Comparative Exoplanetary Science

A Technical Challenge Now, A Galaxy of Worlds Later!

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&
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- American Museum of Natural History
- 22 buildings on 16 acres in Manhattan, numerous field stations around the world
- 220 full time researchers in 9 academic departments
- Over 40 million scientific specimens
- Over 300 expeditions per year
- ~5 million visitors per year
- Division of Physical Sciences includes
  1. Earth and Planetary Science
  2. Astrophysics (~5 years old)

QuickTime™ and a Microsoft Video 1 decompressor are needed to see this picture.

B. Abbott, Digital Universe, Hayden Planetarium: see partiview at haydenplanetarium.org

What is a Planet?

- There is no consensus on a scientific definition:

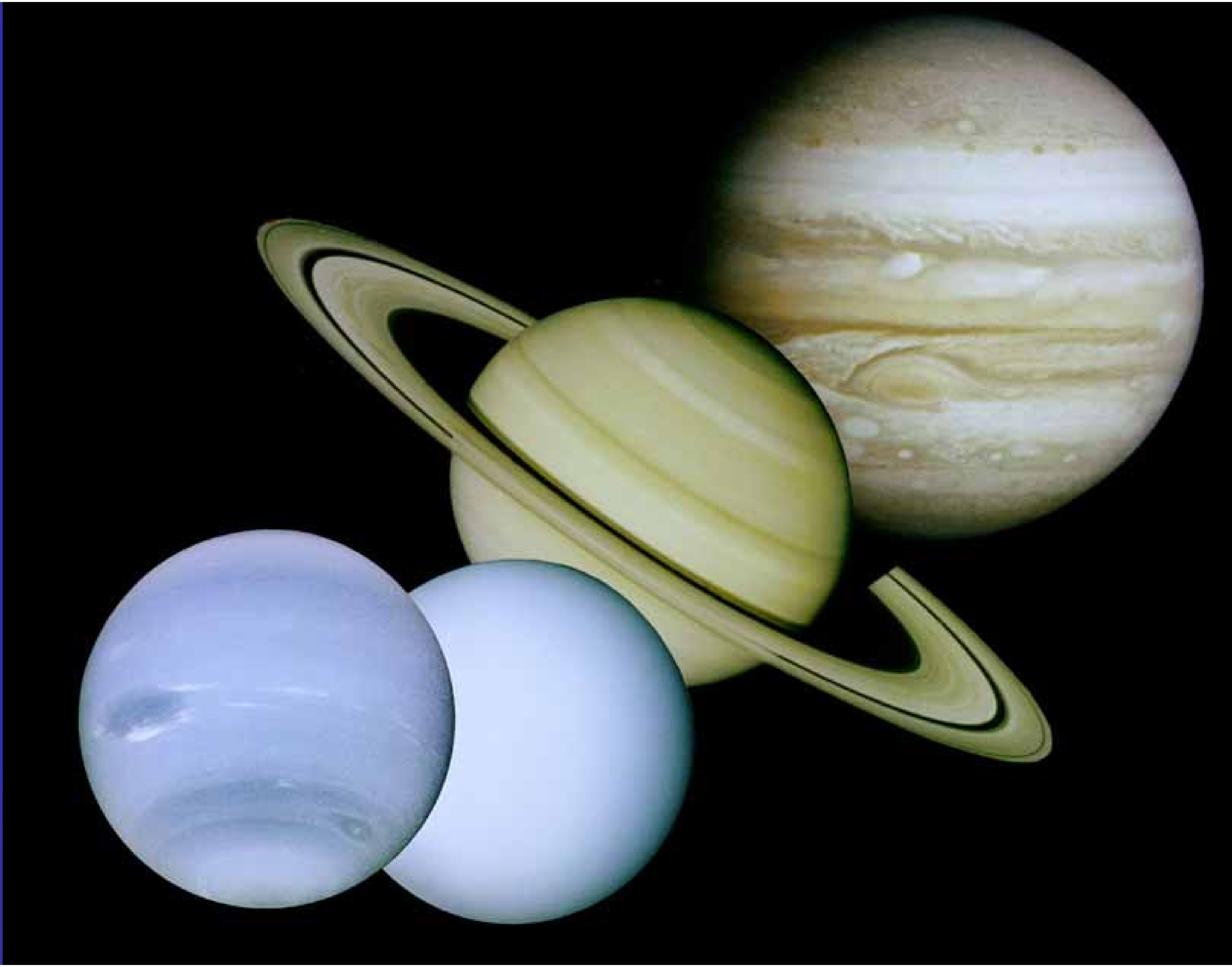
1. Formation Mechanism
2. Interior physics classification (fusion reactions)
3. Wait and see until we have 1000s and classes will be obvious

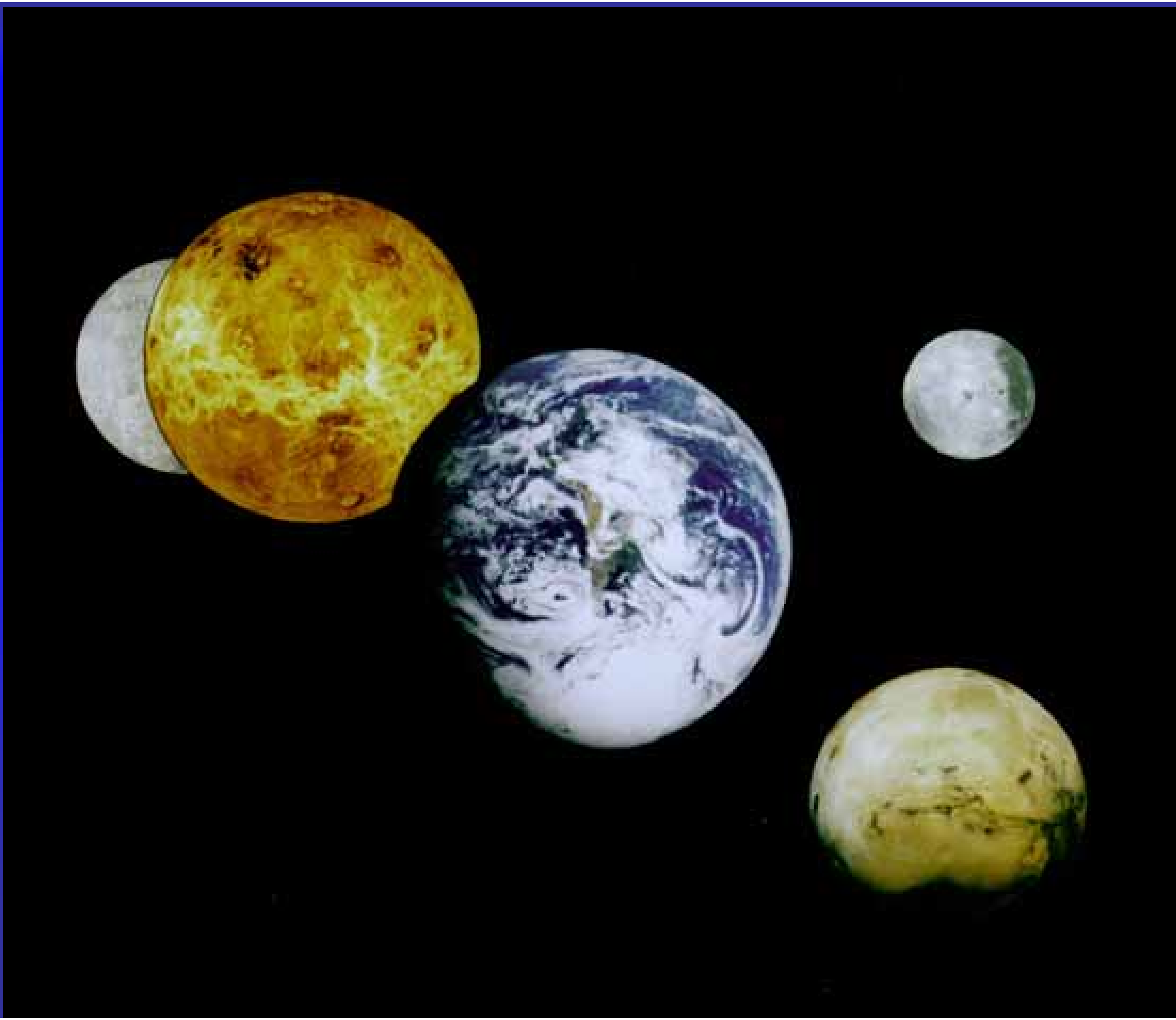
Surprisingly this is a very controversial issue!

Oppenheimer (2005)

Planets are different from other celestial objects

- Vogt-Russell Theorem: "mass and chemical composition are sufficient to completely determine the structure, evolution and outward appearance of a star" (This principle has guided astrophysics theory well beyond stellar structure.)
- Planets have a diversity unmatched in astronomy





Where does the Vogt-Russell Theorem break down?

- The onset of complexity perhaps begins in the brown dwarf mass range:
- Mass-Composition-Age
- In coolest or lowest mass BDs, more complexity: The chemistry and SEDs are drastically affected by minor changes in composition

A few simple parameters are insufficient to determine a planet's salient features.

(This is why I am not a theorist, but I will offer a solution to this problem!)

Comparative ~~Ex~~oplanetary Science

- Observe individual planets in great detail
  - atmospheres, internal physics, geology and perhaps biology
- Observe as many planets as possible
  - At different ages, in different environments and with a broad range of parent stars (including pulsars and white dwarfs, giants and subgiants)

- A tiny taste of what we might learn:
  - What do 50 different $1M_J$ planets have in common?
  - What does a young (or old) Earth mass planet look like?
  - What is a 5 Earth mass planet?
  - Astrolinguistics

How do we do detailed observations?

- We must obtain images and spectra
  - Some very limited techniques can do this now (individual spectral lines for eclipsing systems)
  - Generally requires direct detection: a spatial separation of the planet light from star light
- In the Future:
  - Surface imaging (**very** high resolution imaging)
  - Manned missions (requires some new physics)

Things you need to know to get into this game:

1. Fourier Analysis (Bracewell, 1986 is excellent)
2. Fourier and Fresnel Optics (numerous books)
3. Rudimentary Atmospheric Science (Kolmogorov)
4. Stellar Structure
5. Planet and Brown Dwarf Structure
6. Astrometry (milliarcsec level)
7. Photometry (AO PSF photometry, very little written)
8. Interferometry (Optical/Near IR and sub-mm/radio)
9. Control Theory
10. Signal Processing (can’t be an astronomer without this)
11. As much electronics as possible
12. As much computer expertise as reasonable (don’t get sucked in)
13. Photodetectors (very broad subject, read everything)
14. Mechanical engineering (basic static and dynamic)
15. Thermal engineering
16. Microelectronics (MEMs)
17. Laser physics and laser technology
18. Wavefront control (heritage from weapons systems)

19. HOW TO WRITE (practice, practice practice)

Imaging Exoplanets

Technical Requirements:

1. Angular Resolution

Distance	**10 pc**	**15 pc**	**30 pc**
Maximum Angular Separation: 1 AU orbit	100 mas	67 mas	33.3 mas
Required Telescope Diameter for observations at $\lambda = 1\ \mu m$	2.1 m	3.1 m	6.2 m
Approx. No. Stars Known	325	877	3508

Imaging Exoplanets

Technical Requirements:

2. Contrast

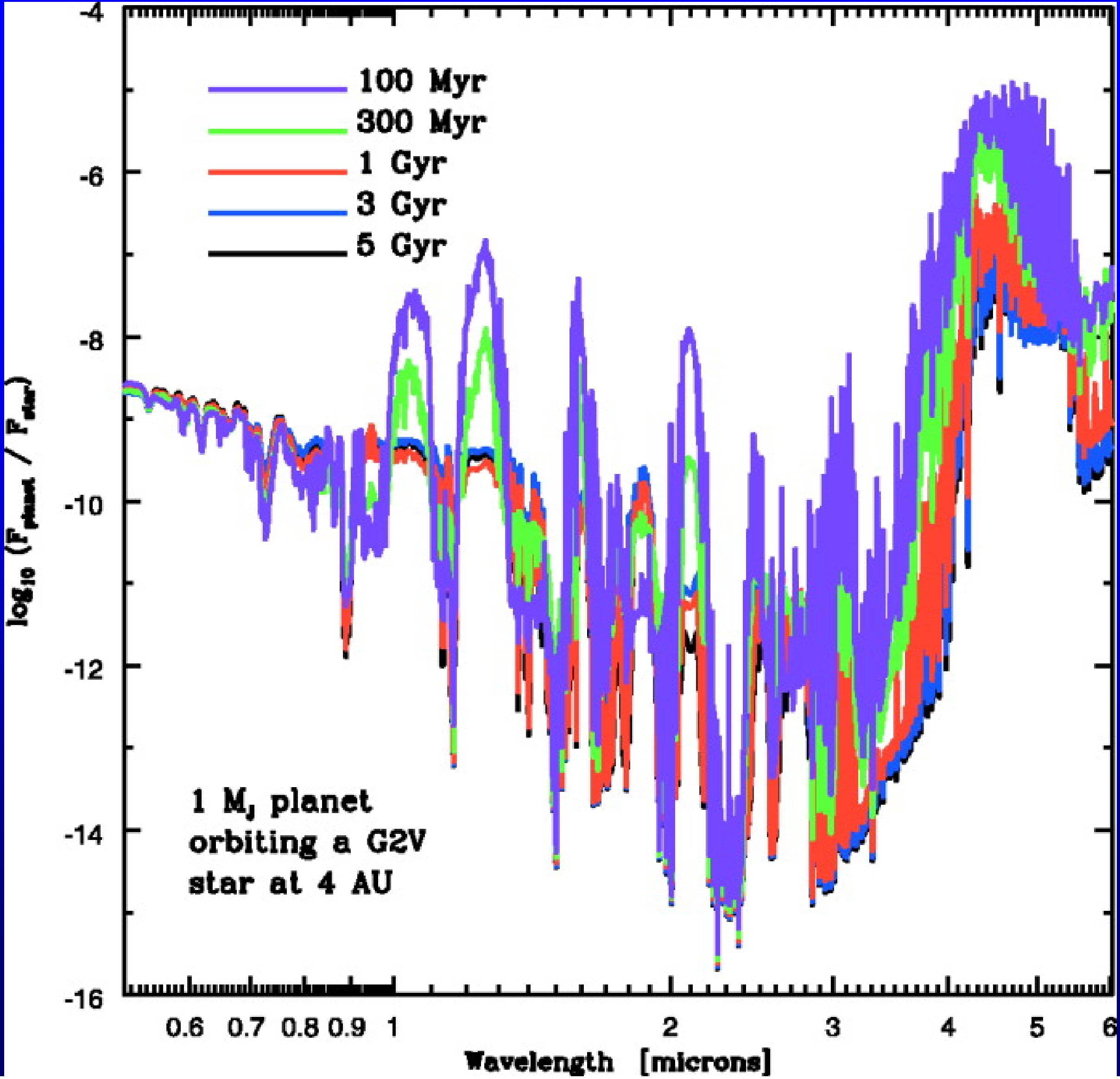
For exact analog of the solar system at 10 pc,

Jupiter: $> 10^8 \times$ fainter than Sun, 0.5 arcsec away

Earth: $> 10^{10} \times$ fainter, 0.1 arsec away

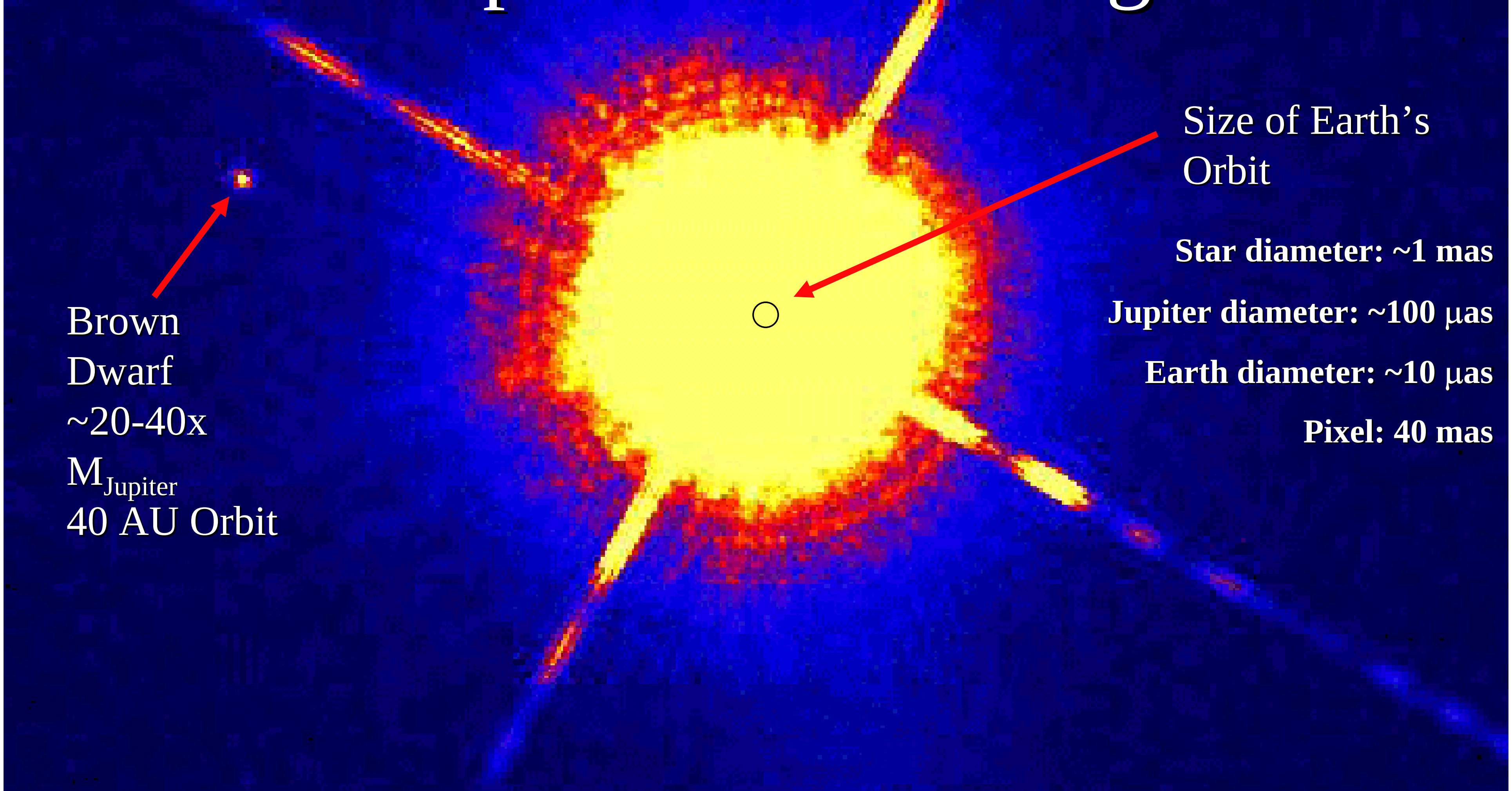
100 x better than current imaging technology in any field

