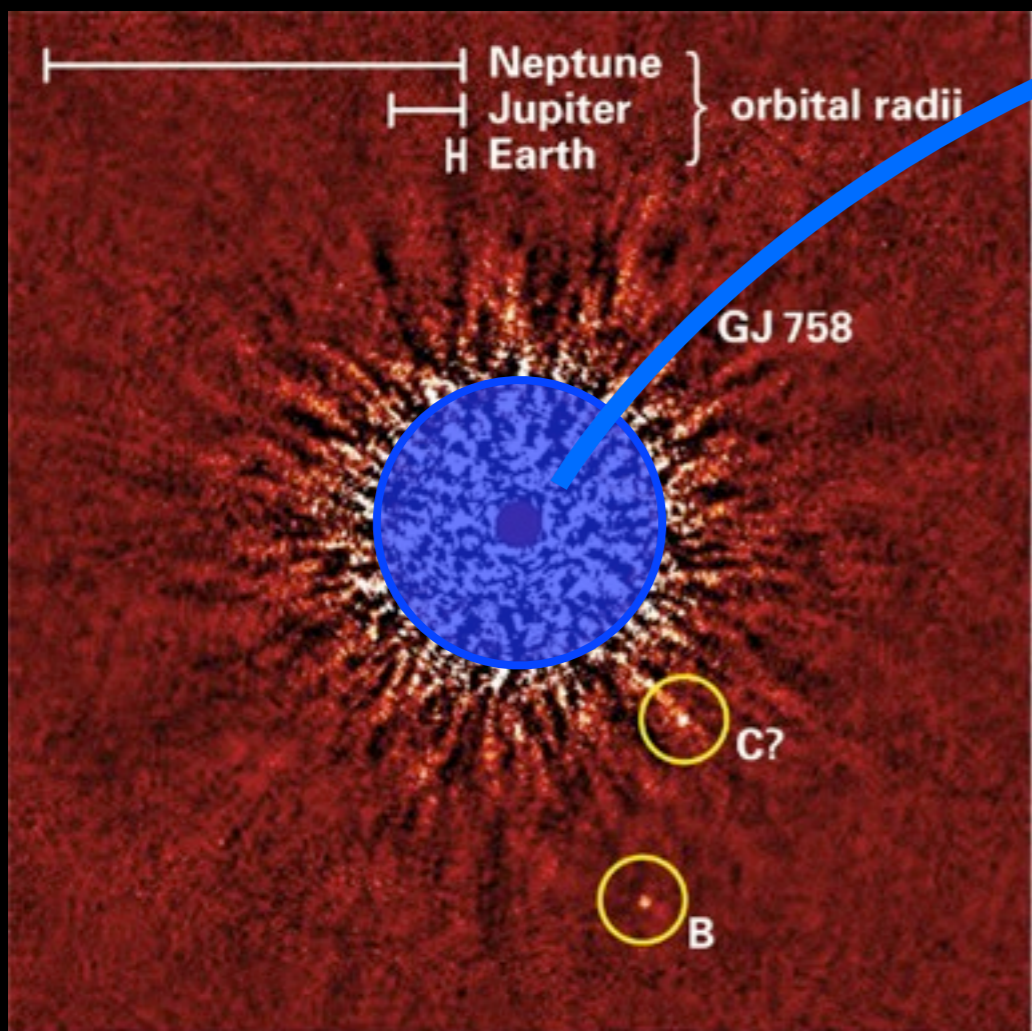




S E E D S



# SEEDS “on the spot” optimized angular resolution with extreme AO

*Frantz Martinache,  
SCEAO project, Subaru Telescope*





# This is not a crazy idea



## Facts:

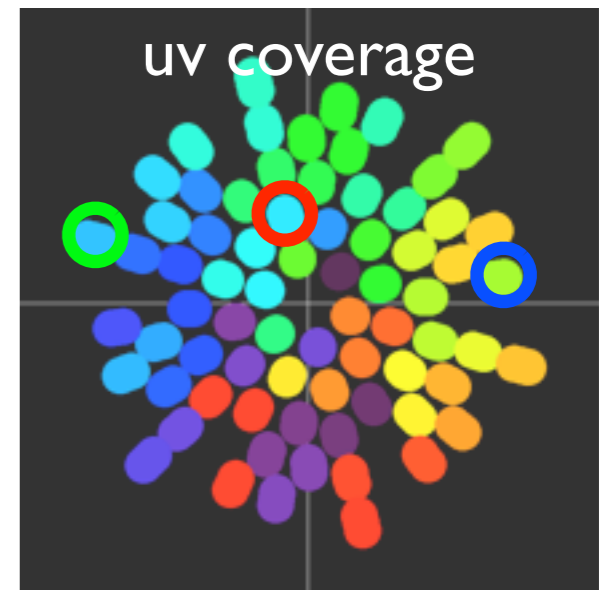
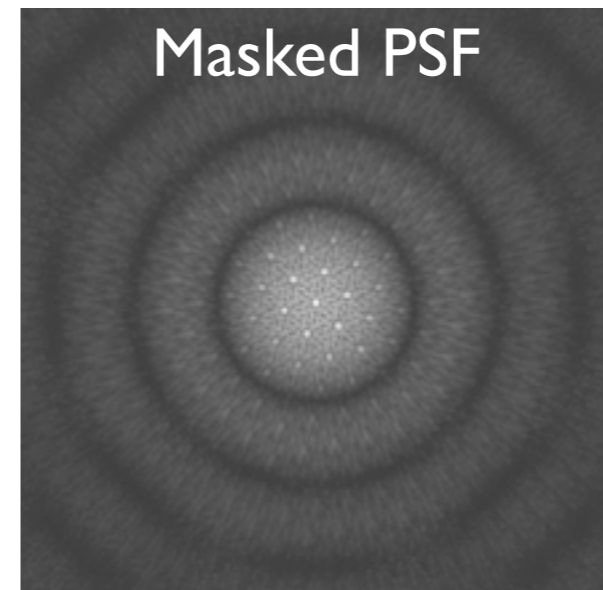
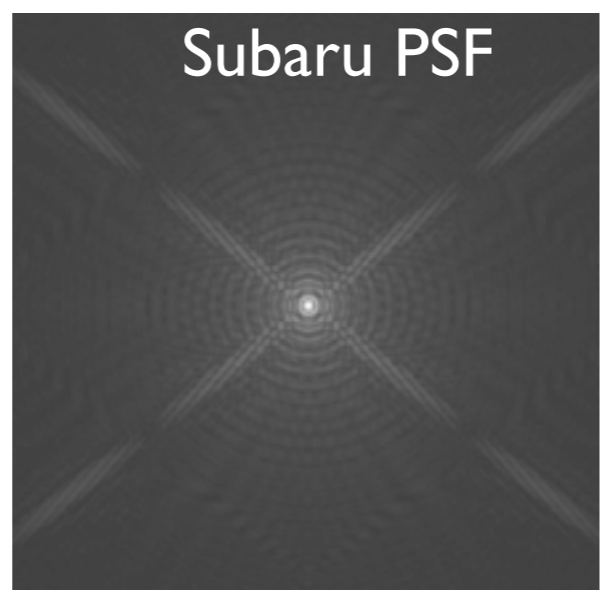
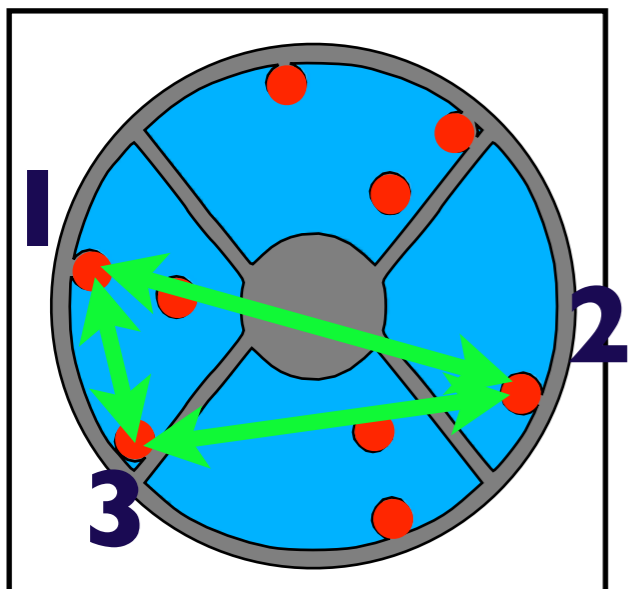
- For the Subaru Telescope:  $\lambda/D = 40$  mas in H-band
- This regime is already being explored.  
ex: NRM interferometry routinely detects companions below this limit ( $\sim 0.5 \lambda/D$ )

Need to be smart, consider the issues faced by high contrast imaging with AO separately, and address each of them appropriately. SCExAO is our response.

SCExAO isn't a heavyweight GPI or a SPHERE, but an adapted answer to a series of simple needs.

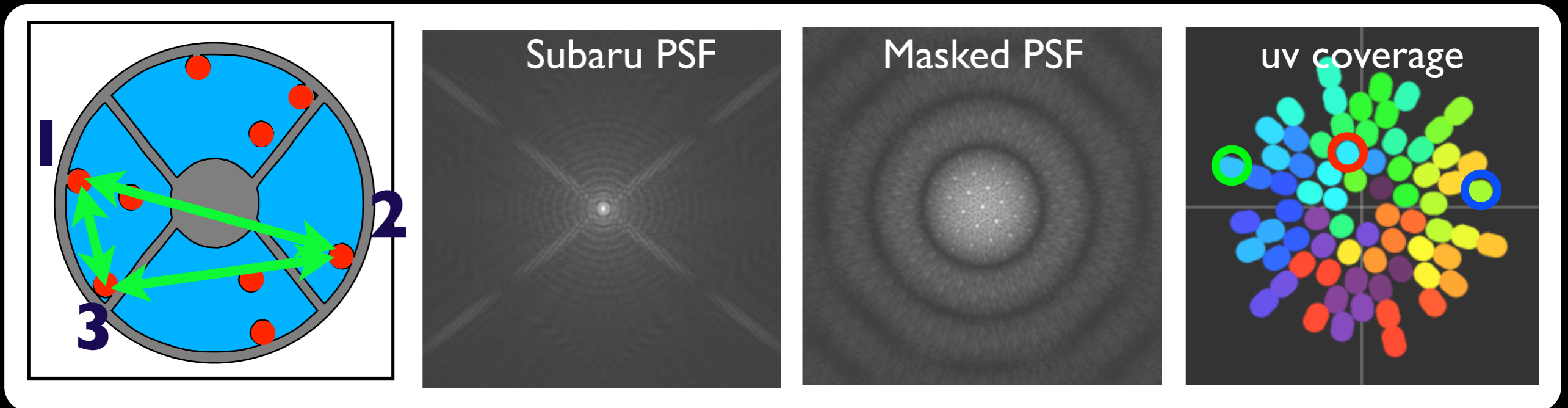


# Masking interferometry





# Masking interferometry



$$\Phi(1-2) = \Phi(1-2)_0 + (\Phi_1 - \Phi_2)$$

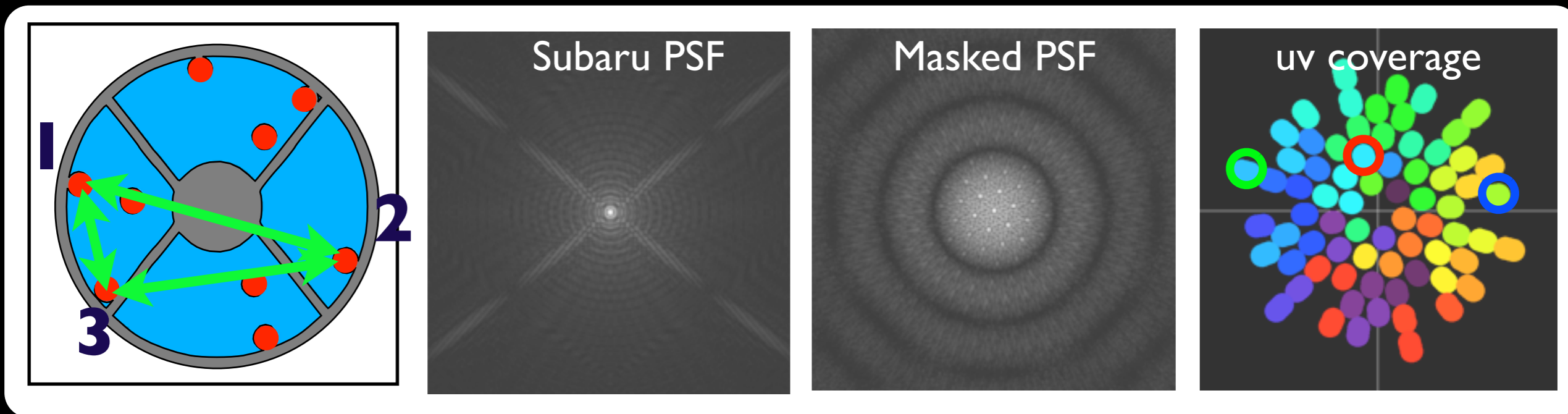
$$\Phi(2-3) = \Phi(2-3)_0 + (\Phi_2 - \Phi_3)$$

$$\Phi(3-1) = \Phi(3-1)_0 + (\Phi_3 - \Phi_1)$$

measured = intrinsic + atmospheric



# Masking interferometry



$$\Phi(1-2) = \Phi(1-2)_0 + (\Phi_1 - \Phi_2)$$

$$\Phi(2-3) = \Phi(2-3)_0 + (\Phi_2 - \Phi_3)$$

$$\Phi(3-1) = \Phi(3-1)_0 + (\Phi_3 - \Phi_1)$$

measured = intrinsic + atmospheric

Signal lost but...

A perfect observable:  
the closure phase!!



