Off-axis coronagraphy and ExAO

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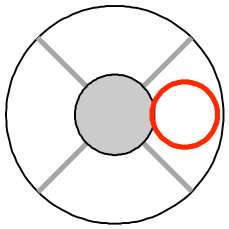
JPL

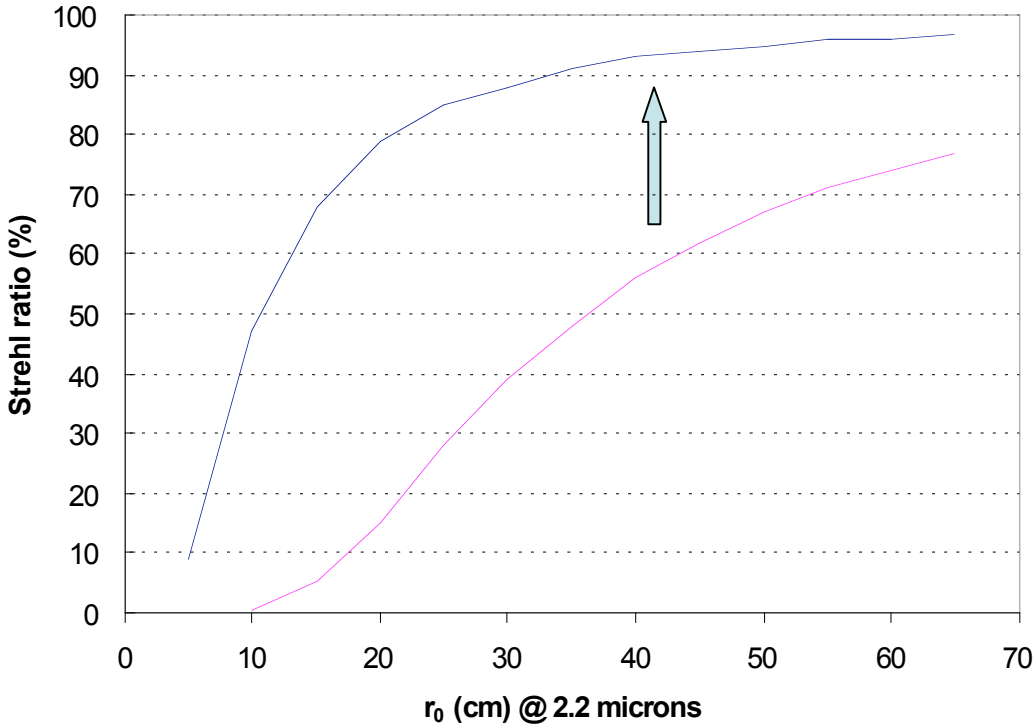
A "well-corrected sub-aperture" (WCS): can be used for ExAO today

- Use existing DM & AO system
- Finely correct a smaller telescope subaperture instead of full aperture

