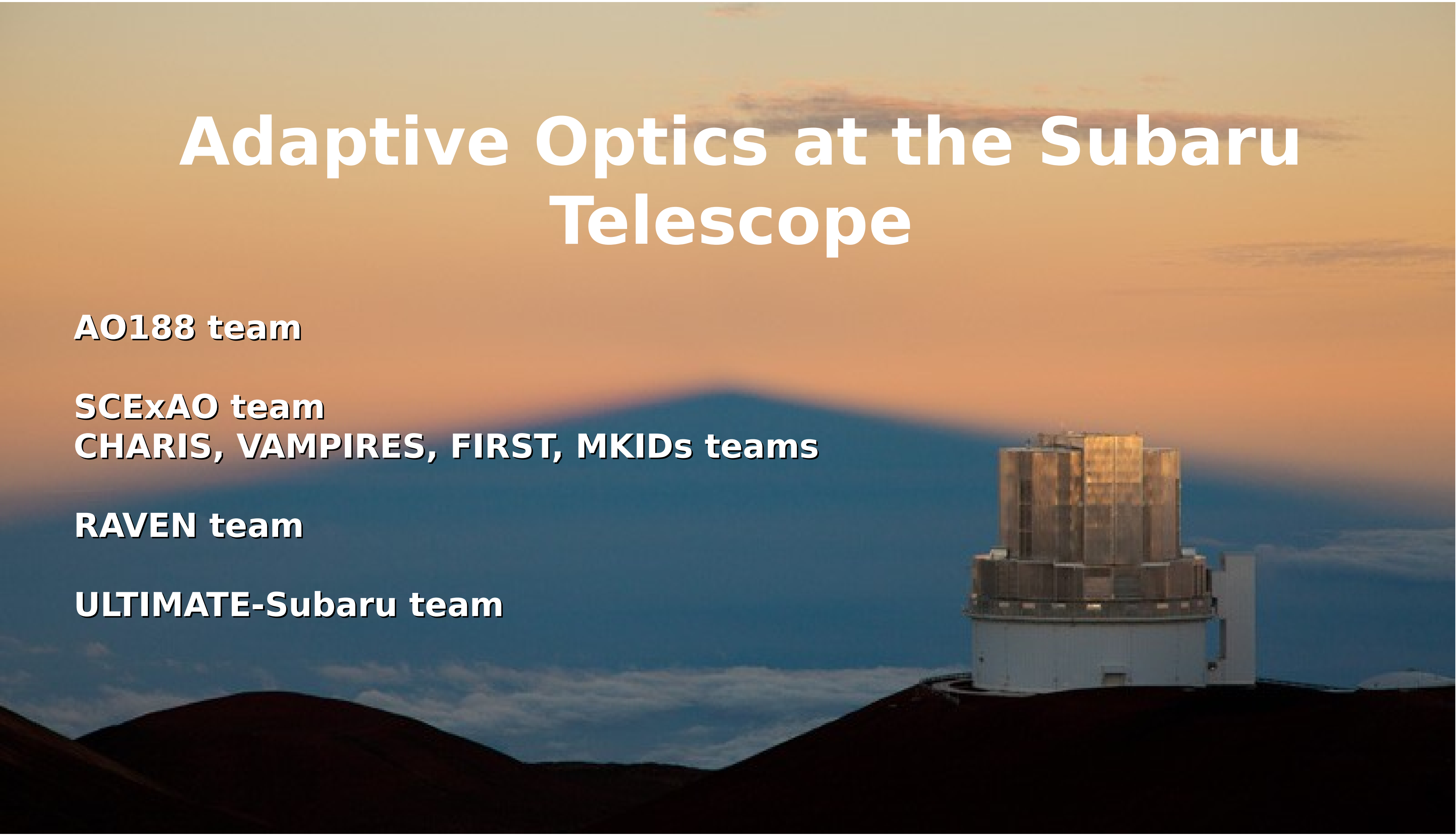
Adaptive Optics at the Subaru Telescope

AO188 team

SCExAO team
CHARIS, VAMPIRES, FIRST, MKIDs teams

RAVEN team

ULTIMATE-Subaru team



Subaru Instrumentation overview

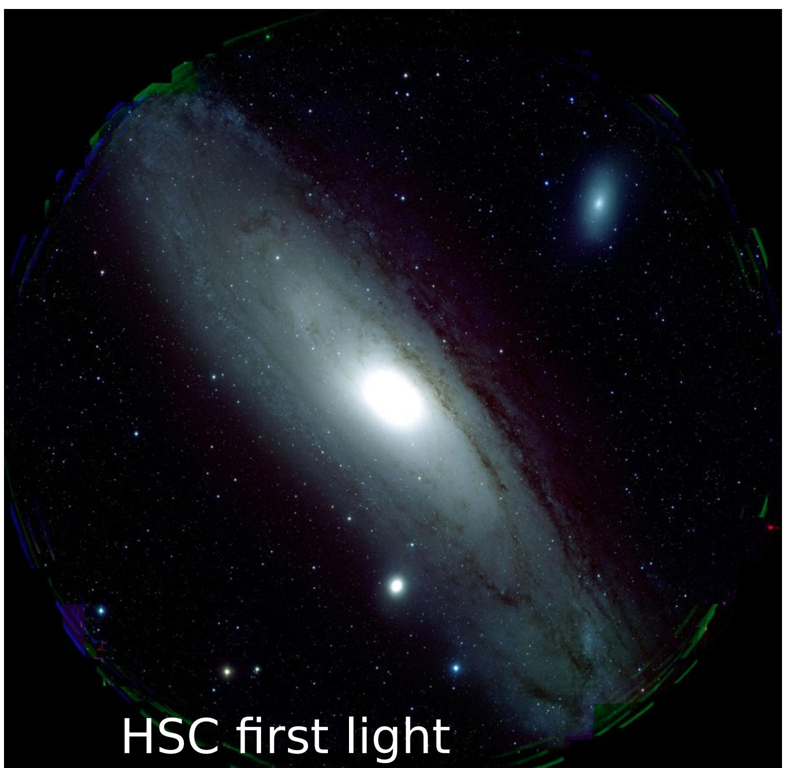
Subaru Telescope's main instrument development: visible wide field imaging and spectroscopy:

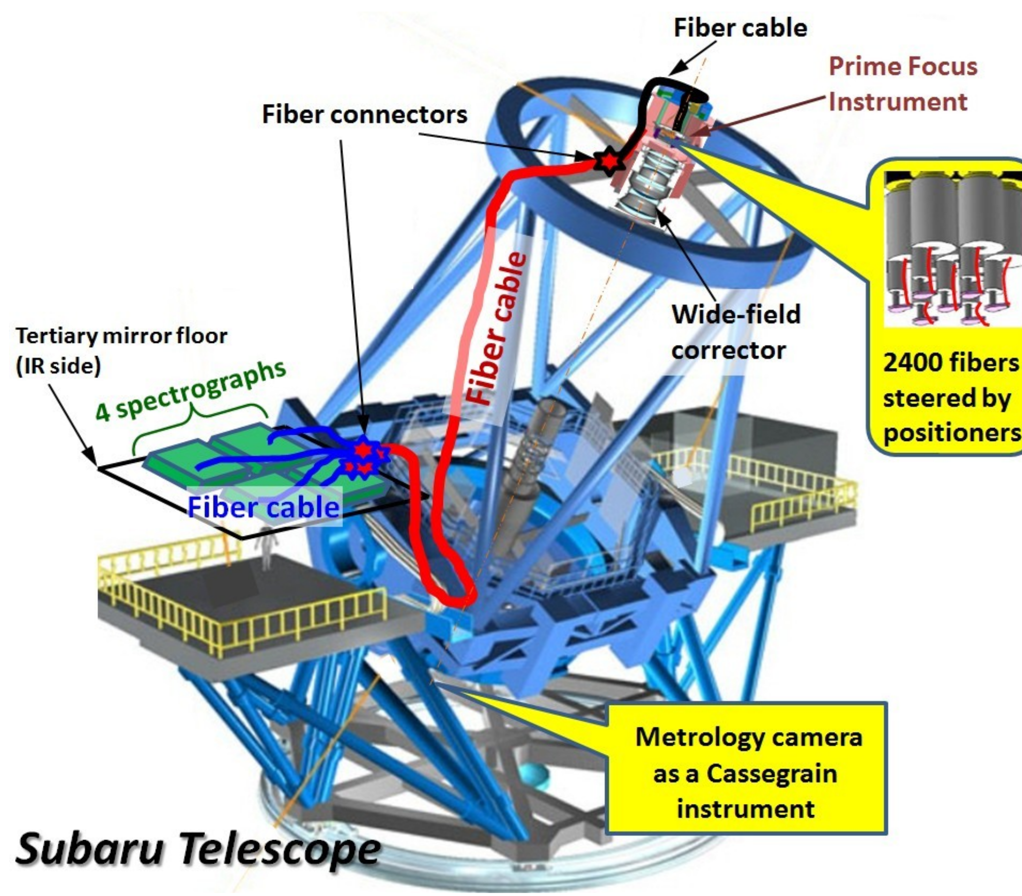
Hyper Suprime Camera (HSC): 1.5 deg diameter FOV

Prime Focus Spectrograph (PFS): 2400 fibers at prime focus

Both instruments share same field corrector

Adaptive Optics instrumentation complements the wide field visible instruments (use of bright time)

