Searching for Other Worlds

Next Generation Extreme Adaptive Optics

on Ground-Based Telescopes

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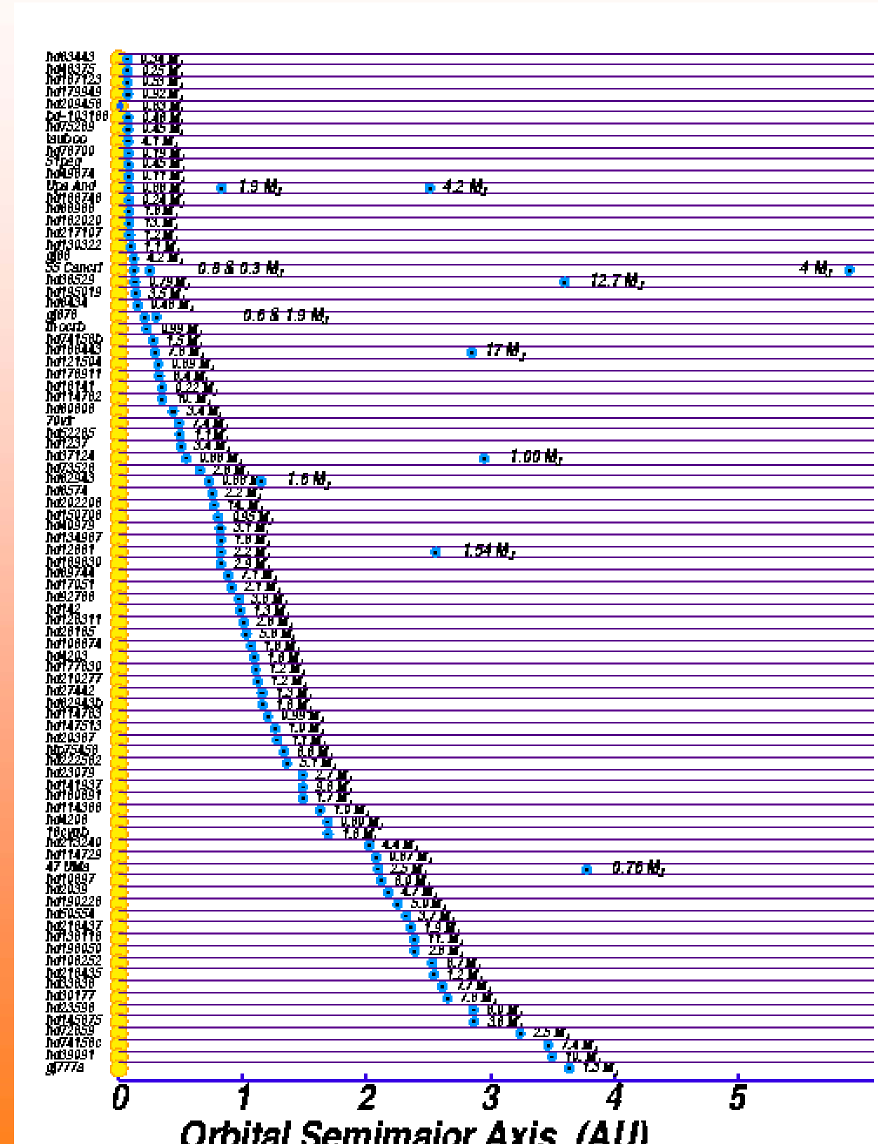
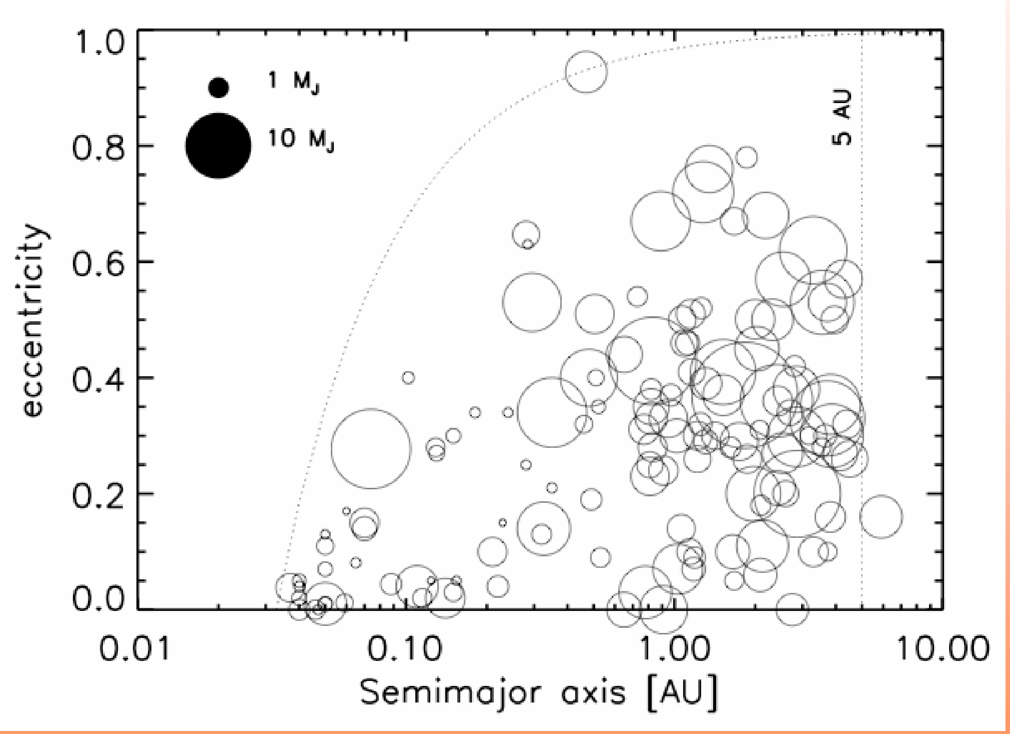
But we’ve already found many…

- Doppler surveys have cataloged >200 planets
  - Indirect searches are limited by Kepler’s third law: $a = P^{2/3}$
    - $P_{Jupiter} = 11$ years
    - $P_{Neptune} = 165$ years
  - Exo-Jupiters remain undetected
  - A survey of outer regions (a > 10 **AU**; P > 31.6 yr) is impractical using indirect methods



Doppler planets

- Only 5% of stars have known Doppler planets
  - Why isn't it 15 to 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?
  - What about M dwarfs?
- How do planets form?
  - Core accretion vs. gravitational collapse
- New questions
  - What is the origin of dynamical diversity?



Why high contrast imaging?

Broad scientific application

- Exoplanet detection
  - Direct methods explore beyond 5 AU
  - Direct methods give all 6 orbital parameters
  - Indirect methods give only *a, M* sin *i,* & *e*
- Circumstellar disks
  - Proto-planetary & debris disks
- Fundamental stellar astrophysics
  - Large mass range main sequence binaries
    - Brown dwarfs & white dwarfs
- Mass transfer & loss
  - Cataclysmic variables, symbiotic stars & supergiants
- Solar system: Jovian/Kronian moons, asteroids

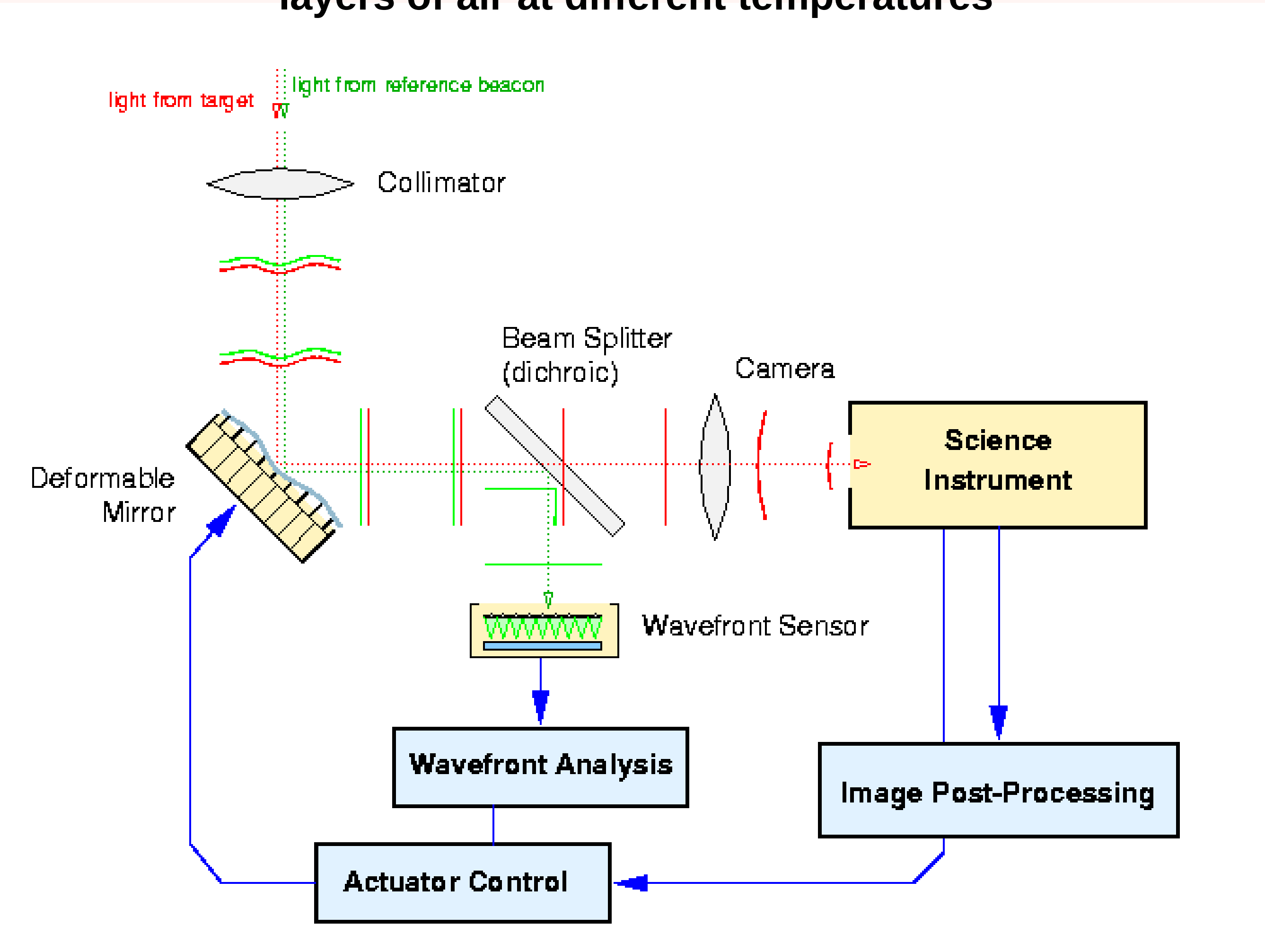
Do it from space?

- Space: expensive high quality optics, stable PSF
  - Low billions of $, 10 year timescales
  - Terrestrial Planet Finder (**T**PF) waiting behind James Webb Space Telescope (JWST) in NASA queue
  - ESA Darwin nulling interferometer
  - For resolution go short wave (terrestrial planets)
  - Lower contrast for self-luminous jovians (JWST mid-IR)

- Ground:
  - Low 10's of millions of $, 5 year timescales
  - Atmospheriic transparency windows
  - Adaptive optics SNR
    - Better wavefront correction at longer λ (J=1.2, H=1.6, K= 2.2 microns)
    - At K and longer, thermal background rises
  - Residual speckles on all timescales

Adaptive Optics (AO) Schematic

Adaptive Optics removes effects of turbulent mixing of layers of air at different temperatures

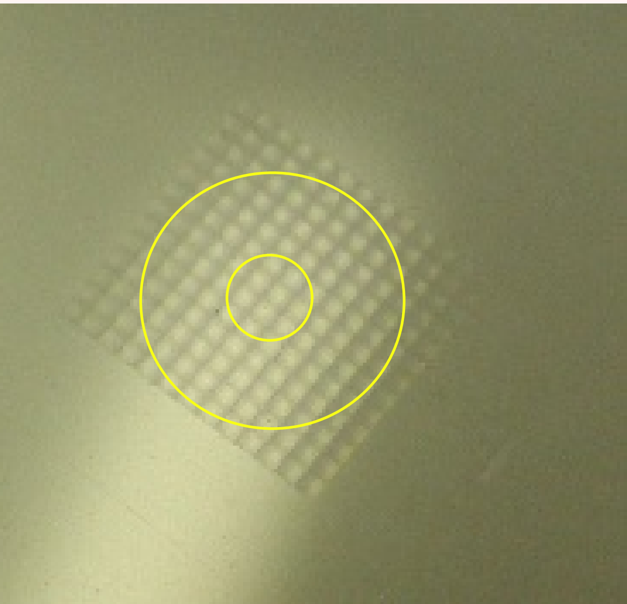


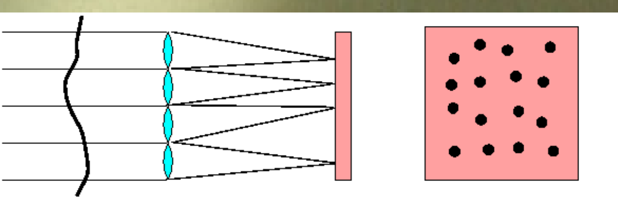
Claire Max, CfAO

Wavefront slope data

Mackay

are needed to see this picture.