# Masking interferometry



3 parameters: angular separation, position angle, contrast  
Error estimate: closure phase scattering  
Small systematic error

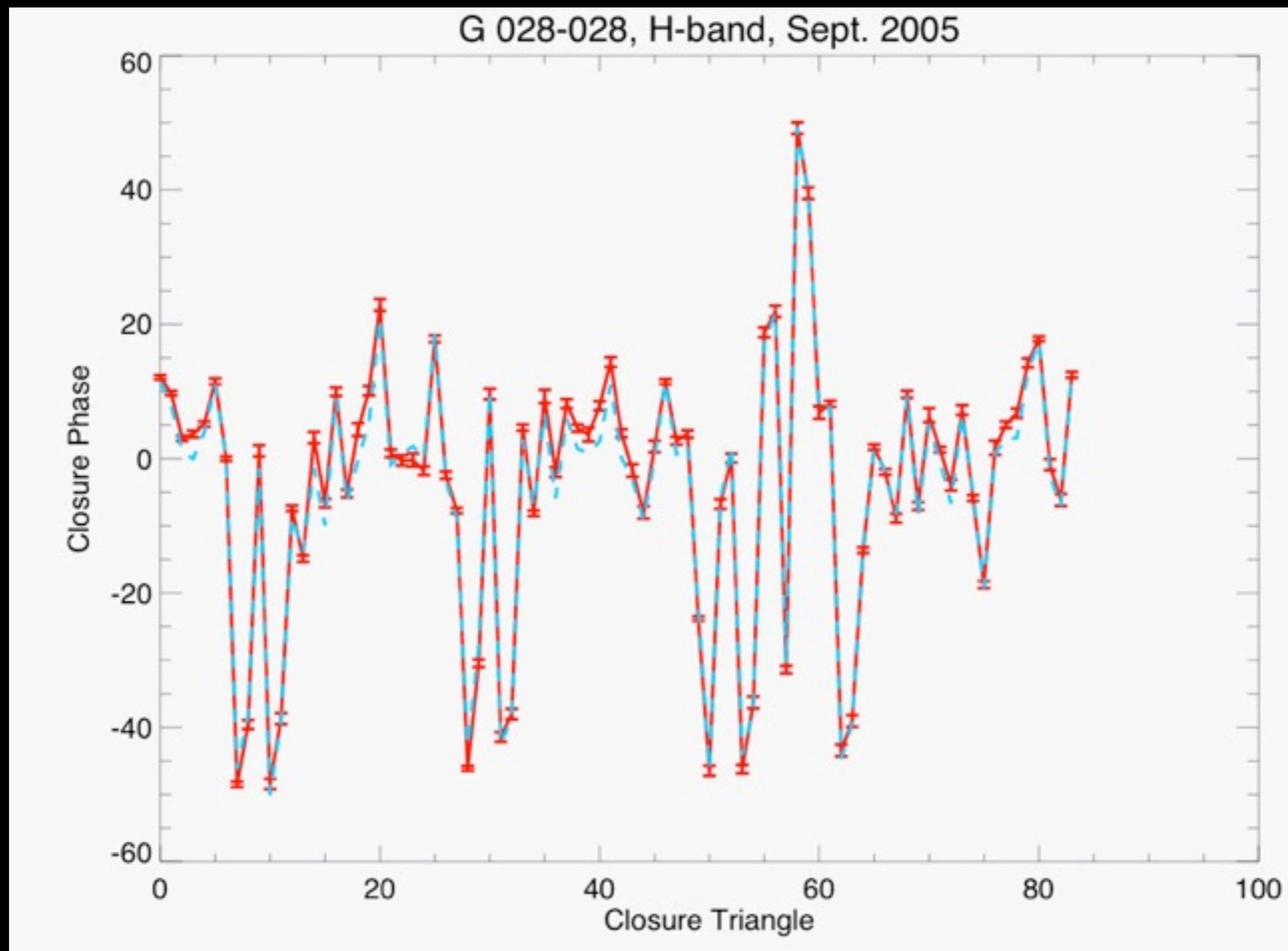
40 % strehl  
0.3 deg scatter  
stability  $\sim \lambda/1000$   
all passive !



# Masking interferometry



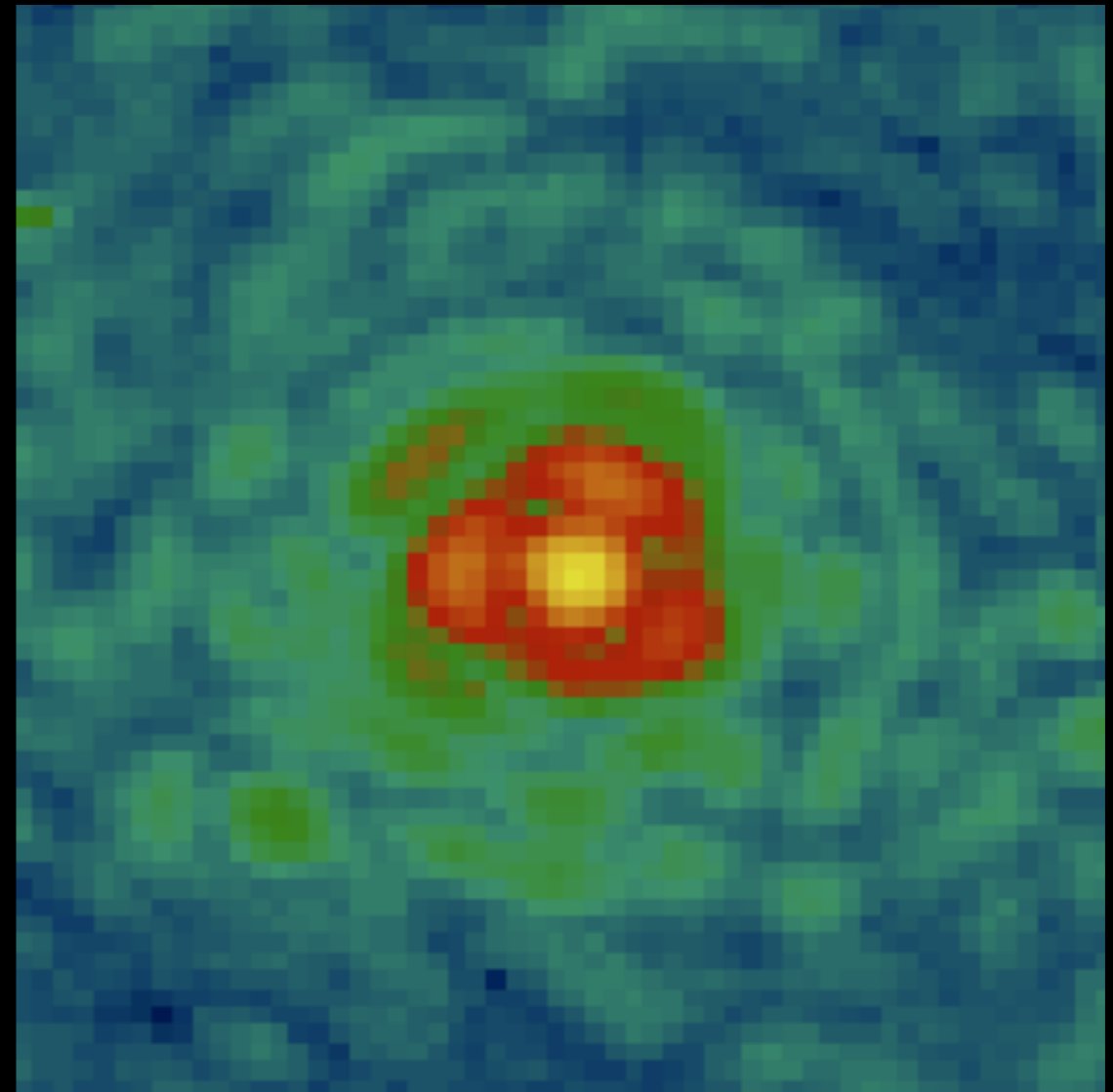
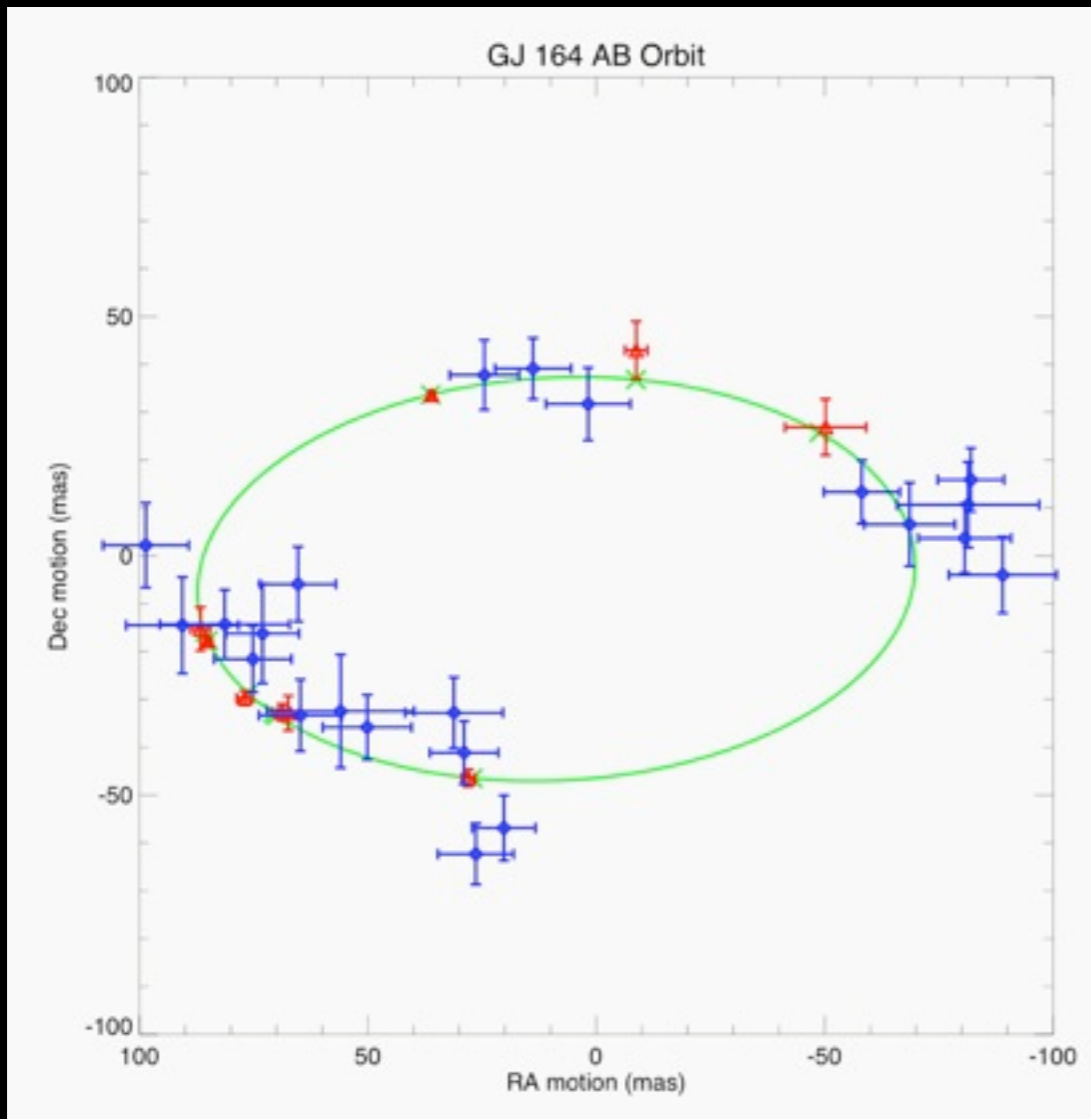
3 parameters: angular separation, position angle, contrast  
Error estimate: closure phase scattering  
Small systematic error



40 % strehl  
0.3 deg scatter  
stability  $\sim \lambda/1000$   
all passive !



# Relevant NRM results



50 - 80 mas separation... on a 5-meter telescope

Astrometry + Direct Detection:

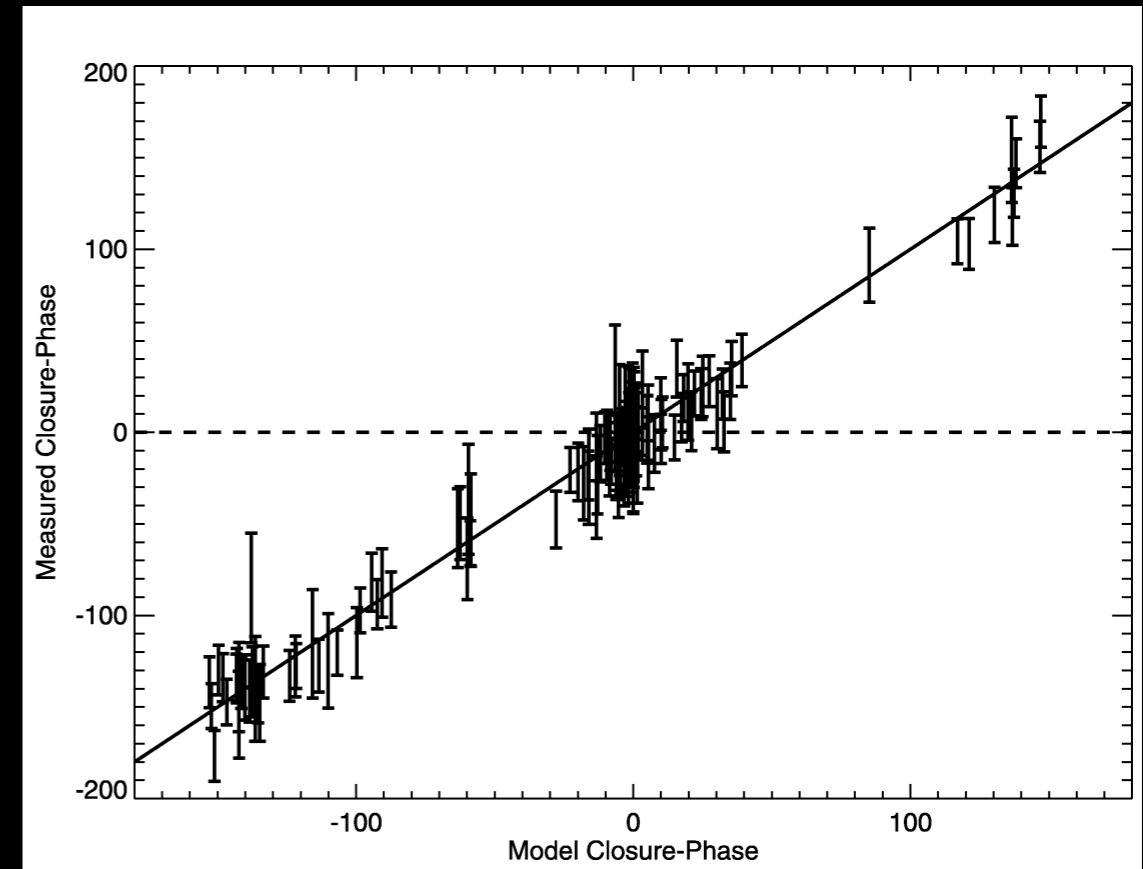
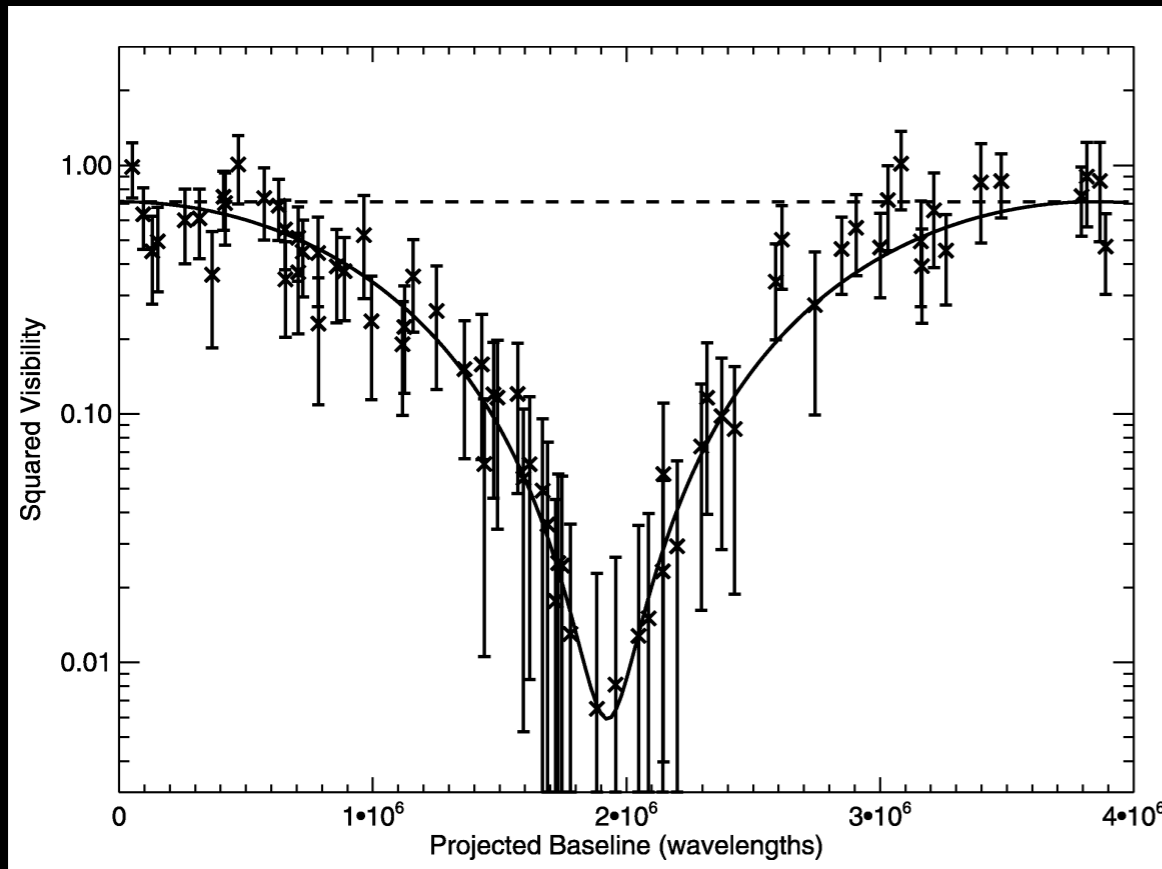
$$M_1 = 0.247 \pm 0.019 M_S$$

