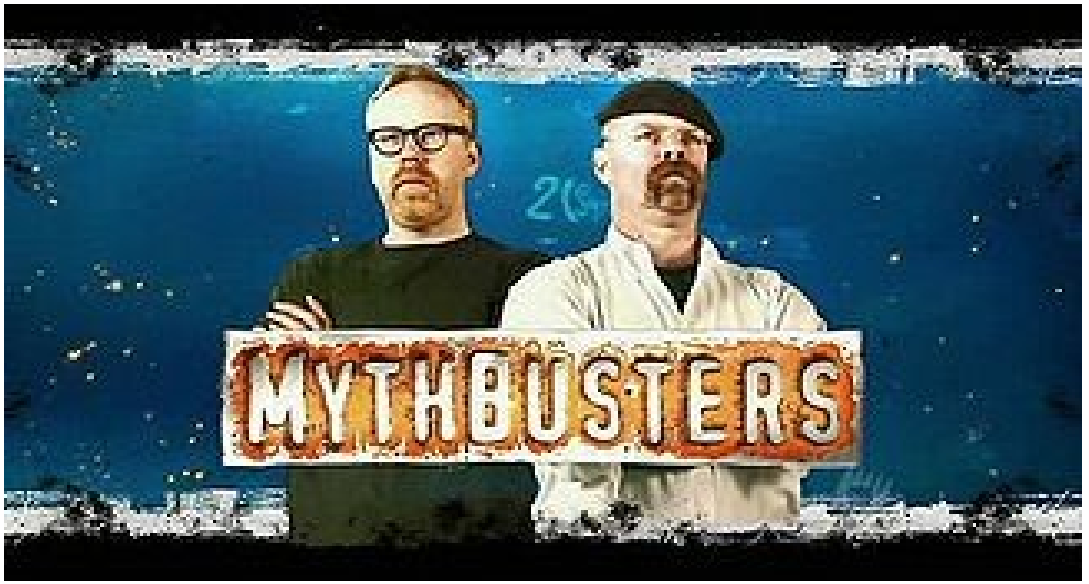
The Subaru Coronagraphic Extreme-AO (SCExAO) system

Olivier Guyon
Frantz Martinache
Vincent Garrel – *Visible light diffraction limited imaging*
Christophe Clergeon – *Visible light WFS*
Celia Blain – *MEMS DM modeling*
Jun-Ichi Morino – *SCExAO/HiCIAO combination*
Tomoyuki Kudo – *SCExAO/HiCIAO combination*
Robert Russell – *CLOWFS operation*
Frederic Vogt – *CLOWFS postprocessing calibration*
(Subaru Telescope, National Astronomical Observatory of Japan)
Tyler Groff – *Focal plane AO optimization*
(Princeton university)

AO188 team, HiCIAO team

Extreme AO Mythbusters

ExAO is extremely difficult



Extreme AO Mythbusters

ExAO is extremely difficult

ExAO is extremely costly

Extreme AO Mythbusters

ExAO is extremely difficult

ExAO is extremely costly

ExAO doesn't work

Extreme AO Mythbusters

ExAO is extremely difficult

ExAO is extremely costly

ExAO doesn't work

ExAO self proclaimed “scientists” don't know what they are doing – they change their mind every year about what is the best way to do it (coronagraphs, wavefront sensor, calibration scheme...)

The Subaru Coronagraphic Extreme-AO (SCExAO) system: overview

High contrast imaging at small angular separation is scientifically extremely valuable:

- allows sytem to probe **inner parts of young planetary systems** (<10 AU)
- constrain planet formation in the **habitable zone** of stars
- **direct imaging** of reflected light planets may be possible (reflected flux goes as a^{-2})

Coronagraphy:
High efficiency 1 λ/D PIAA coronagraph

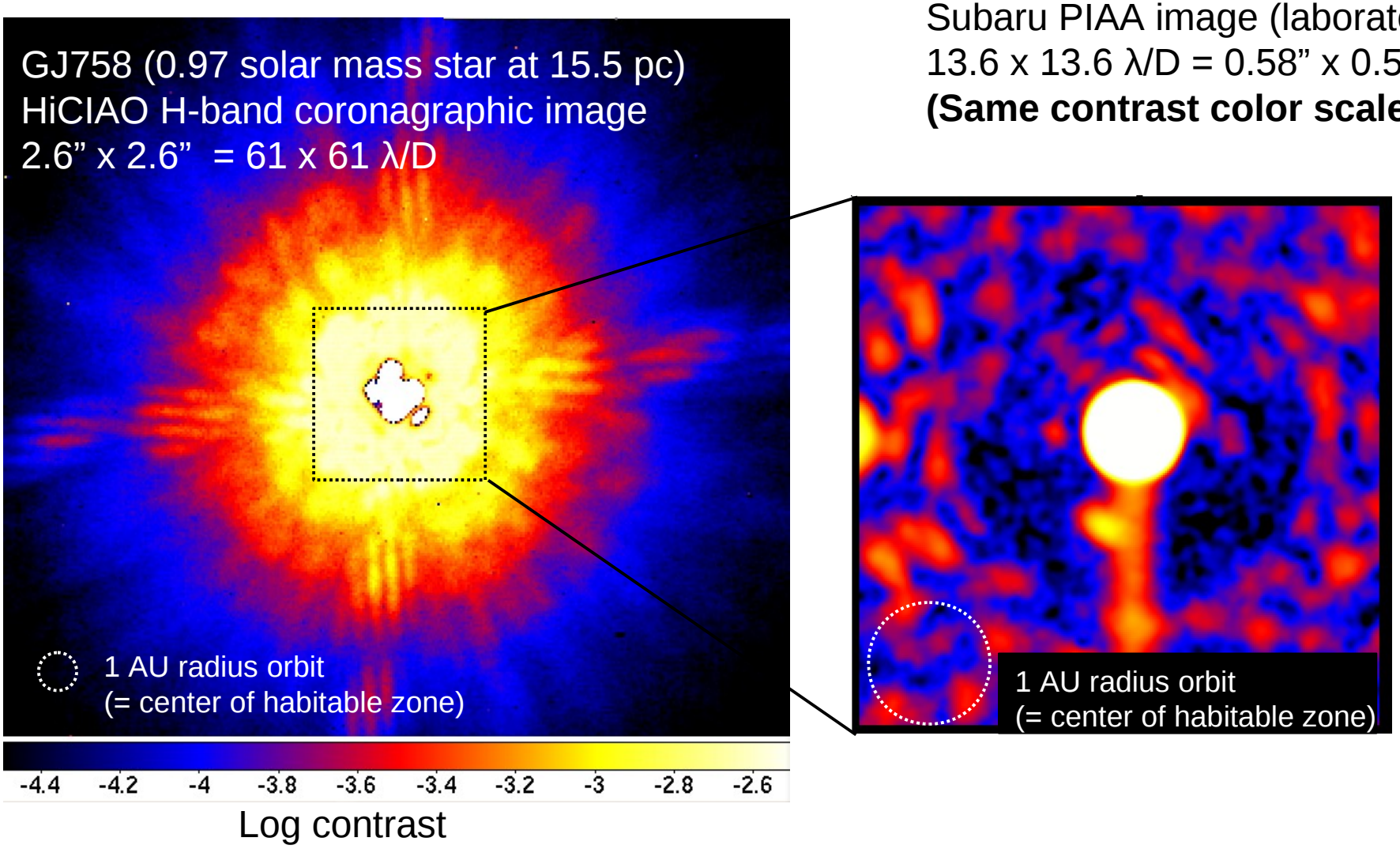
Wavefront control:
- NIR focal plane WF control/calibration
- ExAO-optimized visible WFS visible channel
- Exquisite pointing control