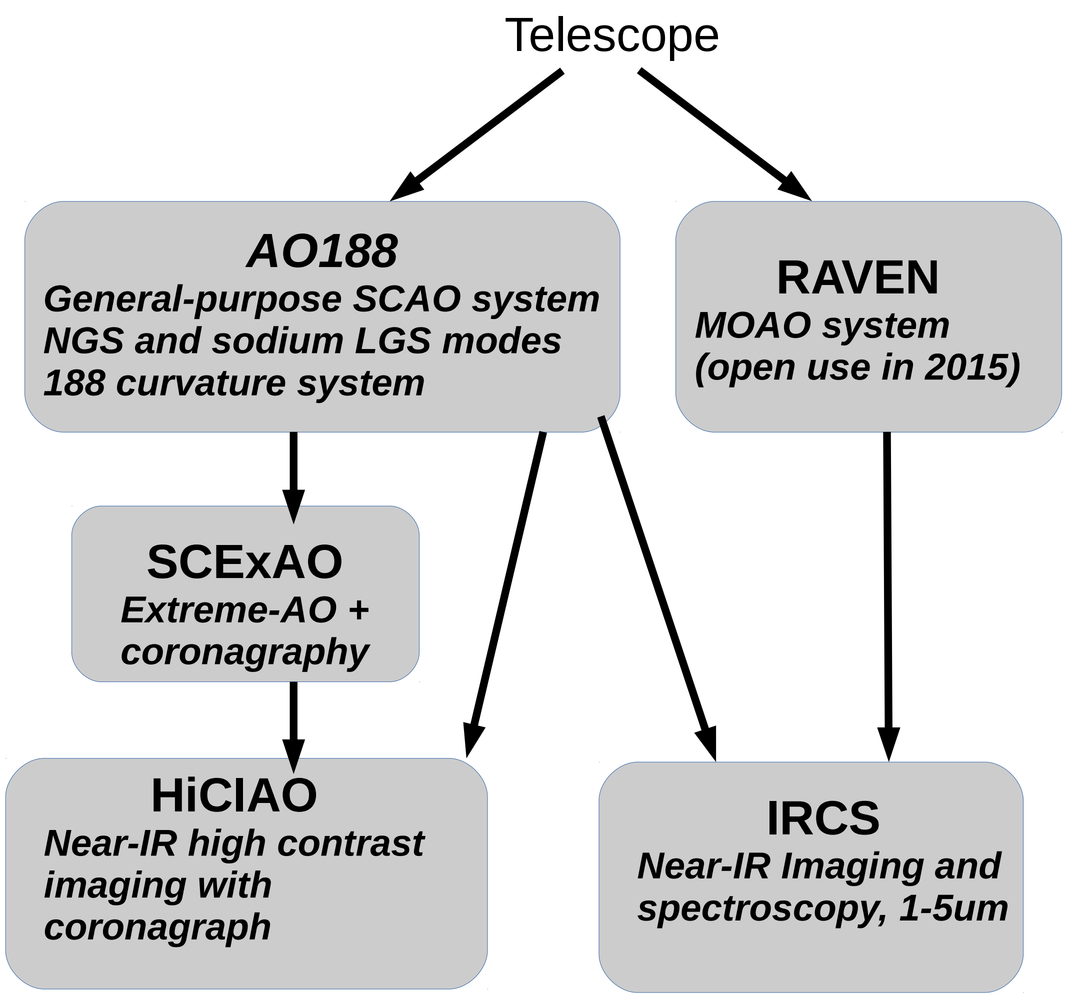


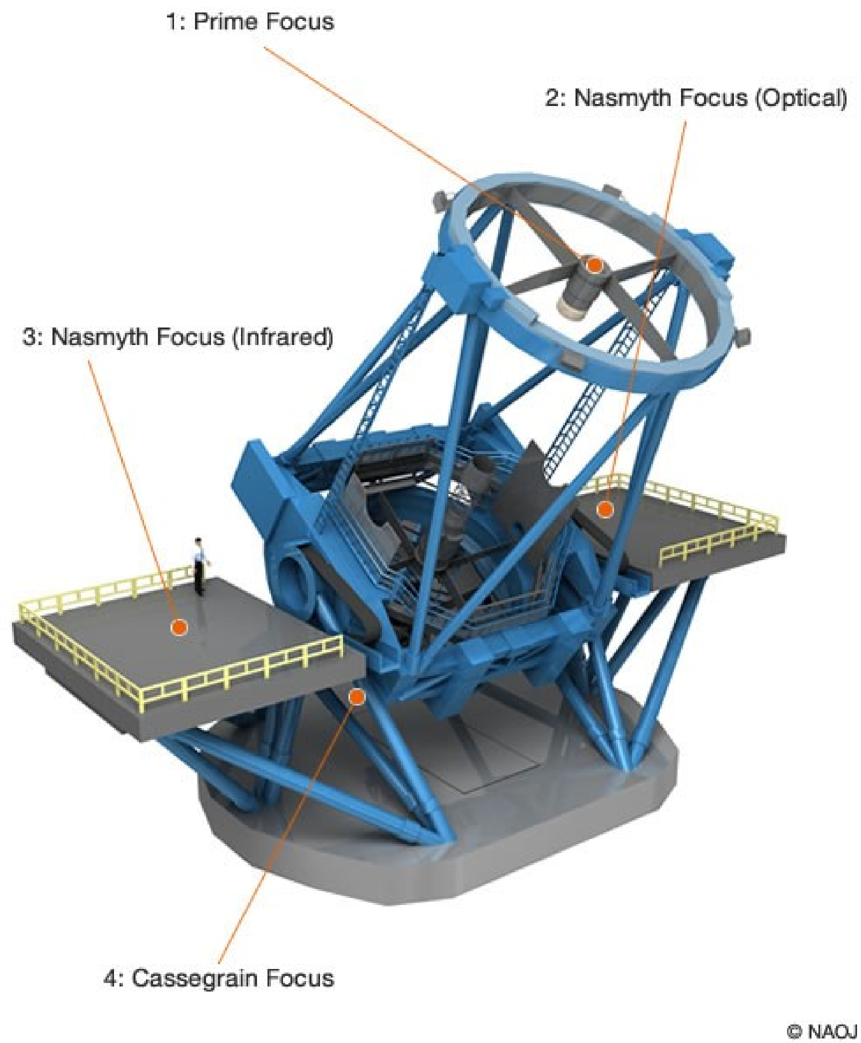


Subaru current AO instrumentation

All AO instrumentation currently on NasIR platform

Development in extreme-AO (SCExAO) and wide-field AO (RAVEN, ULTIMATE-SUBARU)





AO Development at Subaru

Extreme-AO (SCExAO)

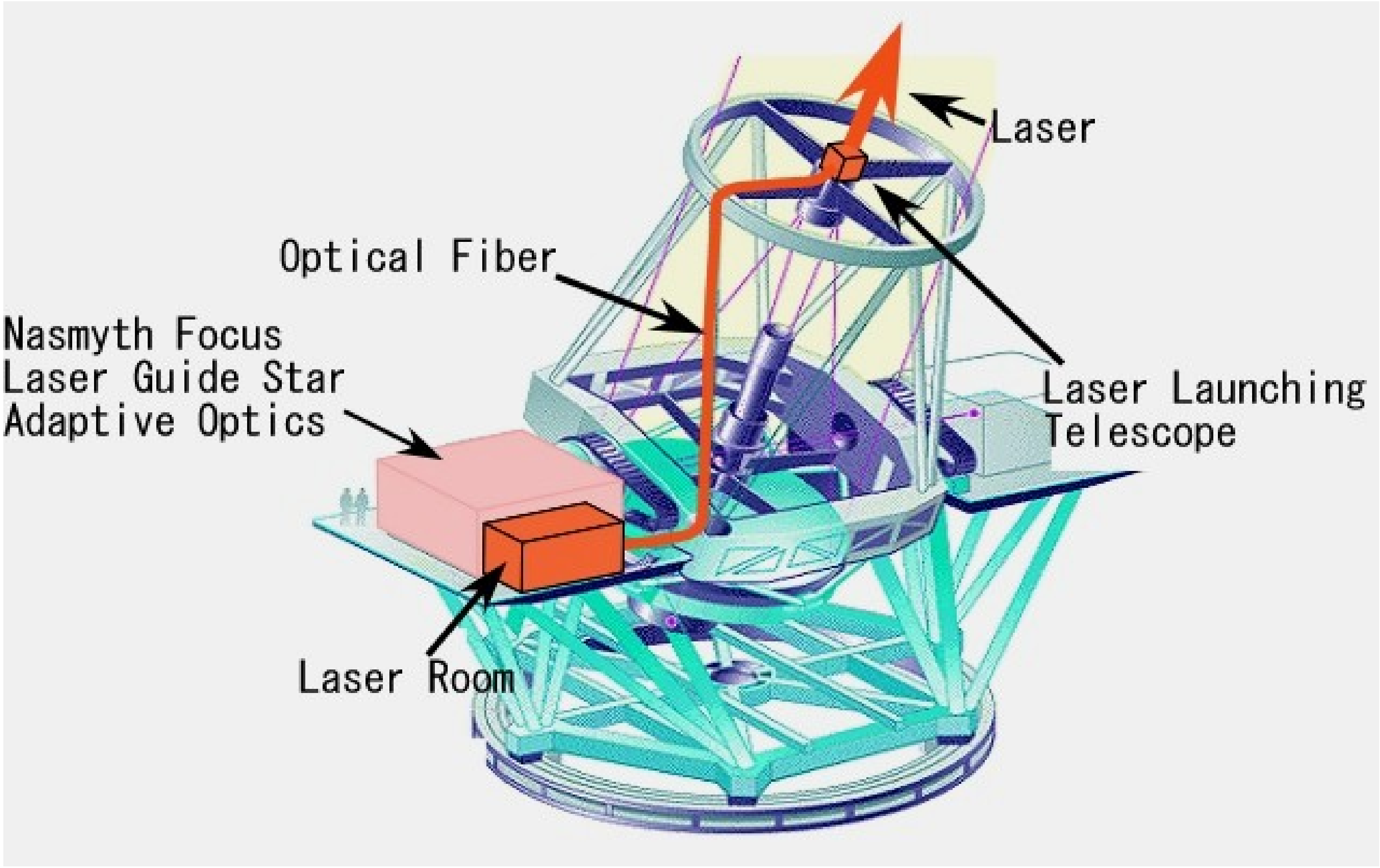
SCExAO system currently offered with phase1 capabilities, still under heavy development
Major future upgrades include:
- near-IR science cameras: IFS (CHARIS) and MKIDs camera (MEC)
- visible light modules (FIRST, VAMPIRES)

Wide-field AO (ULTIMATE-SUBARU)