More Sophisticated Contrasts Needs



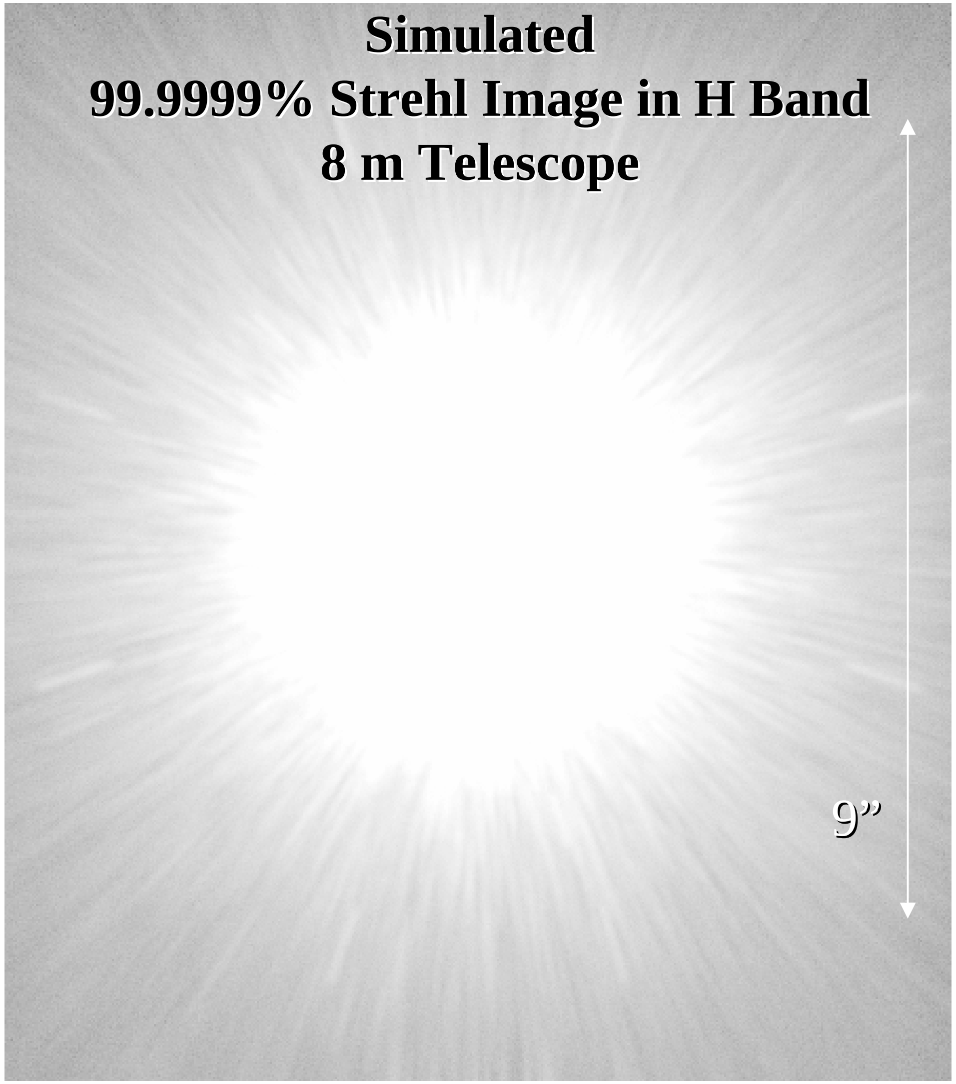
Burrows et al. (2004)

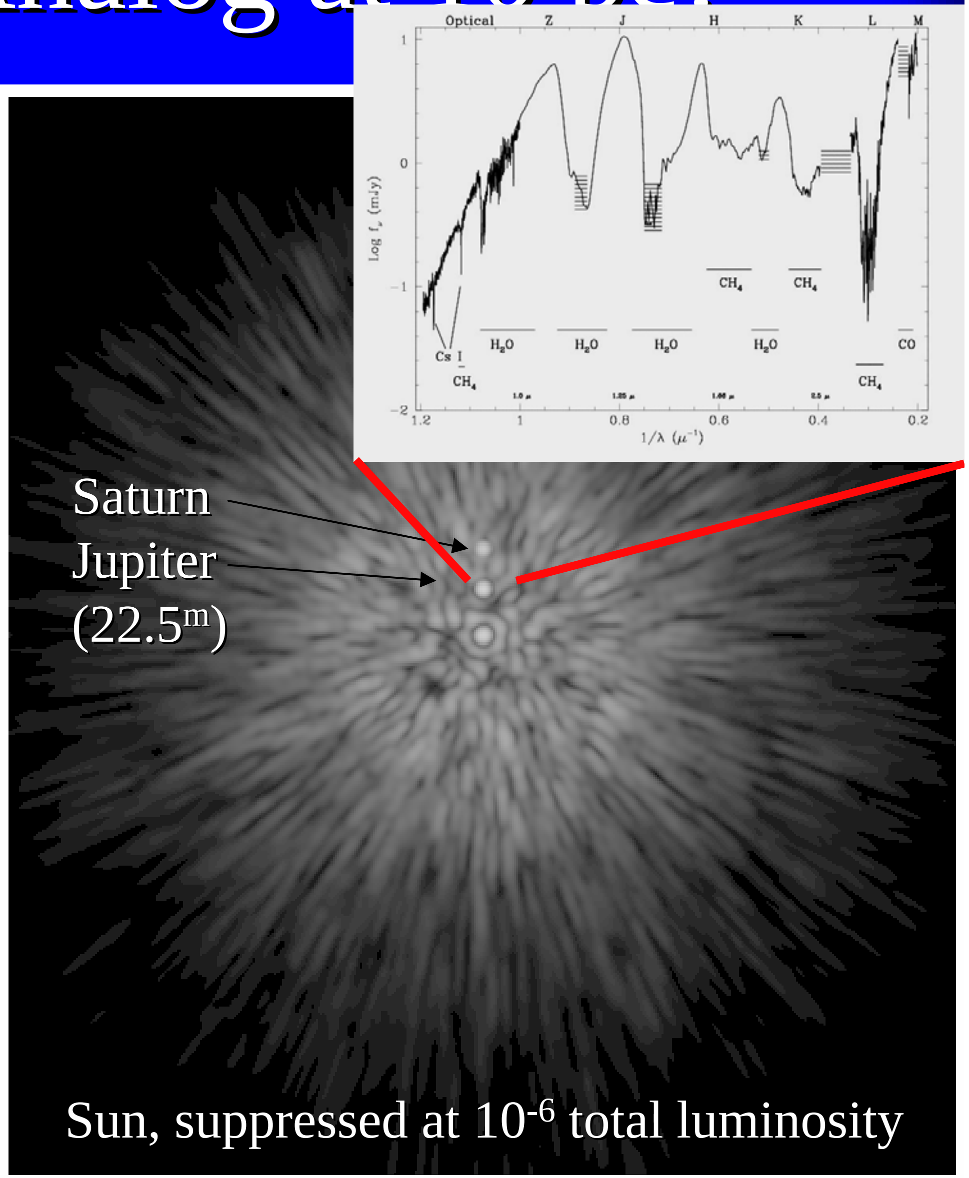
The Real Problem: Precise Control and Manipulation of Starlight



An Earth-like planet will be ***10^{10} to 10^{12}*** times fainter than the star it orbits and fractions of an arcsecond away from it.

Solar System Analog at 10 pc?

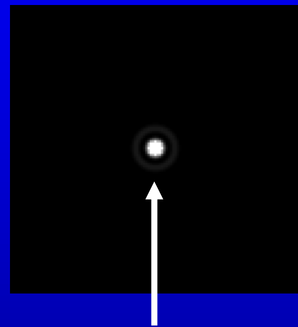




Reality: a Star from the Palomar 5-m

Reality

Perfection



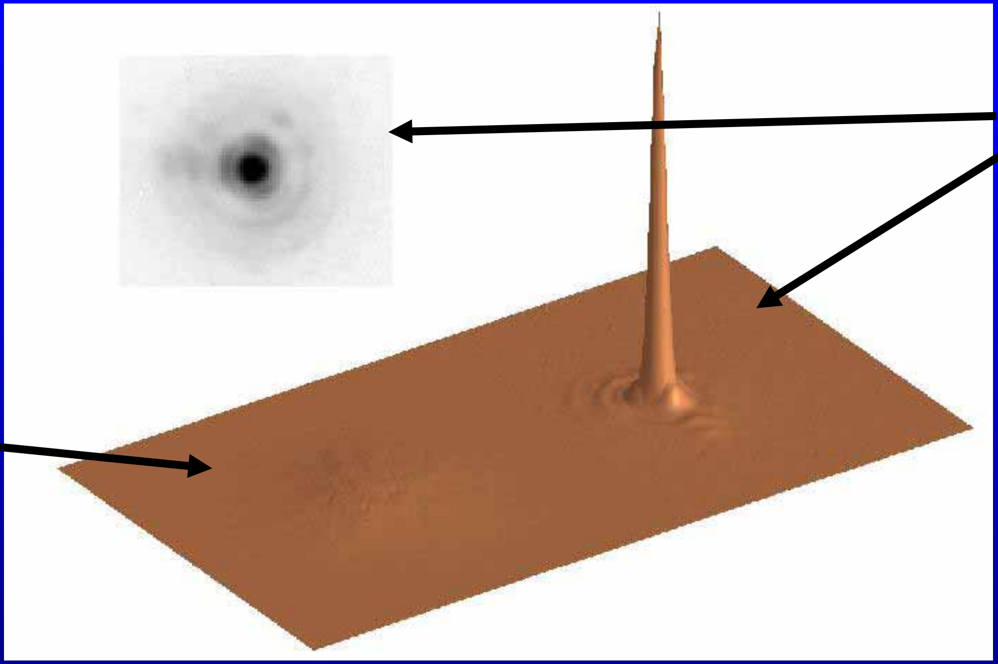
.039 arcsec image width

2.5 Arcseconds

I-band (.8μm)

Image Quality

$$\text{Strehl Ratio: } S = \frac{\text{Peak intensity of real image of a point source}}{\text{Peak intensity of a perfect image}}$$



Expected Image

Real Image

$$S \sim e^{-2\pi\sigma^2}$$

Uncorrected image: S ~ .5%

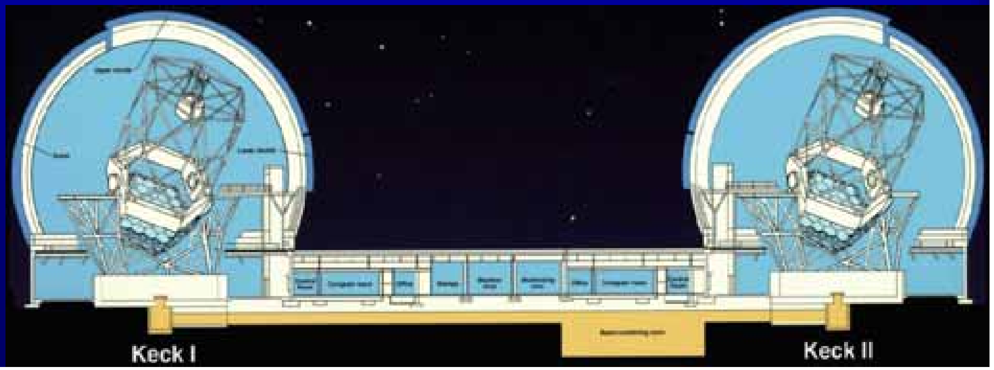
S = 80% means σ ~ 1/14 rms WFE

How Do We Do This?

Achieve extremely high image quality

Block the star optically

Null the star with interferometry



Adaptive Optics

Real K band data from
Palomar AO System

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

Adaptive Optics

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

Integrated images

Stellar Wavefront at Telescope Pupil

Deformable Mirror

Corrected Wavefront

Low-Order AO

Image

Corrected Image (S ~ 40%)

Stellar Wavefront at Telescope Pupil

Deformable Mirror

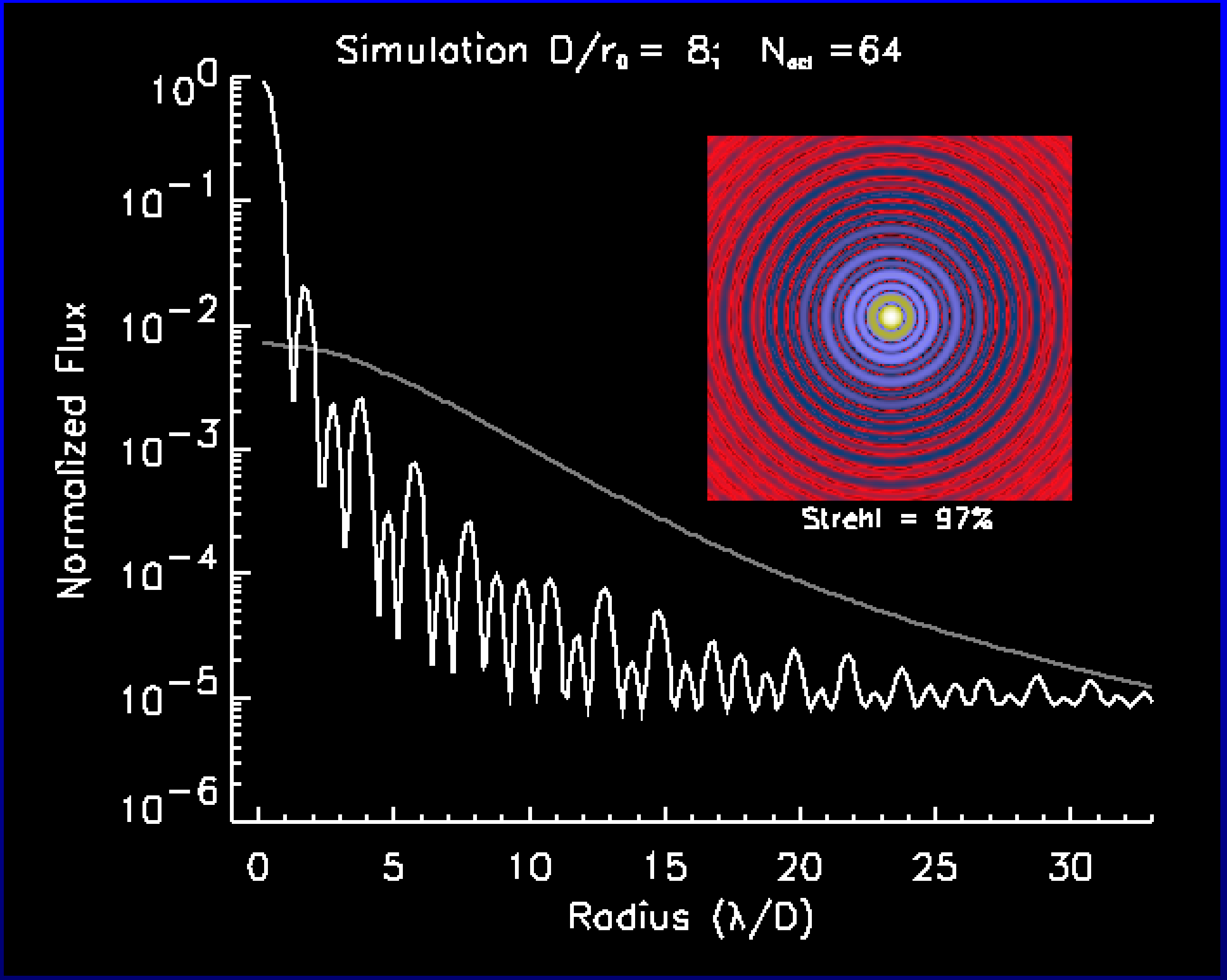
Corrected Wavefront

High-Order AO

Image

Corrected Image (S ~ 96%)

AO Point Spread Functions



Take a Break from listening to me

1. What is the general expression for the radius out to which an AO system can correct a PSF? Use telescope diameter D, linear number of actuators across aperture N_{act}, and λ

2. What is the wave front error in nm in the H-Band (1.6 microns) for 96% and 99.99% Strehl?

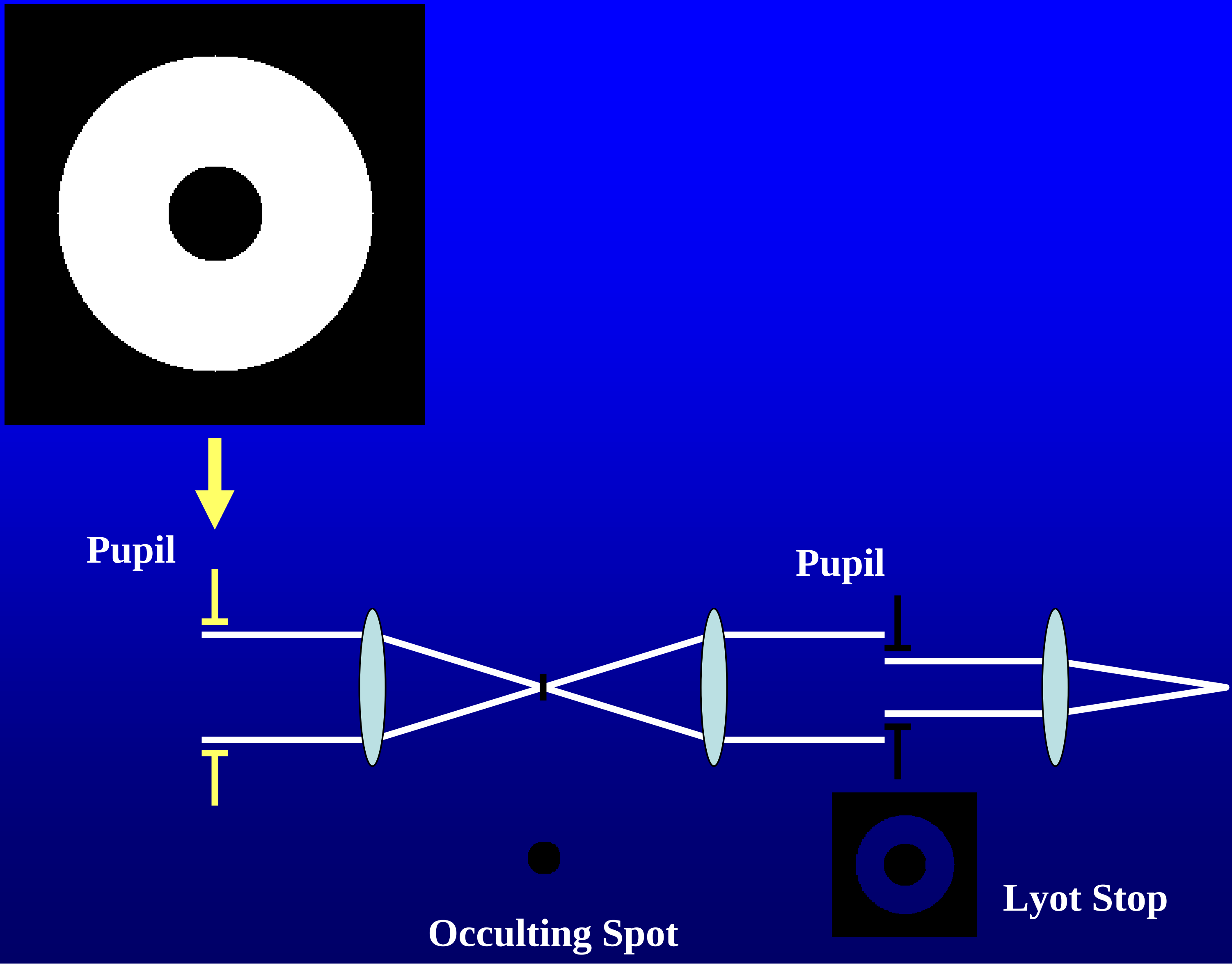
You have 10 minutes

Lyot Coronagraphy

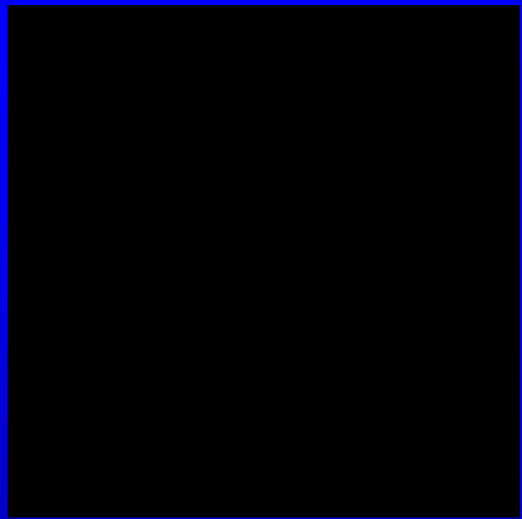
Bernard Lyot, 1939, Pic du Midi

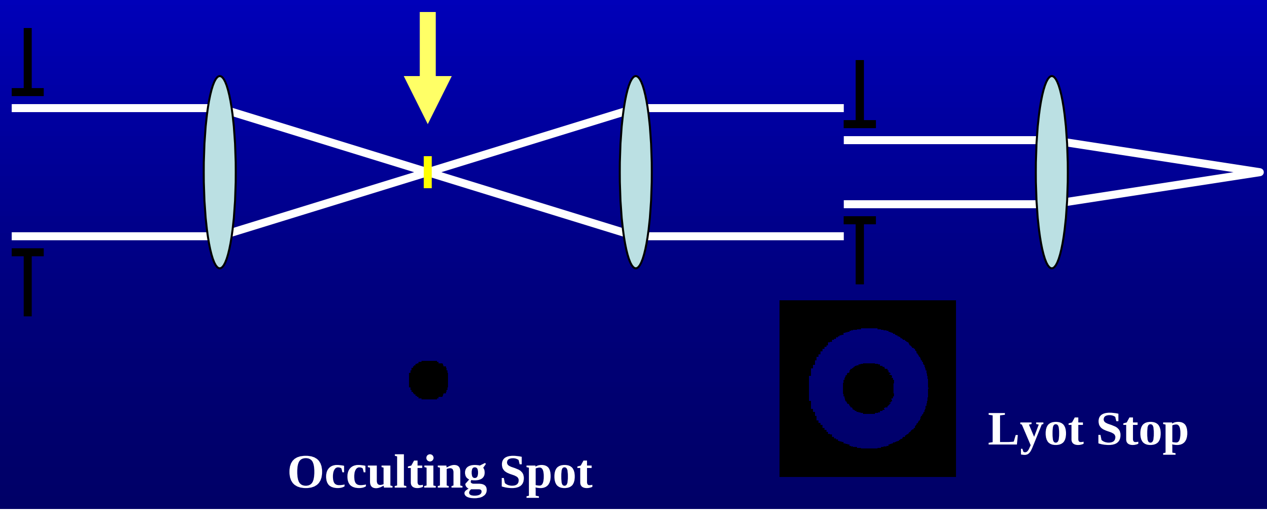
Quanititative theory: Sivaramakrishnan et al. (2001)