Aux. Science modes:
- Non-redundant masking
- Visible light imaging

Designed as a **highly flexible, evolvable platform** (reduce time from lab demo to science)
Efficient use of AO188 system & HiCIAO camera
Technology development overlap with space coronagraphy

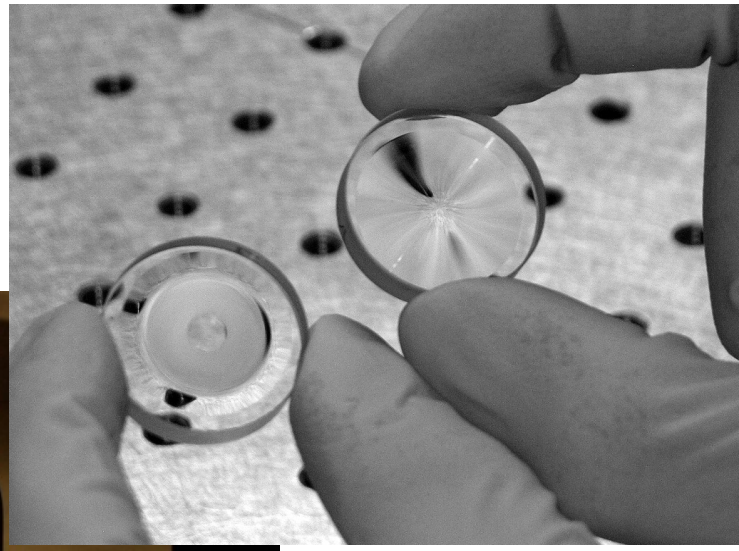
High contrast imaging in lab reaches much higher performance than what is currently achieved on-sky: newer technologies, more stable environment, better calibrations

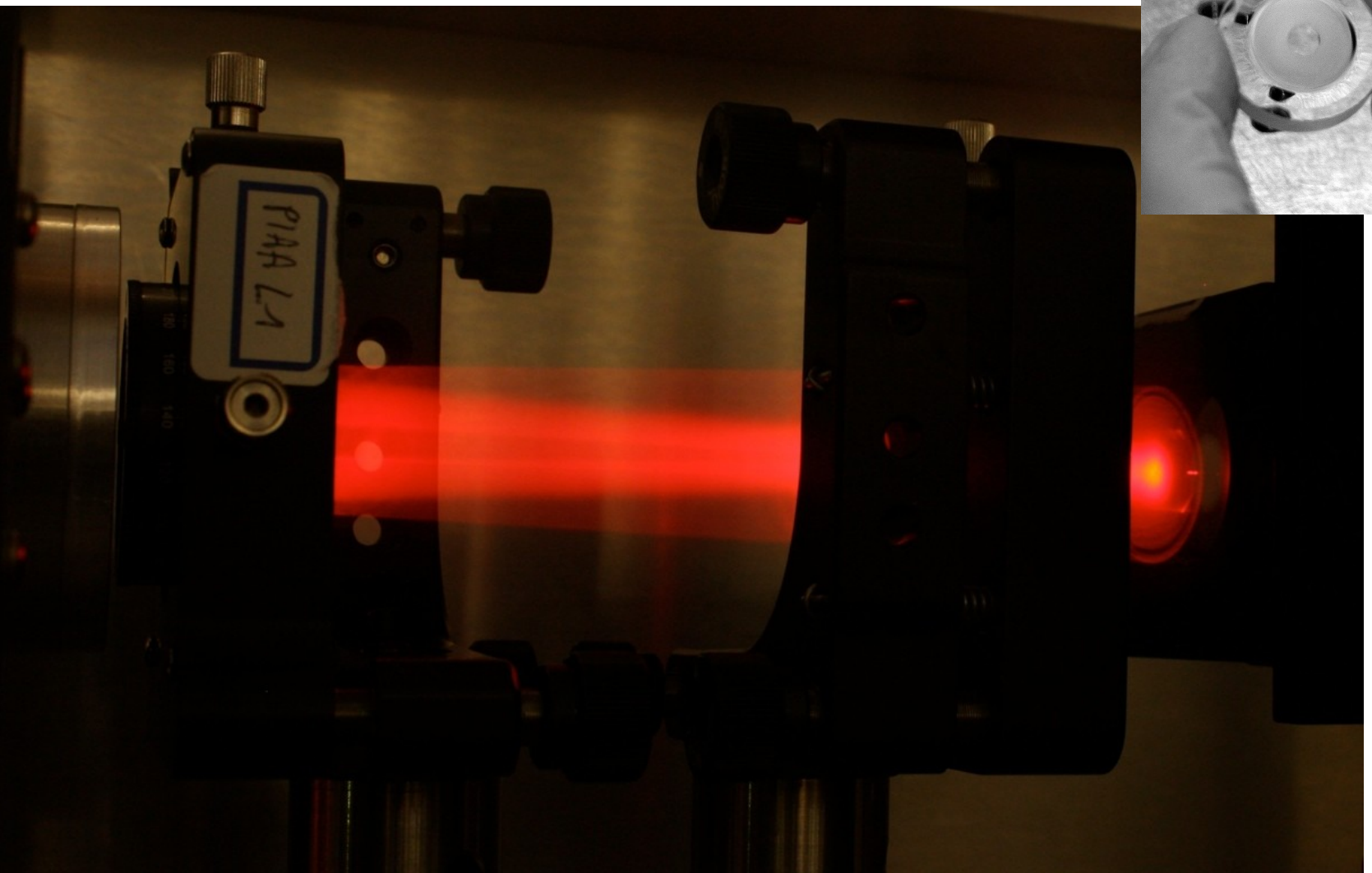
SCExAO's goal is to deploy on the telescope new techniques which have been demonstrated in the lab to offer high performance, and to create the conditions necessary to achieve this high performance