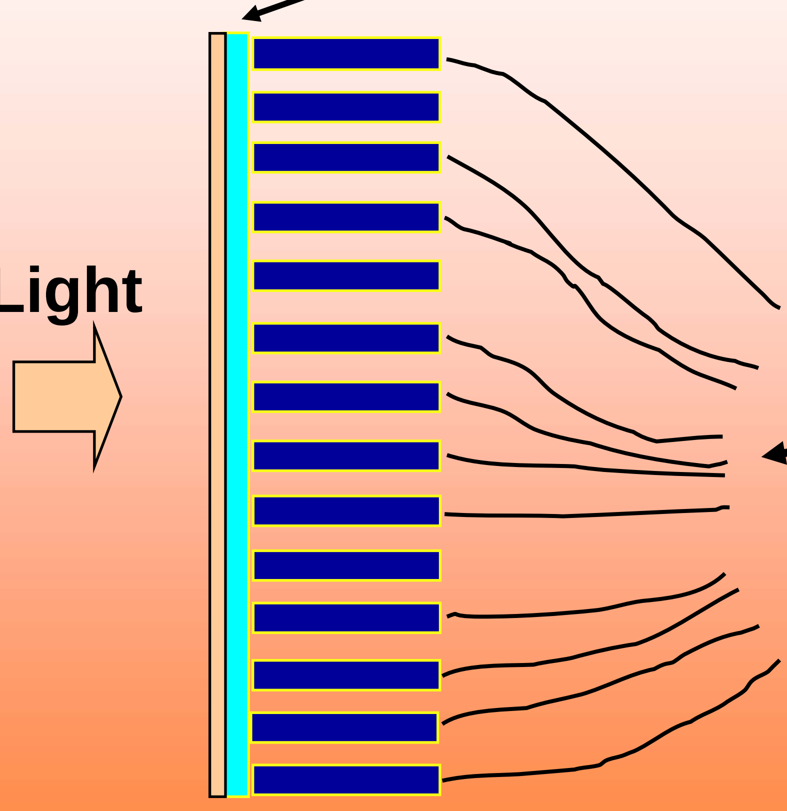




Shack-Hartmann subaperture slope data

Deformable mirror

Claire Max



Oppenheimer

AO - data

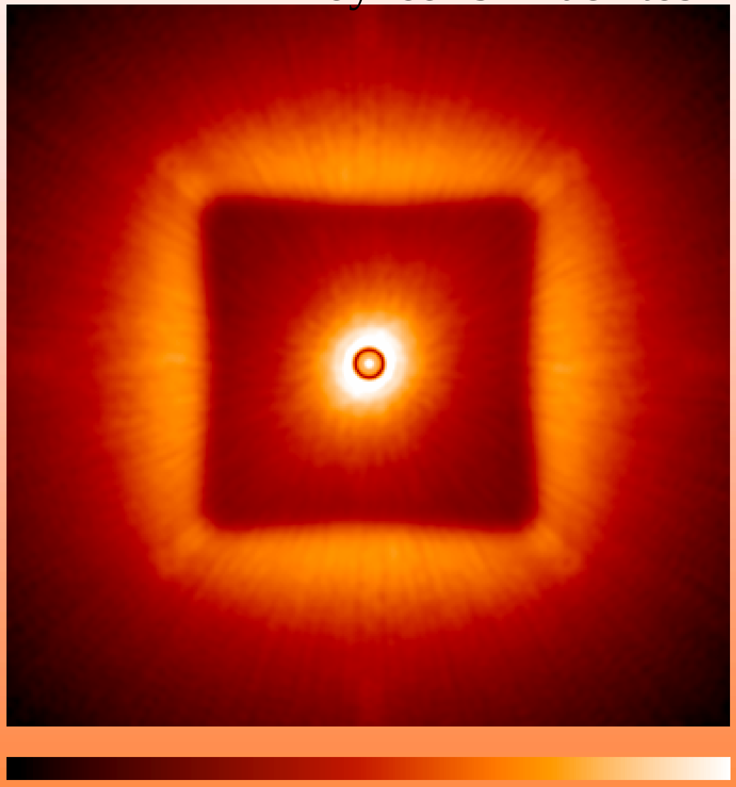
QuickTime™ and a
Animation decompressor
are needed to see this picture.

PalAO - 241 actuators
Strehl ratio ~70%, K band
λ/D = 0”.1
Paschen alpha
Soummer & Lloyd

Spatially filtered wavefront sensing

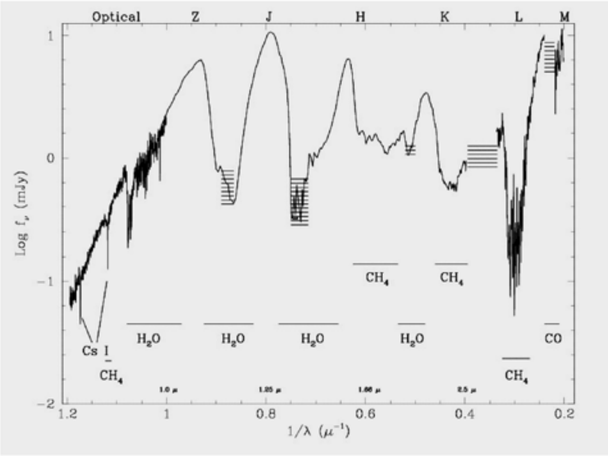
- 5-layer 14.5 cm r0 atmosphere
- 5560 K star, 700-900 nm WFS (25 nm resolution), no atmospheric dispersion
- H-band APLC, no atmospheric dispersion, (1.47,1.52,1.57,1.625 (optimized) 1.78 microns)
- Optimized-gain Fourier control on I_mag=6, 2 kHz

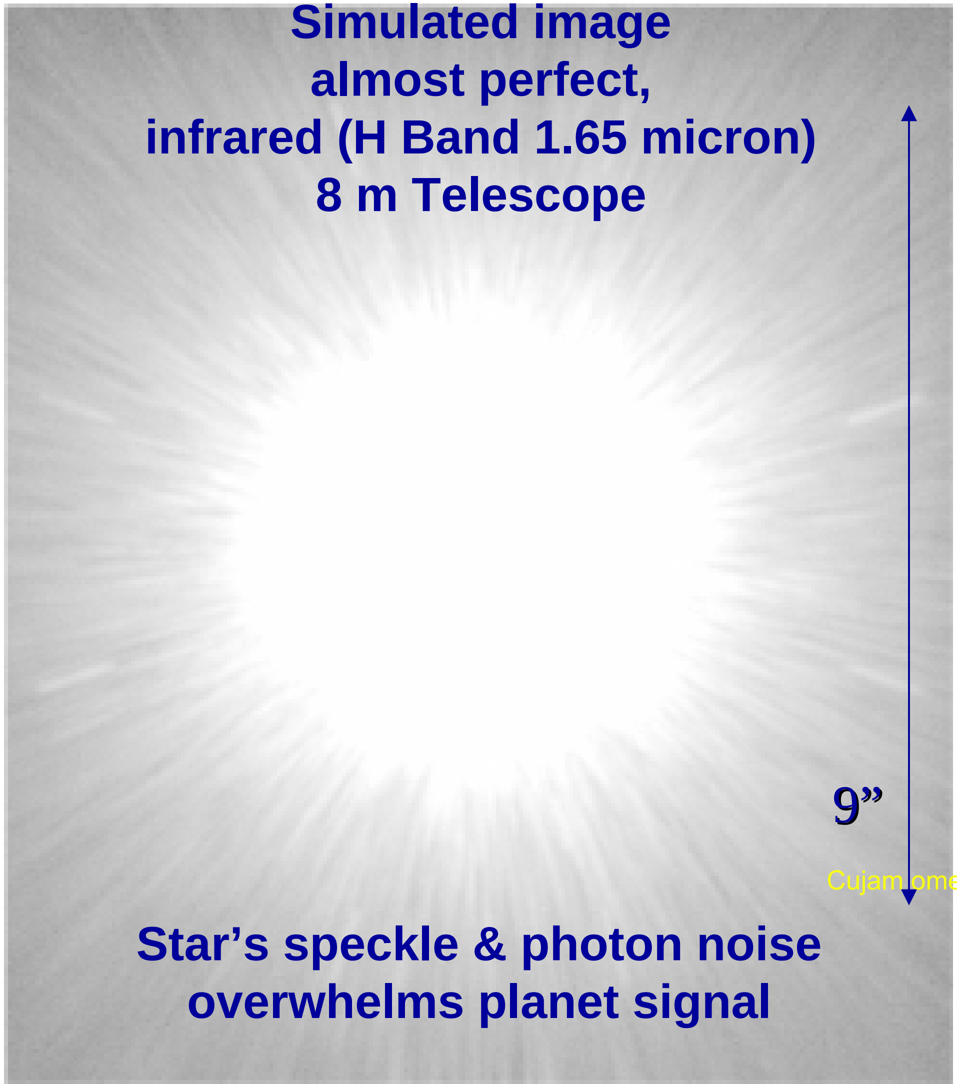
Poyneer & Macintosh

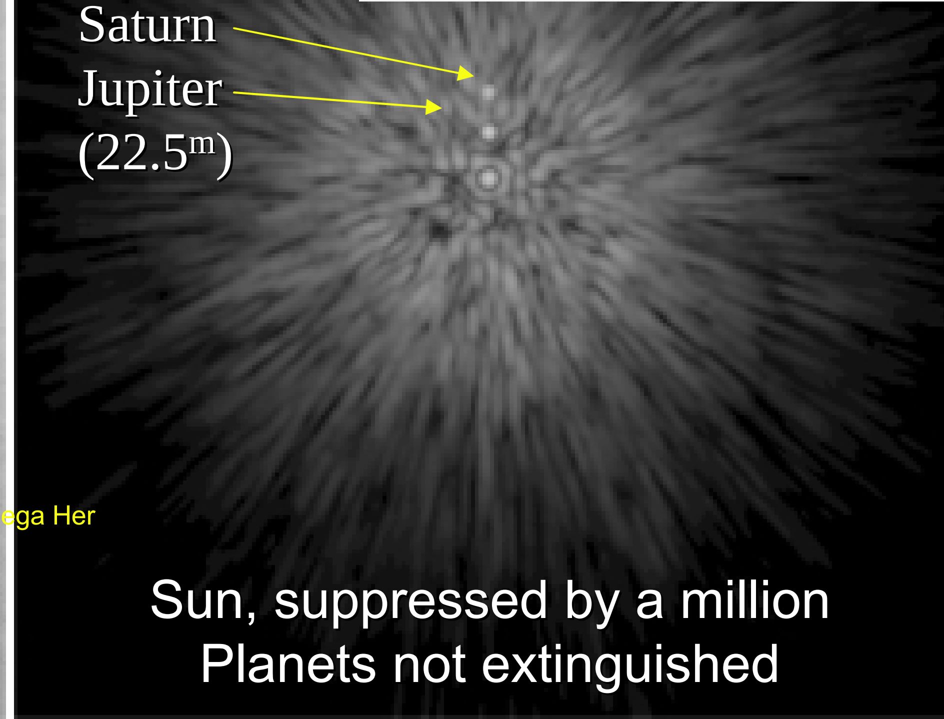


Solar system seen from 10 parsec

Spectrum - atmospheric composition, surface temperature, maybe gravity





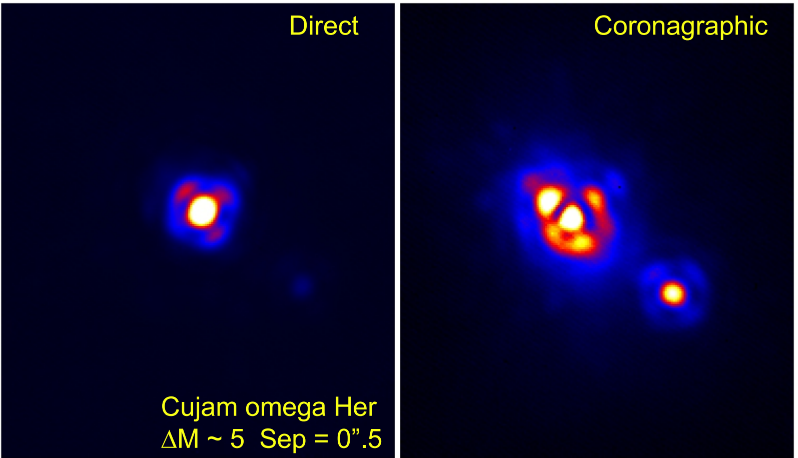


Direct methods

- Interferometry - work mostly in pupil plane
  - Null out central star, see planet
    - Small field of view, narrow spectral bandpass
  - Closure phase and non-redundant masking

- Coronagraphy - work mostly in first image plane
  - Attenuate or cancel central star, see planet

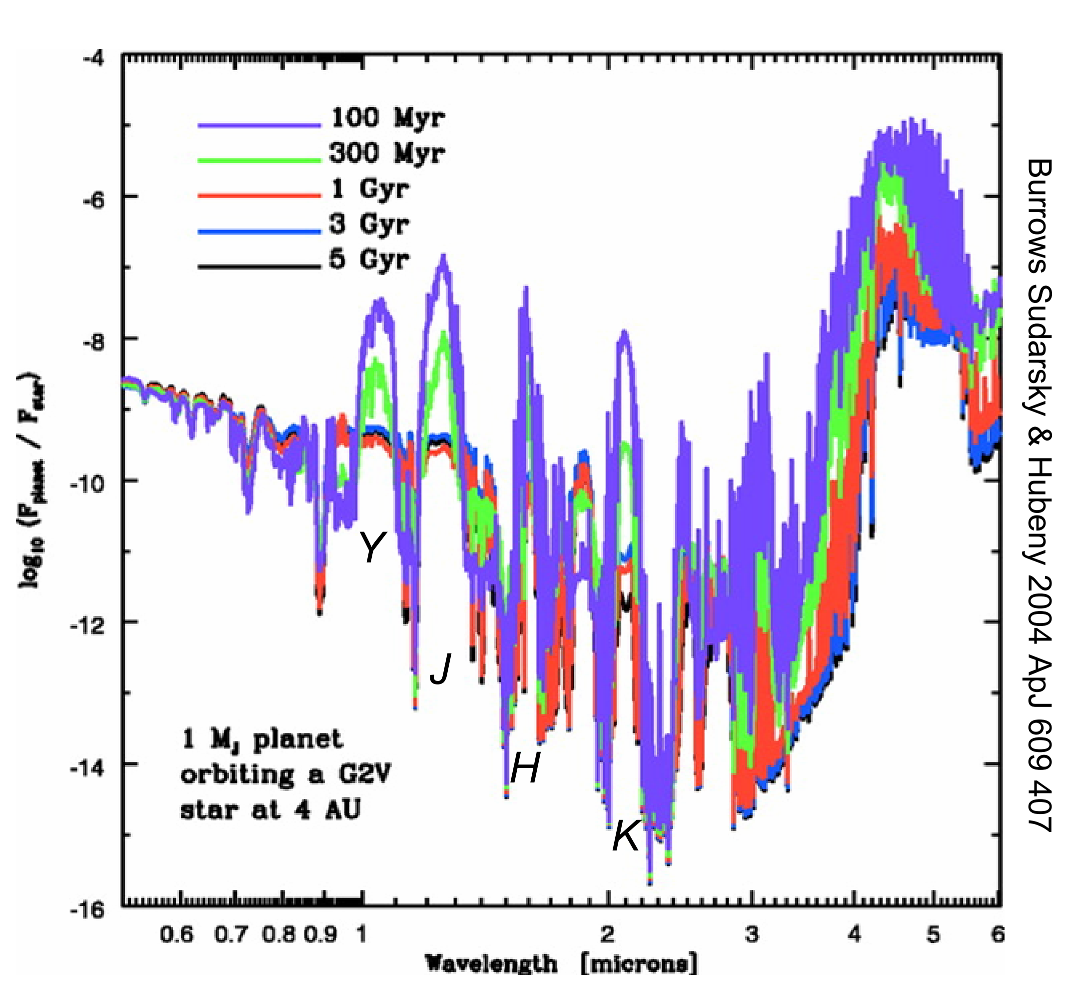
Sivaramakrishnan et al 2001, Oppenheimer et al 2003



USAF Advanced Electro-Optical System (AEOS) 3.6m 1000-actuator AO system on telescope on Maui, H band (1.6 micron) image with Lyot Project coronagraph

