High Contrast Imaging

James R. Graham

UC Berkeley

KITP, March 30, 2010

Outline

- High contrast imaging for planet detection
  - Science motivation
- The two problems
  - Diffraction
  - Speckle noise
- Solutions
  - Coronagraphs & apodization
  - Wavefront control
  - Experimental methods
- State of the art and the future

Thanks to:

- M. Fitzgerald
- O. Guyon (HiCIAO/PICO)
- S. Hinkley (1640)
- P. Kalas
- M. Liu (NICI)
- B. Macintosh (GPI PI)
- M. Marley
- J. McBride
- D. Mouillet (SPHERE PS)
- B. Oppenheimer (1640)
- G. Serabyn
- M. Tamura (HiCIAO/SEEDS)

Recent Reviews

- B. Oppenheimer & S. Hinkley, (2009) "High-Contrast Observations in Optical and Infrared Astronomy" AARA, 47, 253
- W. Traub & B. Oppenheimer (2010) "Direct Imaging" in "Exoplanets" Ed. S. Seager, UofA press

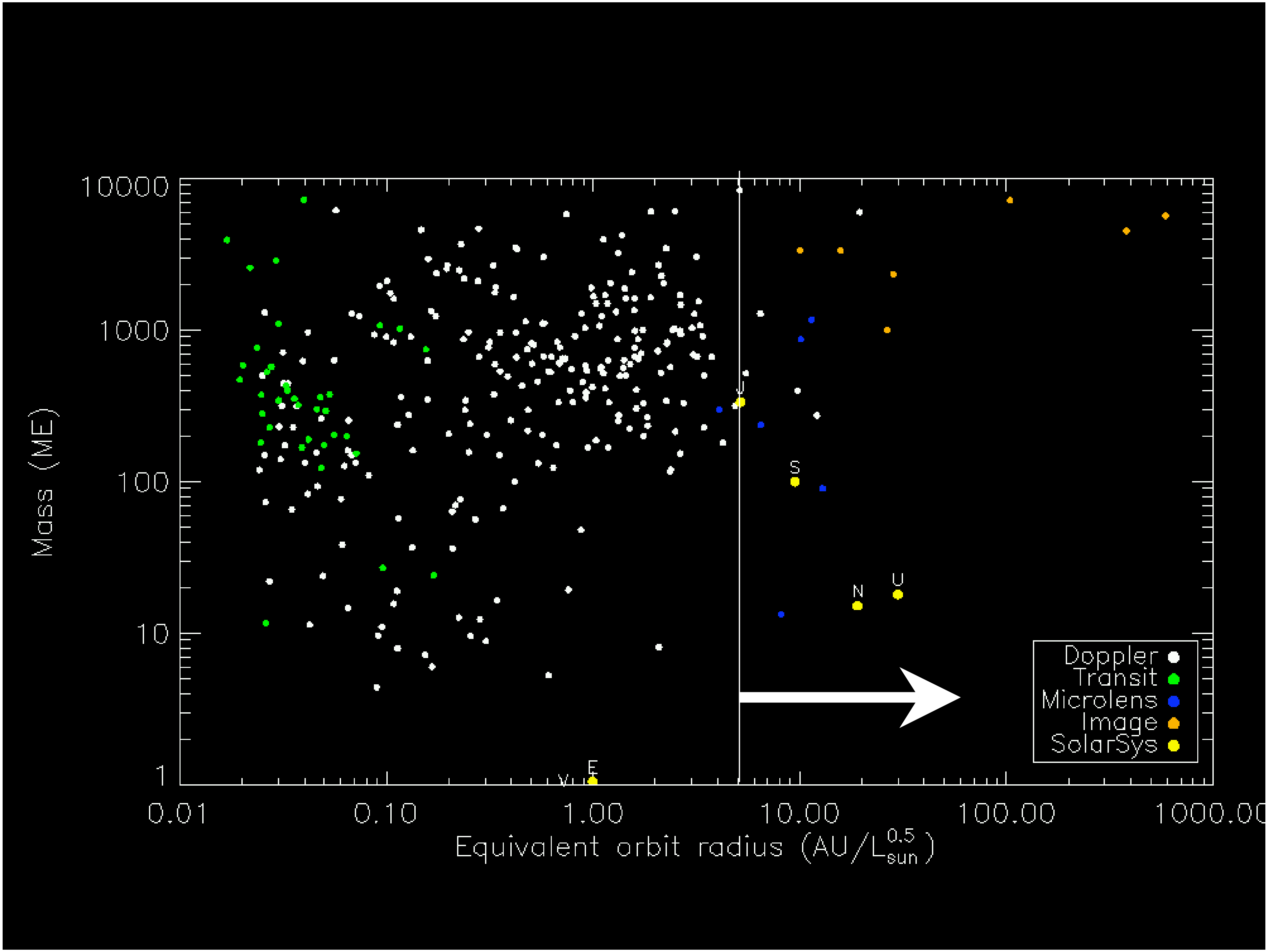
Science Motivation

Why High Contrast Imaging?

- Exoplanet detection
  - Direct methods to explore beyond 5 AU
  - Spectroscopy of exoplanetary light
    - Thermal history & composition
- Circumstellar disks
  - Proto-planetary & debris disks
  - Relationship between planets & disk structures
- Fundamental stellar astrophysics
  - Large mass range main sequence binaries
    - Brown dwarfs & white dwarfs
- Mass transfer & loss
  - Cataclysmic variables, symbiotic stars & supergiants
- Solar system:
  - Jovian & Saturnian moons
  - Binary asteroids

Exoplanet Imaging

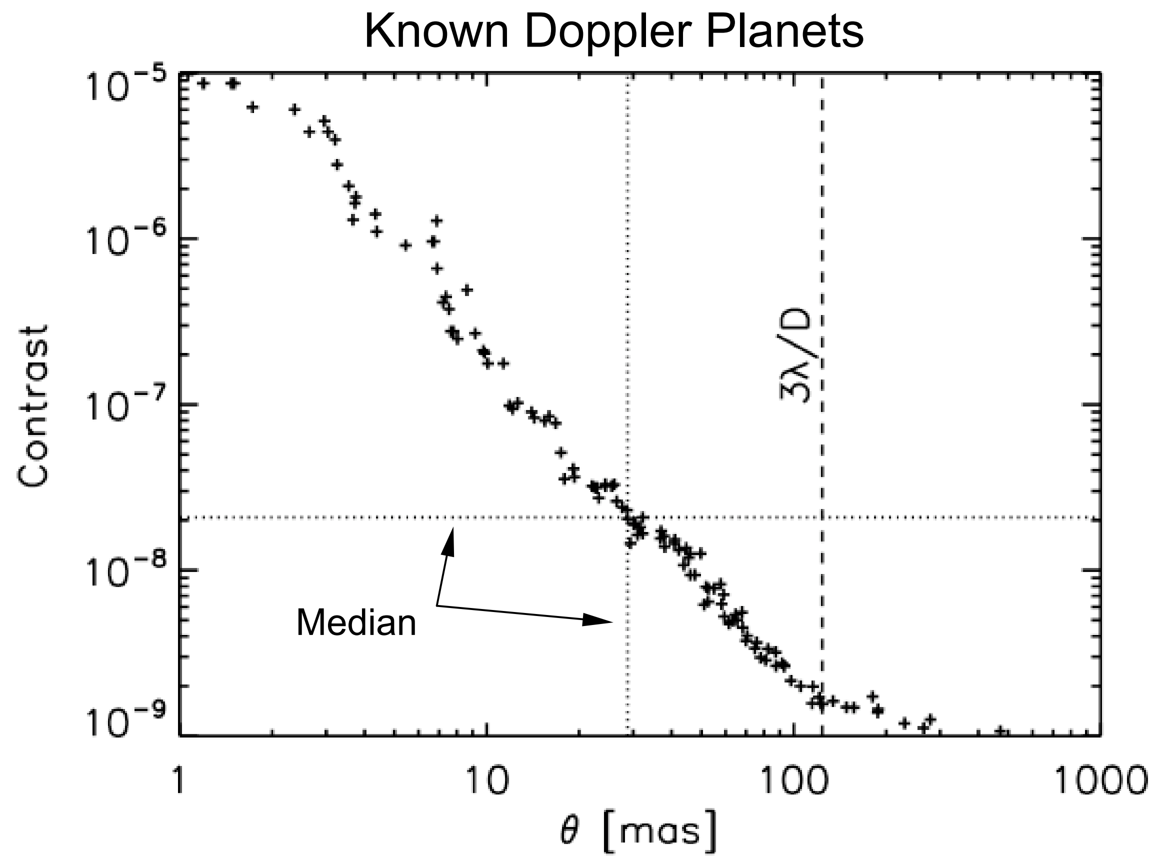
- Only about 5-10% of stars searched have planets
  - Why isn't it 50%?
- A diversity of exoplanets…
  - ≤ 20% of the Solar System's orbital phase space explored
  - Is the Solar System typical?
- Do A & early F stars have planets? M dwarfs?
  - Doppler is not ideal for early type stars
  - Photometric methods are not ideal for active stars
- How do planets form?
  - Core accretion vs. gravitational collapse
- New questions
  - What is the origin of dynamical diversity?


Mass (ME)
10000
1000
100
10
1
0.01
0.10
1.00
10.00
100.00
1000.00
Equivalent orbit radius ($AU/L_{sun}^{0.5}$)
J
S
N
U
V
E
Doppler
Transit
Microlens
Image
SolarSys


Druckmuller http://apod.nasa.gov

Reflected Starlight?

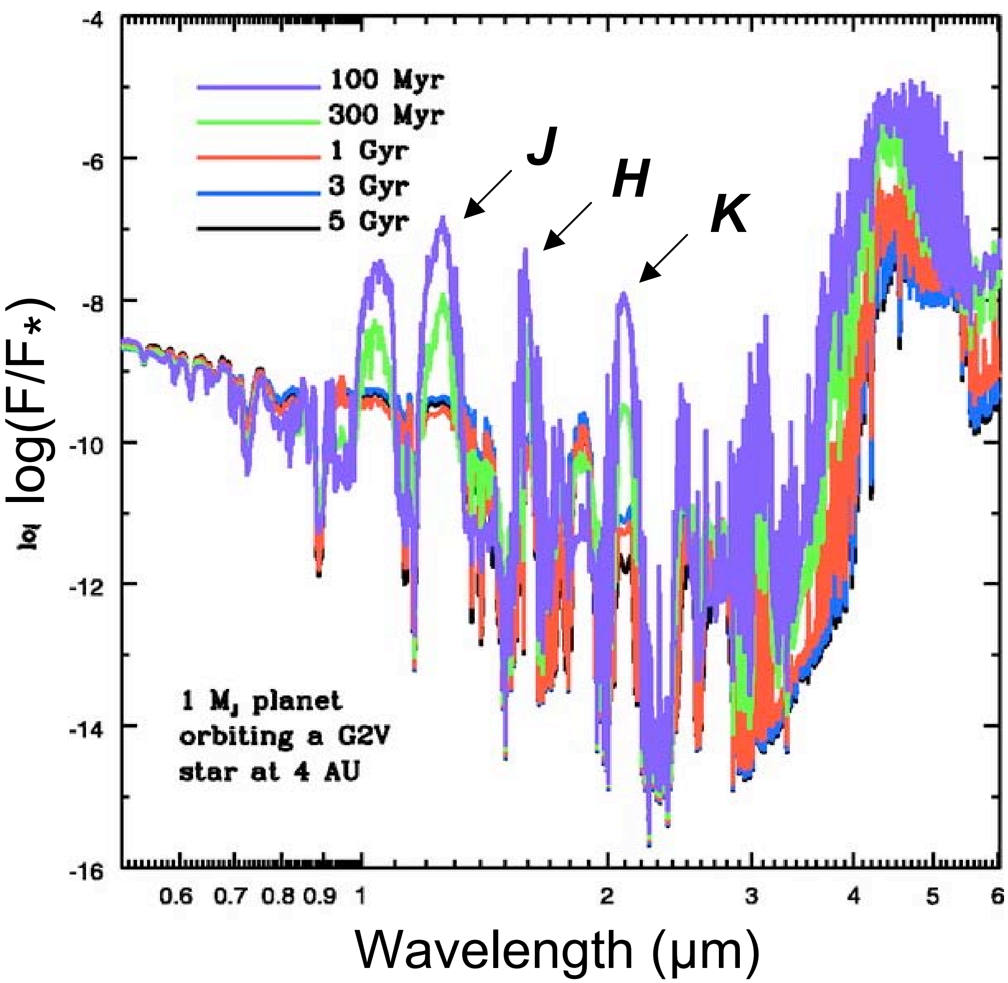
- Median contrast & angular separation for cataloged Doppler planets
  - 2×10^{-8}
  - 30 mas cf. $3\lambda/D$ = 130 mas @ H
- $1/r^2$ dimming of reflected light renders visible light coronagraphs insensitive to planets in Neptune orbits



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

Detection of Cooling Planets

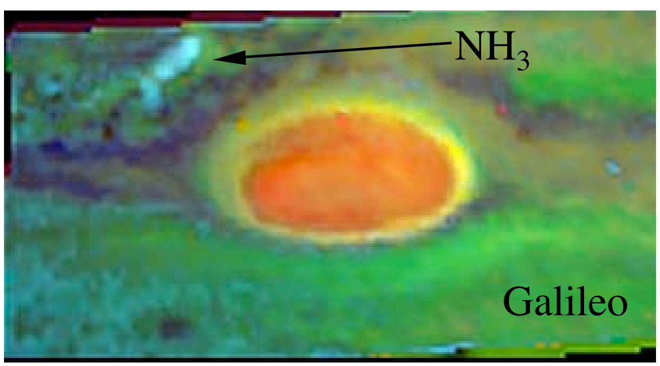
- Contrast required to detect an exo-Jupiter in a 5 AU orbit in the visible is 2×10^{-9}
- Near-IR contrast is 2-3 orders of magnitude more favorable
  - Radiation escapes in gaps in the CH_4 and H_2O opacity at *Y*, *J*, *H*, & *K*