$$M_2 = 0.096 \pm 0.008 M_S$$

*Martinache et al, 2009, ApJ, 695, 1183*



# Relevant NRM results



Transition disk CoKu Tau/4: 53 mas ( $\sim 8$  AU) binary

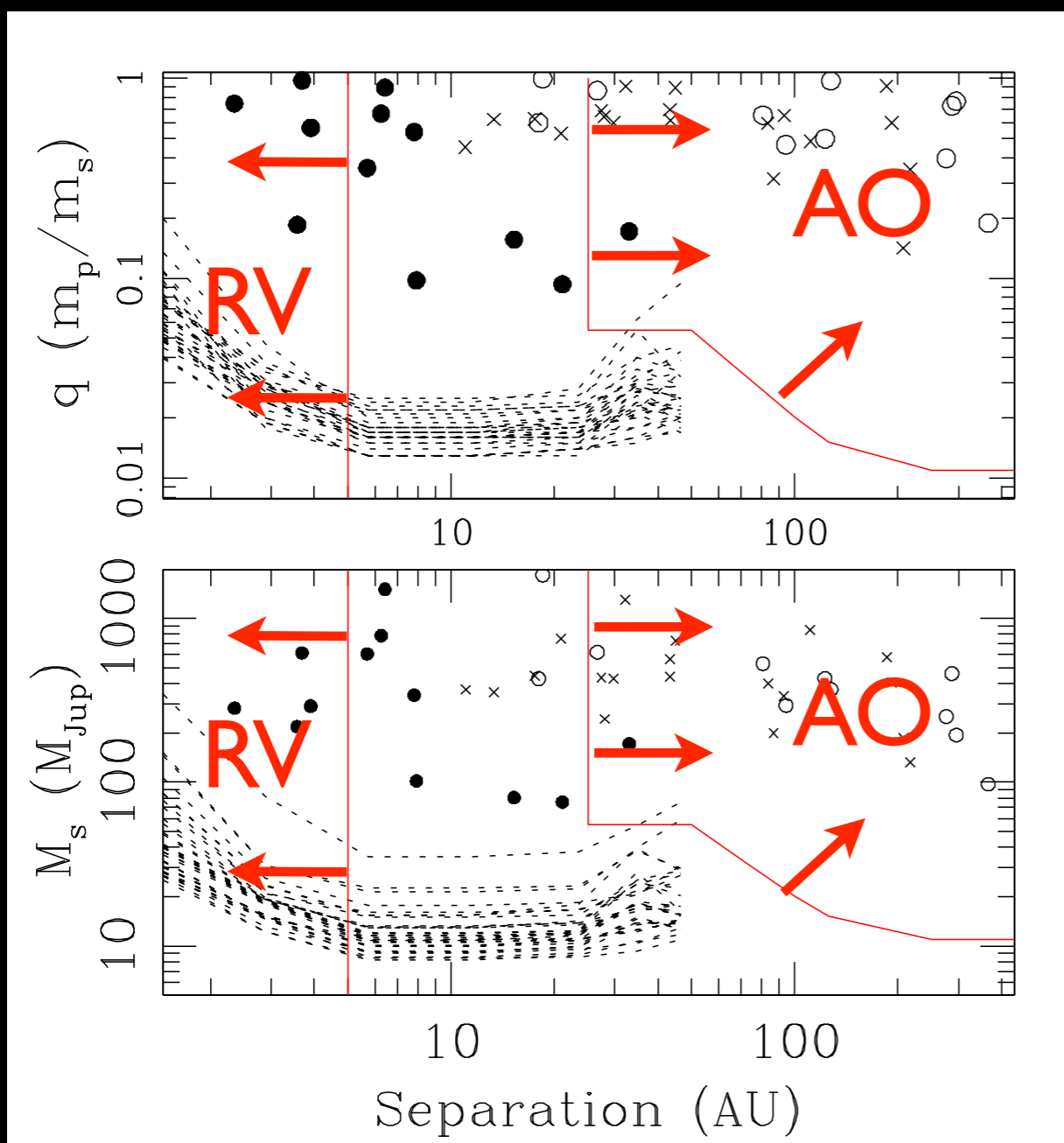
*Ireland & Kraus, 2008, ApJ, 678, 59*



# Relevant NRM results



- Contrast limit:  $\Delta K \sim 5-6$  @ diffraction limit
- 82 targets, 12 new binaries discovered with masking, below the limits of traditional imaging.



as well as 4 lower confidence (97.5-99.5 %) detections of planetary mass candidates (8-12  $M_J$ )

*Kraus et al, 2008, ApJ, 679, 762*



# NRM will fly onboard JWST



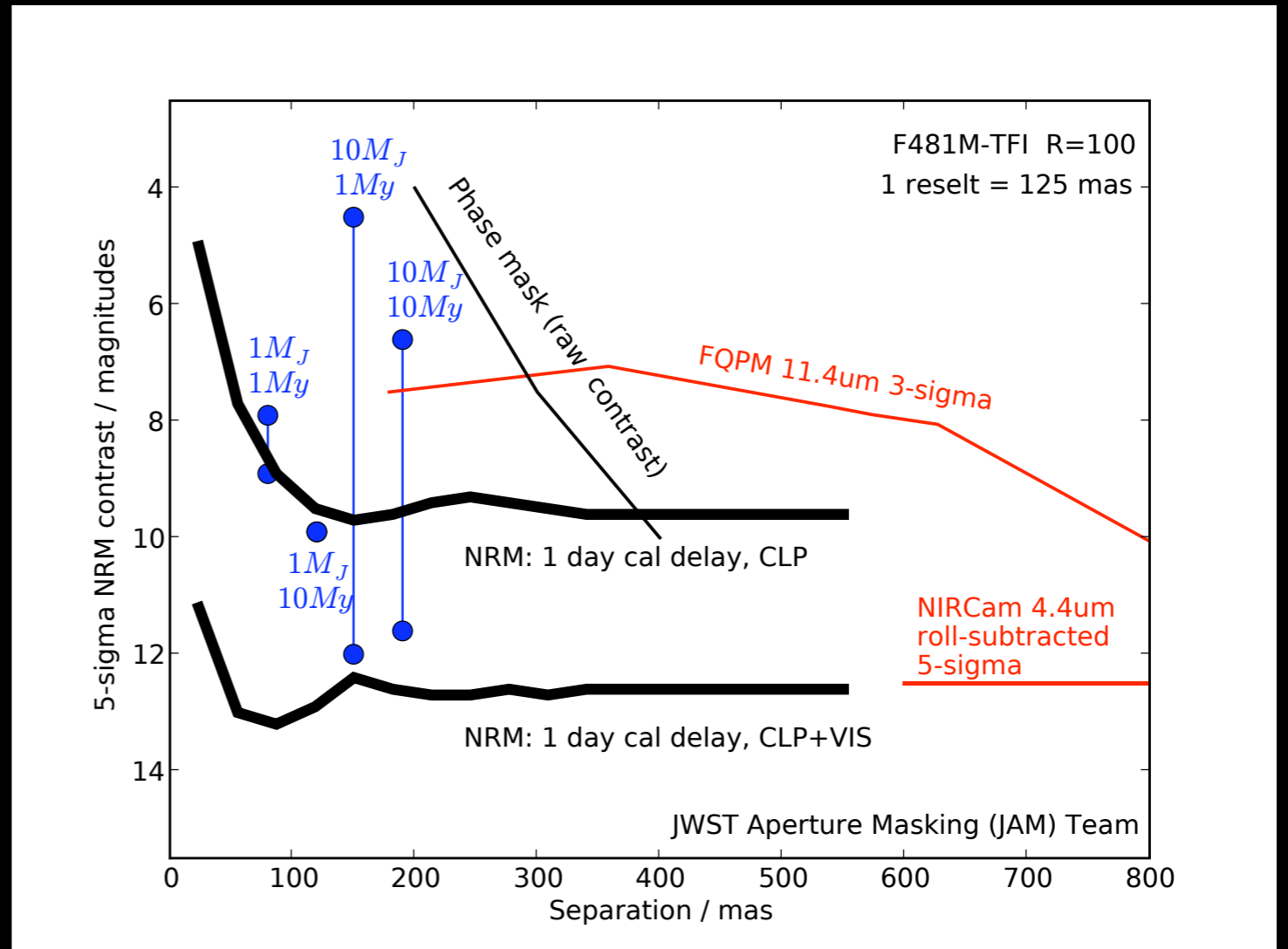
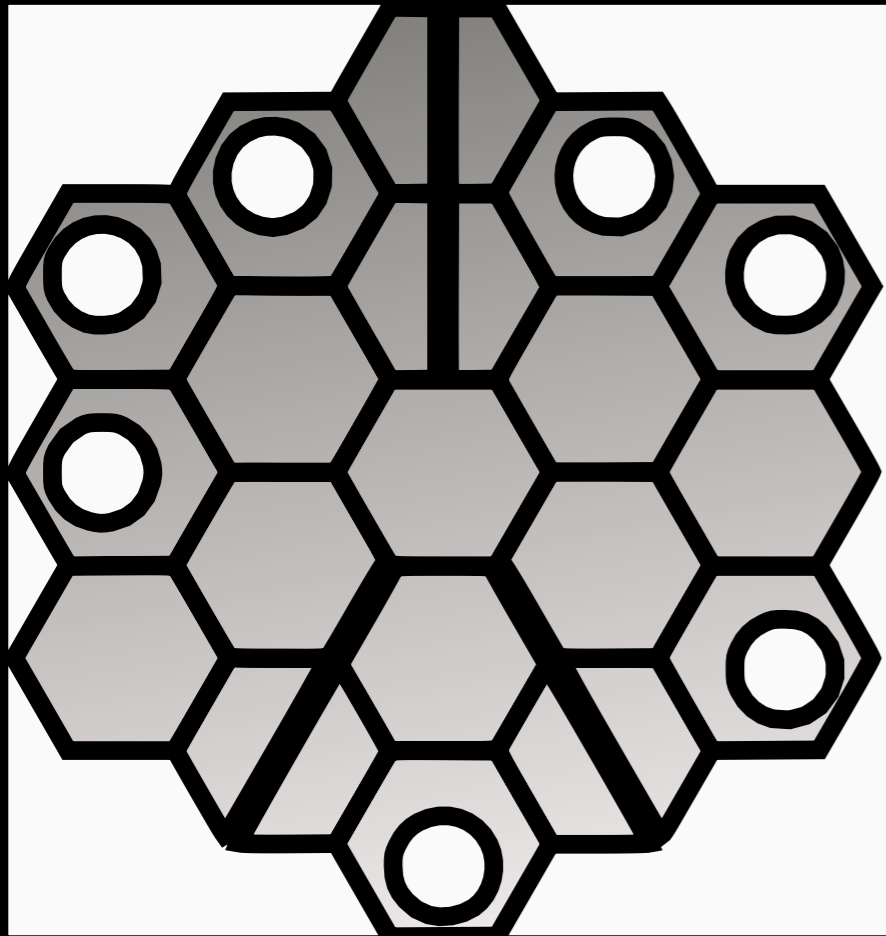
These results got NRM a seat in JWST's FGS-TFI in Sept 2008.

