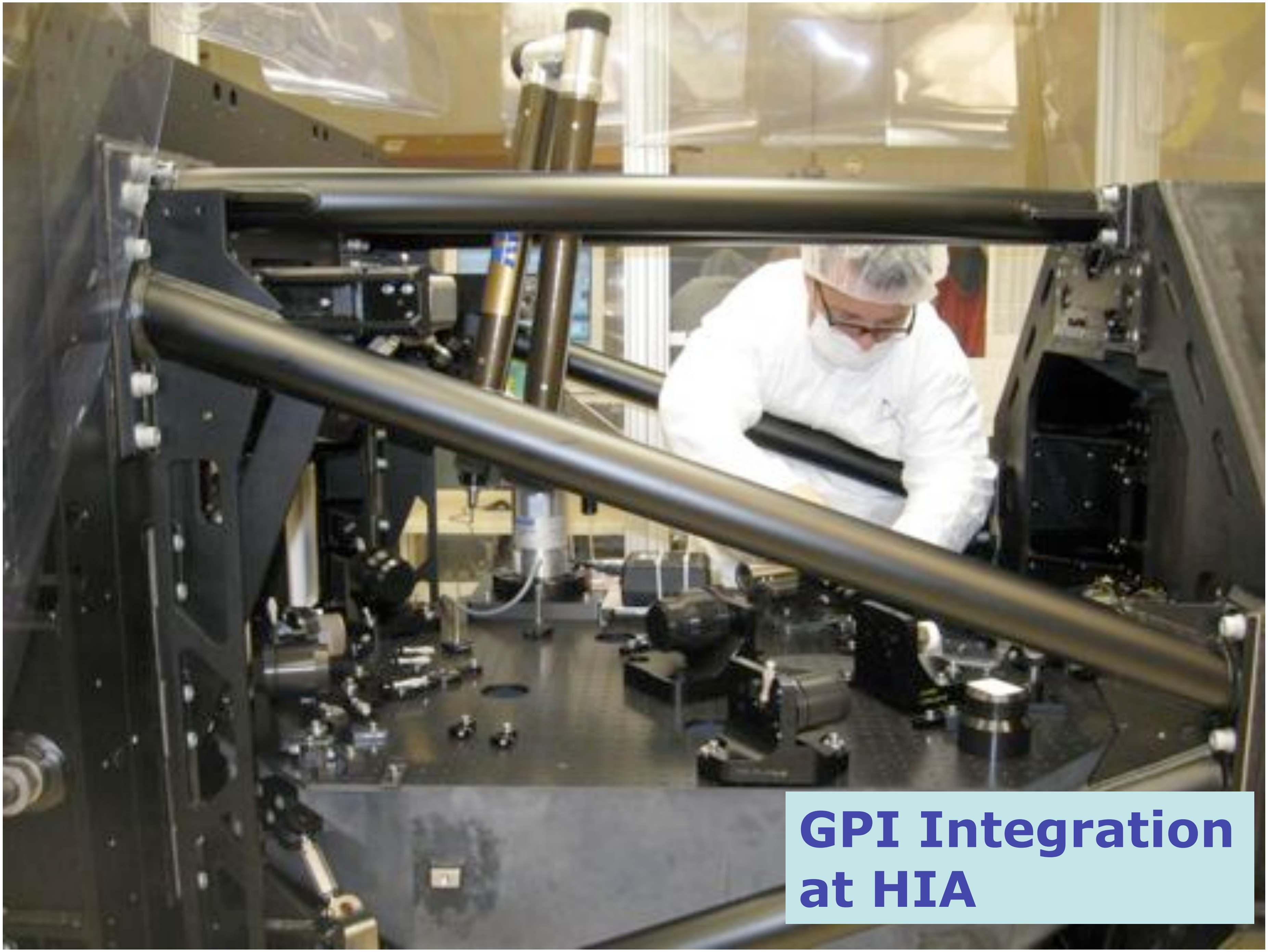


Low spectral resolution (R ~ 50)

High spatial resolution (0.014 arcsec)