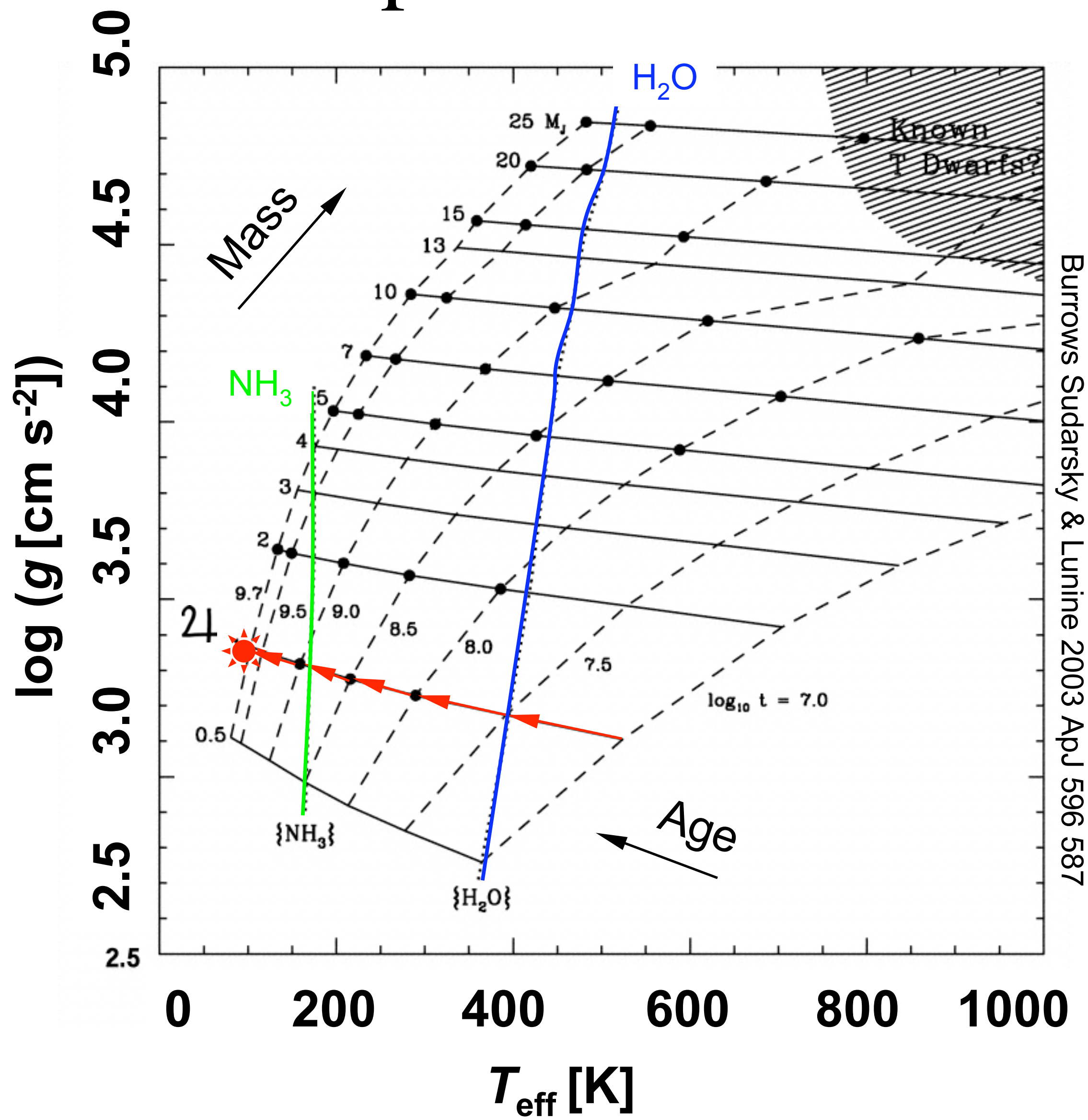


Burrows Sudarsky & Hubeny 2004 ApJ 609 407

Exoplanet Atmospheres

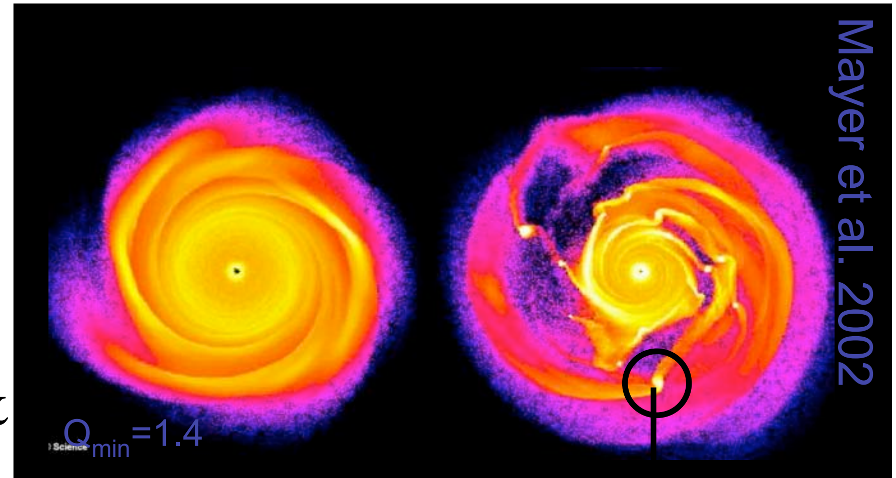
- Exoplanets occupy a unique location in ($\log g, T_{\mathrm{eff}}$) phase space
  - Over 4.5 Gyr a Jovian mass exoplanet traverses the locus of H_2O & NH_3 cloud condensation
- "Last frontier" of classical stellar atmospheres

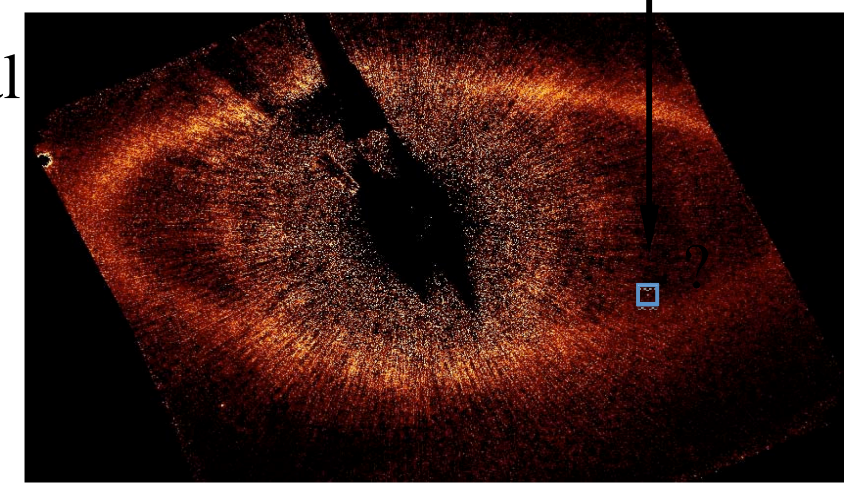




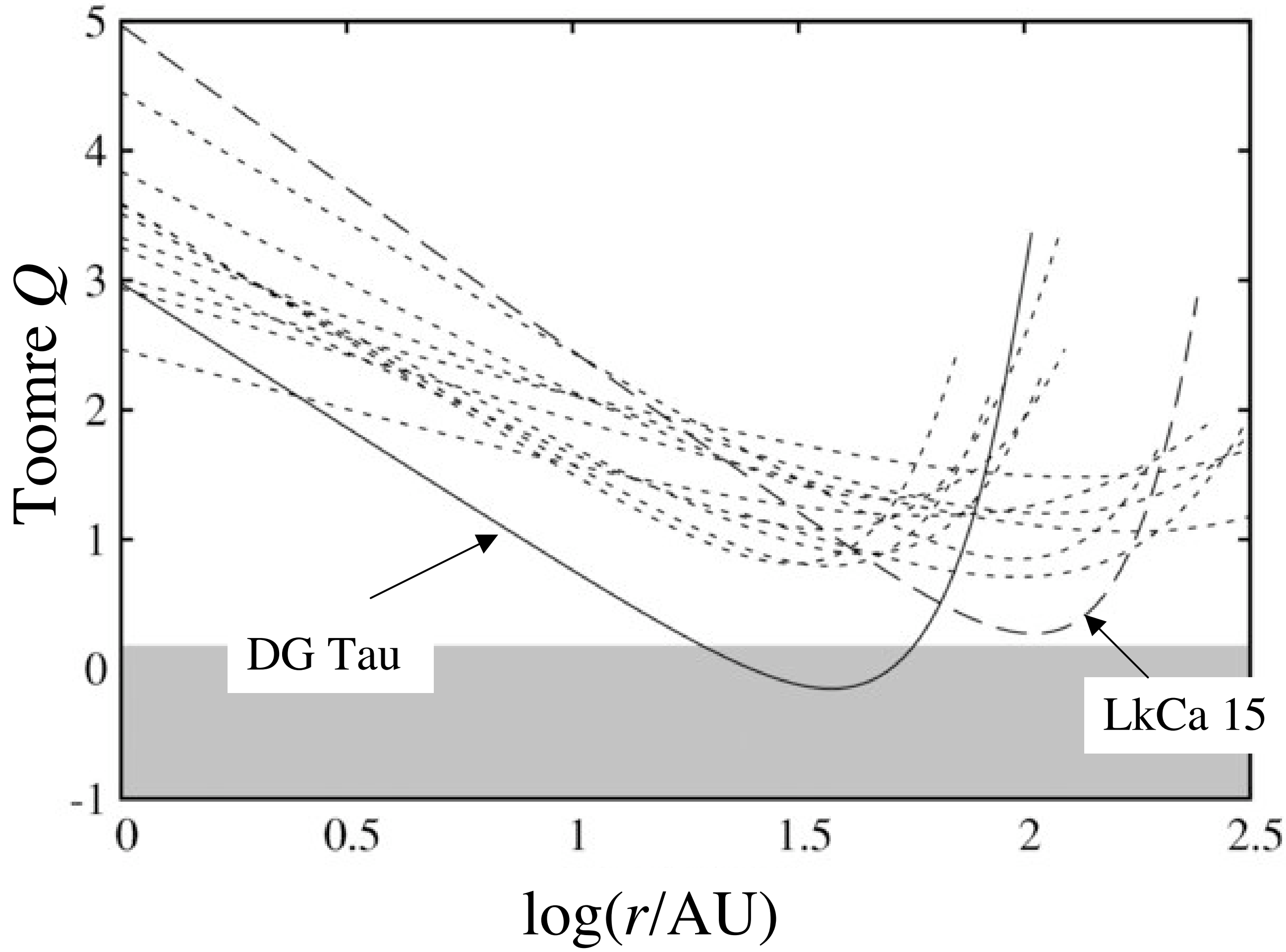
Solar System Imaging

- Fast alternative
  - 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
    - T Tauri 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





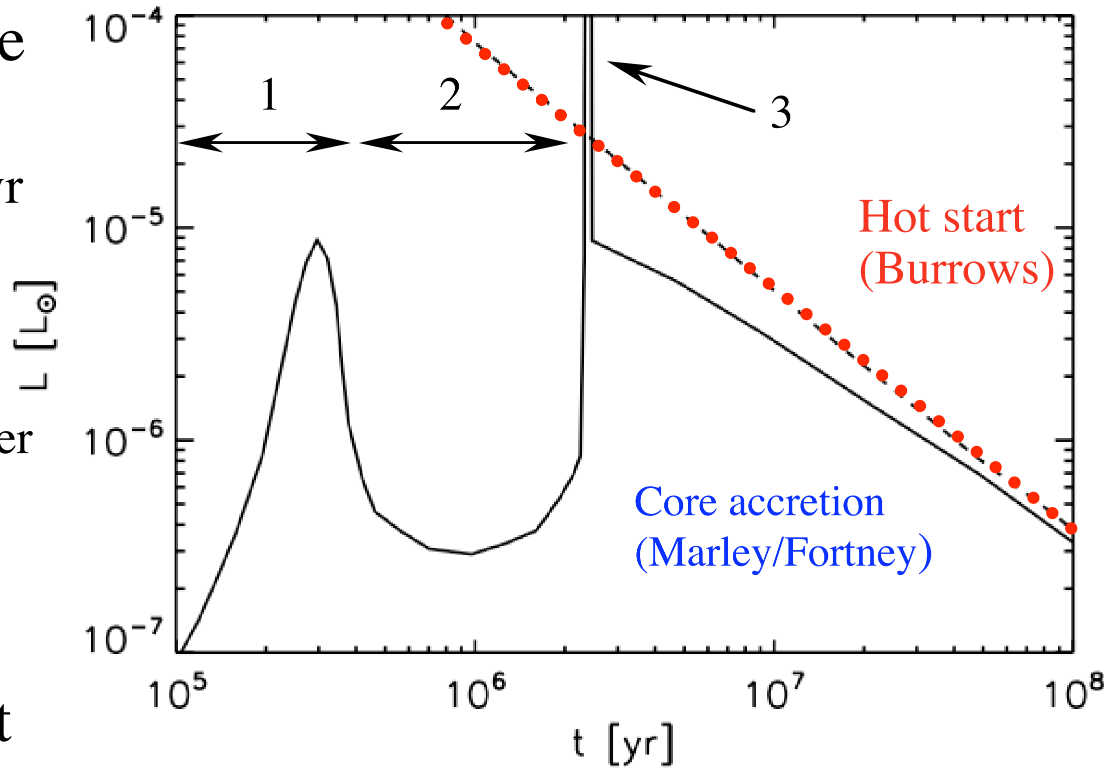
Are Circumstellar Disks Unstable?



CARMA/Isella et al. 2009

Thermal Evolution Reveals History

- Luminosity including the effects of core accretion
  - Planet is formed by 2 Myr
  - The gas accretion luminosity spike lasts about 0.04 Myr
    - The spike may be broader & dimmer due to slow accretion across the gap formed by the proto-planet
- The dashed line is a "hot start" cooling track



1) Accretion of solids

2) Hydrodynamic (gas) accretion

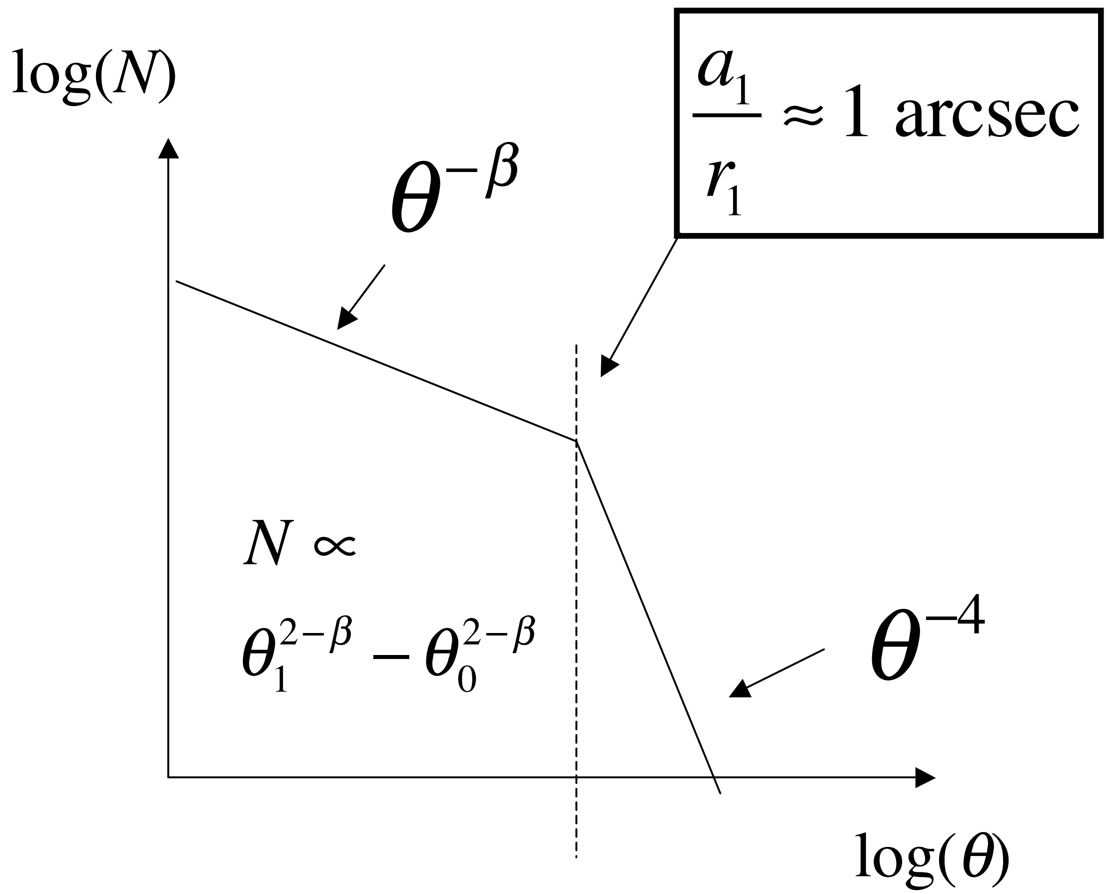
3) Runaway gas accretion

Where are the planets?