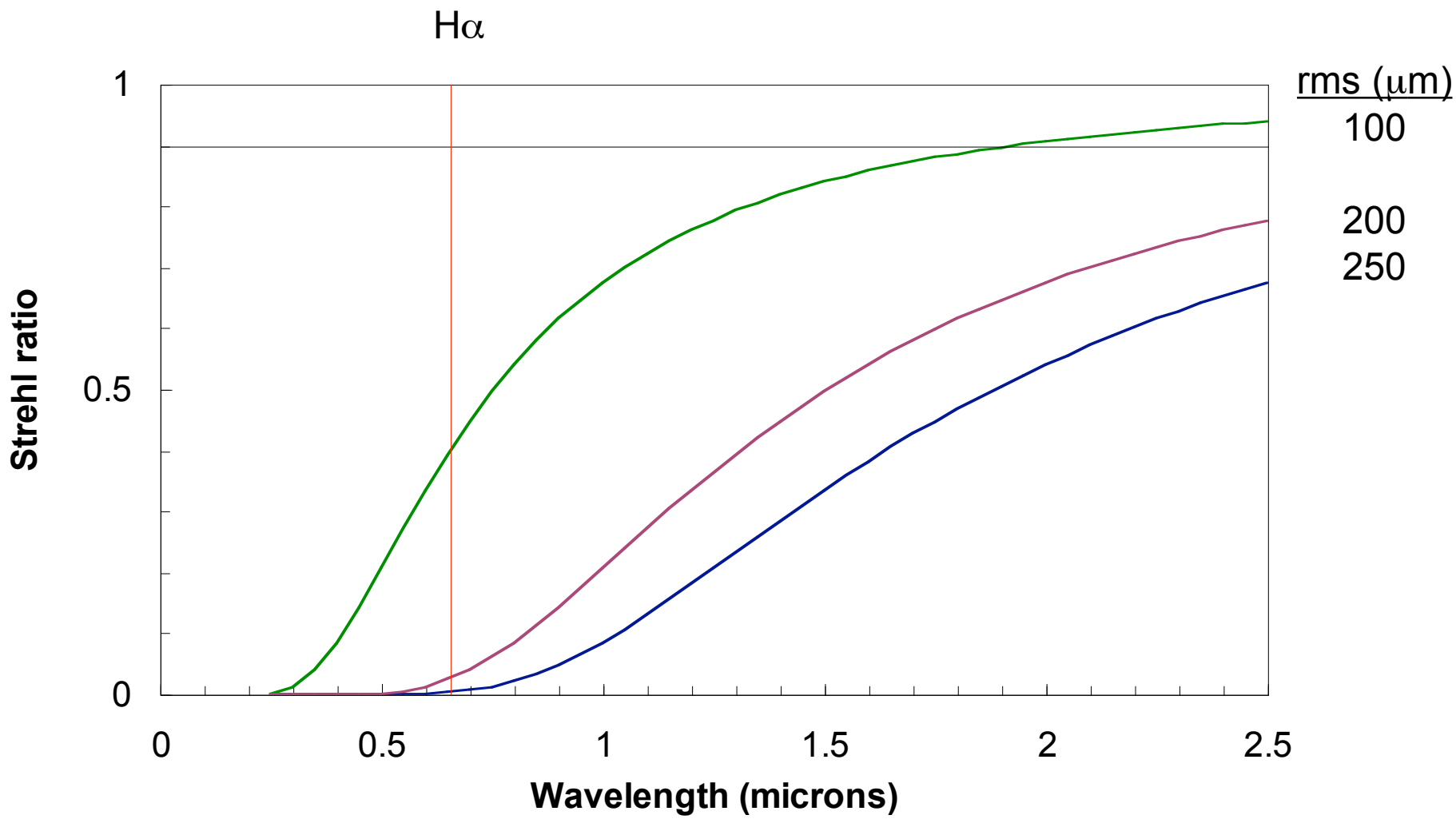


30 cm → 10 cm
actuator spacing

Palomar:
Compare 16x16 system:
1.5 m, unobscured
5.1 m with secondary



Strehl ratio vs. wavelength

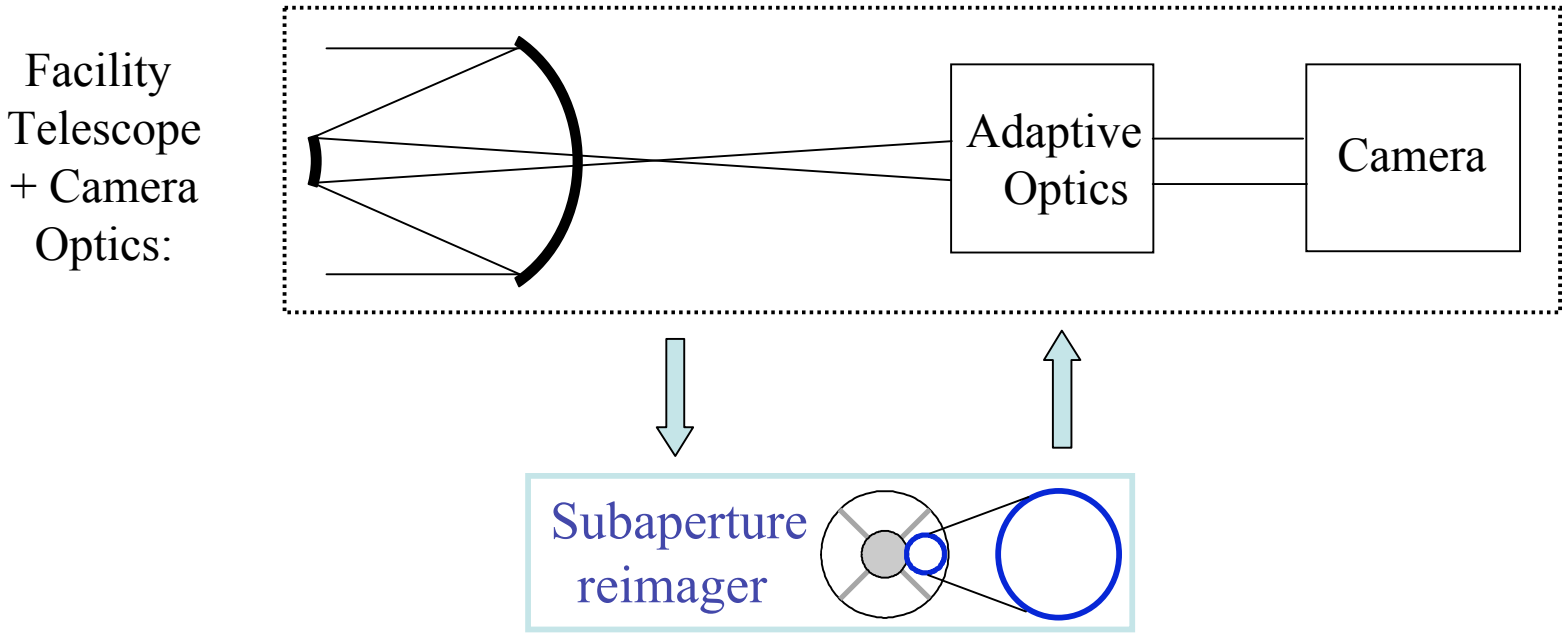


Some potential experiments with a well-corrected sub-aperture

- IR Extreme AO
- High-contrast IR coronagraphy (S > 90%)
- Visible AO
- Predictive AO

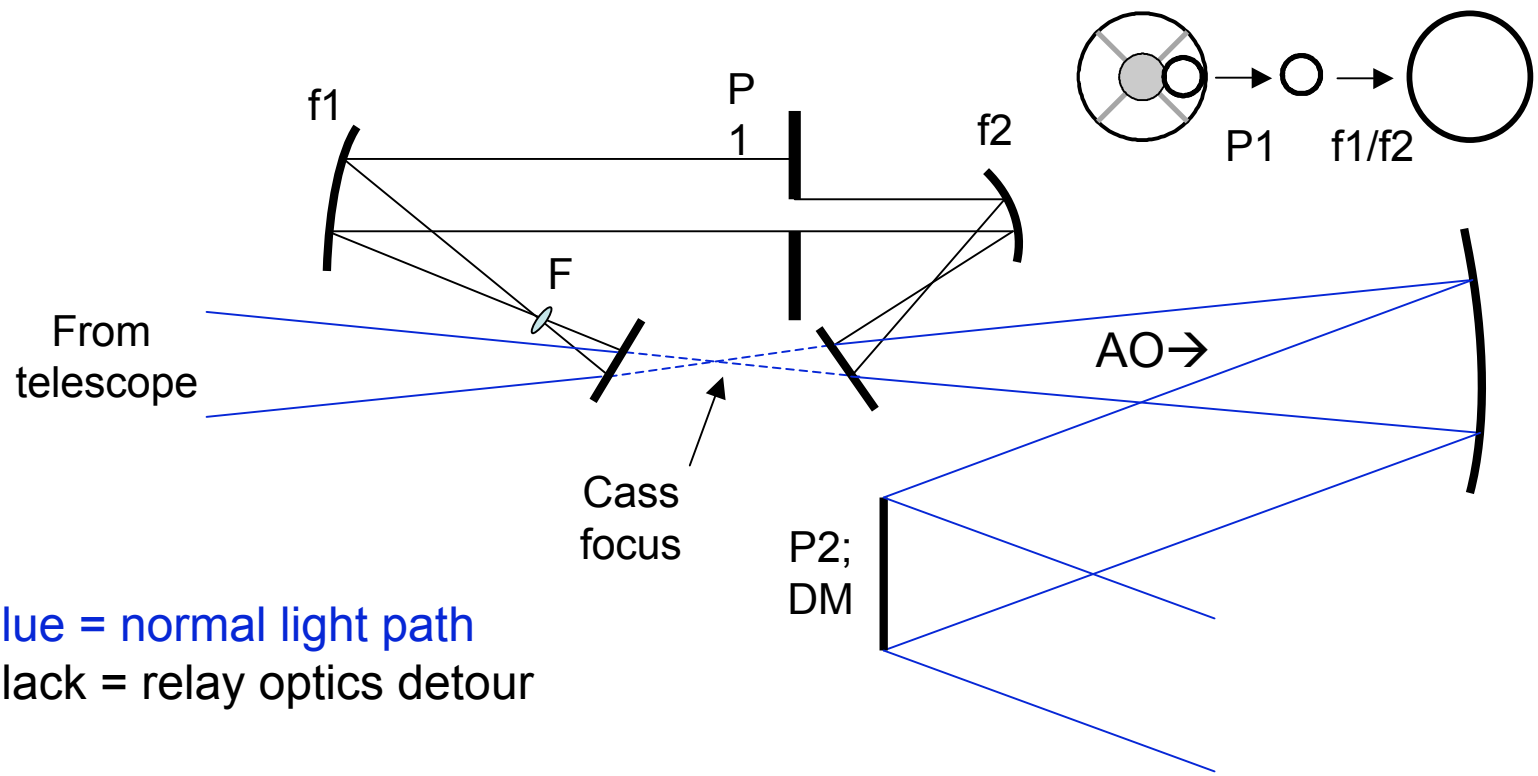
Pupil Magnification Relay Optics

- Produce a well-corrected, unobscured, off-axis telescope
- At Palomar, the off-axis pupil diameter can be 1.5 m
- Decrease rms from ≈ 200 - 250 μm → < 100 μm