Lyot Coronagraphy

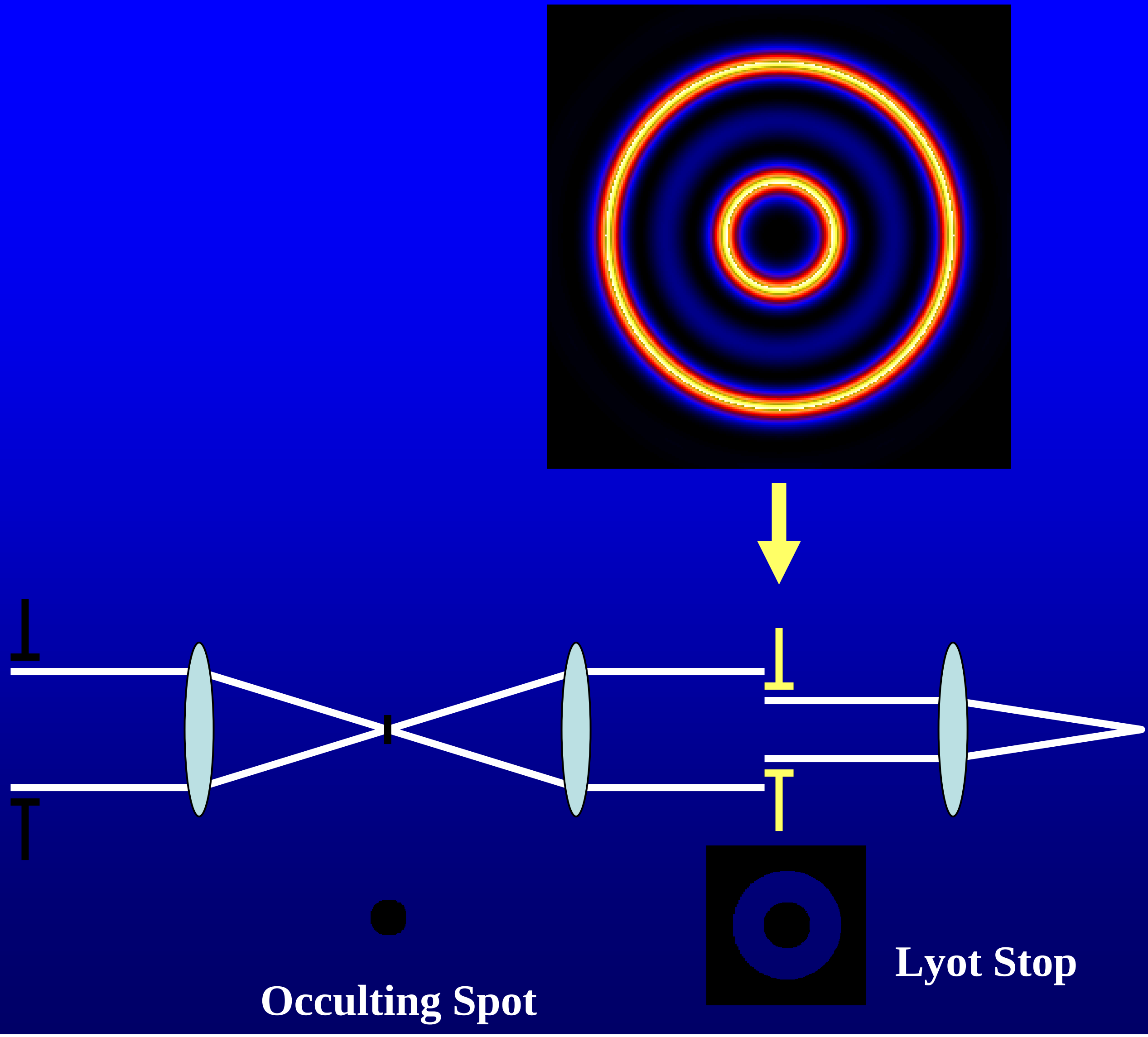


Lyot Coronagraphy





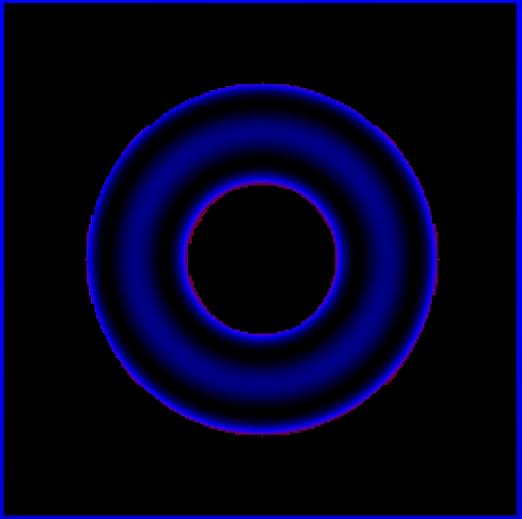
Lyot Coronagraphy

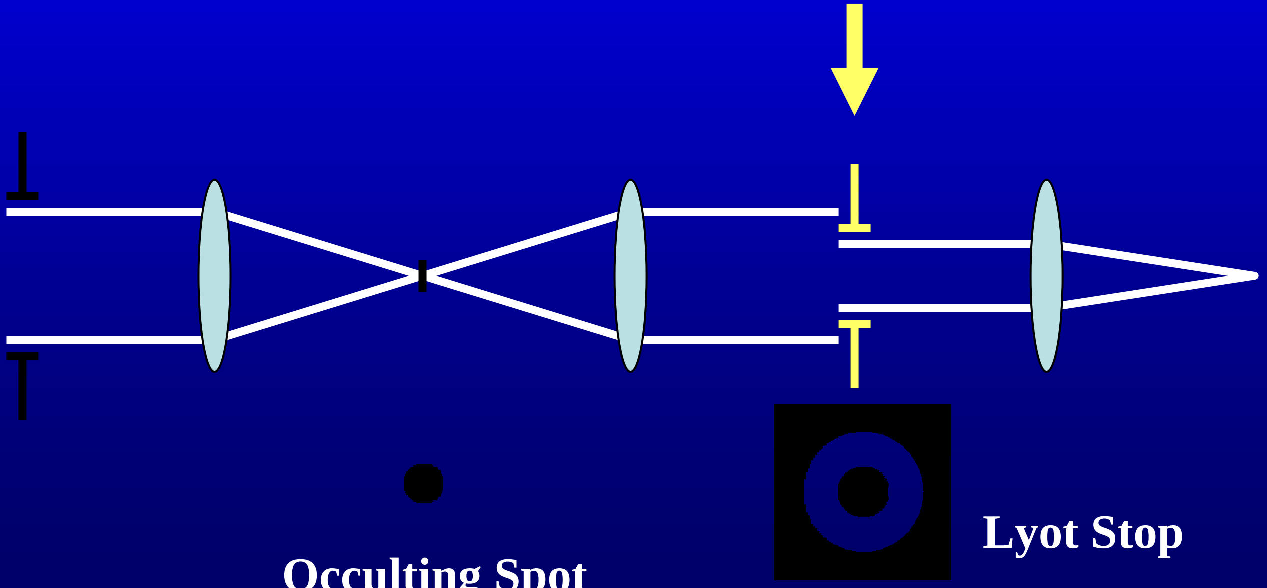


Lyot Coronagraphy

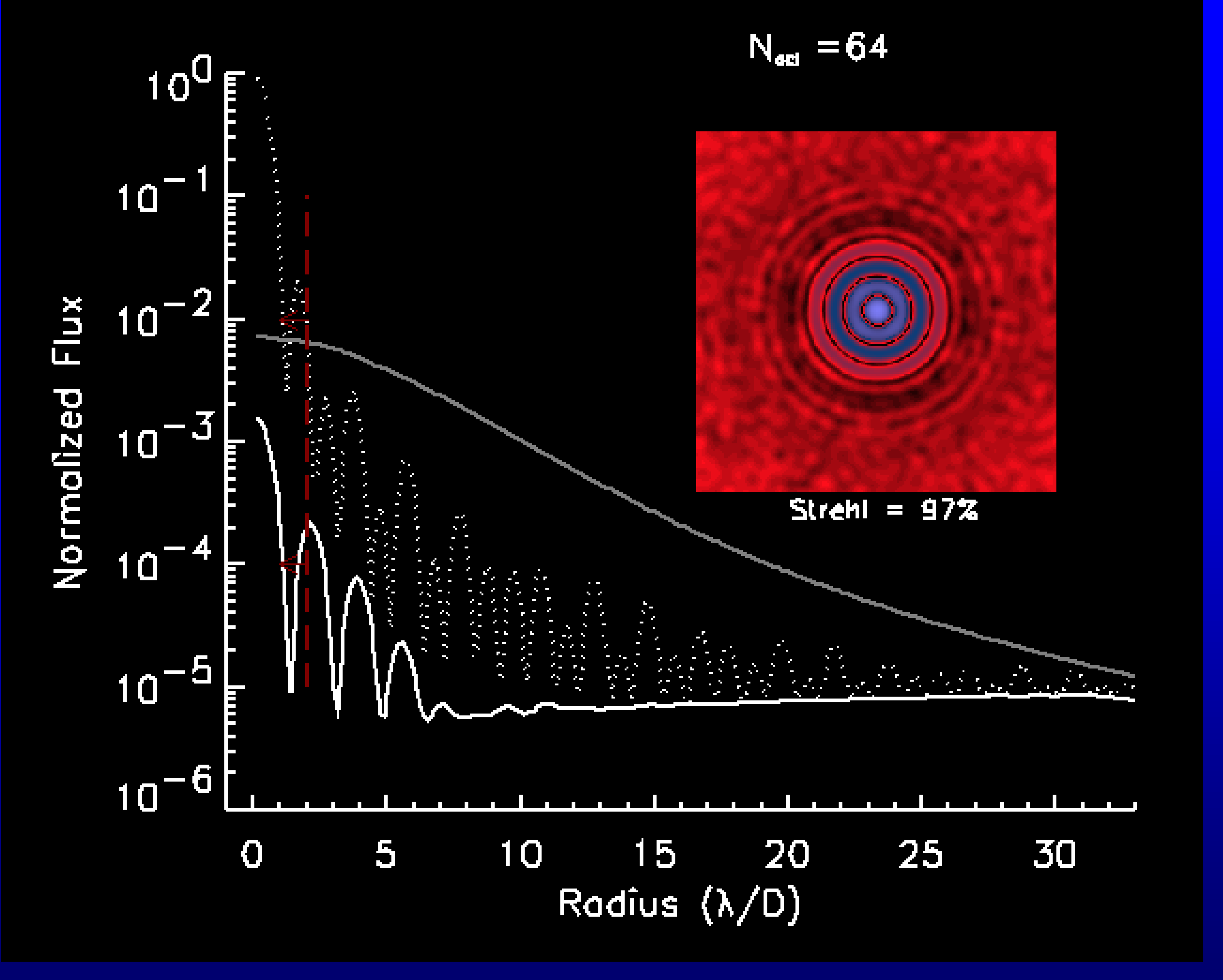
99%
Of starlight rejected

But only 30-50% throughput





Adaptive Optics Coronagraphy



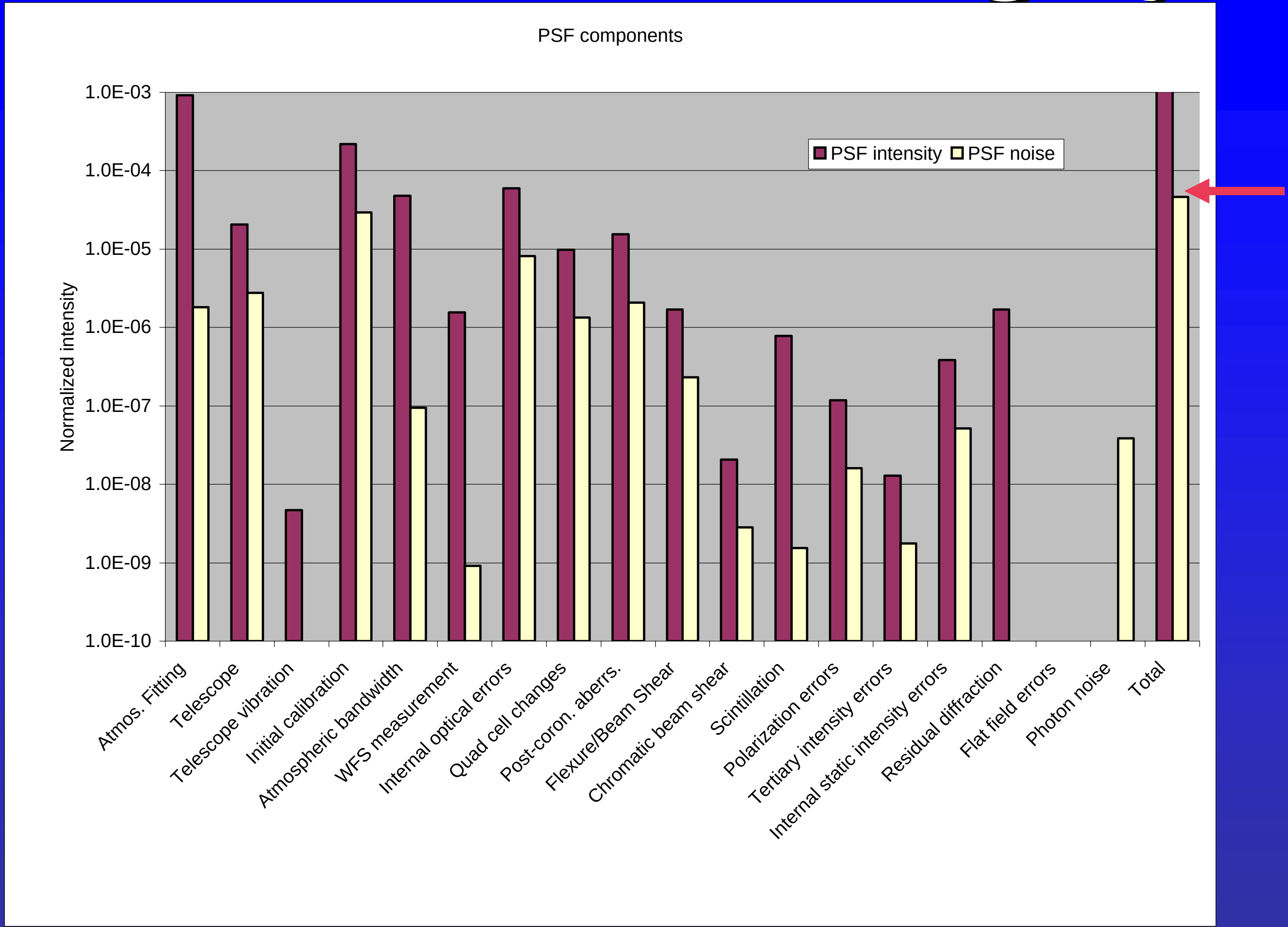
N_{act} = number of actuators along a diameter of the deformable mirror

Grey: uncorrected

Dotted: AO corrected

White: AO + Coronagraph

What Contrast does this get you?



Contrast error budget current AO - red: calibratable yellow: noise

CfAO EXAOC team(2005)

Speckles are *The* dominant source of noise!

What is a speckle?

Think Fourier

sin(x) <=> 2 δ's

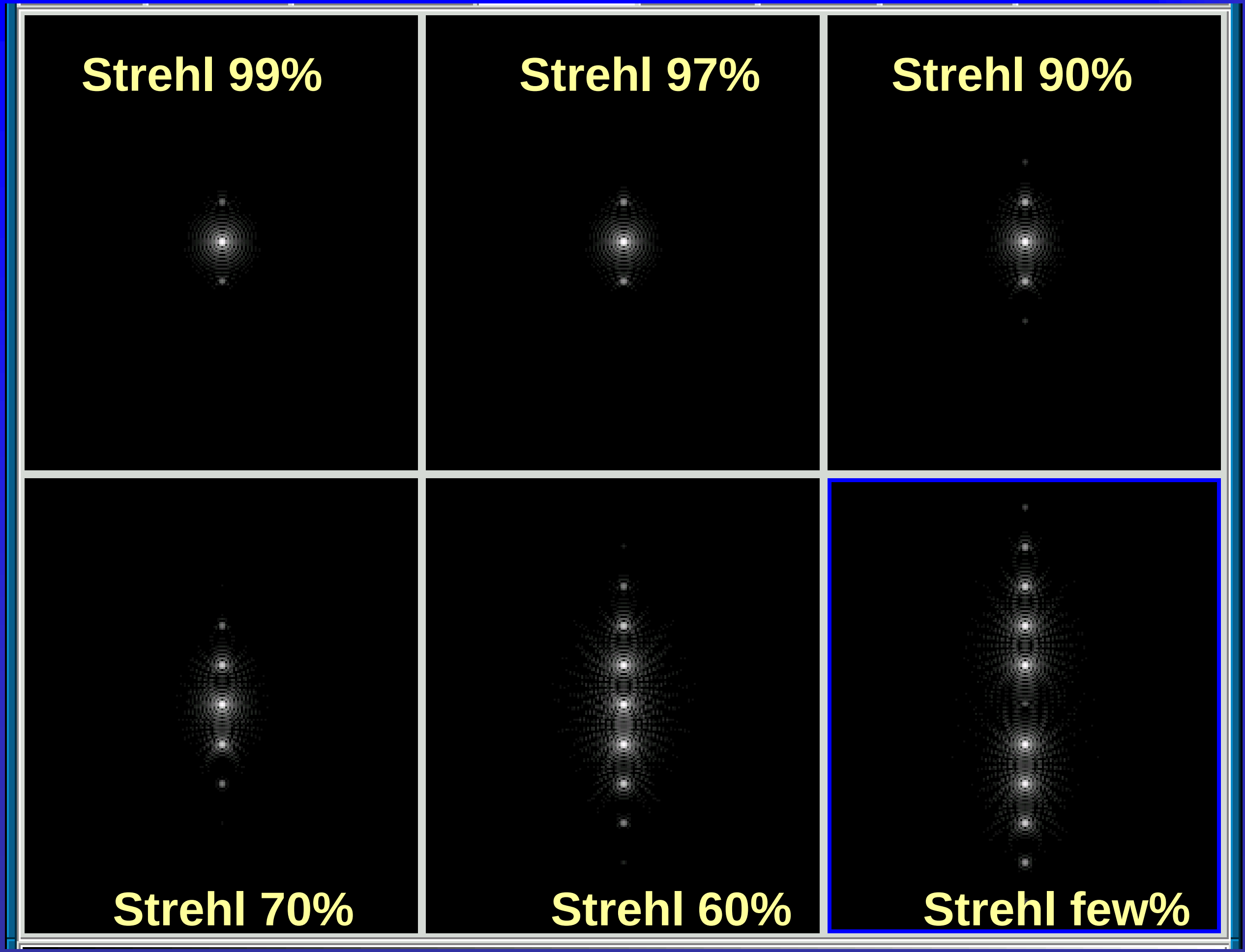
First order

Pupil: exp(iϕ) ~ 1 + iϕ + ...