- Assuming a semimajor axis distribution, d*N*/d*a* (from Doppler) & a Euclidean space distribution d*N*/d*r* –

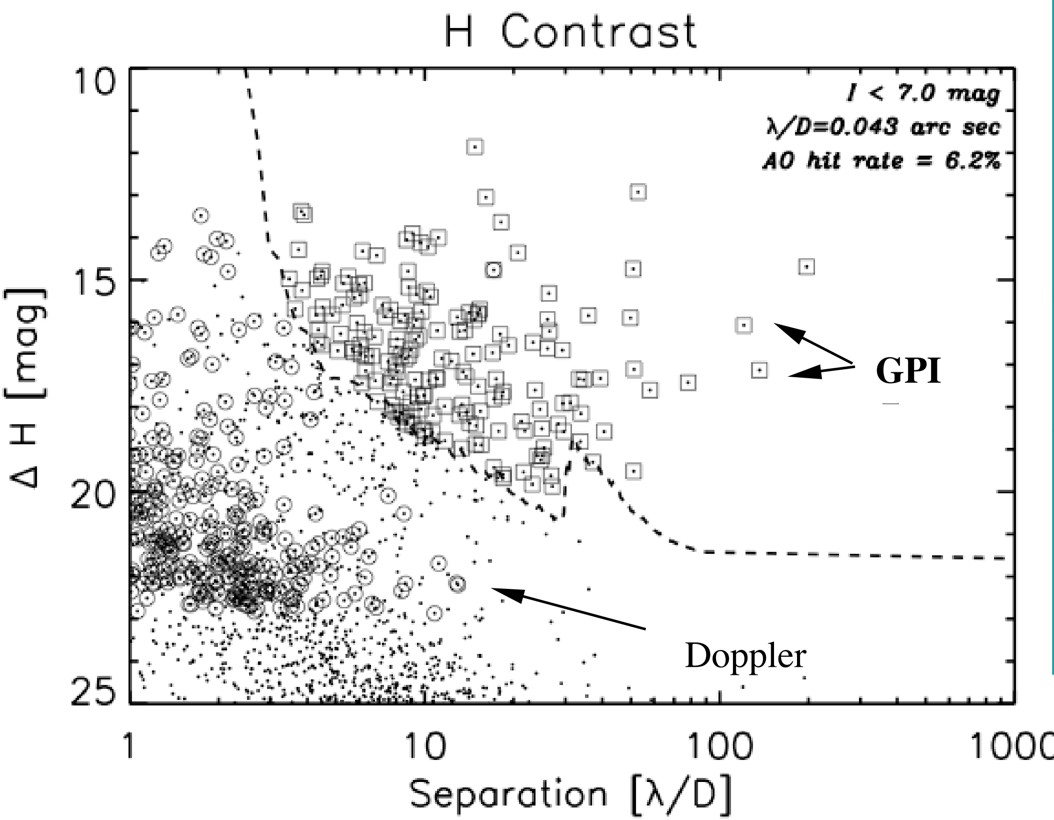
$$\frac{dN}{da} \propto a^{-\beta} \quad 0 < a < a_1$$

$$\frac{dN}{dr} \propto 4\pi r^2 \quad 0 < r < r_1$$



A Simple Example

- 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)

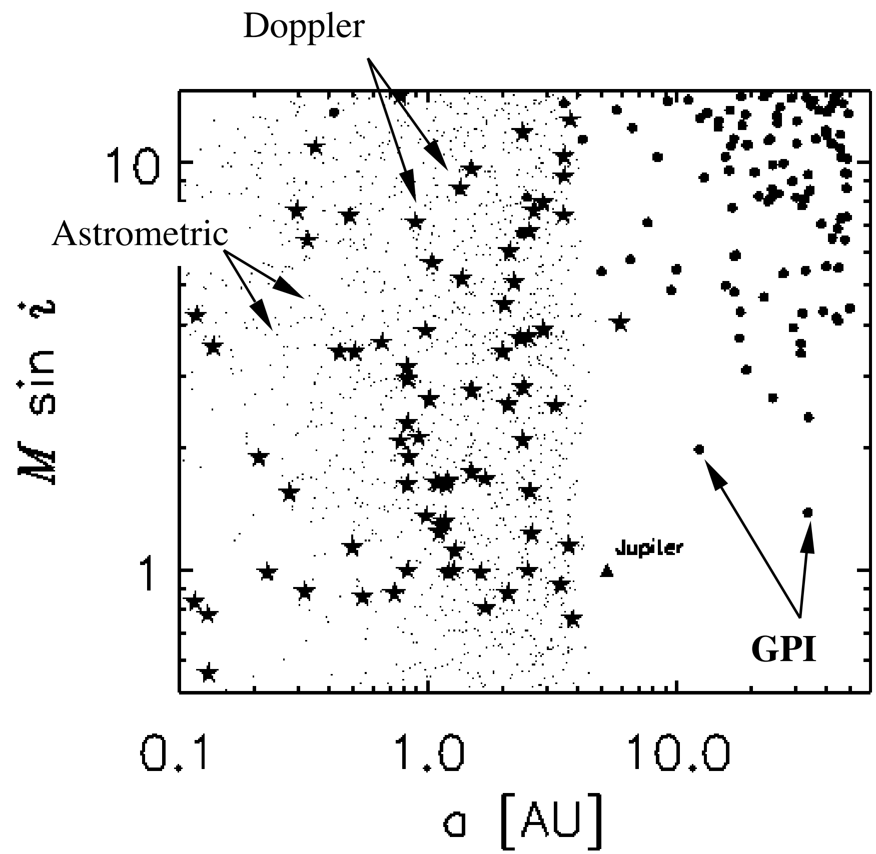


Graham et al. arXiv:0704.1454

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

A Simple Example

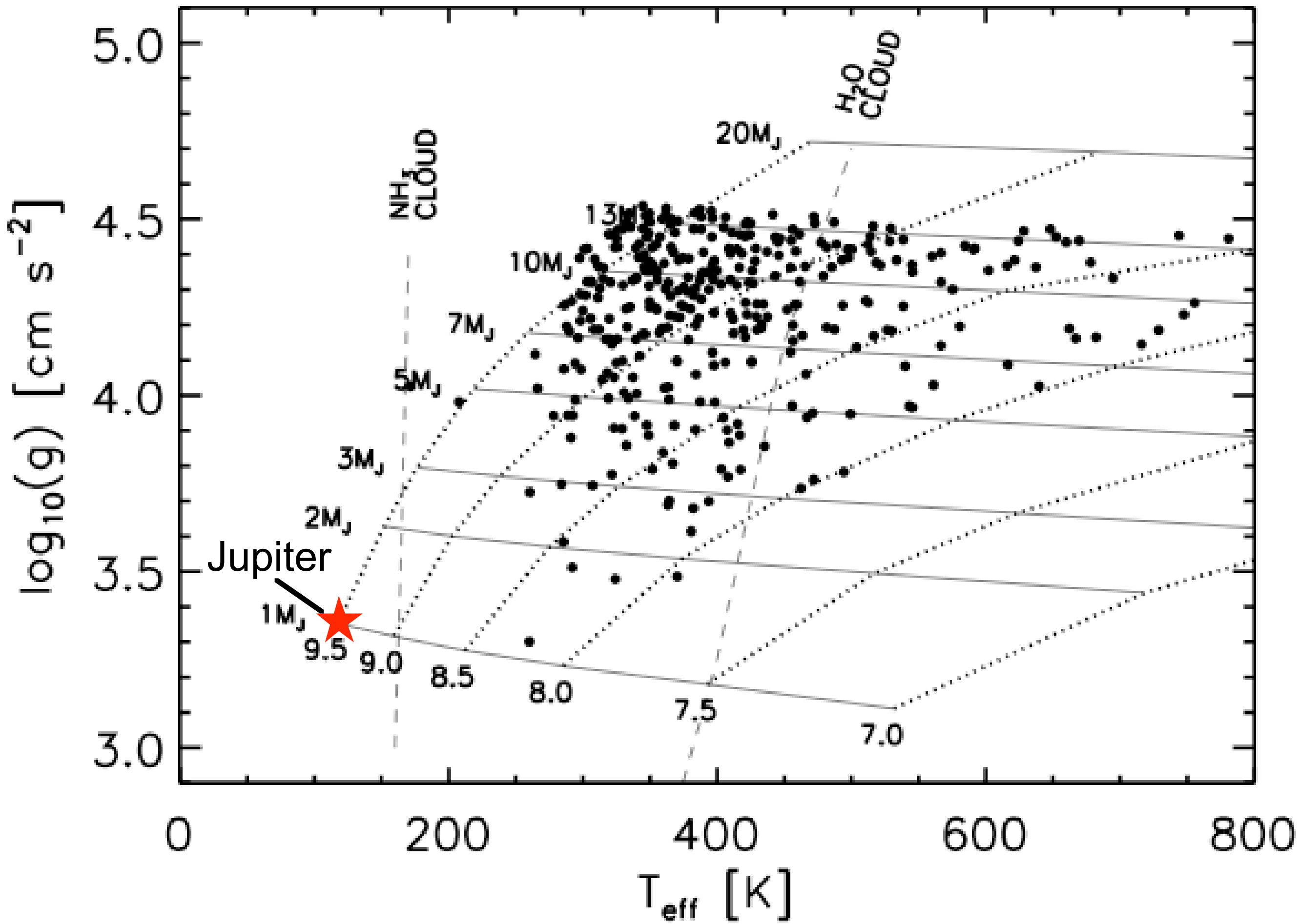
- AO
  - $r_0 = 100$ cm
  - 2.5 kHz update rate
  - 13 cm sub-apertures
    - $R = 7$ mag. limit
- Coronagraph
  - Ideal apodization
- Science camera
  - Broad band H
  - No speckle suppression
- Target sample
  - $R < 7$ mag.
  - 1703 field stars (< 50 pc)



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

Graham et al. arXiv:0704.1454

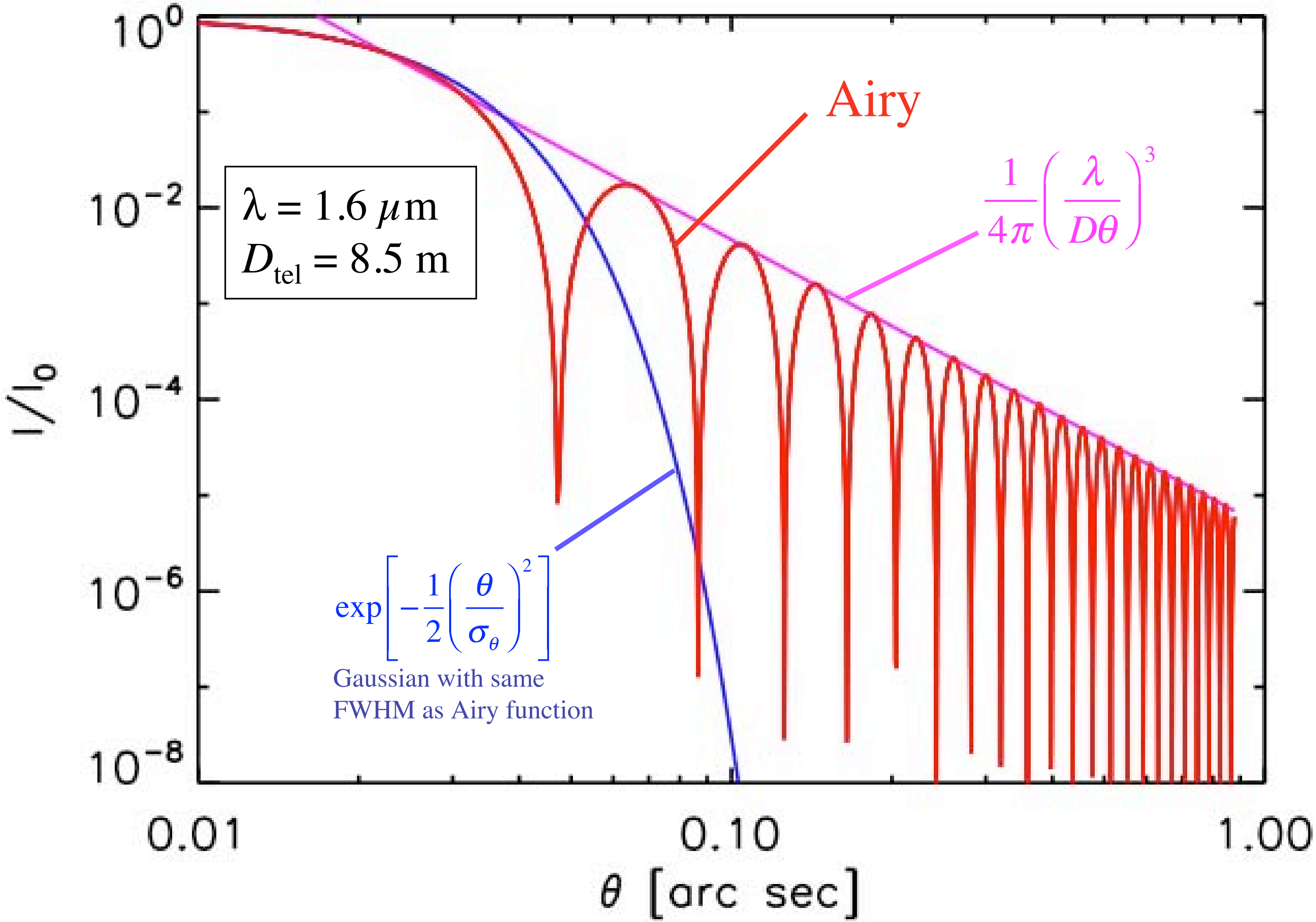
A Simple Example



Graham et al. arXiv:0704.1454

Diffraction & Wavefront Errors

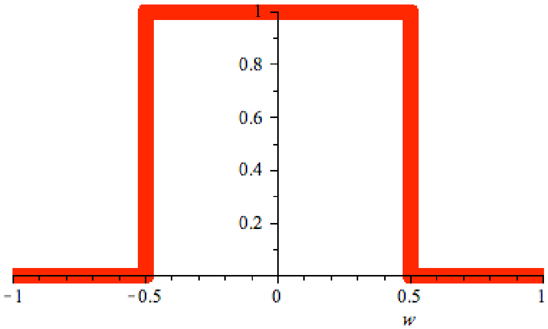
Diffraction-circular pupil



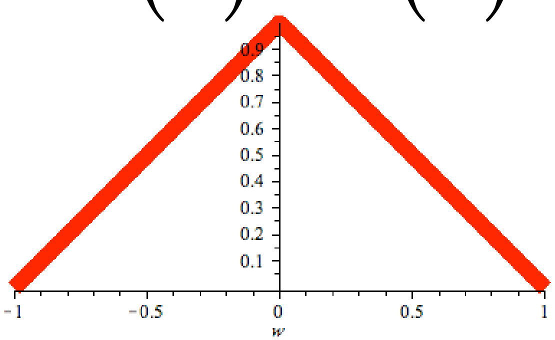
Diffraction

- The PSF drops off slowly with angle for a hard edged pupil
  - Airy function declines as θ^{-3} at large θ
- Basic consequence of Fourier optics
  - The smoother the pupil function, the more compact the PSF
- If a function & its first n-1 derivatives are continuous, its Fourier transform decreases at least as rapidly as $1/k^{(n+1)}$ at large k
  - The top hat function $\Pi(x)$ is discontinuous ($n = 0$),
    - $FT[\Pi(x)] = \mathrm{sinc}(k) \rightarrow 1/k$ as $k >> 1$
  - The triangle $\Lambda(x) = \Pi(x) * \Pi(x)$ is continuous, but its first derivative is discontinuous (n=1)
    - $FT[\Lambda(x)]=\mathrm{sinc}^2(k) \rightarrow 1/k^2$ as $k >>1$