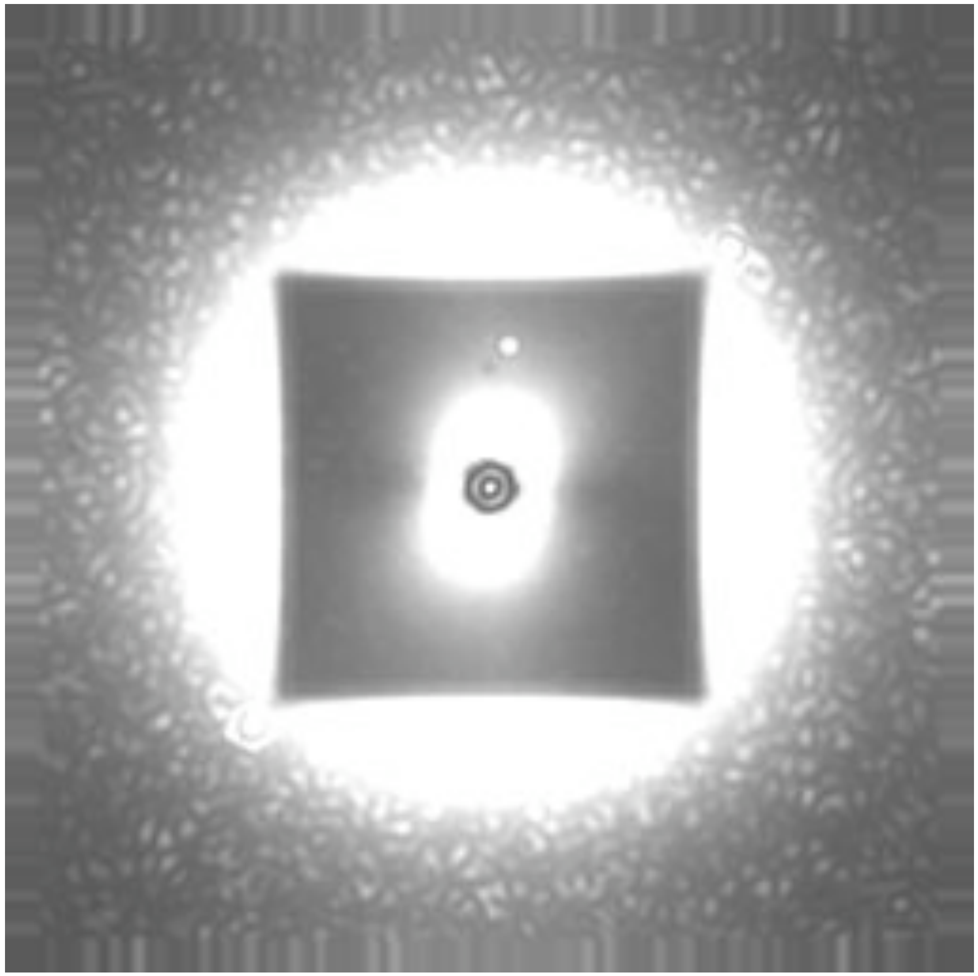
Wide field of view (3 x 3 arcsec)