Detection of cooling planets

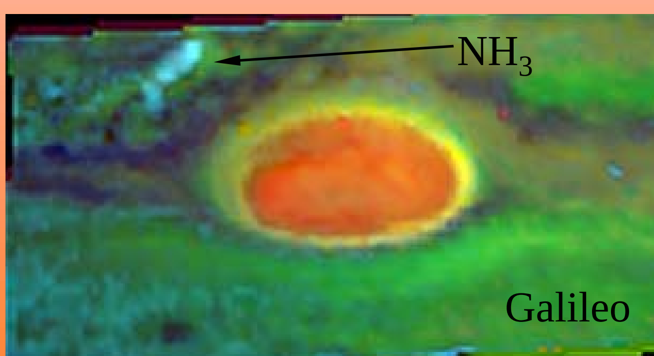
- Contrast required to detect an exo-Jupiter in a 5 AU orbit in the visible is 2 x 10^{-9}
- Near-IR contrast is 2-3 orders of magnitude more favorable
  - Radiation escapes in gaps in the CH_4 and H_2O opacity at *Y, J, H, & K*

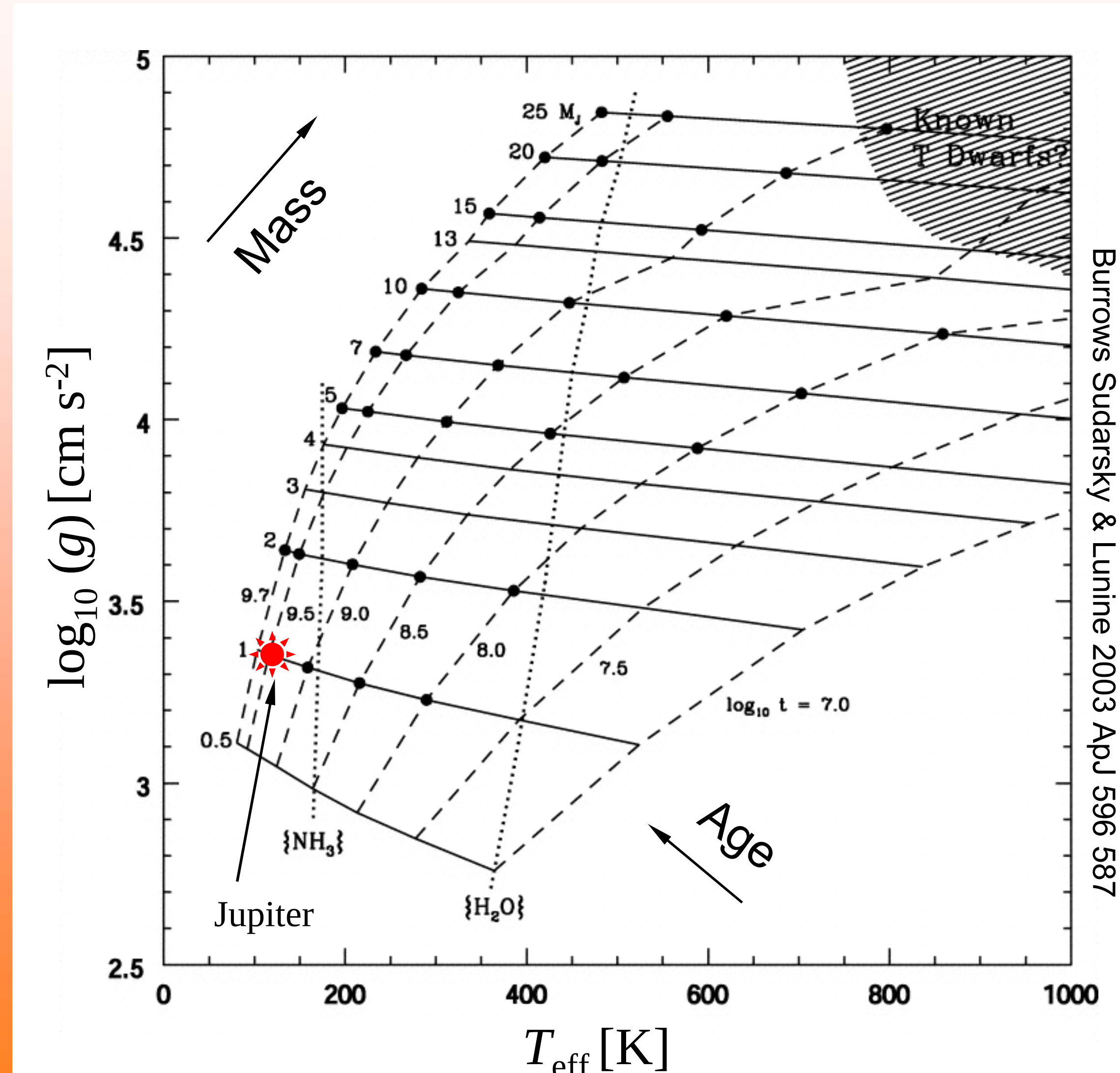


Burrows Sudarsky & Hubeny 2004 ApJ 609 407

Exoplanet atmospheres

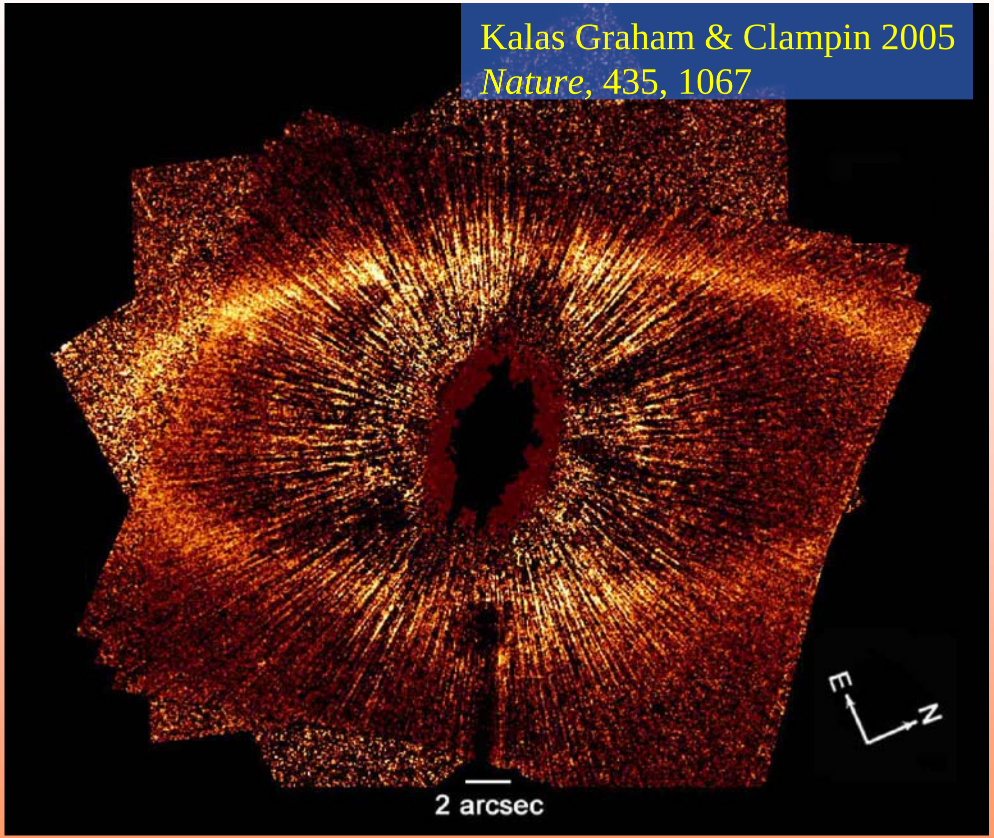
- Exoplanets occupy a unique location in (surface gravity, effective temperature) phase space
  - Over 5 Gyr a Jovian mass exoplanet traverses the locus of H_2O & NH_3 cloud condensation
- “Last frontier” of classical stellar atmospheres





Debris disks

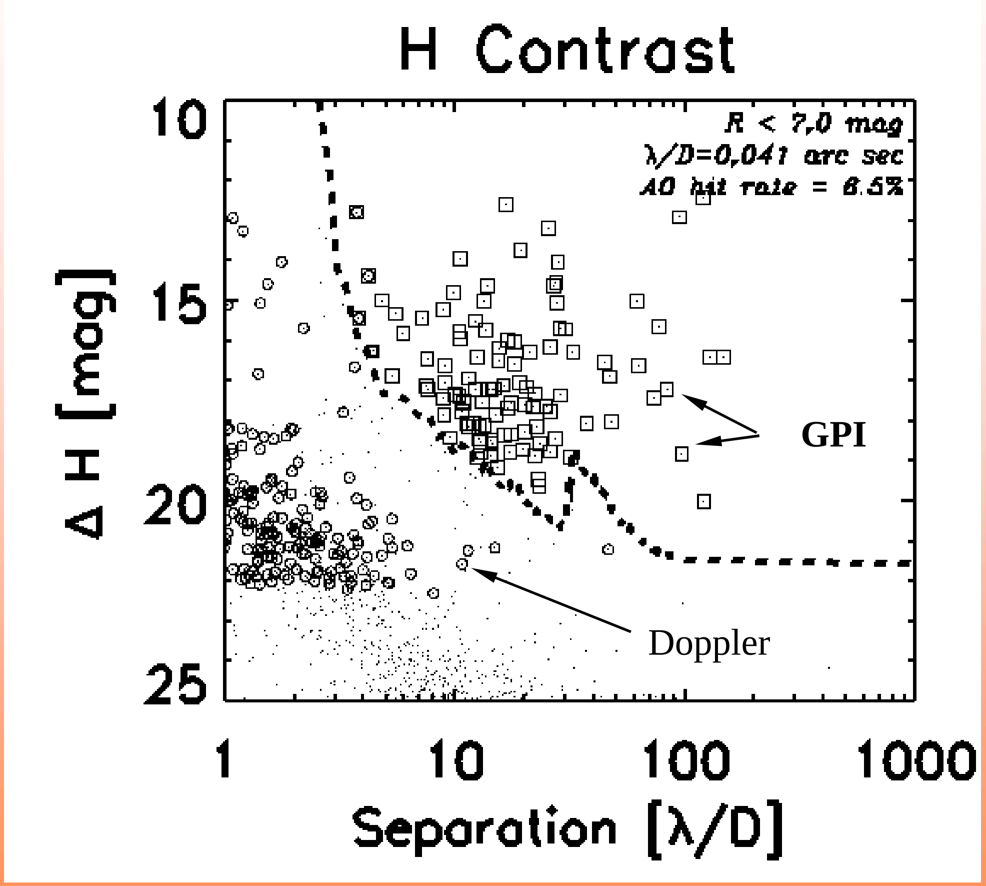
- Gravitationally sculpted disks provide key evidence for exoplanets
  - Morphology of dust trapped in libration points provides key to masses an eccentricities of exoplanets
  - Surface brightness,color, phase function, and polarization indicates quantity composition and grain size distribution
- Fomalhaut debris disk F606W + F814W HST/ACS coronagraph
  - $\mu \approx 20$ mag arc sec^{-2}
  - $\mu/\mu_0 \approx 10^{-10}$
  - High-mass exoplanet in a low eccentricity orbit
- Synergy with ALMA
  - Probe disjoint dust grain populations



Monte Carlo of GPI on 8-m

GEMINI PLANET IMAGER

- GPI
  - AO
    - r_0 = 100 cm
    - 2.5 kHz update rate
    - 13 cm subapertures
      - *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 (6.5 % detection rate)
  - Semimajor axis distribution is complementary to Doppler exoplanets

Complementarity with indirect surveys

- Adaptive Optics
  - r_0 = 100 cm
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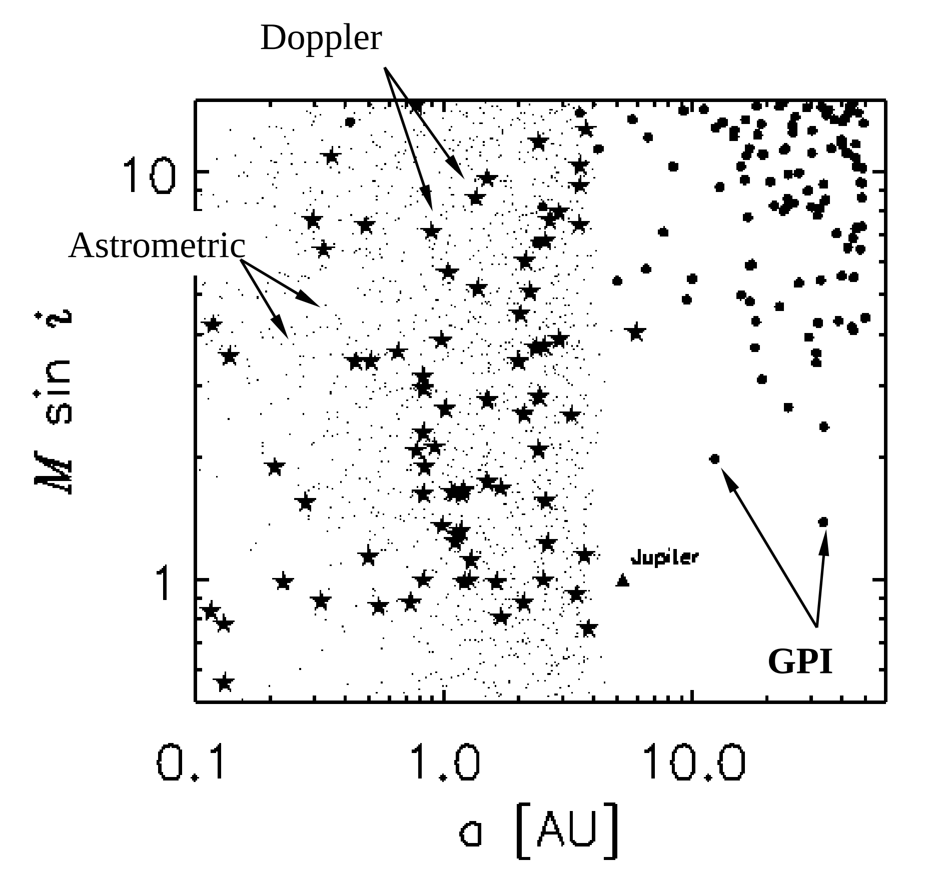