Pupil-Magnifying Relay Optics

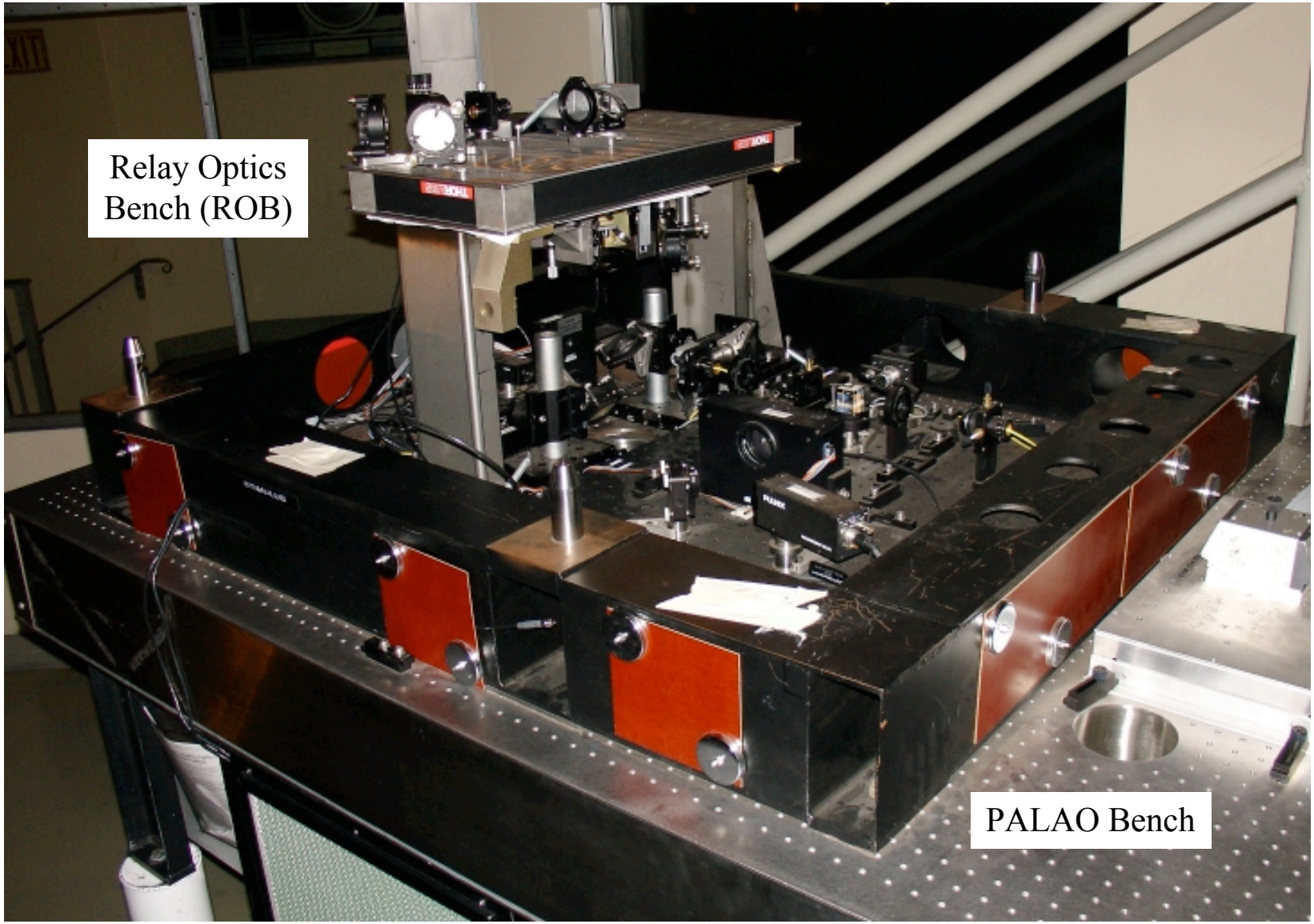
- Magnify pupil
- Maintain pupil location at DM
- Center off-axis sub-pupil on DM
- Maintain F# to AO system
  - camera sees same F# & pupil
  - same camera pixel scale (Fλ)
  - sky plate scale demagnified by f1/f2



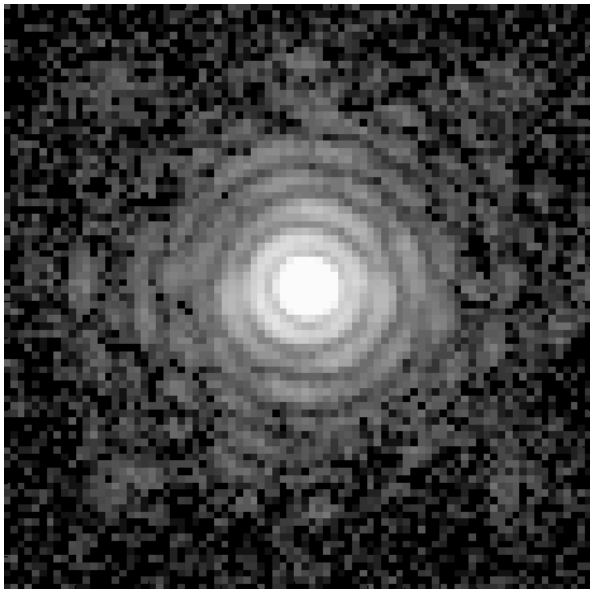
Blue = normal light path
Black = relay optics detour

Relay Optics on the Palomar AO Bench

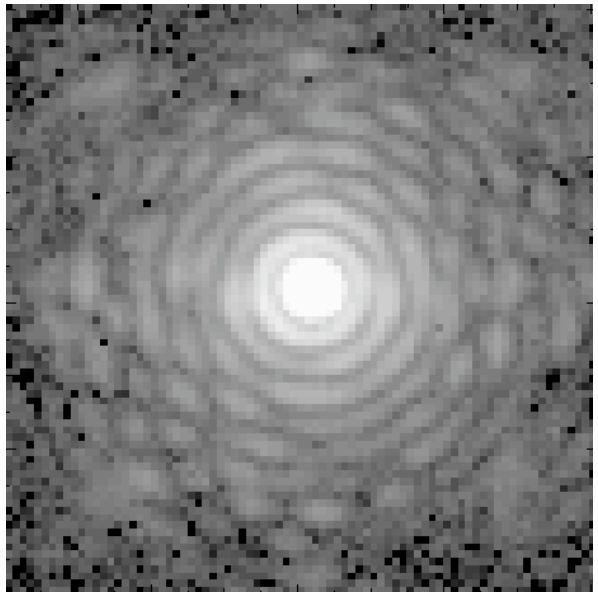
ROB goes in the puka



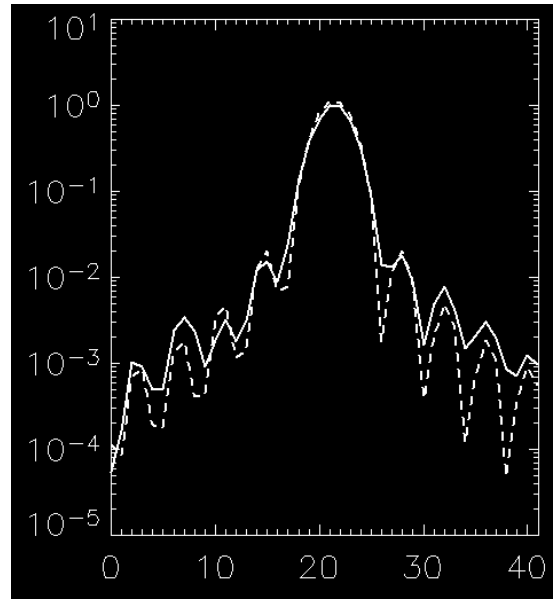
Single star HD121107 in Br γ filter (2.17 μm)



1 exposure (log scale)
Integration time = 1.416 s
(center saturated for better view)

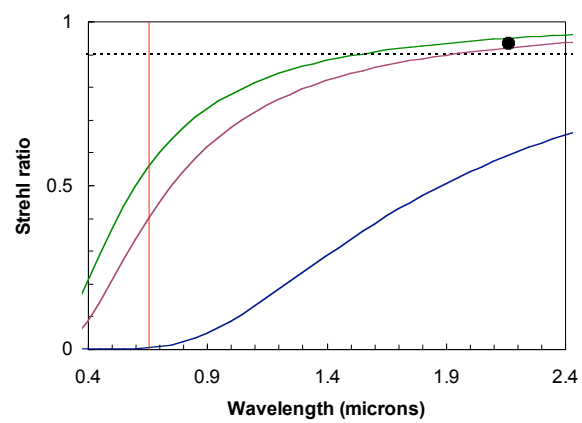


Sum of 20 exposures (log scale)
Integration time = 20 x 1.416 s
(center saturated for better view)