High performance coronagraphy

PIAA type coronagraph, based on lossless beam apodization
Can work down to 1 l/D (40mas) at high contrast with full efficiency
Has reached 1e-8 contrast at 2 l/D in lab (NASA Ames)





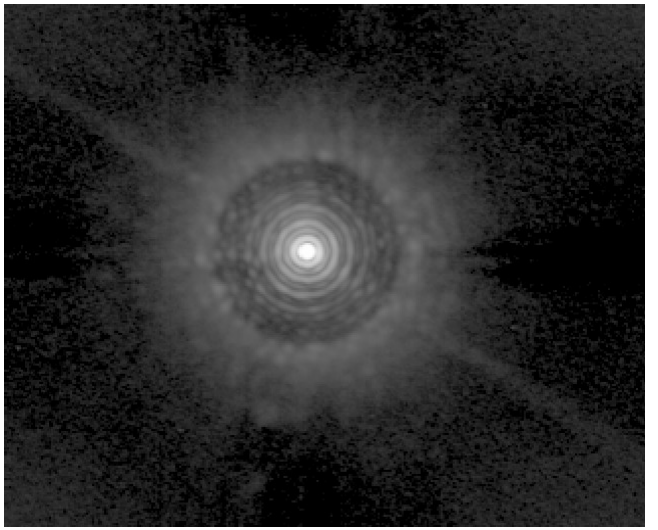
Coronagraphy at ~ 1/D

Separation = 230 mas
H band

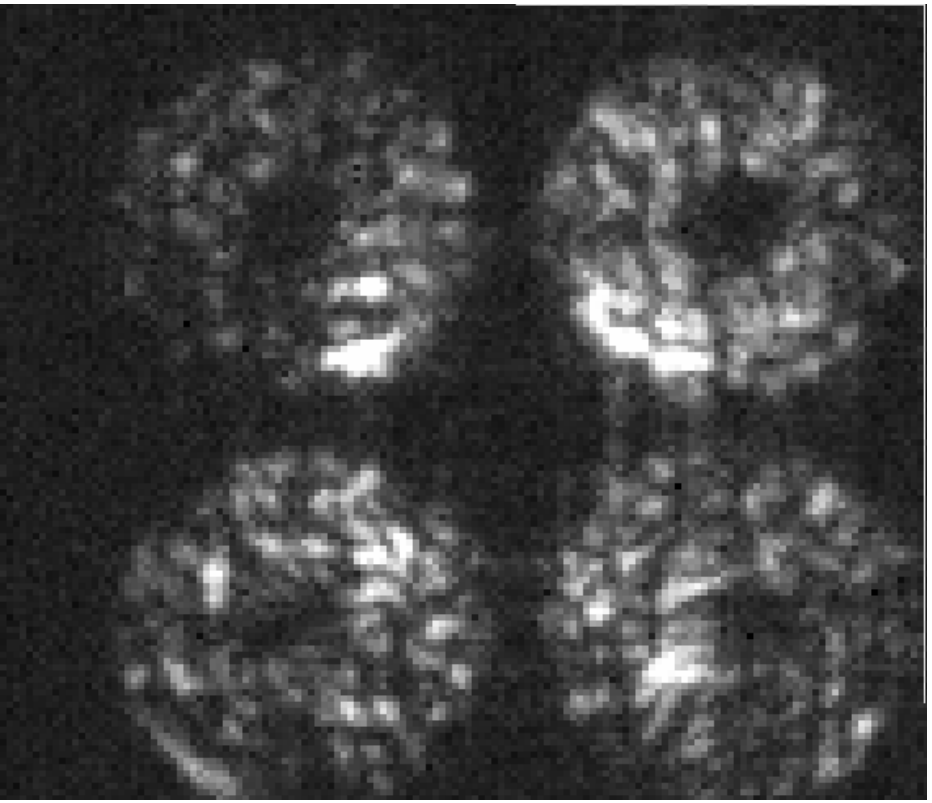
High sensitivity visible WFS

Most commonly used WFSs (SH, curvature) are seeing-limited: the wavefront sensing sensitivity is limited by the seeing size

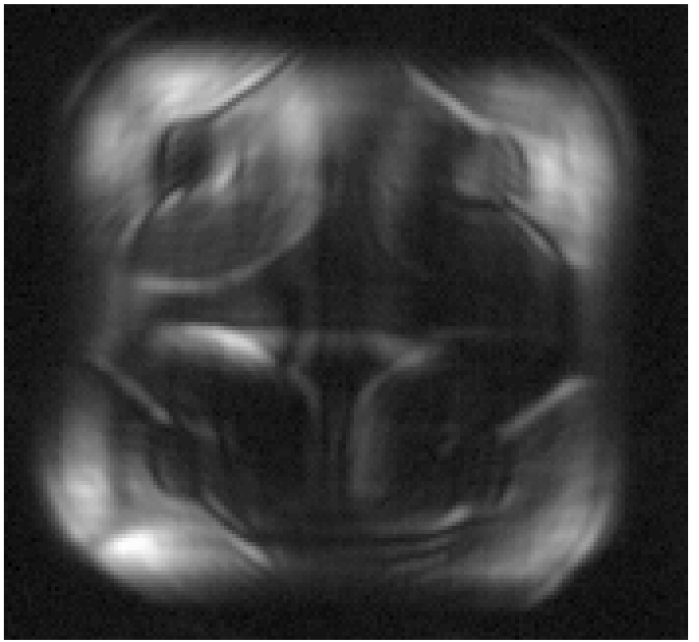
Diffraction-limited WFS offers much improved performance, especially for low order modes (essential for coronagraphy)
Example:
Tit-tilt measurement done with diffraction-limited PSF vs. Tip-tilt measurement done with seeing-limited PSF: equivalent light ratio is D/r0^2 (at least !) = 2500 = 8.5 mag
… using SH is equivalent to putting 0.04 % transmission ND



LBT PSF with Pyramid WFS
(80 – 85% SR with 0.8” seeing)