Image: δ(0) + FT(sin) + …

Higher order

The … terms create higher frequency harmonics



Speckle theory - approach

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THE STRUCTURE OF HIGH STREHL RATIO POINT-SPREAD FUNCTIONS

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ABSTRACT

We describe the symmetries present in the point-spread function (PSF) of an optical system either located in space or corrected by an adaptive optics (AO) system to Strehl ratios of about 70% and higher. We present a formalism for expanding the PSF to arbitrary order in terms of powers of the Fourier transform of the residual phase error over an arbitrarily shaped and apodized entrance aperture. For traditional unapodized apertures at high Strehl ratios, bright speckles pinned to the bright Airy rings are part of an antisymmetric

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: $A \exp(i\,\phi) = A\,A_\phi$

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   Φ, ϕ are FT pairs   star is convolution

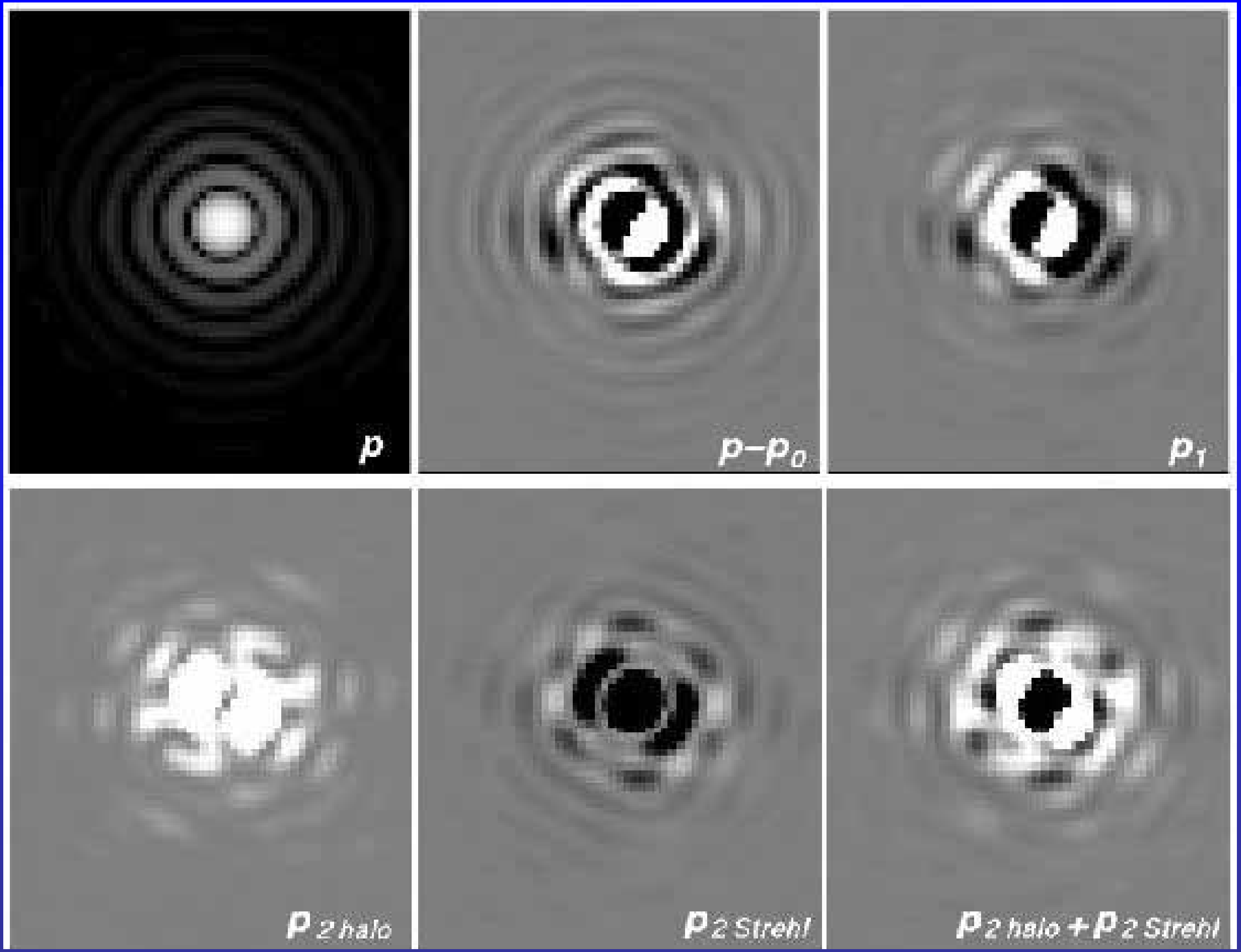
$$\begin{aligned} p_{AO} &= p_0 + p_1 + p_2 \\ &= aa^* \\ &\quad -i[a(a^* \star \Phi^*) - a^*(a \star \Phi)] \\ &\quad +(a \star \Phi)(a^* \star \Phi^*) \\ &\quad -\frac{1}{2}[a(a^* \star \Phi^* \star \Phi^*) + a^*(a \star \Phi \star \Phi)], \end{aligned}$$

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

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

First order pinned speckle, second order halo, second order Strehl term
Enables analytical proof that “Speckle Decorrelation” 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

no **net** power is contained in any term except the zero-order perfect PSF term

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

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

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

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

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

Shows why pupil apodization reduces speckle noise (think Fourier space! Outer edges of aperture=high freq. In pupil plane--- p_2 Halo), and ‘shaped pupil’ approaches are extra-sensitive to aberrations

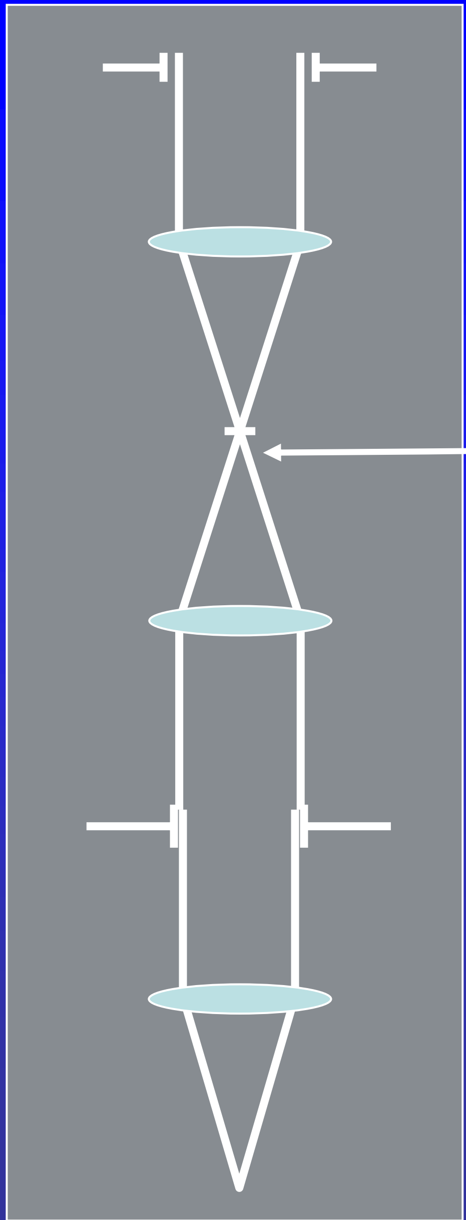
Speckle Theory: λ Dependence

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

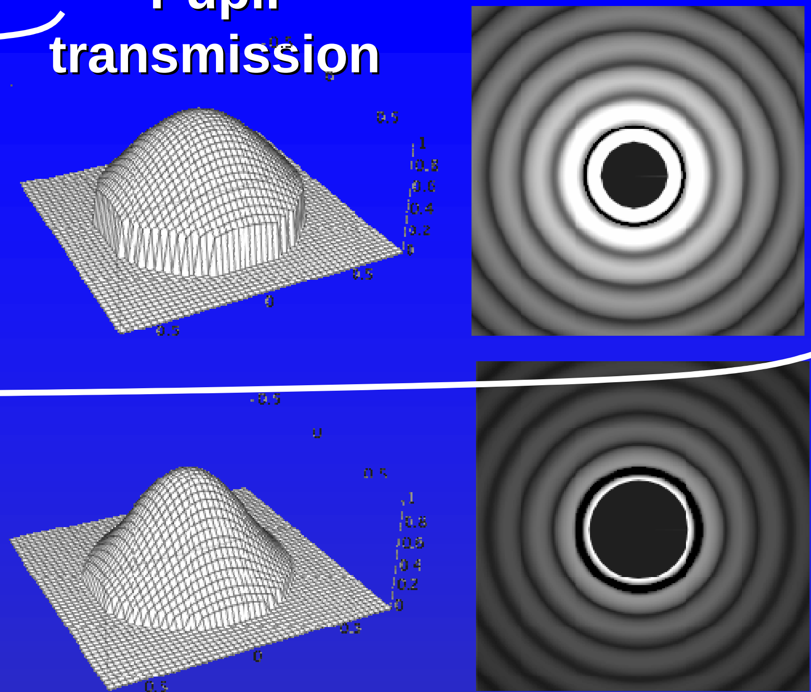
Data Cube Movie
Across an astronomical filter

10 nm Steps
S ~ 90%
λ = 1.6 μm (1.0 at left)

Apodized Pupil Lyot Coronagraph



Pupil transmission



PSF intensity

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

99.9%
Of starlight rejected

60-80% throughput

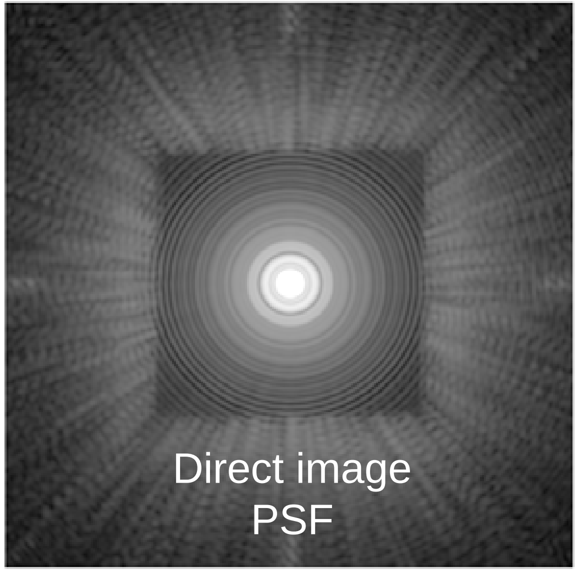
Soummer, Aime & Falloon (2003)
Soummer (2005)

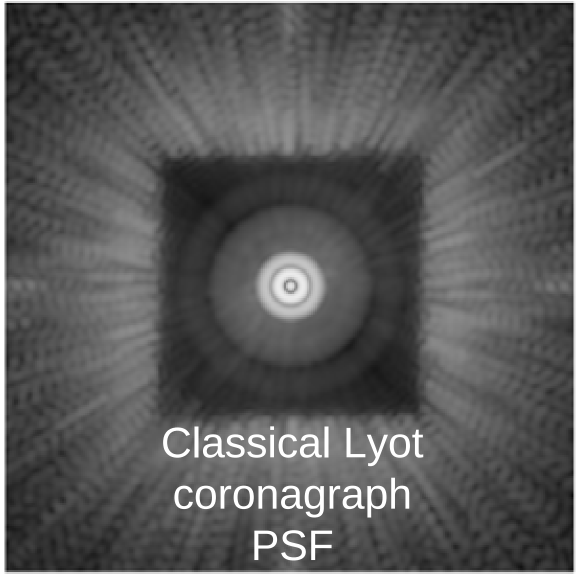
Types of Coronagraphs

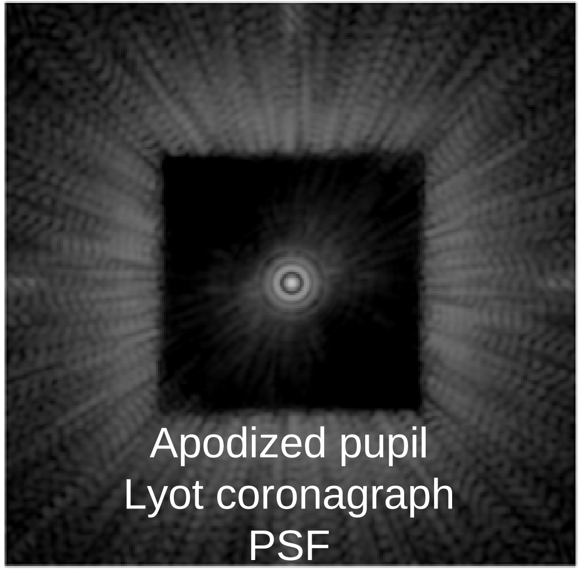
Type	PSF at 0.4" (0 nm WFE)	Alignment Tolerance	Manufacturable	Proven Technique?	Observing Efficiency	Other
Lyot	10^{-6}	Easy	Yes	Yes	40-50%	Excludes most science goals
Apodized Lyot	10^{-7}	Easy 2% of pupil	Yes in visible (1950) Medium-risk	AP no LC yes	50%	
Band limited	In theory, infinite for a given λ	Easy	No in IR High-Risk	Yes in visible No in IR	10% within $10\lambda/D$ 50% outside	Throughput is poor
Shaped Pupil	10^{-7}	Easy	<10 nm precison	Proven only at extremely high SR	10 %	Excludes most science goals
Phase Mask	10^{-7}	Tilt must be < 30 μas	Prototype exists but high risk	Yes at 10^{-4} at $4\lambda/D$	80%	Vibration sensitivity
Pupil mapping	10^{-7}	Very Hard	Expensive High-Risk	Low performance prototype	100%	Excludes most science goals without reversing PR
Pupil nulling	10^{-7}	Hard	Probably but High-risk	Yes at 10^{-4} in visible in lab	20-50%	Excludes some science goals

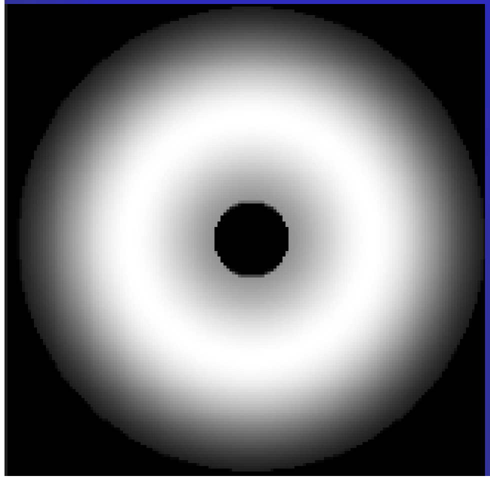
Extreme AO + APLC

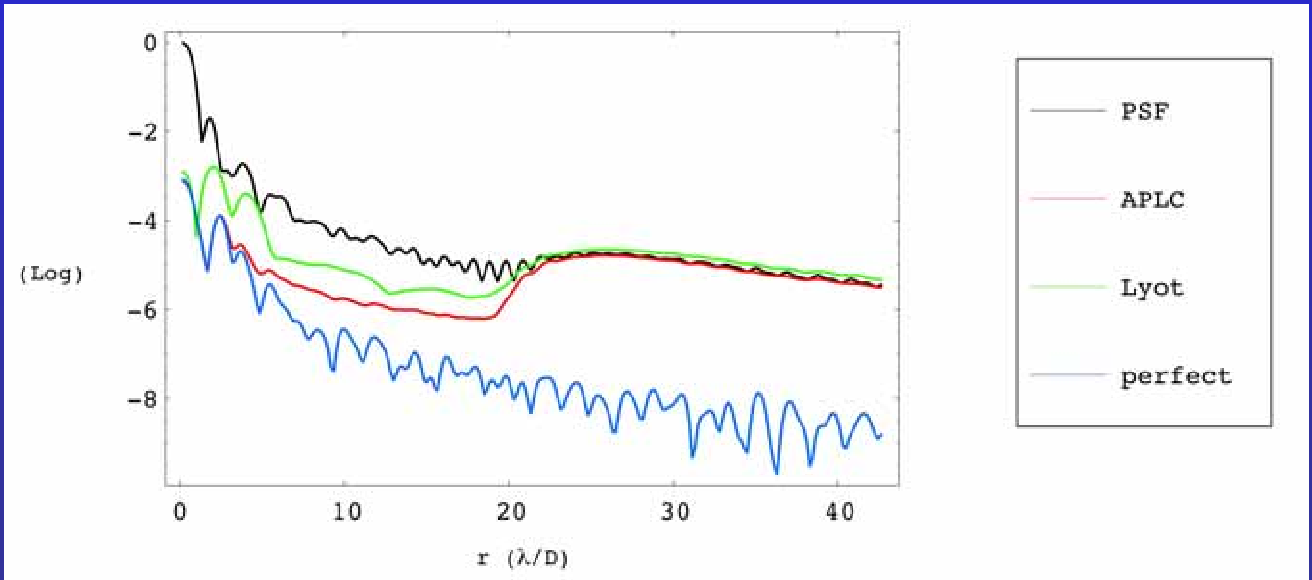
Coronagraph by Soummer (ApJL 2005)
PAOLA AO simulation by Jolissaint (2005)
Spatially-Filtered Wavefront Sensing AO by Poyneer & Macintosh (JOSA 2004)