- Results
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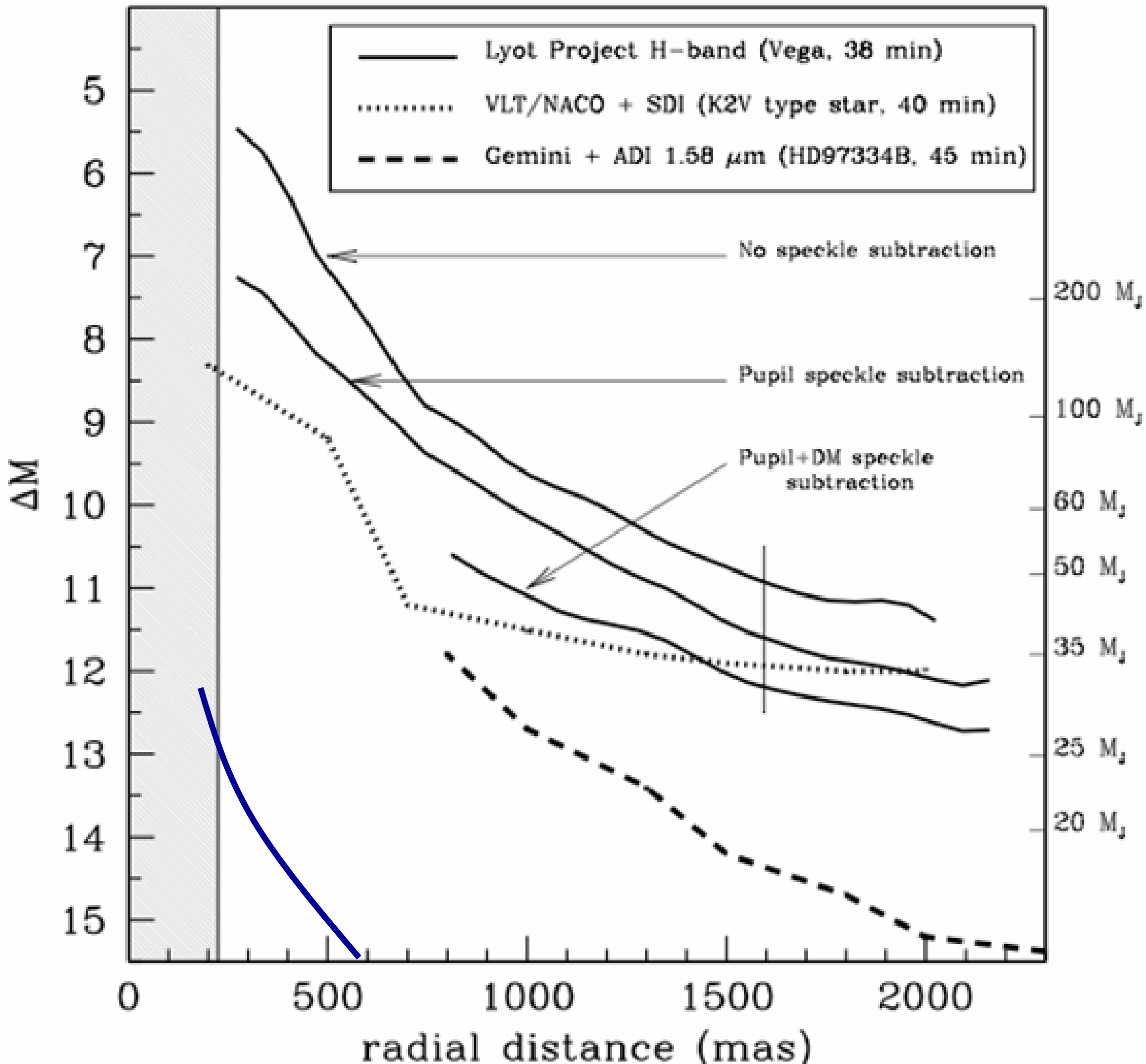
What is needed to get there?

- Adaptive Optics
  - Faster, better
  - Fewer **speckles**
- Coronagraph
  - Better suppression of central star
  - Less **speckle** amplification
- Science camera
  - Integral Field Spectrograph
  - Better **speckle** identification
- Data analysis
  - Better **speckle** subtraction



Multi-wavelength imaging (MWI)

λ=1.2 – 0.8 microns SR ~85% at H-band (simulation)

QuickTime™ and a
Animation decompressor
are needed to see this picture.

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Animation decompressor
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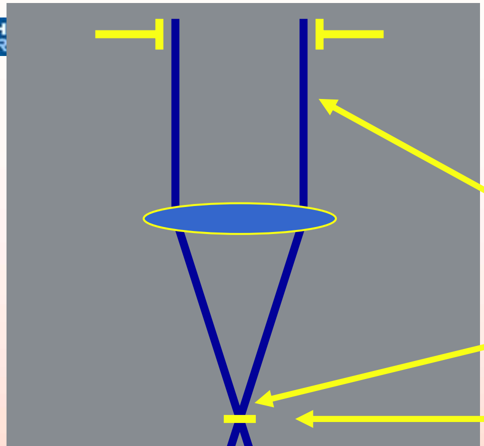
Remi Soummer

Coronagraphic train

Suppress unaberrated light from the on-axis star



Entrance pupil or aperture of telescope

First image plane - “direct image”

Opaque stop or transmissive but phase-changing stop “focal plane mask” (FPM)

Coronagraphic train

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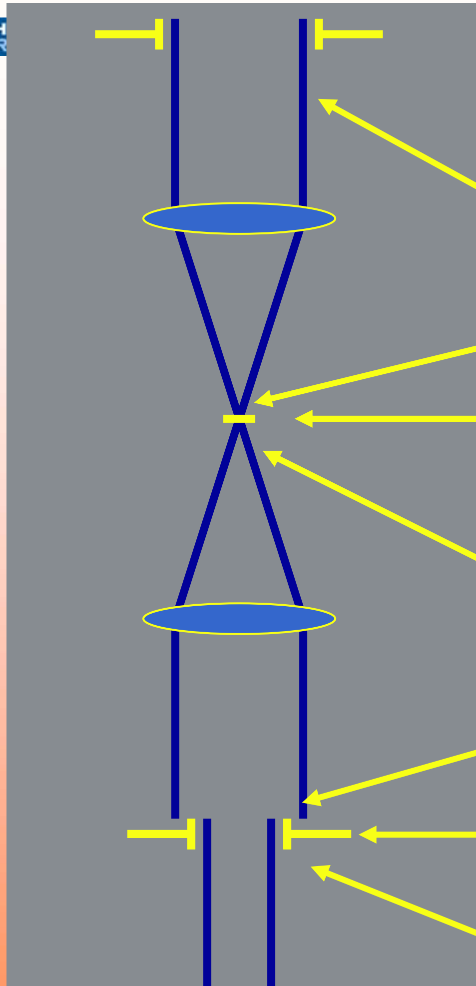

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Occulted image after FPM

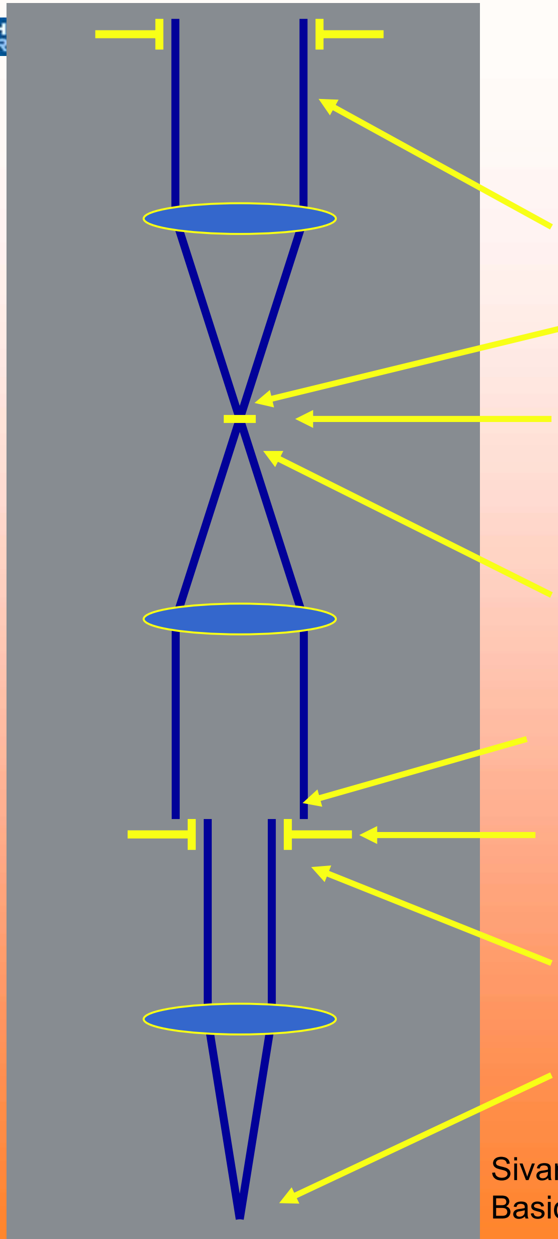
Re-imaged pupil: "Lyot pupil"

Lyot stop: smaller than aperture for opaque FPM or the same size for phase mask coronagraphy

'Stopped down' Lyot pupil

Coronagraphic train

Suppress unaberrated light from the on-axis star



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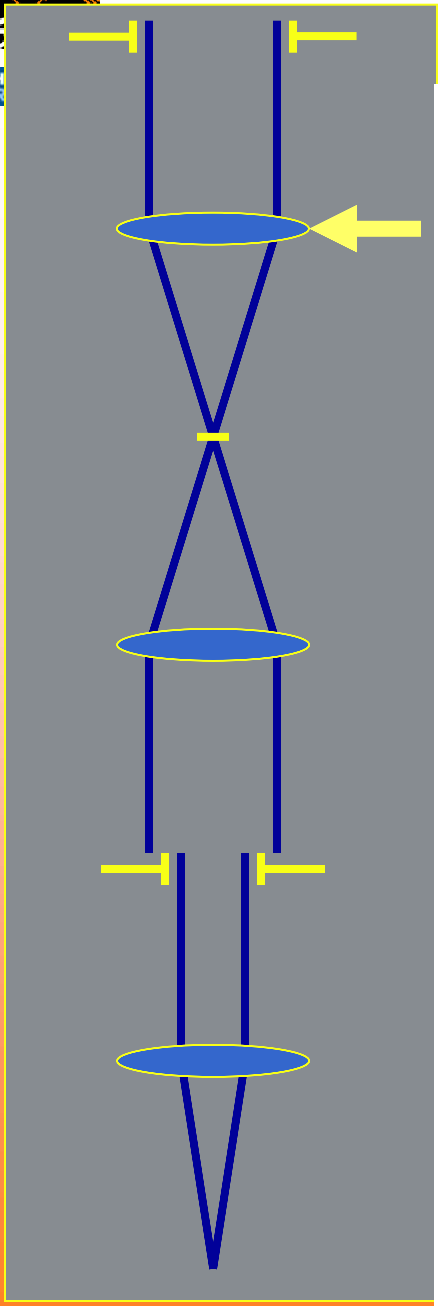
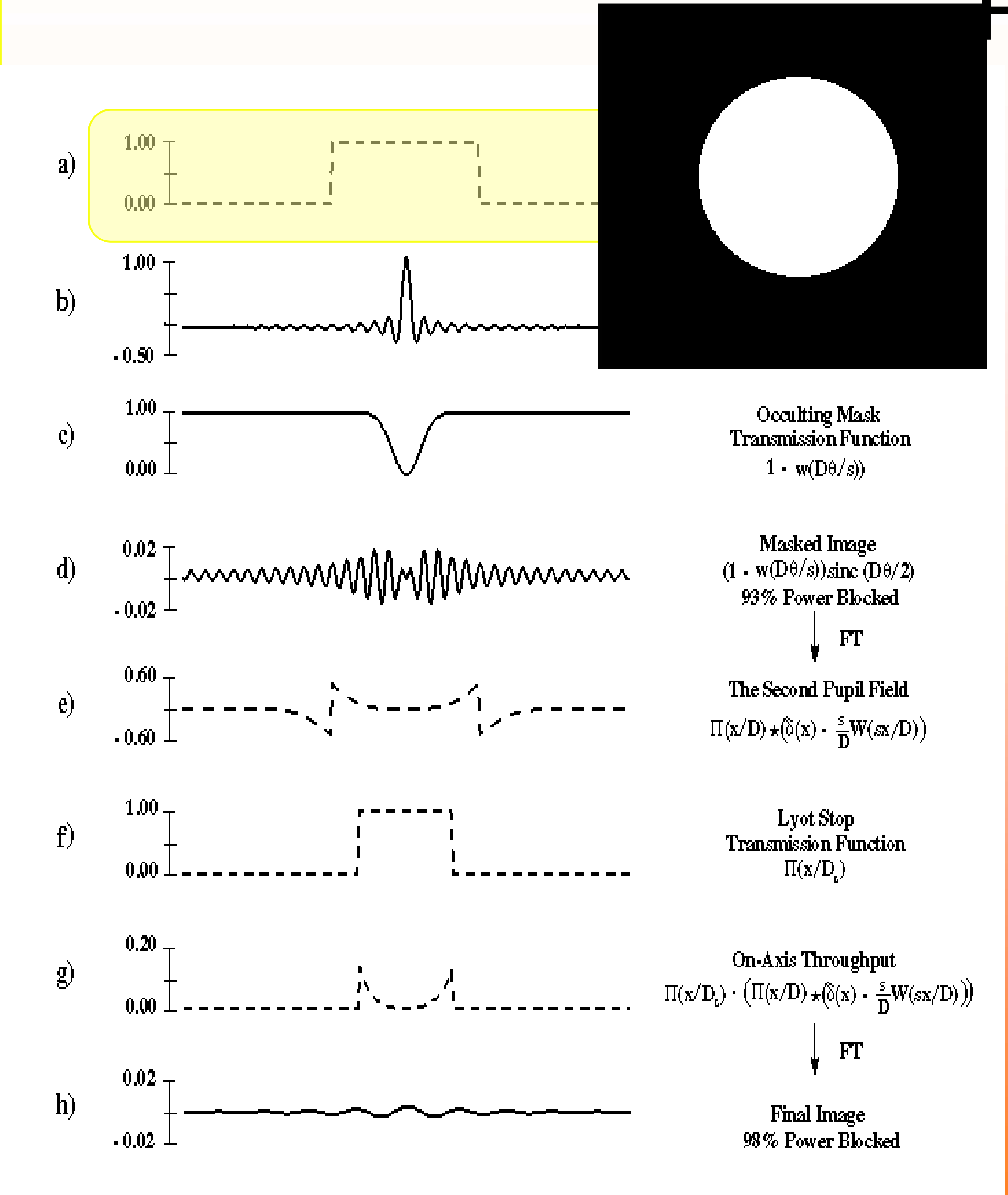
Final coronagraphic image

Sivaramakrishnan, Koresko, Makidon, Berkefeld, Kuchner (2001) ApJ 552, 397
Basic coronagraphic theory, mask optimization, Gemini ExAO simulation