Minimal scattered light

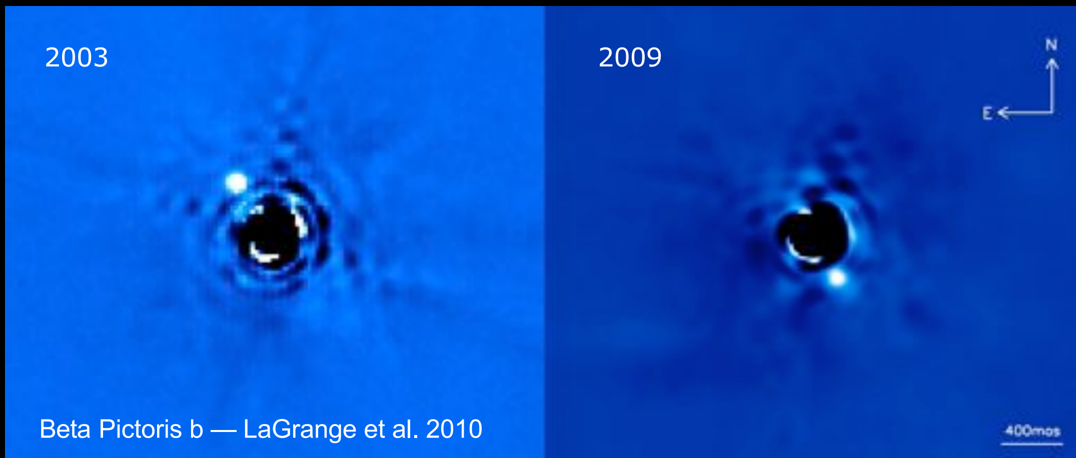


GPI Integration at HIA

Full Fresnel simulation

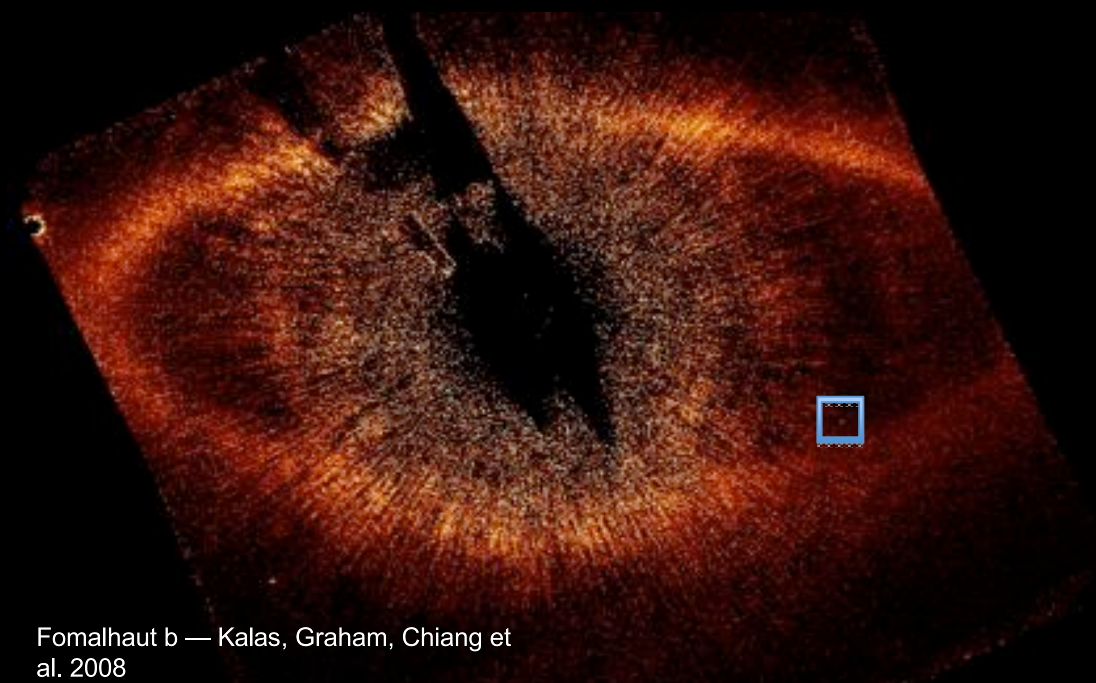


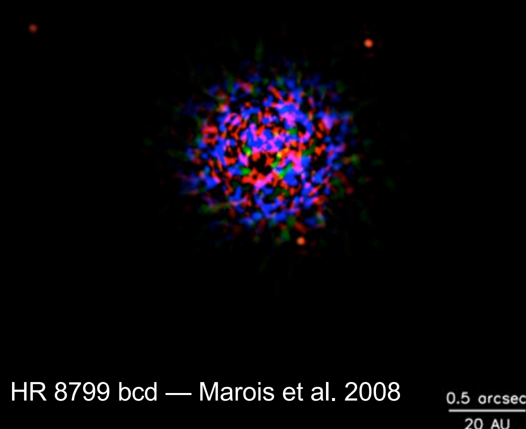
Christian Marois, HIA



Beta Pictoris b — LaGrange et al. 2010


1RXS J160929.1-210524
Jayawardana et al 2008


Fomalhaut b — Kalas, Graham, Chiang et al. 2008



HR 8799 bcd — Marois et al. 2008

Thirty Meter Telescope