We are the JAM team

*Sivaramakrishnan et al, Astro2010T, 40*



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*Sivaramakrishnan et al, Astro2010T, 40*



# Lessons from this experience



A little hardware goes a long way

Inner working angle matters

Benefits add up: in its niche  $AO + NRM > AO$

NRM is passive: an active system will do better

Low order aberrations dominate



# Consequences for SCExAO



A coronagraph with good inner working angle and good throughput: we have the PIAA

A 1024-actuator DM should do the trick

Do not mess with AO I 88: SCExAO and AO I 88 simply ignore each other

Low-order wavefront sensor

And by the way:

Something that takes care of these crazy diffraction spikes

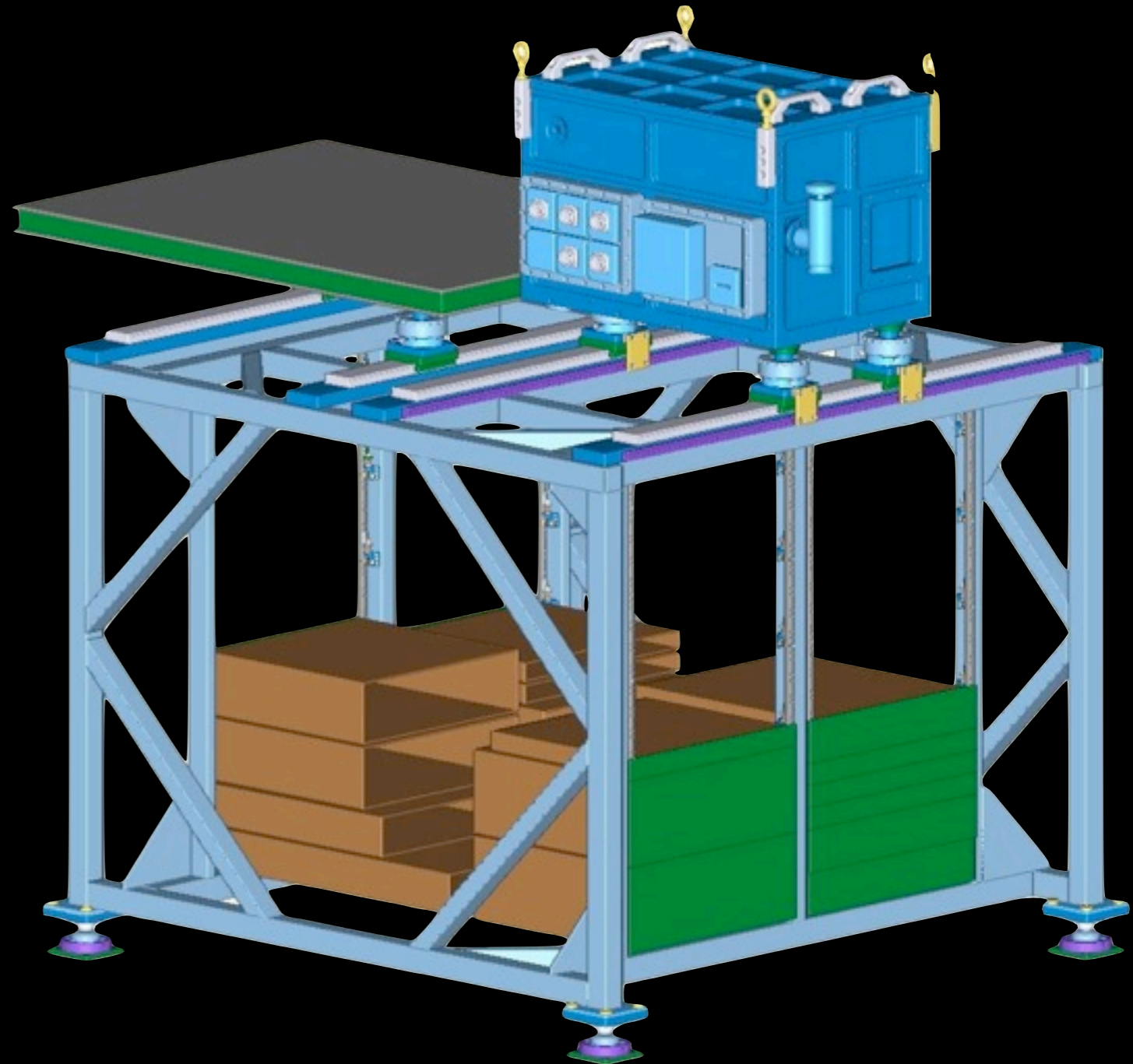
Do not mess with SEEDS current observing modes!



# A new frame for HiCIAO



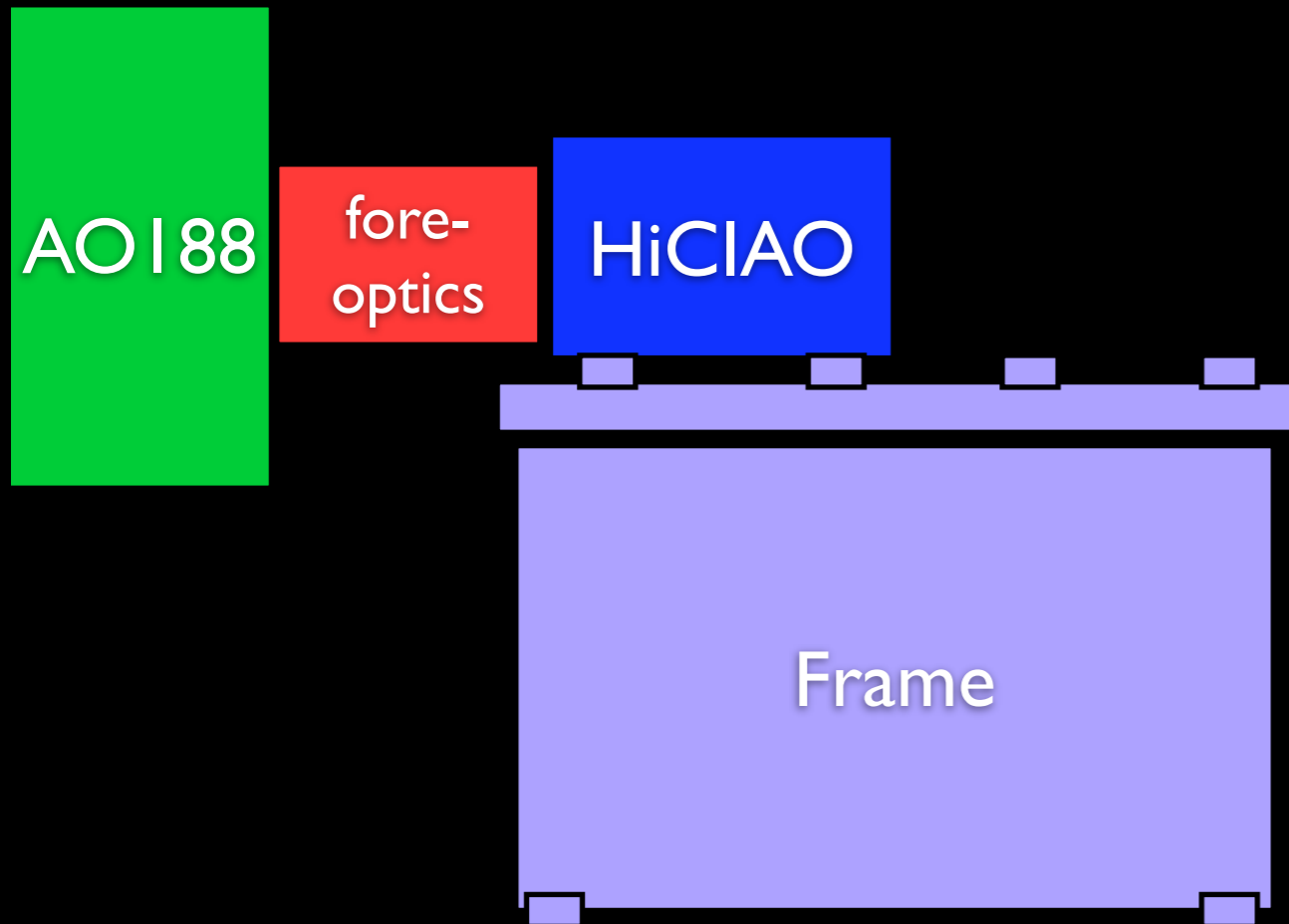
- Design meetings involved: SCExAO, HiCIAO and instrumentation groups
- Features 3x as much rack space as the “old” frame
- Significantly lighter
- Dual railing system
- Vibration damping system
- **Big enough to host guests**



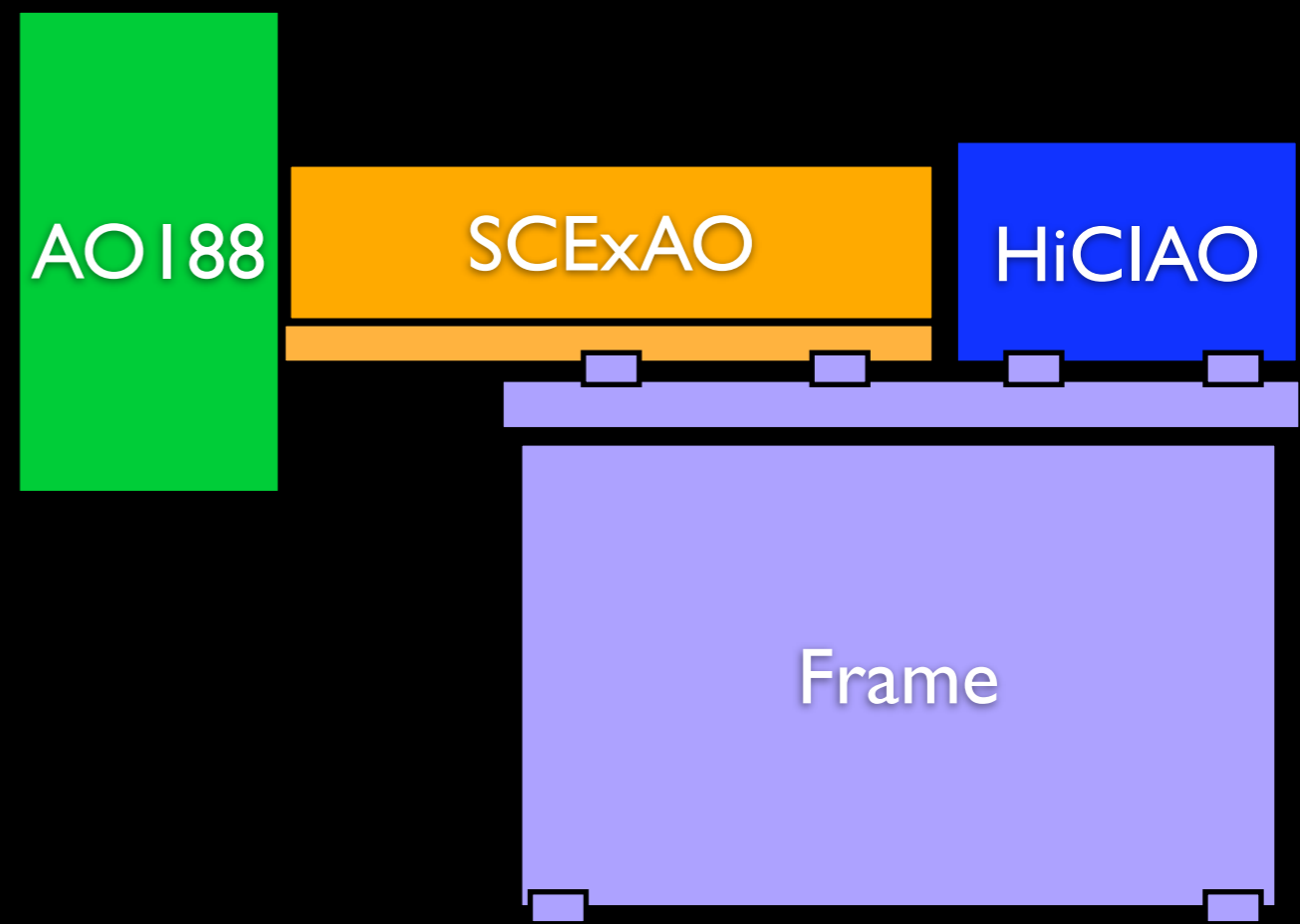
*CAD drawings by Yoshi Doi*



# Flexible frame for multiple modes



HiCIAO front position



SCExAO front position

- Minimize impact on telescope and instrument interface
- No mechanical interface between AOI 88 and SCExAO
- Optical design accommodates errors of alignment