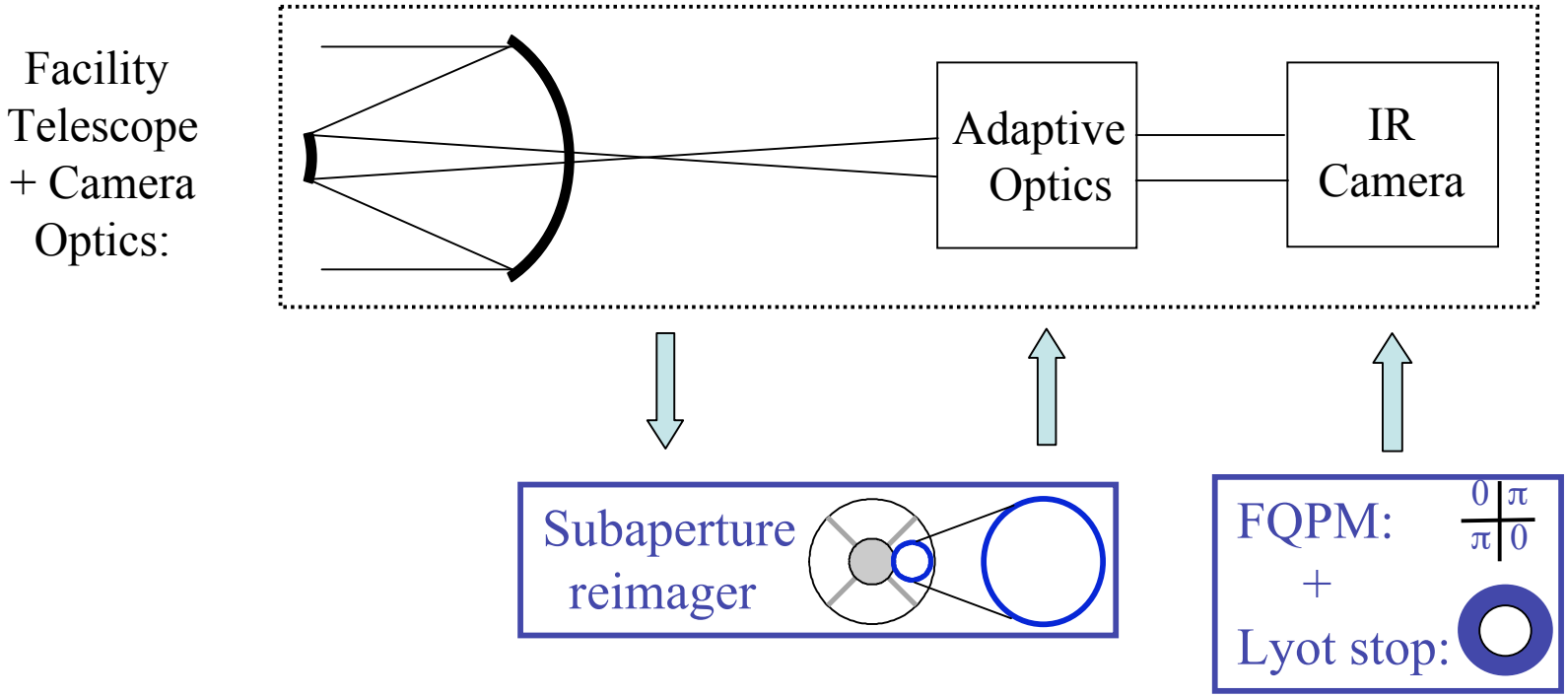
1 exposure
Integration time = 1.416 s

Best Strehl ratio ≈ 0.92-0.94
rms ≈ 85 -100 nm



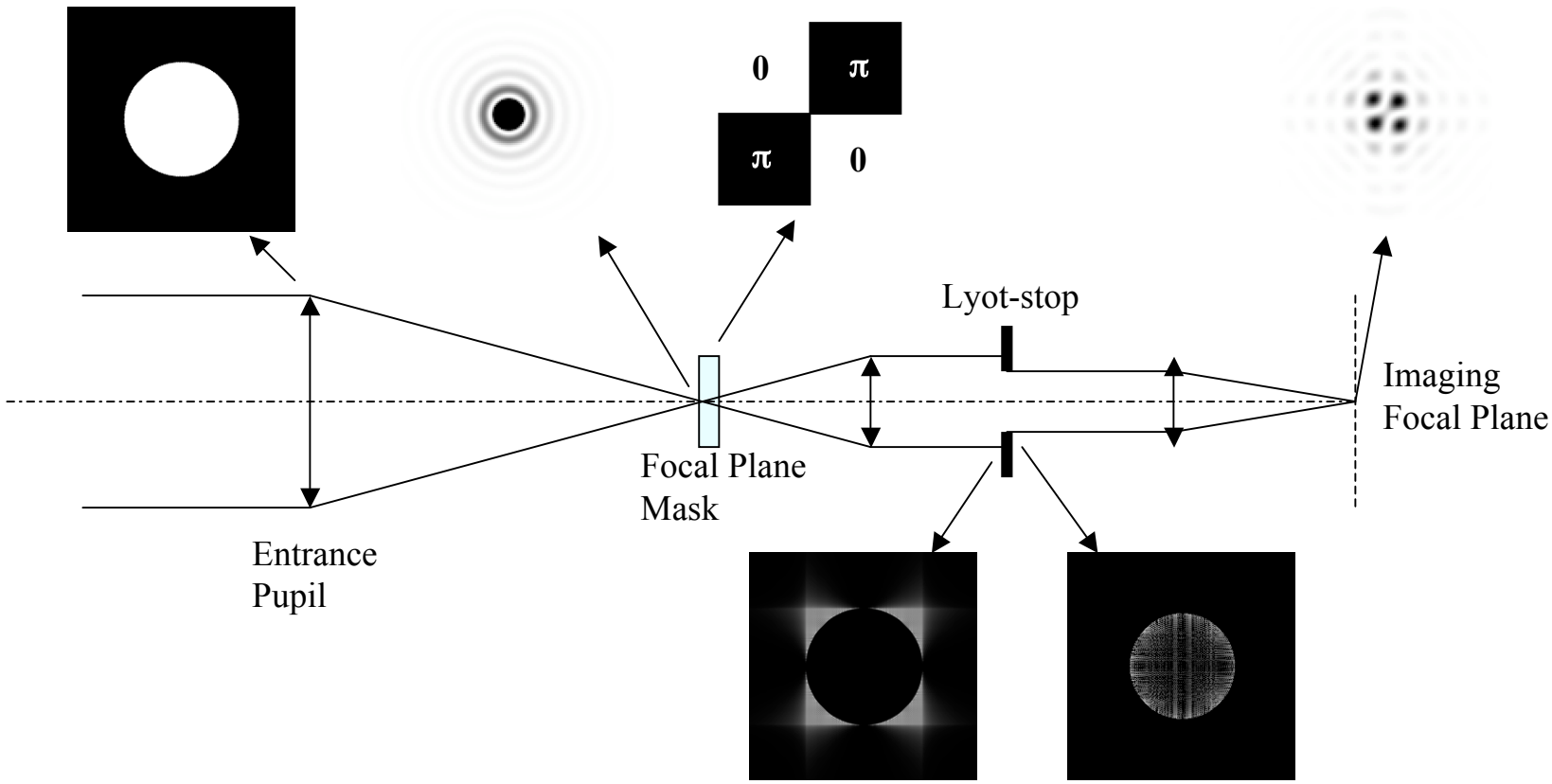
Optics Layout for coronagraphy

- FQPM coronagraph:
- Circular unobscured aperture is ideal match to FQPM
- Small IWD because phase-based



