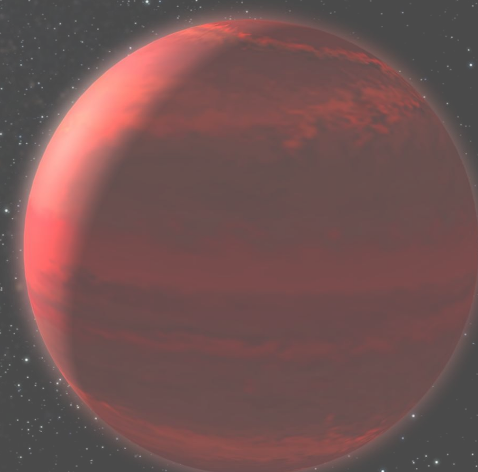
# On-sky wavefront correction with a 2048 actuator MEMS

**Olivier Guyon**
**(on behalf of SCExAO team)**

- **Subaru/NAOJ**
- **University of Sydney (VAMPIRES)**
- **Observatoire de Paris (FIRST)**
- **UC Santa Barbara (MKIDs)**
- **JPL (Vortex coronagraph)**
- **Hokkaido University (8oct coron)**

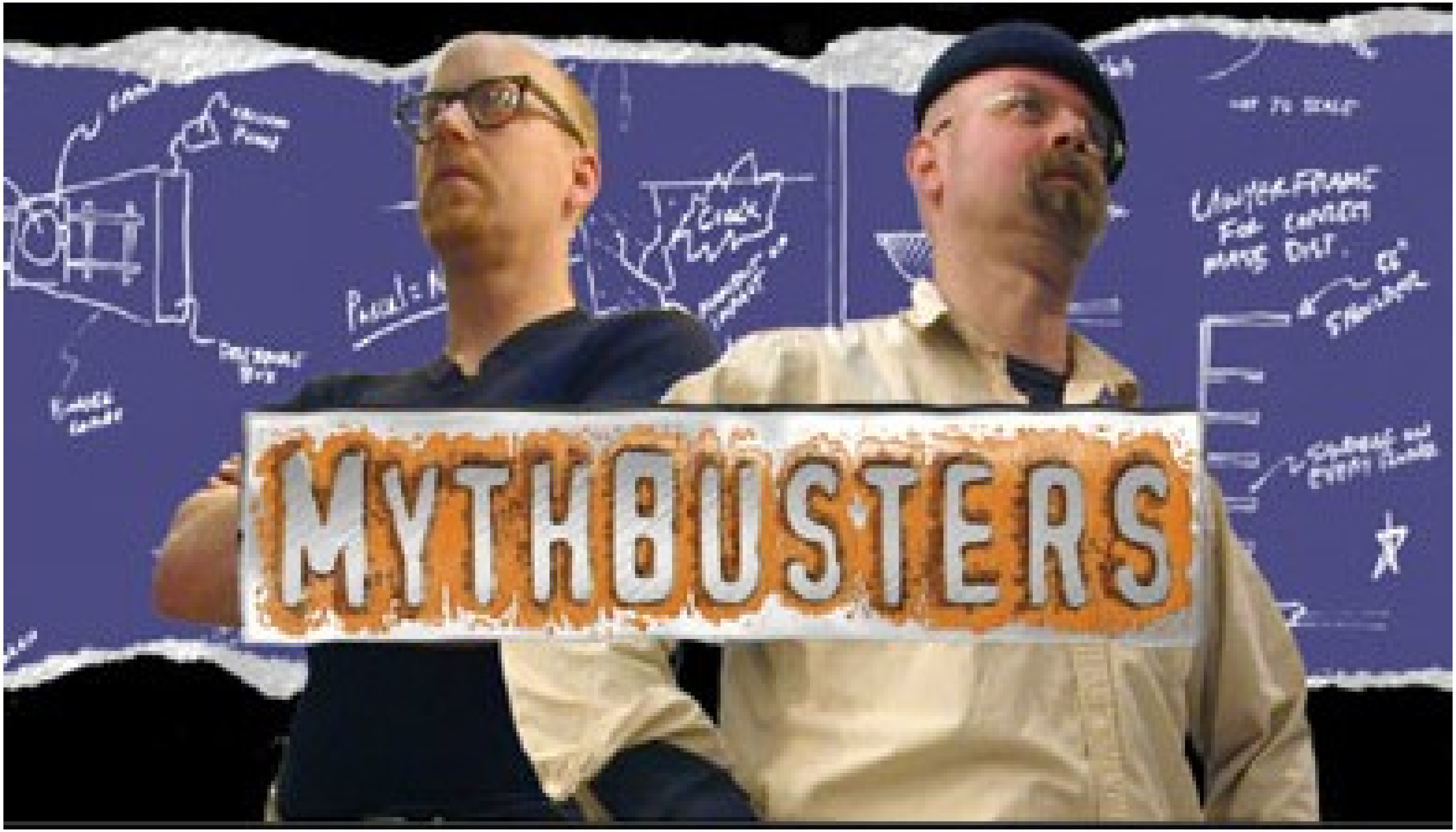
Subaru Telescope & Univ. of Arizona



*SPIE Photonics West, Feb 2, 2014*

***Contact: oliv.guyon@gmail.com***

# Extreme AO systems (superAO+coronagraph) myths



# Extreme AO myth #1

**ExAO = “Extremely complicated/costly AO”**

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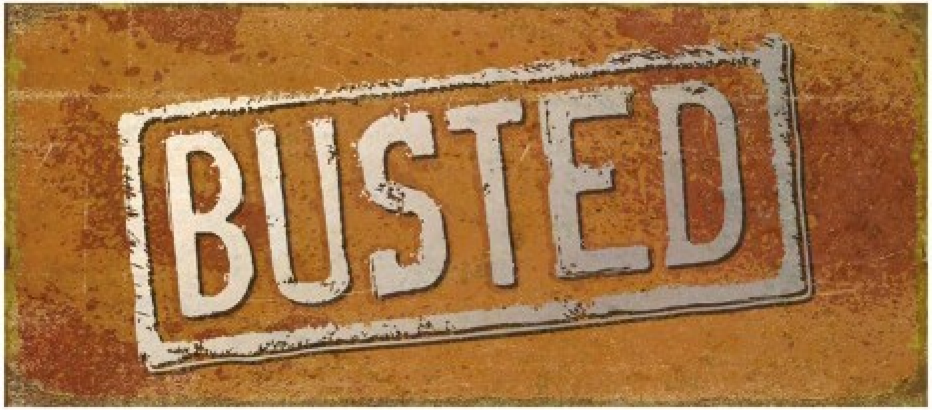
**ExAO = "Extremely complicated/costly AO"**

→ ExAO is in many respects simpler than other AO systems:

- bright on-axis natural guide star (no lasers, easiest configuration for cophasing segments)
- zero field of view system (small optics, single DM OK)



# Extreme AO myth #2

**High contrast imaging is all about achieving super low wavefront error**
**→ we always need more actuators**

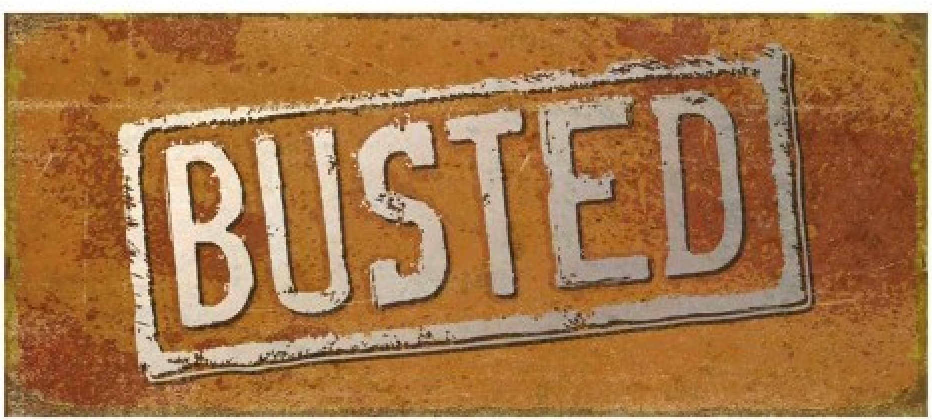
# Extreme AO myth #2

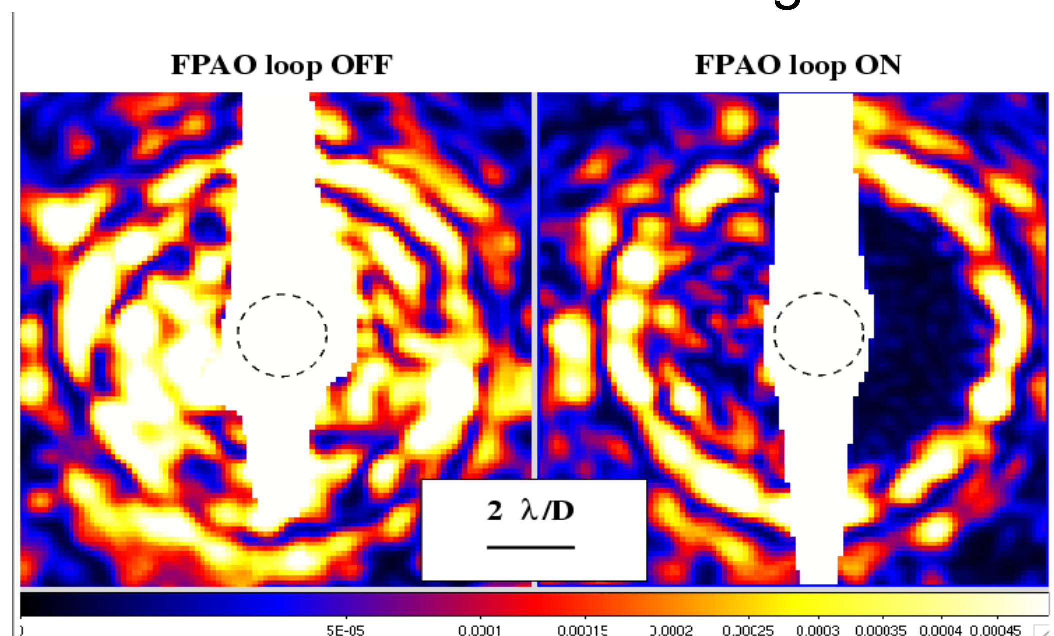
**High contrast imaging is all about achieving super low wavefront error**
**→ we always need more actuators**

ExAO is not about making the star's image sharper.. it is about making sure no uncalibrated starlight falls on the exoplanet.
In ExAO, the number of actuators in the DM defines the field of view, not the contrast

→ small field = no need for high number of actuators

→ detection of planets at up to ~20 l/D can be done with existing DMs



# Extreme AO myth #3

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**Directly imaging habitable planets will require a space telescope.**

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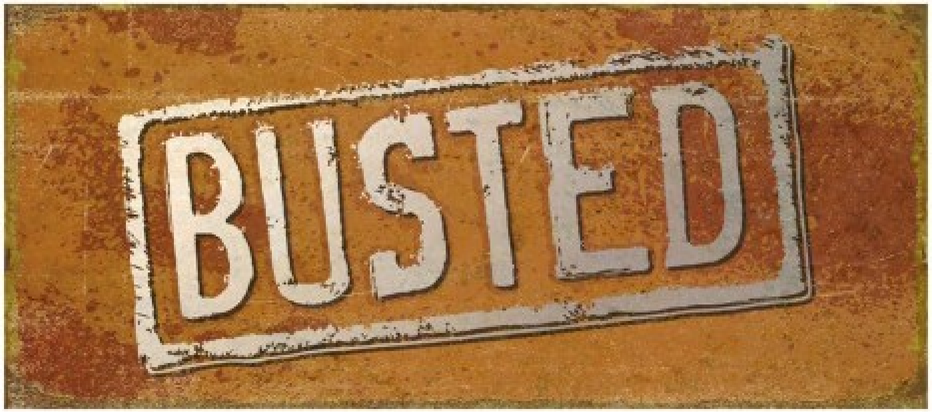
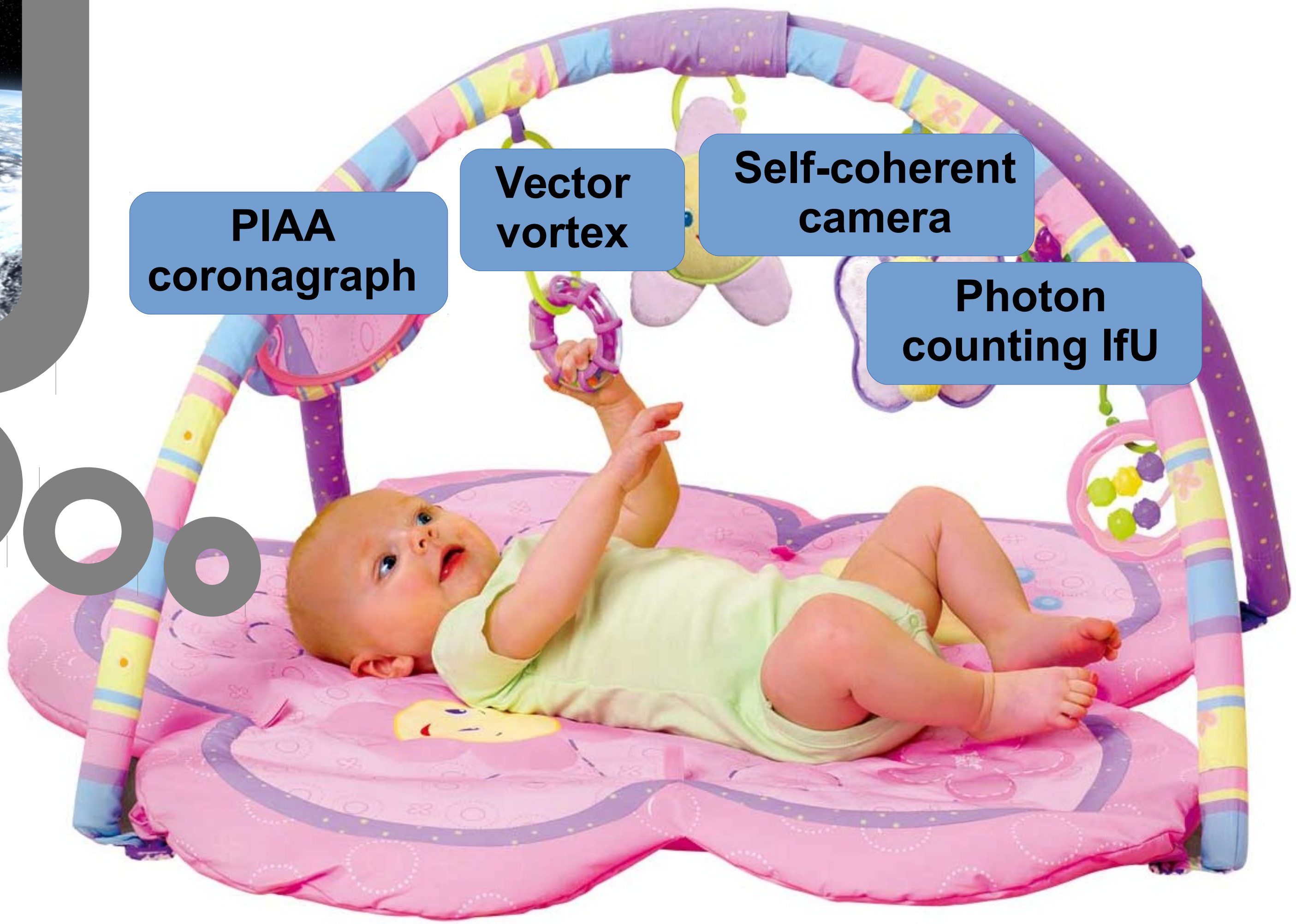



New generation of Extremely Large Telescopes (ELTs) + key technologies (including MEMS) will allow direct imaging of Earth-size planets around nearby low-luminosity stars

# Extreme AO myth #4

**ExAO people have no clue what they are doing.**
**They change their mind about what coronagraph or wavefront sensor to use every two years.**



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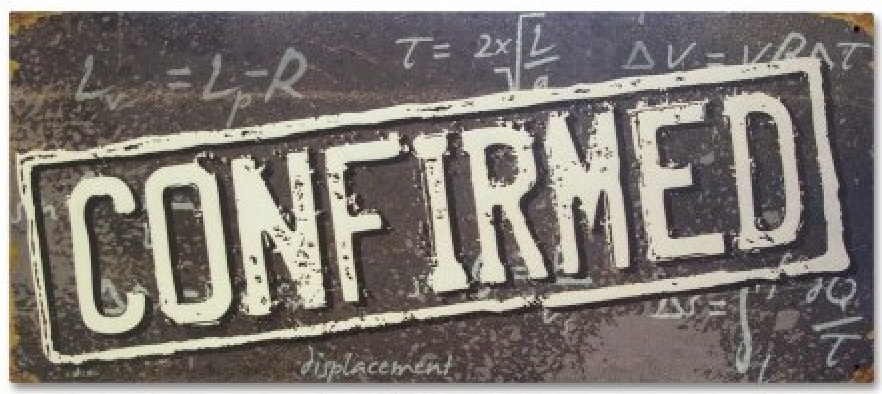



→ ExAO instrument with flexible evolutionary path has a lot of value (SCExAO)
→ don't design ExAO system details too much in advance