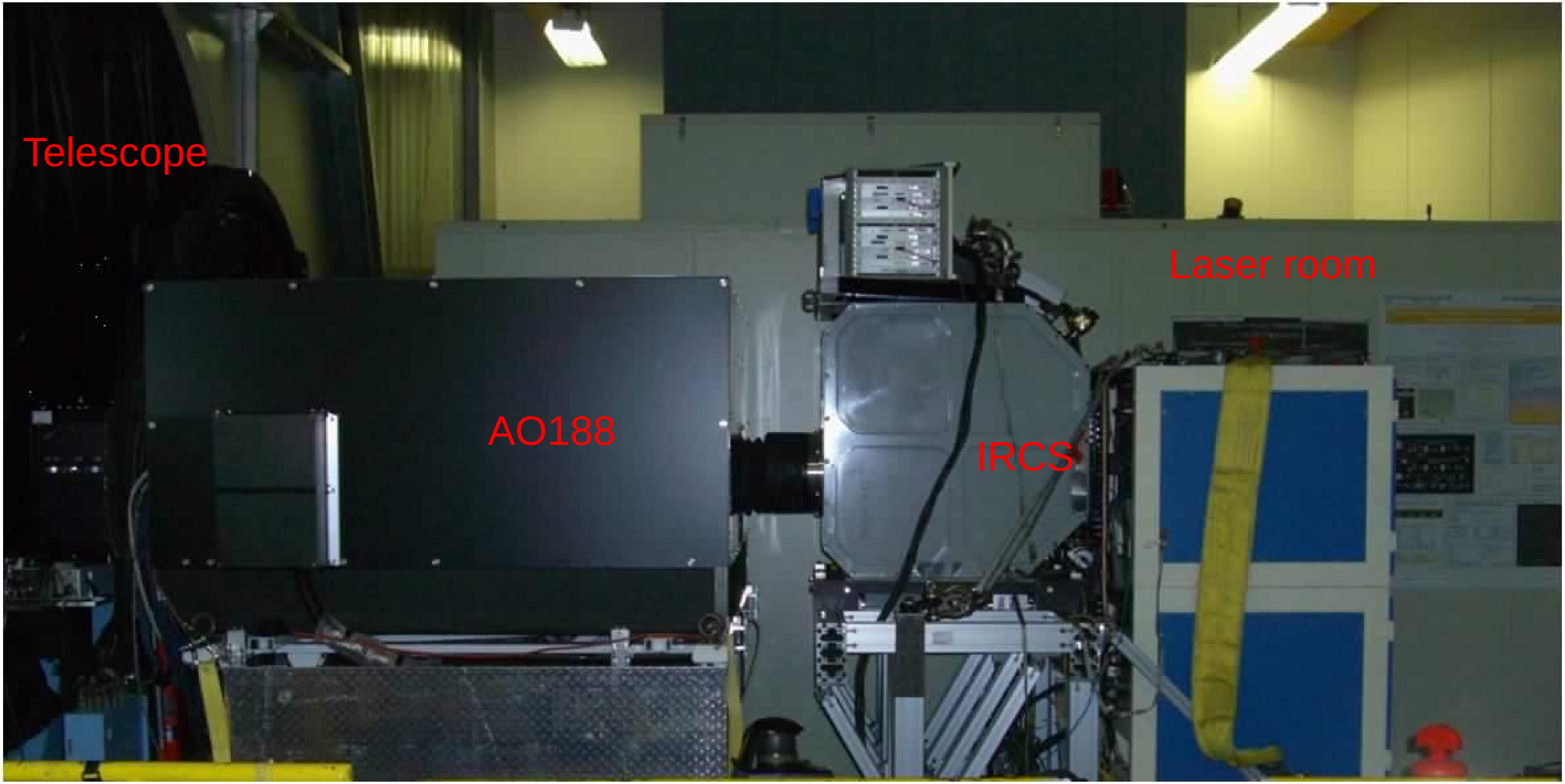
Multi-phase upgrade path to wide-field GLAO with multiple LGS
Includes telescope upgrade with adaptive secondary mirror + 4 LGSs

AO development at Subaru prepares ELT era (Japan is major partner in TMT):
Extreme-AO development at Subaru → imaging exo-Earths on ELTs
Wide-field AO → complements narrow-field ELTs (target identification)