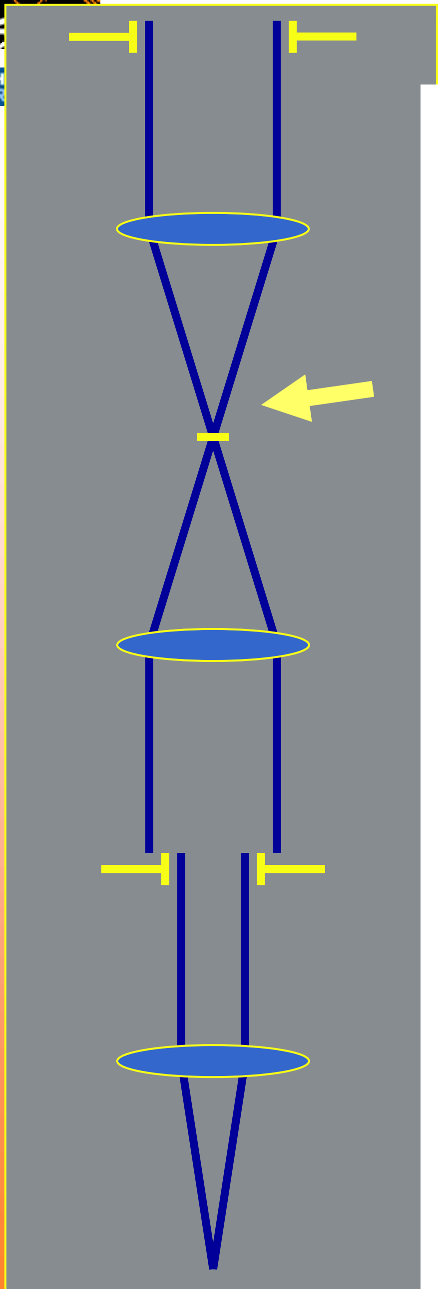
Pupil

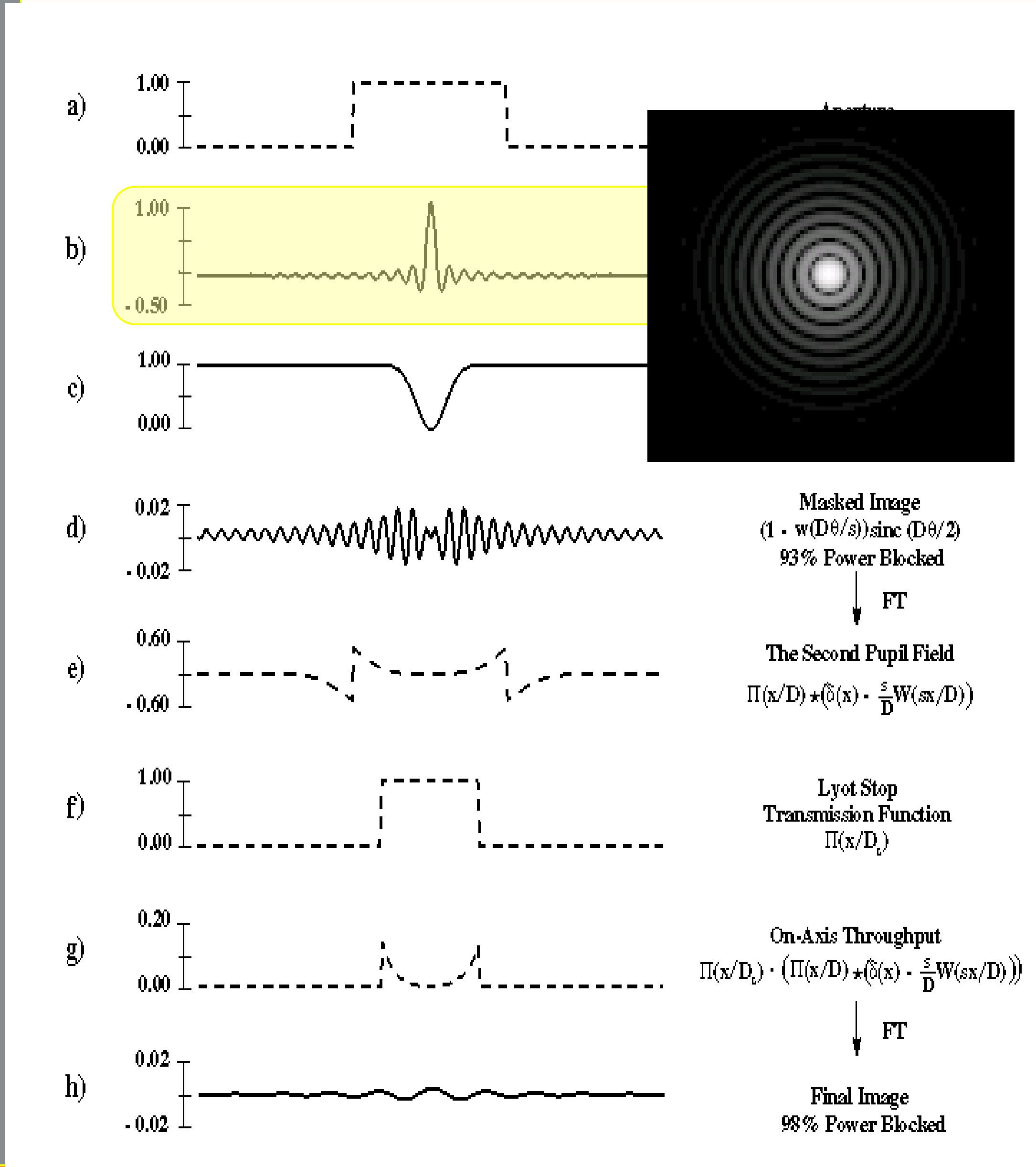




a)
1.00
0.00
b)
1.00
-0.50
c)
1.00
0.00
Occulting Mask
Transmission Function
1 - w(Dθ/s))
d)
0.02
-0.02
Masked Image
(1 - w(Dθ/s))sinc (Dθ/2)
93% Power Blocked
FT
e)
0.60
-0.60
The Second Pupil Field
f)
1.00
0.00
Lyot Stop
Transmission Function
g)
0.20
0.00
On-Axis Throughput
FT
h)
0.02
-0.02
Final Image
98% Power Blocked

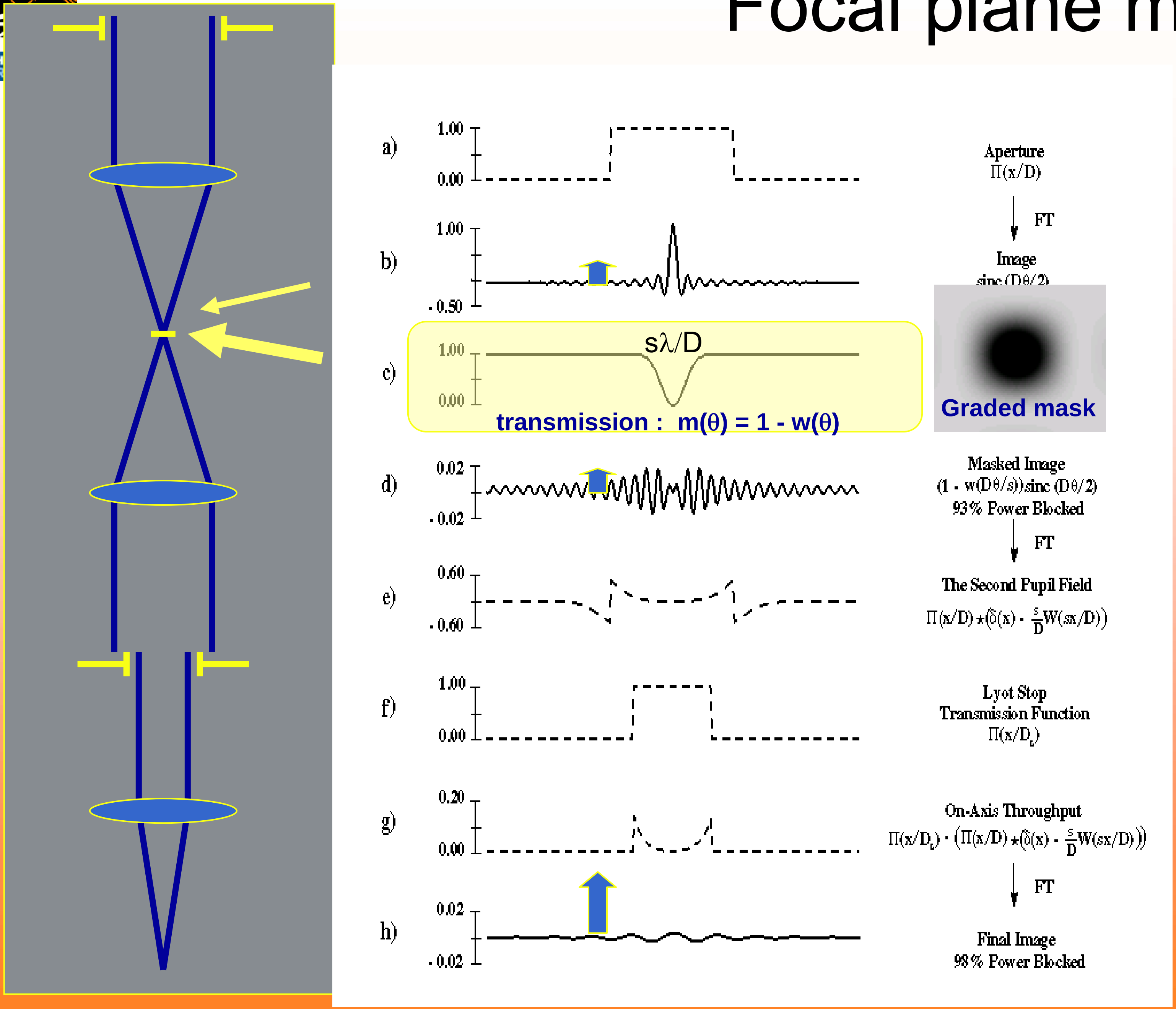
Image



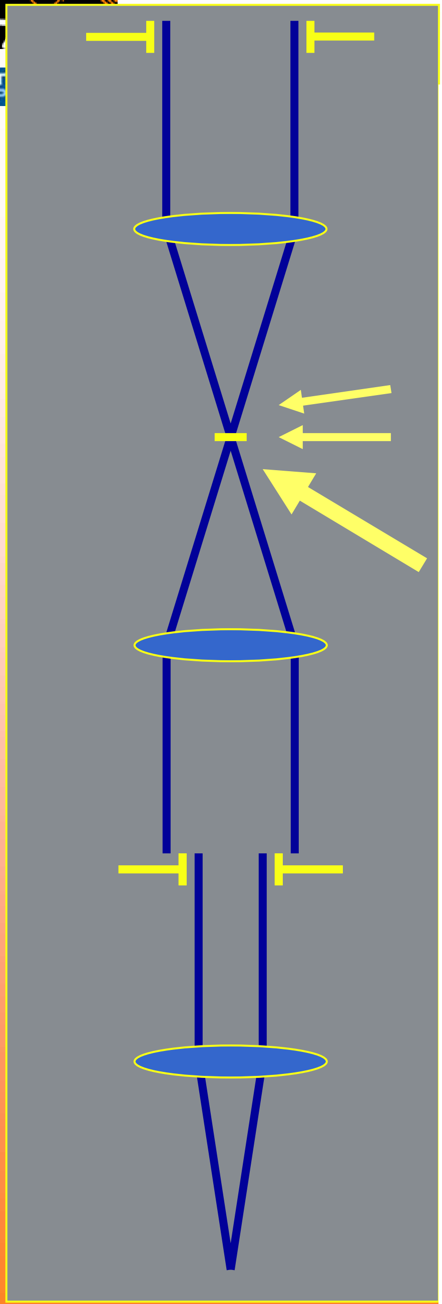


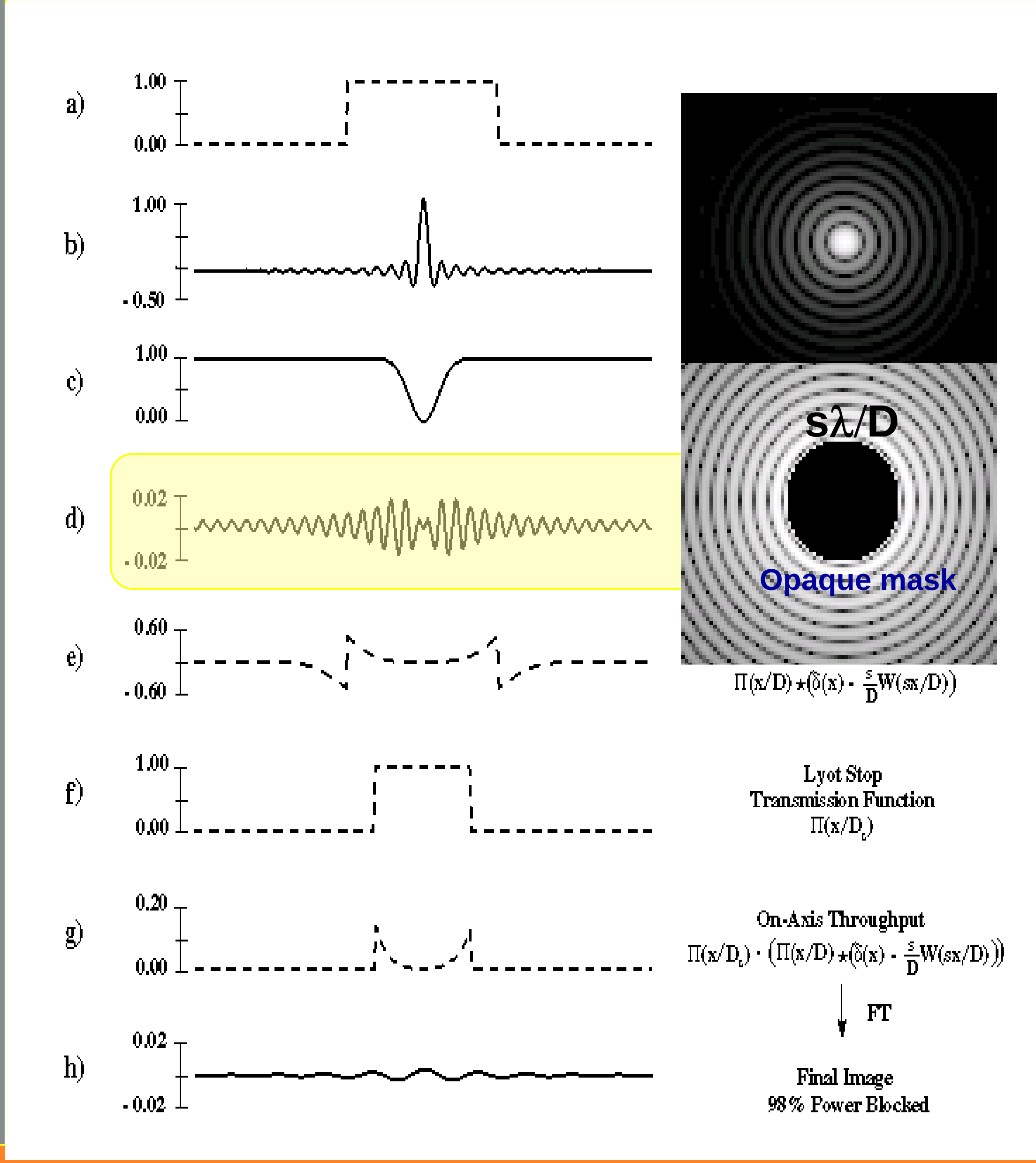
a)
b)
c)
d)
e)
f)
g)
h)
Masked Image
(1 - w(Dθ/s))sinc (Dθ/2)
93% Power Blocked
FT
The Second Pupil Field
Π(x/D)⋆(δ(x) - s/D W(sx/D))
Lyot Stop
Transmission Function
Π(x/D_L)
On-Axis Throughput
Π(x/D_L) · (Π(x/D)⋆(δ(x) - s/D W(sx/D)))
FT
Final Image
98% Power Blocked