Develop & prototype on 8-m, telescopes → quickly move to ELT when ELT is ready

# Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) goals

**Highly flexible high contrast imaging instrument**

Reduce time from new concept to on-sky science

Provide platform to validate new technologies/approaches on sky

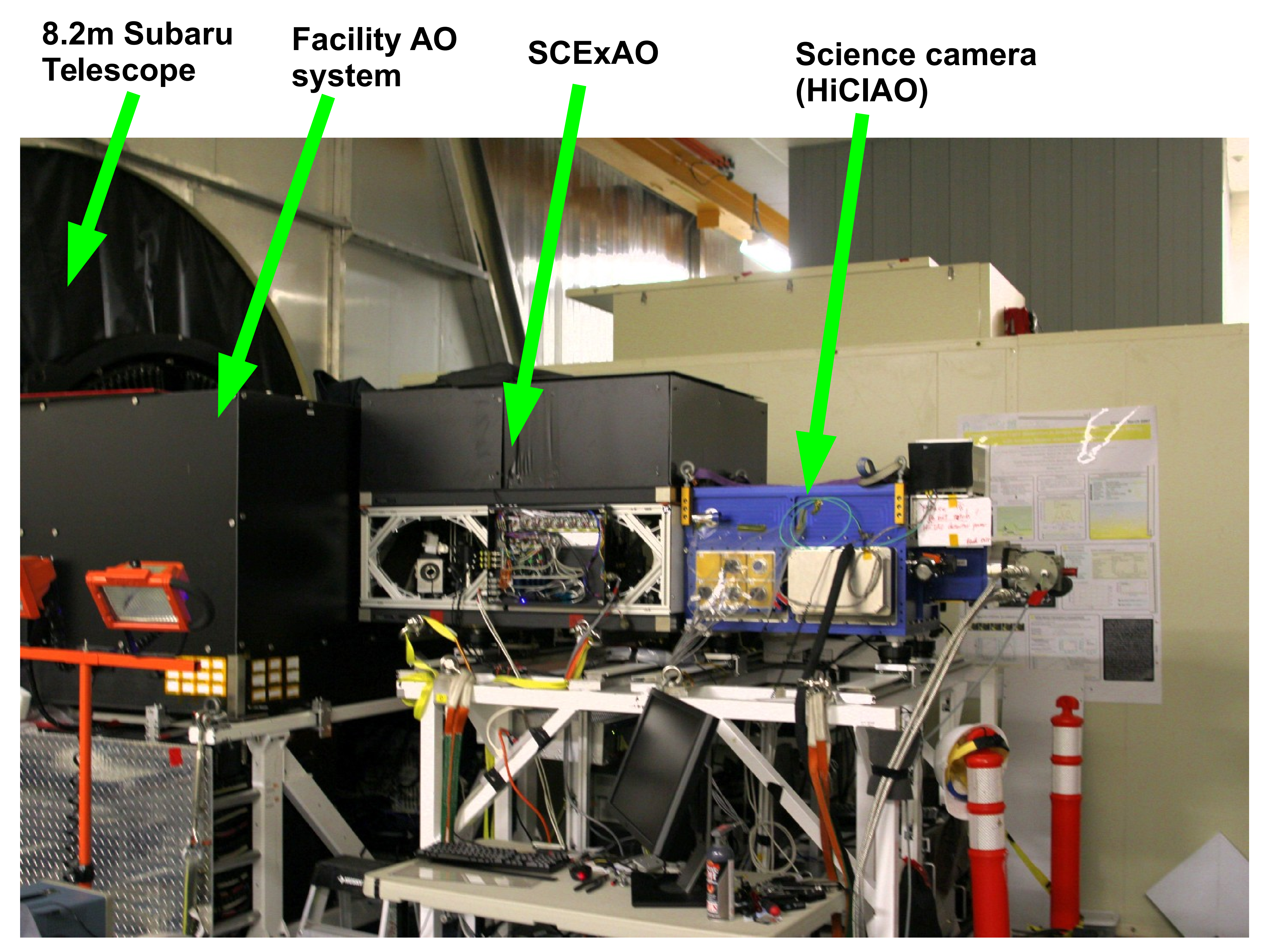
Continuously evolving/improving. SCExAO is in the lab, and only goes to the telescope for observing runs.

**Complementary to GPI and SPHERE** (use somewhat more mature technologies for large consistent survey)

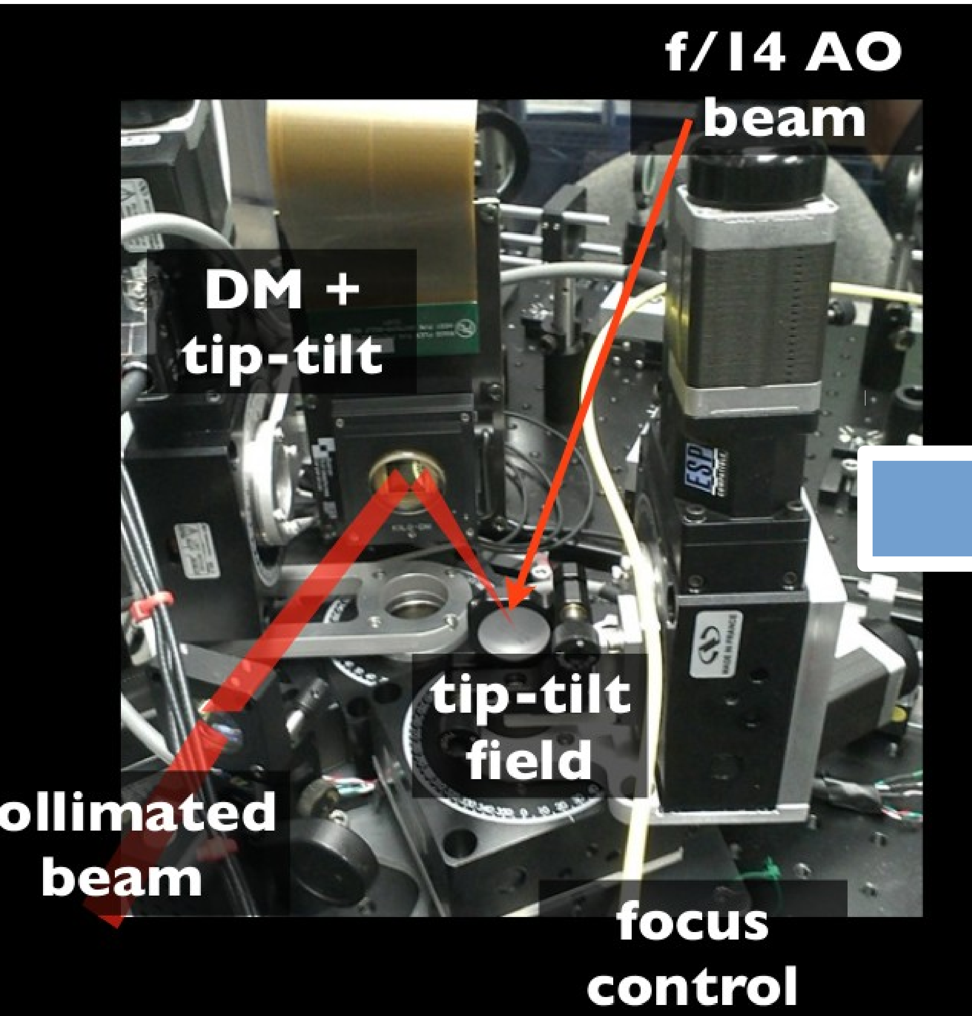
**Emphasis on high contrast at very small angular separation**

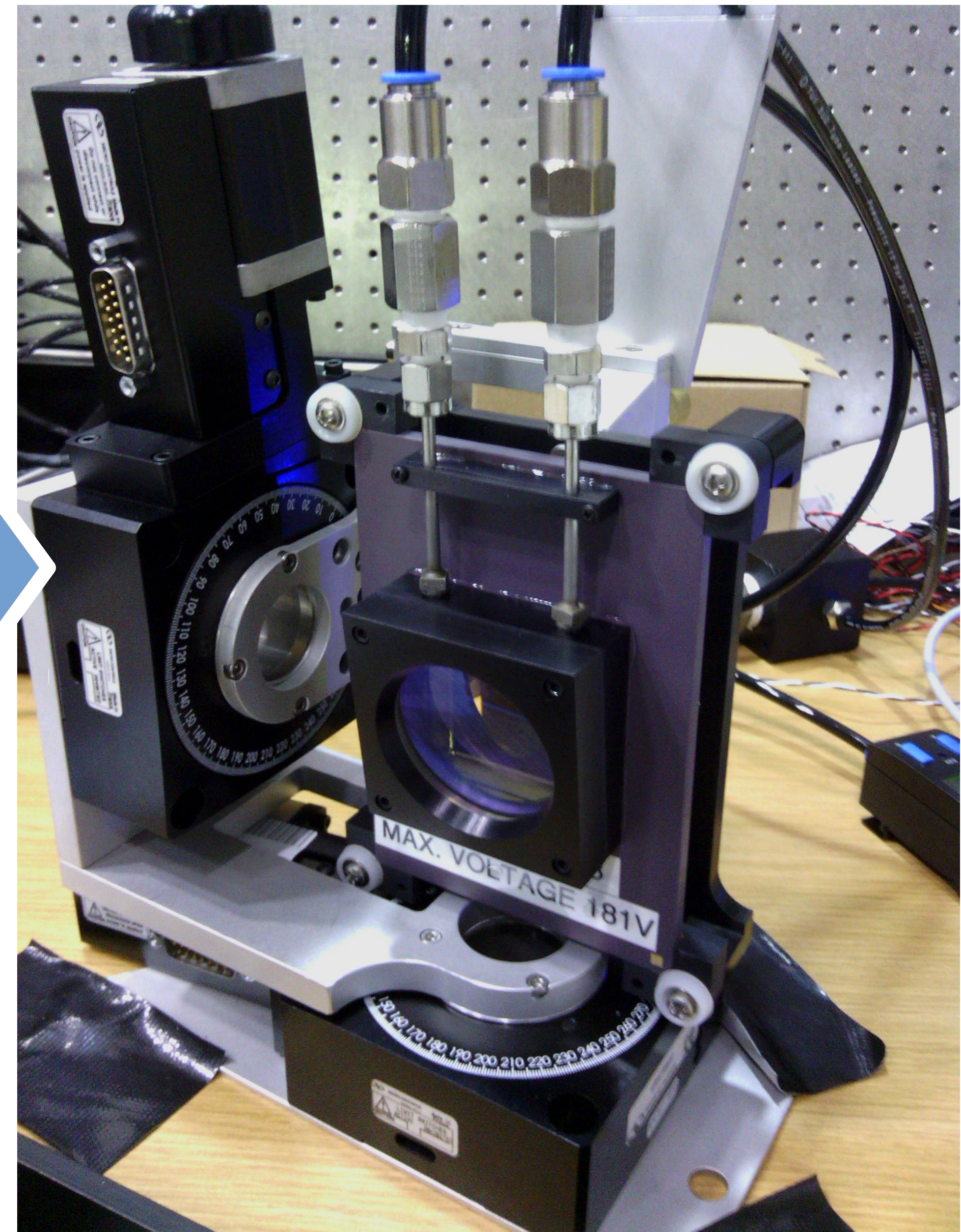
→ able to probe the inner parts of exoplanetary systems, near habitable zones

→ direct precursor to a habitable planet imager on ELTs

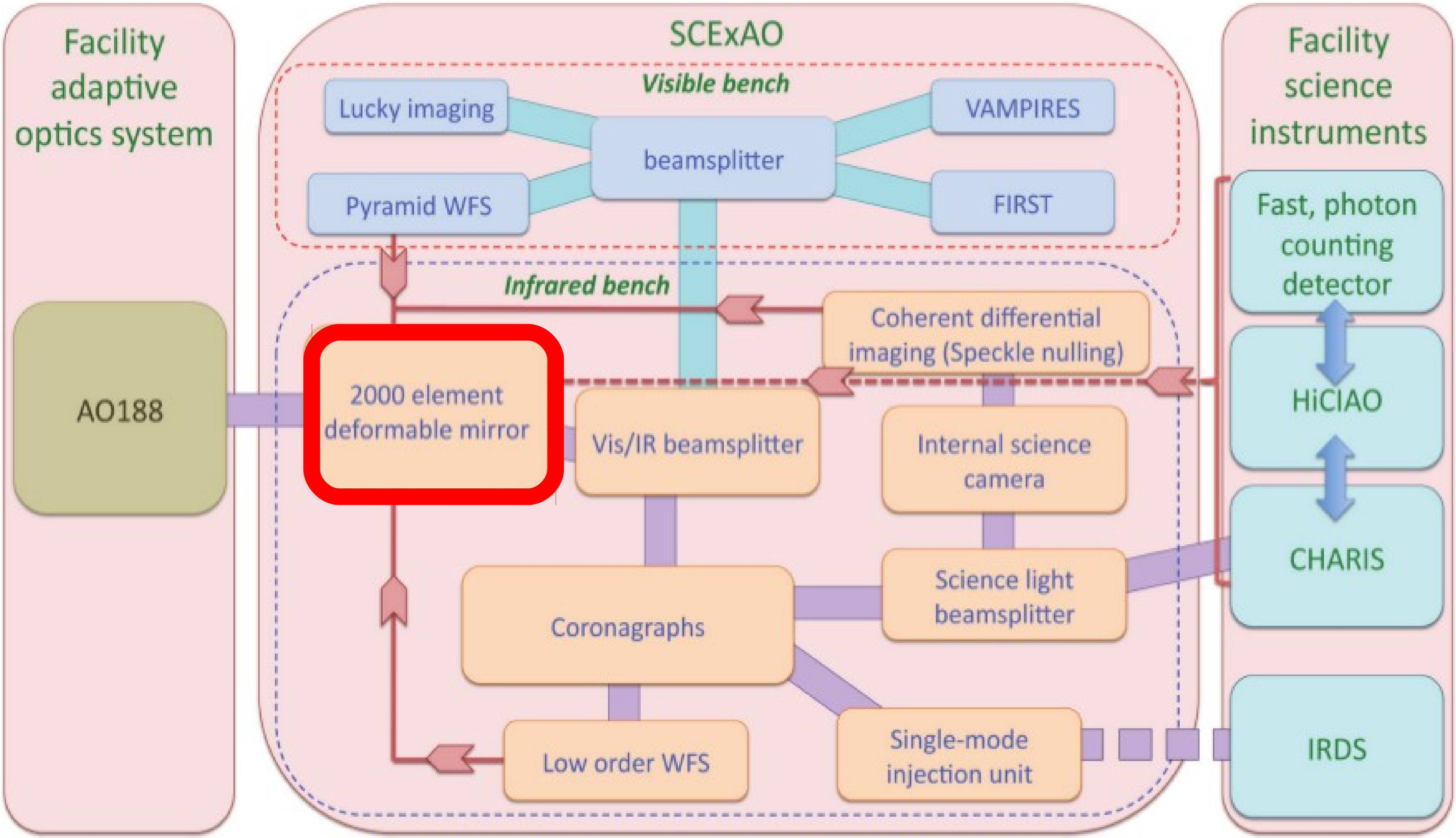

8.2m Subaru Telescope
Facility AO system
SCExAO
Science camera (HiCIAO)