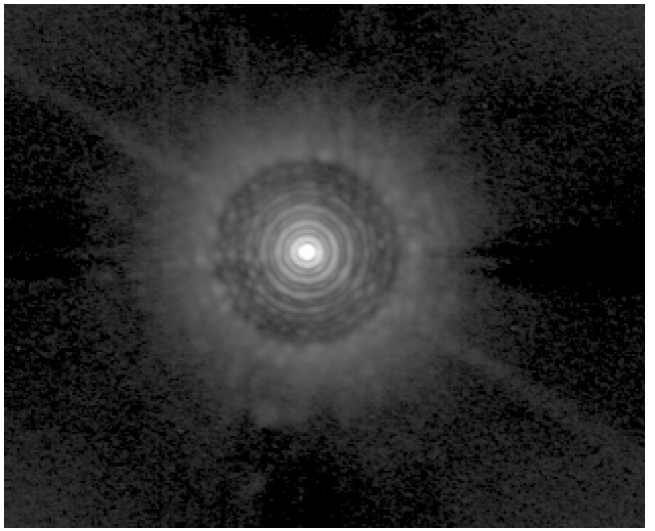
← **On-sky SCExAO pyrWFS data**
Magn 4.11 star, vis light shared between EMCCDs and pyrWFS
1ms exposure, 280 MHz pixel readout rate, 1e- RON



High sensitivity visible WFS

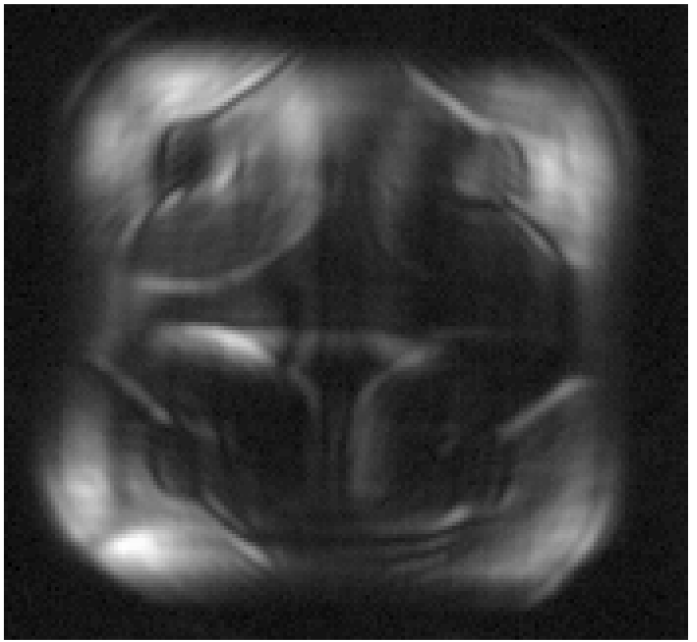
Most commonly used WFSs (SH, curvature) are seeing-limited: the wavefront sensing sensitivity is limited by the seeing size

Diffraction-limited WFS offers much improved performance, especially for low order modes (essential for coronagraphy)
Example:
Tit-tilt measurement done with diffraction-limited PSF vs. Tip-tilt measurement done with seeing-limited PSF: equivalent light ratio is D/r0^2 (at least !) = 2500 = 8.5 mag
… using SH is equivalent to putting 0.04 % transmission ND



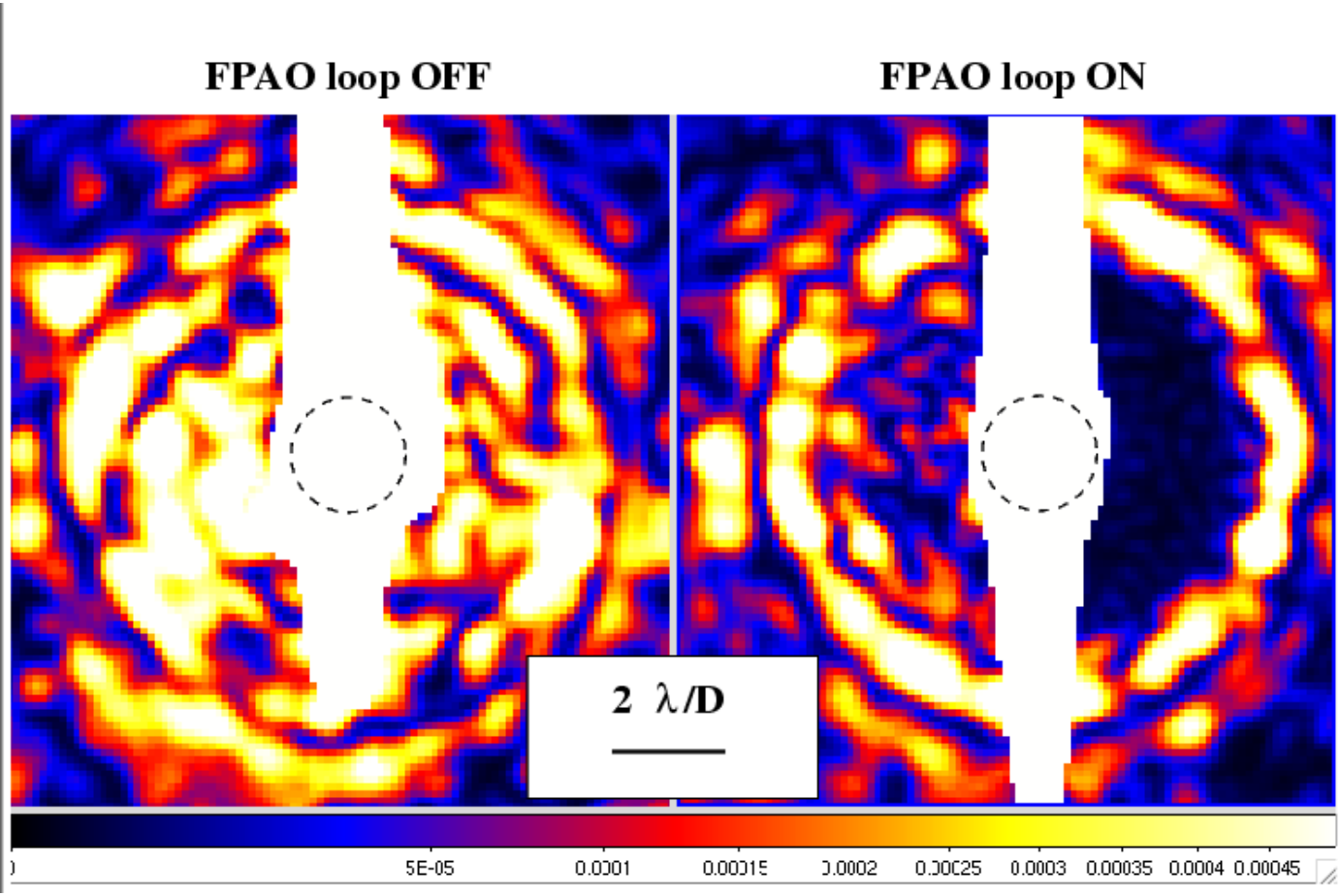
LBT PSF with Pyramid WFS
(80 – 85% SR with 0.8” seeing)