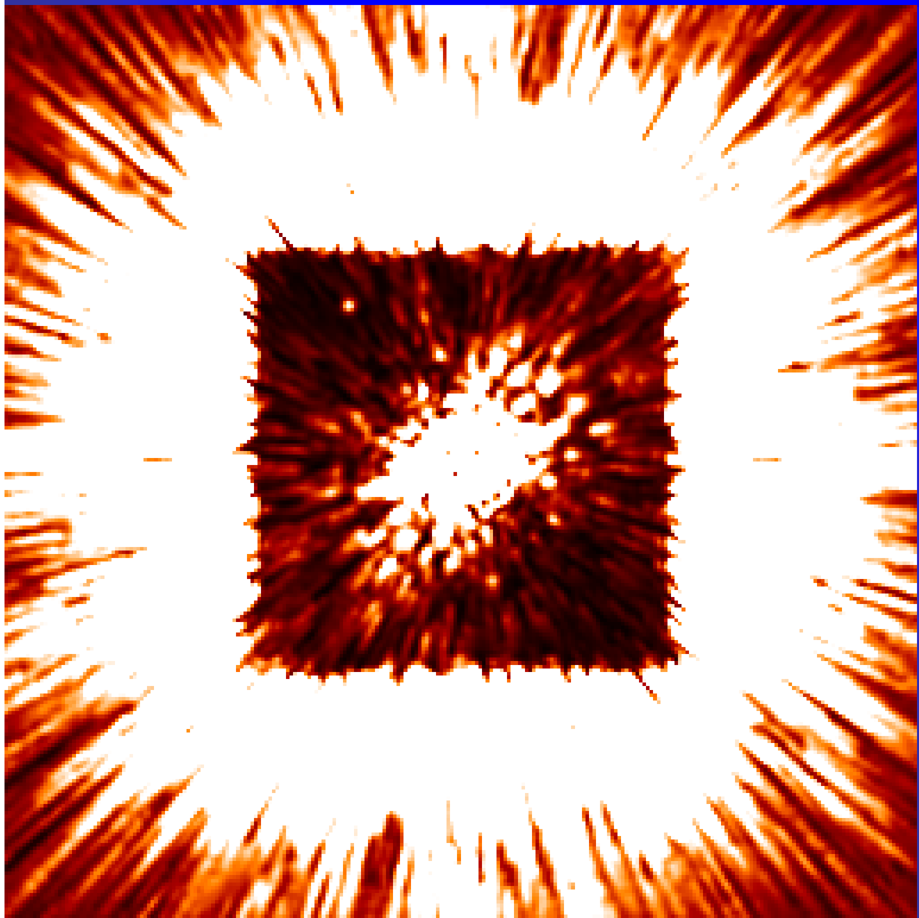




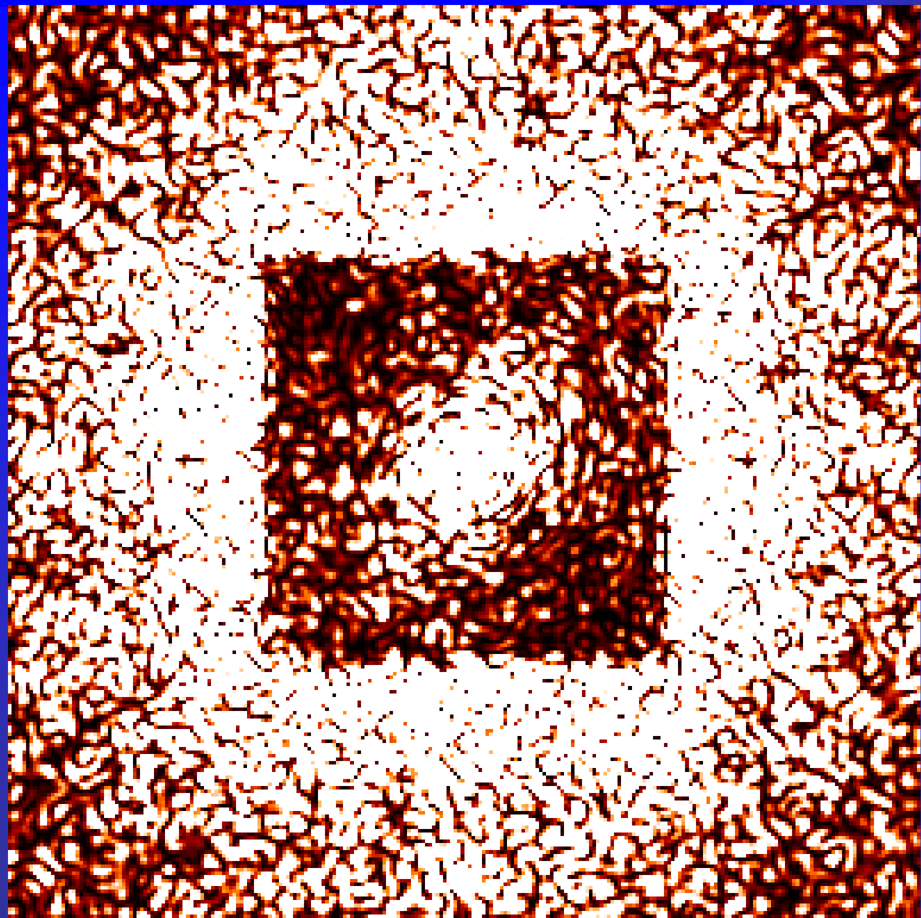




Extreme AO + APLC + IFU

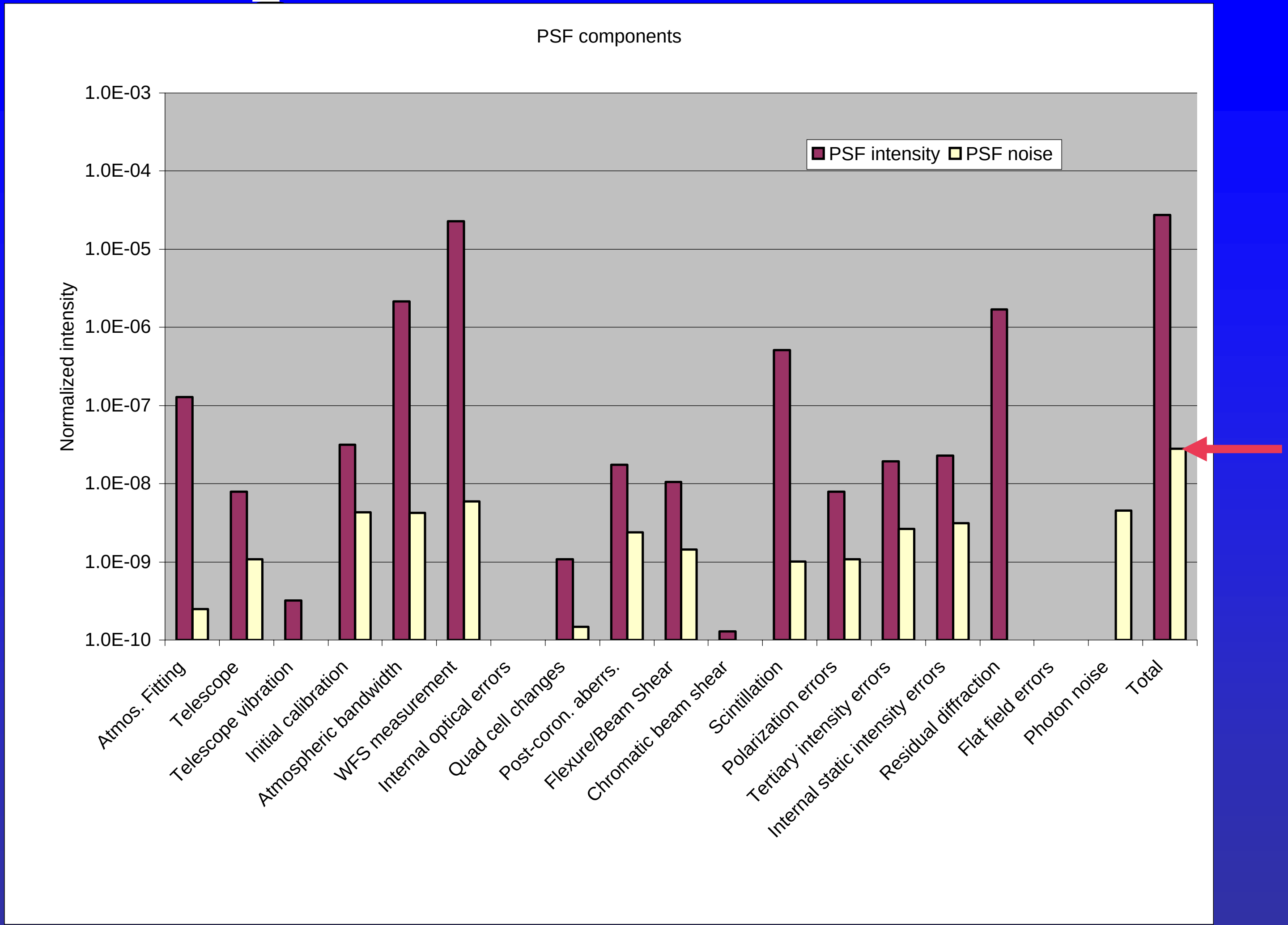


Control Radius Carved Out



IFU provides Speckle removal

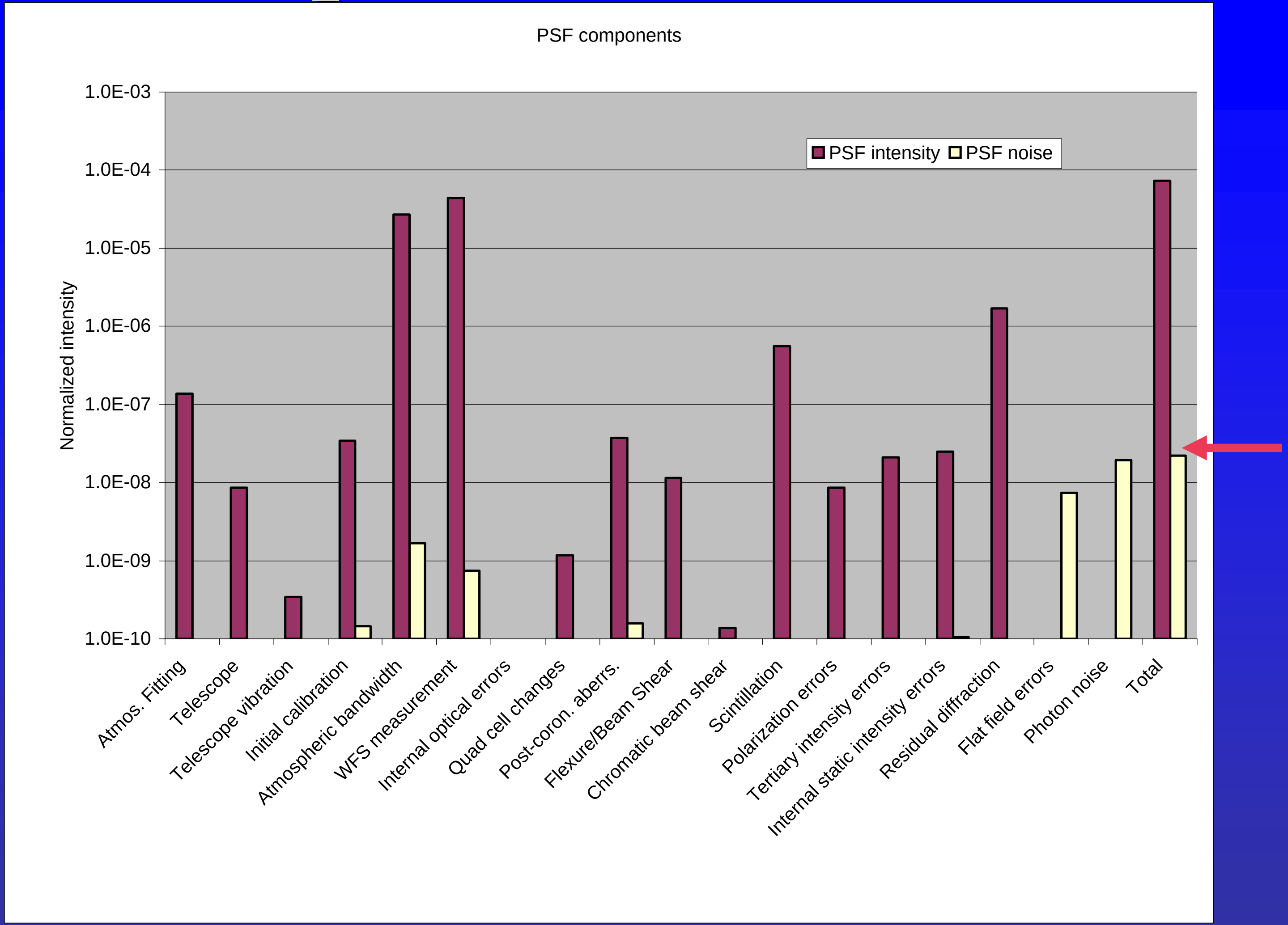
PSF components - ExAO + APLC



Contrast error budget ExAO - red: calibratable yellow: noise

CfAO EXAOC team(2005)

PSF components - ExAO + IFU



Contrast error budget for ExAO with Multi-wavelength Imaging

I=7 one hour exposure 5-sigma detection

CfAO EXAOC team(2005)

Summary: Qualitative

- Control your Wave Front Errors
- Get rid of as much starlight as practical
- For residual wave front errors, get as much information as possible so you can remove them in post processing

Summary: Quantitative

- Starlight Removal:
  - Lyot Coronagraph removes 99% of starlight
  - Modified Lyot can remove 99.95% (apodizers)
  - Novel designs do better but require Strehl ratios near 99% (not obviously achievable on ground, perhaps in space)

Summary: Quantitative

- Residual Wave Front Errors must be less than about 1 nm for 10^{-8} contrast without differential image subtraction or spectral information on speckles
- Spectral imaging can improve contrast by up to a factor of 100 (infinite signal to noise, see Sparks and Ford 02)

Summary: Space vs. Ground

- Space is not a perfect solution to these problems
- Wave front errors persist and must be controlled, but are much slower
- May be possible to control wave fronts at angstrom level or better with modest advances in technology. Needed for 10^{-10}-10^{-12} contrast (TPF)

Coming up after the break: What is it like to do this for a living?

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Jeffrey R. Kuhn
University of Hawaii

Lewis C. Roberts, Jr.
The Boeing Company

http://lyot.org

Air Force Maui Optical Site

Atop Haleakala, Maui

10,000 ft Observatory
Since early 1950s

Leader in AO Development

US Air Force Advanced Electro-Optical System (AEOS)

- 3.6 m telescope
- Atop Haleakela (Maui)

- StratCom's Space Surveillance Program

- 941 actuator deformable mirror
  N_{act} = 32 **(highest in world)**

- 30% Strehl at I-Band
- 80-90% at H-Band

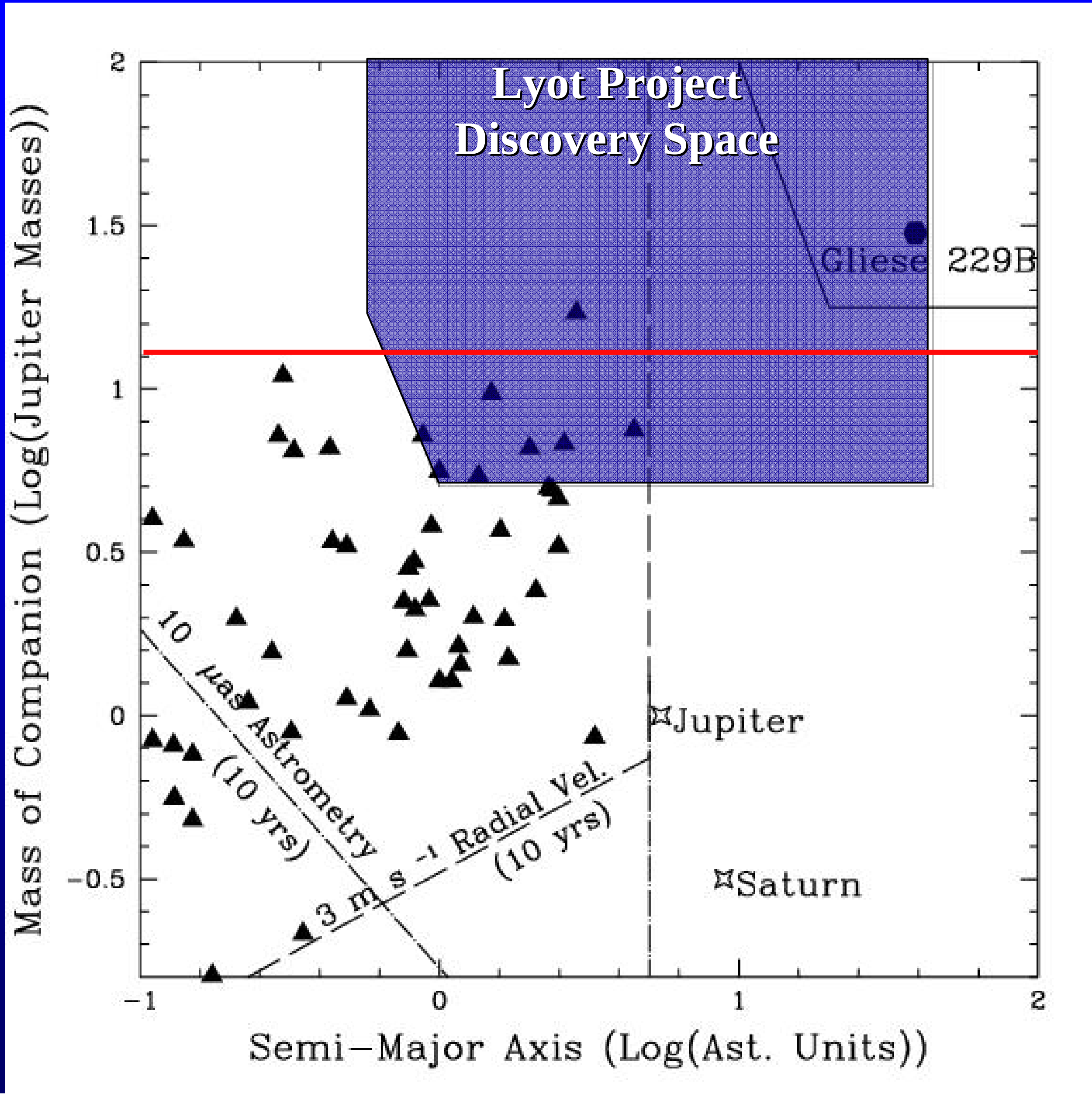
AEOS

- Tracking speed 17 degrees/sec

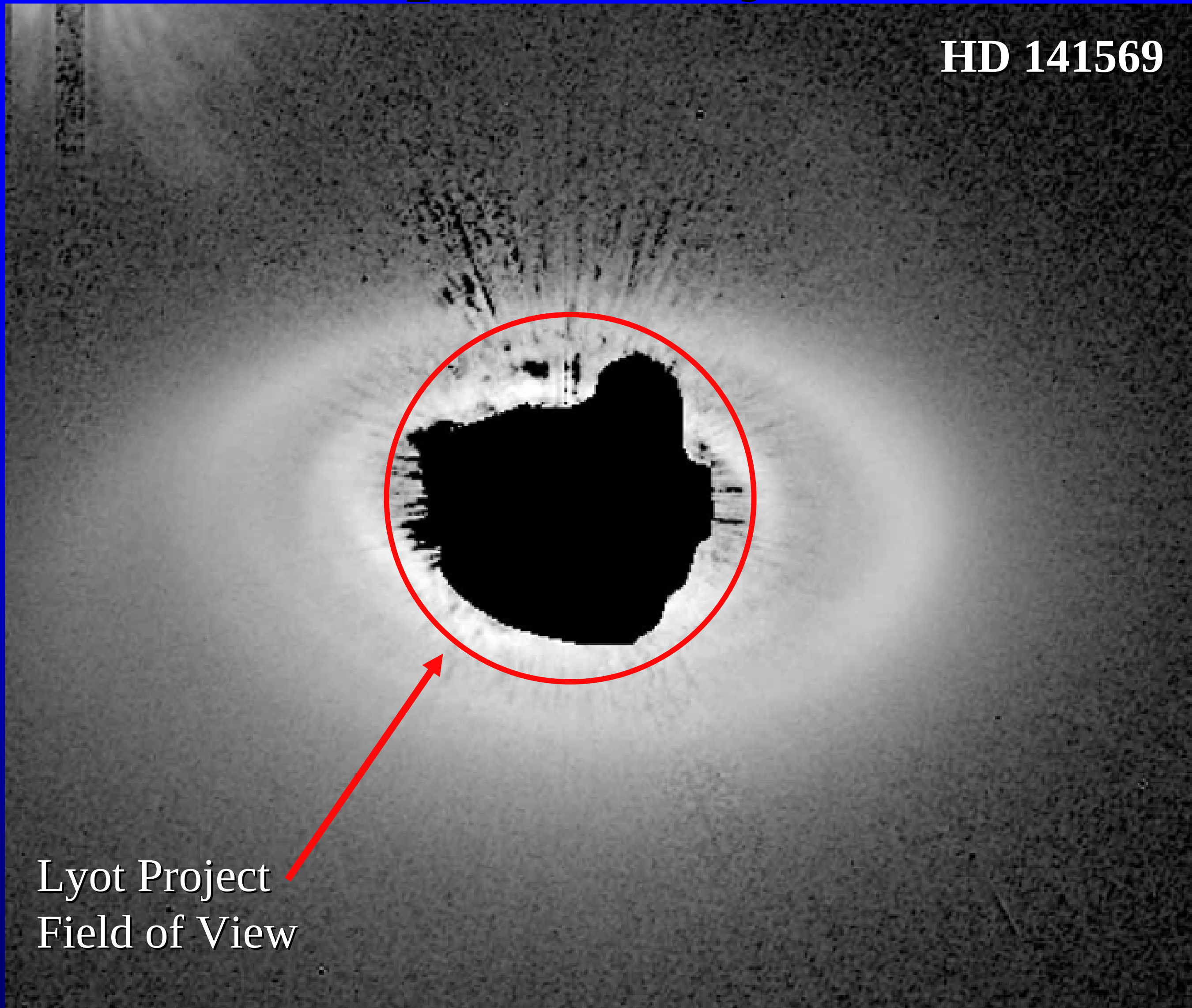
QuickTime™ and a
H.263 decompressor
are needed to see this picture.