# SCExAO replaced kiloDM with new 2048 actuators MEMS (July 2013)



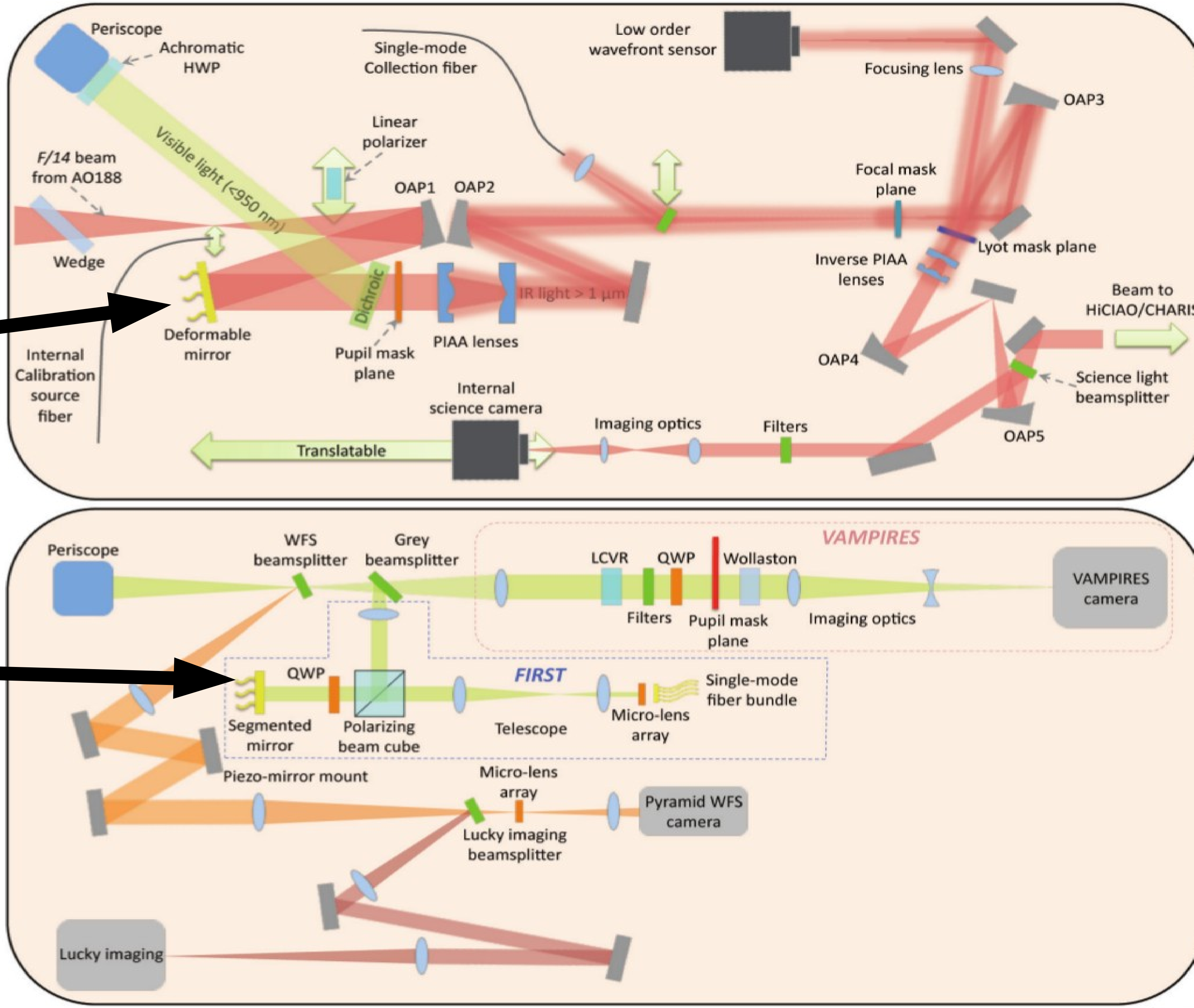



# SCExAO overview

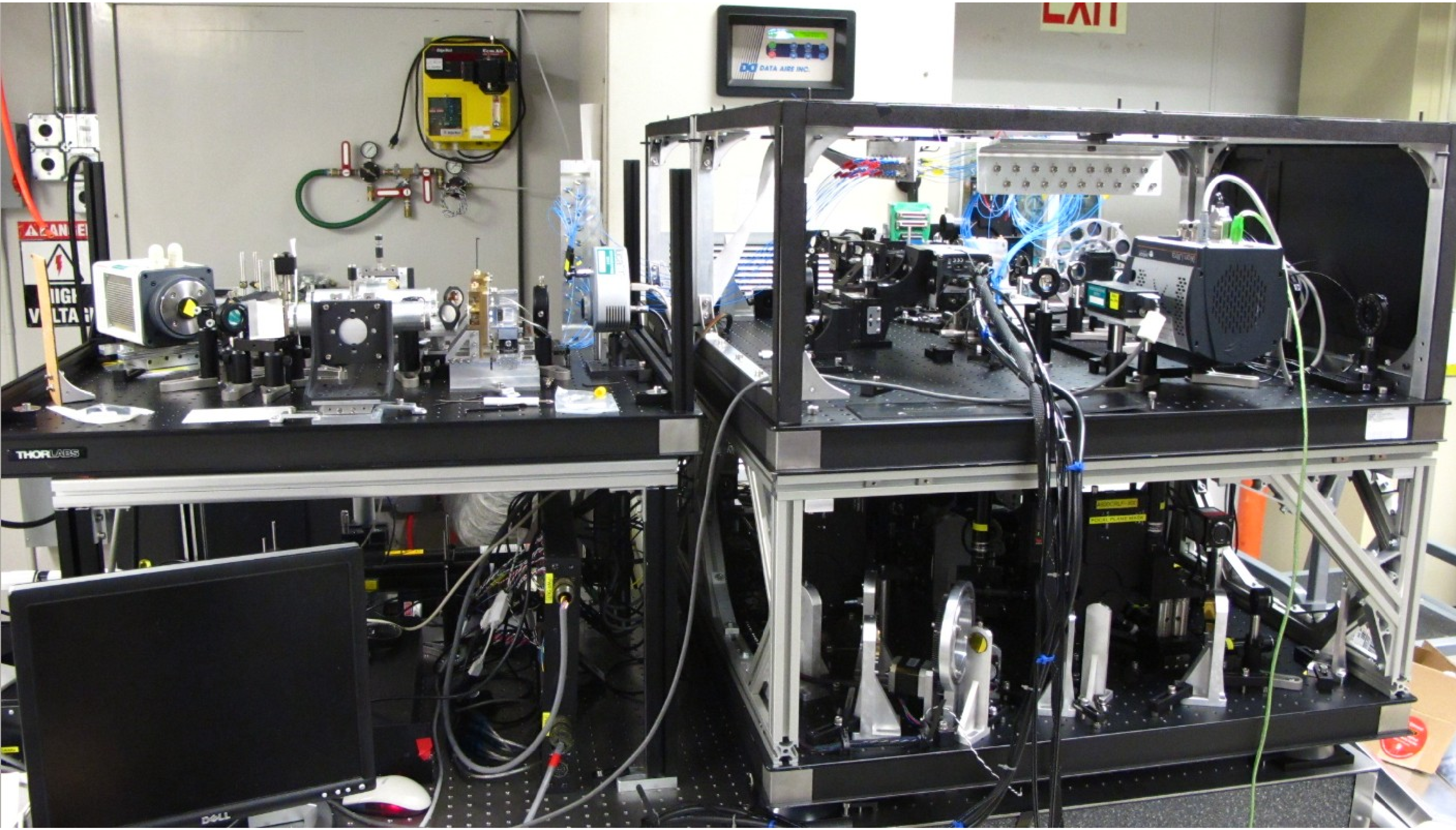


2048-actuator MEMS (Boston Micromachines) 20mm beam

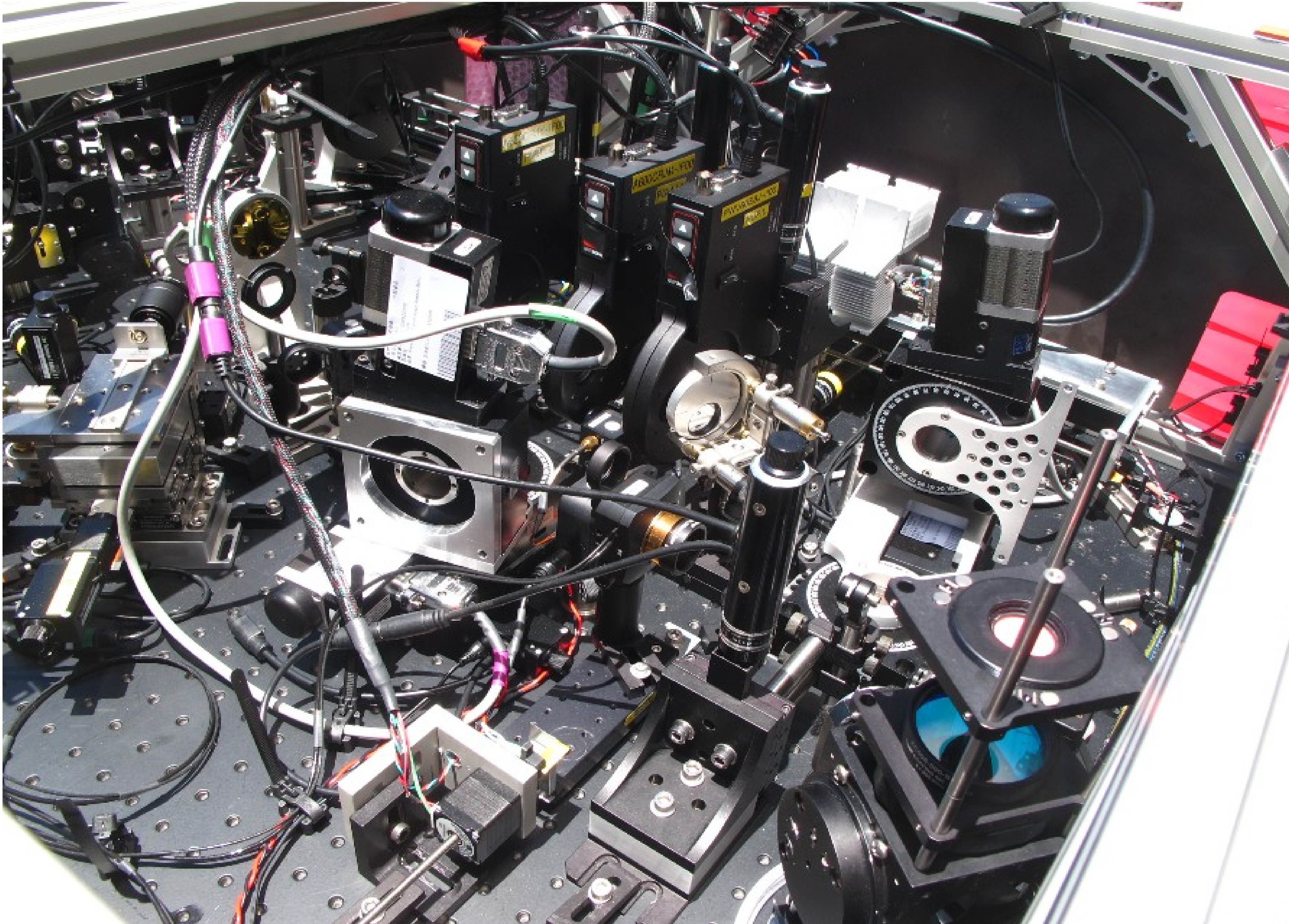
Segmented MEMS DM (IRIS-AO)



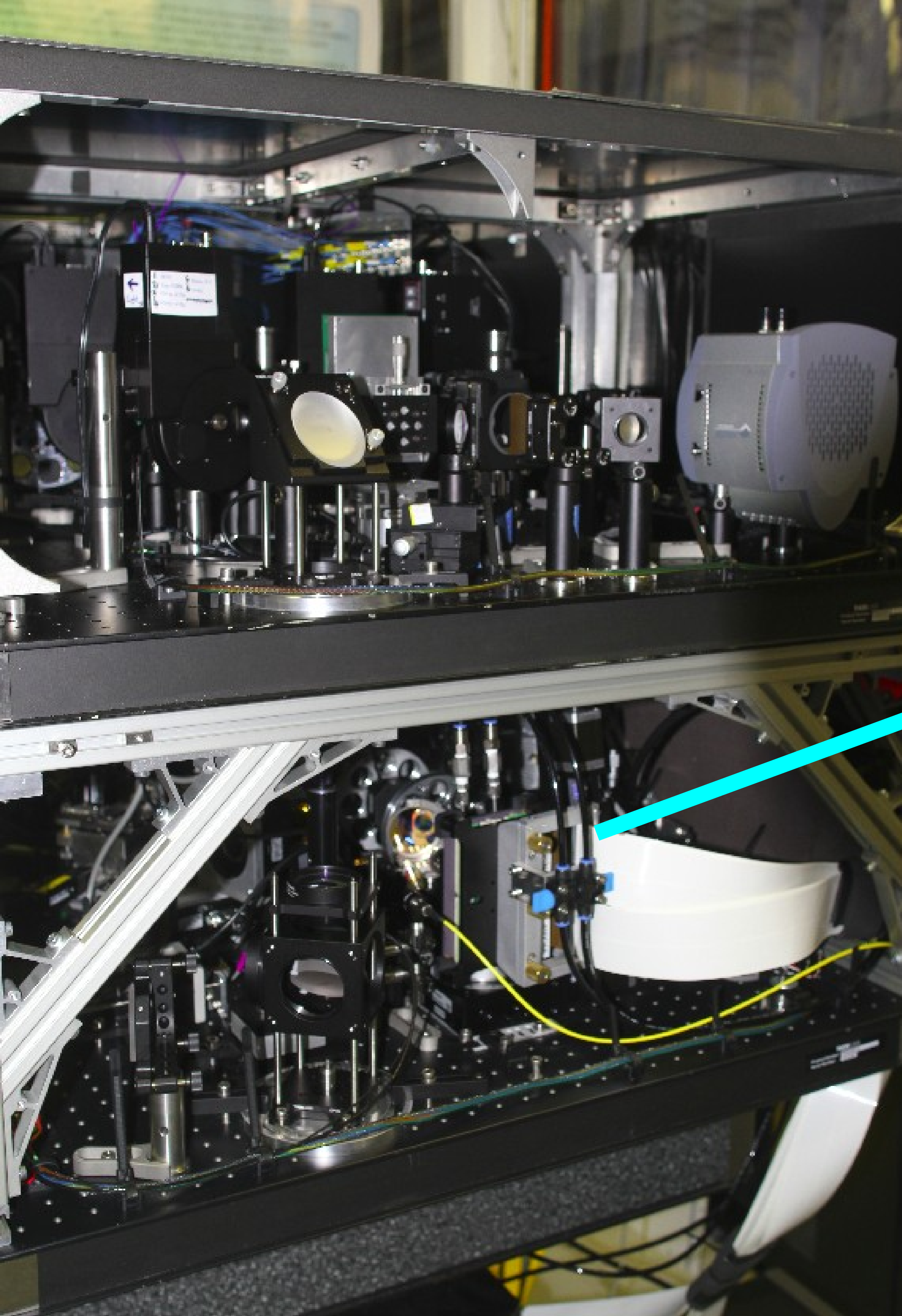
# Subaru Coronagraphic Extreme-AO (SCExAO) system
(July 10 2013)

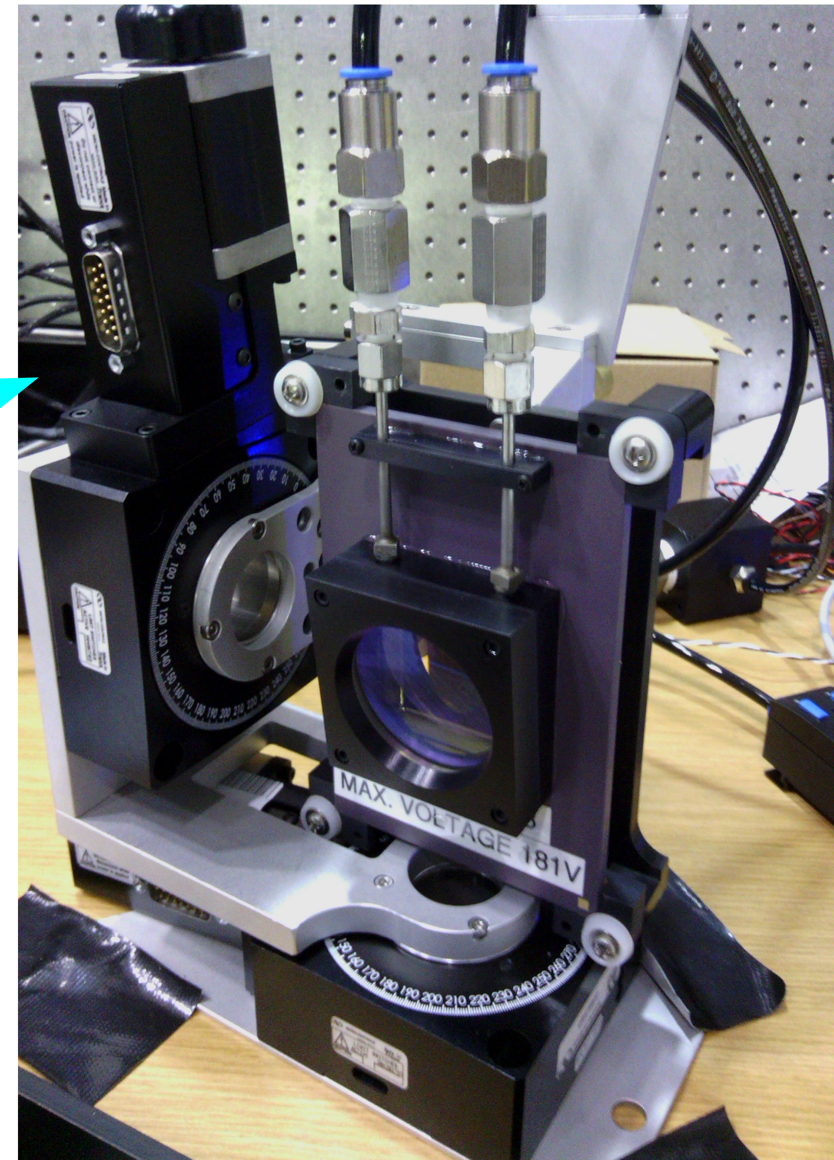


# Detail (PIAA optics)



**2048 actuator MEMS (Boston Micromachines) mounted on Tip-Tilt stage**





## DM dry air supply ensures that MEMS is never powered if humidity >~10%

Very small air flow to MEMS chamber

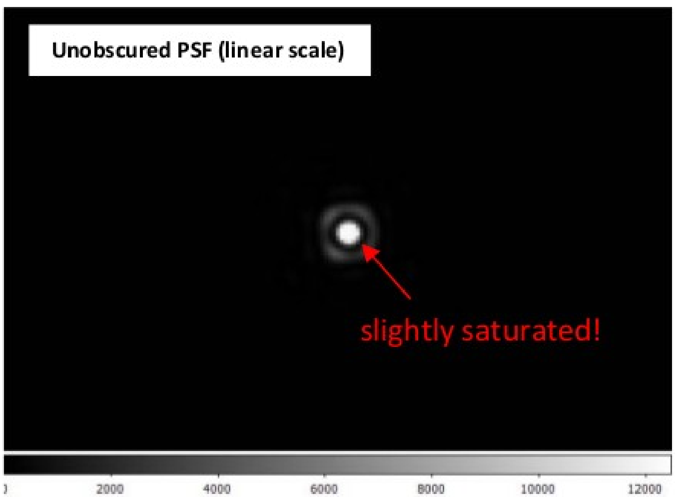
Pressure sensor on output (post MEMS) detects leaks or hose disconnect → interlock to DM power