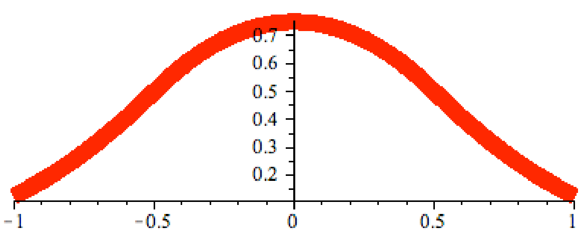
$$\Pi(x)$$

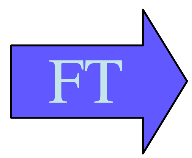


$$\Pi(x) * \Pi(x)$$

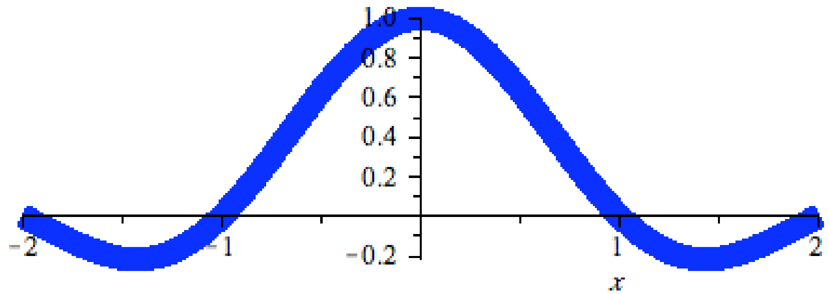


$$\Pi(x) * \Pi(x) * \Pi(x)$$

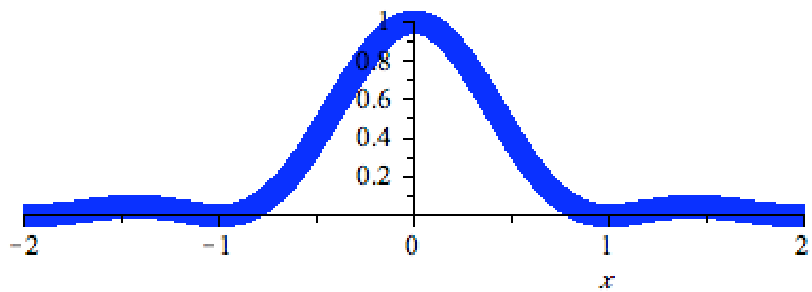




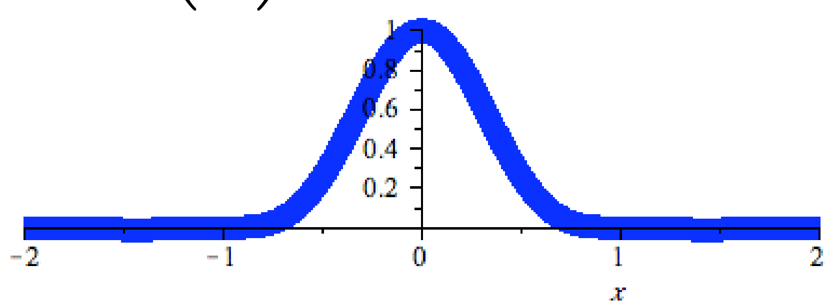
$$\mathrm{sinc}(k) \sim k^{-1} \quad k \to \infty$$



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



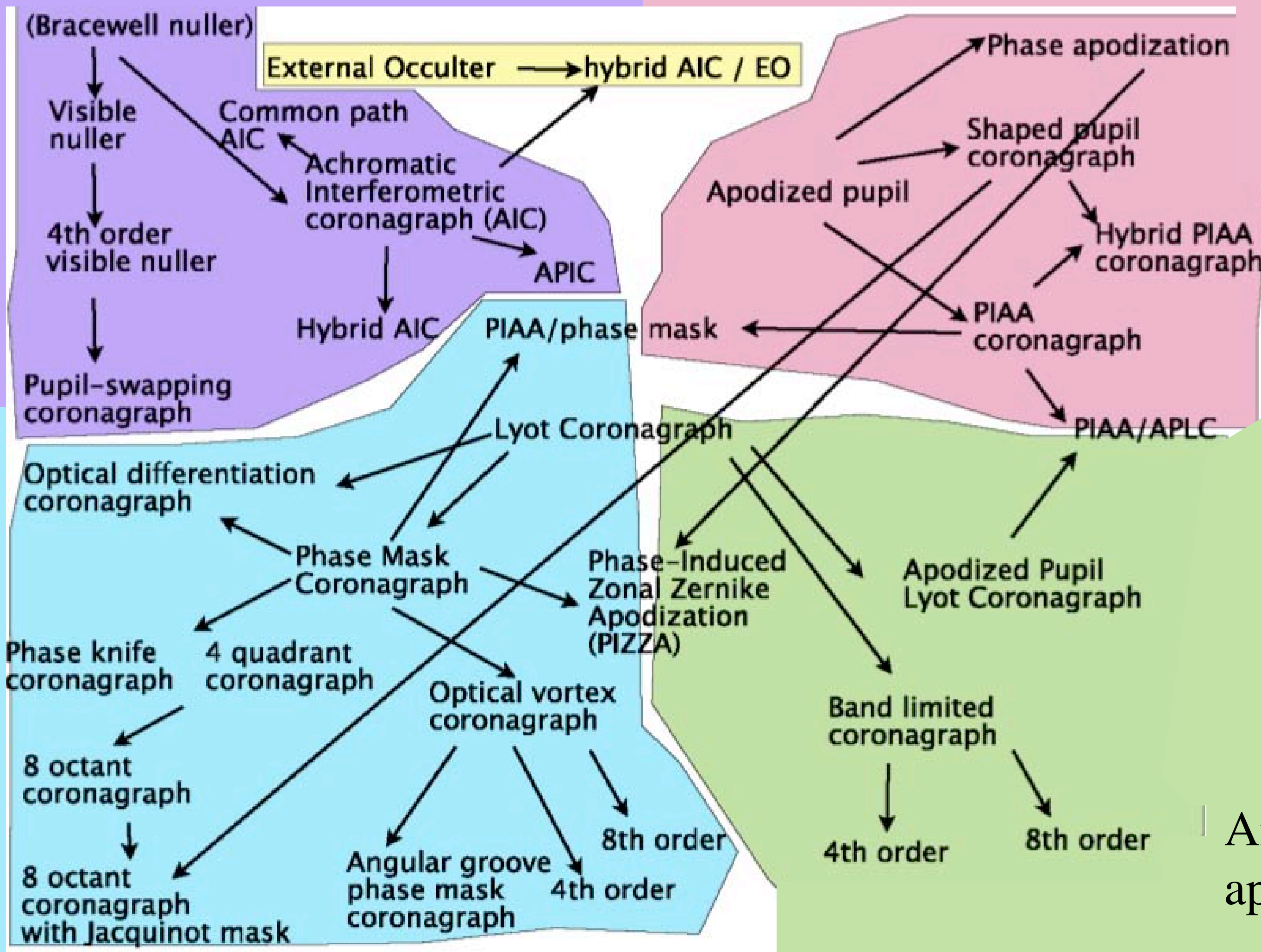
$$\mathrm{sinc}^3(k) \sim k^{-3} \quad k \to \infty$$



Coronagraph Land

Nullers

Pupil apodization



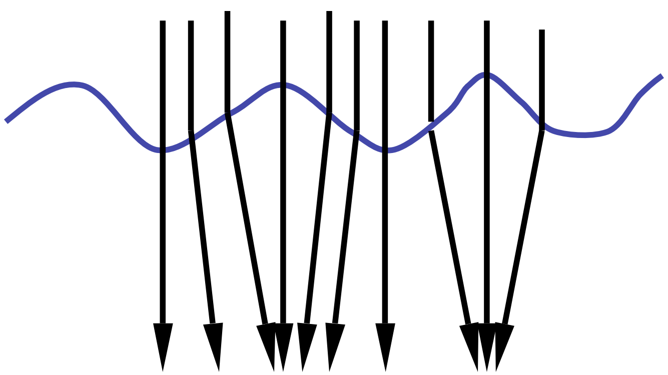
Amplitude apodization

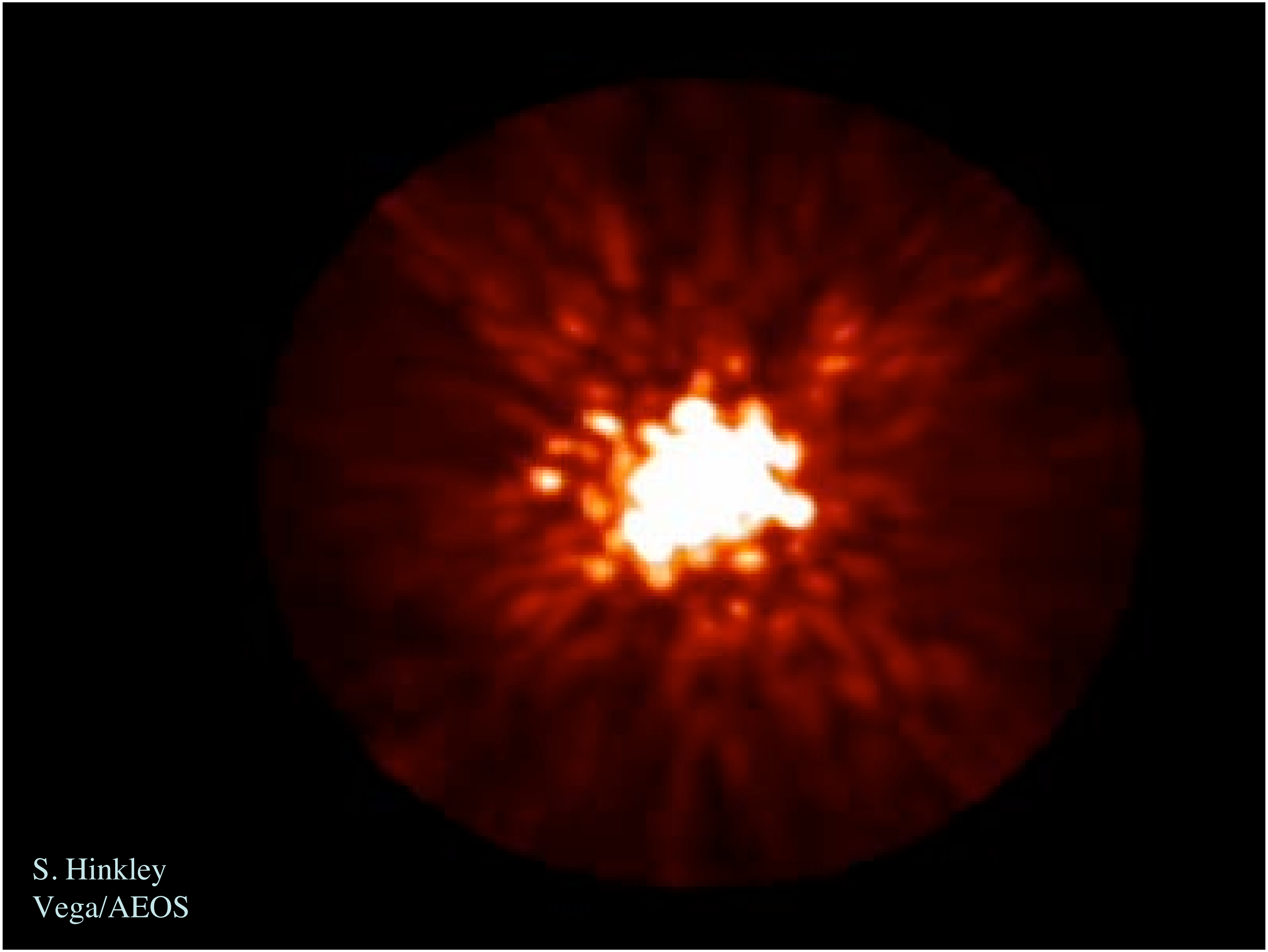
Focal plane phase masks

Guyon 2009 “Exoplanets & Disks”

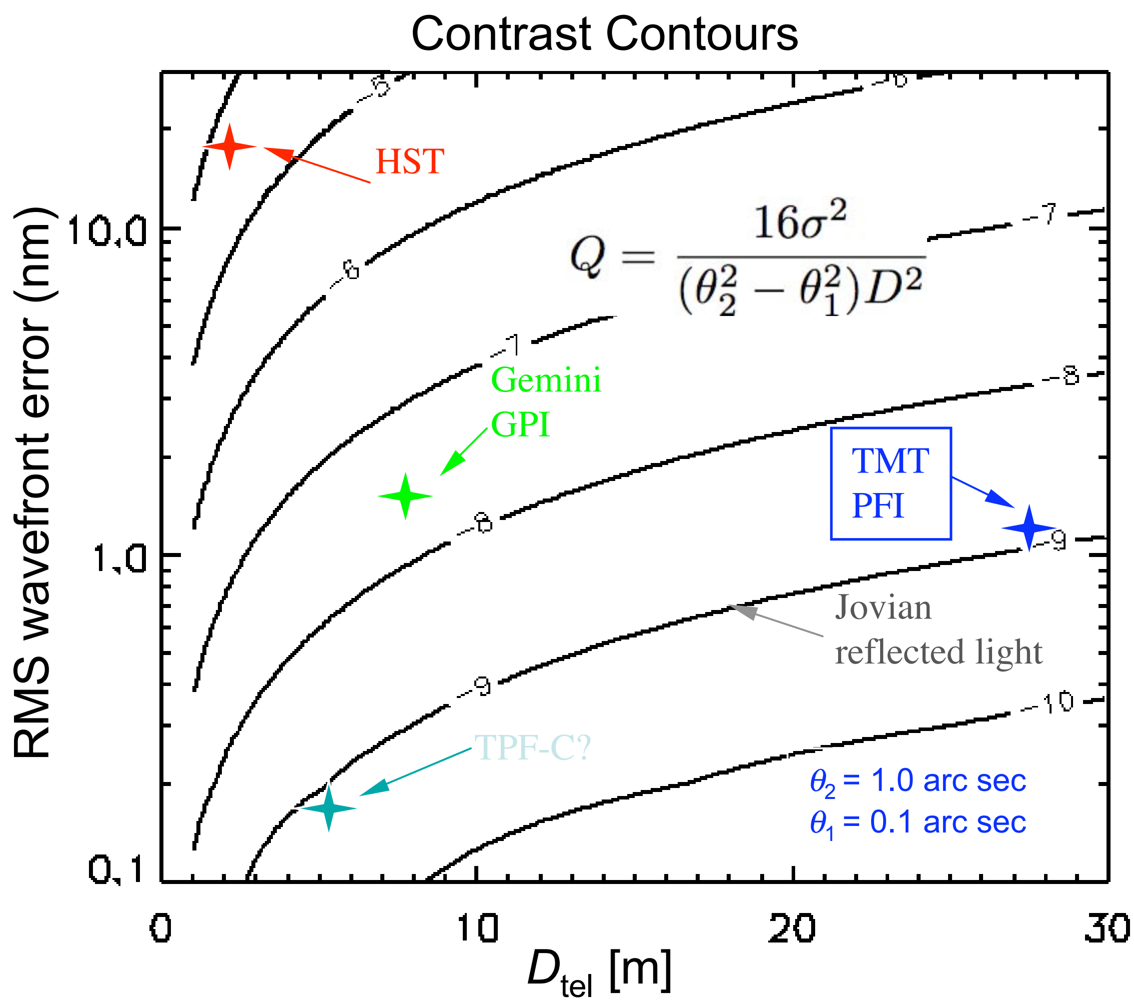
Wavefront errors

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




S. Hinkley
Vega/AEOS

Wavefront errors



Sivaramakrishnan et al. 2002

Dynamic & Static Phase Errors

Sivaramakrishnan et al 2002

Uncorrelated static & dynamic phase errors

$$p = \left| FT(A\Phi) \right|^2 \quad \text{where} \quad \Phi = \Phi_0 + \Phi(t)$$