# The new frame is ready



integration HiCIAO on frame  
in Subaru simlab, June 2010



# The new frame is ready



**SCExAO**



integration HiCIAO on frame  
in Subaru simlab, June 2010



# The SCExAO bench



**“HiCIAO side”**



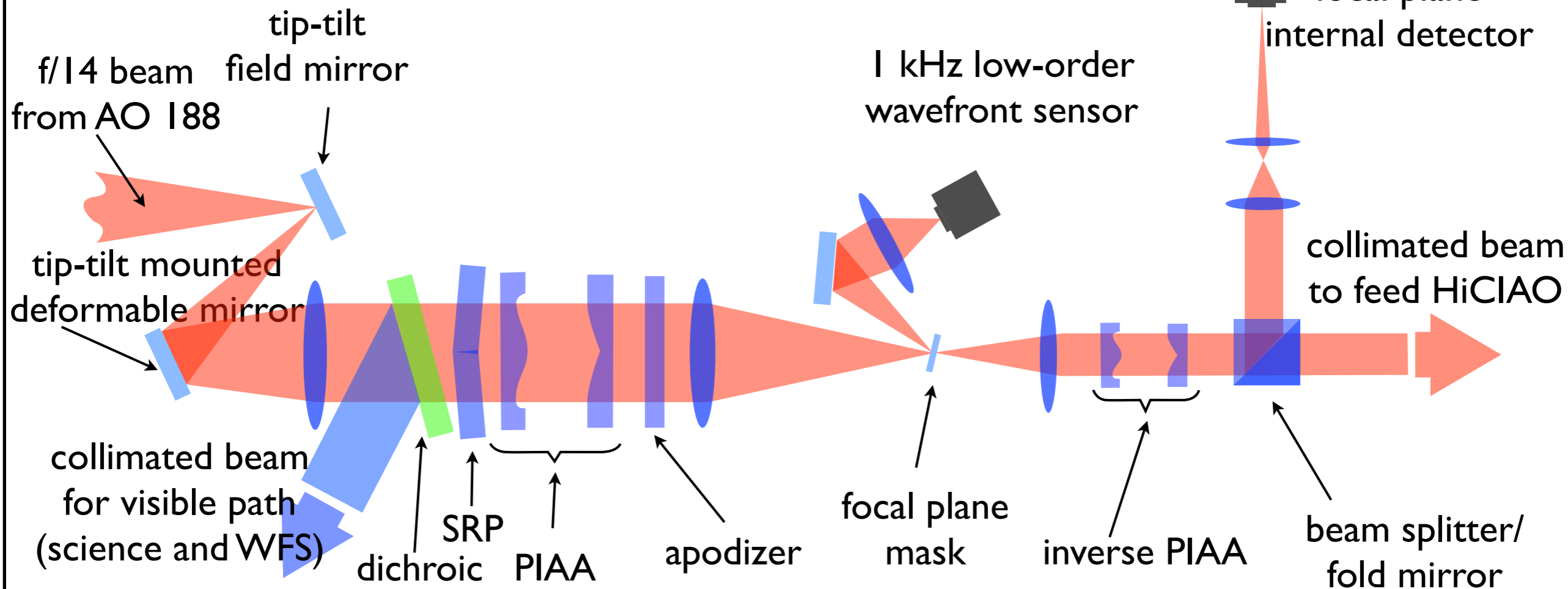
**“AOI88 side”**



# SCExAO Phase I optical design



## Optical design

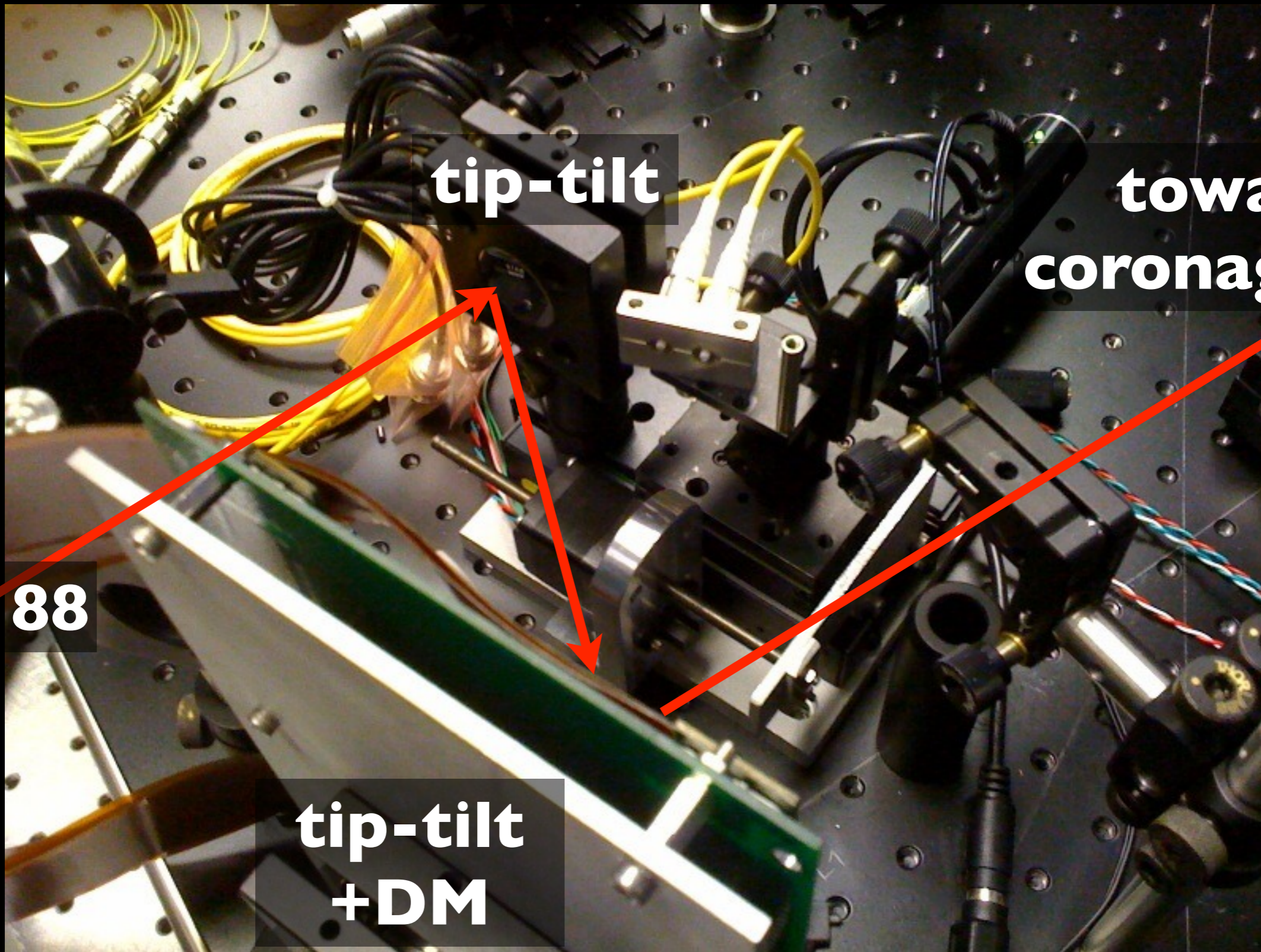


Not an extreme AO yet, but extremely cool nevertheless

*Martinache et al, 2010, SPIE, 7636, 216*



# Injection module



**tip-tilt**

**toward  
coronagraph**

**AOI 88**

**tip-tilt  
+DM**



# Specialization in narrow field



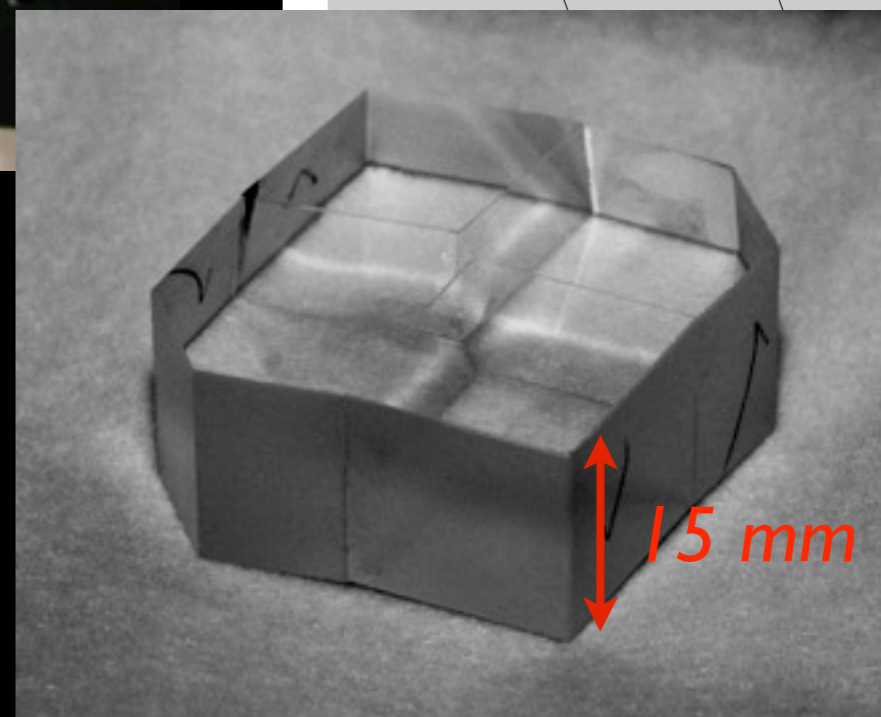
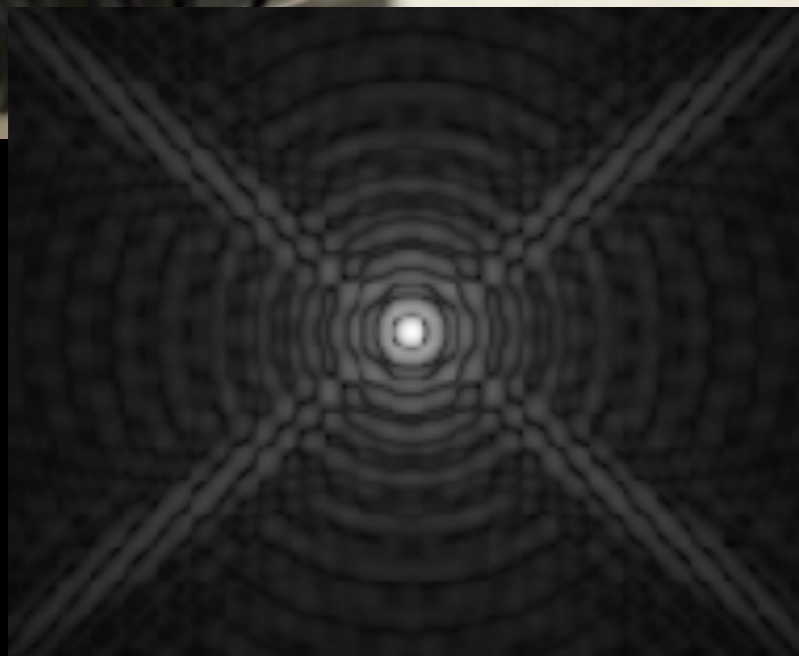
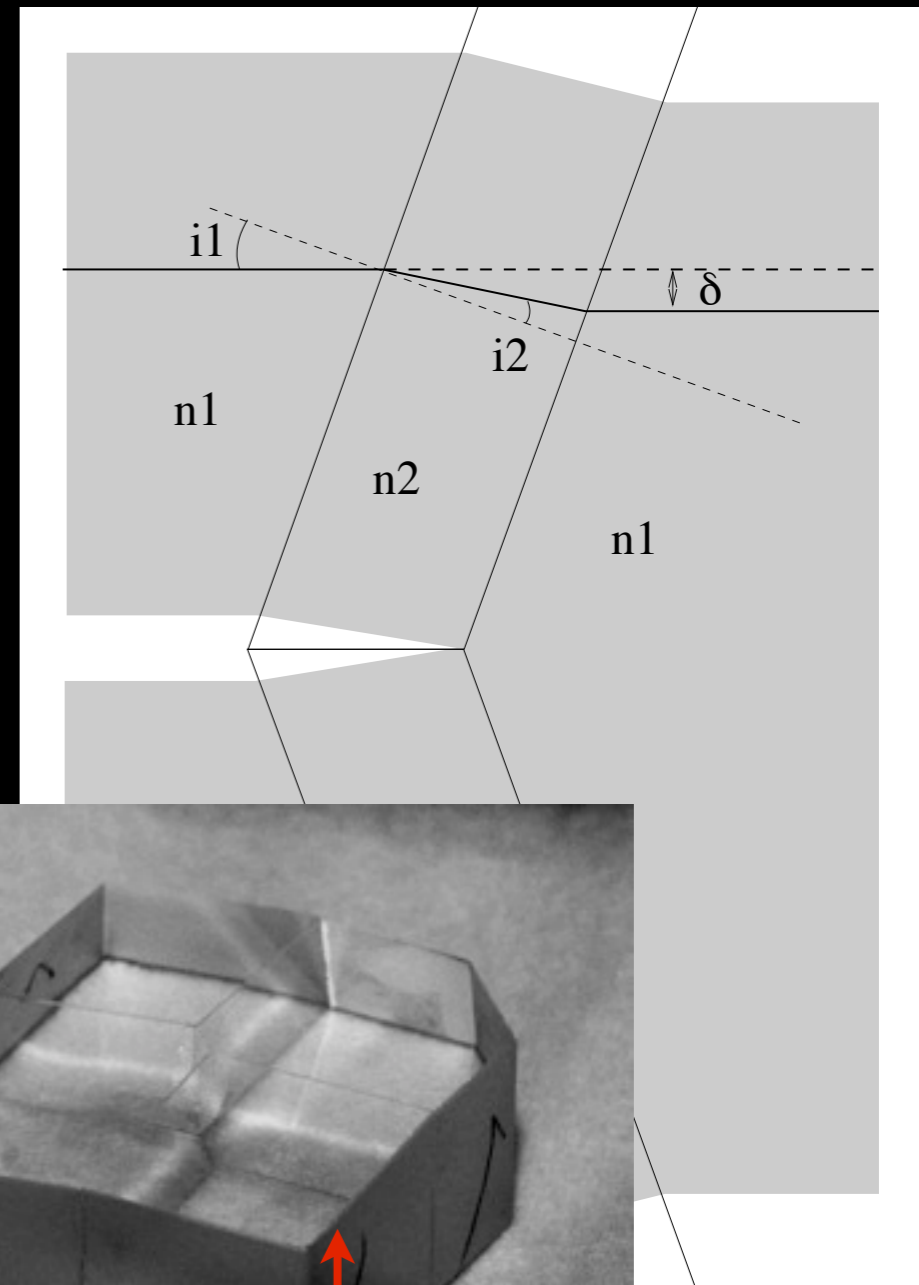
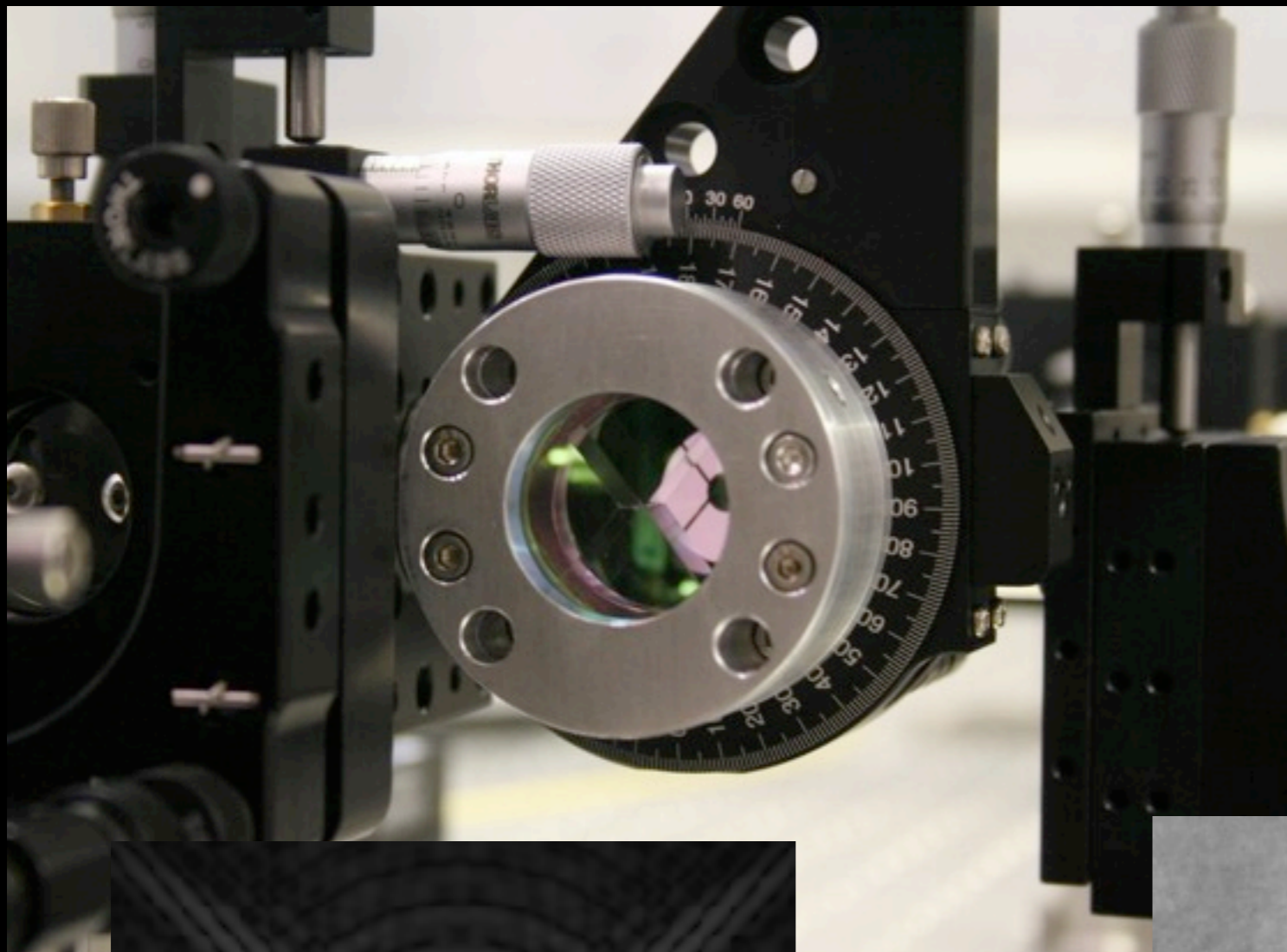
32x32 actuators translate at best into a  $16 \lambda/D$  field of view: 0.5 arc second