Humidity sensor → interlock to DM power

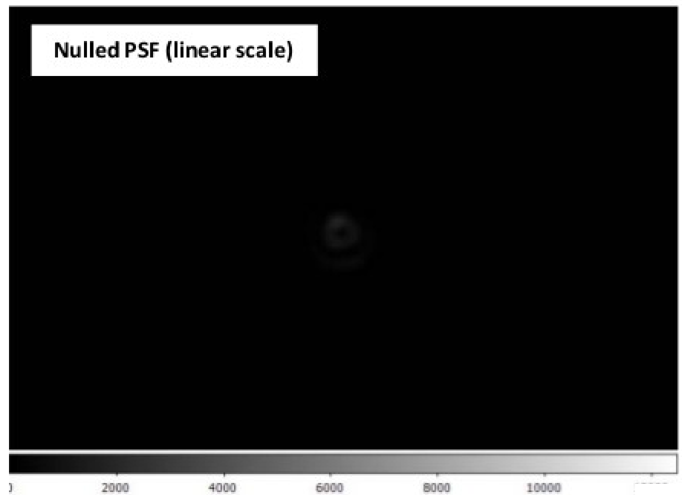
DM electronics

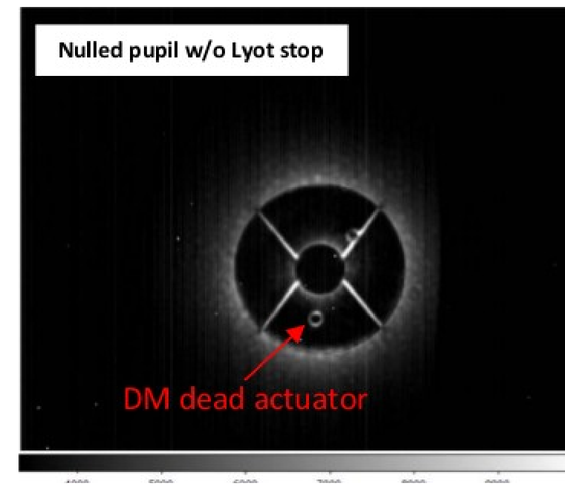
# Example coronagraph image with 2048 actuator MEMS

Vortex-out




Vortex-in



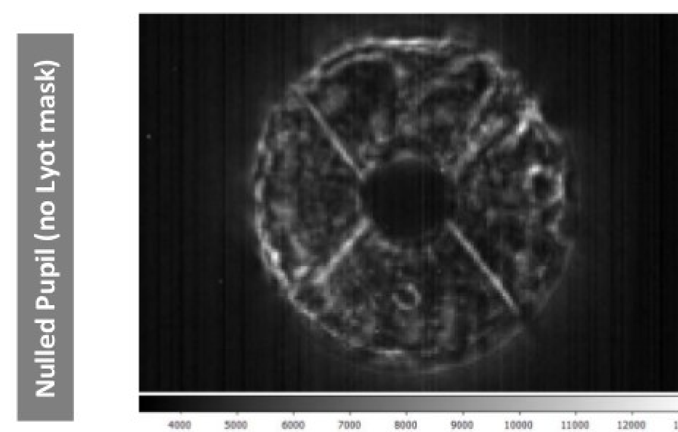




Pupil plane

One defective actuator in telescope pupil → can be mitigated by coronagraph design

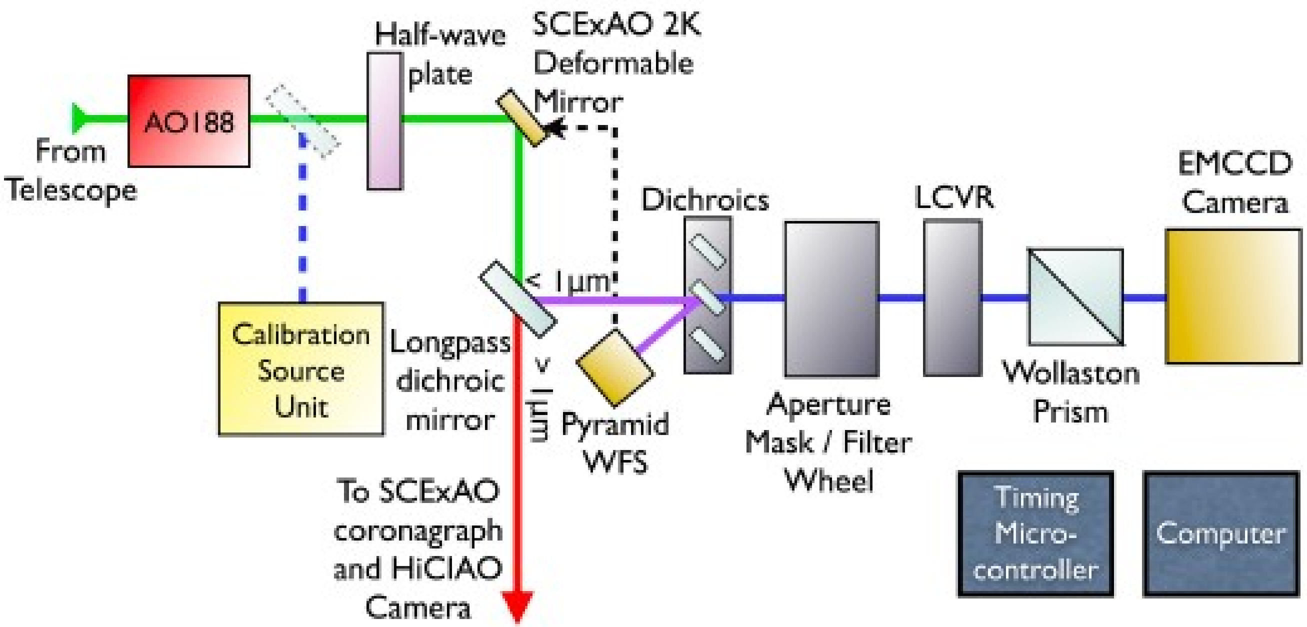
Vortex coronagraph lead: G. Serabyn (JPL)

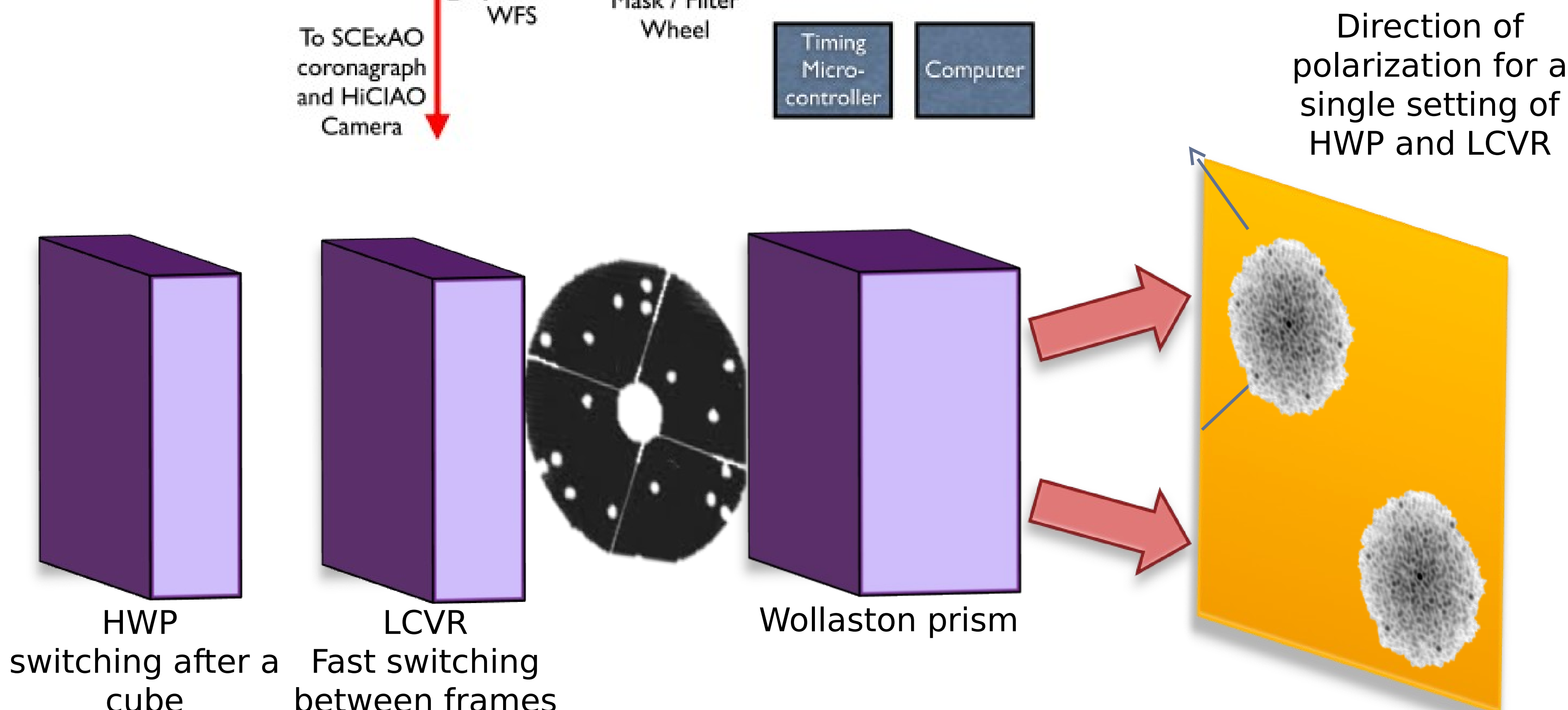
On sky →



# VAMPIRES (Univ. of Sydney)

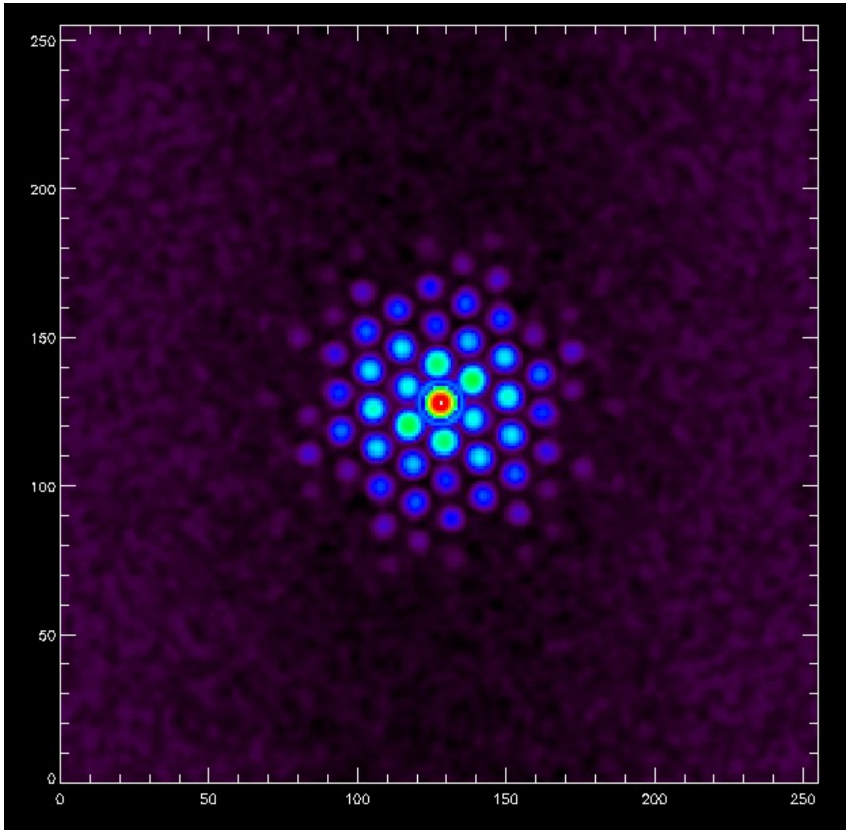
- Aperture masking interferometry for imaging *<1λ/D*
- 3 levels of polarization control in the visible
- Builds on work with NACO at VLT



# Chi Cyg diameter

No polarised structure detected around
chi cyg. However (unpolarised) diameter still measured:




Chi Cyg Power spectrum (log scale)
Note fall-off in power at longer BLs,
since object is resolved.

VAMPIRES Measurement
(U.D. Diameter):

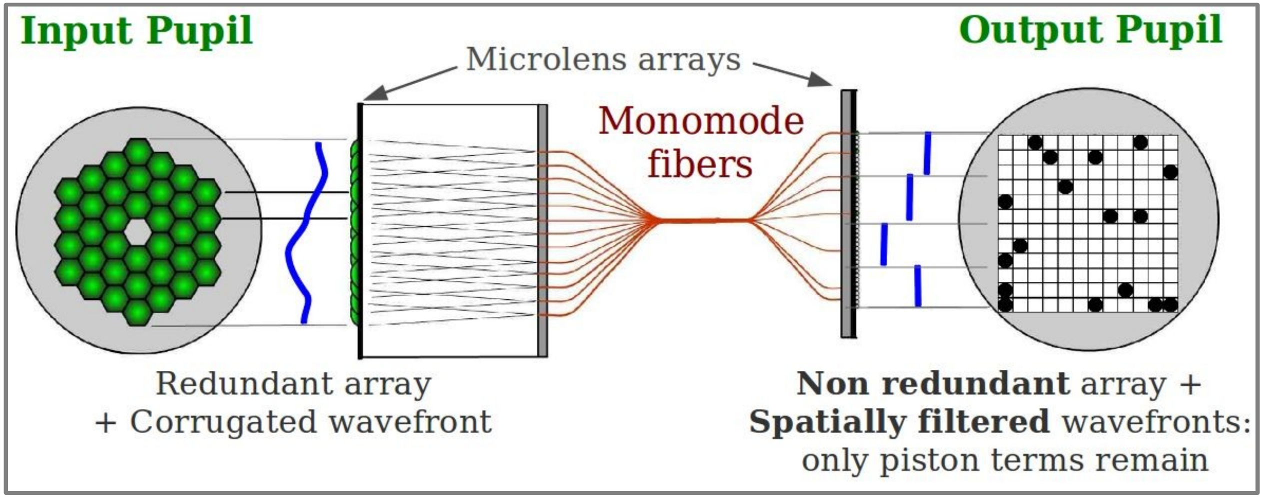
**32.2 ± 0.13 mas** (750 nm)

Literature Values
(U.D. Diameter):

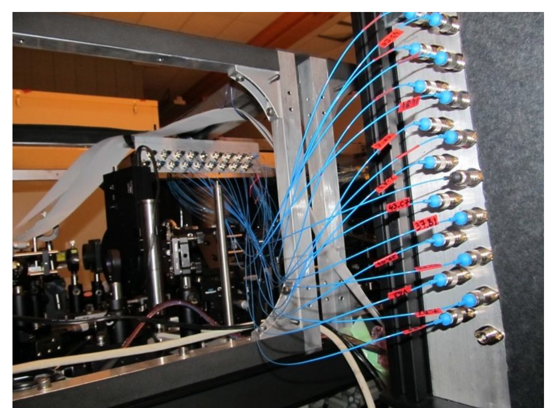
32.8 ± 4.10 mas (V band)