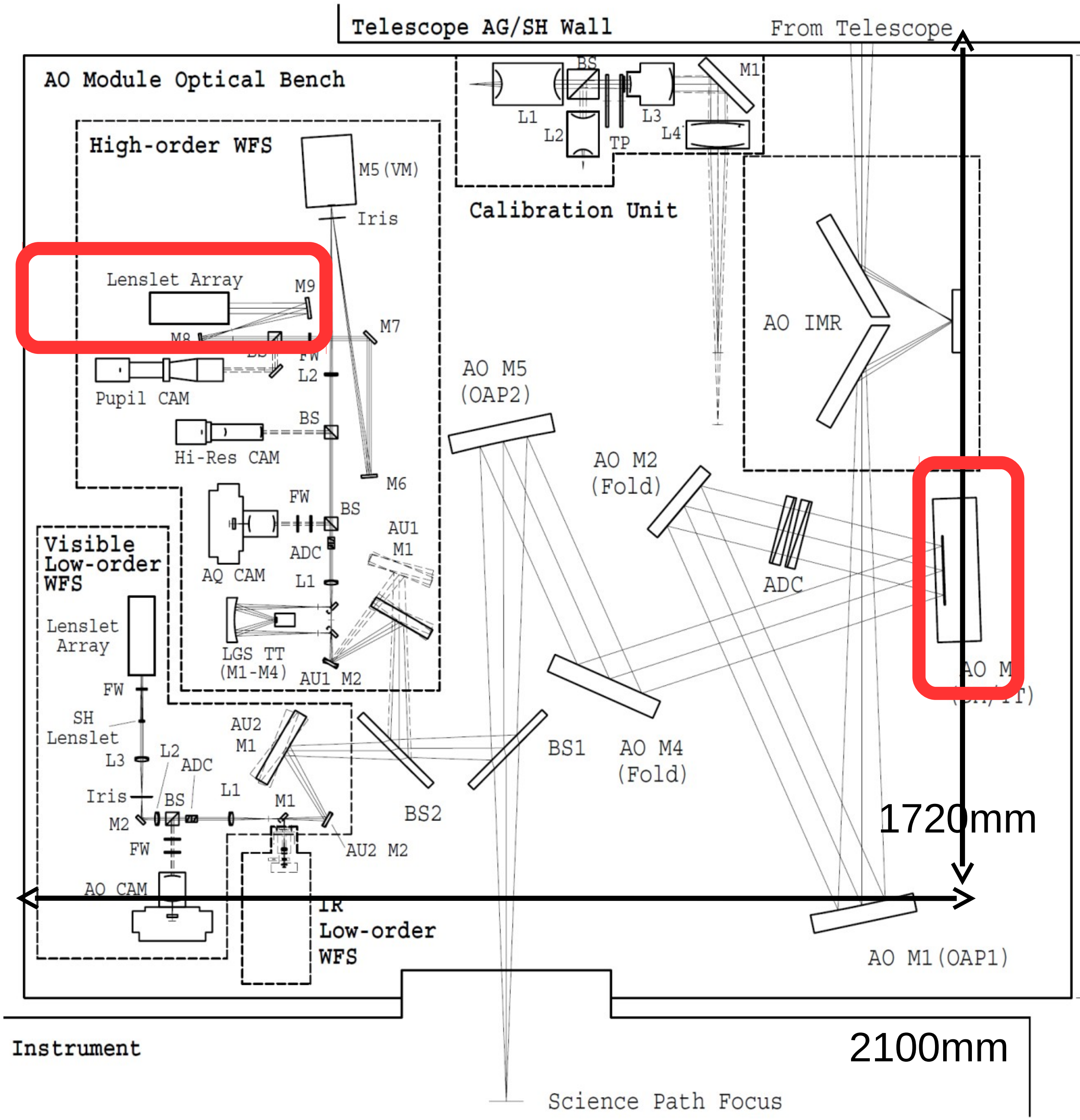
Layout of Subaru AO188/LGS

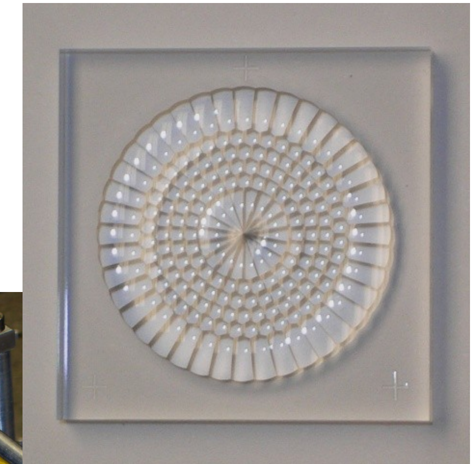


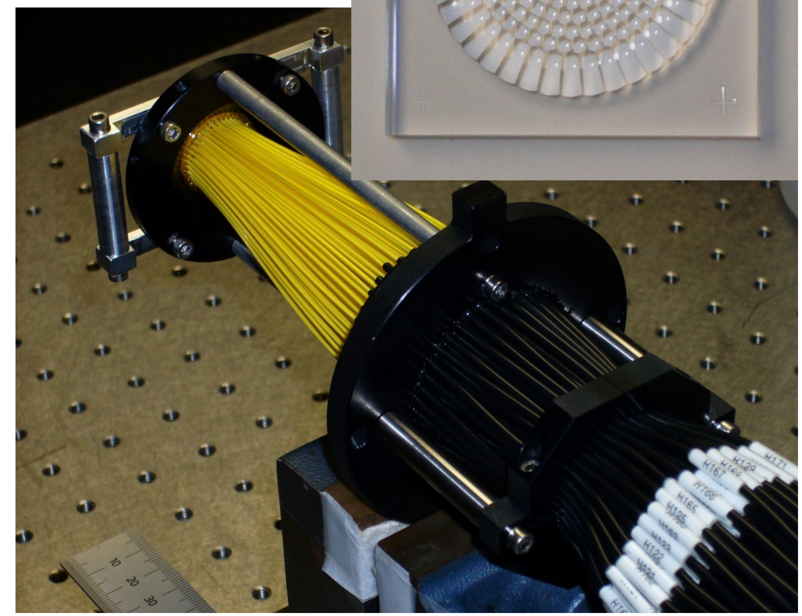
AO188 and IRCS on the Ns platform

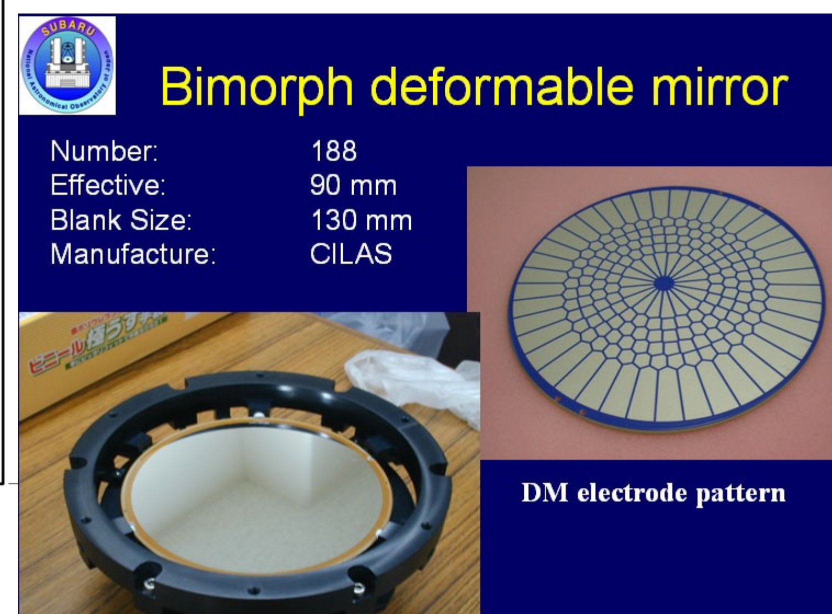


AO188 optics



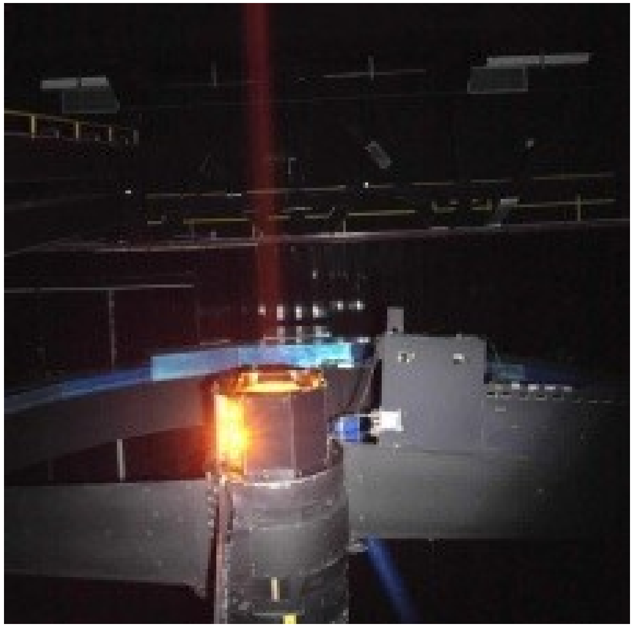


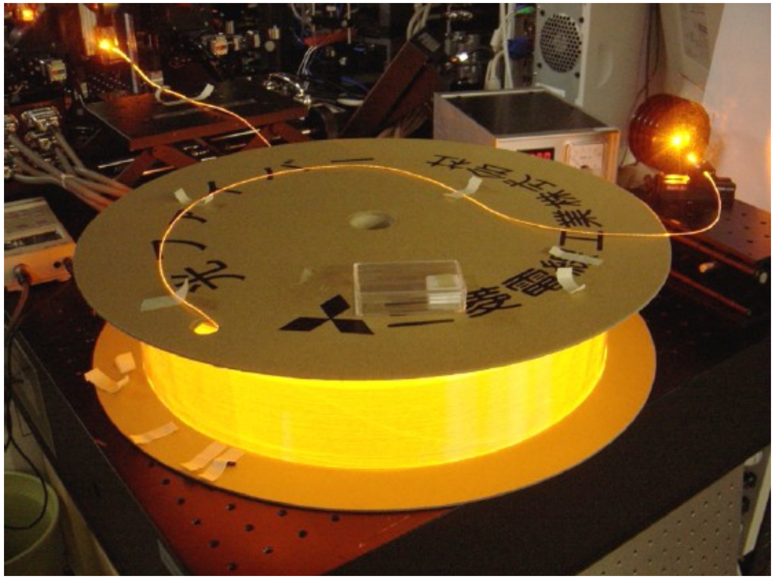


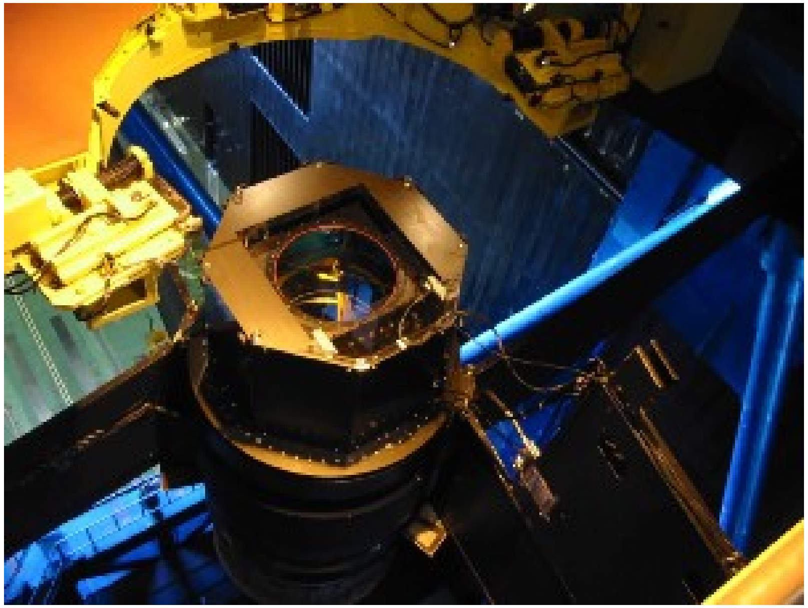


589nm laser

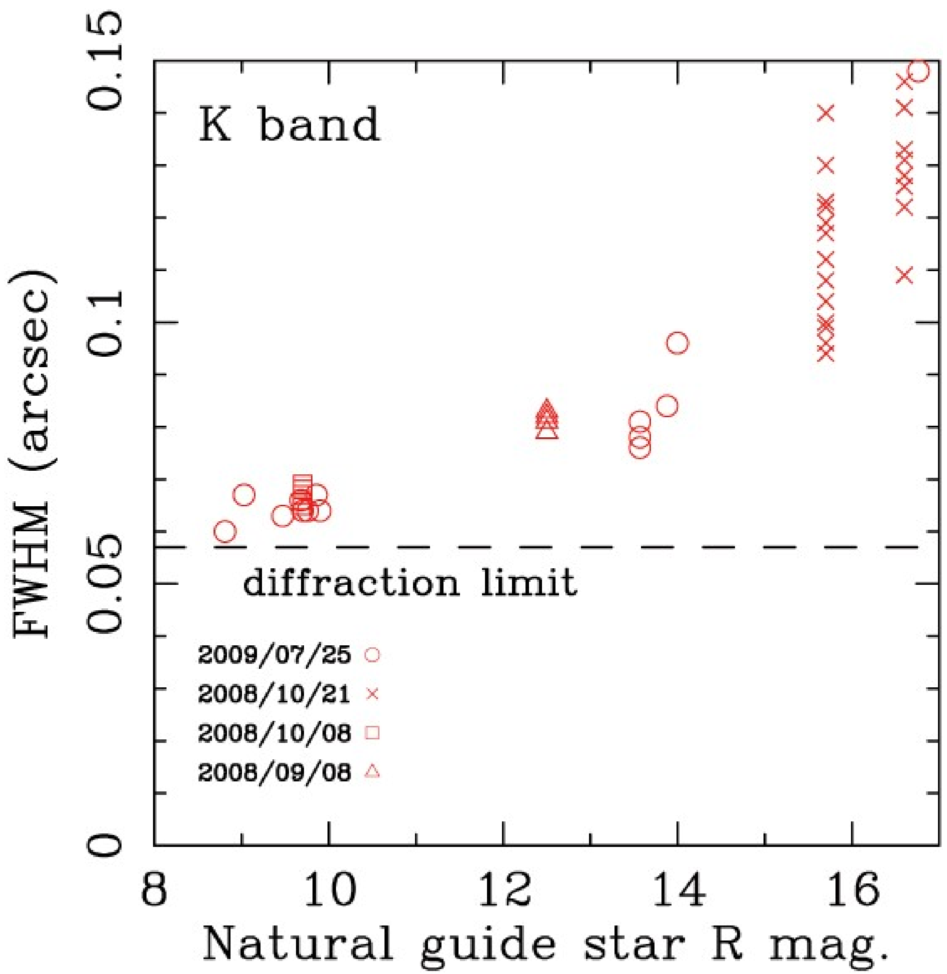
6.8W laser beam transported by single mode fiber to 500mm diameter laser launch telescope (center launch) → mR ~ 12 LGS