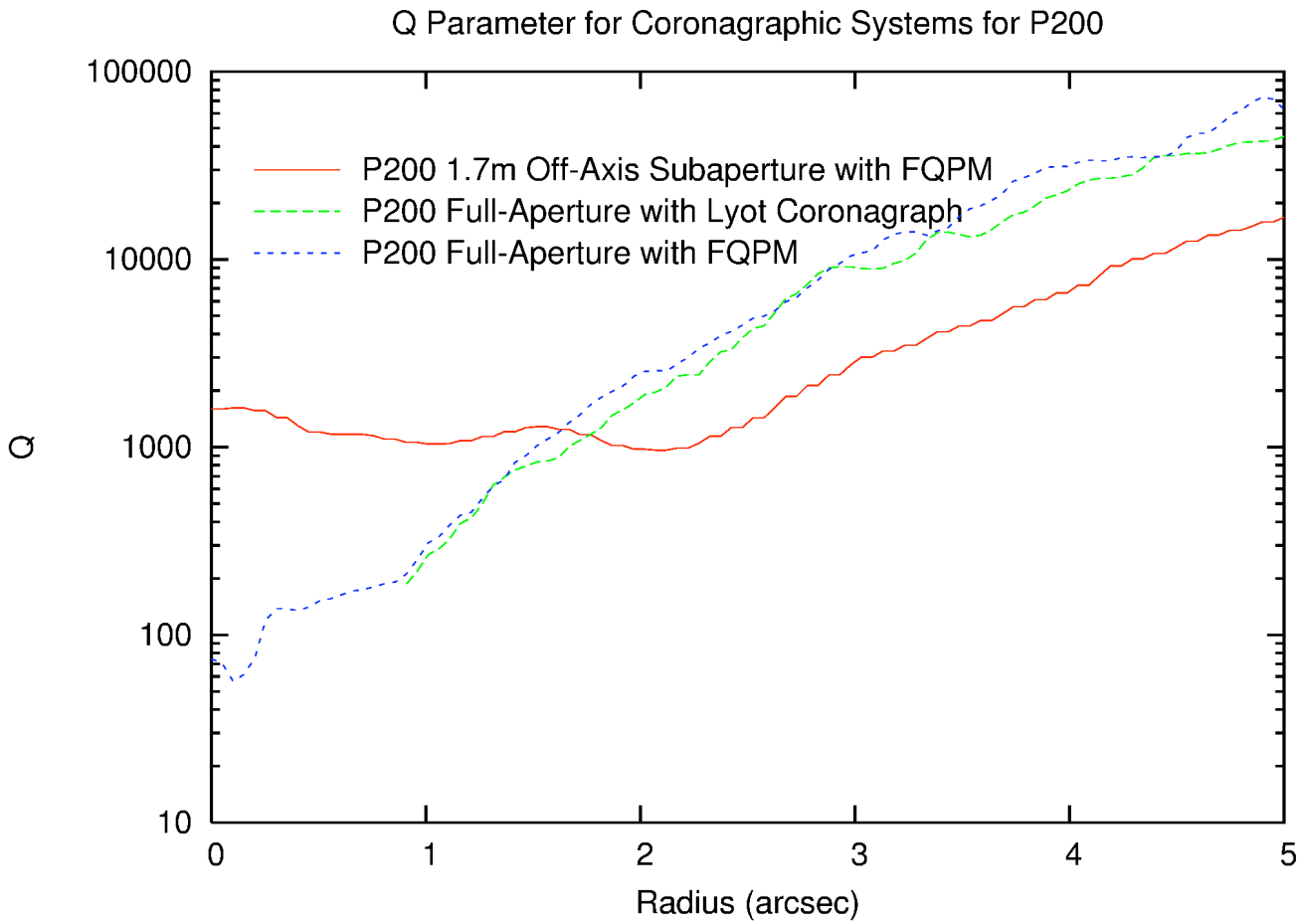
FQPM coronagraph

- Use a transparent phase mask to apply a π-phase shift in 2 of 4 quadrants
- A Lyot stop in the pupil plane then blocks the starlight
- Inner working angle ≈ λ/2d ≈ 3λ/2D



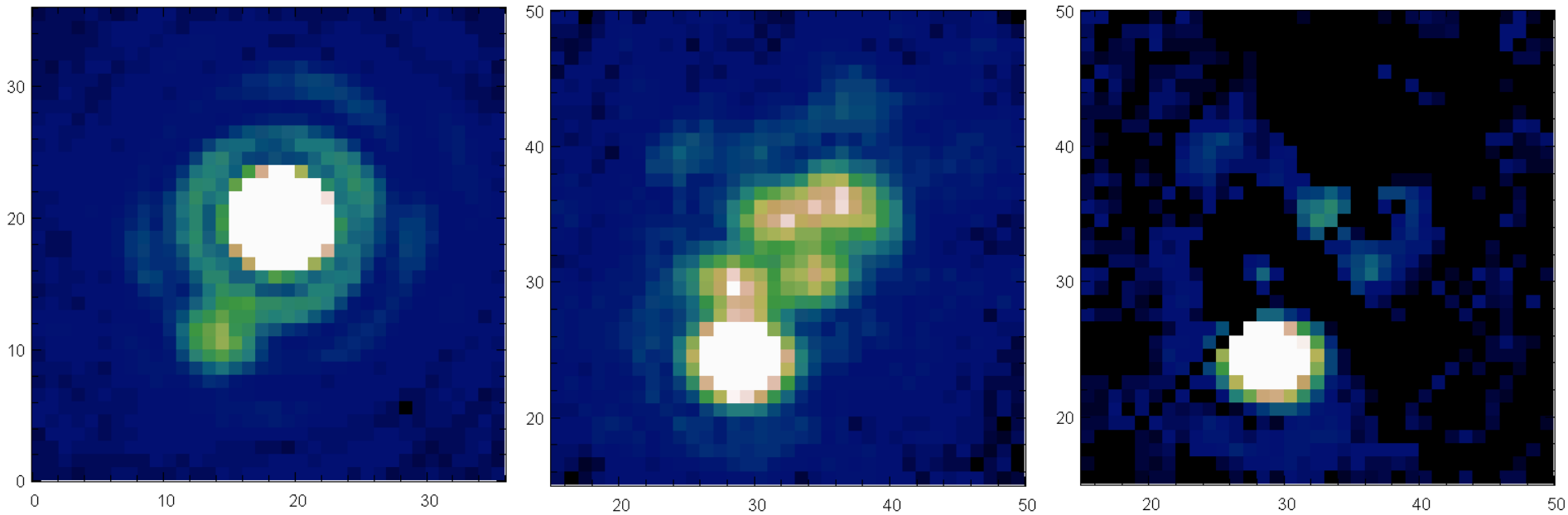
1. D. Rouan et al., "The Four-Quadrant Phase Mask Coronagraph. I. Principle,", PASP **112**, pp.1479-1486, Nov. 2000.

Expected Performance at Palomar



- Q is the ratio of the brightness of the central star to that of a companion star equal in brightness to the scattered light halo (in a diffraction limited aperture)
- Q is higher for subaperture for r < 1.5 arcsec (central 10 x 10 beam area)
- Note: angular resolution is lower: $\lambda_{2.167}/D_5$ = 100 mas; $\lambda_{2.167}/D_{1.7}$ = 300 mas

The Binary Star HD148112 through a FQPM



Normal
"off-FQPM" image

"Through–FQPM" image

Peak extinction = 80
Mean of 5 short exposures
(total time = 21.24s)

Cross-diagonal subtraction

Peak extinction = 235
≈ 6 mag

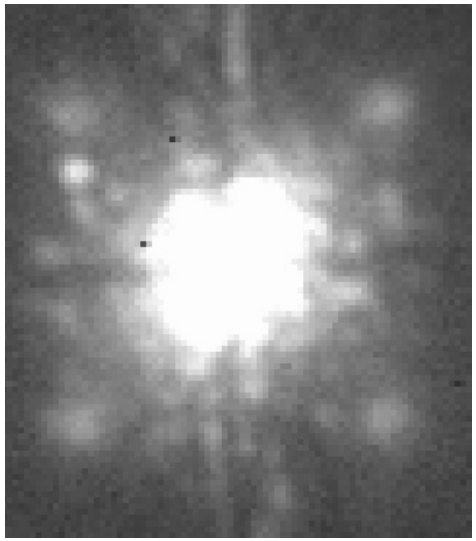
May 2006: Brown Dwarf pair HD130948 at K_s