CHARM Catalogue, Richichi et al. 2005

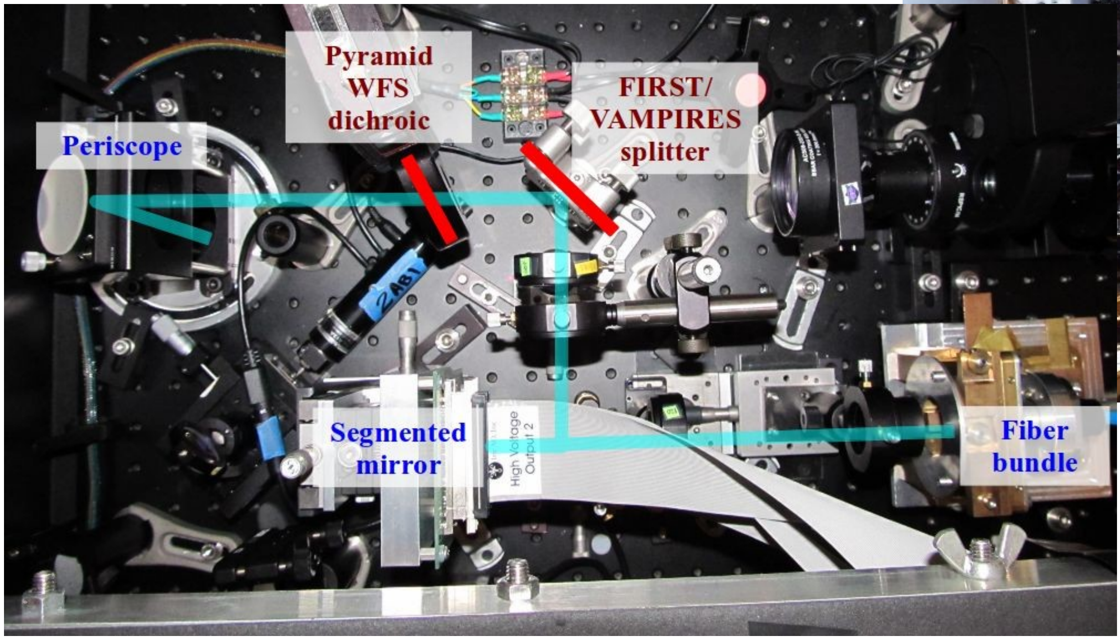
# FIRST module on SCExAO visible bench



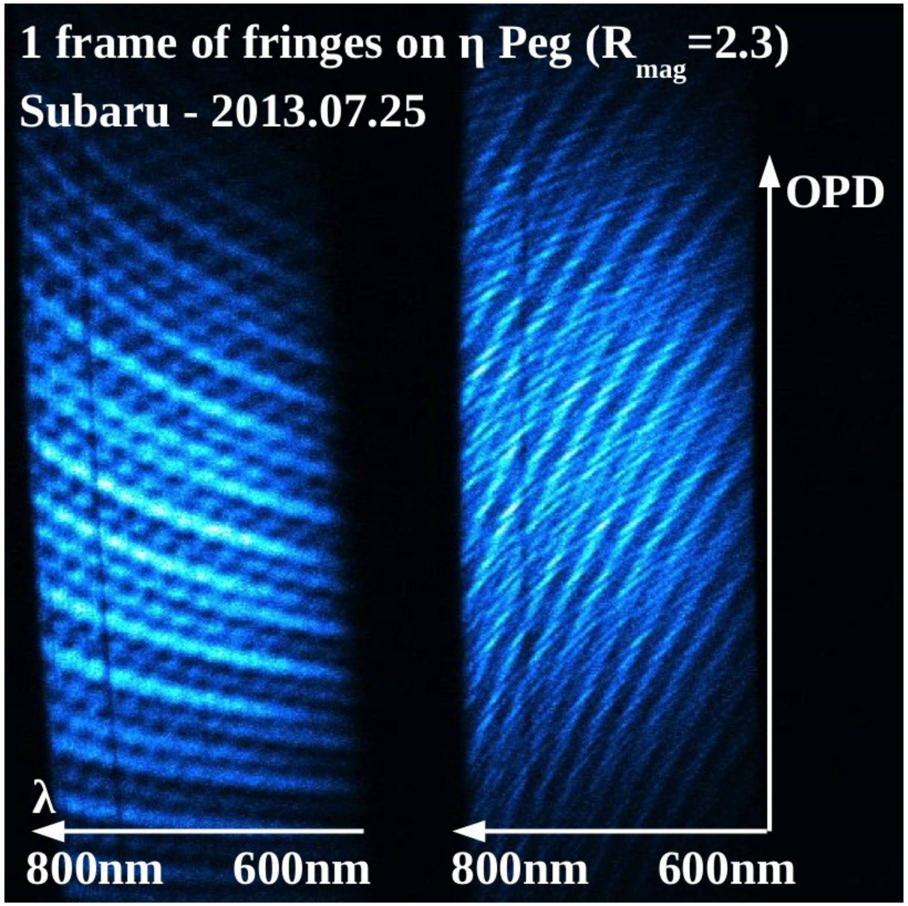

## FIRST recombination bench

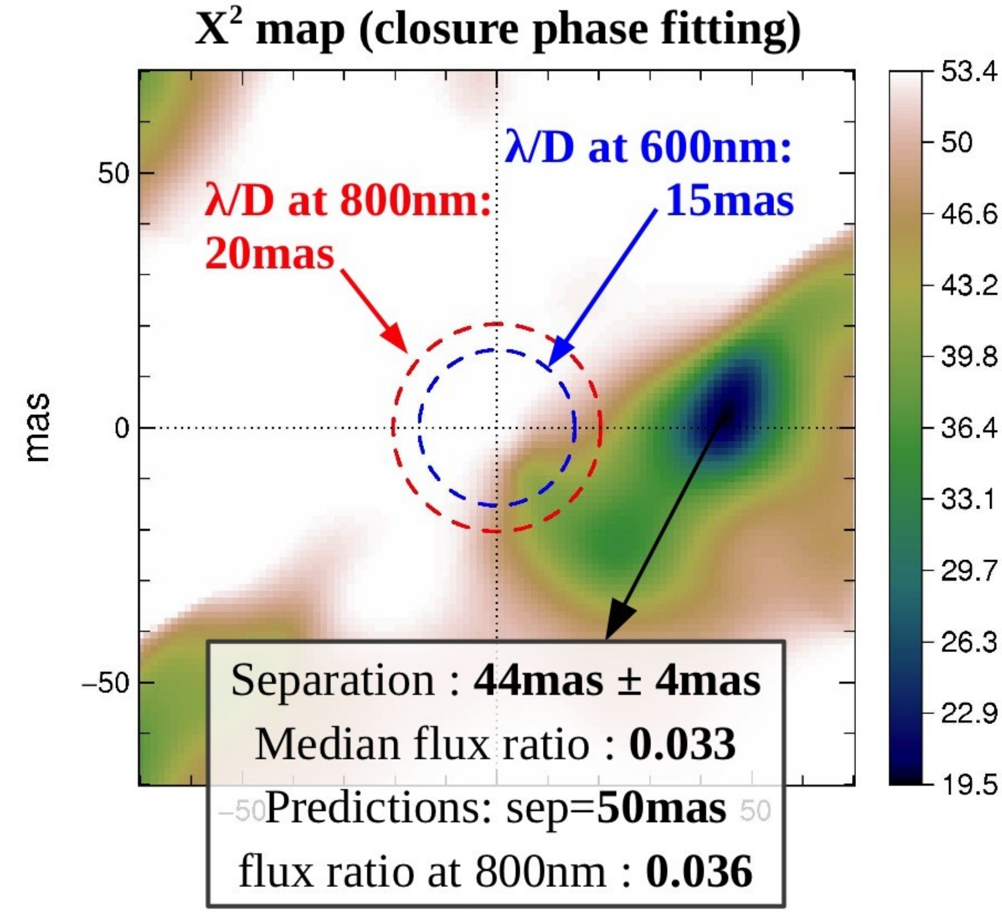



## FIRST injection part



# η Pegasi: Preliminary results




**Achievements at Lick Observatory (3m)**

η Peg : Sep ~ **λ/D** ; **Δm=3.6** at 800nm

(+ other binaries : β CrB, χ Dra, β Peg)

Median CP statistical error : **1.5°**

Median CP systematic error : **1.7°**

Sensitivity limit : $\mathbf{R_{mag} < 3.5}$

**Preliminary analysis of Subaru data taken on July 25th 2013**

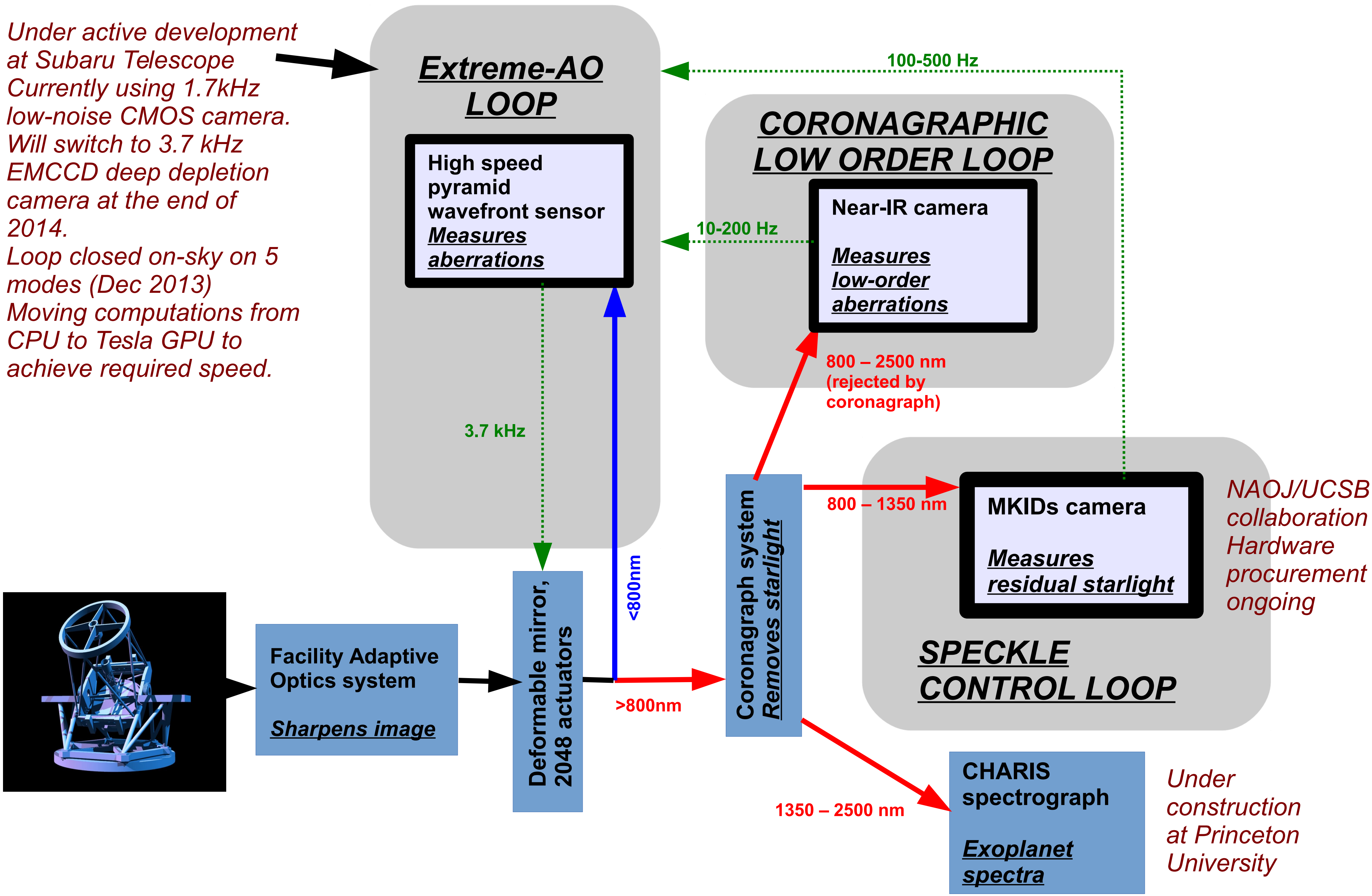
Median CP statistical error : **0.8°**

Median CP systematic error : **1.0°**

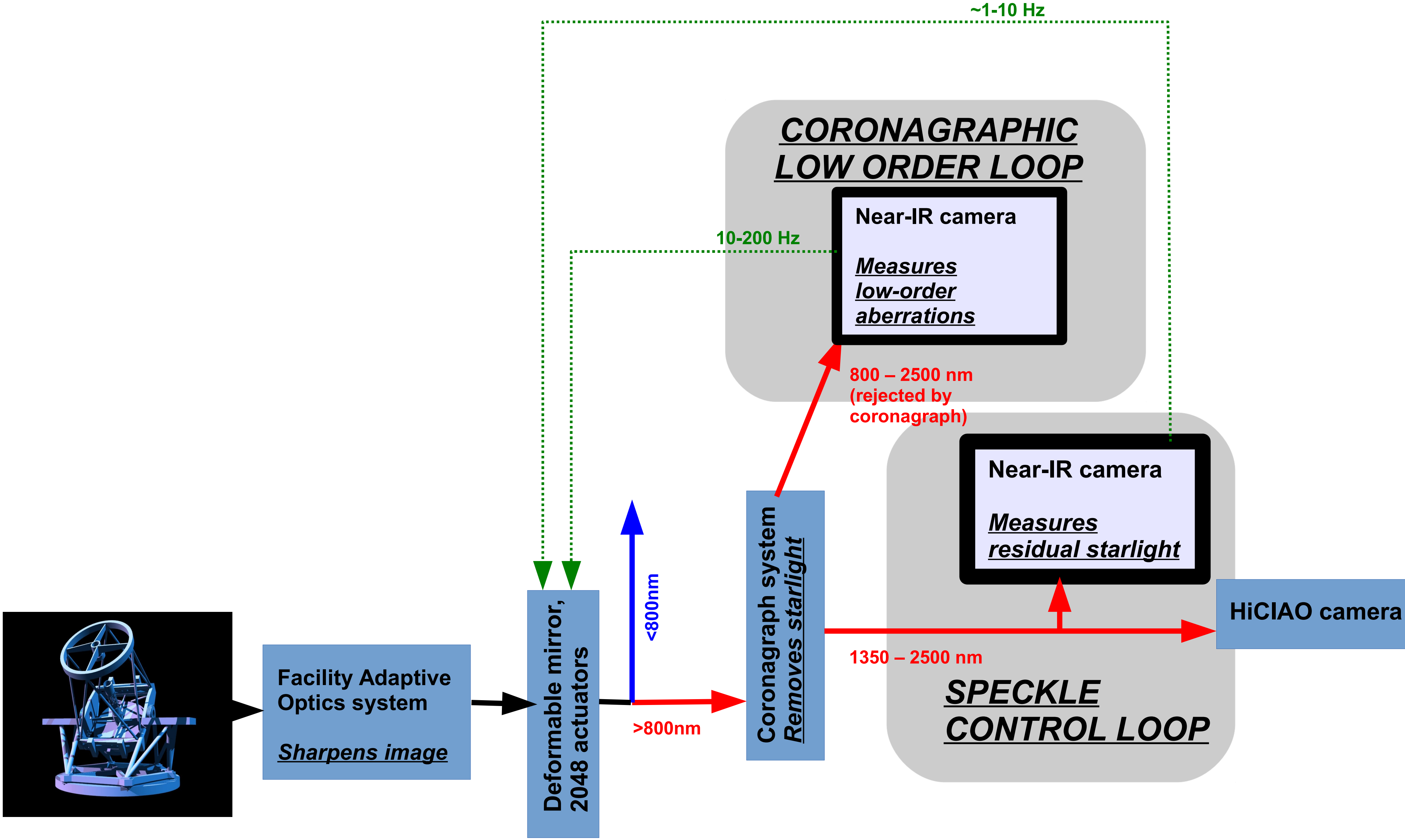
**→ detection limit (4σ) : 240 at λ/D**

Sensitivity limit : $\mathbf{R_{mag} < 4.5}$

# Wavefront control architecture (under construction)



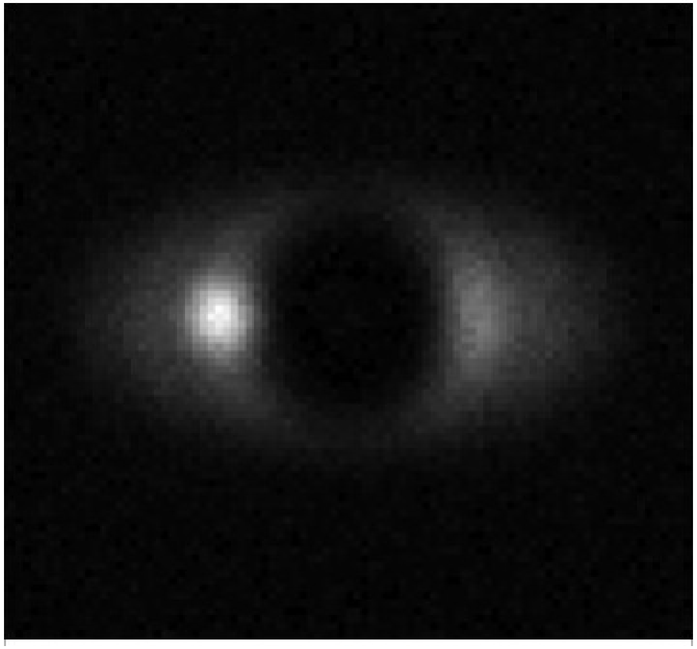
# Current on-sky wavefront control status

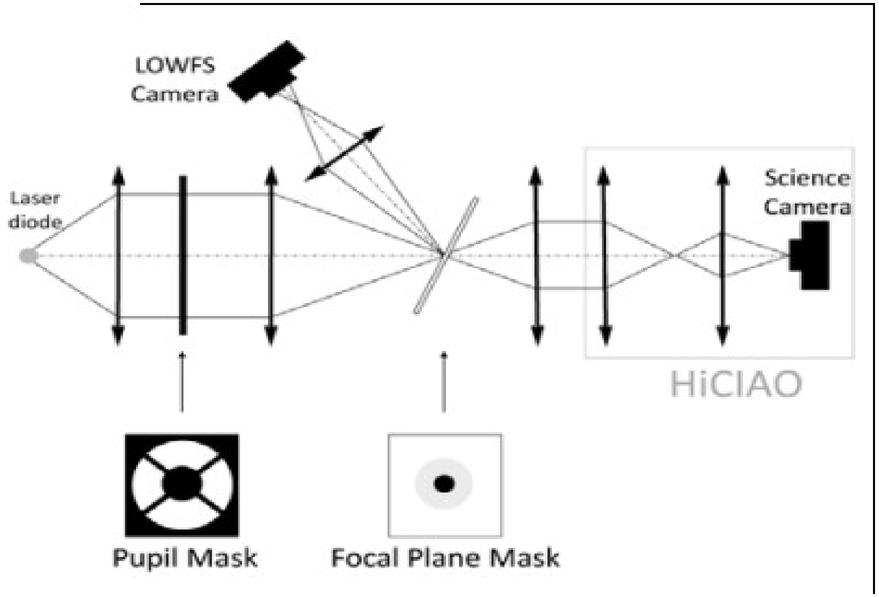


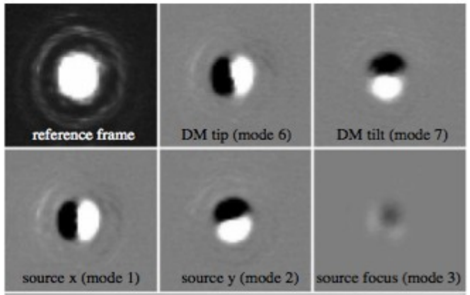
# Low-order WFC

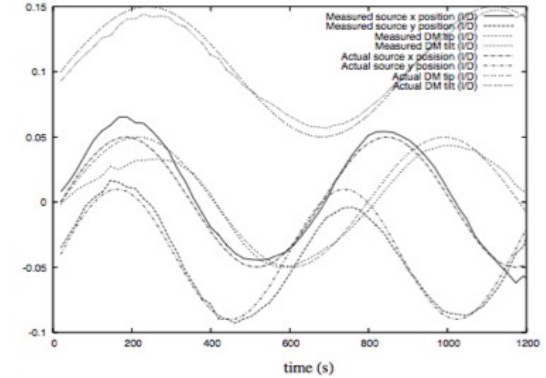
**Problem**: planets at small separation look very similar to pointing error signature