ADI starts working there, HiCIAO and SCExAO+HiCIAO are complementary

Specialization allows SCExAO to be good at what it is doing and keep things simple



# Spider Removal Plate

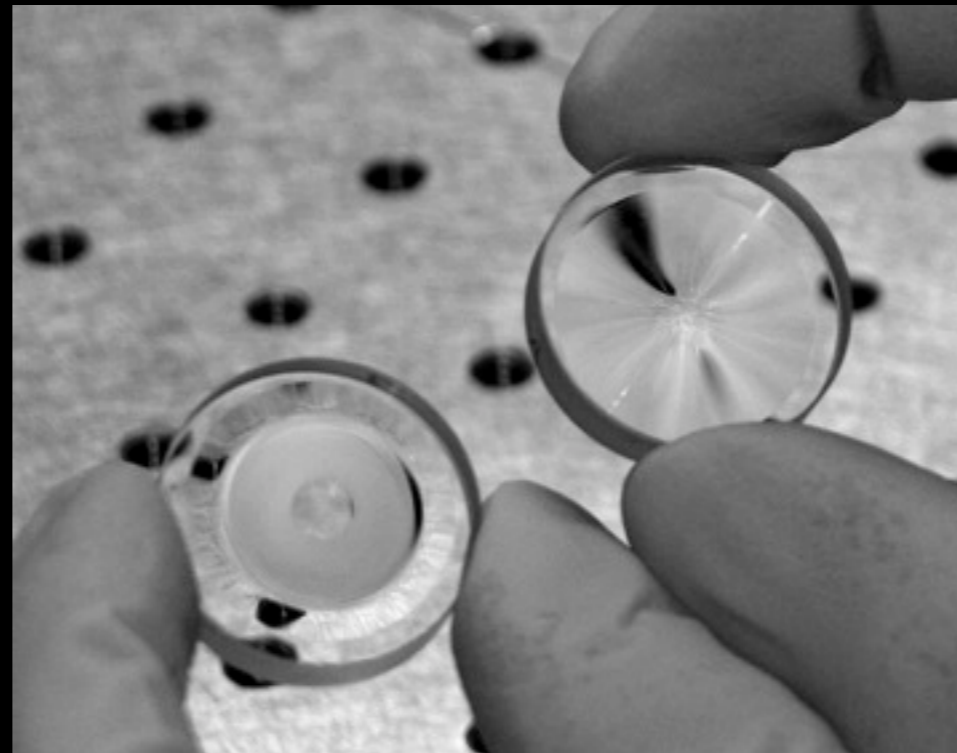




# PIAA apodization

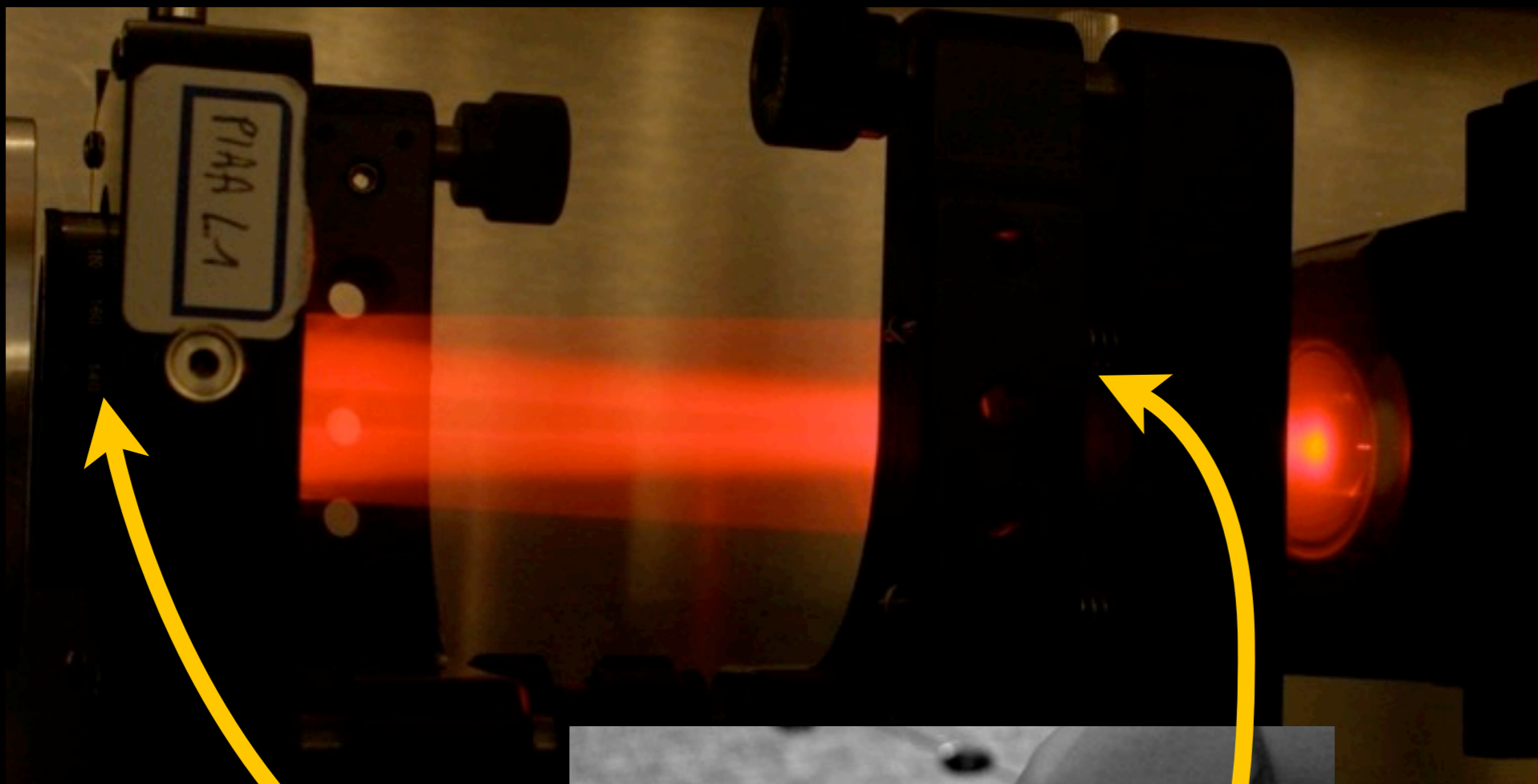


- On-axis lenses
- Apodize the beam
- Remove the central obscuration





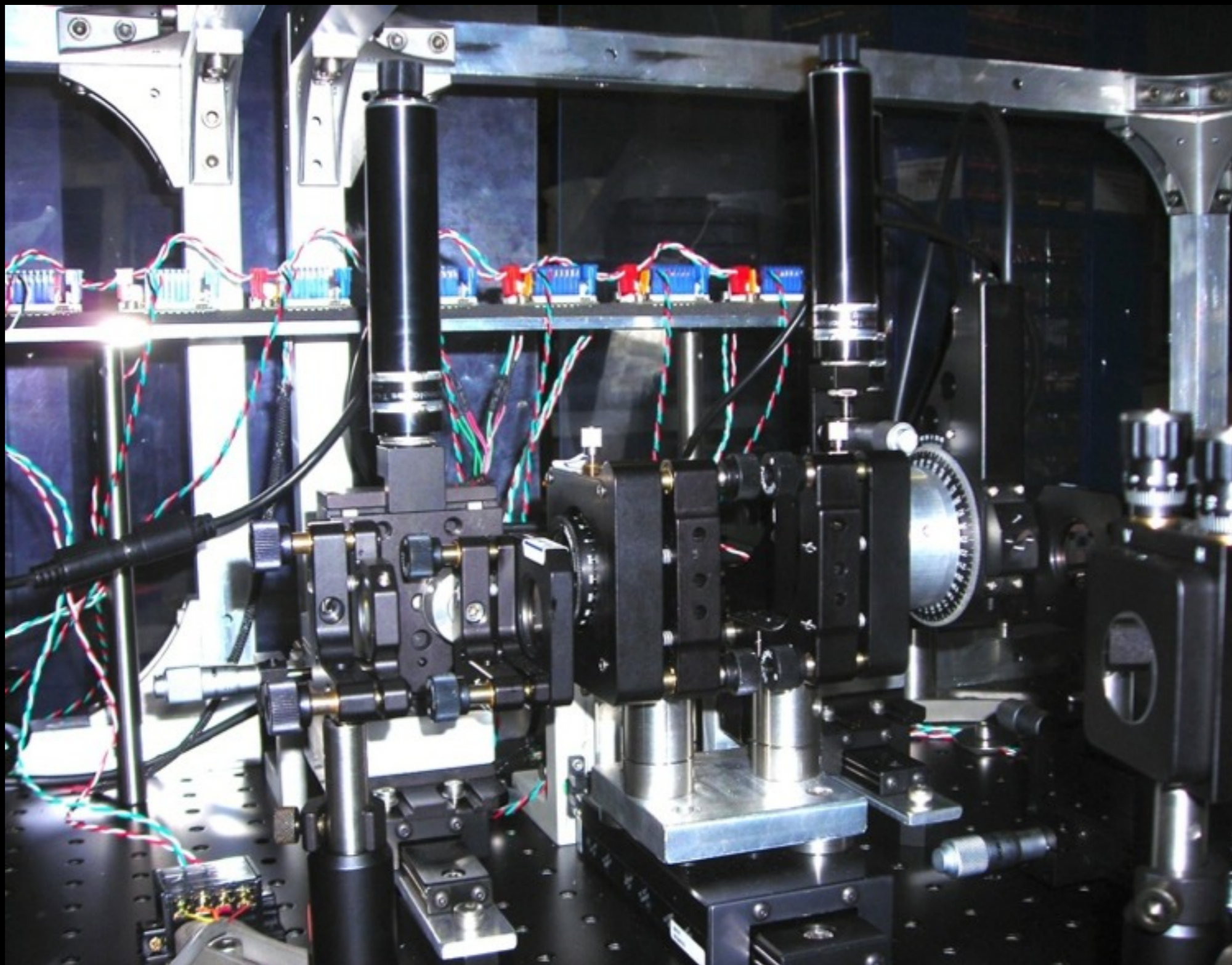
# PIAA apodization



- On-axis lenses
- Apodize the beam
- Remove the central obscuration

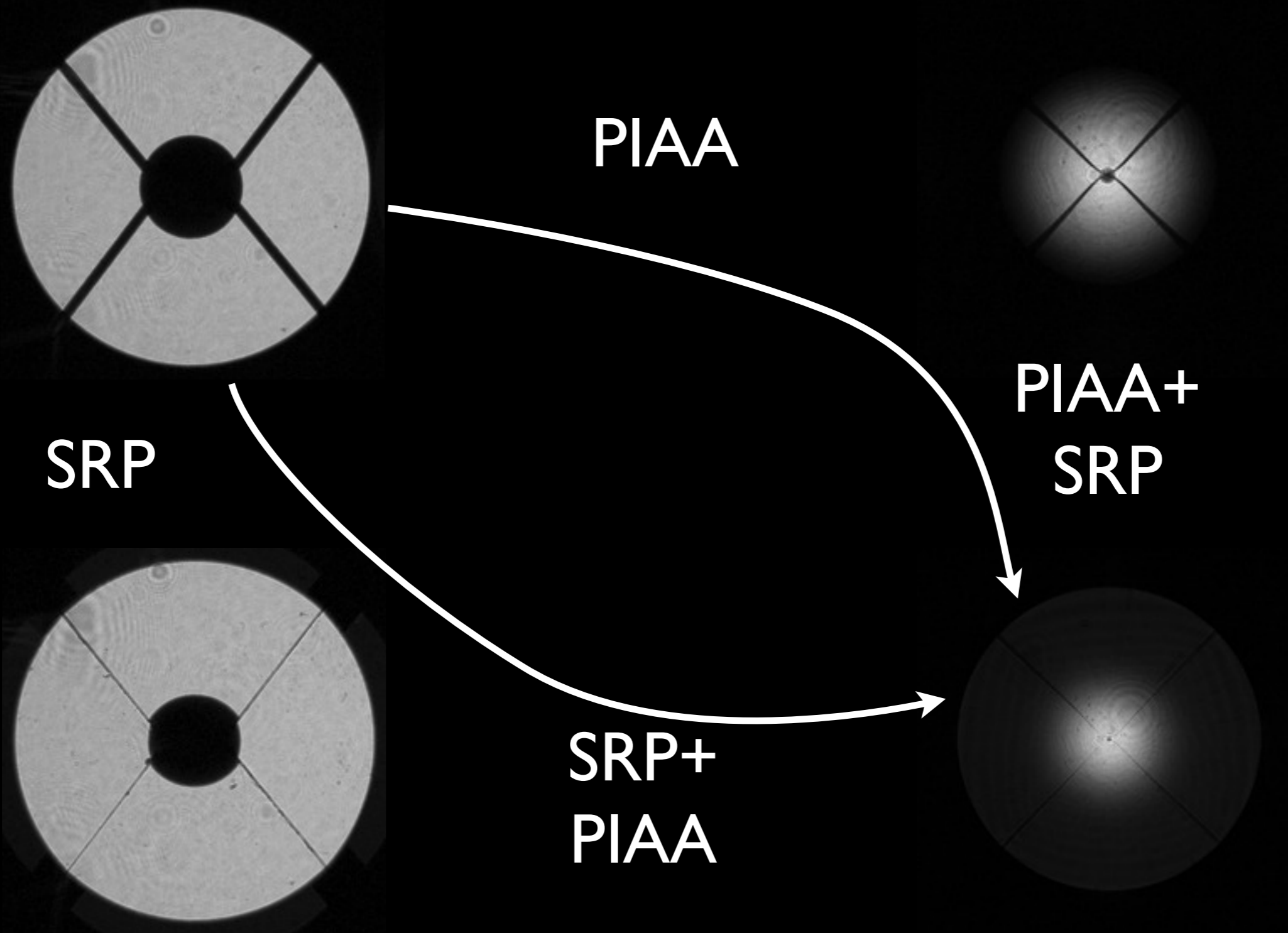