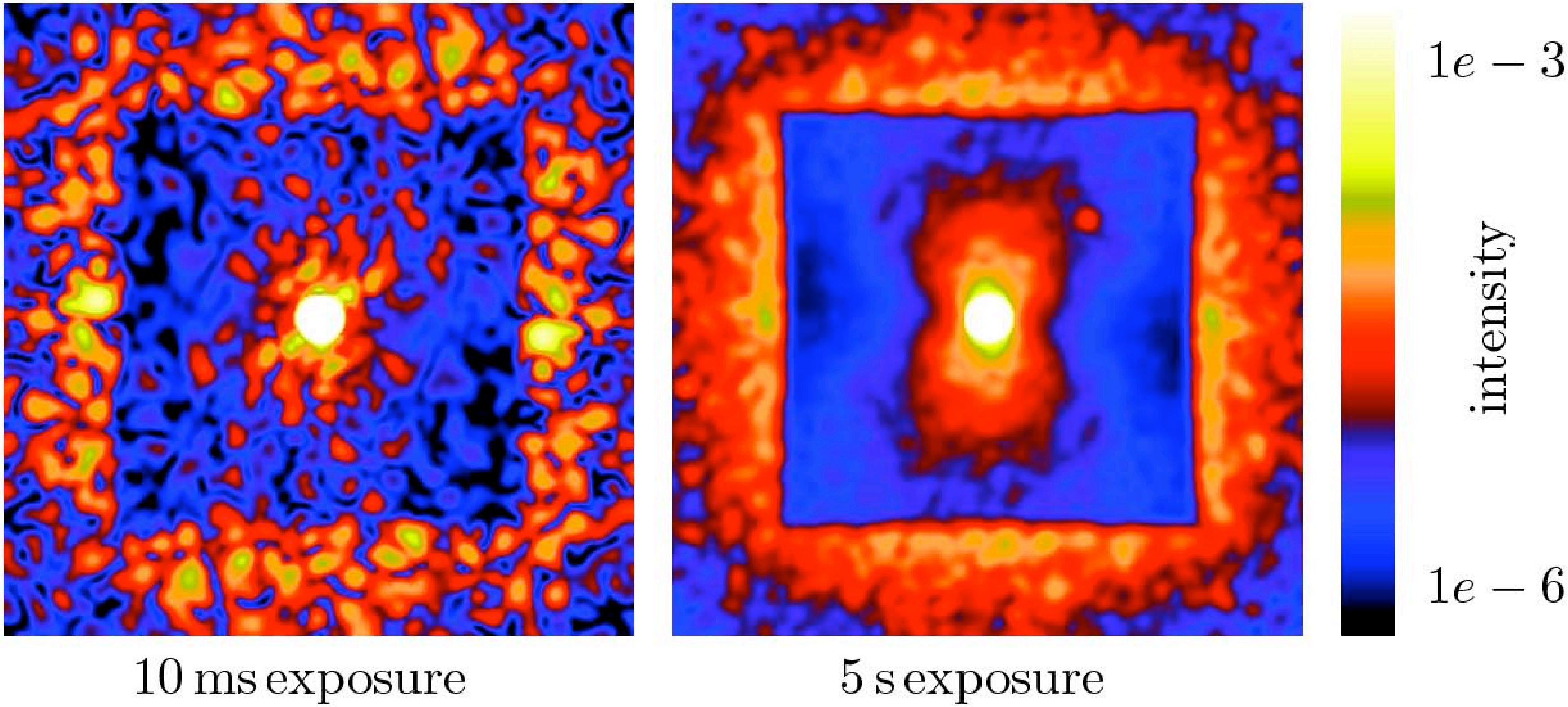
$$p = \left\langle \left| FT(A\Phi(t)) \right|^2 \right\rangle_t + \left| FT(A\Phi_0) \right|^2$$

Averages to a smooth "halo" over the decorrelation time

"Static" speckles

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

Atmospheric speckles smooth out

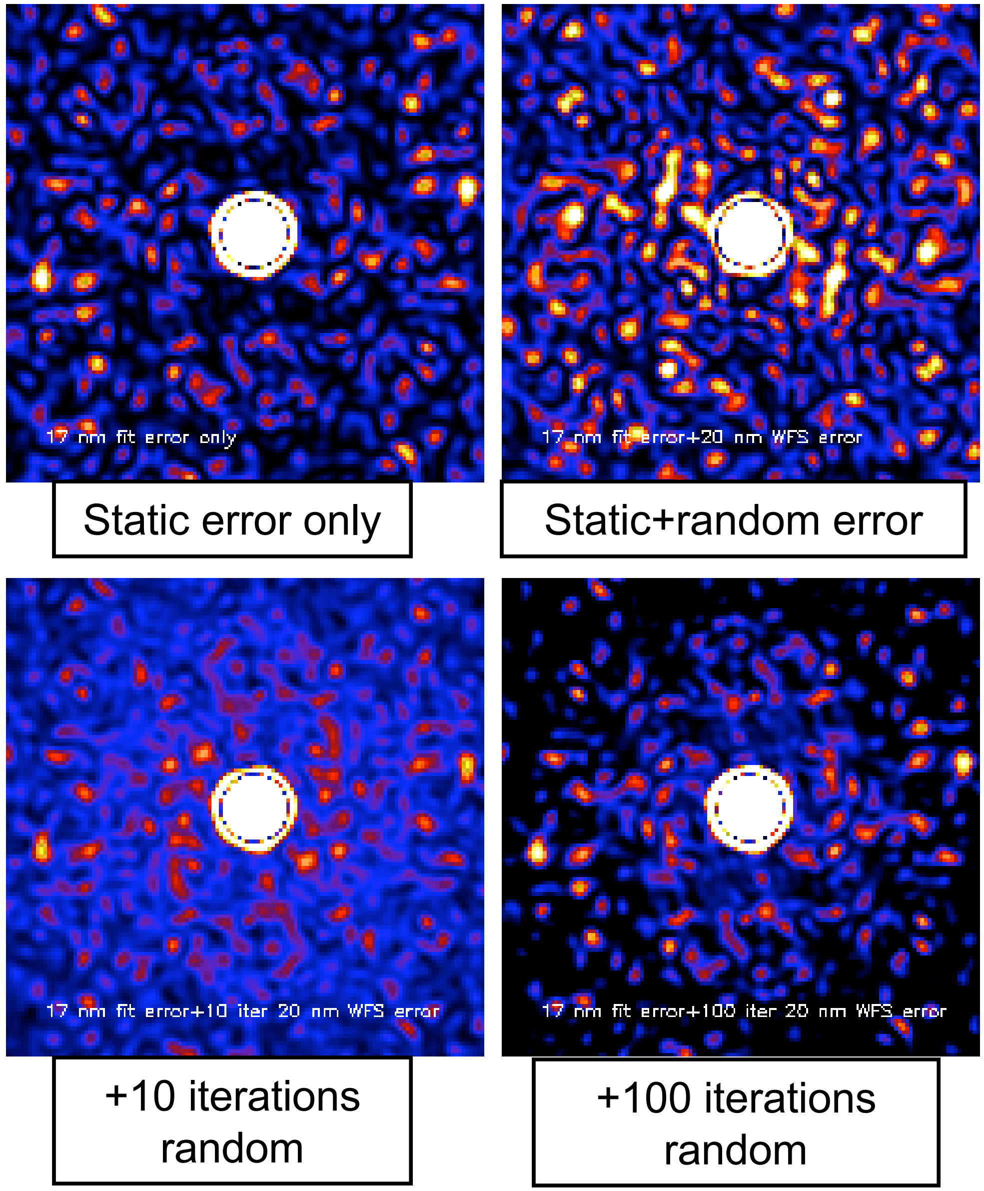


(Macintosh et al 2005 Proc. SPIE)

- 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

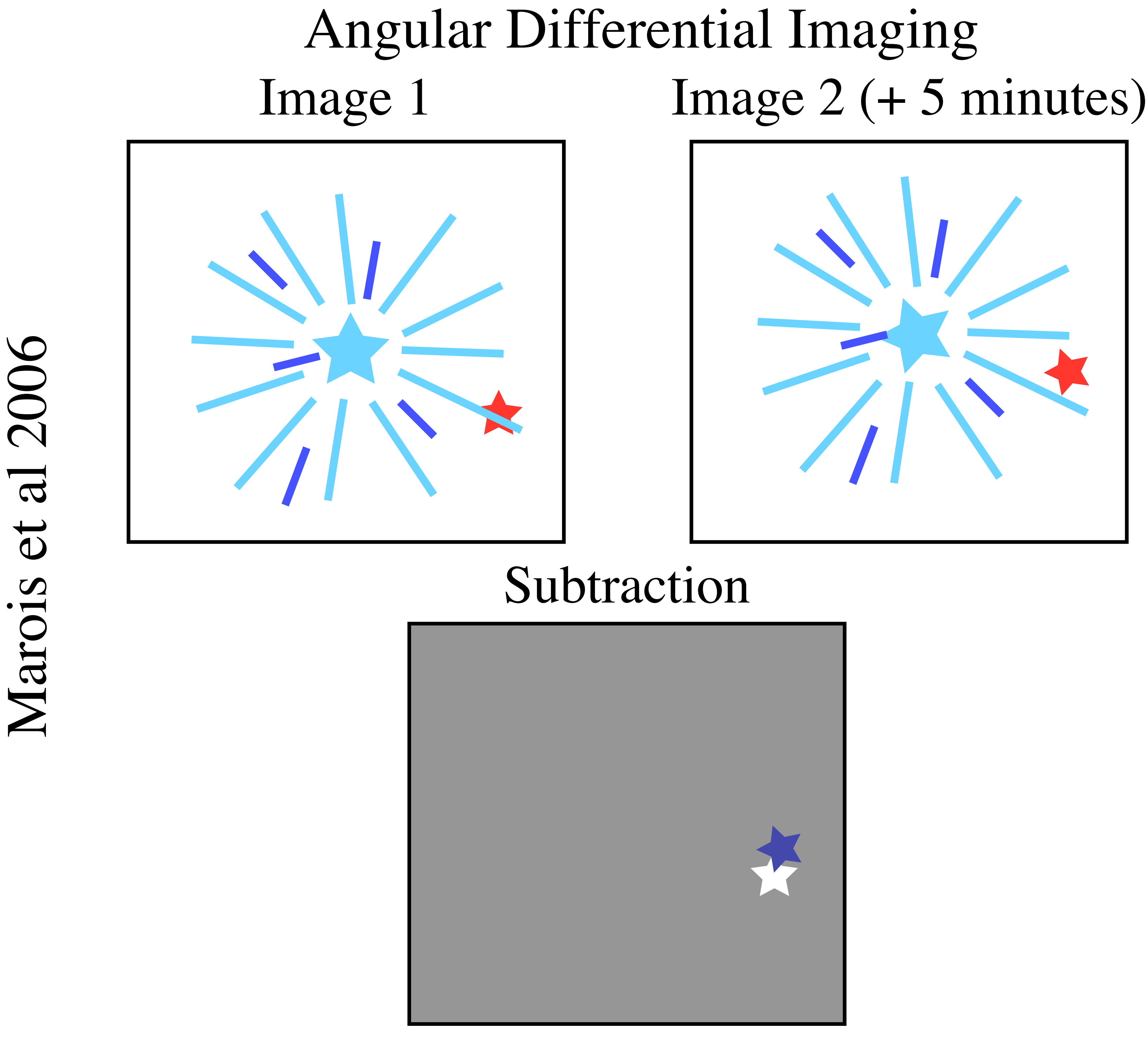
Static errors do not average out

(Sivaramakrishnan et al 2002)



Mitigating Static Errors

- Differential imaging
  - Angular differential imaging (ADI)
    - Marois et al. 2006 (ADI)
    - Lafreniere et al. 2007 (LOCI)
  - Spectral differential imaging (SDI)
    - Sparks & Ford 2002
  - Polarization differential imaging (PDI)
    - Perrin et al. 2004
- Precision wavefront measurement & control

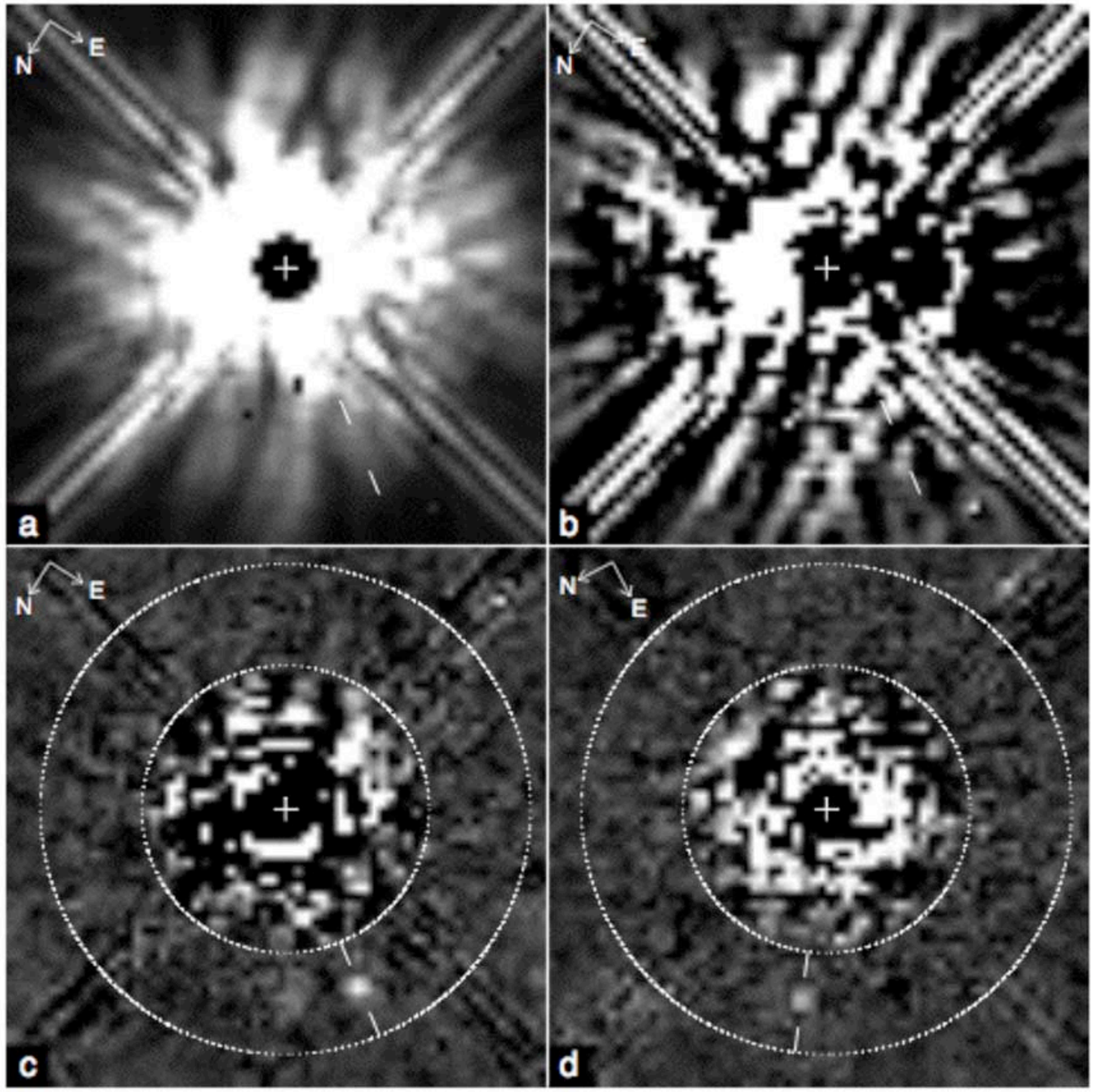


Angular Differential Imaging
Image 1
Image 2 (+ 5 minutes)
Subtraction
Marois et al 2006