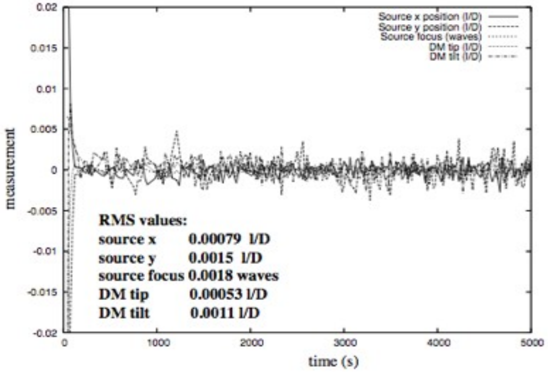
- **Solution**: measure real-time pointing inside coronagraph using starlight, for both correction and calibration

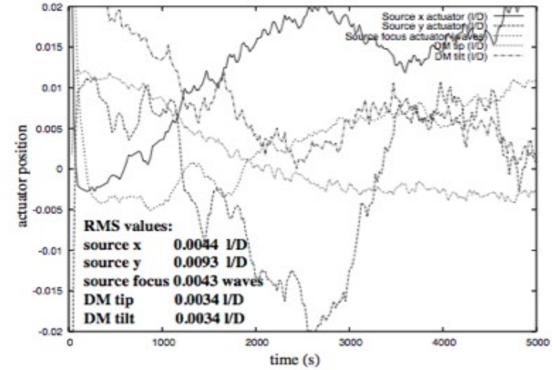




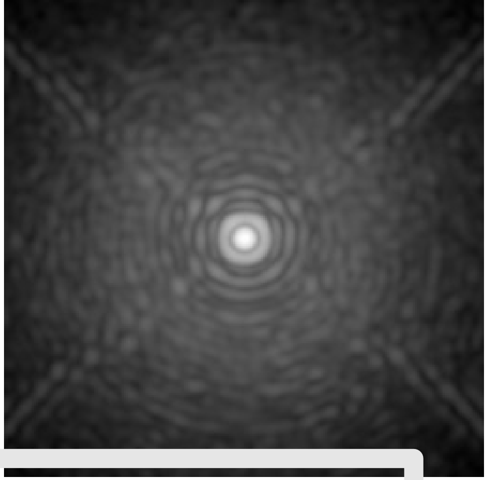



# Focal plane speckle control



***"It is much easier to break something in a way you understand than to fix something you don't understand"***

Use Deformable Mirror (DM) to add speckles

**SENSING**: Put "test speckles" to measure speckles in the image, watch how they interfere

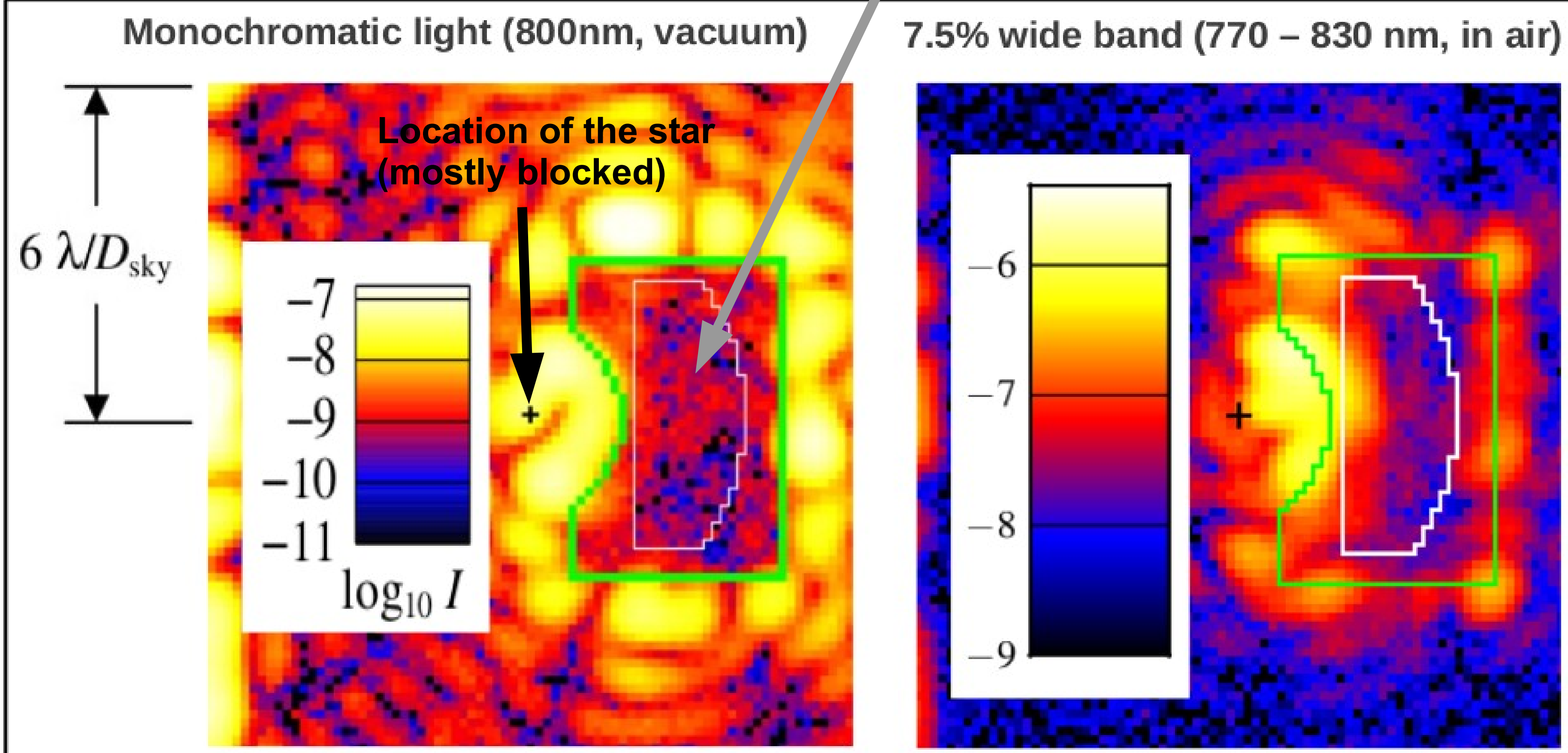
**CORRECTION**: Put "anti speckles" on top of "speckles" to have destructive interference between the two (Electric Field Conjugation, Give'on et al 2007)

**CALIBRATION**: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing:
"What you see is EXACTLY what needs to be removed / calibrated"

# PIAA testbed at NASA JPL : lab results (B. Kern, O. Guyon, A. Kuhnert et al.)

An Earth-like planets could be seen !

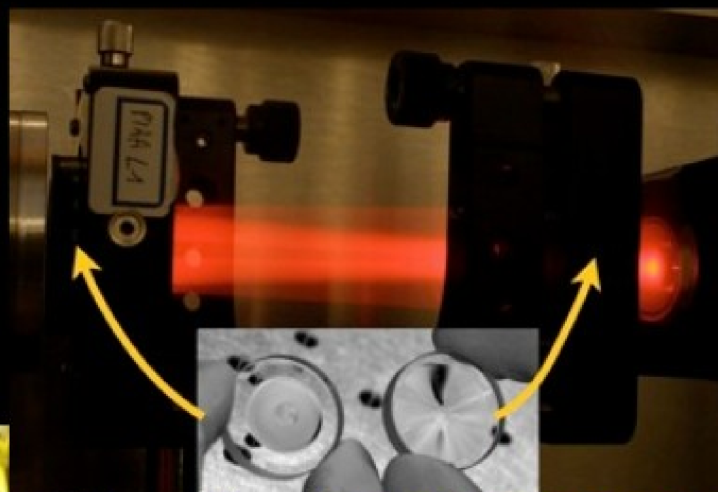



3 runs, contrast values averaged from 2 to 4 λ/D between $5.10^{-10}$ to $9.10^{-10}$ (figure shows $7.3.10^{-10}$ result)

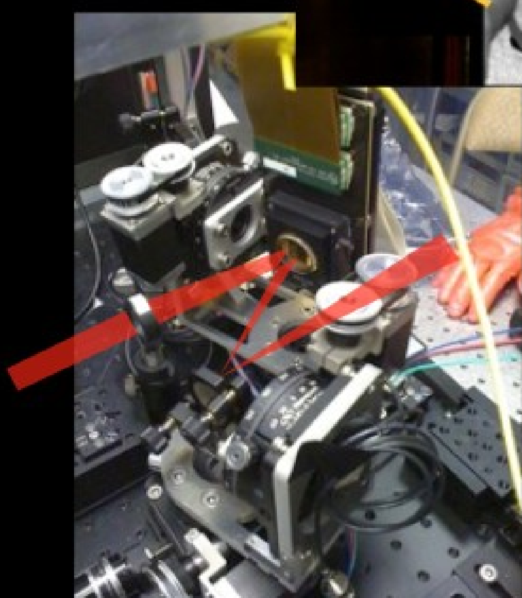
$5.10^{-8}$ contrast from 2 to 4 λ/D,
$2.10^{-8}$ contrast from 3 to 4 λ/D
Contrast performance limited by wavefront instability (test in air)

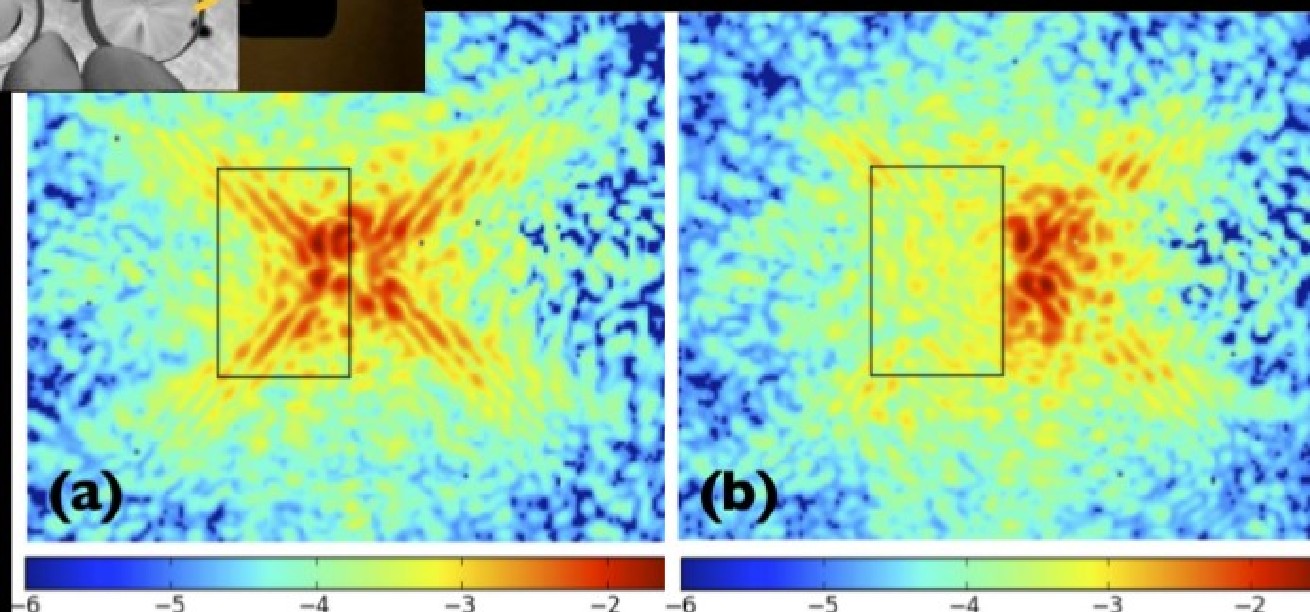
# Active speckle control

Active MEMS DM to replace a passive ADI approach at small angular separation



Taking advantage of the full PIAA - focal plane mask - PIAA$^{-1}$ optical configuration






SCExAO's PIAA coronagraph permits speckle control from 1.5 to 14 λ/D

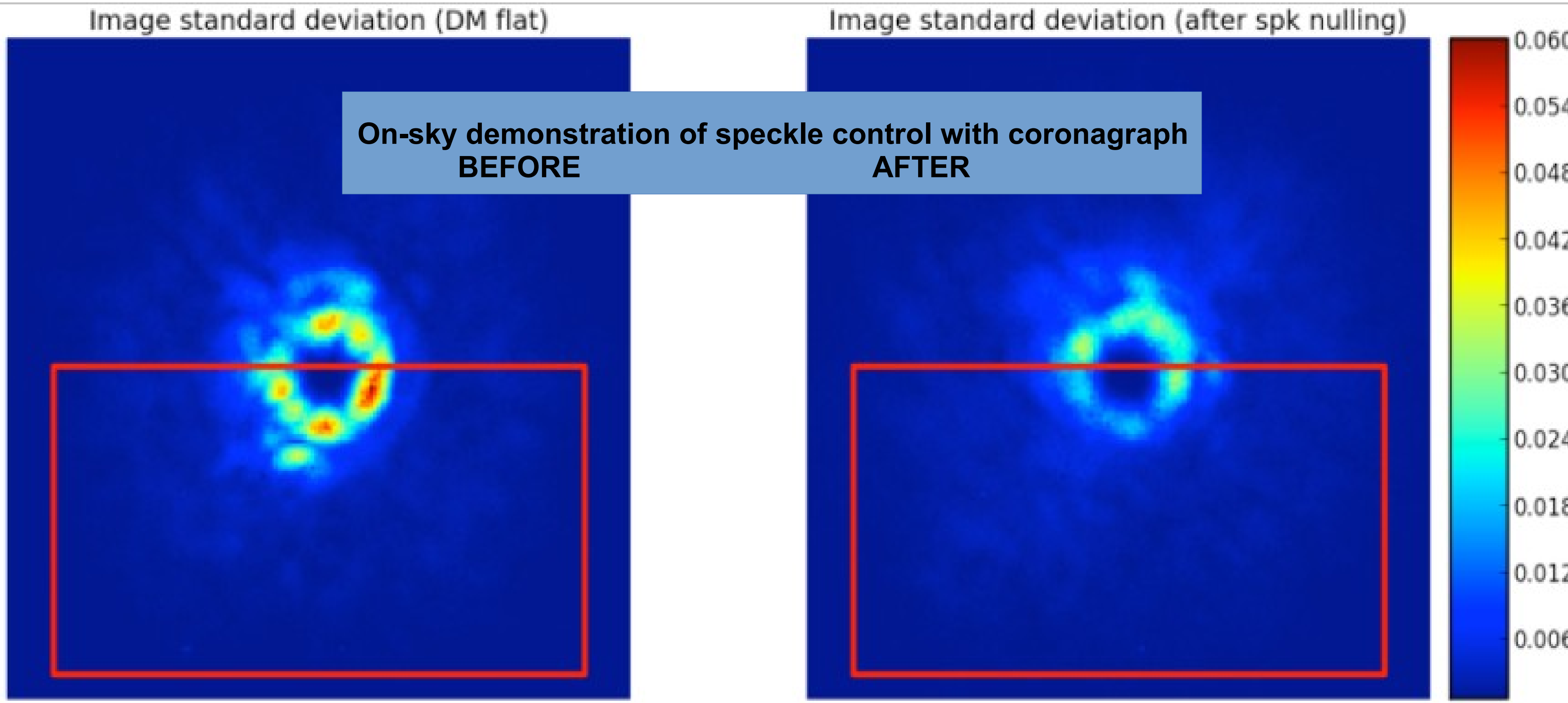
Raw contrast ~ 3e-4 inside the DM control region

*Martinache et al, 2012, PASP, 124, 1288*

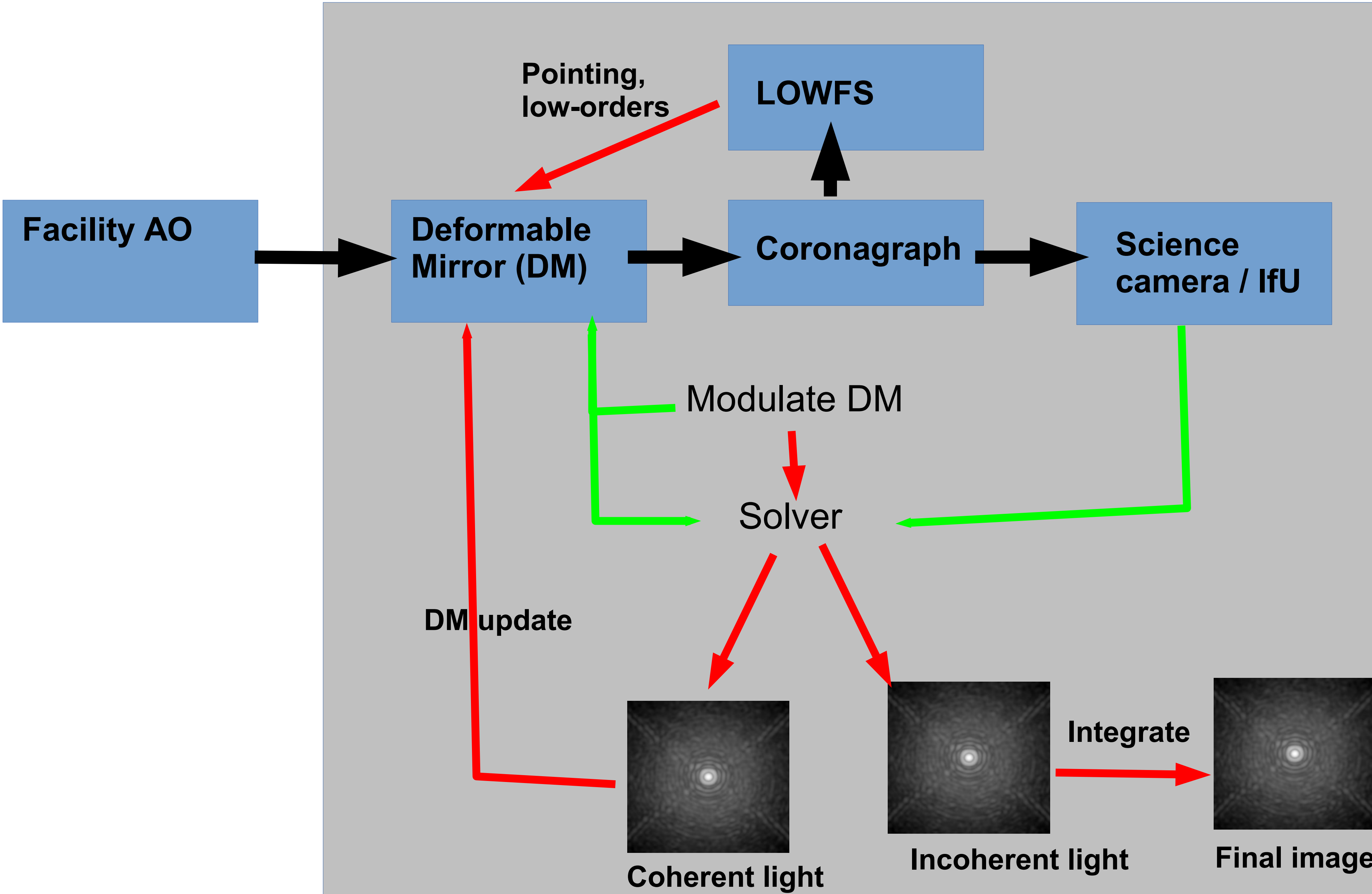
# Using a deformable mirror to measure and control focal plane speckles: on-sky demonstration with SCExAO