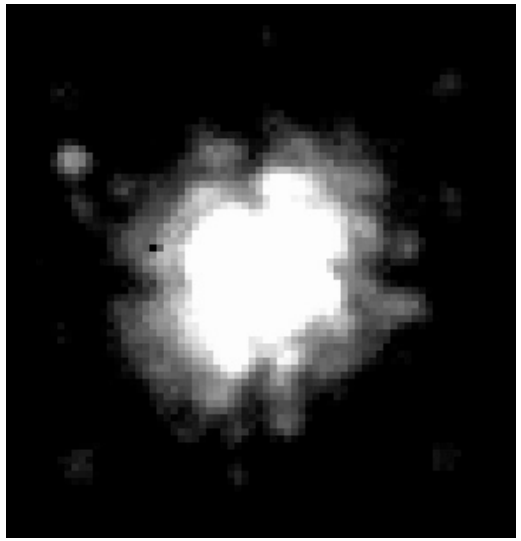
- Broadband: K_s
- Stellar rejection ≈ 35:1
- $\Delta K_s = 6.9 \pm 0.5$
- separation = 2.61 ± 0.08“
- azimuth (E of N)= 103.8 ± 2.9 deg

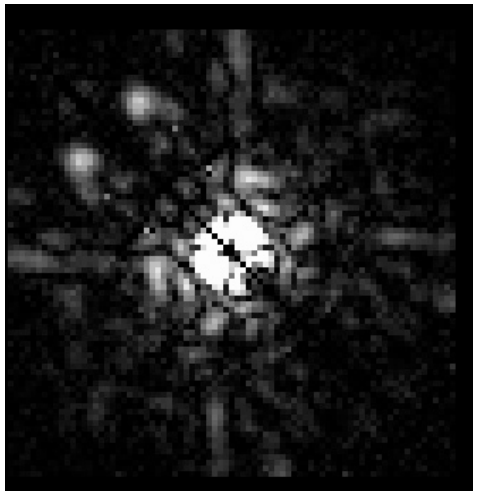
- Does not yet include cross-diagonal subt.
- At ≈ 7.5 λ/D_{Lyot} –
  Could see it to 1/3 that radius: 1.5 λ/D_{Lyot}

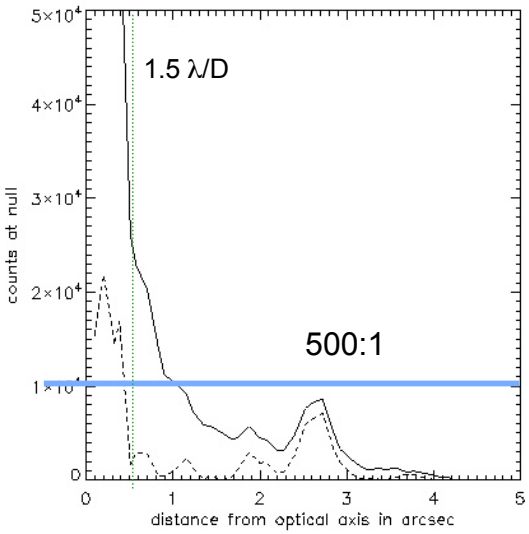
- Limitations:
  - Mask performance
  - SSM mirror actuator accuracy!
    - Need to stay on the crosshairs