HR 8799 HST/NICMOS

Raw HST

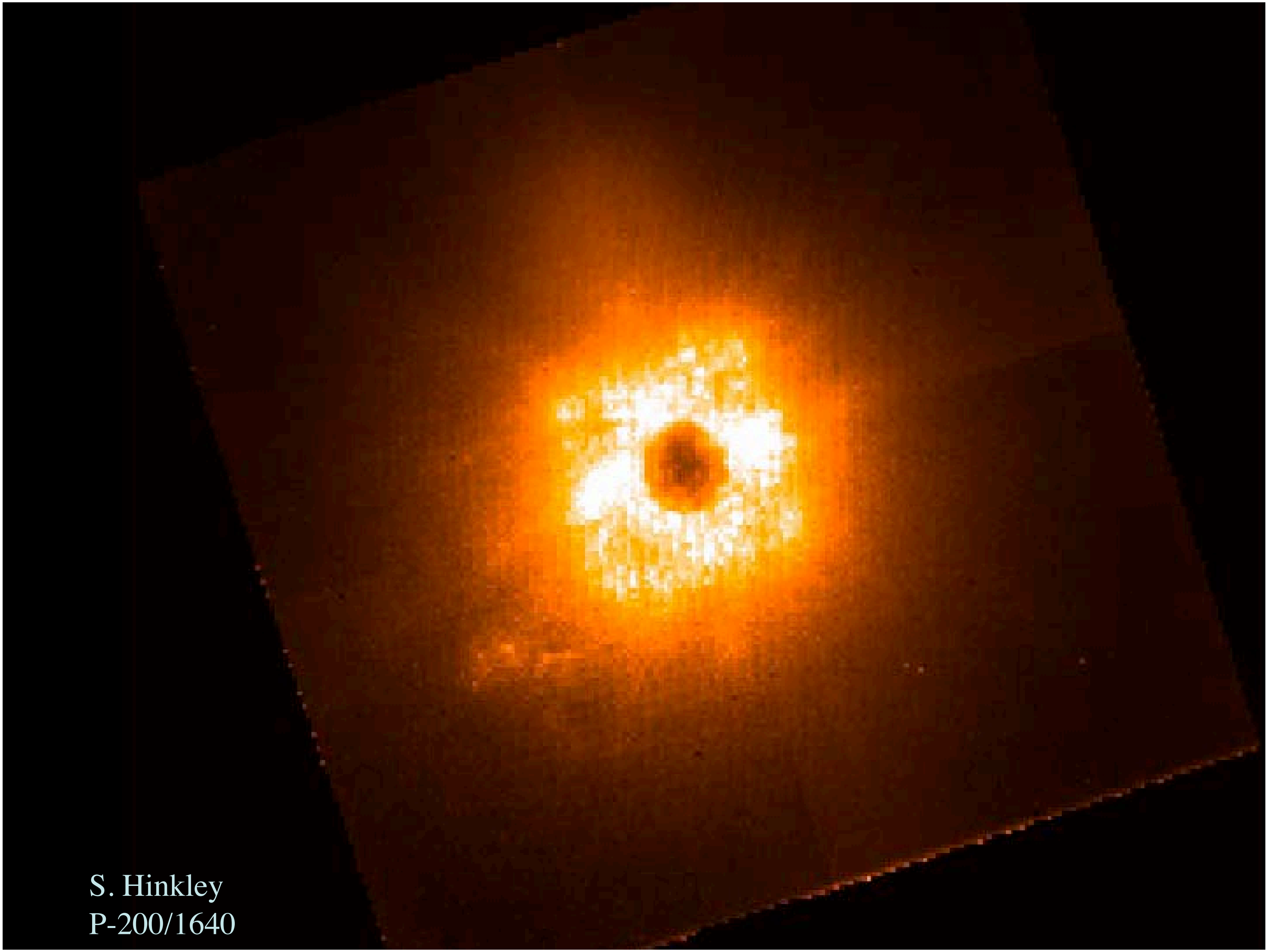
HST roll subtraction



LOCI with PSF library

Lafreniere et al. 2009

~10× better PSF subtraction


S. Hinkley
P-200/1640

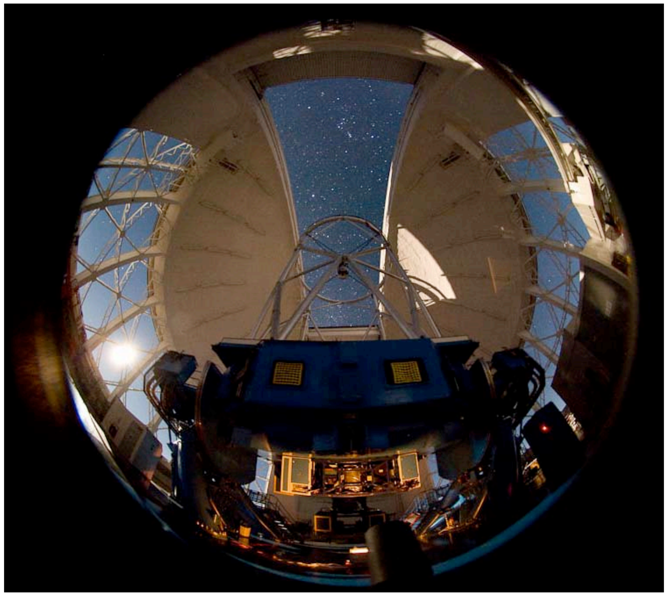
High Contrast Campaigns

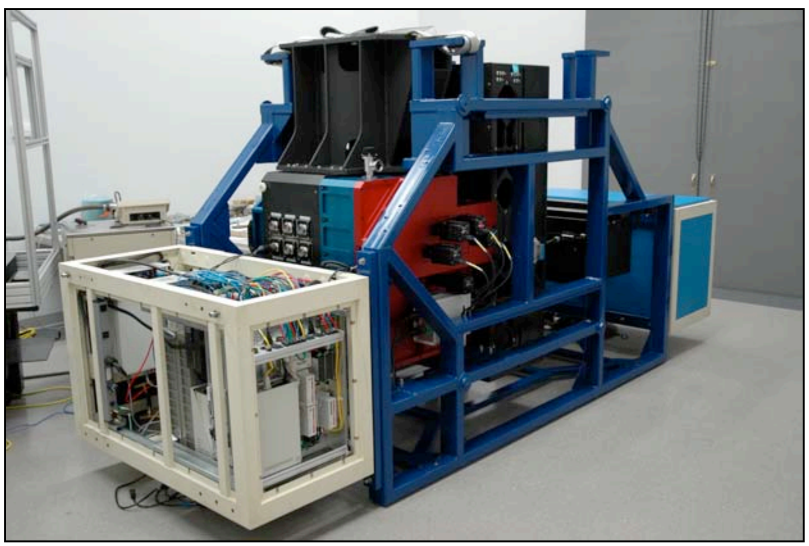
- Gemini-South/NICI (M. Liu)
  - 85 element AO curvature-based system
  - Dual channel imager/Lyot coronagraph/ADI
  - 50 nights of observing time/300 stars
  - ΔH = 15 mag. at 1”
- Palomar/Project 1640 (Oppenheimer/Hinkley/Dekaney)
  - PALAO 241 actuator SH system
  - J+H integral field spectrograph/APLC
    - Upgrade to PALM-3000
  - 100 night campaign
- Subaru/HiCIAO/SEEDS (M. Tamura)
  - AO188: Curvature-sensing AO with 188 elements
    - SCExAO1024 upgrade
  - Lyot coronagraph, PDI, SDI
  - 120 night/5-year strategic survey

High Contrast Campaigns

- VLT/SPHERE (J.-L. Beuzit)
  - High-order AO/APLC/4QPM
    - 41×41 actuator DM
  - IFS/IRDIS/ZIMPOL instruments
  - $\Delta H \approx$ 15.5-17.5 mag. at 0.15-1”
  - First light 2nd half 2011
  - ~ 200 night campaign
- Gemini South (B. Macintosh)
  - High-order AO/APLC
    - 64×64 actuator MEMS DM
  - Integral field spectrometer
  - Precision interferometric wavefront control
  - $\Delta H \approx$ 14.5-18 mag. at 0.2-1”
  - First light March 2011
  - Campaign TBD

NICI Campaign: Status

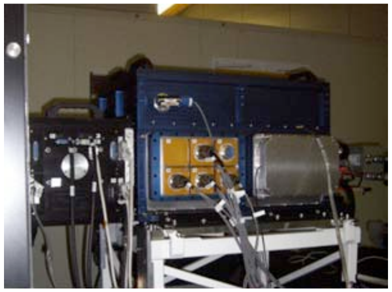




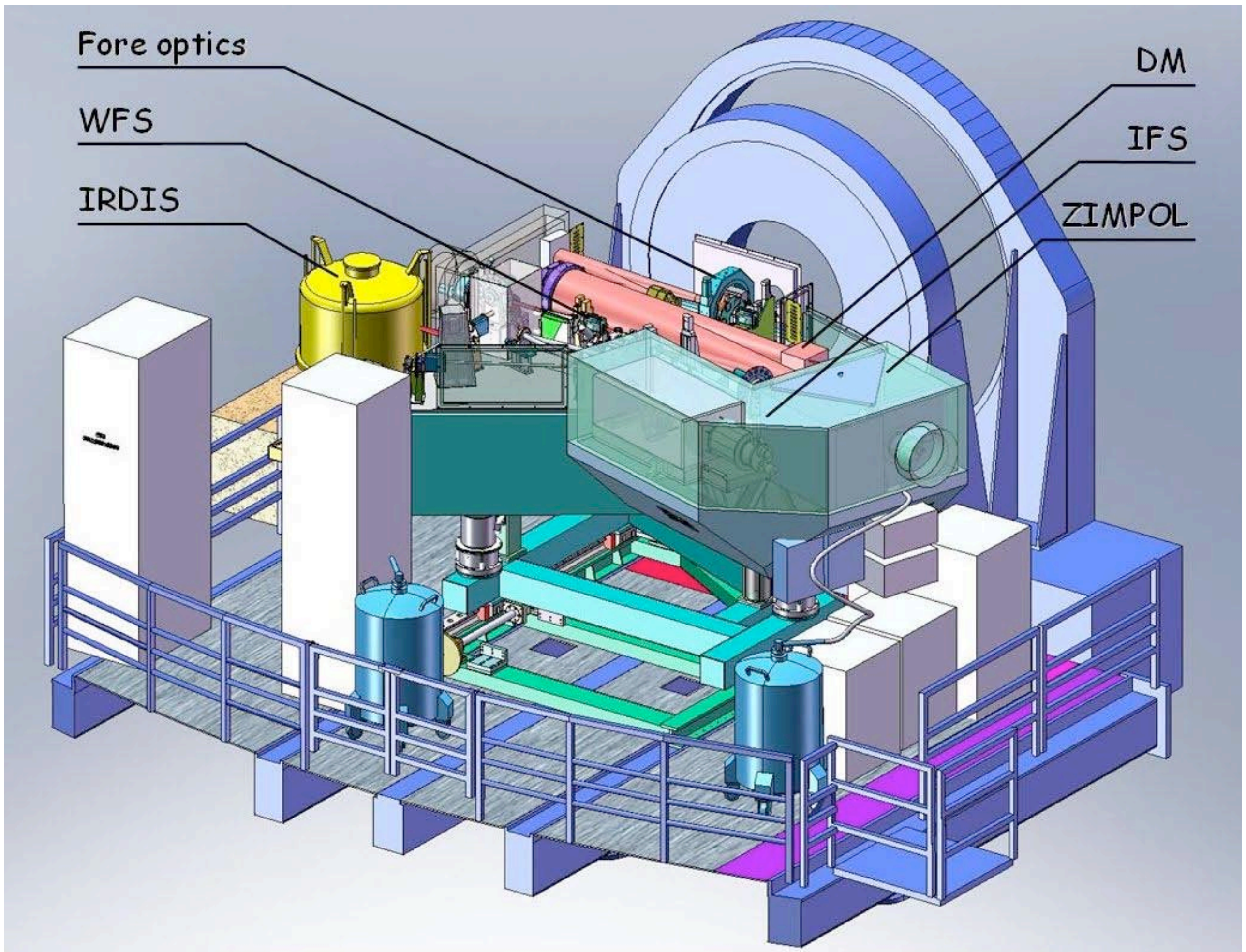
- Dec 2008 – Apr 2009: monthly science runs
  - 132 stars observed
- Dec 2009 – May 2010: Year-2 observing
  - Observe new targets
  - Obtain 2nd epoch confirmation (or not) of candidate companions.
  - Follow-up imaging + spectra of confirmed exoplanets.

Subaru & HiCIAO

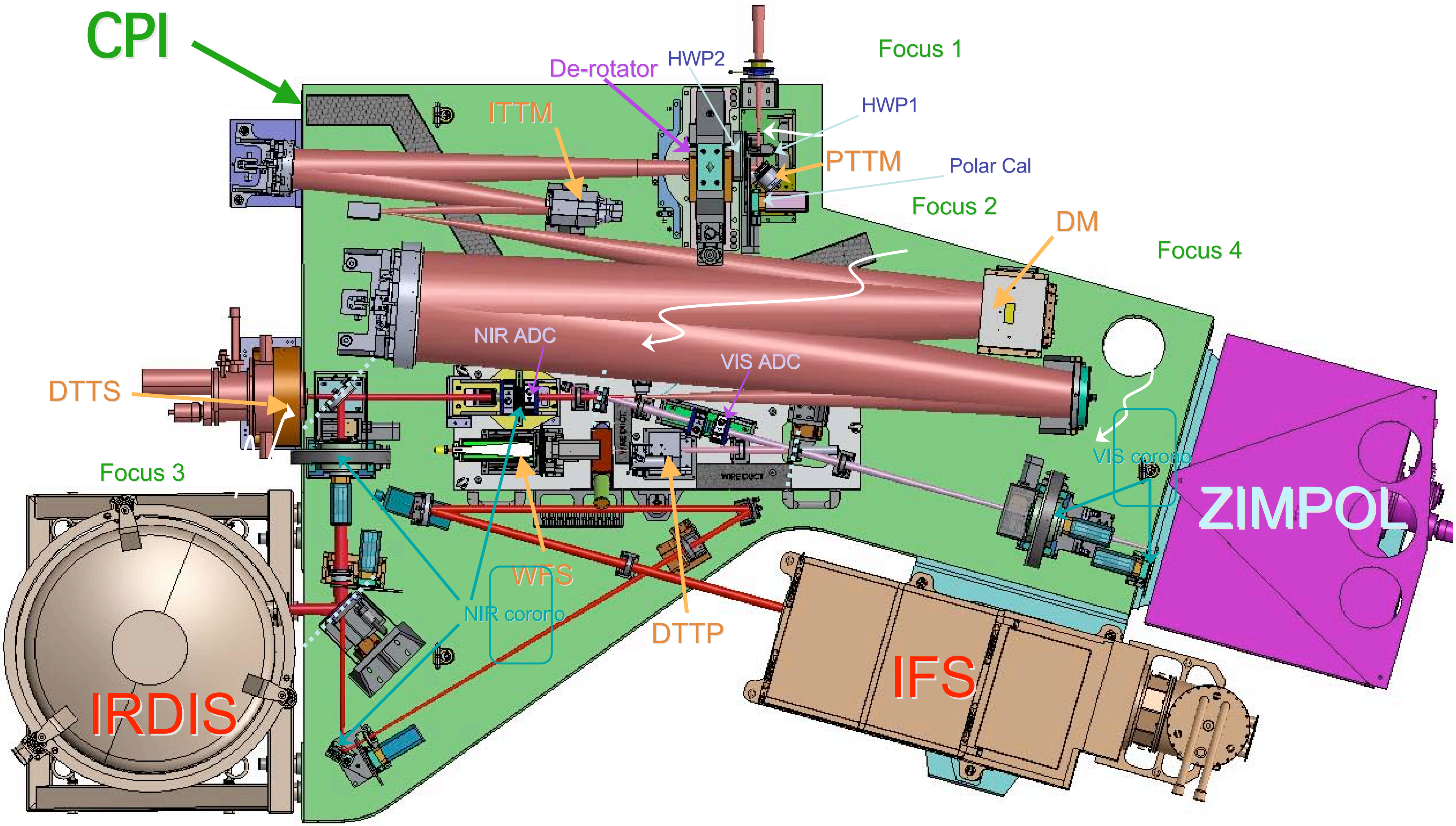
- PI: Motohide Tamura (NAOJ)
  - Co-PIs: Tomonori Usuda, Hideki Takami (NAOJ)
  - 94 scientists/24 institutes (including Princeton, UH, MPIA)
- AO, Coronagraph, Science camera: HiCIAO
  - Curvature-sensing AO with 188 elements (SCExAO1024 upgrade)
  - 20" FoV, Lyot coronagraph, PDI, SDI available.
- Commissioned 2009 (including Princeton/MPIA for angular differential imaging)
- 120 night/5-year strategic survey "SEEDS" for planets and disks now launched
- Direct imaging and census of giant planets around solar-type and massive stars in the outer regions (a few - 40 AU)
- Exploring protoplanetary disks and debris disks for origin of their diversity and evolution at the same radial regions
- Links between planets and protoplanetary disks