Planet and Brown Dwarf Sensitivity

▲ **Known but unseen exoplanets (Marcy et al. 2003)**



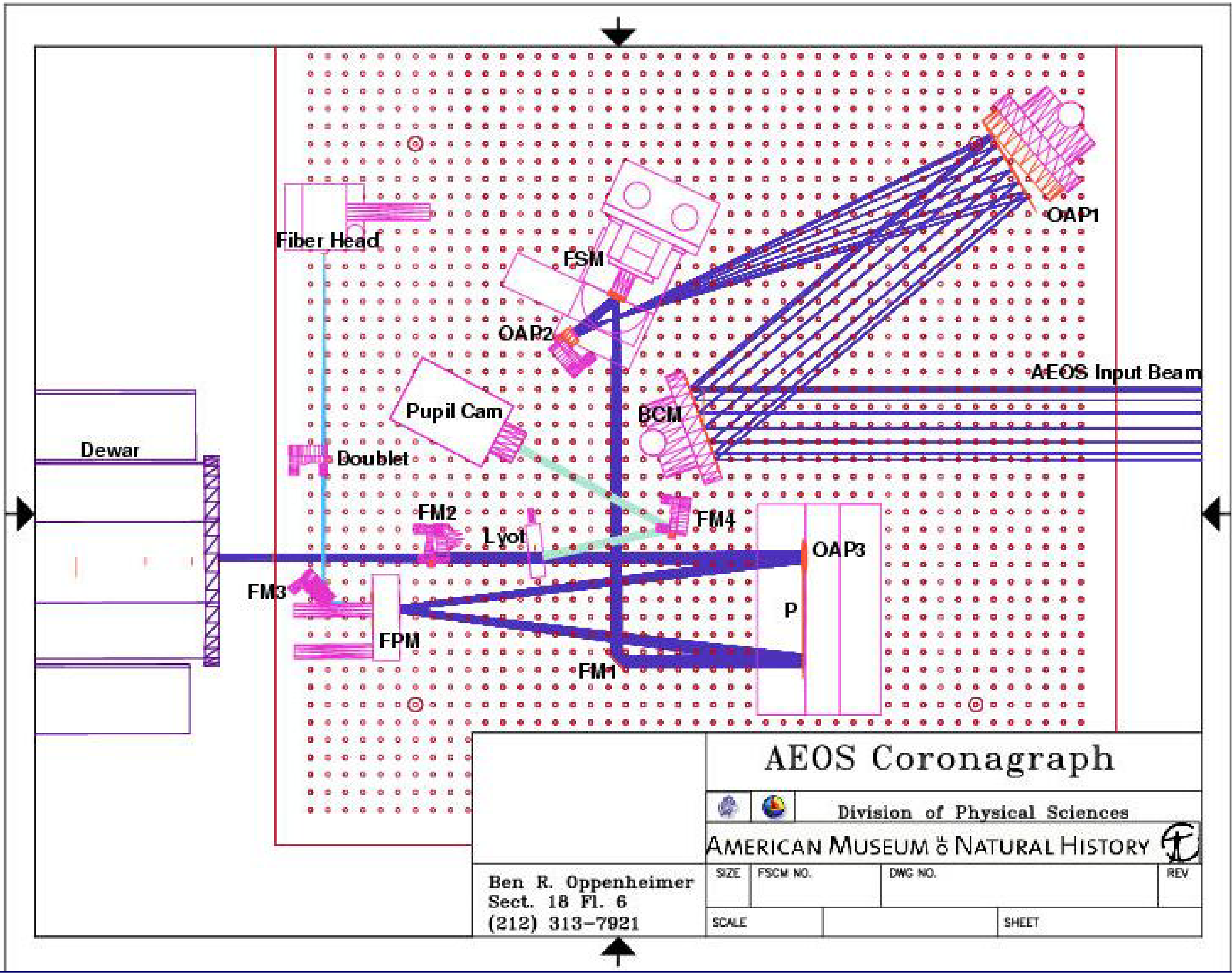
Protoplanetary Disks



10 Myr
A Star
100 pc

Hubble ACS image **Clampin et al. 2003**

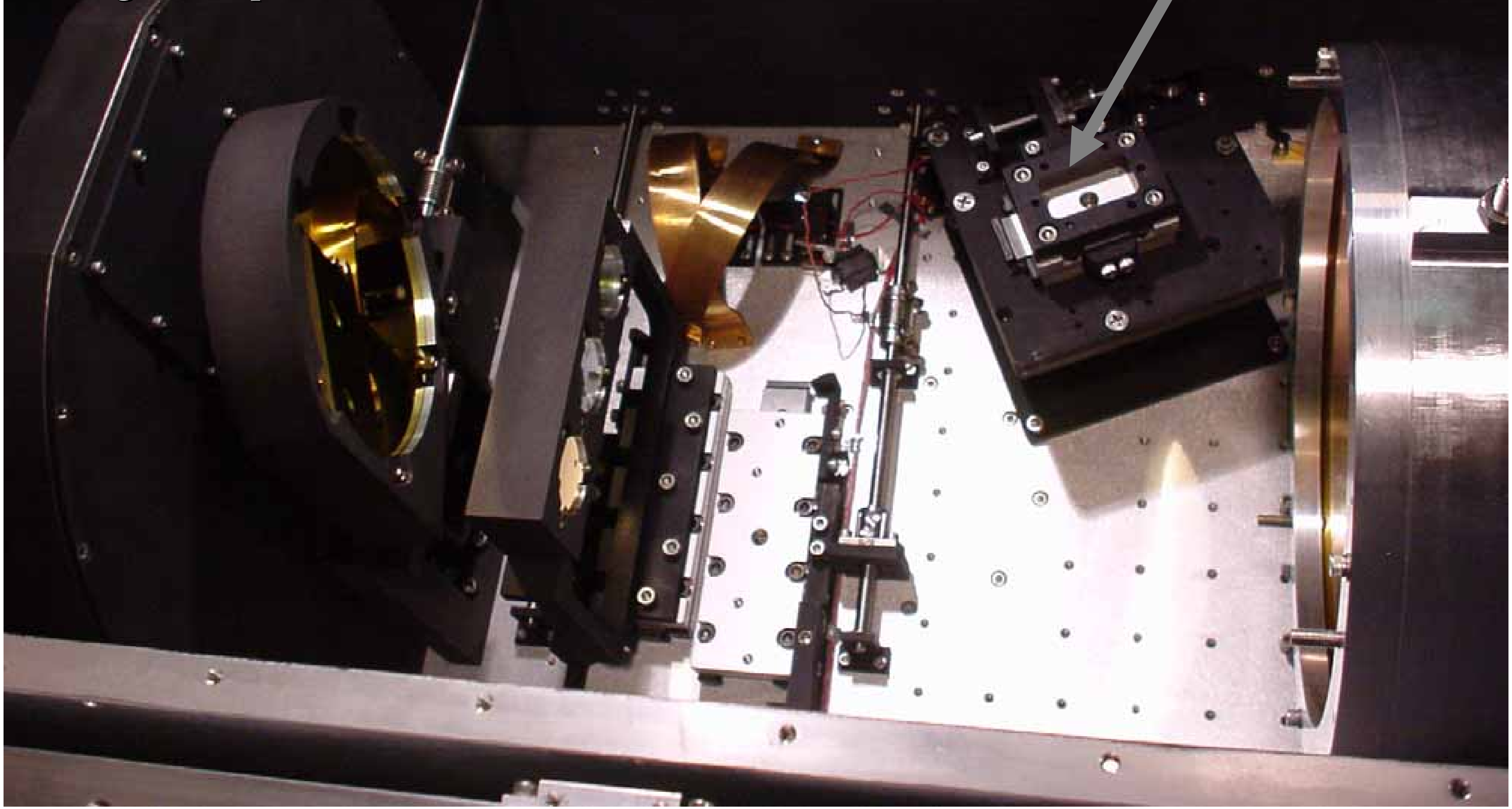
Lyot Project Coronagraph



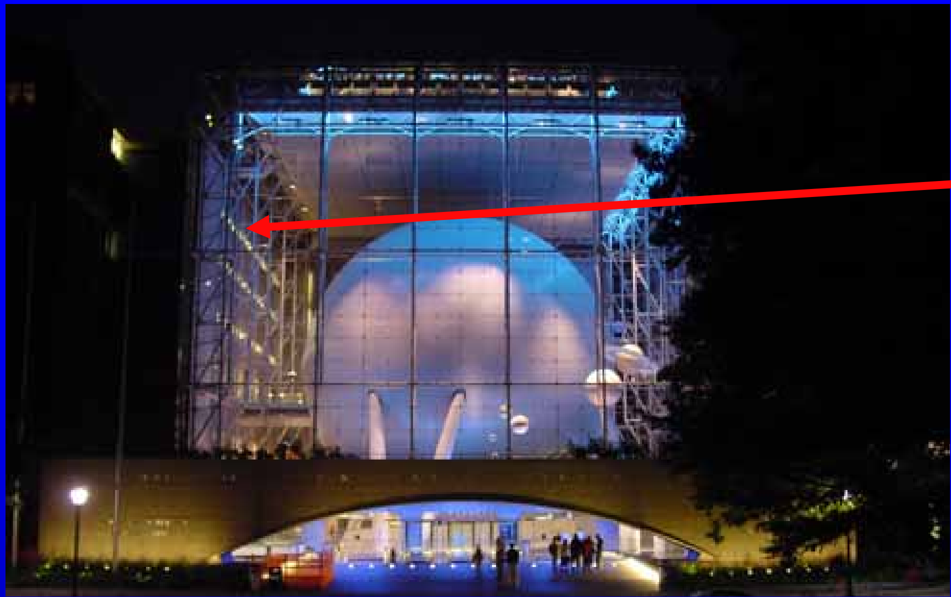
Kermit IR Camera

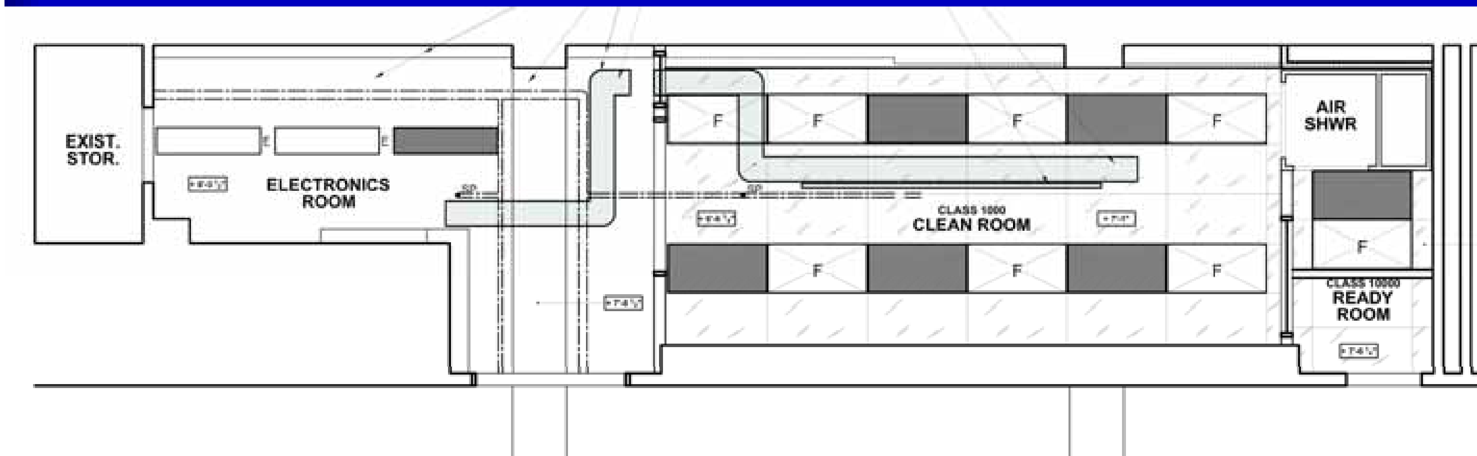
Built by UH/UC Team Members

First light in April 03



The AMNH Astrophysics Lab





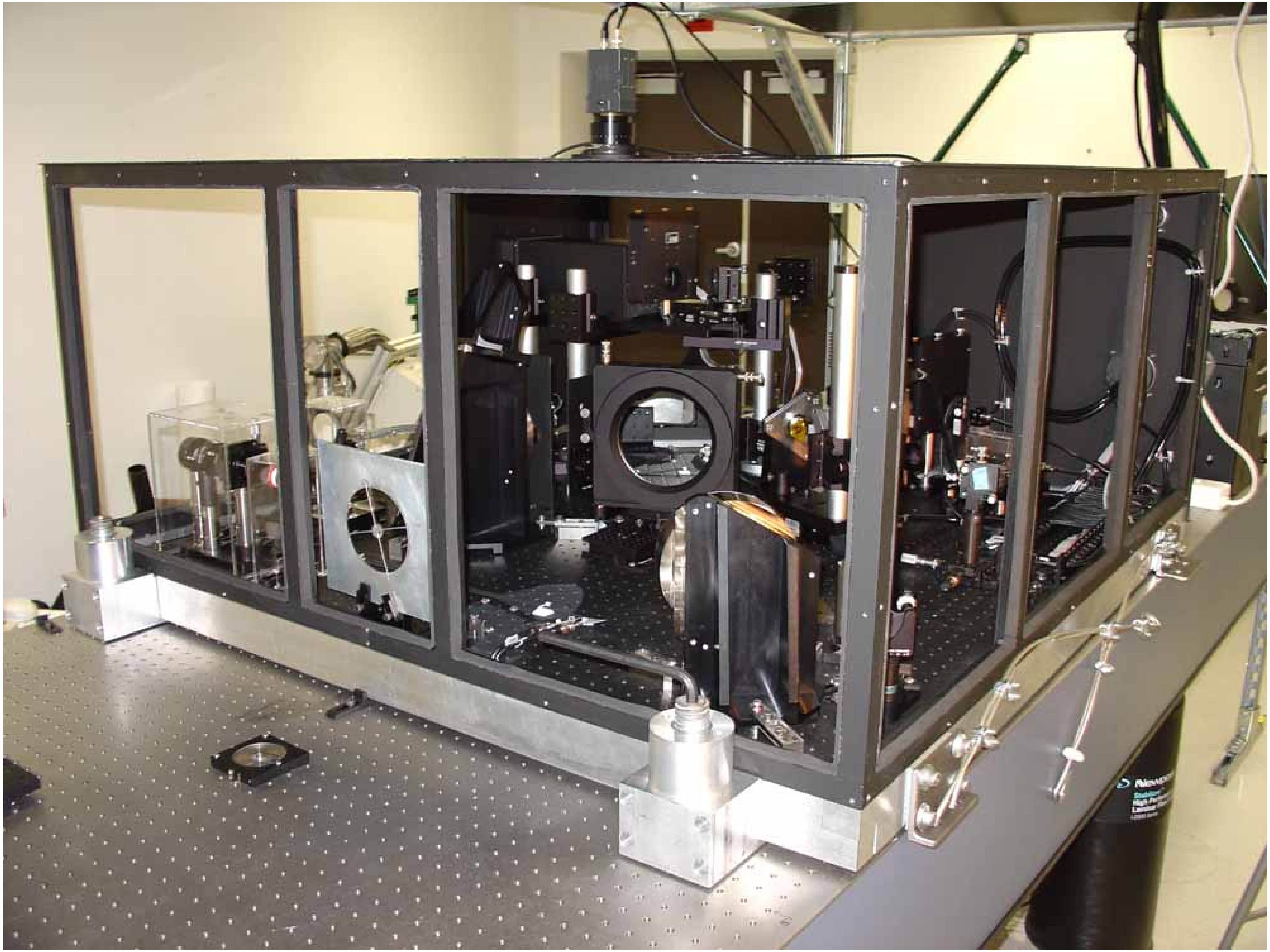
Class 10000 Clean Room

Zygo GPI-xHR

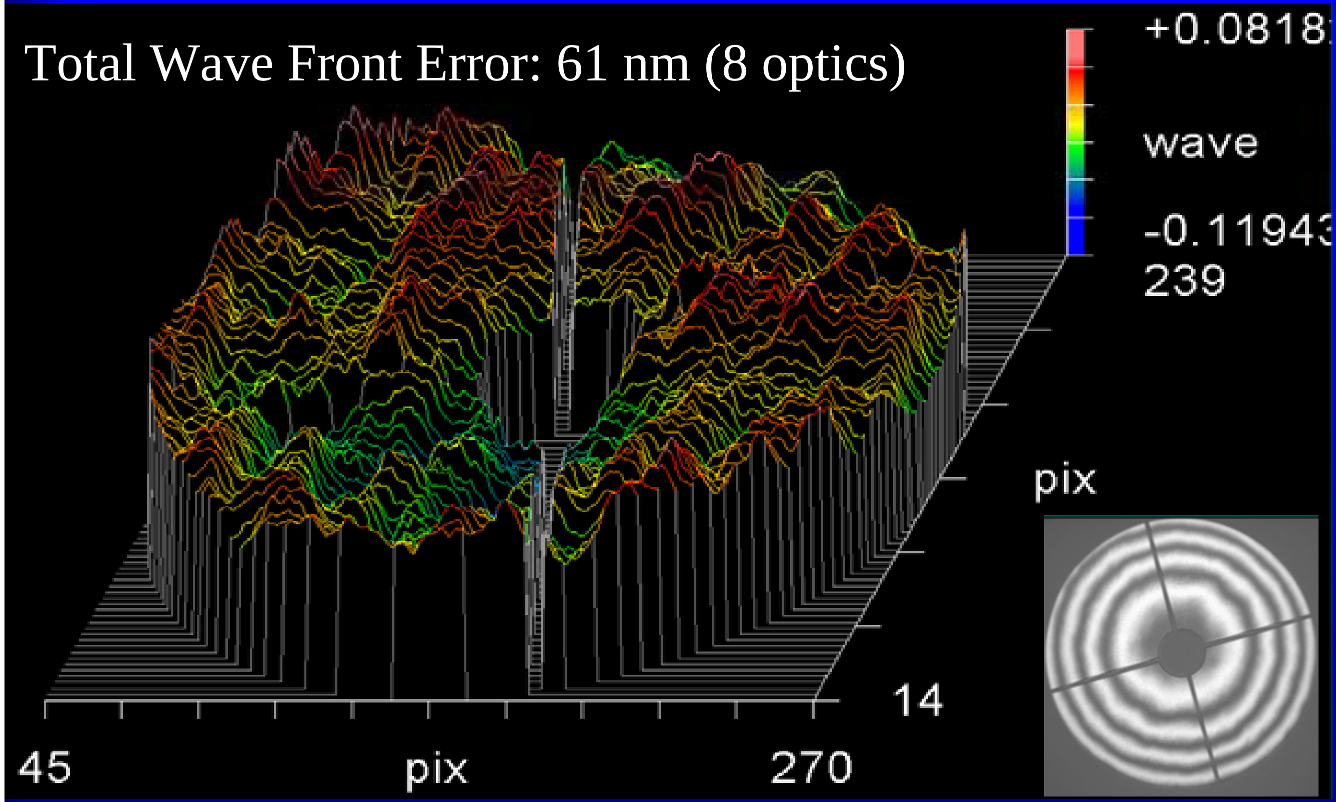
Expanding Now:
- **Class 1000 CR**
- **CMM**