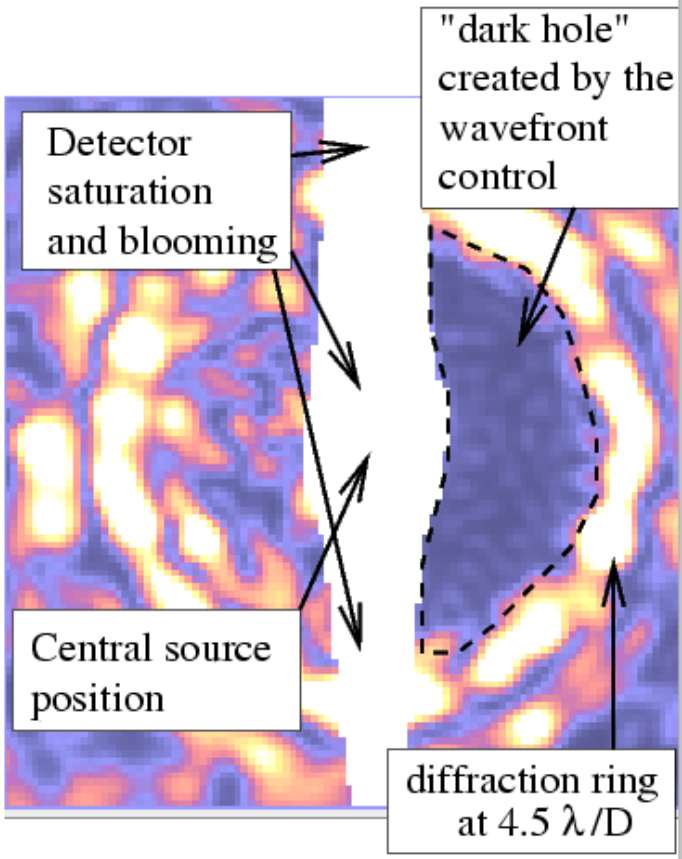
← **On-sky SCExAO pyrWFS data (~1sec slowed down to 76sec movie)**
Magn 3 star, vis light shared between EMCCDs and pyrWFS
0.5ms exposure, 280 MHz pixel readout rate, 1e- RON