Focal plane mask

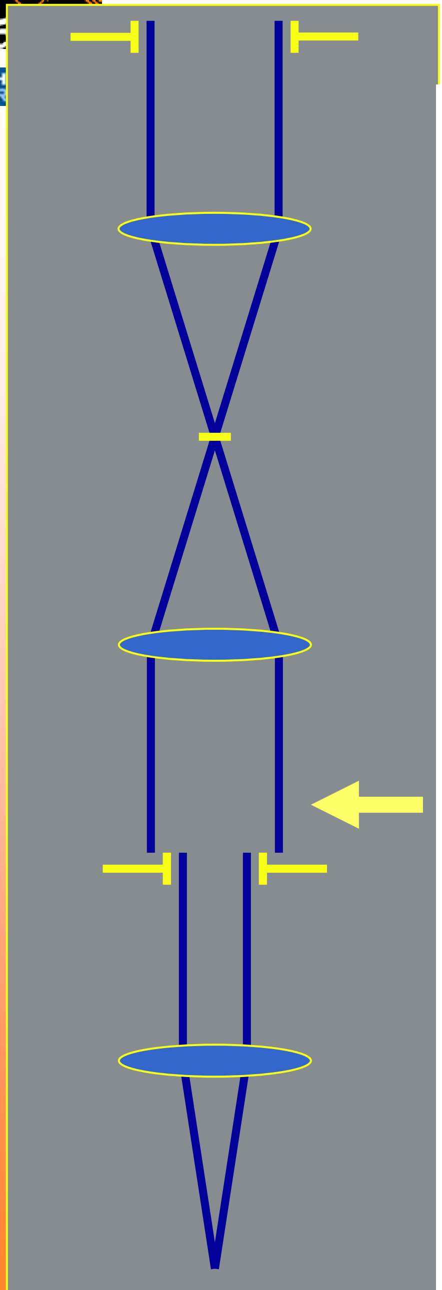


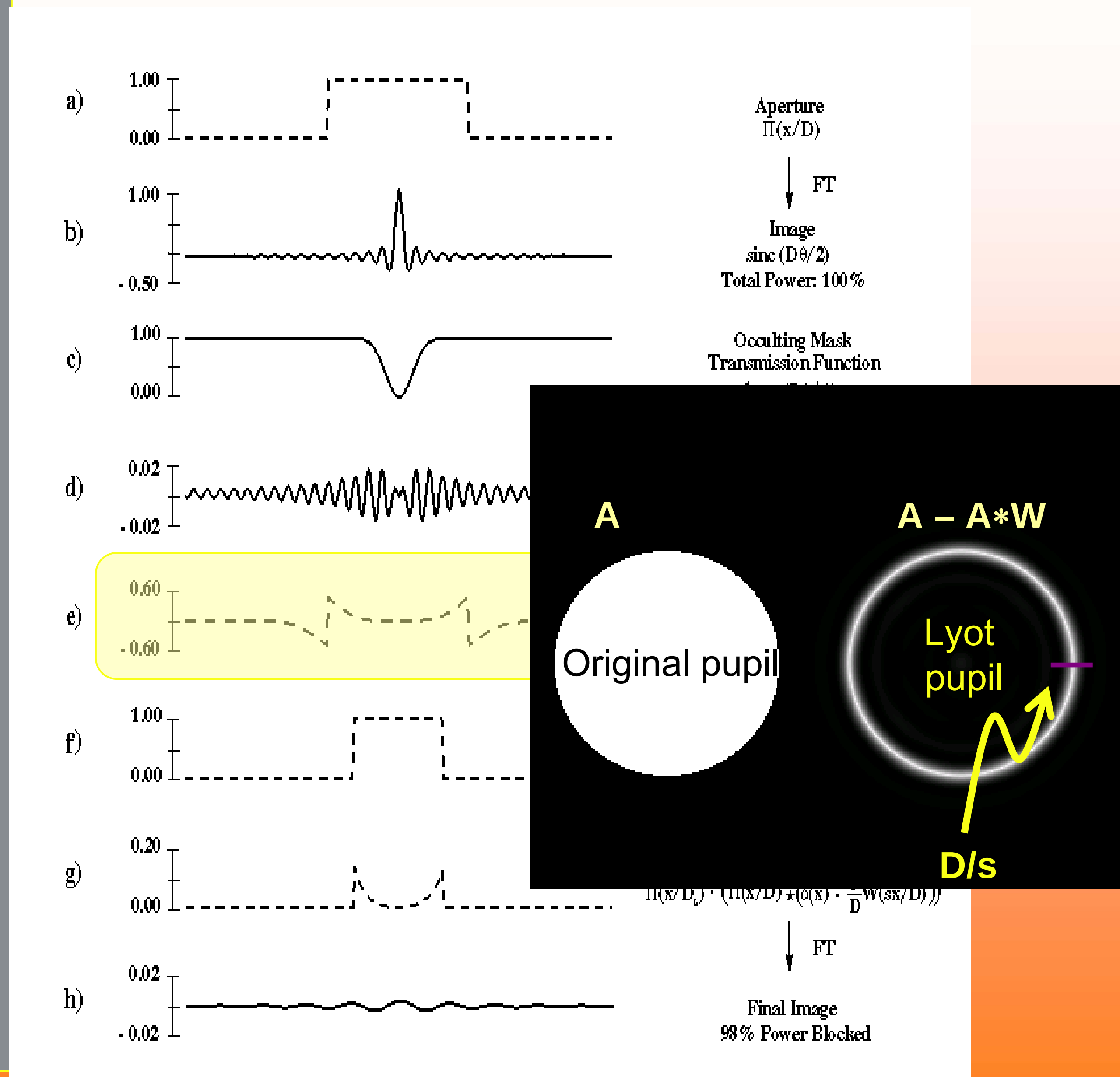
Occulted image





Lyot pupil



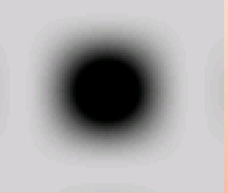


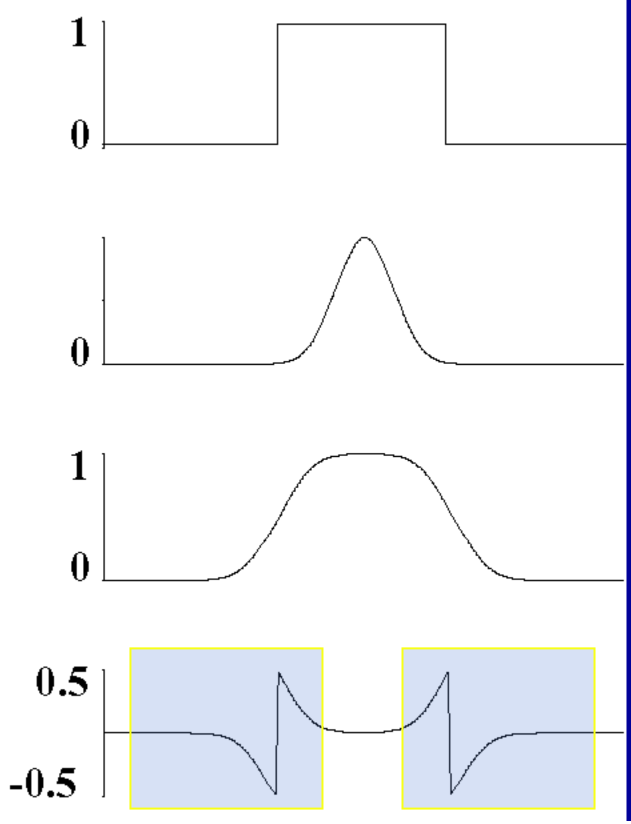
a)
1.00
0.00
Aperture
Π(x/D)
FT
b)
1.00
-0.50
Image
sinc(Dθ/2)
Total Power: 100%
c)
1.00
0.00
Occulting Mask
Transmission Function
d)
0.02
-0.02
e)
0.60
-0.60
f)
1.00
0.00
g)
0.20
0.00
FT
h)
0.02
-0.02
Final Image
98% Power Blocked
A
A – A∗W
Original pupil
Lyot
pupil
D/s

Lyot field construction

Sivaramakrishnan, Koresko, Makidon, Berkefeld, & Kuchner (2001) ApJ

Gaussian
occulting stop
5 λ/D FWHM





Entrance aperture function: A(x)

FT of image plane occulting spot's density profile: W(x)

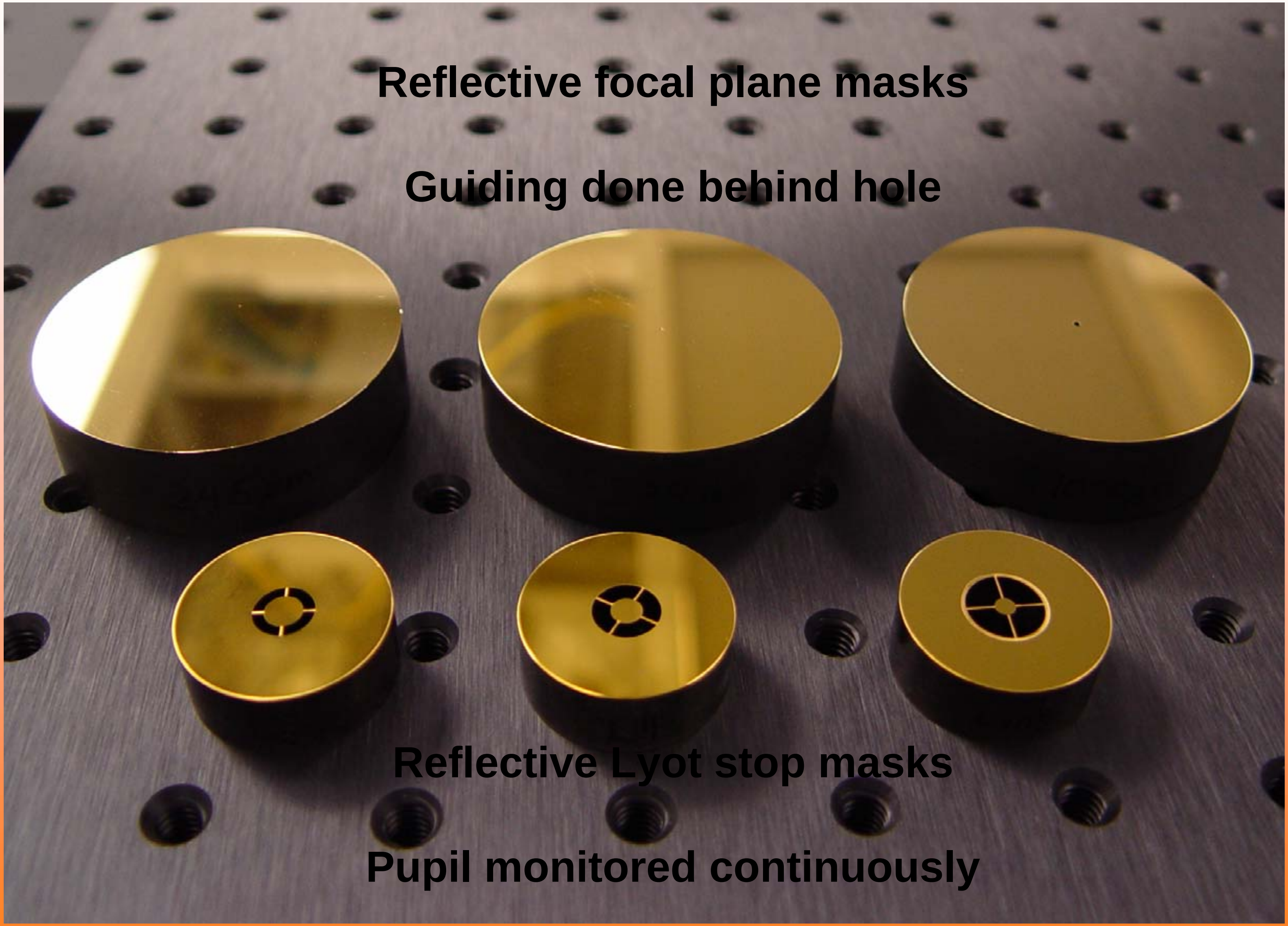
$A(x) * W(x)$

Lyot pupil field
$A(x) - A(x) * W(x)$

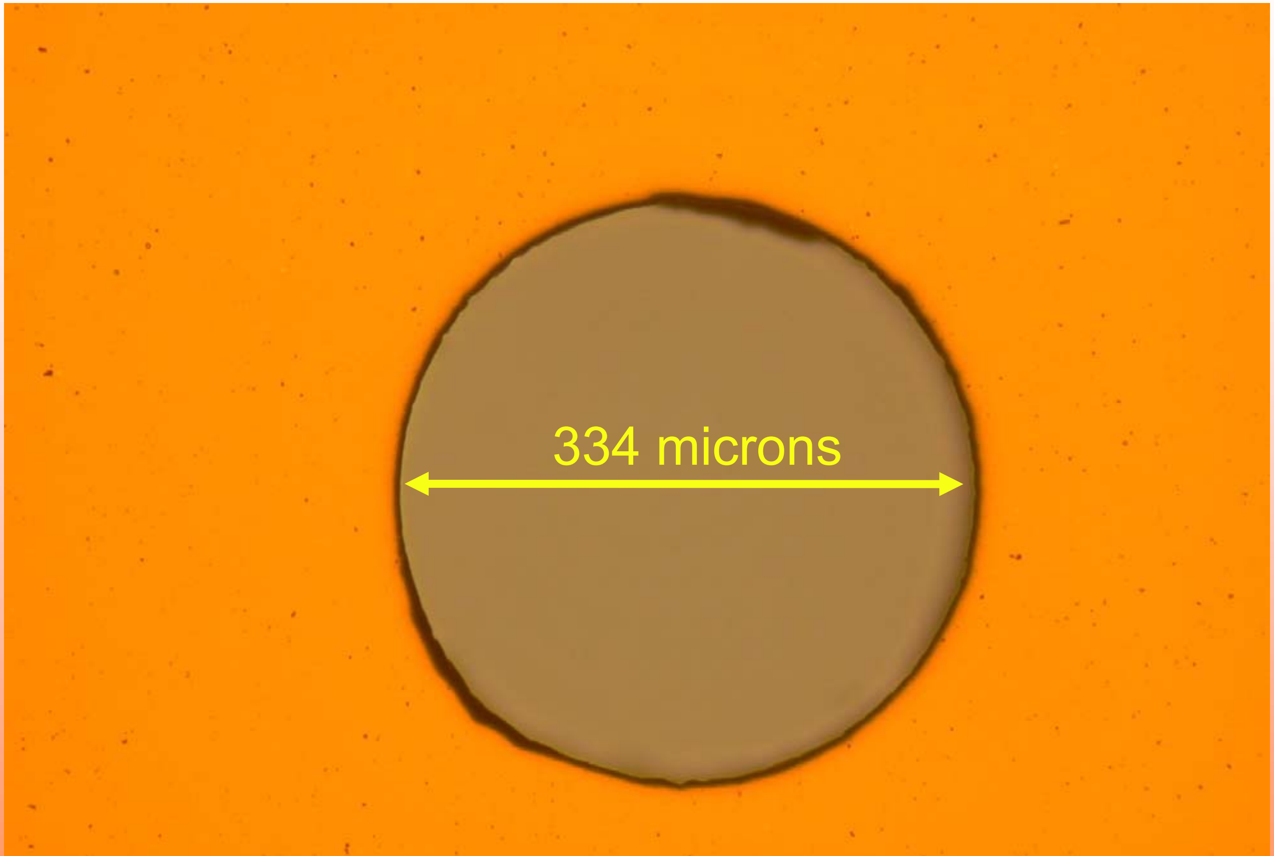
Jean Baptiste Joseph Fourier: if w, W are transform pairs,
the product of their equivalent widths is unity, or EW(W) = 1/EW(w)