SCExAO used a kilo-DM to modulate, control and cancel speckles to detect exoplanets

(Martinache 2012 - 2014)



# System architecture



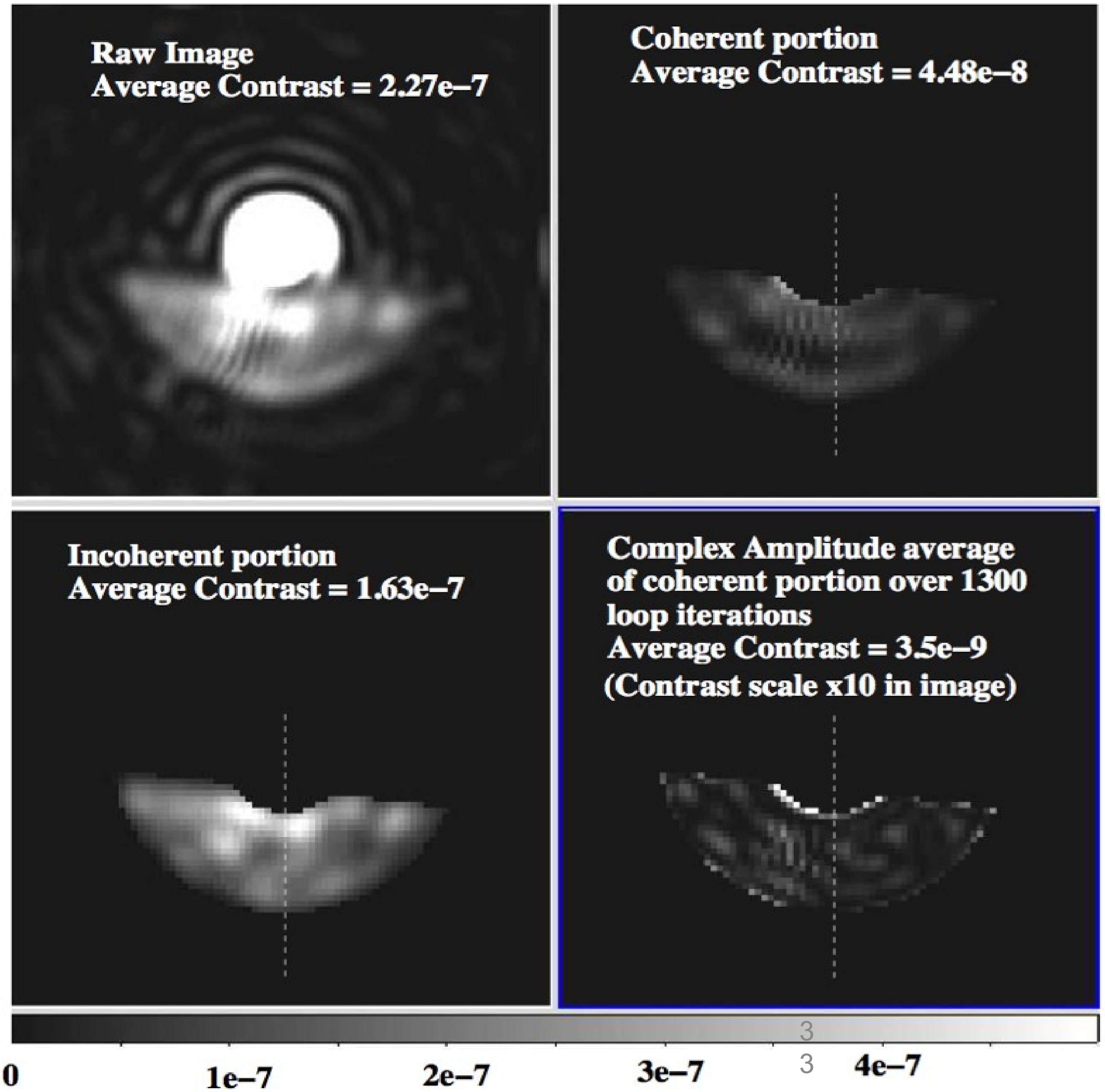
# Focal plane WFS based correction and speckle calibration

2e-7 raw contrast obtained at 2 λ/D

Incoherent light at 1e-7
Coherent fast light at 5e-8
Coherent bias <3.5e-9

Test demonstrates:
- ability to separate light into coherent/incoherent fast/slow components
- ability to slow and static remove speckles well below the dynamic speckle halo

*Guyon et al. 2010*



# Speed vs performance:
# ~100 Hz frame rate would achieve significant gain

**Static and slow speckles (due to optics) calibrated with low speed**

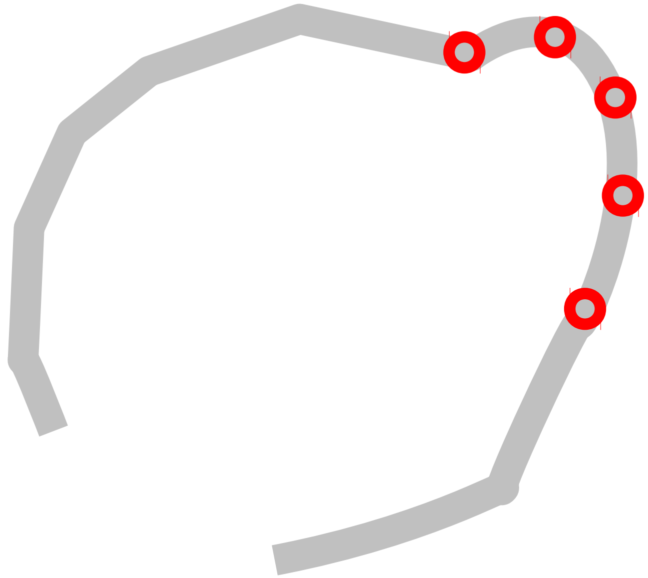
**Chromaticity, Time lag (& to some degree aliasing) timescale:**

**Intensity : crossing time D/v ~ few sec**

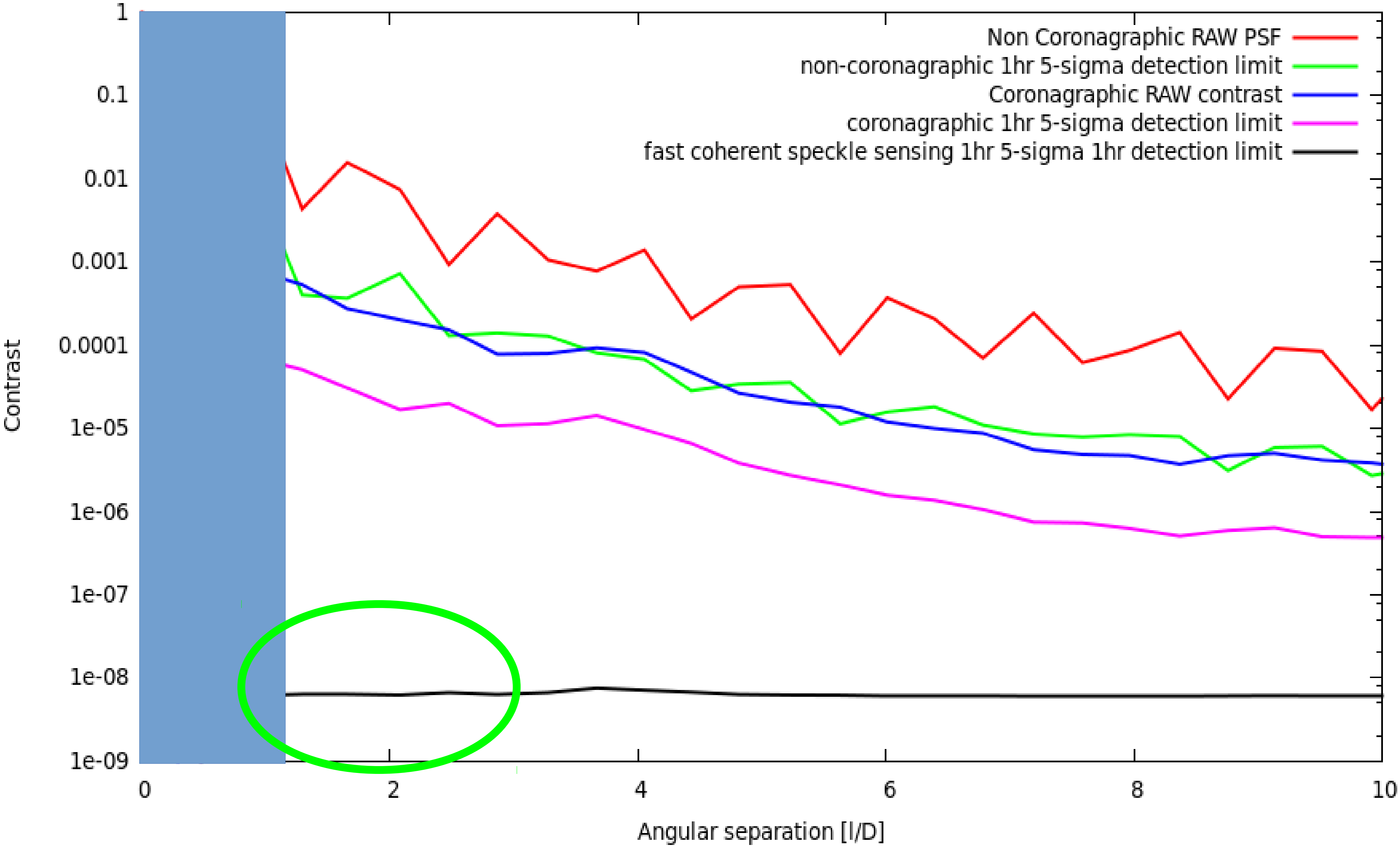
**Complex amplitude : D / (2 π α v) < crossing time**

**(α = separation in λ/D)**

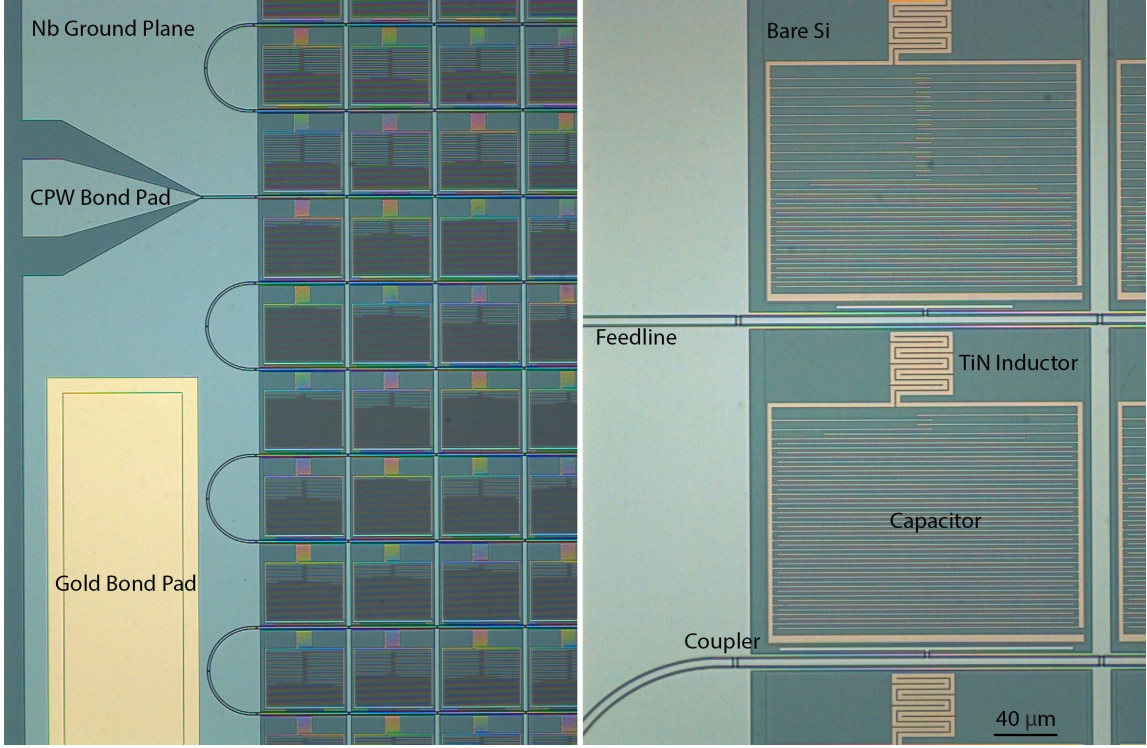
**ATTENUATION = π dt v α / D**



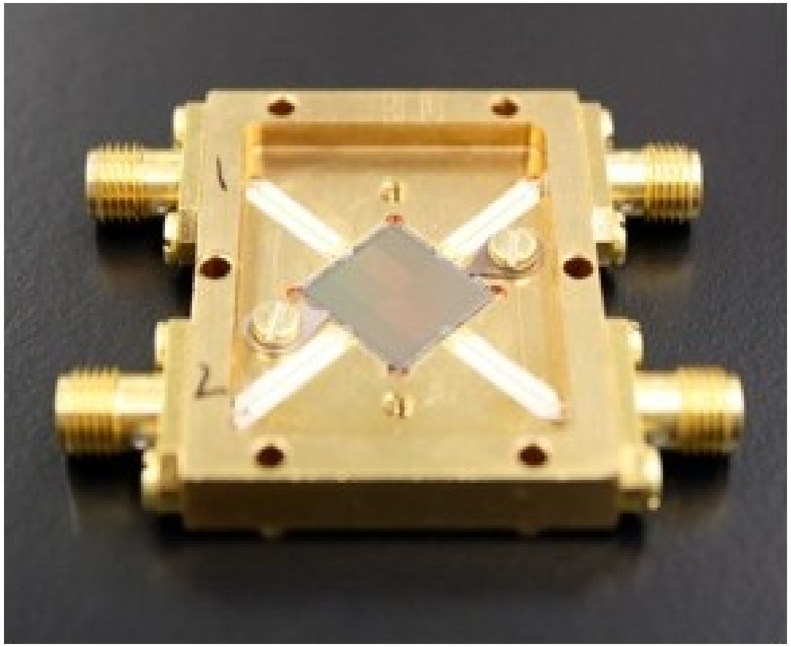
# Speed vs performance (no predictive control): ~100 Hz required for significant gain (photon noise excluded – bright star case)



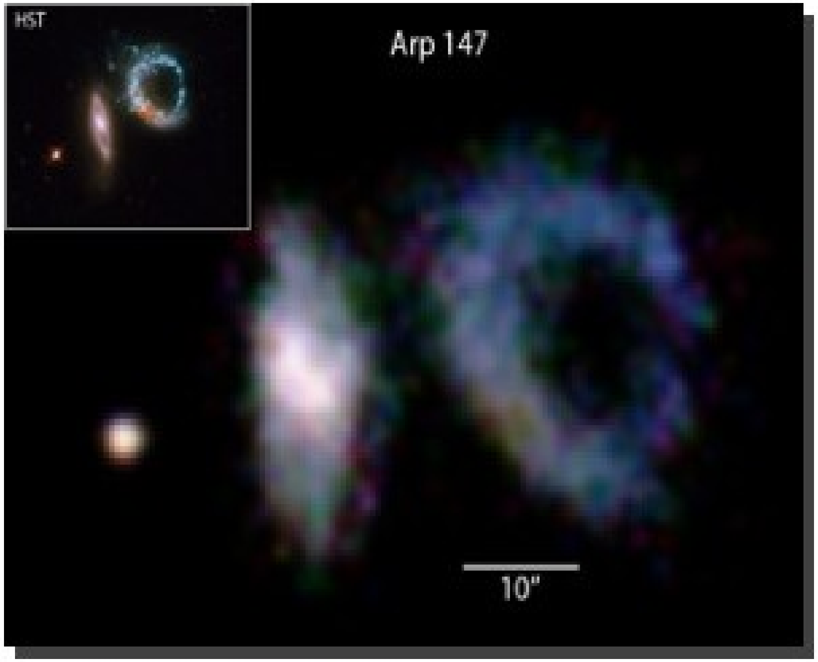
# MKIDs + MEMS for a smart focal plane high contrast camera (NAOJ / UCSB)