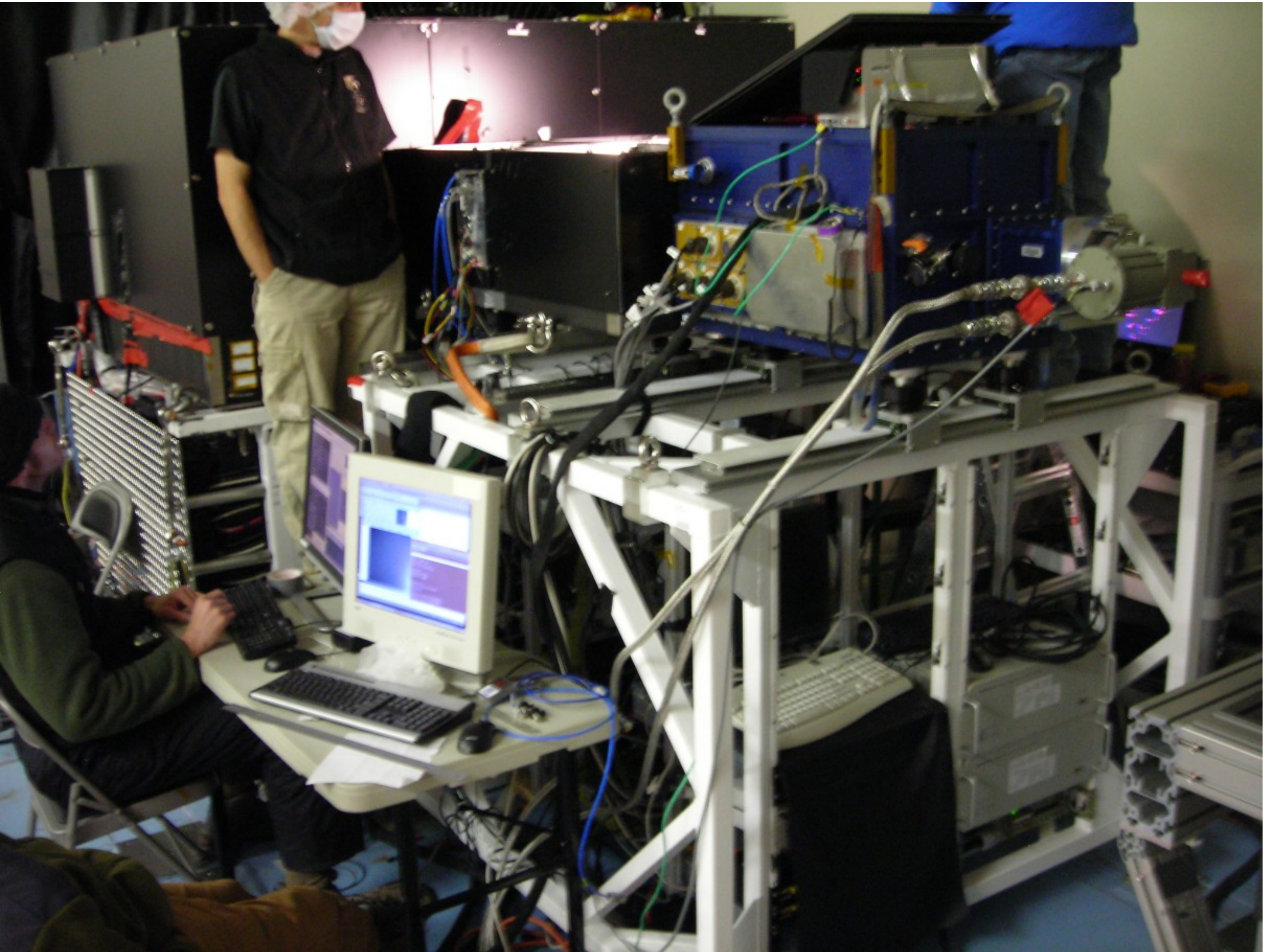


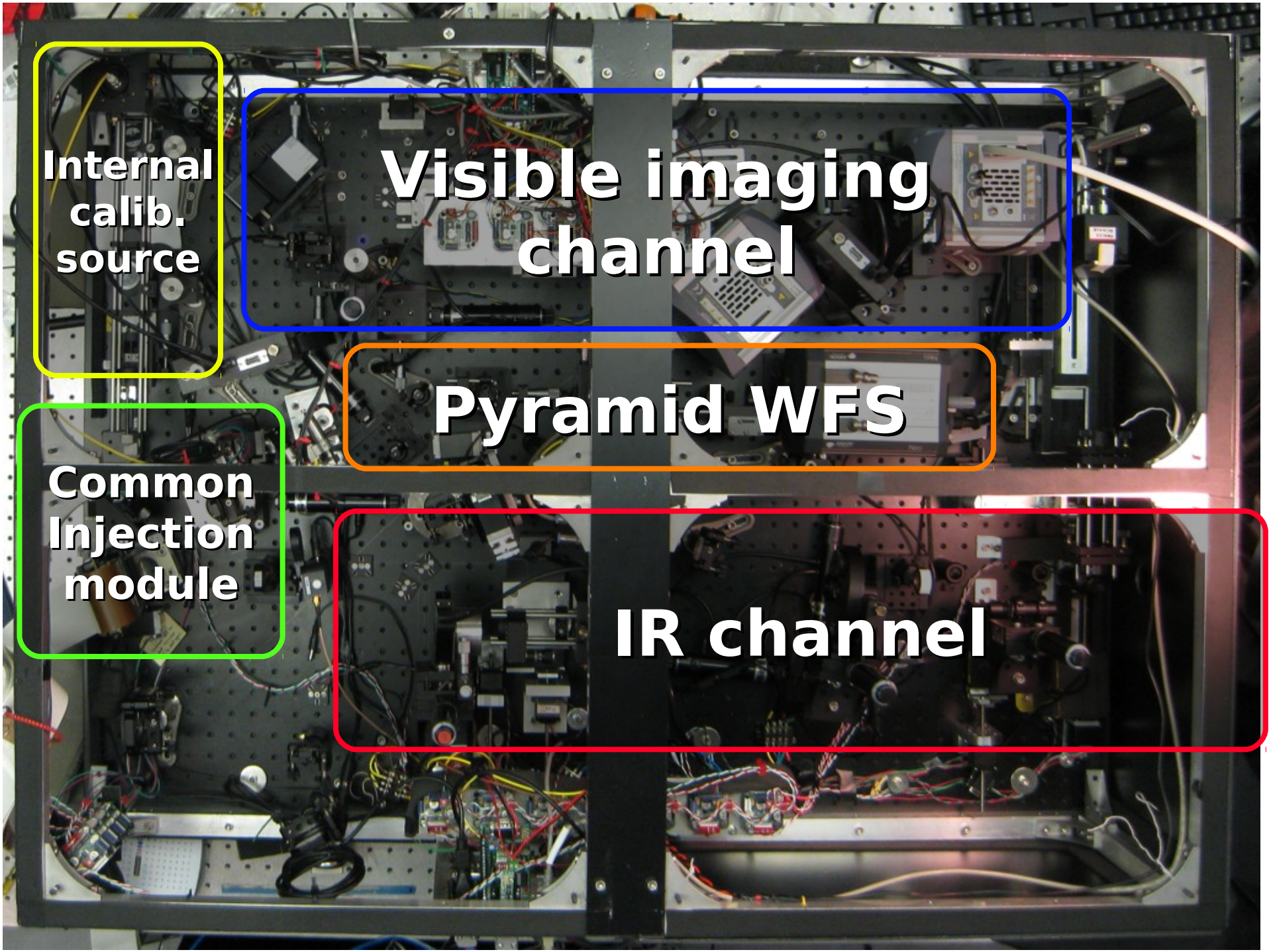
Speckle control and nulling

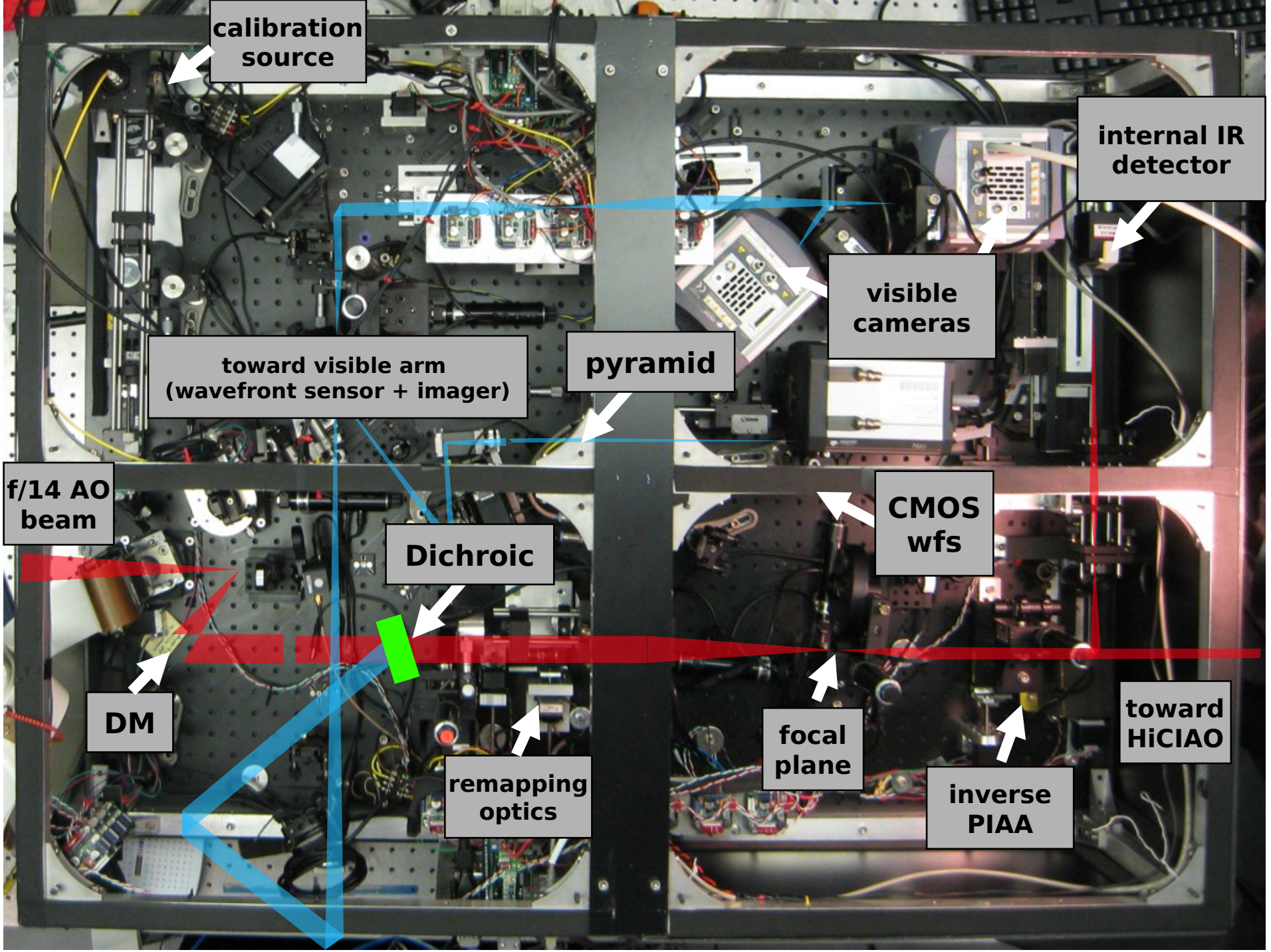
Speckle nulling
Subaru lab results with PIAA coronagraph + 32x32 MEMs DM