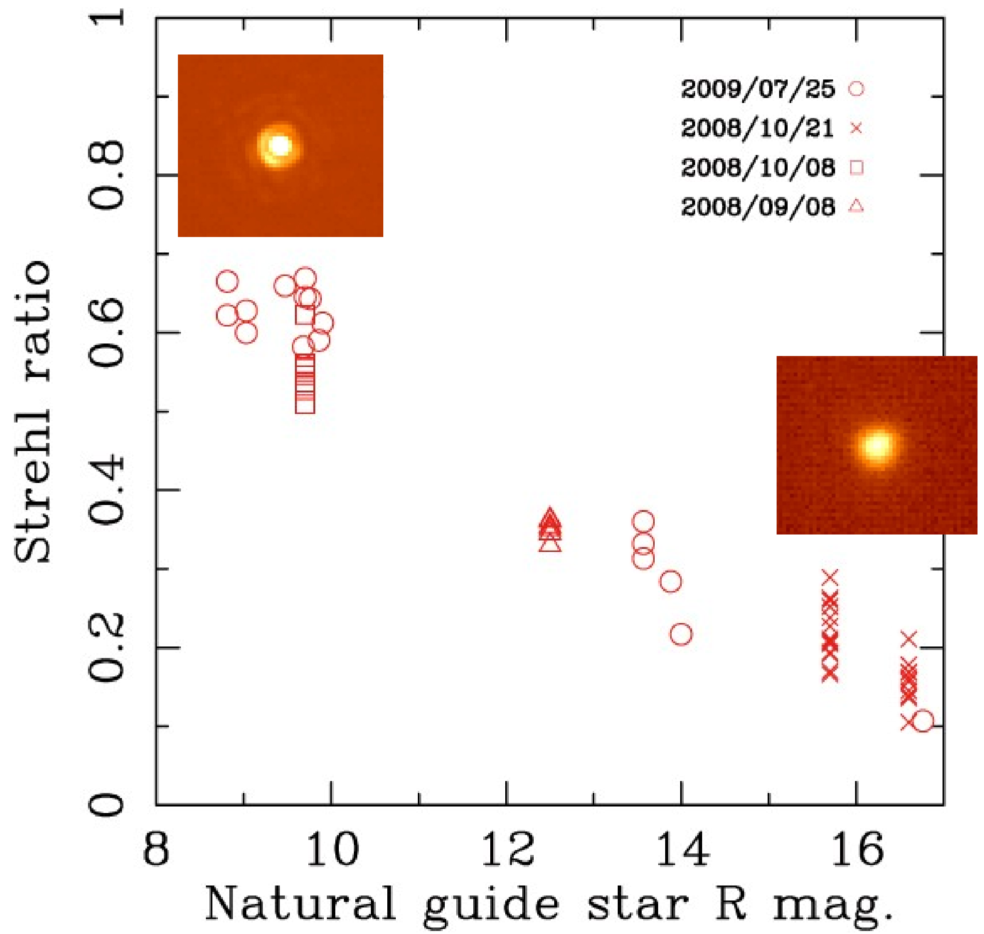




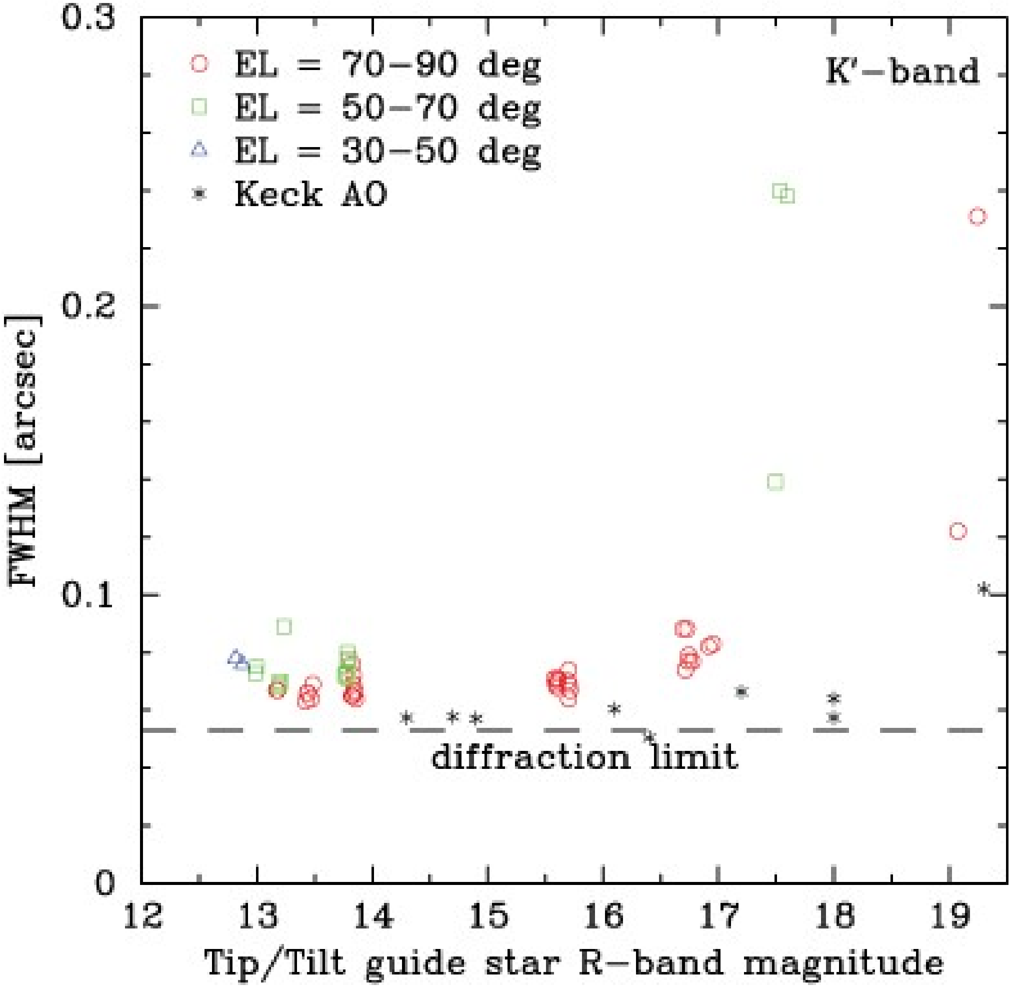


Performance v.s. GS mag (NGS mode)

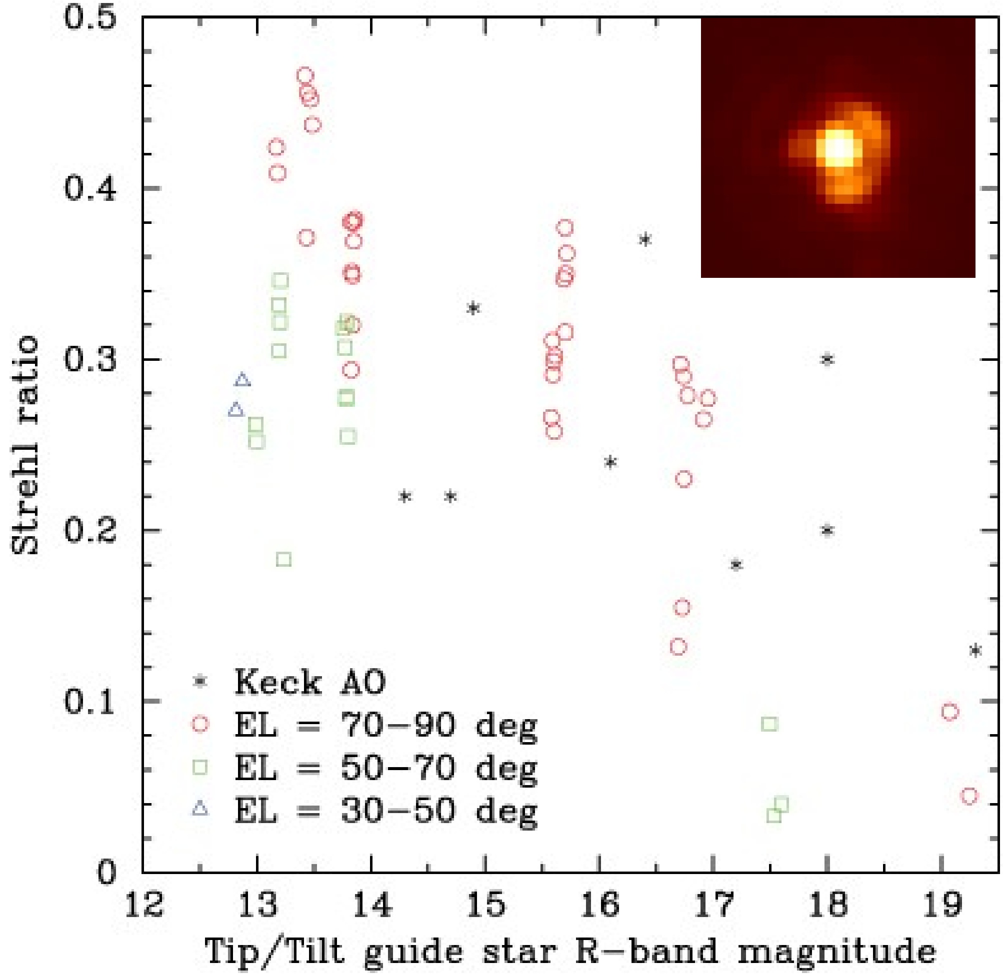




Performance v.s. TT/GS (LGS mode)



SR~0.45 PSF



High contrast imaging / exoplanets (<2014)