# Pupil remapping on the bench





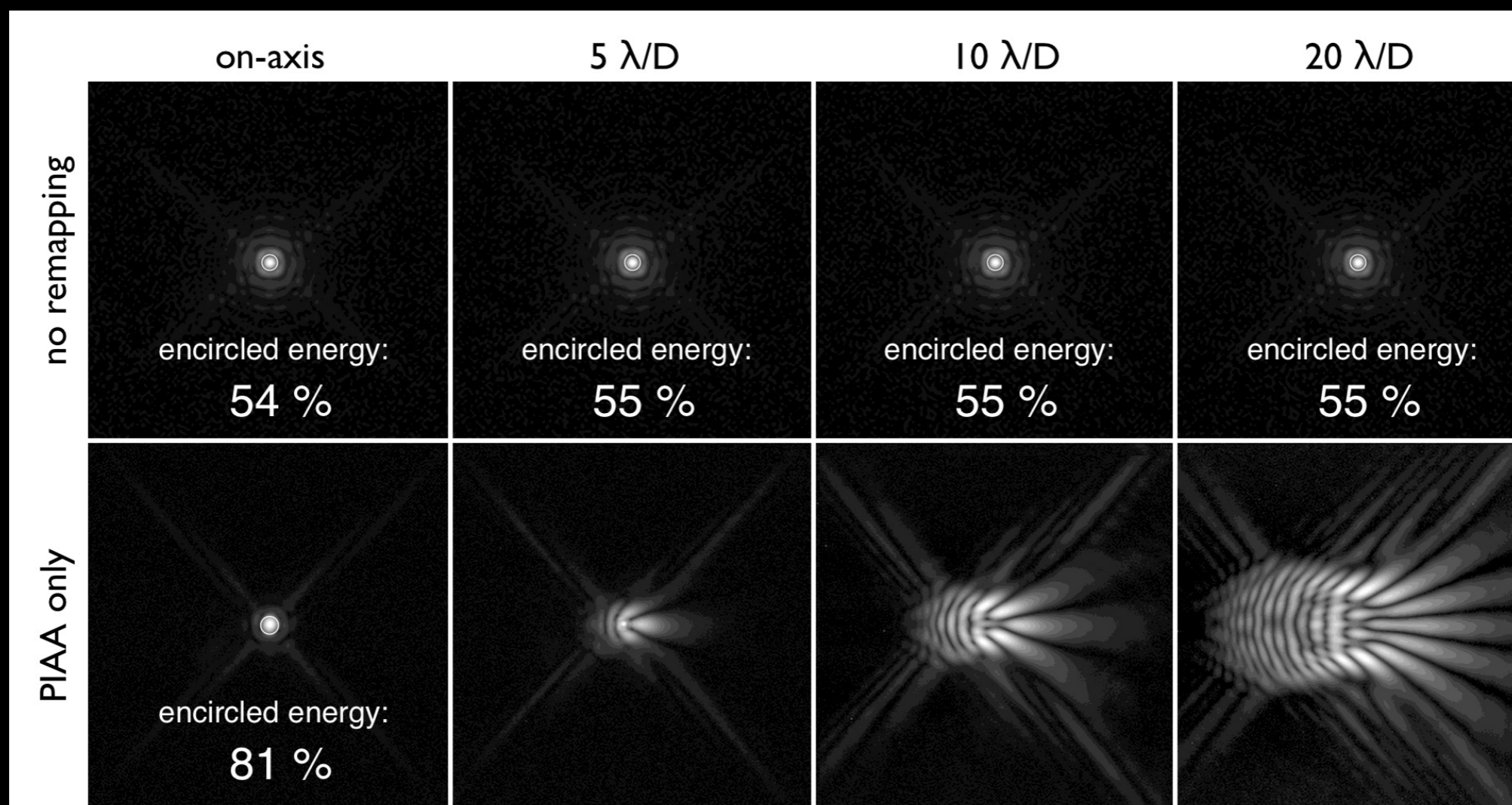
# Put it together



*Lozi et al, 2009, PASP, 121, 1232*



# Isn't doing that forbidden?



*Lozi et al, 2009, PASP, 121, 1232*

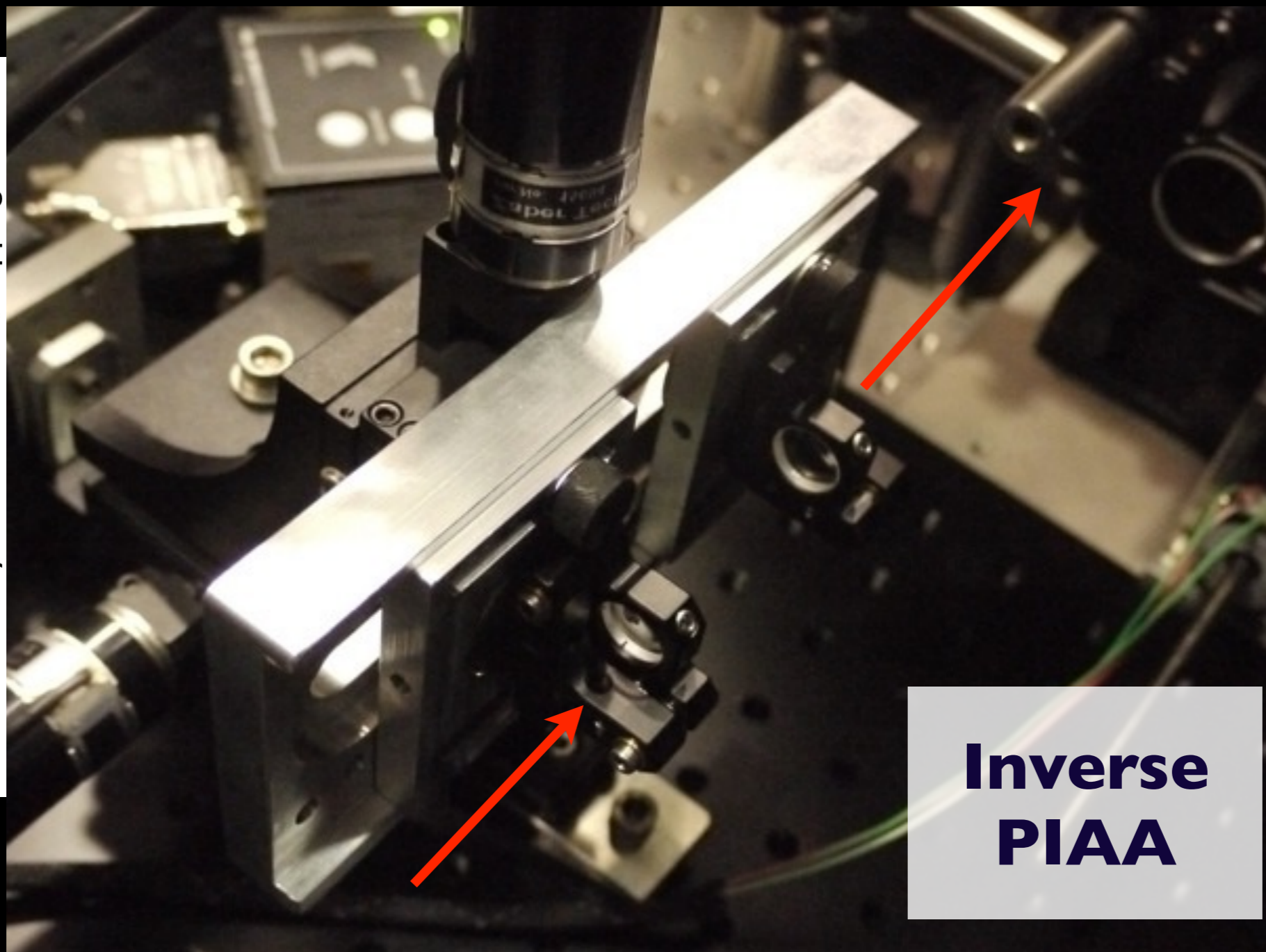


# Isn't doing that forbidden?



no remapping

PIAA only

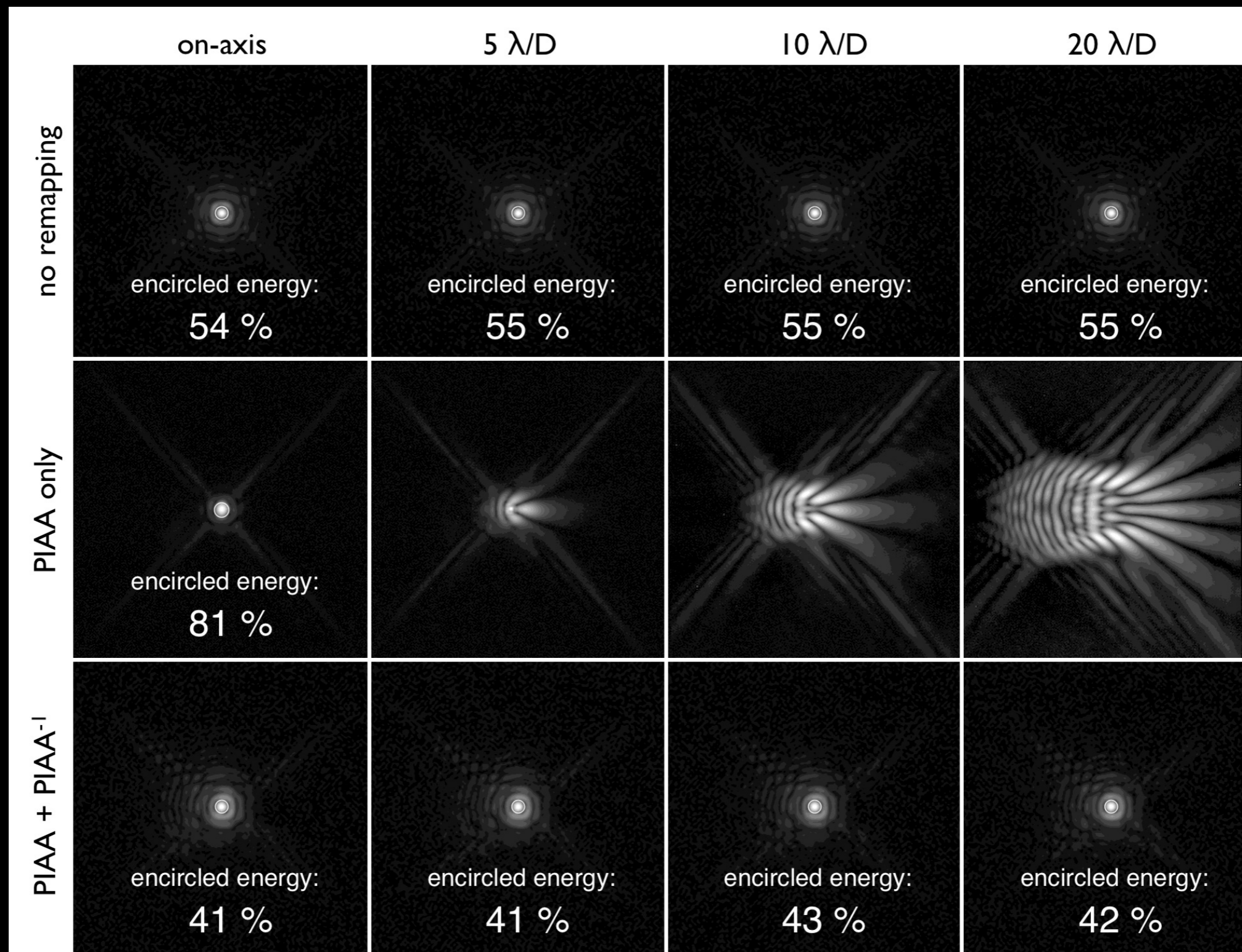


**Inverse  
PIAA**

*Lozi et al, 2009, PASP, 121, 1232*



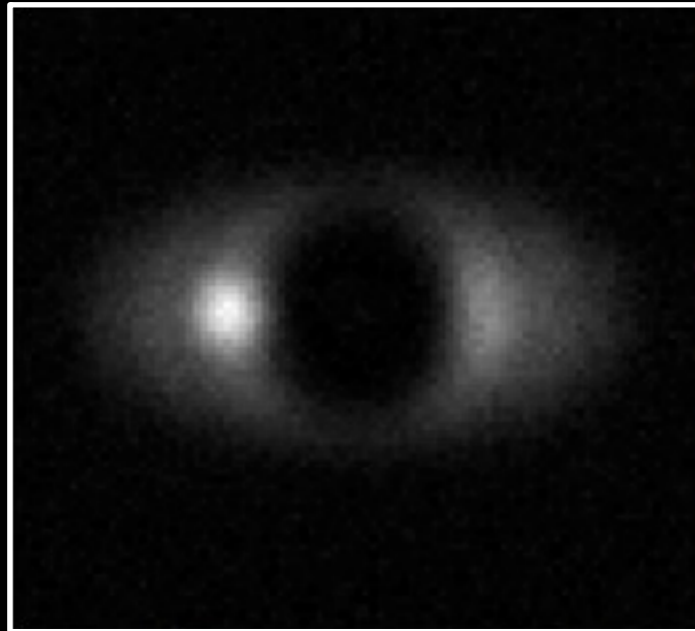
# Isn't doing that forbidden?



*Lozi et al, 2009, PASP, 121, 1232*

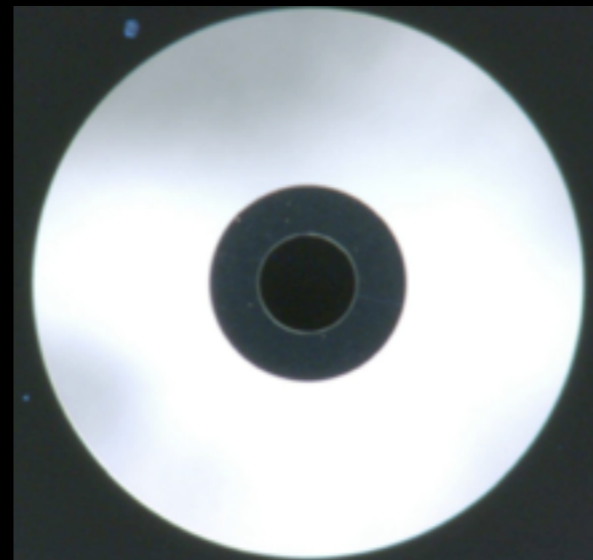
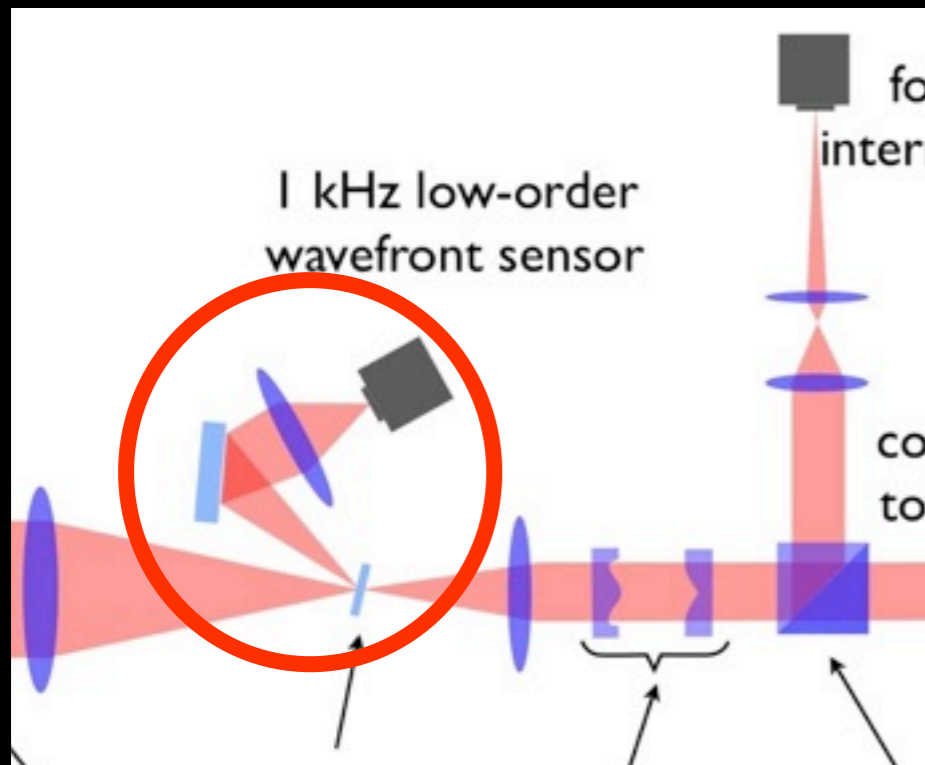