Optimized masks

Oppenheimer, Sivaramakrishnan & Makidon



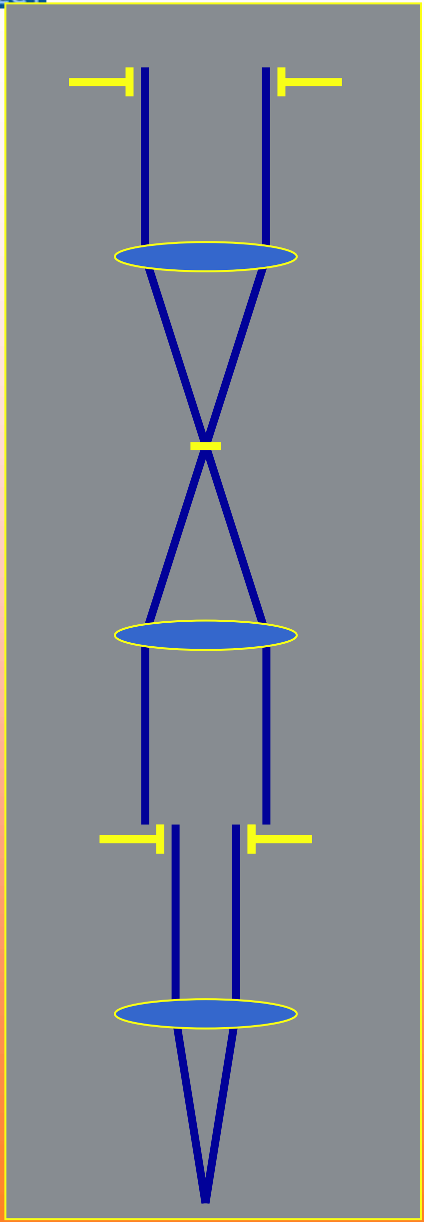
Focal plane mask quality



Microscope Image by Jacob Mey and Charlie Mandeville
(AMNH EPS Microprobe Lab, Lyot Project)

How do small imperfections affect performance?

Effects of tip-tilt

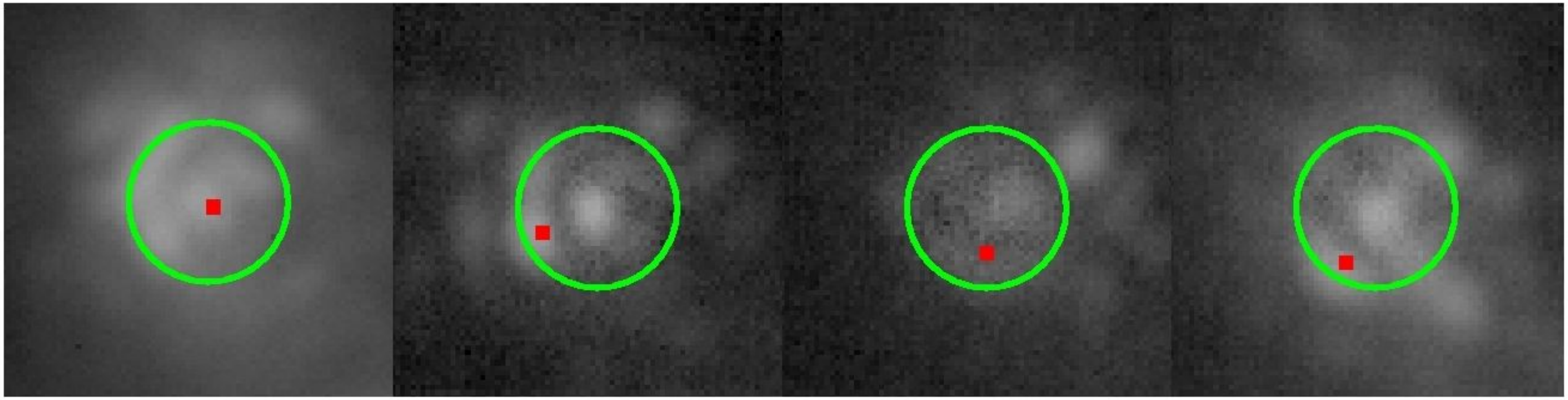


QuickTime™ and a
Animation decompressor
are needed to see this picture.

Movie of 50 minutes of Lyot Project H-band data (2004)

Effects of tip-tilt

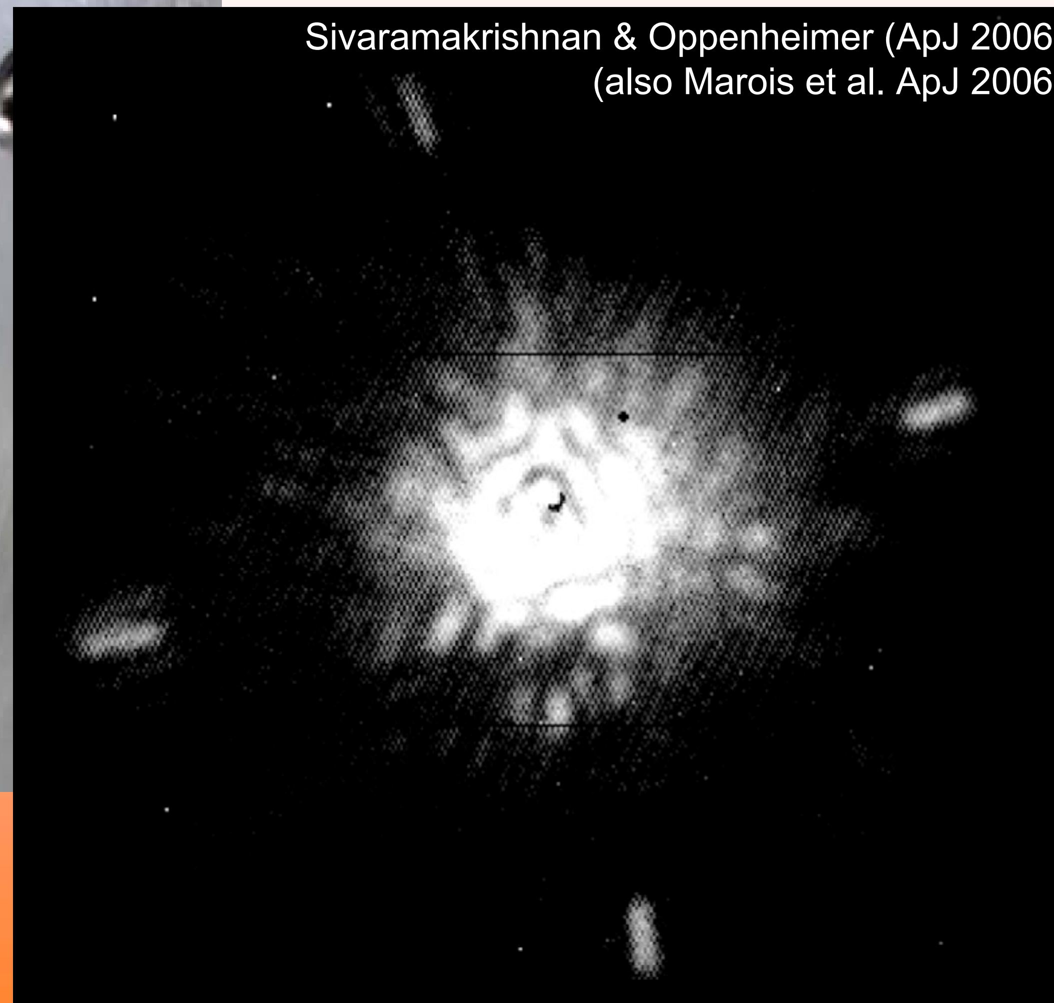
Digby et al. (2006)



Guessing game: Where is the central star?

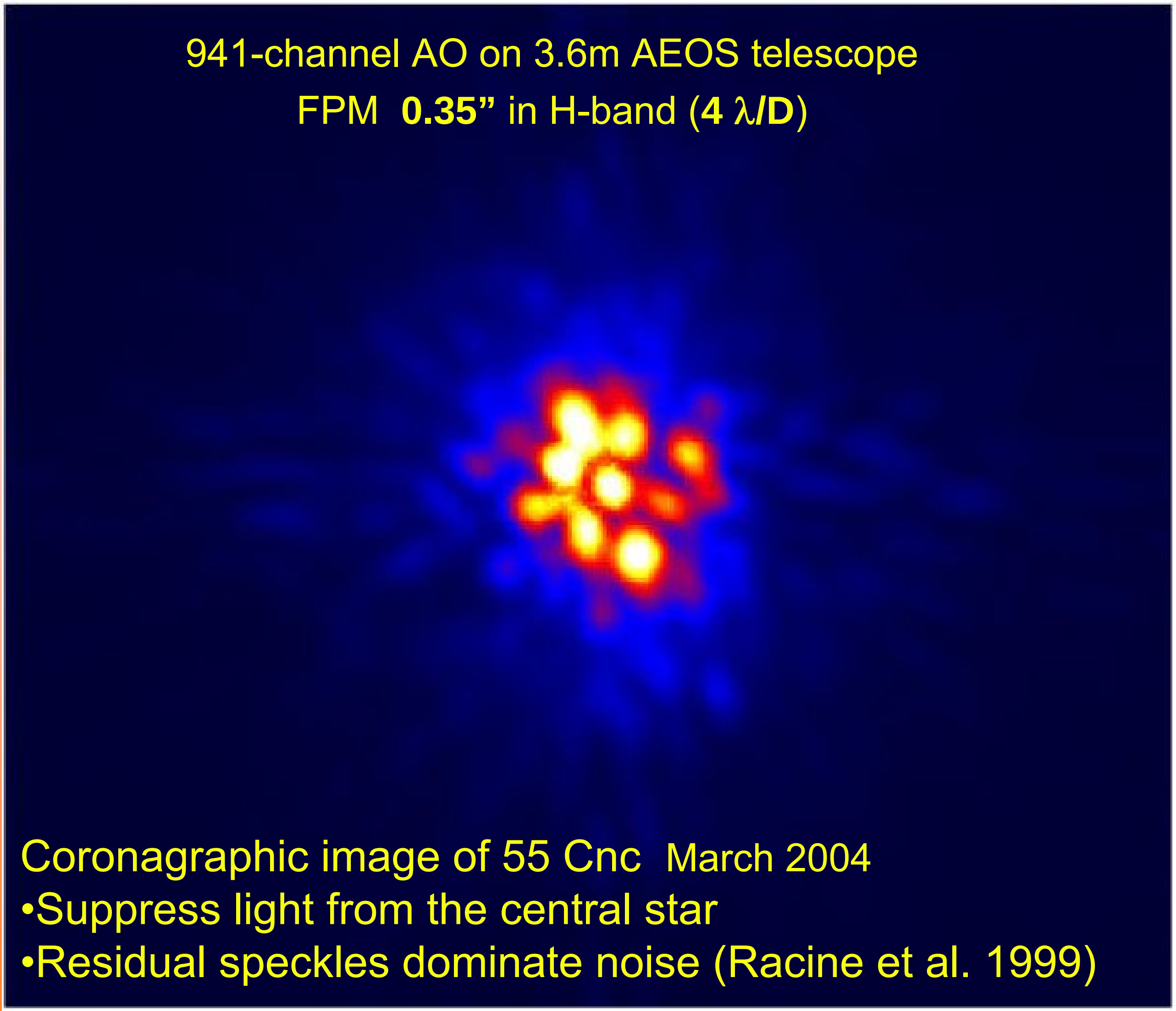
Prizes for a fast answer include:
- Shorter survey length (ground)
- Shorter mission duration (space)

Effects of tip-tilt



Lyot Project first light

Oppenheimeret al.



What is a speckle?