Telescope

↓

AO188
General-purpose SCAO system
NGS and sodium LGS modes
188 curvature system

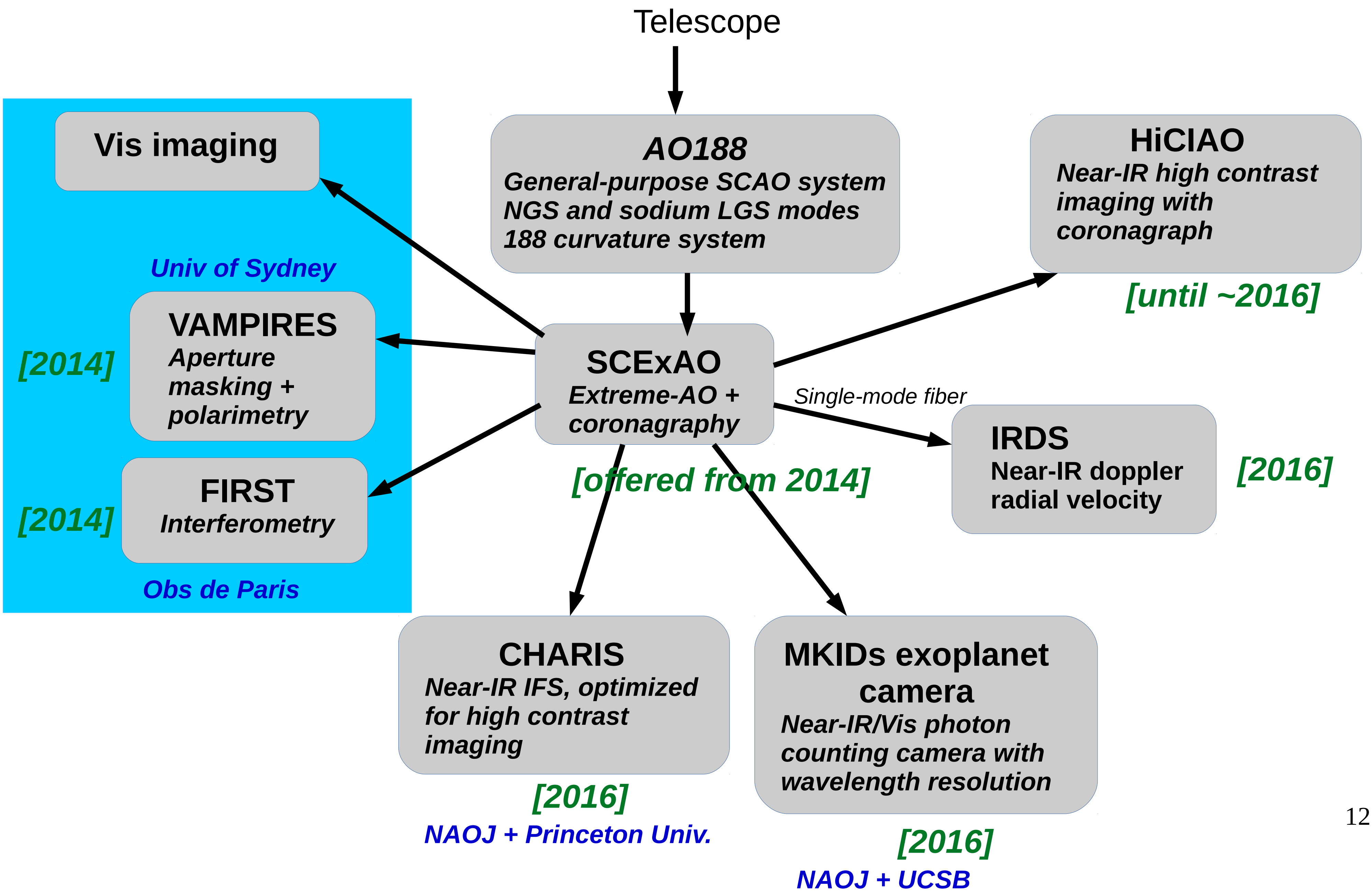
→

HiCIAO
Near-IR high contrast imaging with coronagraph

Lyot Coronagraph

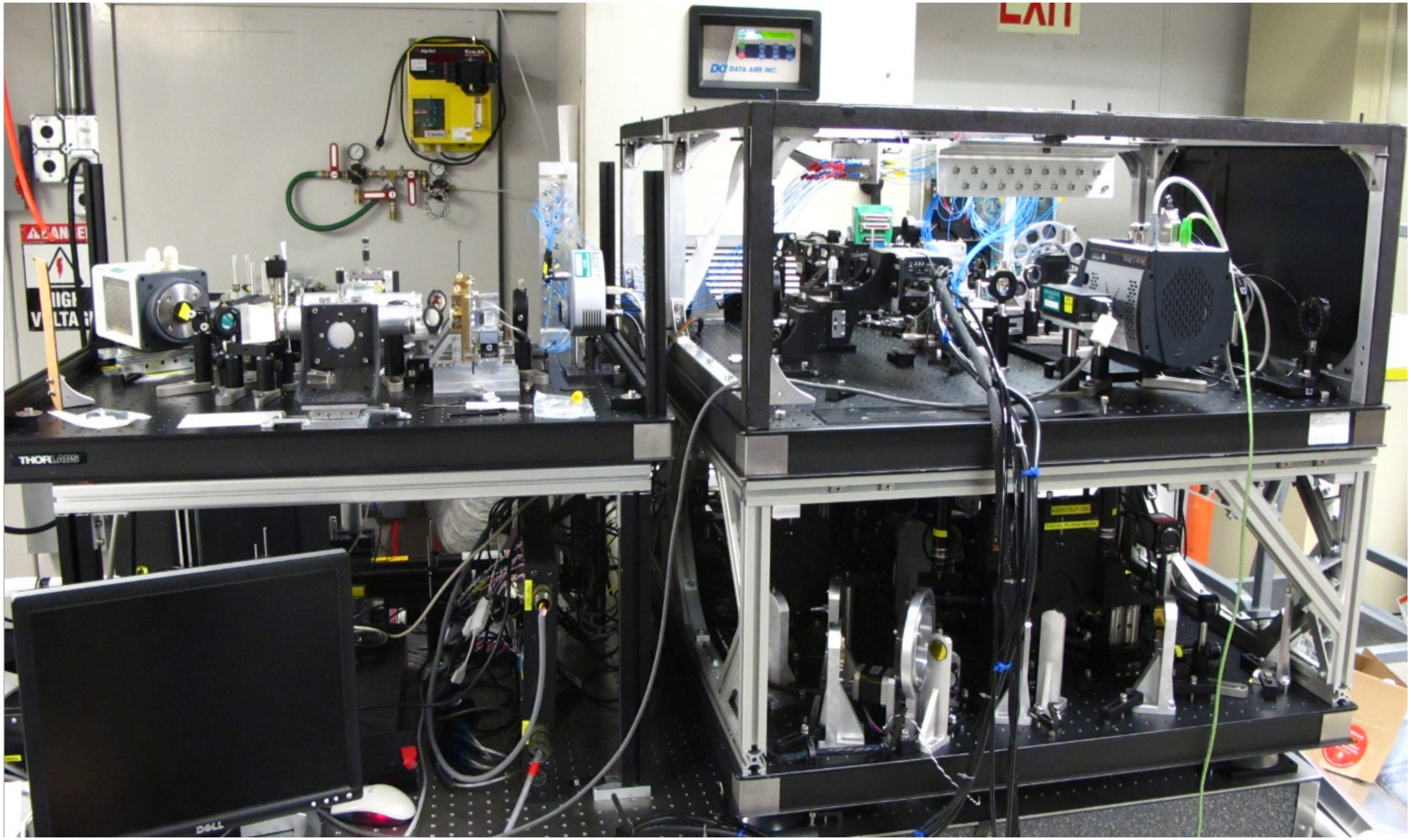
Differential imaging camera
Spectral and polarimetric differential imaging

High contrast imaging / exoplanets (2014+)



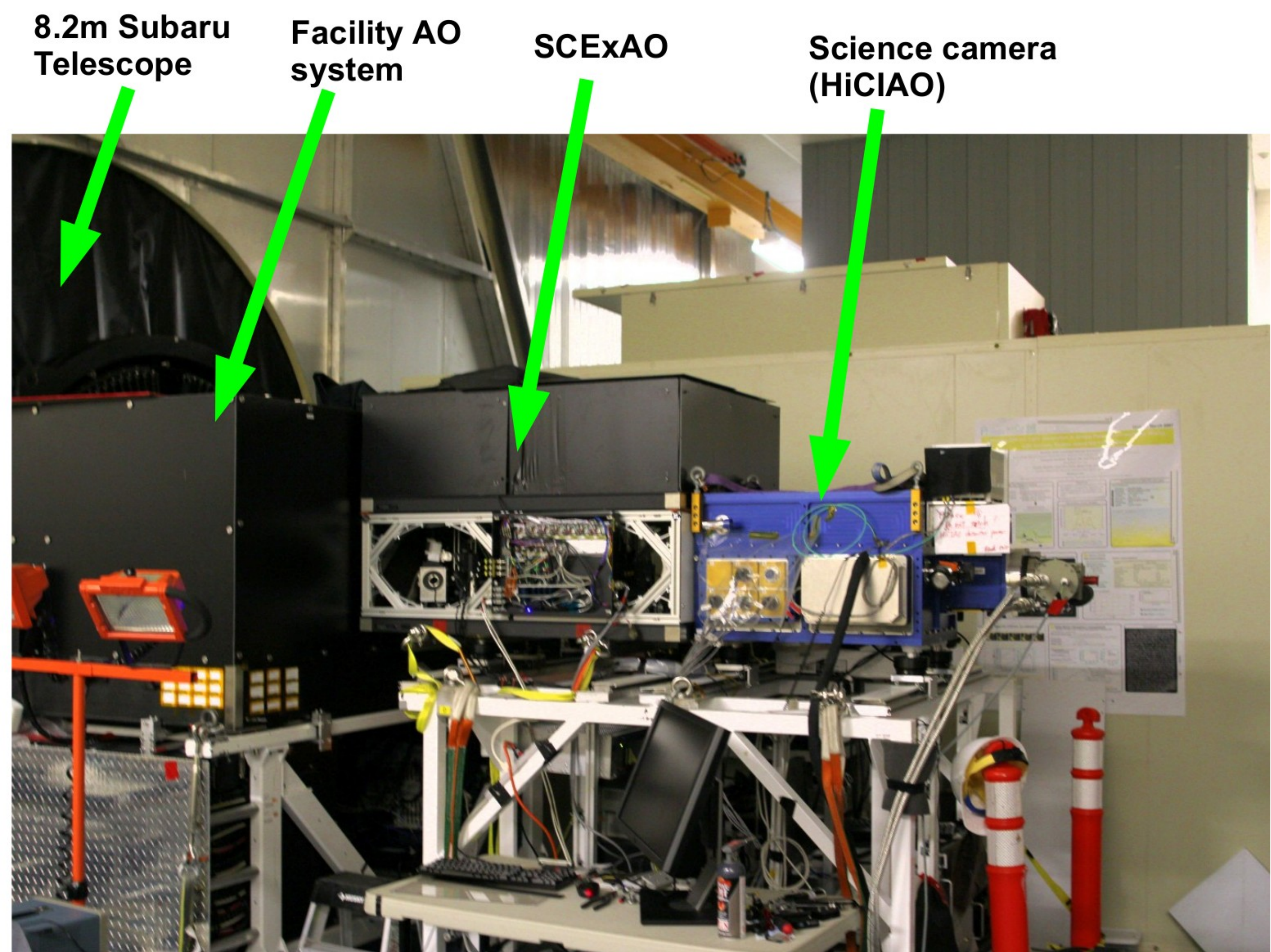
SCExAO (summer 2013)

Visible bench:
- **ExAO WFS**
- **VAMPIRES**
- **FIRST (injection)**
- **Vis imaging**