- Looked at fainter, closer BDs 9/06
  - now 50:1 K_s



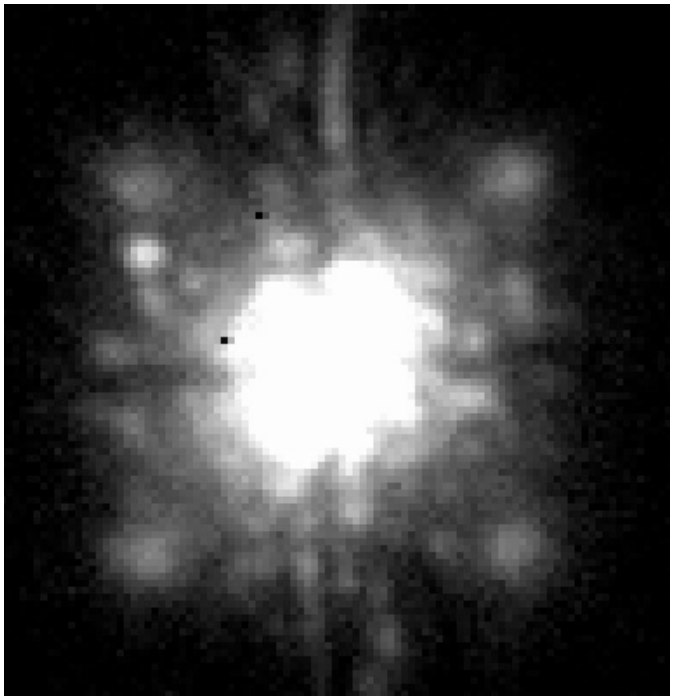


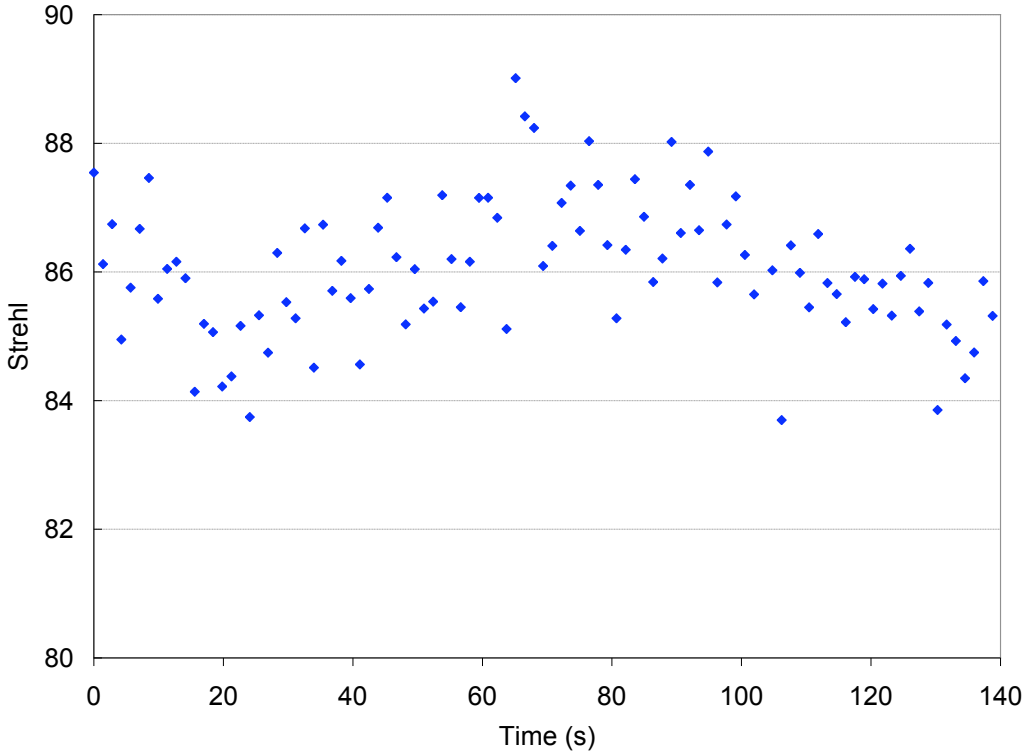




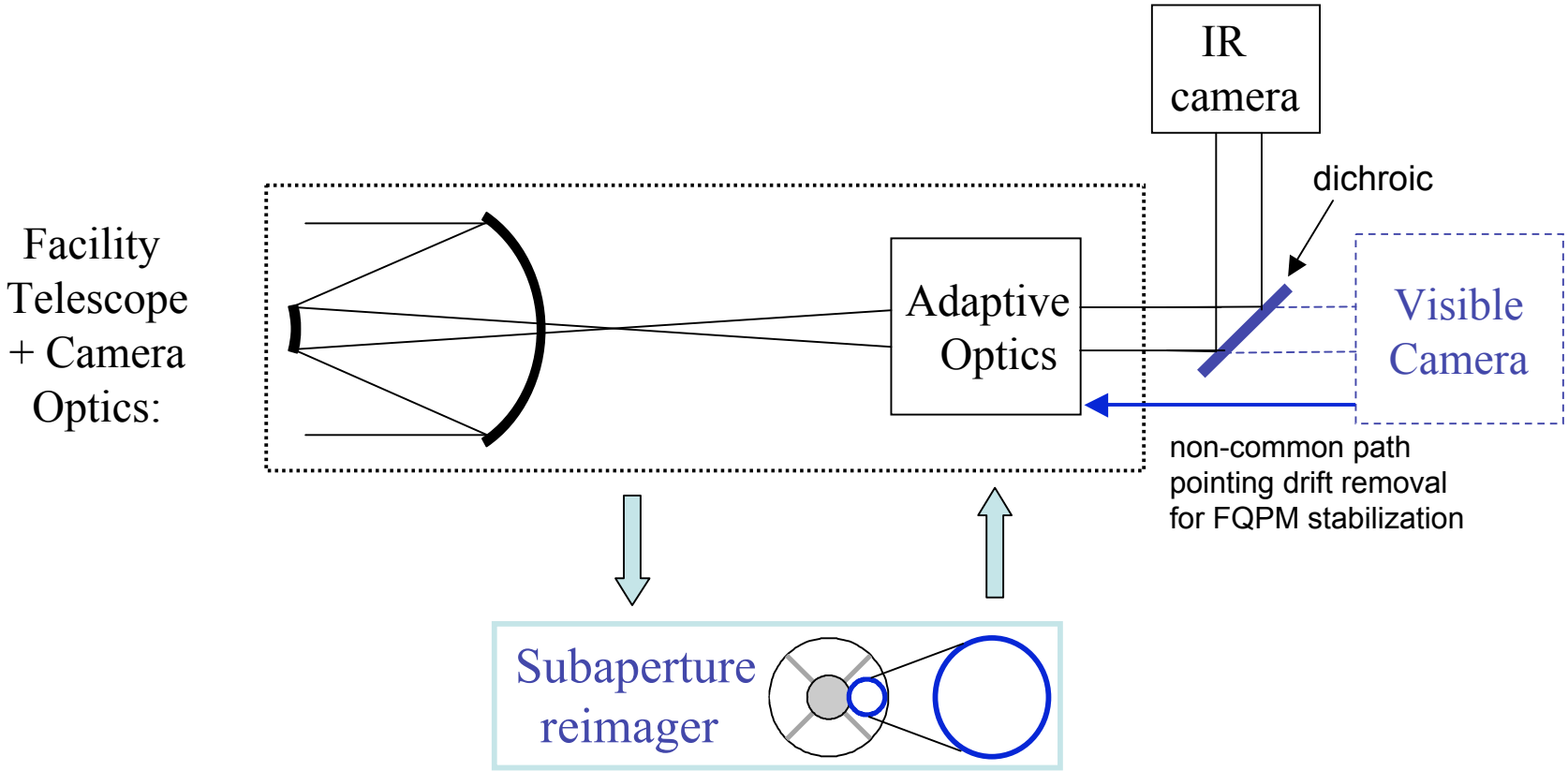
ExAO PSF Properties

- Dark hole region: note checkerboard mode corners
- Strehl stability
- WFS spatial filtering





Optics Layout for pointing stabilization and visible AO



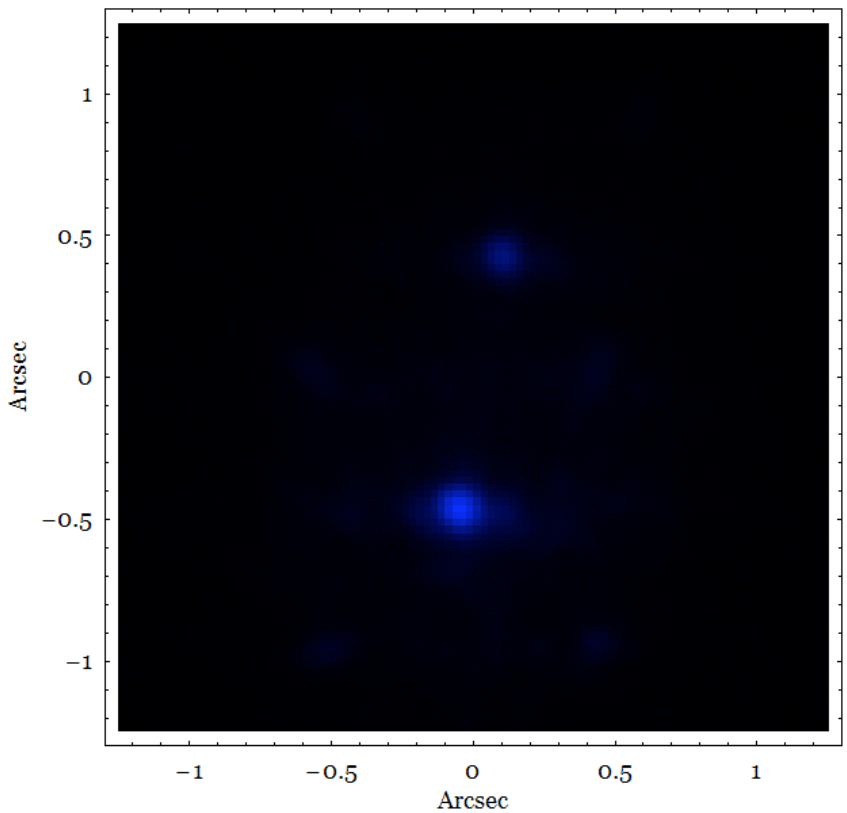
- At Palomar, WFS works in the VIS, so throughput is near zero, except in the blue/violet
- Vis camera was used relatively successfully for non-common path drift removal
- Try AO in the blue

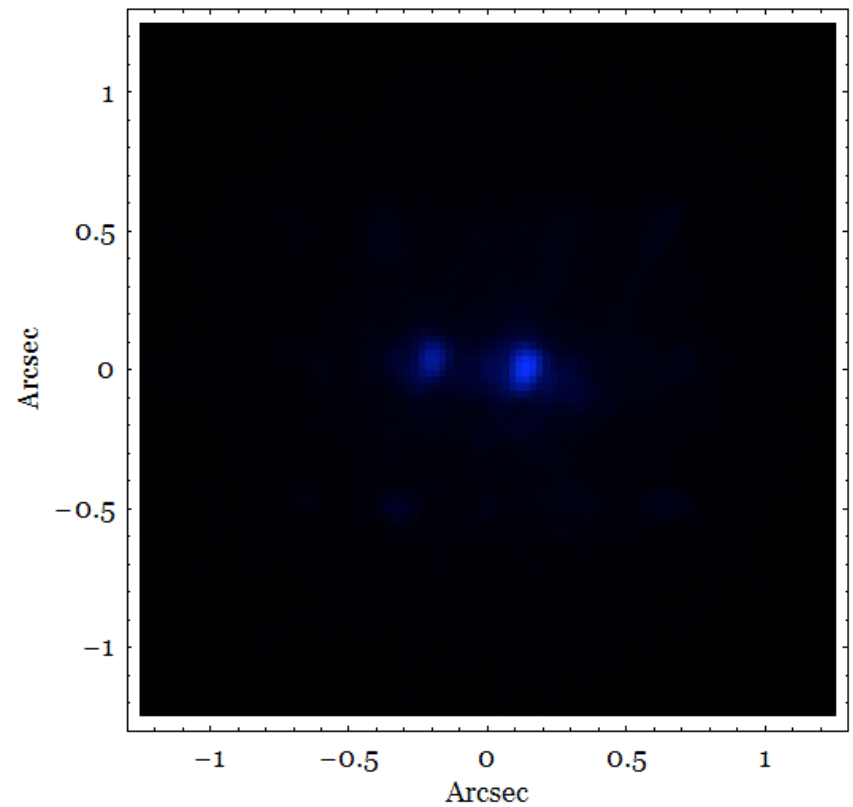
Visible AO in the B-band (400-450 nm):