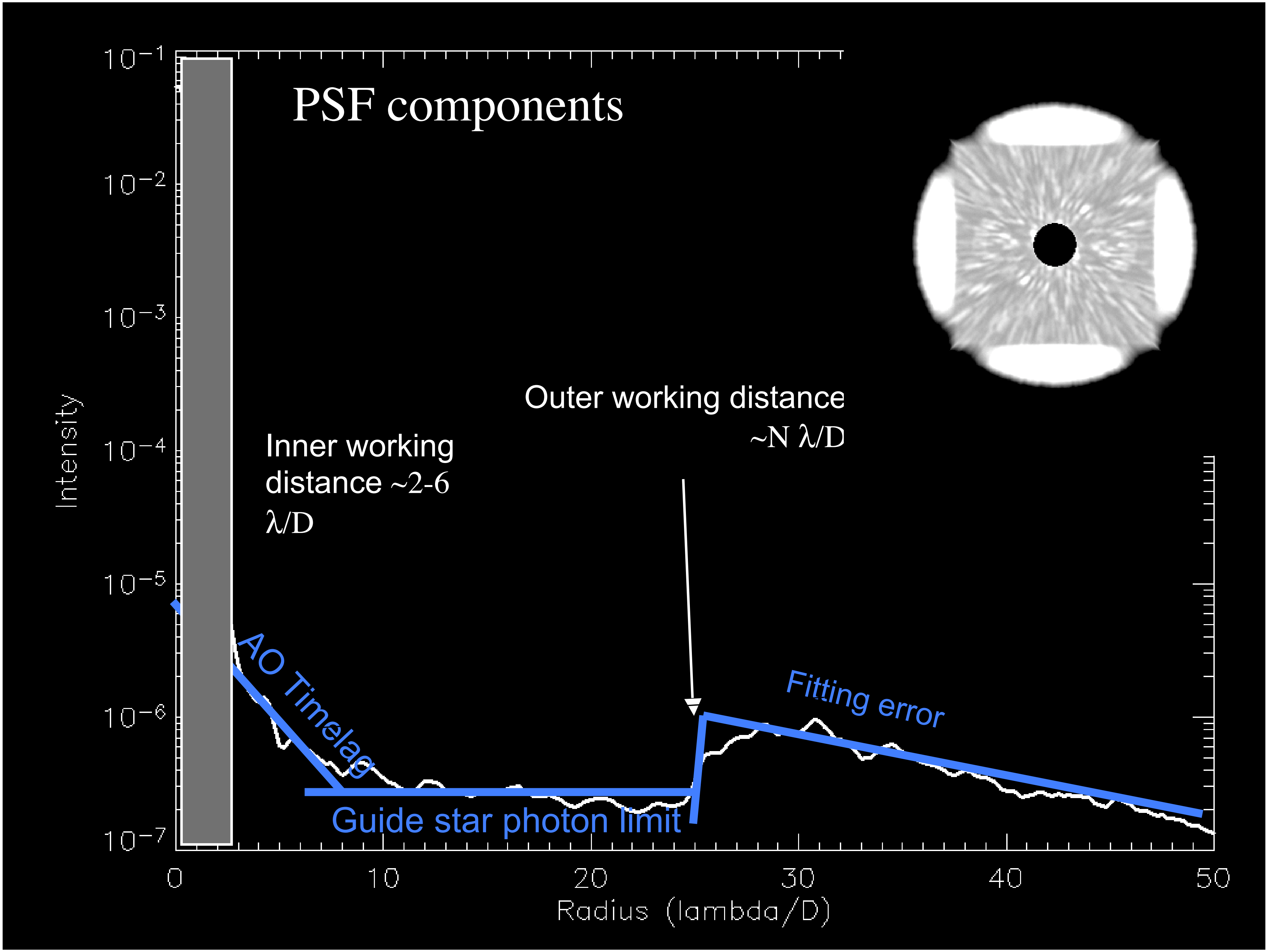
VLT/SPHERE



VLT/SPHERE



CPI
Focus 1
De-rotator
HWP2
HWP1
ITTM
PTTM
Polar Cal
Focus 2
DM
Focus 4
NIR ADC
VIS ADC
DTTS
Focus 3
VIS corono
ZIMPOL
WFS
NIR corono
DTTP
IFS
IRDIS



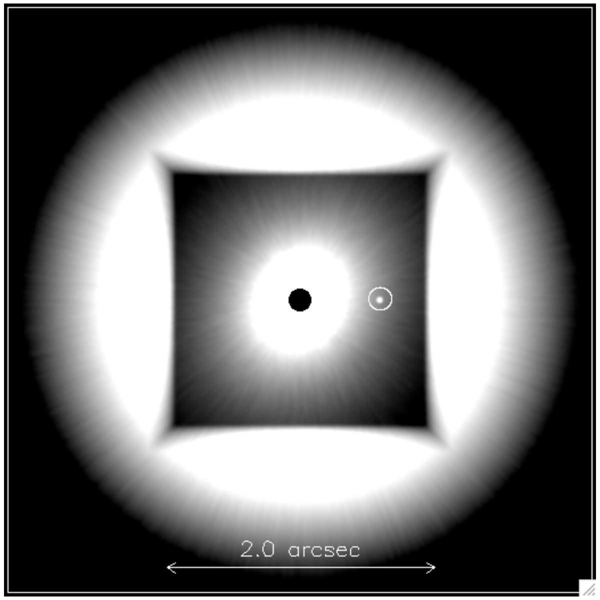
PSF components
Inner working distance ~2-6 λ/D
Outer working distance ~N λ/D
AO Timelag
Guide star photon limit
Fitting error
Intensity
Radius (lambda/D)
10−1
10−2
10−3
10−4
10−5
10−6
10−7
0
10
20
30
40
50

Requirements for High-Contrast

- Advanced AO for good control of dynamic aberrations + external static aberrations
- Coronagraph to control diffraction to target contrast level
- Non-common-path error control
- Differential imaging
  - ADI: Cassegrain focus on Al/Az telescope
  - SDI: Integral field spectrograph
- Amplitude errors must be small (or controlled…)
- Stability

Example: Gemini Planet Imager

- 1800-actuator AO system
- Strehl ratio ~ 0.9 at *H*
- Superpolished optics & precision calibration
- APLC coronagraph
- Integral field spectrograph + polarimeter