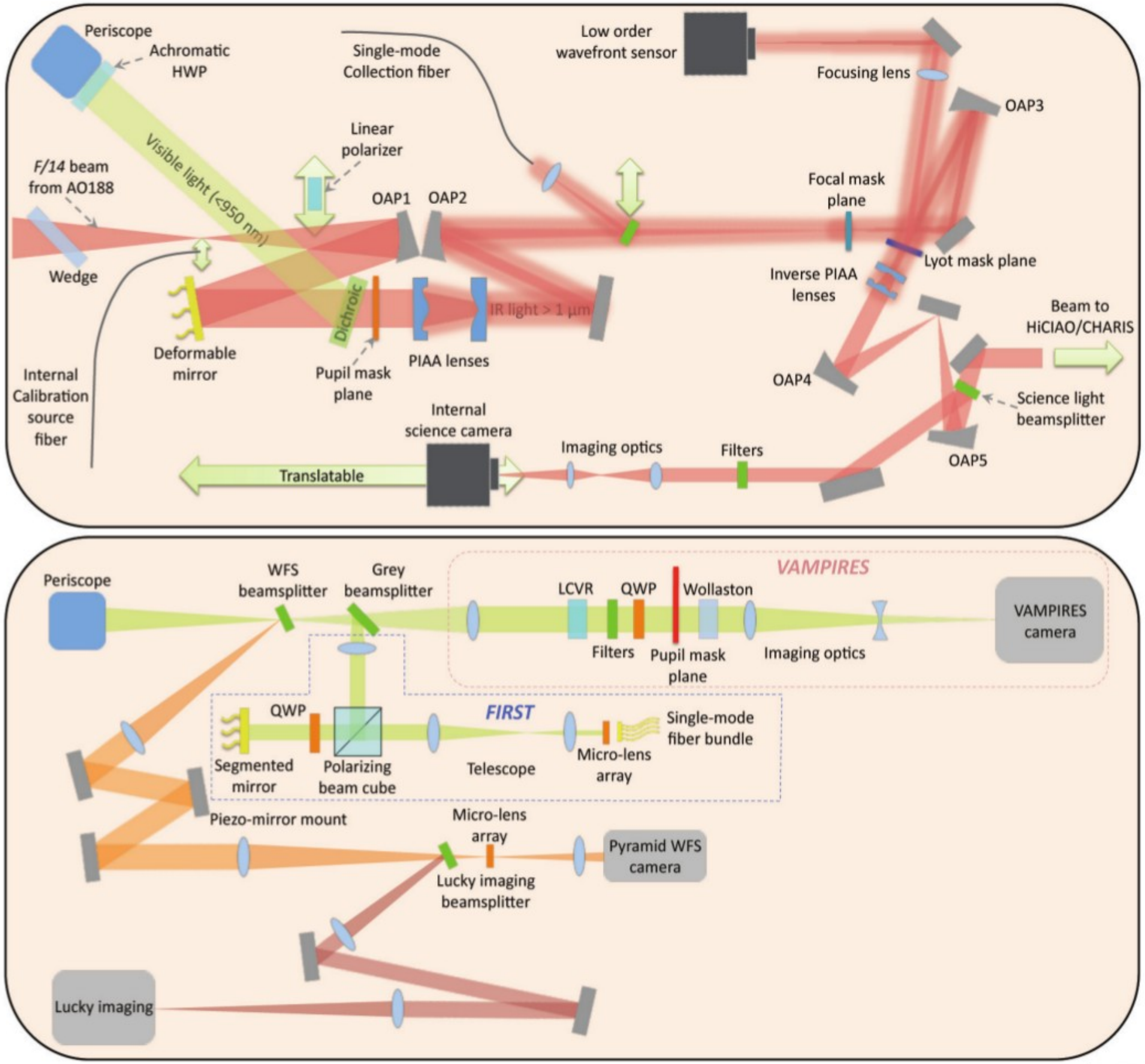


FIRST recombination bench

Near-IR bench:
- **ExAO correction (2000 act DM)**
- **Coronagraphy (PIAA, OVC etc..)**
- **Near-IR WFS (LOWFS + speckle control)**


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

SCExAO architecture



Optimized for high contrast imaging at small inner working angle

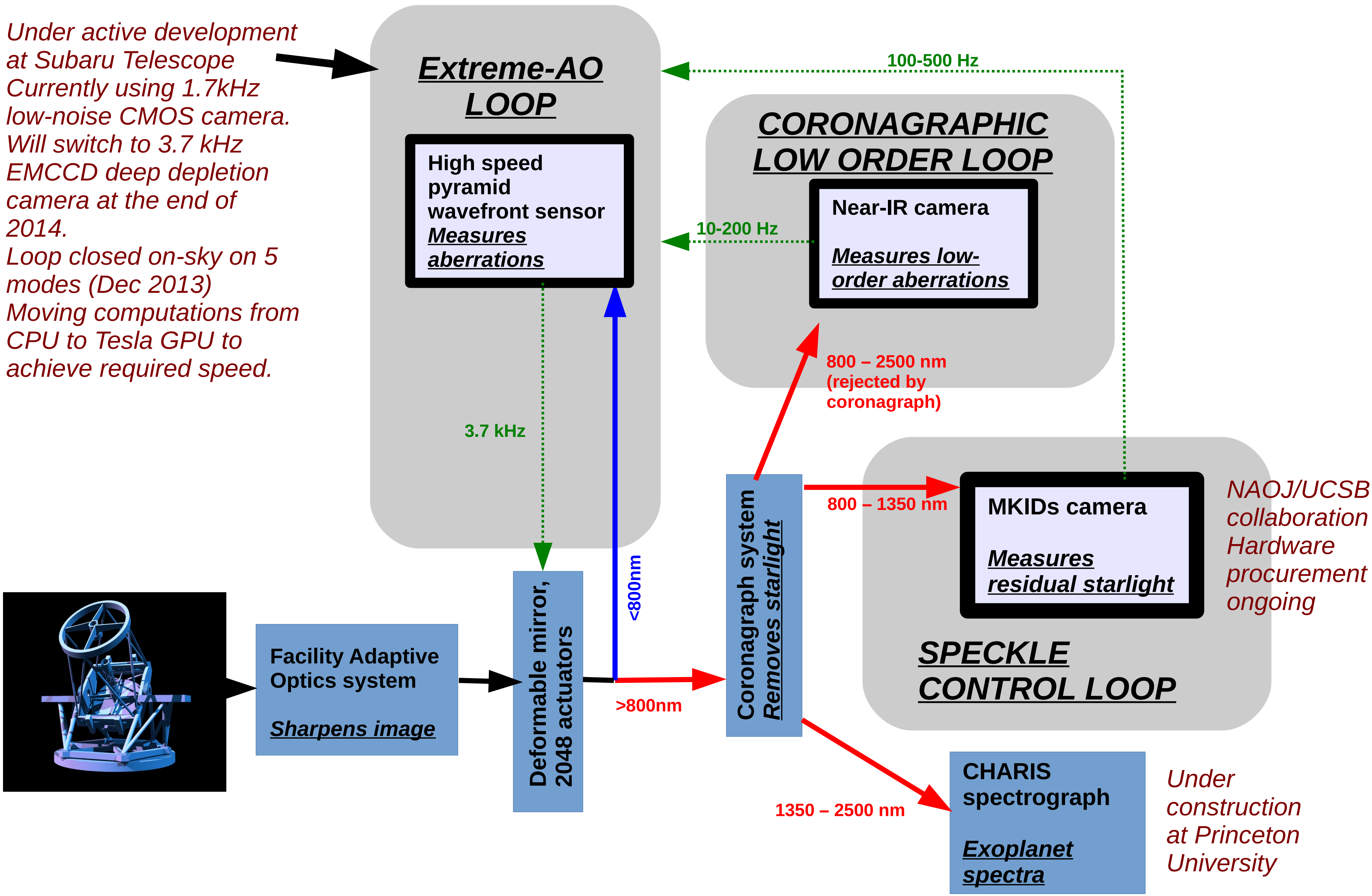
coronagraphs: PIAA(CMC), OVC, 4QPM, SPC, 8OCT

Wavefront sensors:

VISIBLE:
- Non-modulated pyramid, 3.7kHz sampling

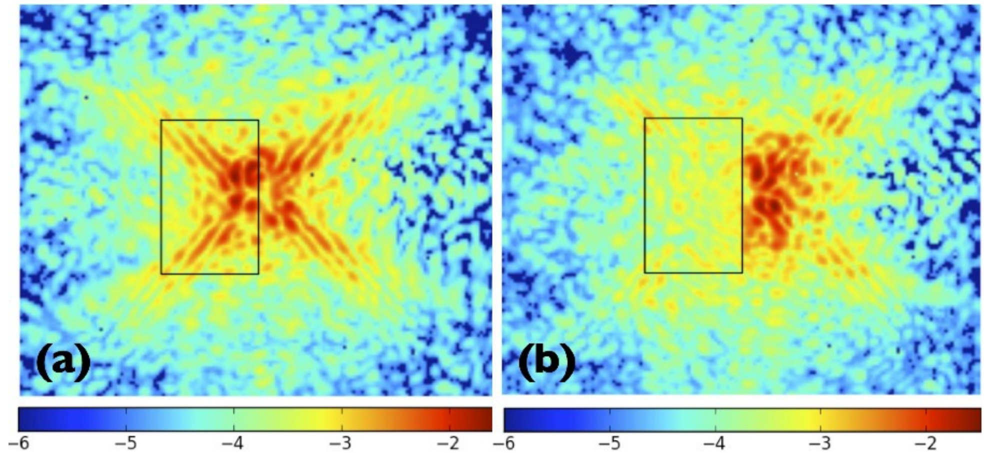
Near-IR:
- coronagraph LOWFS, integrated with coronagraph design
- Speckle control (currently with InGaAs detector, soon with MKIDs)