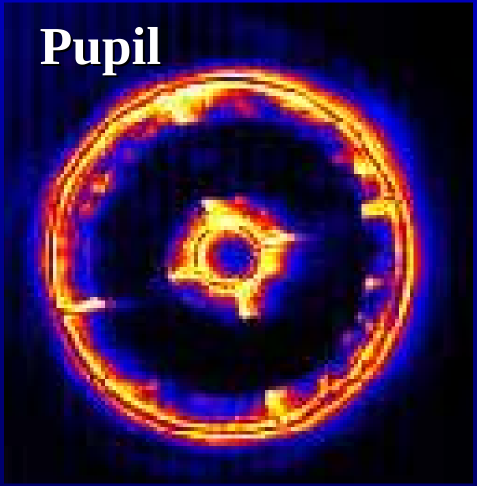
Initial Assembly

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

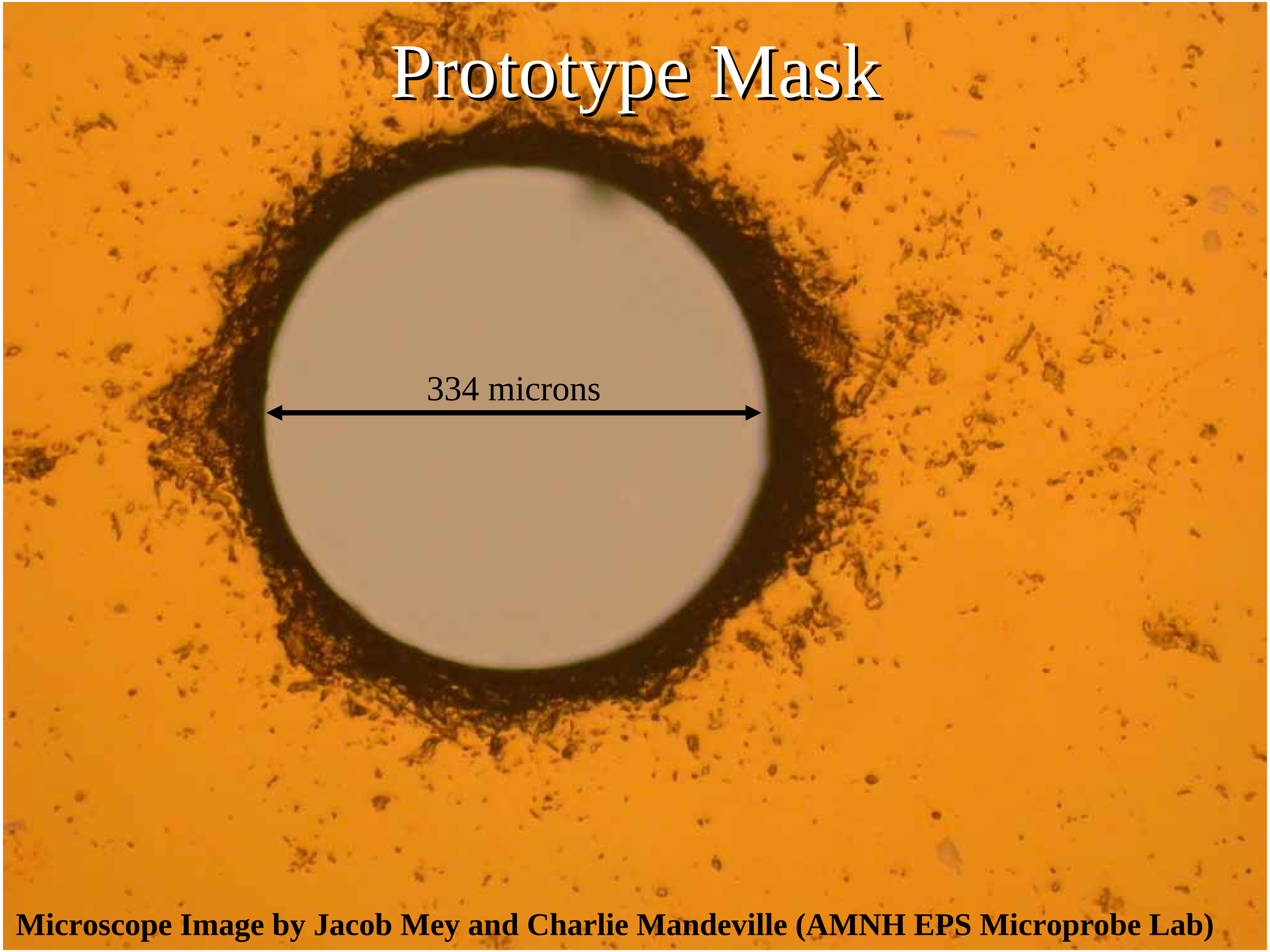


In Lab Performance

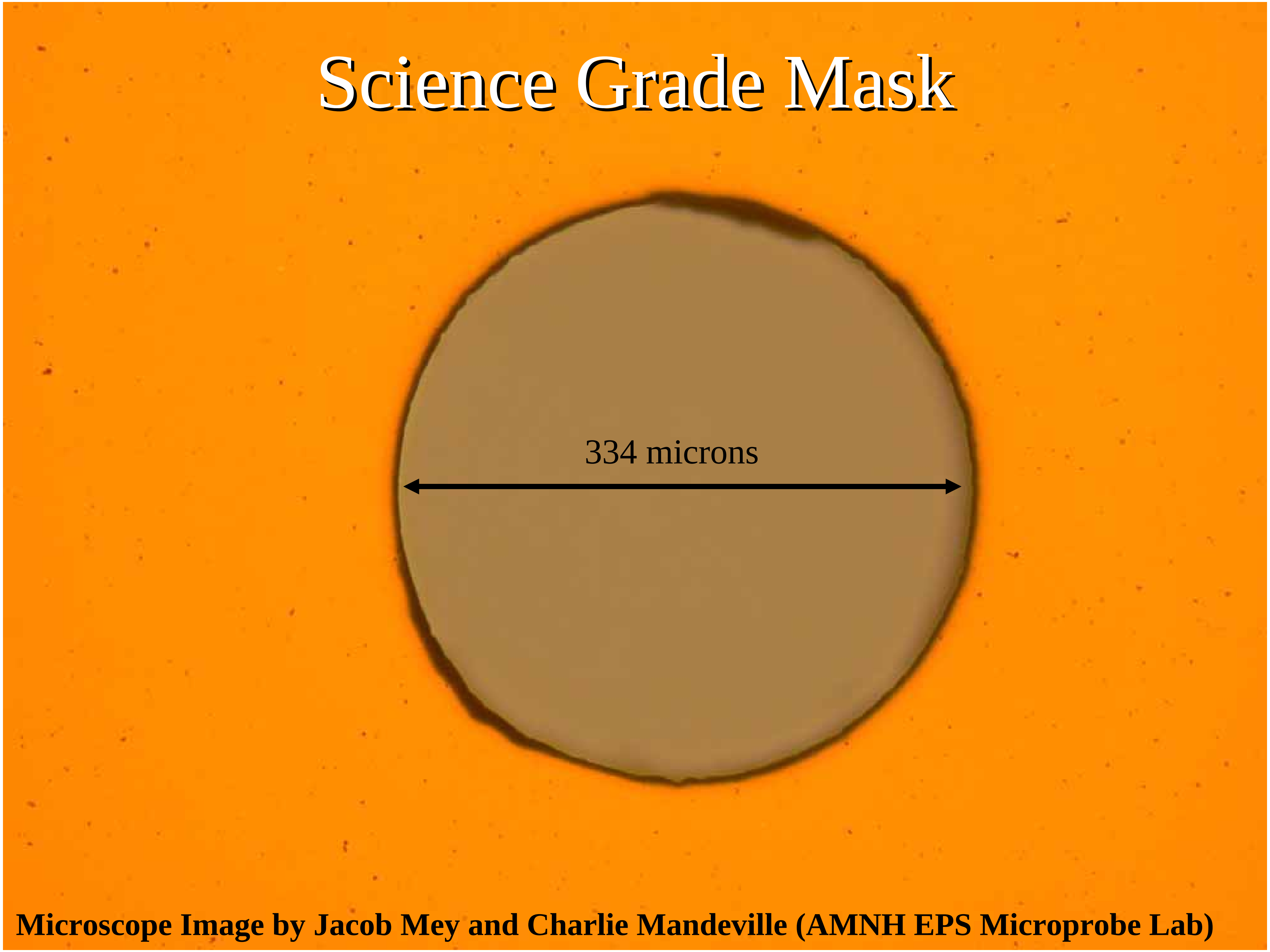




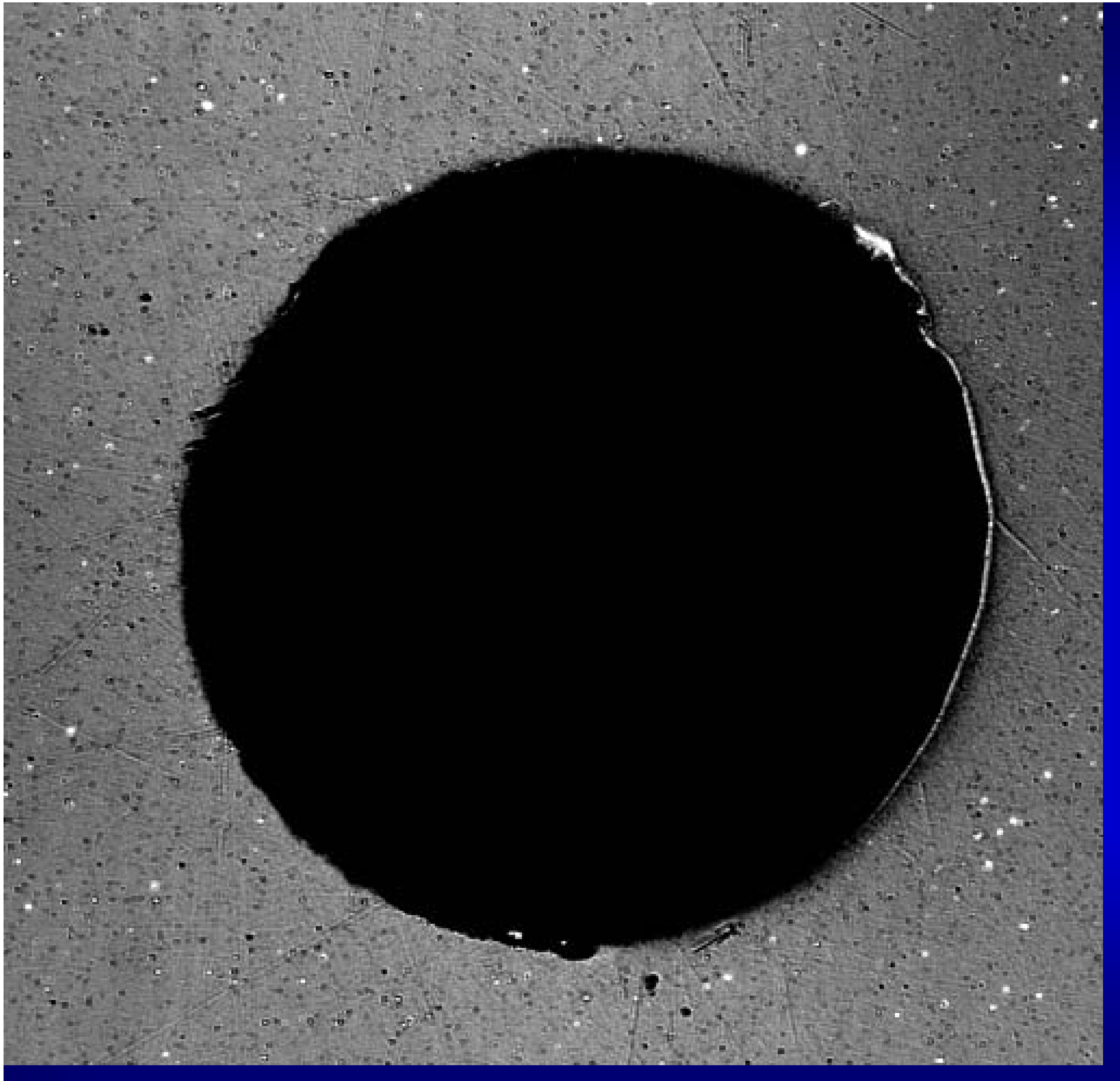
96% Strehl at H band (1.6 microns)


Prototype Mask
334 microns
Microscope Image by Jacob Mey and Charlie Mandeville (AMNH EPS Microprobe Lab)

Science Grade Mask



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



245 um mask
Pure Nickel with
Gold Coating

Confocal Microscopy

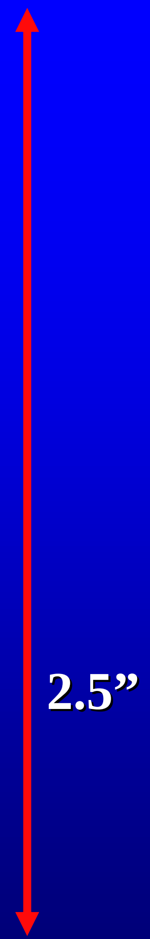
SiC may be
A better solution

Welcome to Sunny Maui!


SAT
SAT

Unocculted Images

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

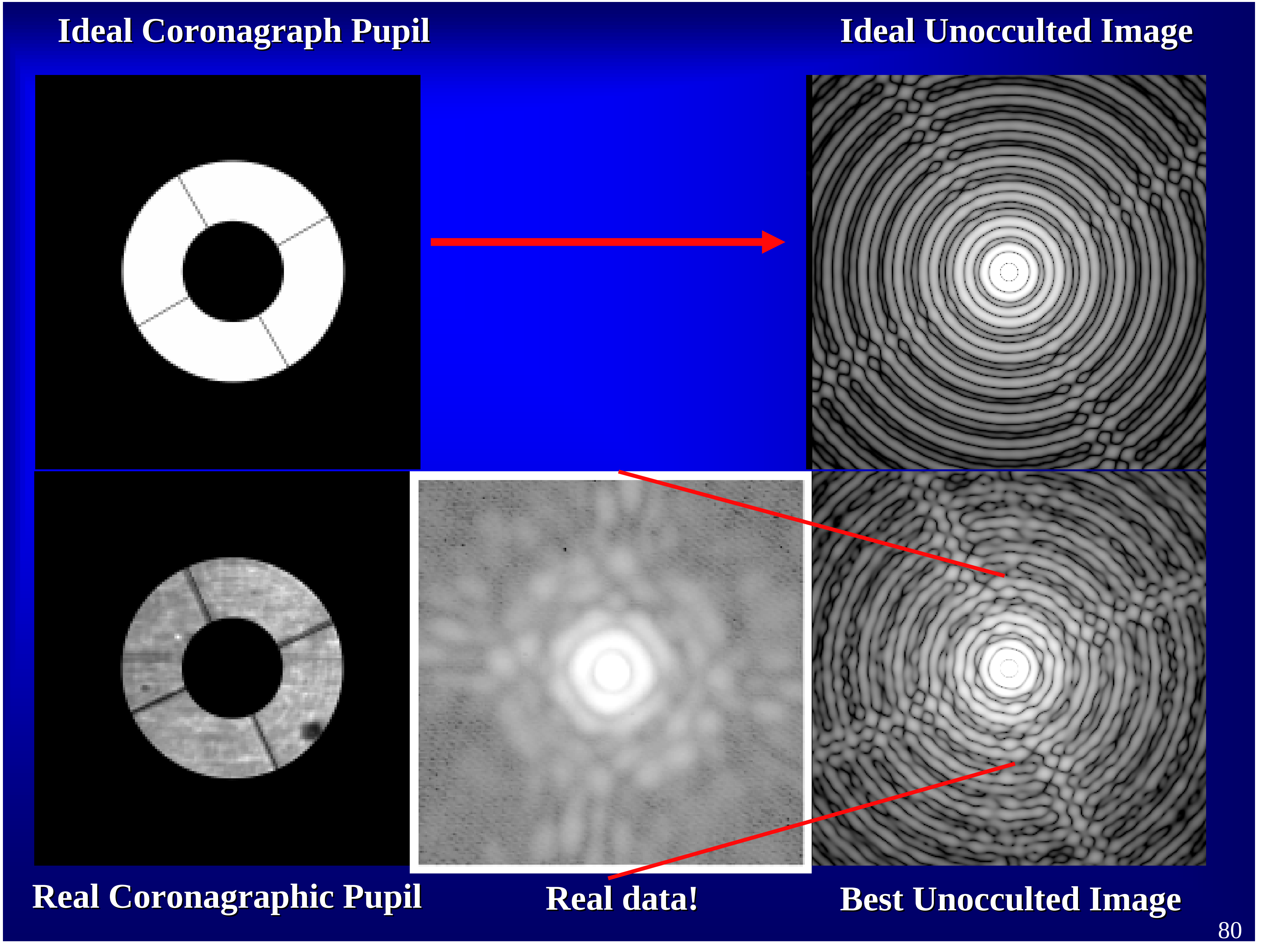


S ~ 90%

Composite
Log Scale

Core: .2 s
Wing: 2 s

unocculted H band image of delta Hercules (V = 3 mag. A3IV, 25 pc)


Ideal Coronagraph Pupil
Ideal Unocculted Image
Real Coronagraphic Pupil
Real data!
Best Unocculted Image

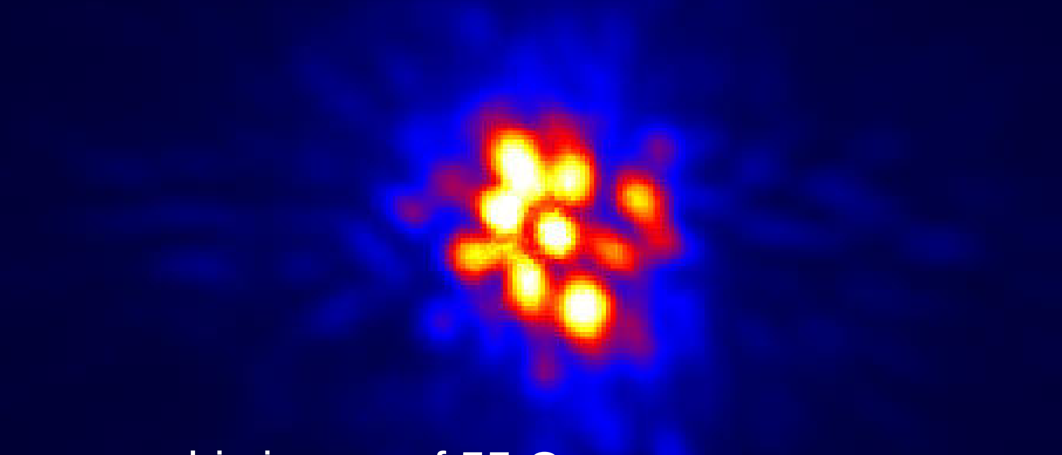
Lyot Project first light: 85-90% Strehl

Oppenheimer, Digby, Perrin, Roberts , Sivaramakrishnan, Soummer & Makidon (2005)

941-channel AO on 3.6m AEOS telescope

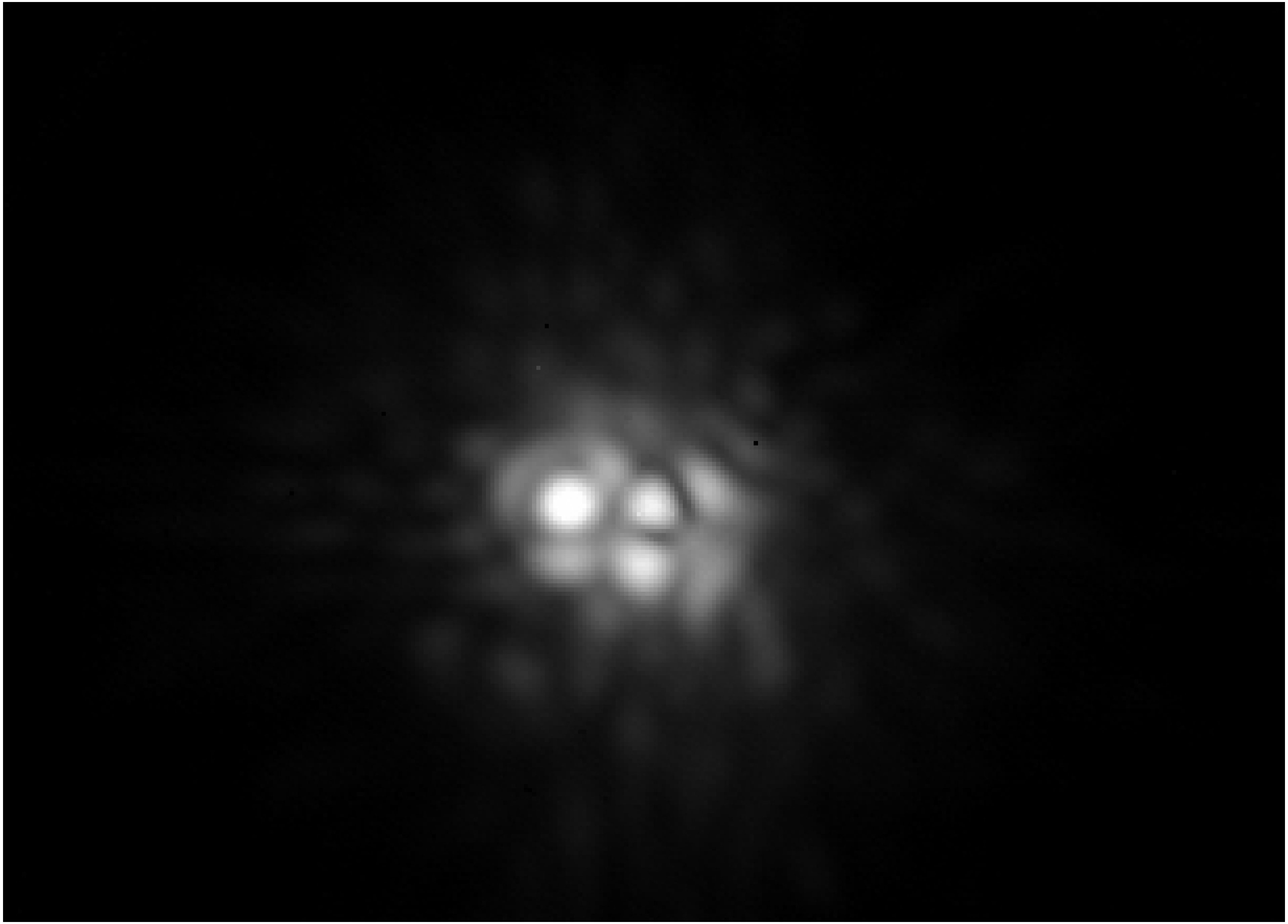
Occulter **0.35”** in H-band (**4 λ/D**)