Enables photon-counting performance in near-IR, with energy resolution



**MKIDs detector**

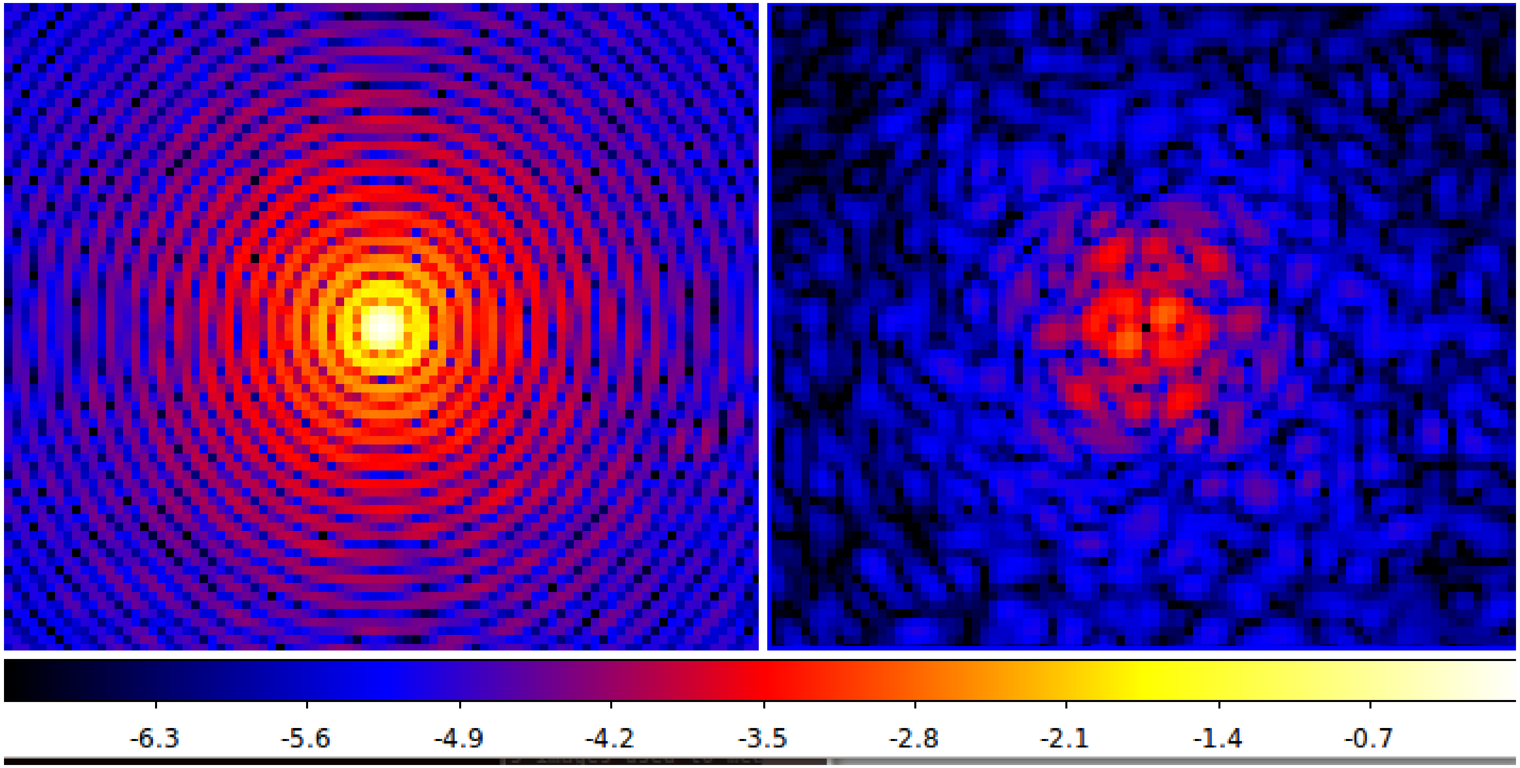



**MKIDs image @ Palomar**

# ELT simulated ExAO

**30m telescope, Sensing at 600nm, Imaging at 1600nm**

- **4 kHz loop speed + 200us delay, integrator, gain = 0.5**
- 1cm WF sampling, chromatic diffractive propagation through atmosphere computed at 4kHz, 100kHz internal frequency → 20 TB for 10 sec




**Without coronagraph** **With coronagraph**

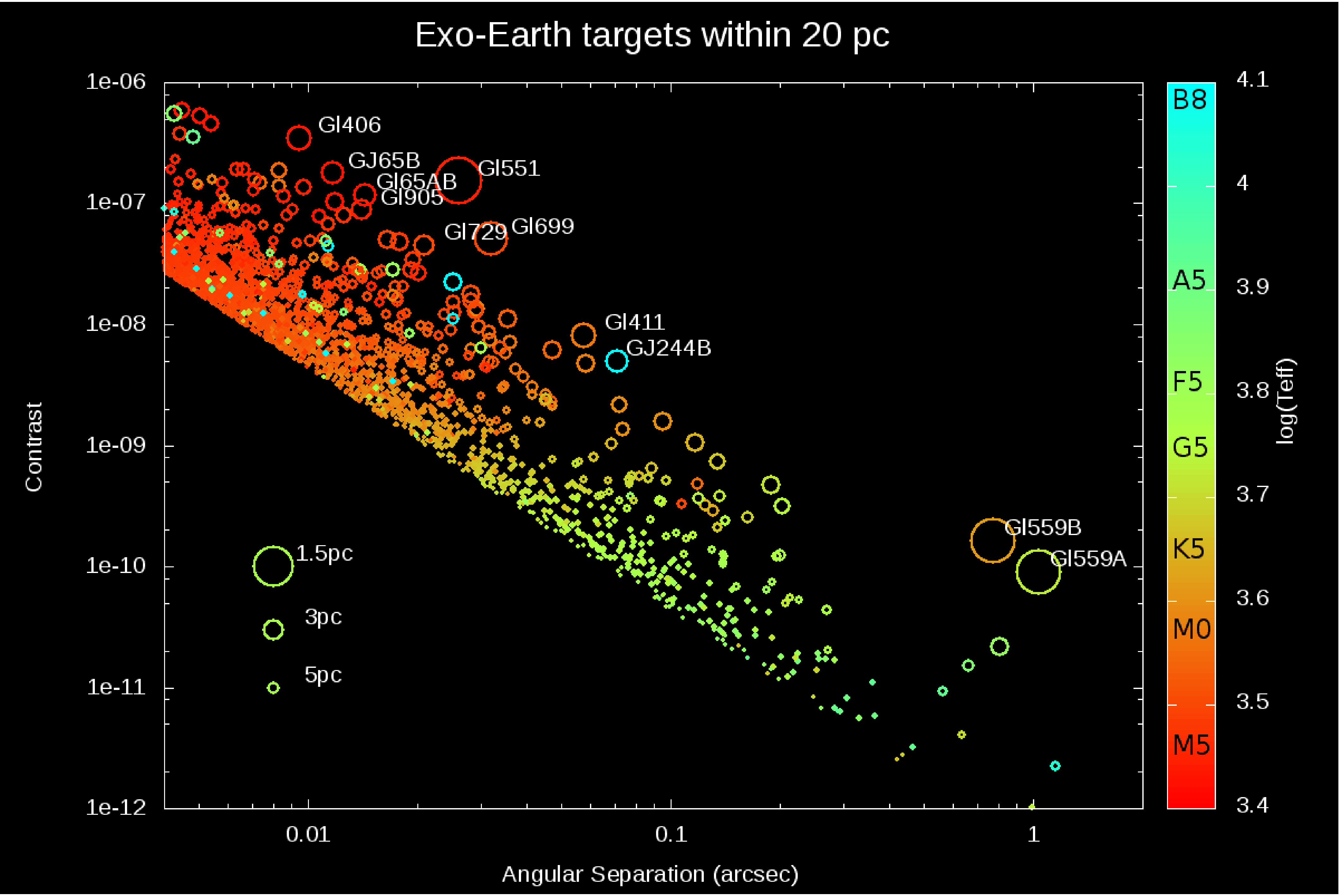
1e-4 speckles due to:

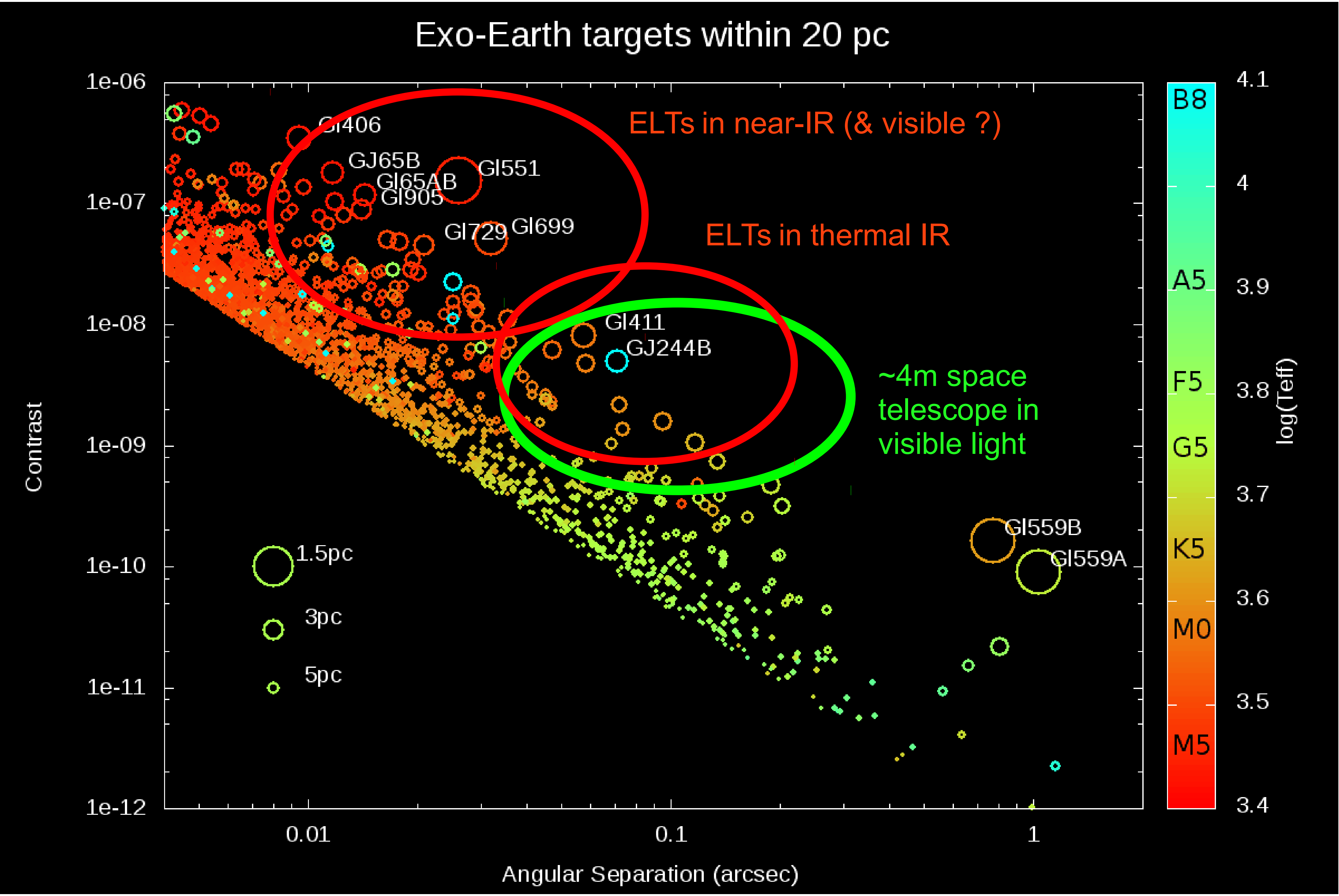
**Chromaticity**
→ WFS at longer wavelength

**Time lag**
→ predictive control

**Scintillation**

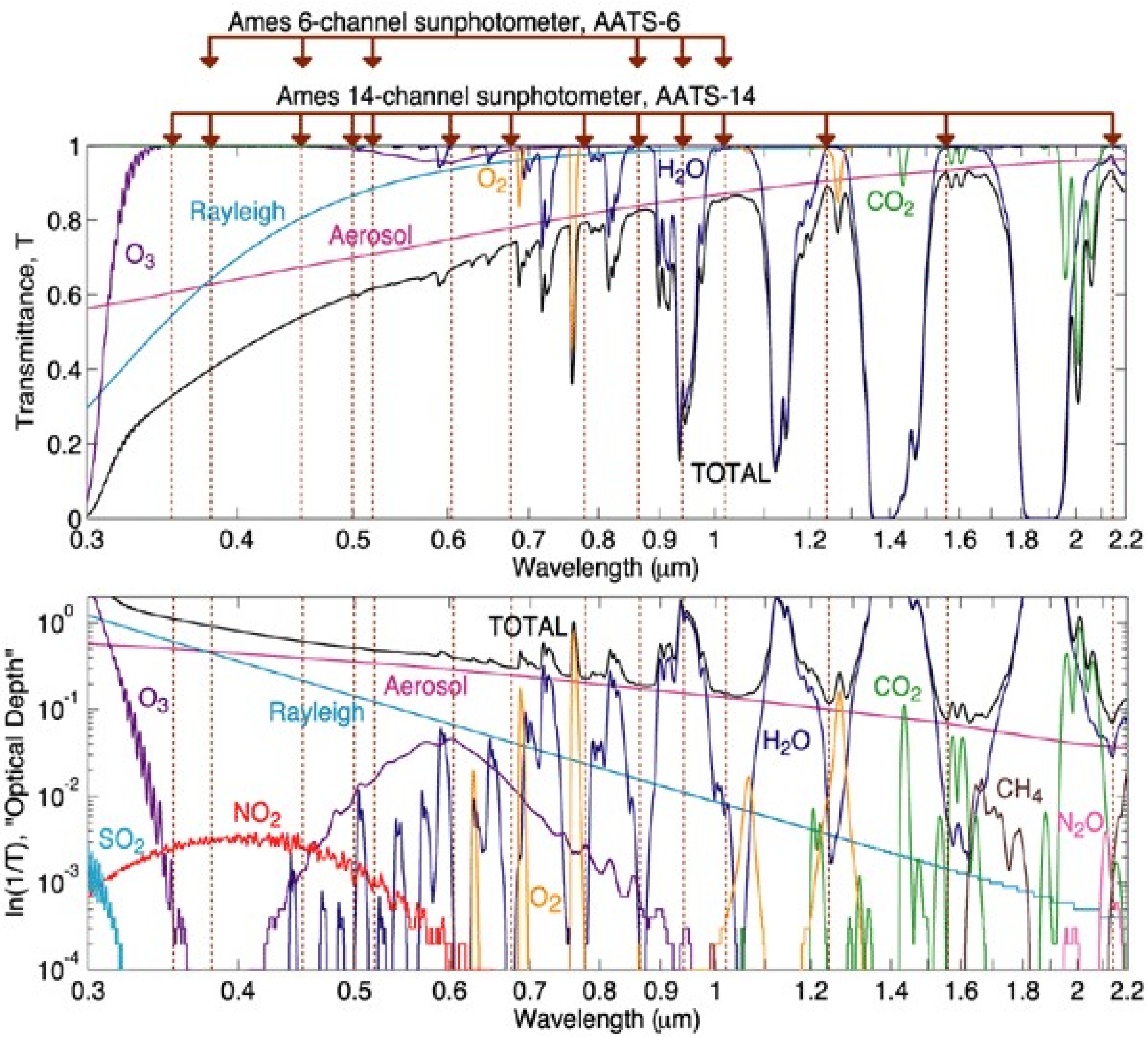
Catalogs: ***HIPPARCOS (revised), RECONS, 2MASS, CNS3, SUPERBLINK***





Exo-Earth targets within 20 pc
ELTs in near-IR (& visible ?)
ELTs in thermal IR
~4m space telescope in visible light
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
Contrast
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
0.01
0.1
1
Angular Separation (arcsec)
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9
3.8
3.7
3.6
3.5
3.4
log(Teff)

# Habitable Planets Spectroscopy in near-IR




Atmosphere transmission:
$O_2$ (see Kawara et al. 2012)
$H_2O$
$CO_2$
$CH_4$

Polarimetry

Cloud cover, variability
Rotation period

Reflectivity from ground in atmosphere transparency bands
(Ice cap, desert, ocean etc...)

# Conclusions

2048-actuators MEMS DM now part of SCExAO instrument, since July 2013 (replaces kilo-DM)

On-sky validation of:

- coronagraphic LOWFS using starlight rejected by coronagraph
- speckle control loop
- partial correction using Pyramid WFS
- FIRST instrument, fed by SCExAO
- VAMPIRES instrument, fed by SCExAO

Next steps:

Integrate Pyramid-based ExtremeAO loop

Upgrade Pyrmid WFS camera to 3.7kHz deep depletion EMCCD

Integrate SCExAO with CHARIS spectrograph

Upgrade speckle-sensing camera to photon-counting energy resolving MKIDs camera

Lots of software and algorithms...

**Combination of MEMS + fast low noise focal plane camera is extremely powerful**

**SCExAO is a powerful precursor to direct imaging of habitable planet around M-type stars with ELTs**