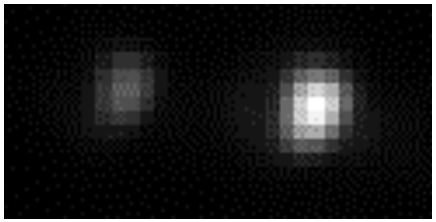
- SAO 70505
- V = 4.5, 6.0
- sep = 0.90 arcsec

Sept. 2006
1 pix. = 25.3 mas
λ/D (B) = 59 mas

- SAO 37735
- V = 5.1, 6.3
- sep = 0.34 arcsec

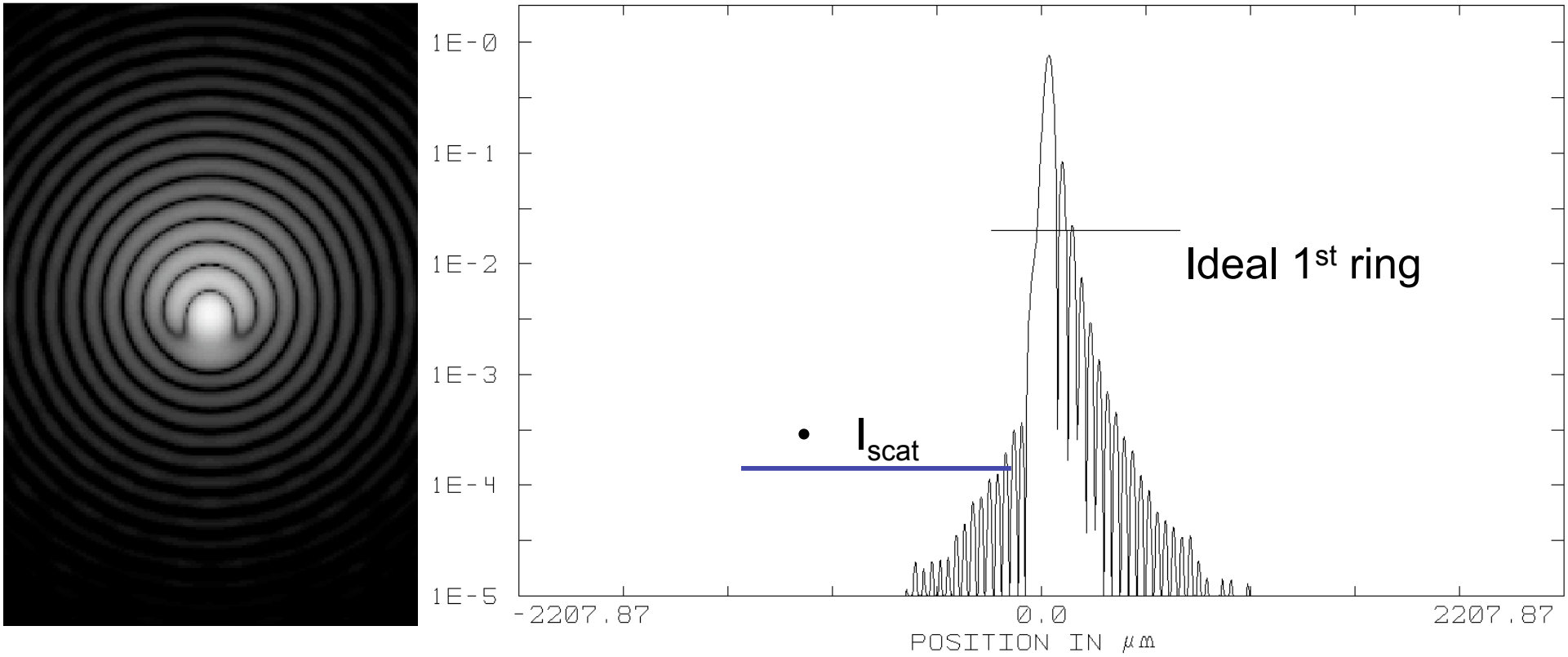






ExAO Dark Hole by Means of Coma

- $I_{scat} = (1-S)/N^2 \approx 4 \times 10^{-4}$
- Example: 1.4 waves PV of coma at 2.16 μm



Initial trial carried out 9/06: worked
Can go on to more complex phase distributions and/or speckle nulling

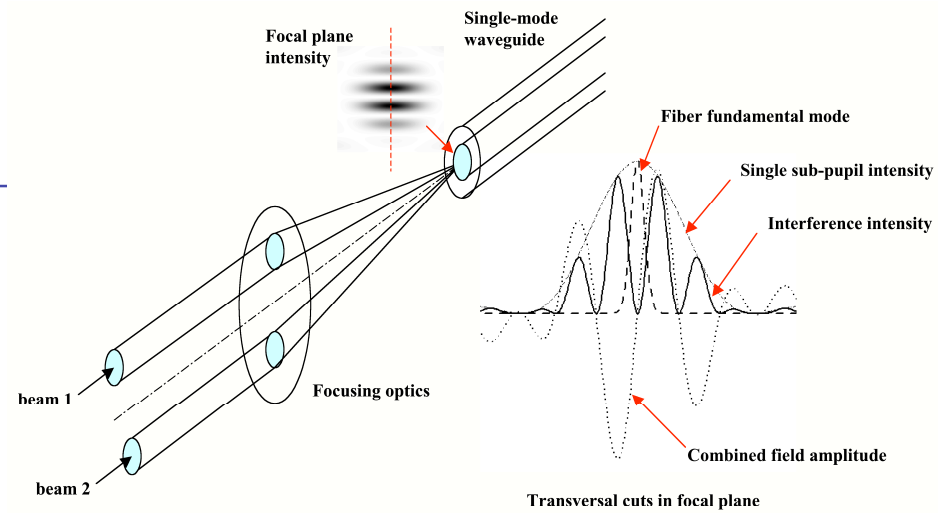
What can one do with a well-corrected sub-aperture?

- Extreme AO
  - Non-common path error reduction (tip-tilt first)
  - PSF properties/stability in high-Strehl regime
  - Dark hole generation and properties
  - Spatial filtering in WFS
- Visible AO
  - Initial demo on bright stars
  - Atmospheric properties (isoplanatic angle…)
  - Close companion science on bright stars, resolve stellar disks
  - Solar system objects
  - Laser guide star visible AO
- High-contrast IR coronagraphy (S > 90%)
  - FQPM
  - Band-limited, vortex, apodized pupil, etc…
  - Dark-hole, PSF subtraction, dual-λ imaging, dual-polarization imaging…
- Predictive AO
  - Sense beyond the science sub-aperture

- Lots of room for collaboration
- Can an off-axis WCS beat the full telescope for coronagraphy?
  - Larger sub-apertures on larger telescopes:

Next: Can also use two subapertures!

- Goal: High contrast imaging very near b stars
  - Demonstrate stellar nulling on the Palomar 200-inch telescope, with a novel "fiber nuller" and a TPF-like rotating baseline



- Significance:
  - Very small inner working angle
  - Demonstration of very simple nulling approach on a telescope
  - Demonstration of nulled signal acquisition and reconstruction with rotating baseline
  - Validation of TPF-I planet finding approach
- Schedule:
  - Funded
  - Have already demonstrated broadband K-band nulls of a few 1000:1
  - Phase control being worked on (next couple of months)
  - Should be able to bring a first generation nuller to Palomar by the spring