Think Fourier

sin(x) <=> 2 δ's

First order

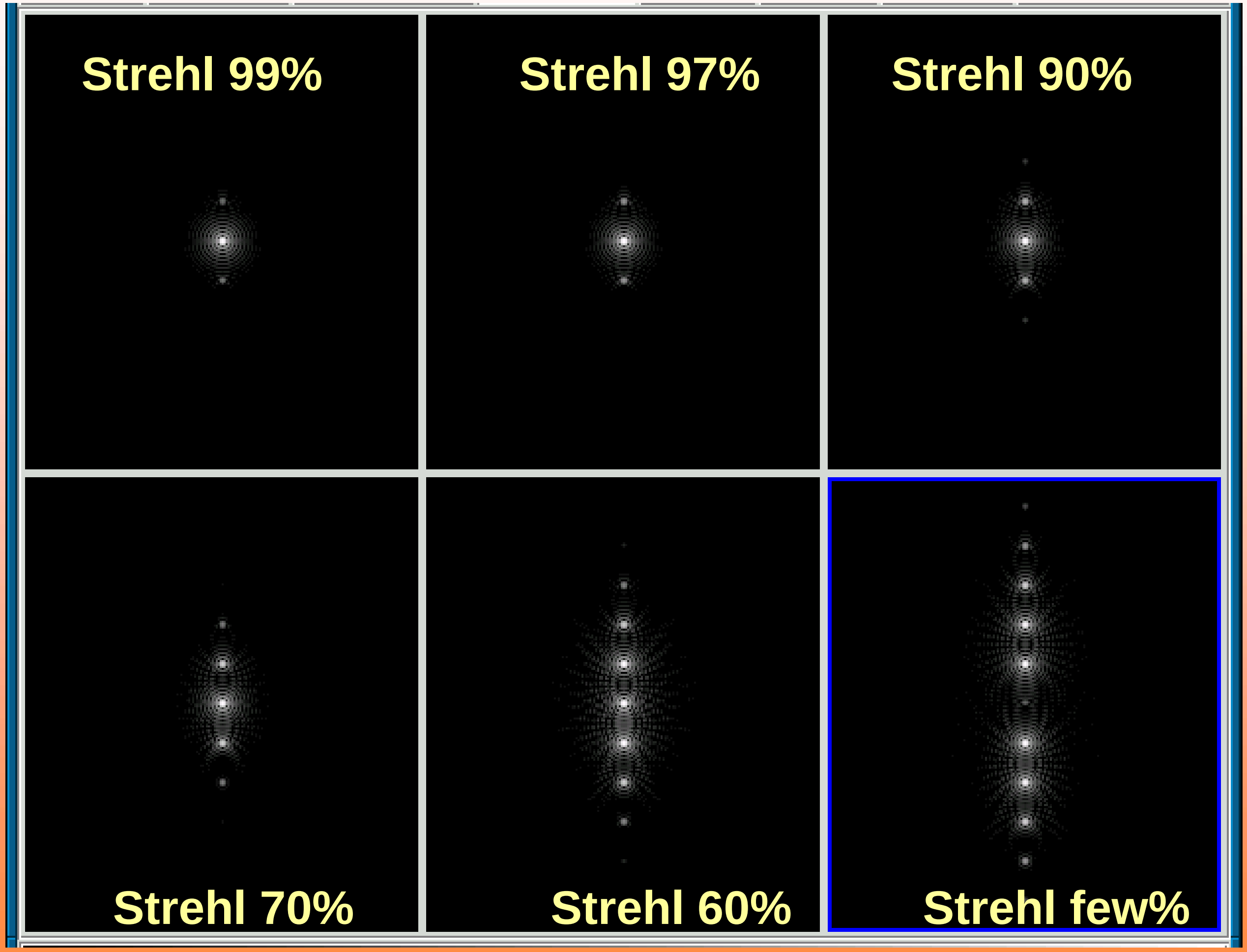
Pupil: $\exp(i\phi) \sim 1 + i\phi + ...$

Set $\phi = \varepsilon \sin(2n\pi x/D)$

Image: $\delta(0) + \varepsilon\, FT(\sin) + \ldots$

Higher order

The … terms create higher frequency harmonics



Speckle theory - approach

Sivaramakrishnan, Lloyd, Hodge and Macintosh (2002) ApJL

Aperture A(x,y): real function

Phase $\phi(x,y)$: real function

Electric field over aperture: $A \exp(i\,\phi) = A\,A_f$

For $\phi < 1$ truncate expansion of $\exp(i\,\phi)$ at second order in ϕ :

$$A_{AO} = AA_{\phi} = A(1 + i\phi - \phi^2/2 + \ldots).$$

FT this to get image plane electric field

Speckle theory - results

Sivaramakrishnan, Lloyd, Hodge and Macintosh (2002) ApJL

A, a are FT pairs F, f are FT pairs star is convolution

$$\begin{aligned} p_{AO} &= p_0 + p_1 + p_2 \\ &= aa^* \\ &\quad -i[a(a^* \star \Phi^*) - a^*(a \star \Phi)] \\ &\quad +(a \star \Phi)(a^* \star \Phi^*) \\ &\quad -\frac{1}{2}[a(a^* \star \Phi^* \star \Phi^*) + a^*(a \star \Phi \star \Phi)], \end{aligned}$$

$$p_1 = -i[a(a^* \star \Phi^*) - a^*(a \star \Phi)] = 2\mathrm{Im}[(a(a^* \star \Phi^*))],$$

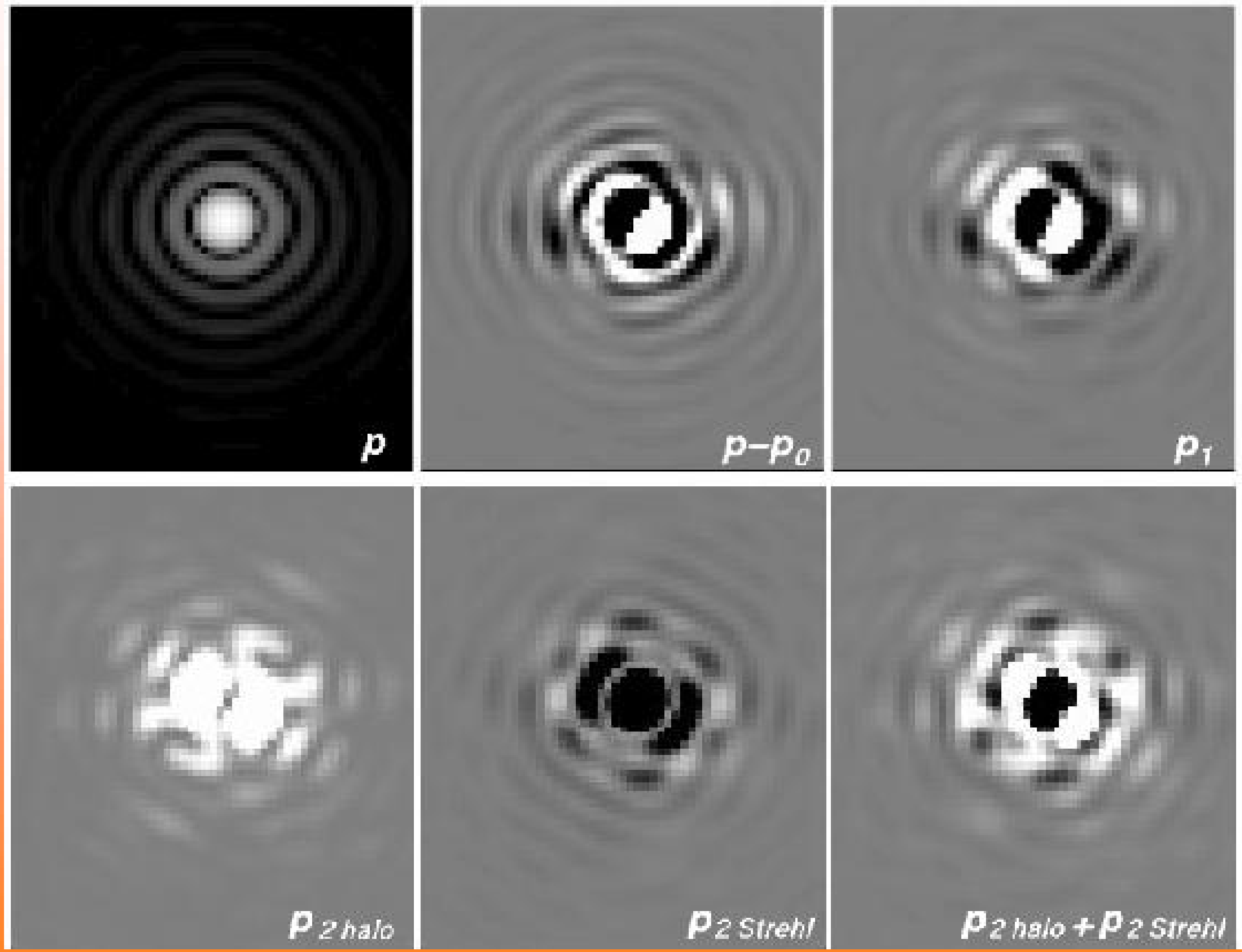
$$p_2 = (a \star \Phi)(a^* \star \Phi^*) - \frac{1}{2}[a(a^* \star \Phi^* \star \Phi^*) + a^*(a \star \Phi \star \Phi)].$$

First order pinned speckle (Bloemhof ApJL 2000)
Second order halo, second order Strehl term

Enables analytical proof that “Speckle Decorrelation” (Angel 1994) idea does not work

Speckle theory - pictures

Perrin, Sivaramakrishnan, Makidon, Oppenheimer, Graham (Oct 2003) ApJ



Speckle theory - infinite order expansion

Perrin, Sivaramakrishnan, Makidon, Oppenheimer, Graham (Oct 2003) ApJ

$$A_{AO} = AA_\phi = A(1 + i\phi - \phi^2/2 + \ldots).$$

$$a_{ao} = \sum_{k=0}^{\infty} \frac{i^k}{k!}(a \star^k \Phi),$$

$$p_{AO} = \sum_{k=0}^{\infty} \sum_{j=0}^{\infty} \frac{i^k}{k!}(a \star^k \Phi) \frac{(-i)^j}{j!}(a^* \star^j \Phi^*).$$

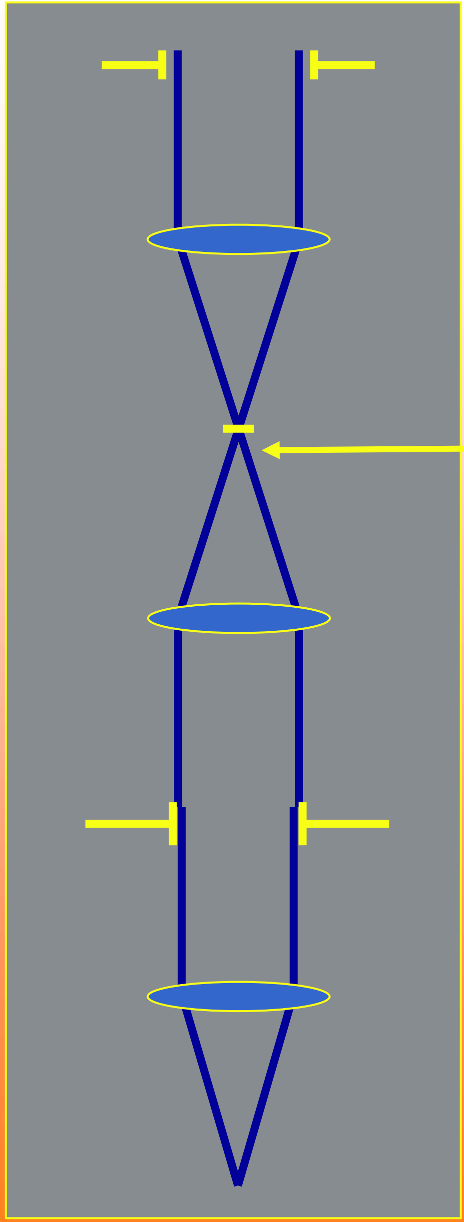
$$p_{AO} = \sum_{n=0}^{\infty} \sum_{k=0}^{n} \frac{i^k (-i)^{n-k}}{k!(n-k)!}(a \star^k \Phi)(a^* \star^{n-k} \Phi^*).$$

$$p_n = i^n \sum_{k=0}^{n} \frac{(-1)^{n-k}}{k!(n-k)!}(a \star^k \Phi)(a^* \star^{n-k} \Phi^*),$$

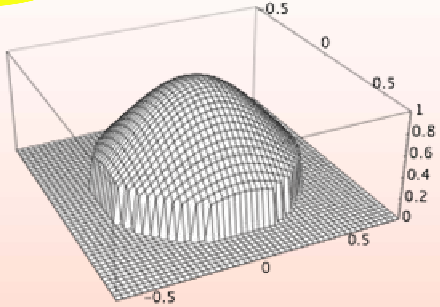
Speckle theory - up to 5th order

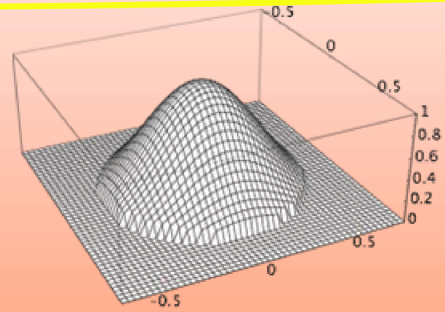
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Apodized pupil Lyot coronagraph

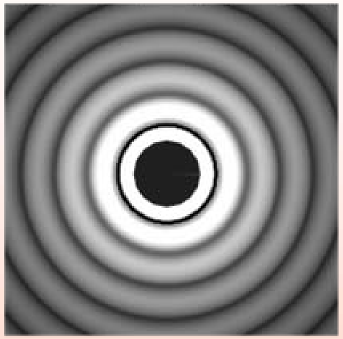


Pupil transmission





PSF intensity

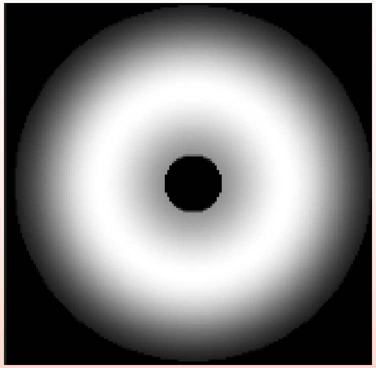


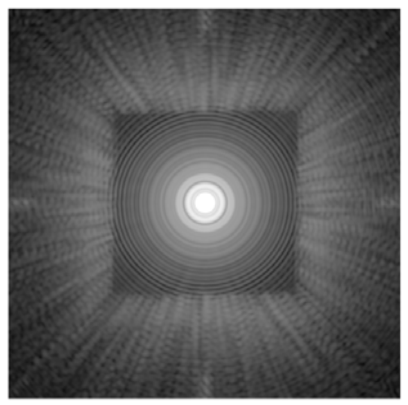
At Lyot pupil no under-sizing required. Increased throughput and resolution

Soummer, Aime & Falloon (2003)
Soummer (2005)

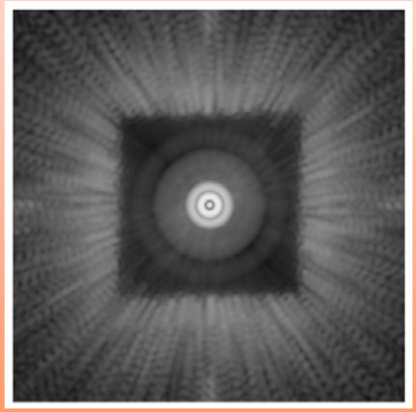
ExAO Apodized pupil Lyot coronagraph

Apodize (shade) entrance pupil -
Reduce "ringing" due to hard edges
and improve dynamic range
Reduces speckle amplitudes
'bagel'

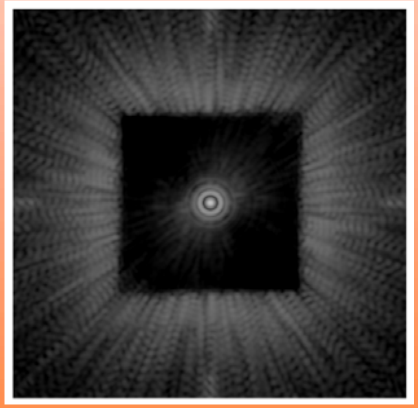




Direct image
PSF



Classical Lyot
coronagraph
PSF



Apodized pupil
Lyot coronagraph
PSF

Coronagraph by Soummer (ApJL 2005)
PAOLA AO simulation by Jolissaint (2005)
Spatially-Filtered Wavefront Sensing AO by Poyneer & Macintosh (JOSA 2004)

Lyot Project first light