March 2004

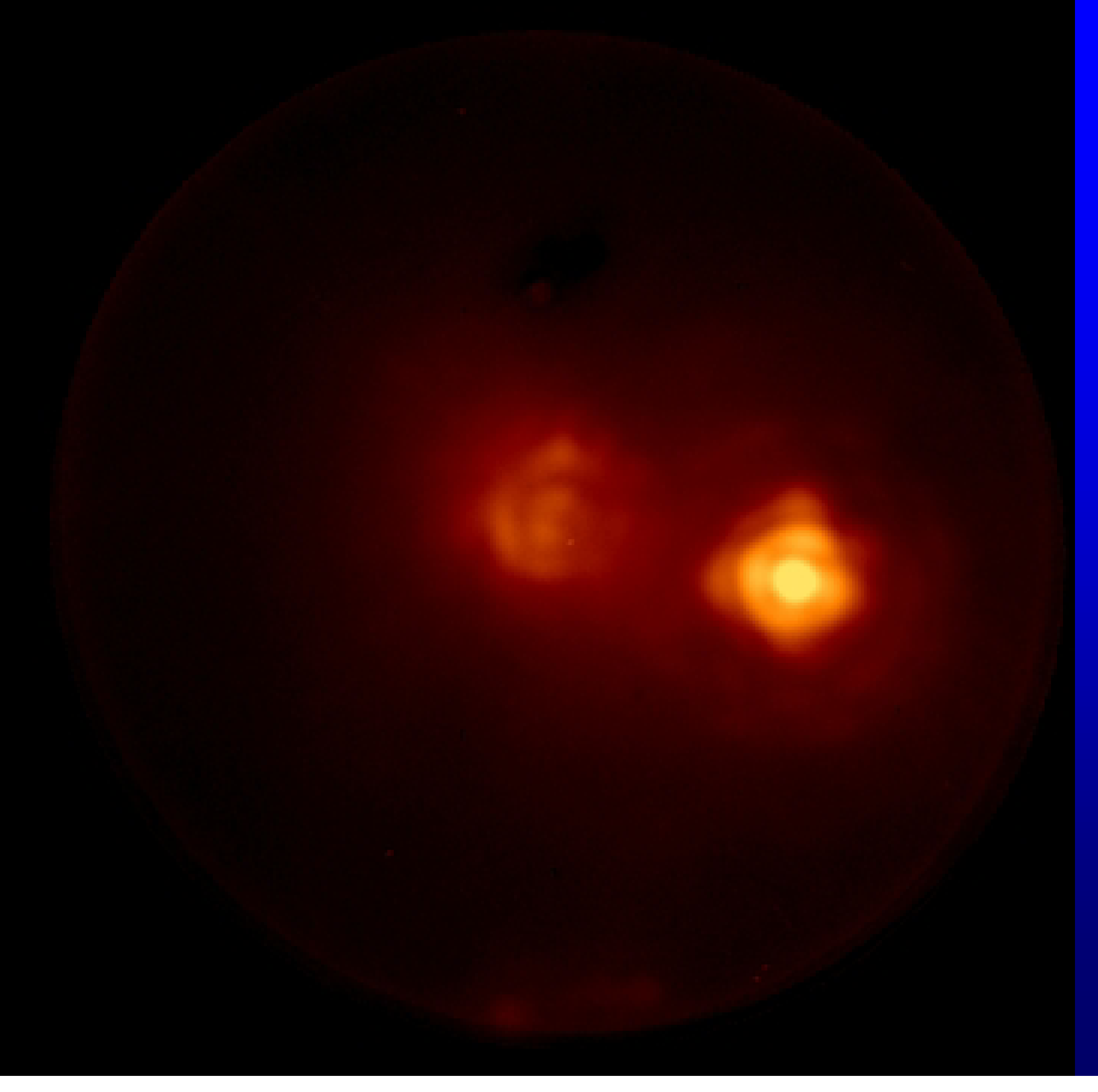


Coronagraphic image of 55 Cnc
Residual speckles dominate noise

- Speckle pinning
- Speckle amplification
- Symmetric halo speckle
- Chromaticity of speckles



Calibration Binary



15 min
Total Int.
Time

H-Band

Delta Herculis

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

H band
5” FOV
150 20 sec images

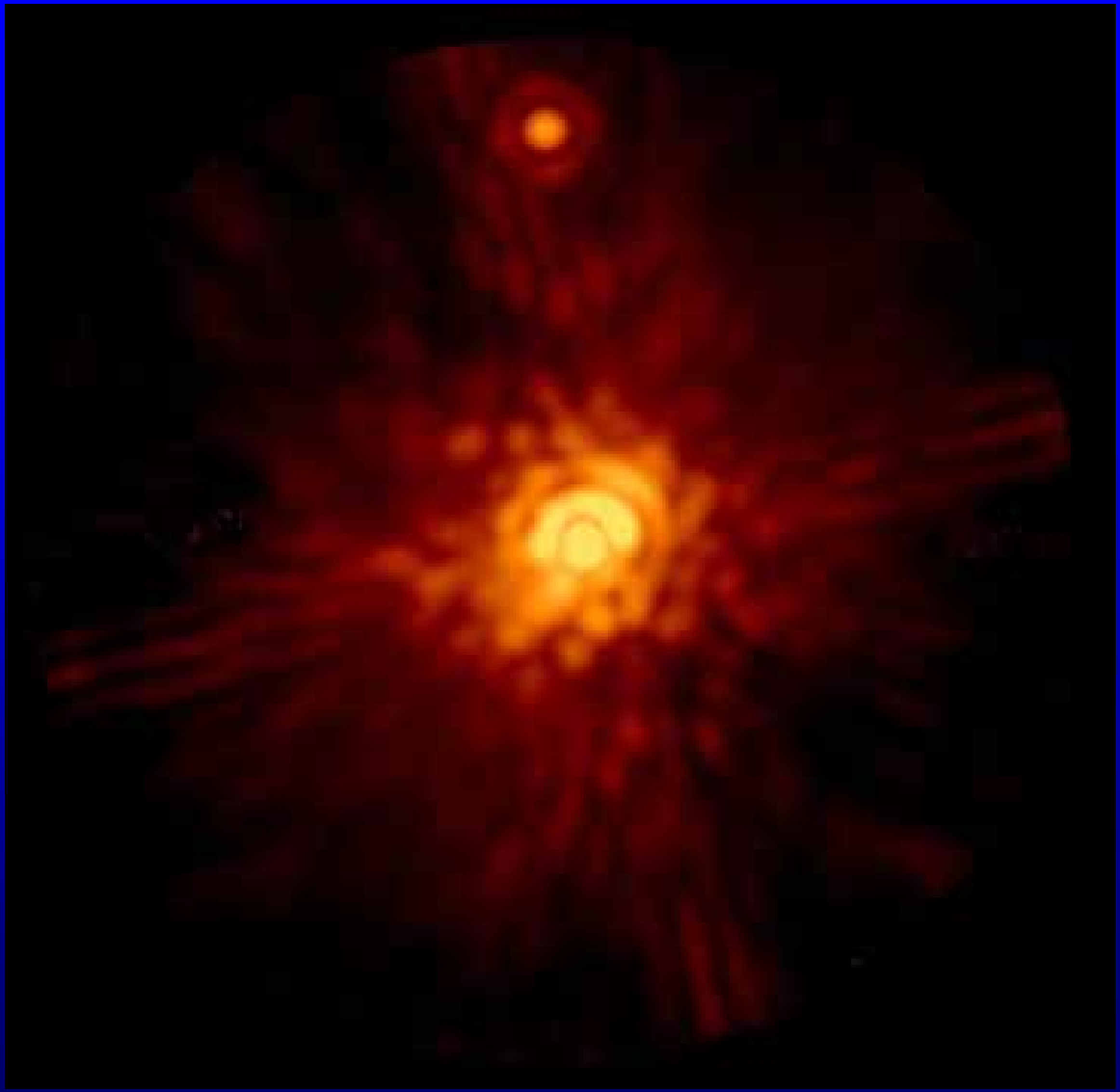
Scintillation ~10% (I)

ΔH = 11 mag at .3”
in single exposure

14 in 20 minutes

Nearby Star

H-Band
15 Min exp.



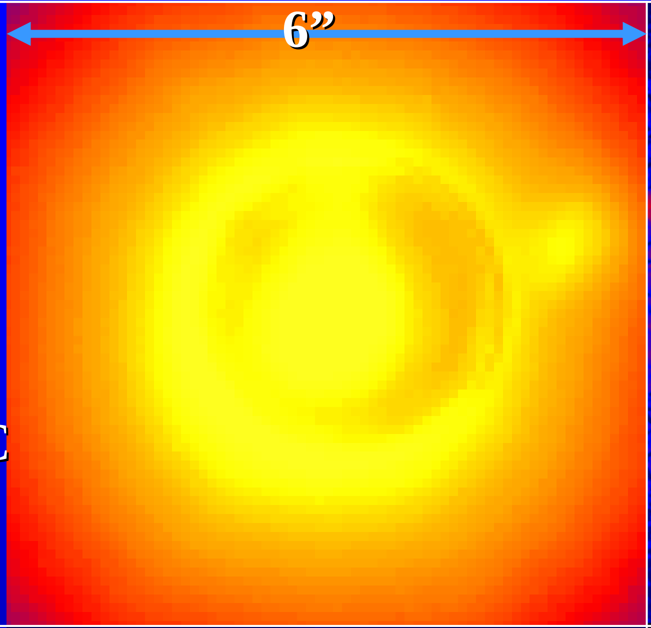
5"

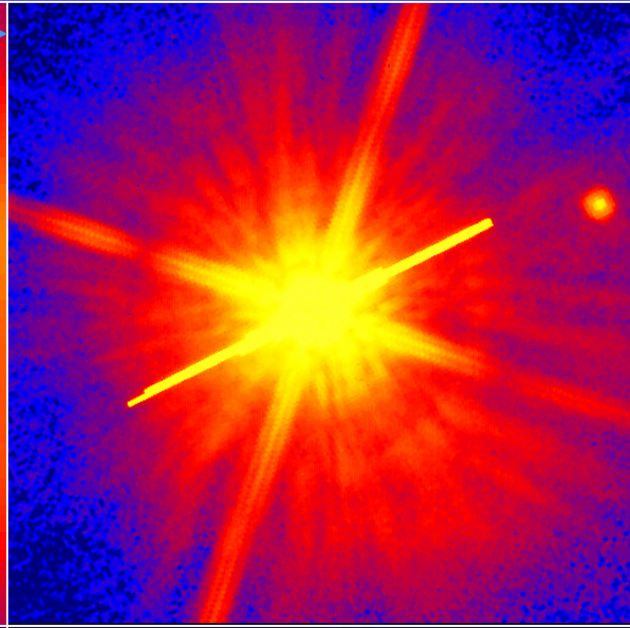
Lyot Project Data in Perspective

Palomar 60”
Coronagraph
I band

1994

Gliese 105AC





Hubble
WFPC2
I band

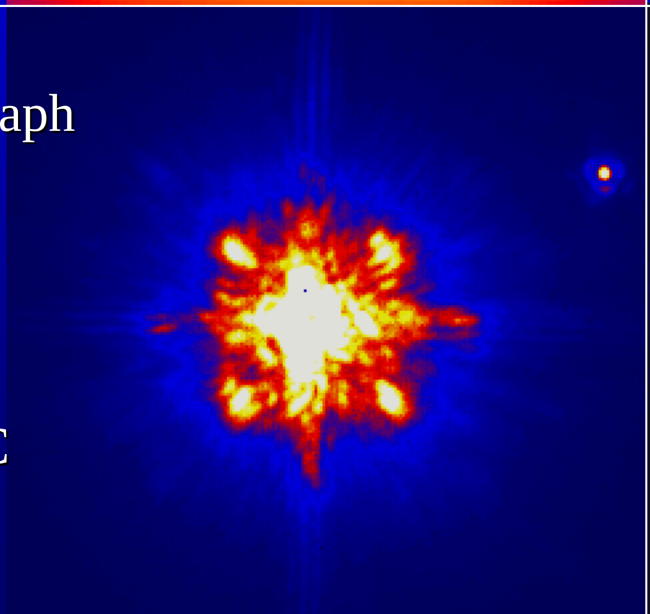
1995

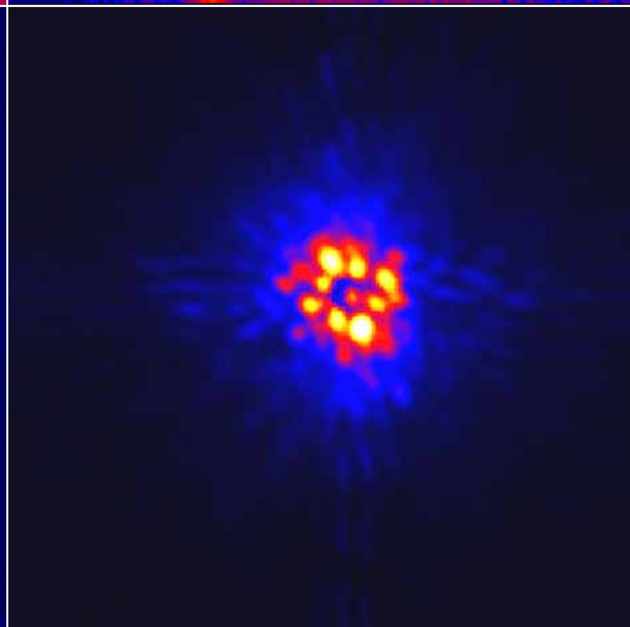
Gliese 105AC

Palomar 200”
AO Coronagraph
K-Band

1999

Gliese 105AC





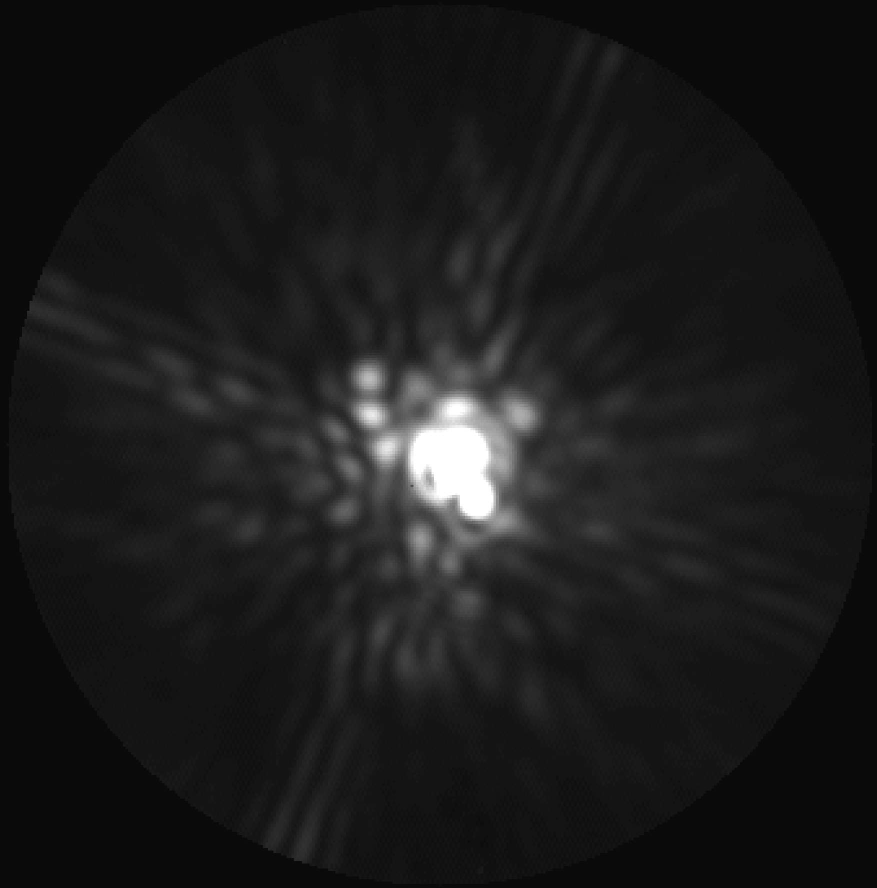
Lyot Project

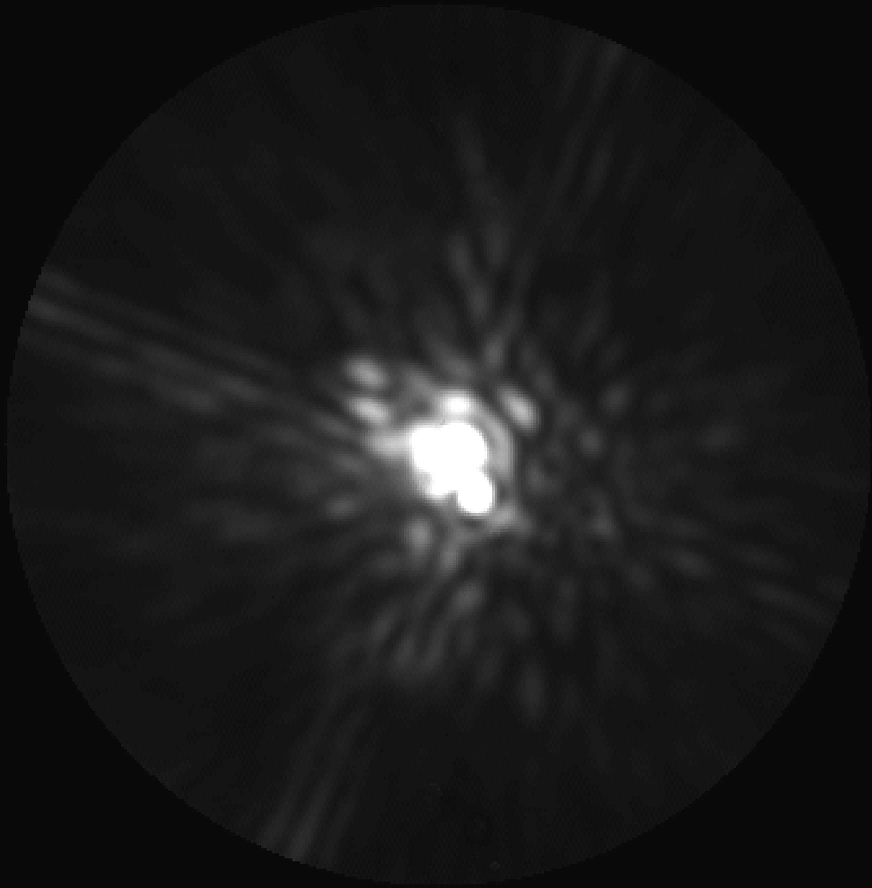
H-band

2004

55 Cancri

Dual Mode Imaging for Polarimetry: Derivation of Q and U Stokes Parameters





P_0 Fully Functional May 2005 **P_{90}**

Set of 4 acquired for each observation (P_0P_{90}, $P_{90}P_0$, $P_{45}P_{135}$, $P_{135}P_{45}$)

Simultaneous Multiwavelength Data

J H K

An IFU for the Lyot Project!

Other Projects

Gemini Extreme AO Coronagraph

Led by Bruce Macintosh (exaoc.ucolick.org) with AMNH building the coronagraphic optics (funding pending)

VLT Planet Finder

Led by Jean-Luc Beuzit (funding pending)

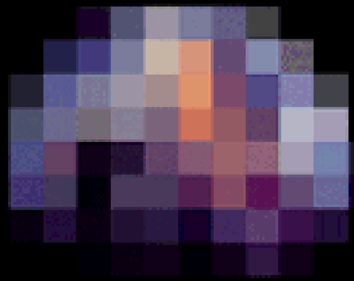
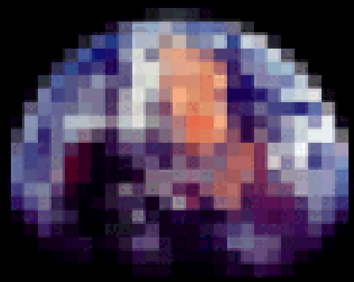
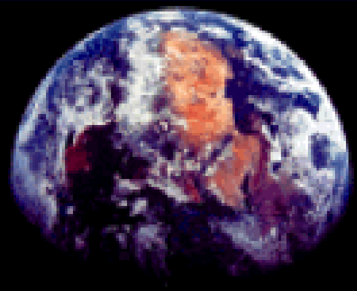
New High-Order CIAO on Subaru?

Led by Motohide Tamura

TPF-Coronagraph Mission

Science goals being defined now (STDT and see M. Turnbull’s poster)

I haven’t even mentioned any of the interferometry projects!

Pixel / Diameter	Pixel size @ planet (km)	Image	Interferometer Requirements		
10	1276		IR Visible	64 m² 576 m²	2,400 km 120 km
				Collecting Area	Baseline
25	510		IR Visible	1,024 m² 9,216 m²	6,000 km 303 km
100	128		IR Visible	0.64 km² 5.76 km²	24,000 km 1,200 km
				Collecting Area	Baseline
400	32		IR Visible	144 km² 1,296 km²	100,000 km 5,000 km

Resolving Earth

AD 2060: Time Resolved Exoplanetary Surface Imaging

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.