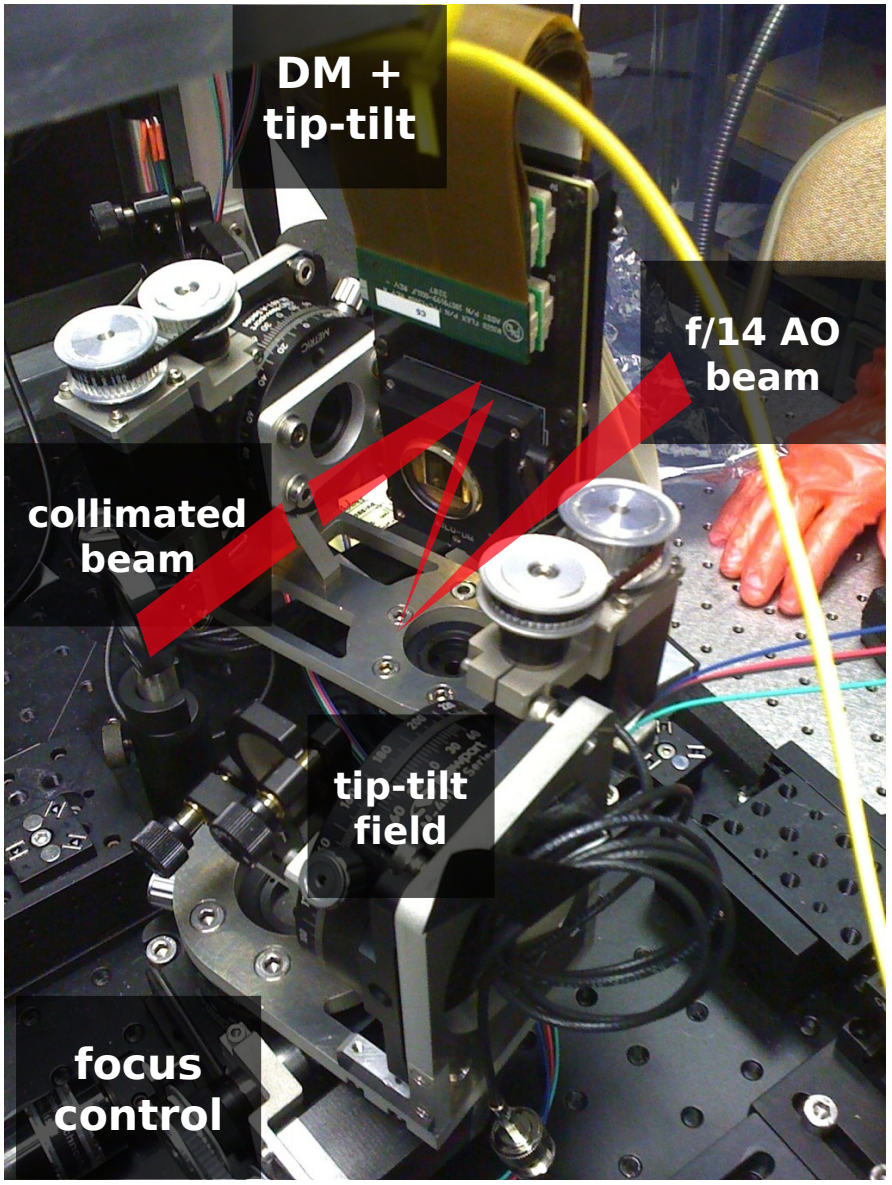





Internal calib. source
Visible imaging channel
Pyramid WFS
Common Injection module
IR channel


calibration source
internal IR detector
visible cameras
toward visible arm (wavefront sensor + imager)
pyramid
f/14 AO beam
CMOS wfs
Dichroic
DM
remapping optics
focal plane
inverse PIAA
toward HiCIAO