# Pointing control



At small angular separation ( $< 2 \lambda/D$ ):  
A tip-tilt excursion will mimic  
companion signal

Good knowledge and control  
of pointing are essential

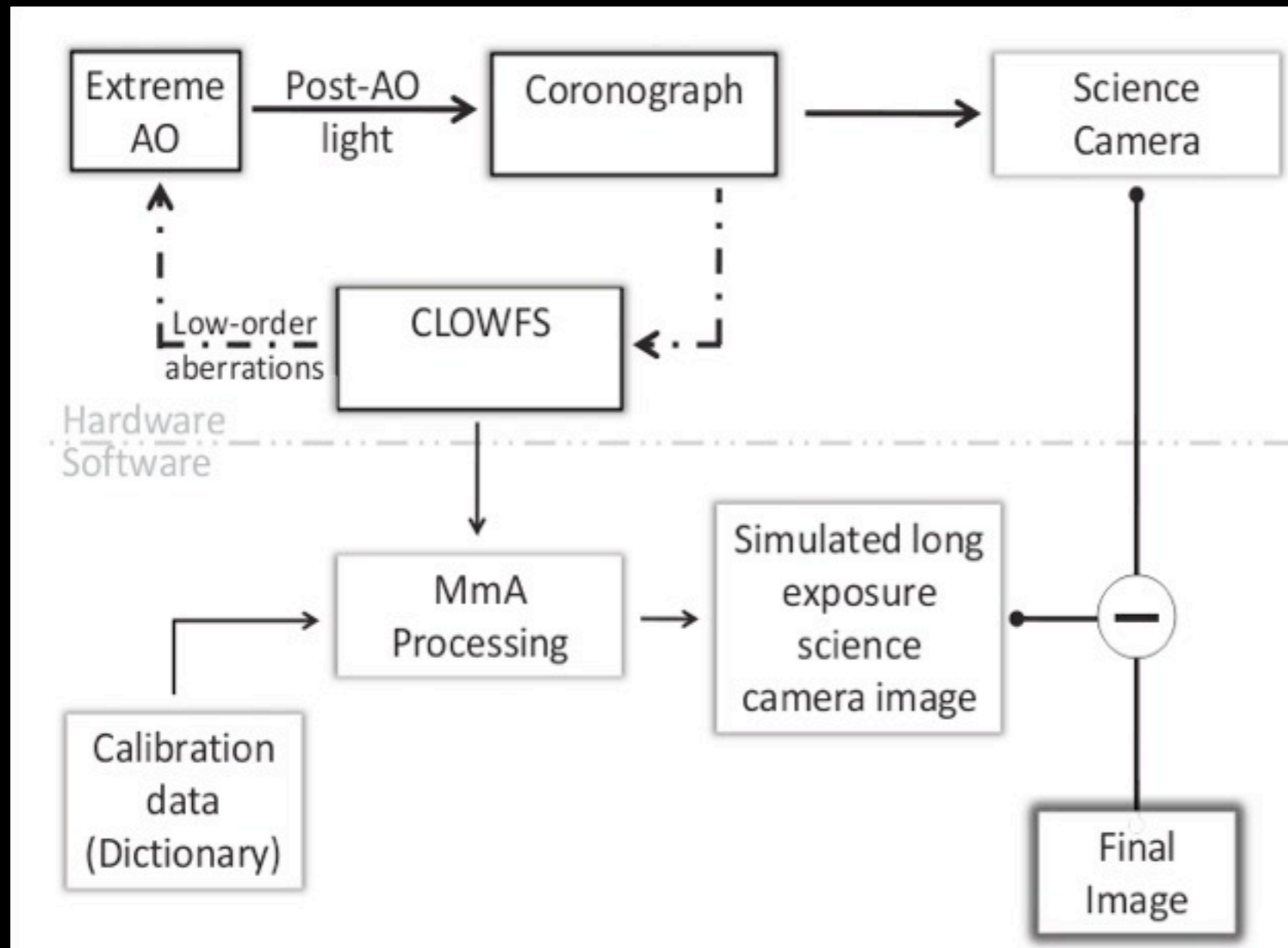


Precision:  
 $10^{-3} \lambda/D$

*Guyon et al, 2009, ApJ, 693, 75*



# Pointing control loop



Link CLOWFS  
telemetry to  
coronagraphic  
leaks...

with a dictionary!

*Vogt et al, 2010, SPIE, 7736, 37*



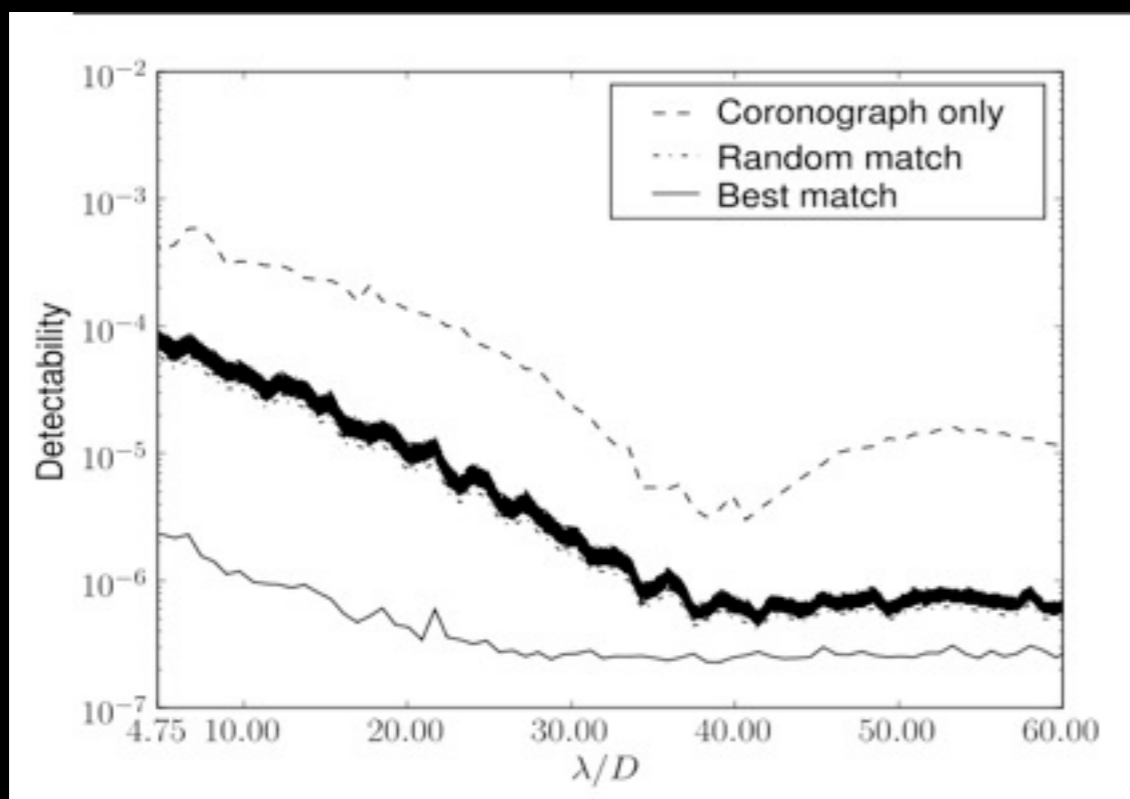
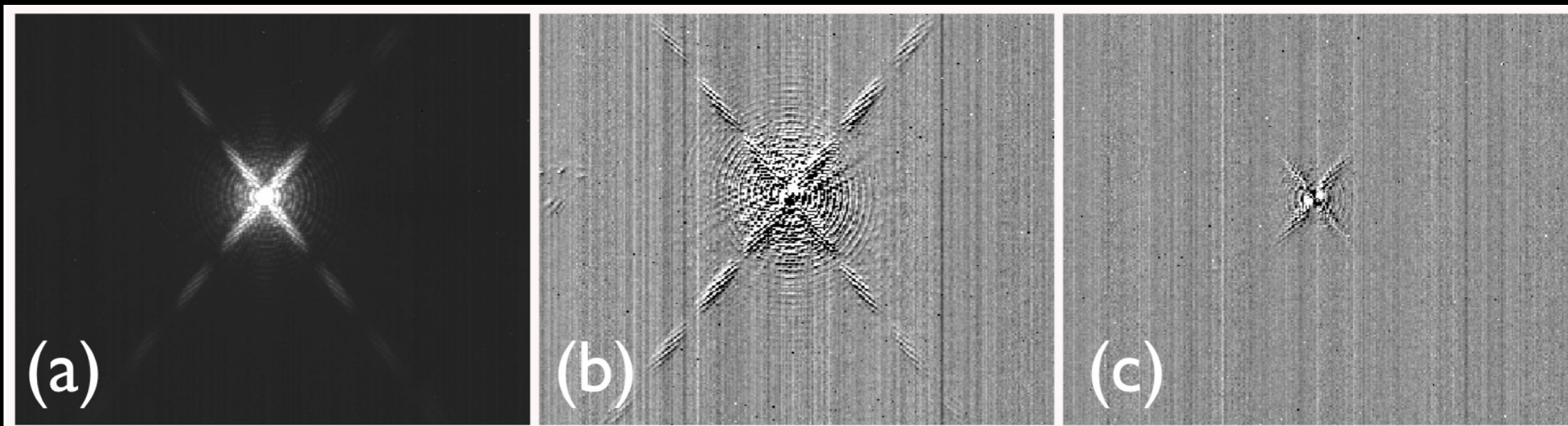
# Post-processing calibration



Long exposure

Std PSF subtraction

CLOWFS calibration



*Vogt et al, 2010, PASP, in preparation*



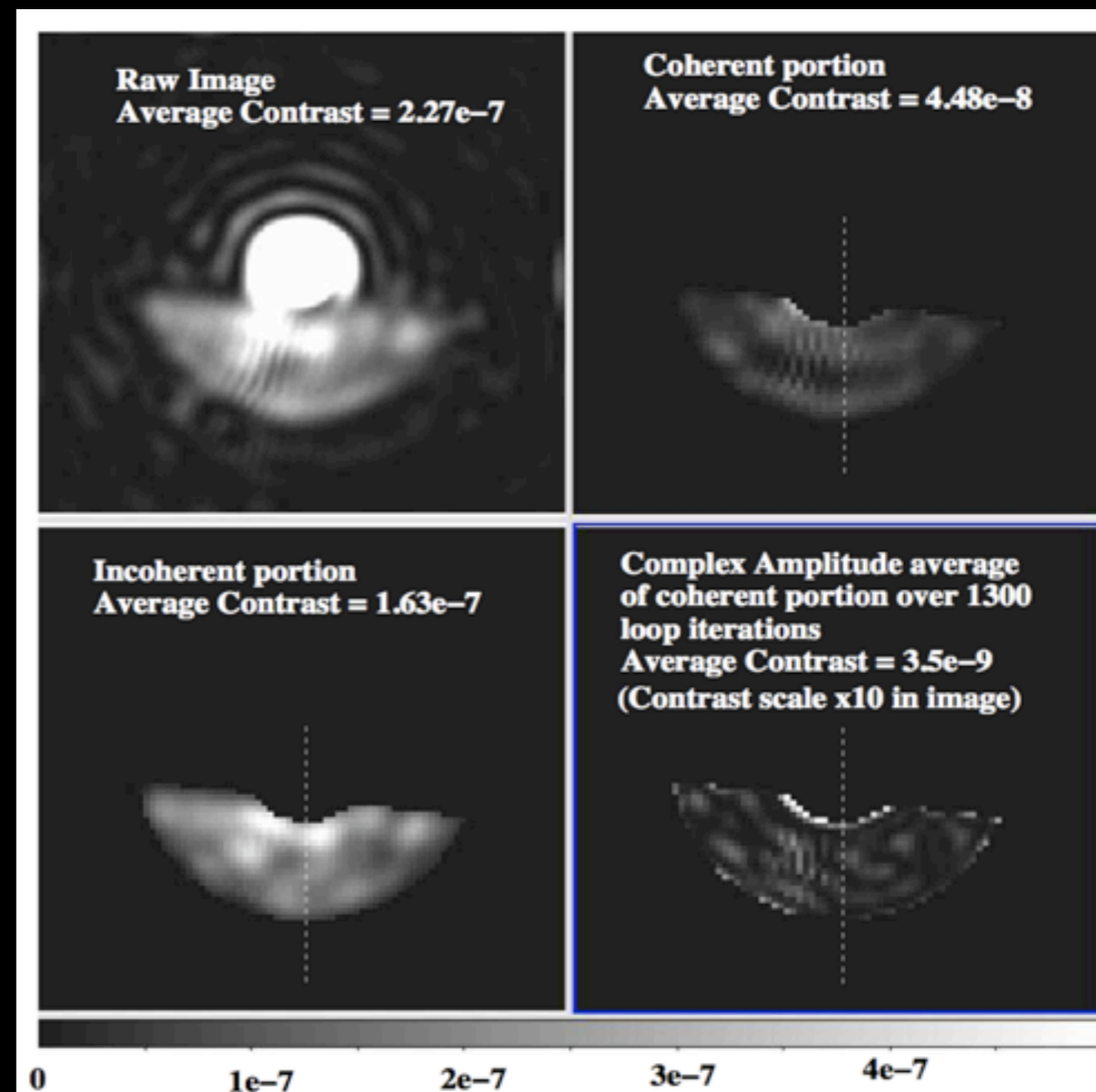
# Focal plane WF sensing



ADI only works at angular large separations

Simple idea: use the DM to introduce phase diversity, in a manner that does not disturb the contrast

$2 \times 10^{-7}$  raw contrast @  $2 \lambda/D$ ,  
better ( $\sim 100\times$ ) including  
coherence considerations



*Guyon et al, 2010, PASP, 122, 71*



# Space parameter for SCExAO?