LLNL: Project lead + AO

AMNH:Coronagraph masks

HIA: Optomechanical + software

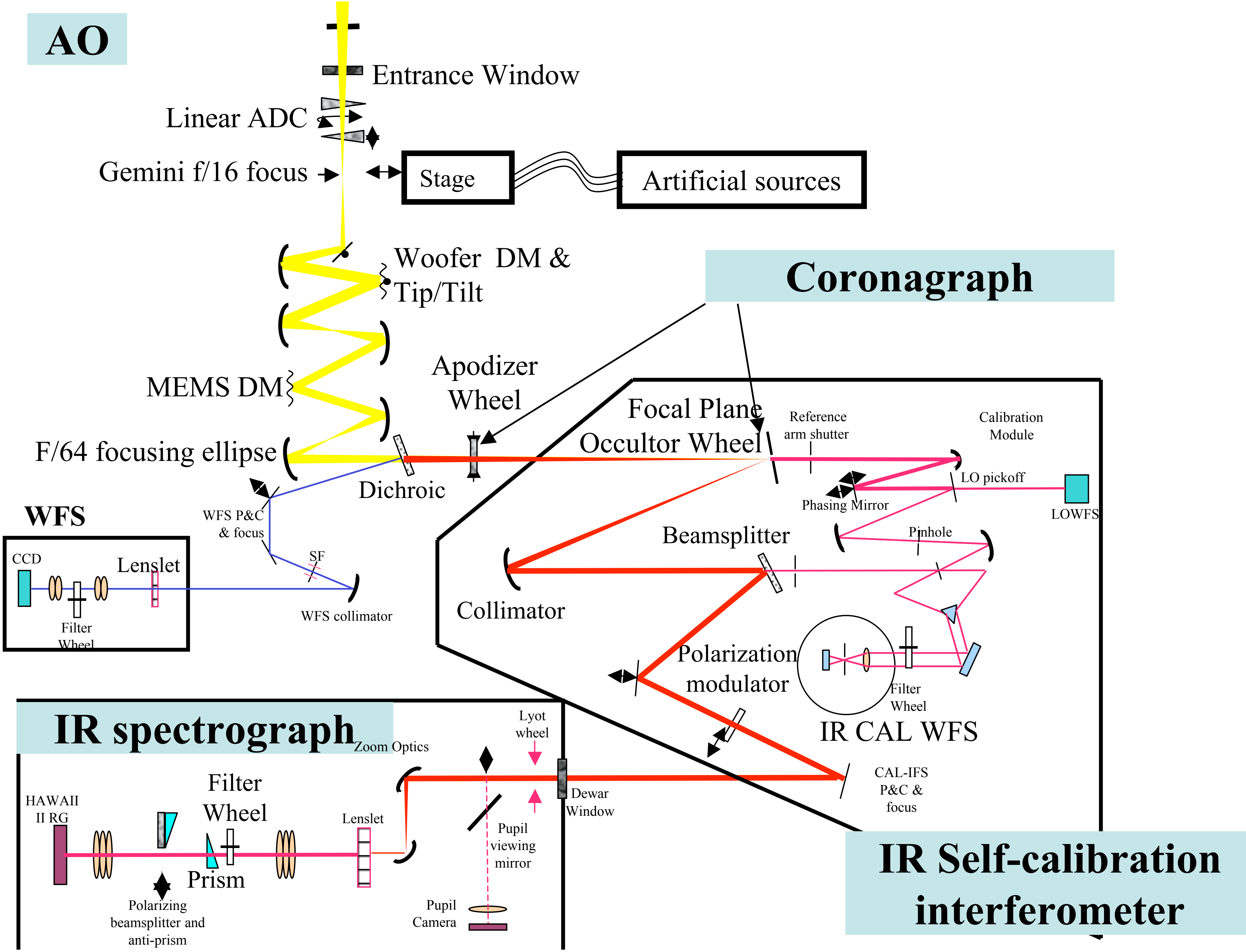
JPL: Interferometer WFS

UCB: Project scientist

UCLA: IR spectrograph

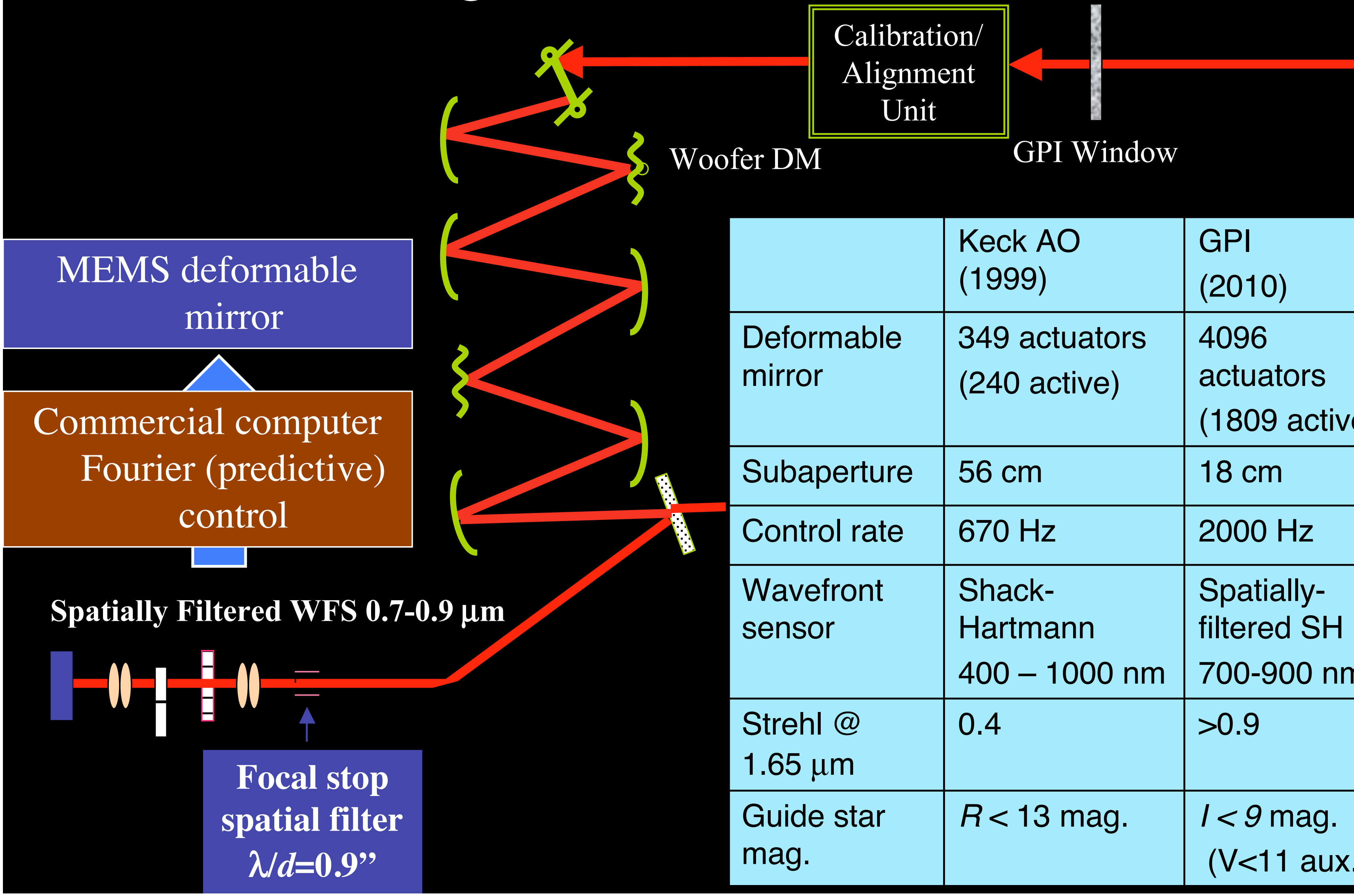
UdM: Data pipeline

UCSC: Final integration & test



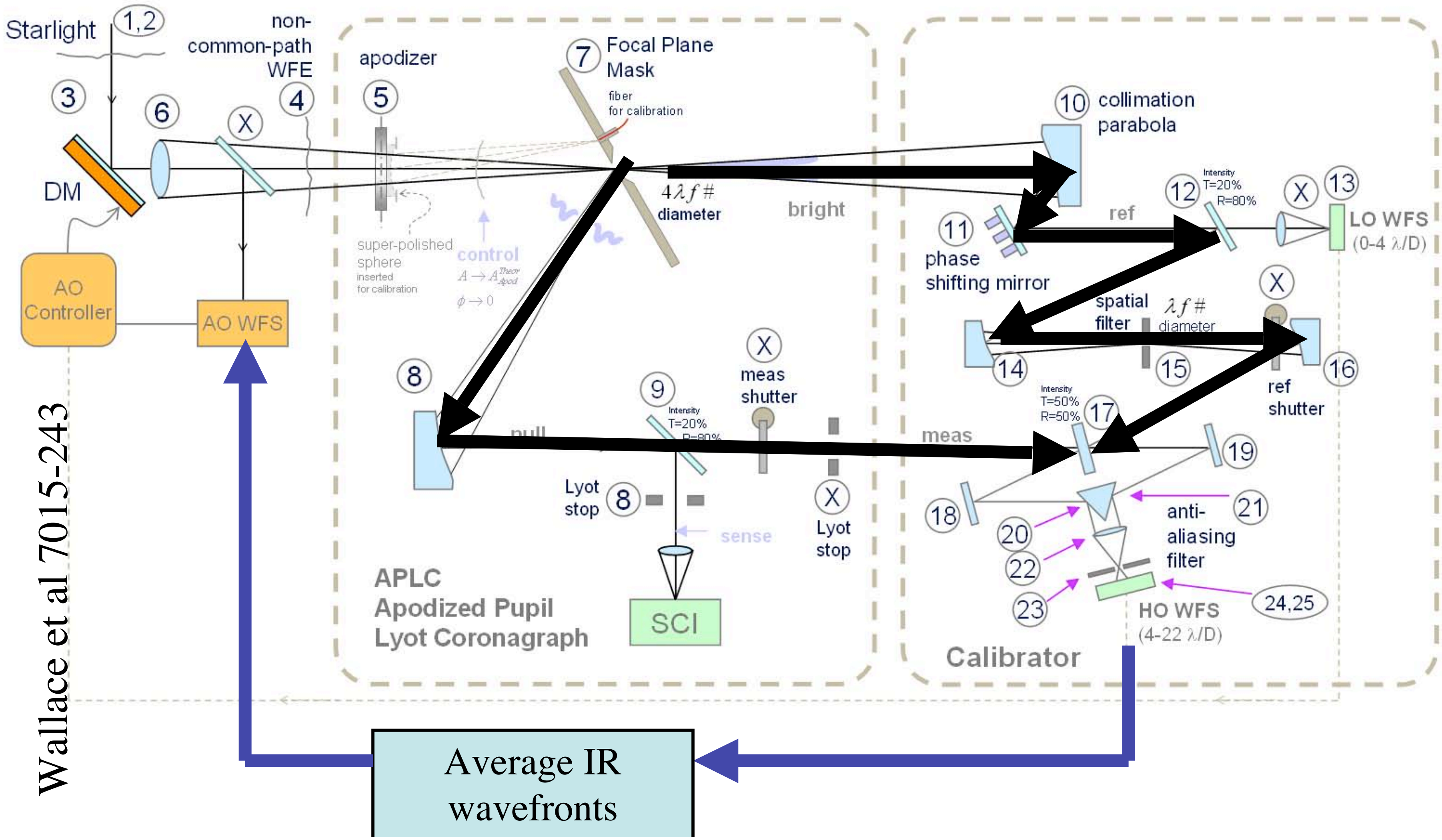
AO
Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
Woofer DM &
Tip/Tilt
MEMS DM
Apodizer
Wheel
F/64 focusing ellipse
Dichroic
WFS
WFS P&C
& focus
CCD
Lenslet
SF
Filter
Wheel
WFS collimator
Coronagraph
Focal Plane
Occultor Wheel
Reference
arm shutter
Calibration
Module
LO pickoff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

Fast, high-order anti-aliased AO



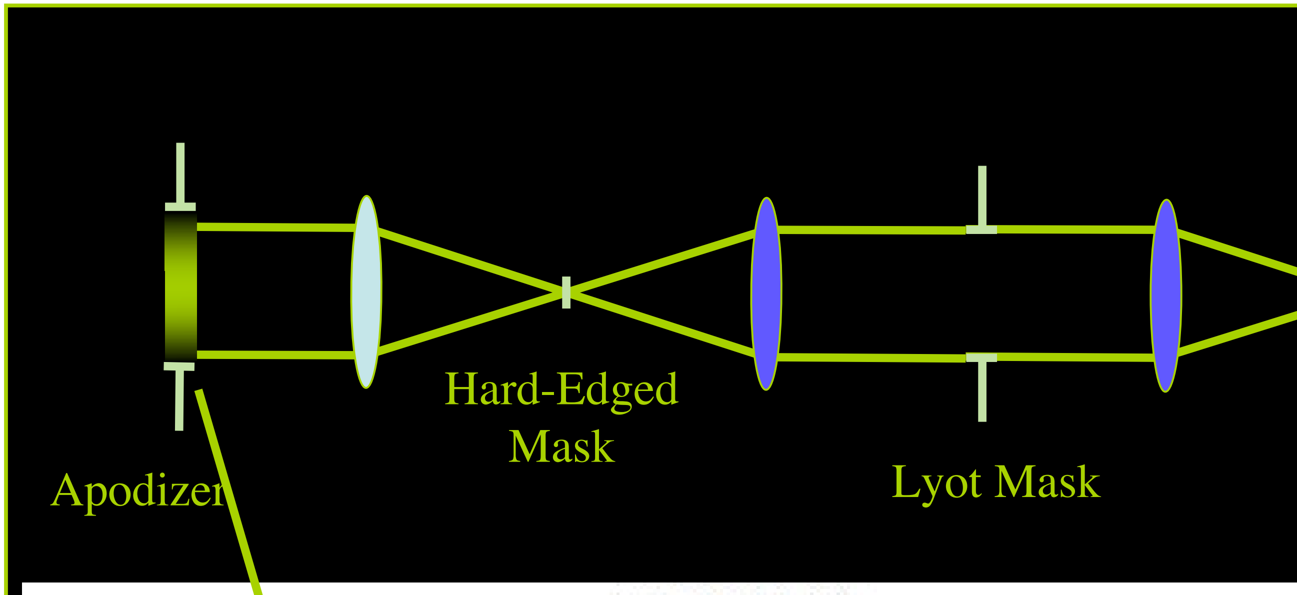
	Keck AO (1999)	GPI (2010)
Deformable mirror	349 actuators (240 active)	4096 actuators (1809 active)
Subaperture	56 cm	18 cm
Control rate	670 Hz	2000 Hz
Wavefront sensor	Shack-Hartmann 400 – 1000 nm	Spatially-filtered SH 700-900 nm
Strehl @ 1.65 μm	0.4	>0.9
Guide star mag.	$R < 13$ mag.	$I < 9$ mag. (V<11 aux.)

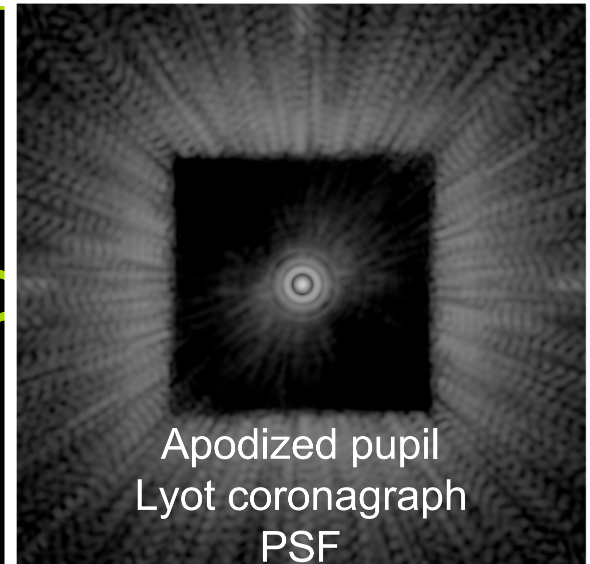
Interferometer Measures Science Wavefront

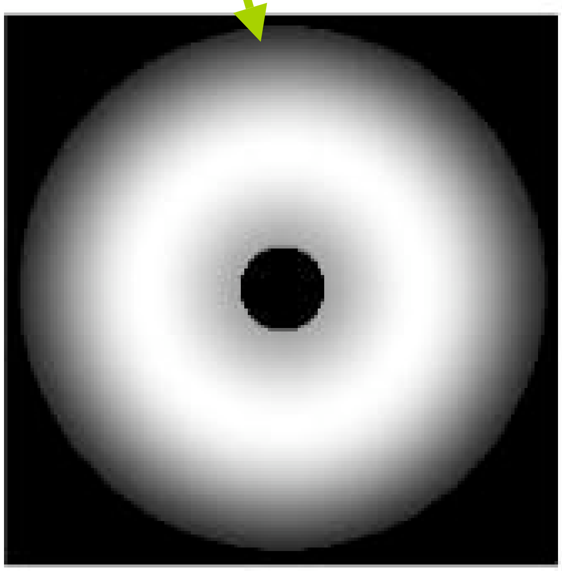


Wallace et al 7015-243

APLC Optimized for Obscured Pupil



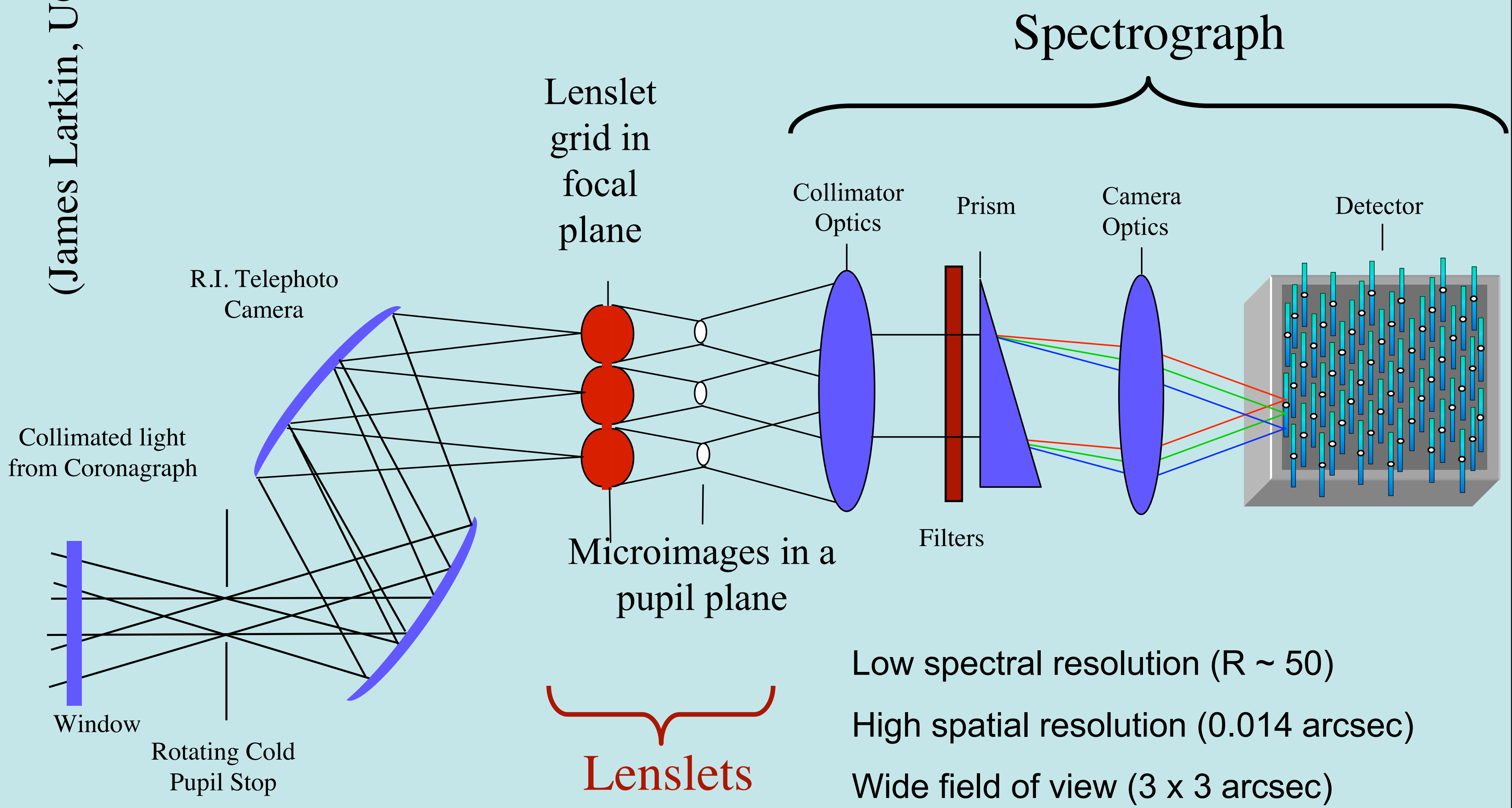




- *H*-band optimized
  - Additional mask for *Z*, *J*, & *K*
- Achromatic
  - Contrast < 10^{-7} for 1.5-1.8μm
- Inner working angle 0.2 arc sec

Integral field spectrograph

(James Larkin, UCLA)



Low spectral resolution (R ~ 50)

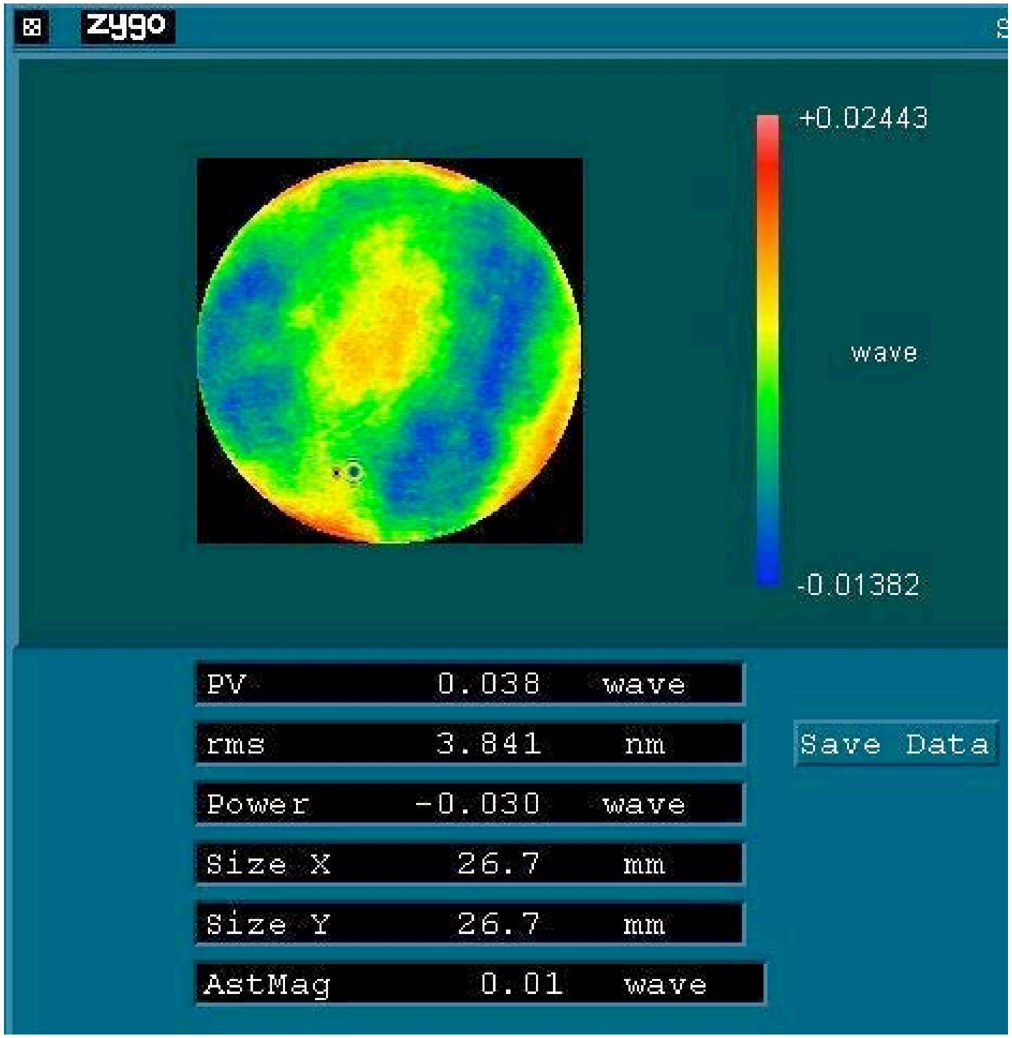
High spatial resolution (0.014 arcsec)

Wide field of view (3 x 3 arcsec)

Minimal scattered light

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 CL = 300
- Transmissive optics minimized
- Atmospheric dispersion corrected early in the system




GPI Hardware