Common injection module



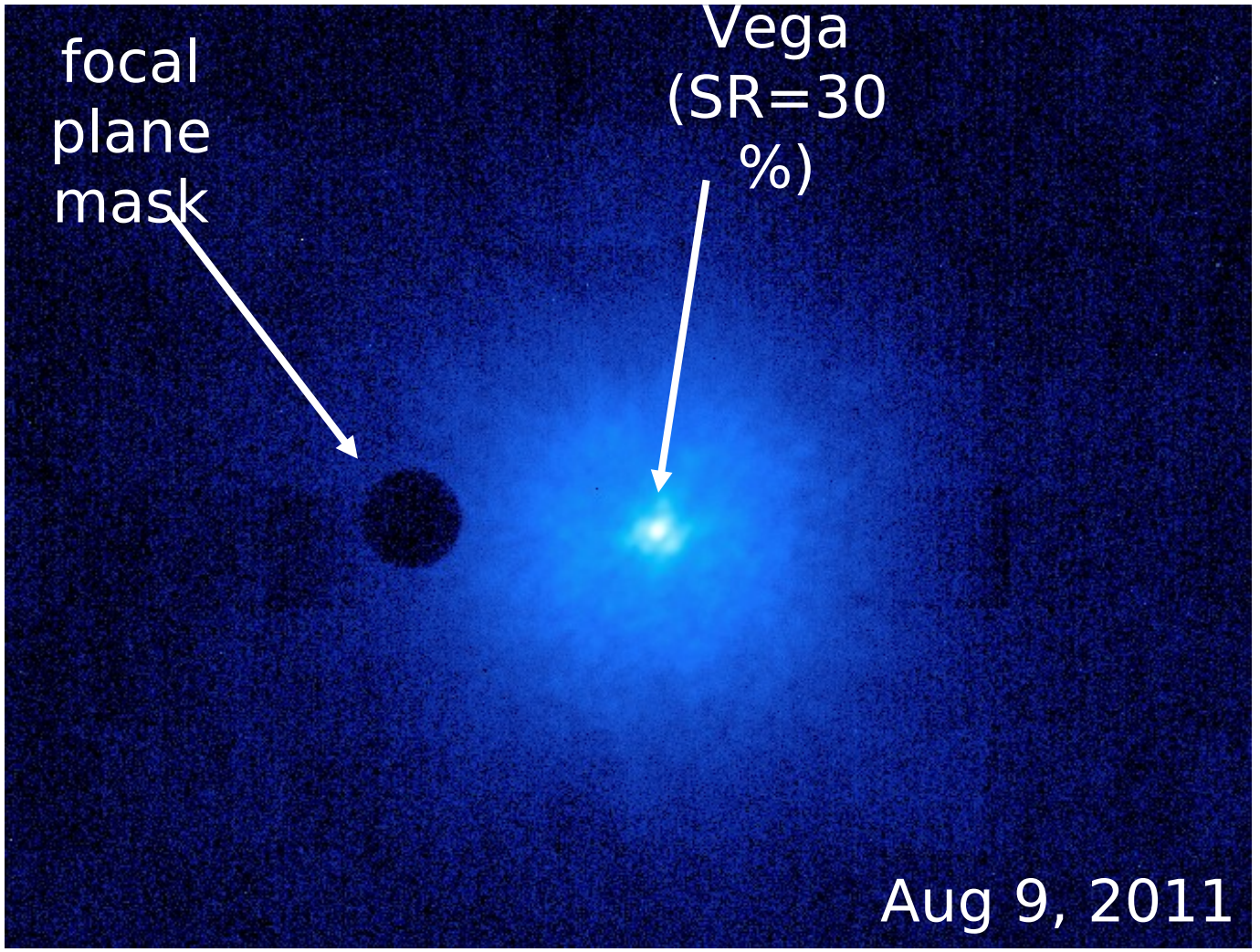
High contrast experts out there, beware:

DM not located in a pupil plane!

DM needs to be taken off of the bench after each observing run

SCExAO/HiCIAO first light

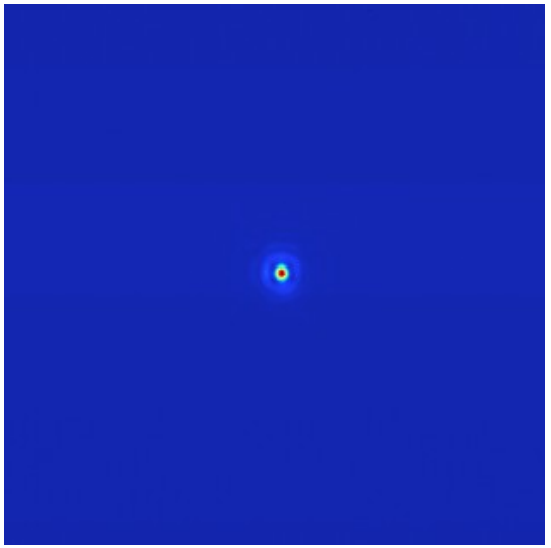
After quite some time fiddling with fine collimation adjustments,
and hesitations due to bad seeing:

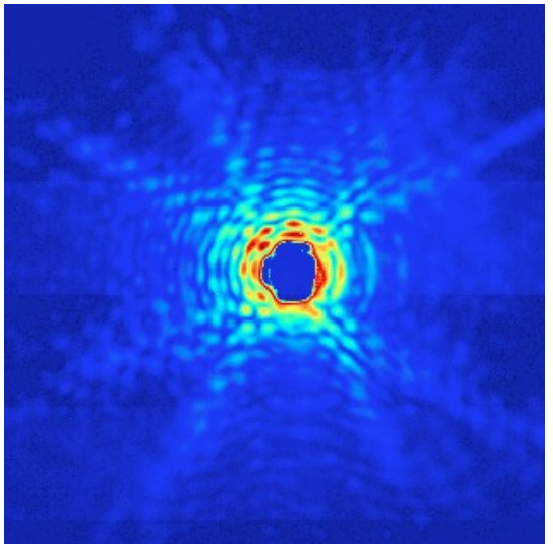


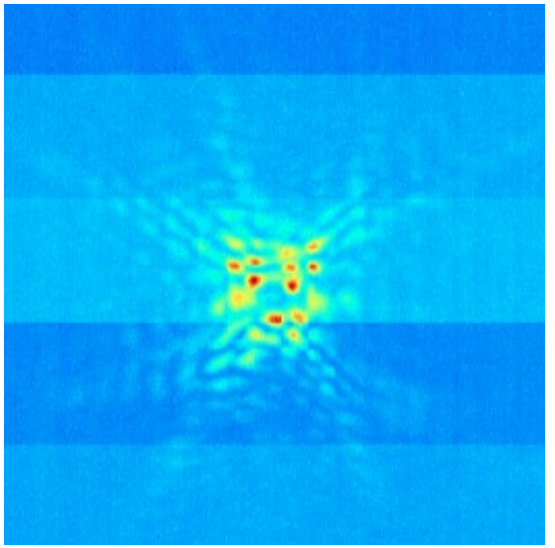
The rest of the observing night however ruined by weather...

The SCExAO/HiCIAO combination

With PIAA + inverse PIAA (no SRP)







non-saturated image:
SR ~ 80 % on internal calibration source

DM flat-map calibrates well low-order aberrations

saturated image:
diffraction spikes attributable to a non-optimal conjugation between PIAA and inverse PIAA

coronagraphic image:

unlike Lyot coronagraph image, attenuation is global

Visible diffraction limited imaging

100 frames sequence on Mira
Sqrt scaling
Individual frames are almost diffraction limited

Two EMCCDs
512x512 pixels, 35 Hz full frame
Fast mode: 1kHz, 64x64 pixel
Wavelength diversity (first test on Sept 11 2011)

Fourier-based signal selection
10x more efficient that Lucky imaging

Can achieve diffraction limited imaging (17mas) is seeing is 2” or better on bright sources

Current status (Sep 2011)

- SCExAO has validated <2 l/D coronagraphy on sky
- SCExAO speckle control running in lab, modulation working on sky
- LOWFS loop was closed on sky (up to 10% loop gain)
- Fixed pyramid WFS acquisition working (open loop only) in Sep 2011 run, using CMOS with ~1e- RON

Next steps:

- Demonstrate on-sky speckle control (end 2011)
- Close loop with Pyramid WFS in lab, then sky (early 2012)
- Design and implementation of IfU (funded)
- Upgrade to 2k actuators (funded)
- Science … (integration to HiCIAO and SEEDS survey)