Wavefront control architecture



Using a deformable mirror to measure and control focal plane speckles

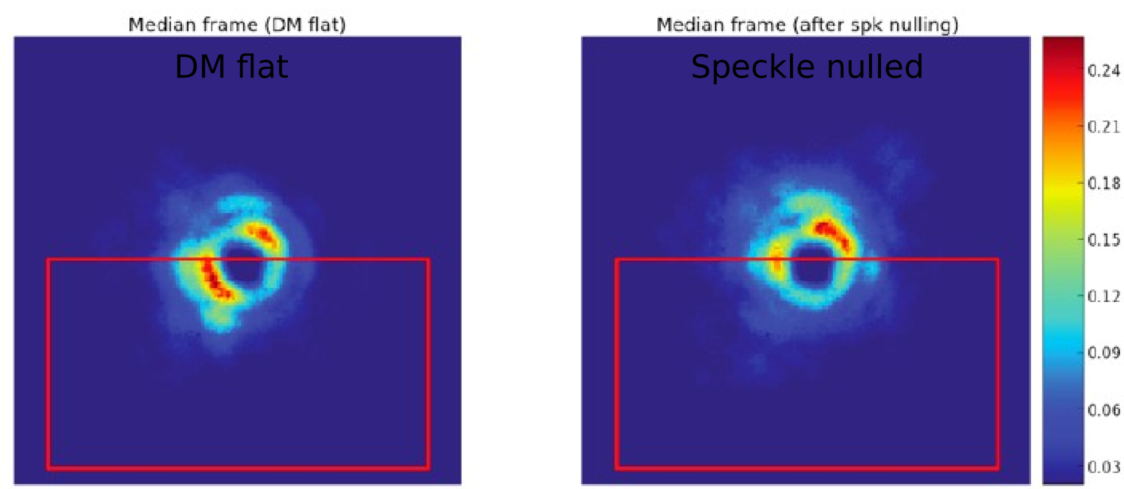
In lab →



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

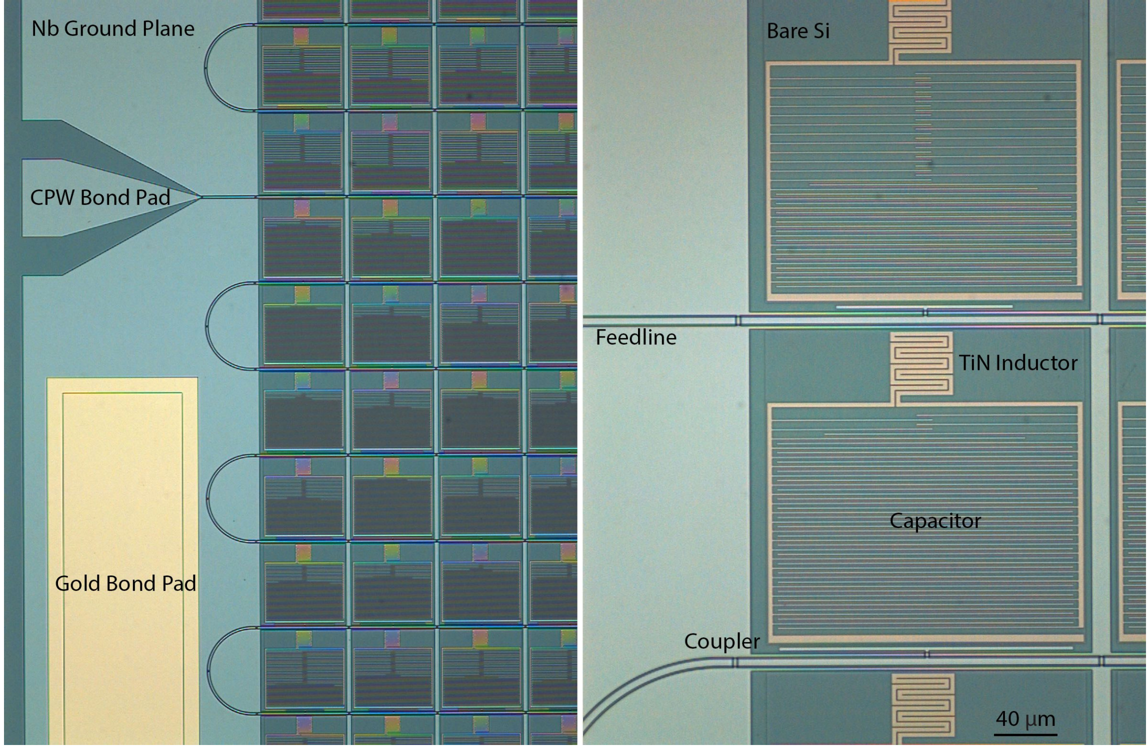
On sky →



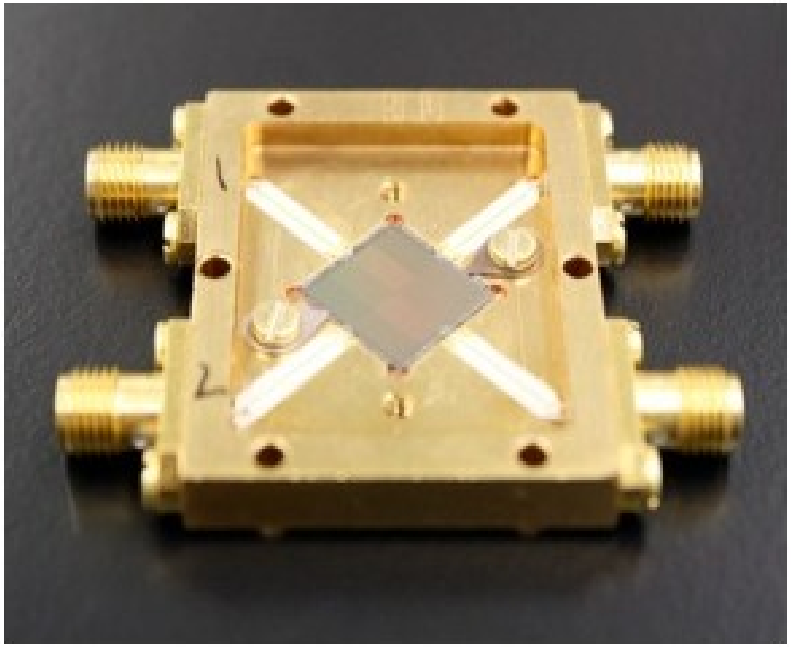
SCExAO DM control region

Single pair of long exposures (1.5 sec) on Pollux by HiCIAO
Reduction of the diffraction features in raw images – mean increase in contrast of ~2 for brightest ring.
Standard deviation reduced by 7x

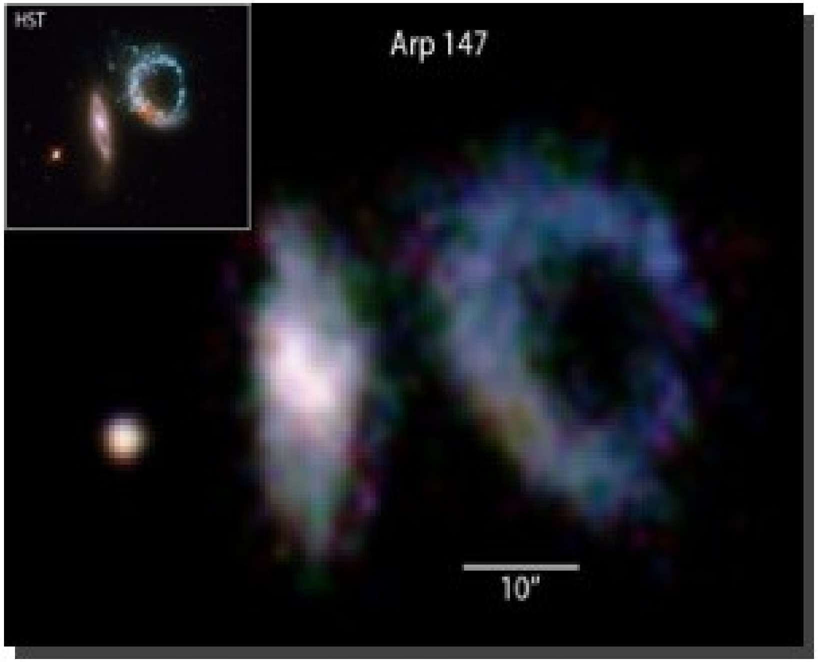
MKIDs + MEMS for a smart focal plane high contrast camera (NAOJ / UCSB)



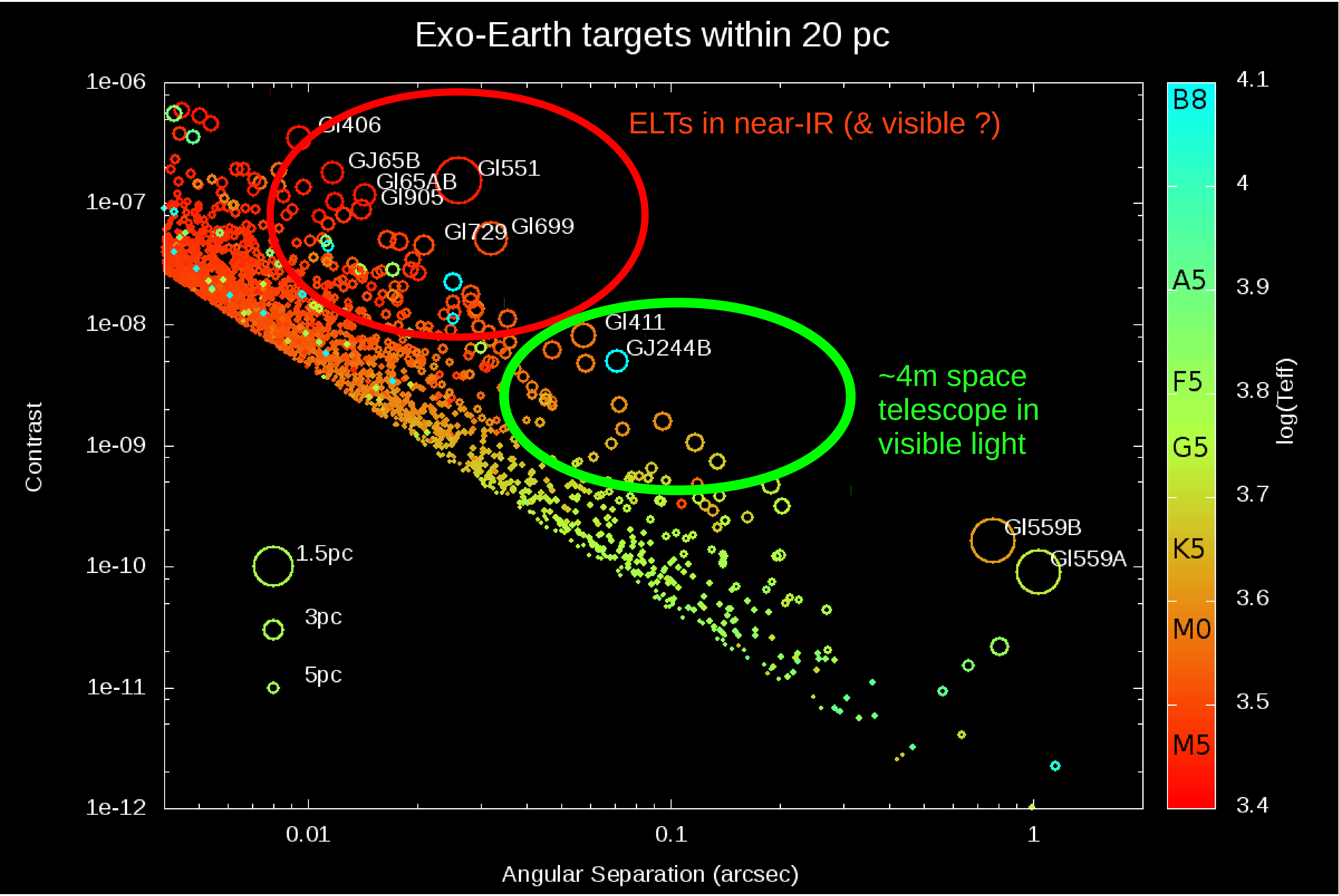
Enables photon-counting performance in near-IR, with energy resolution



MKIDs detector

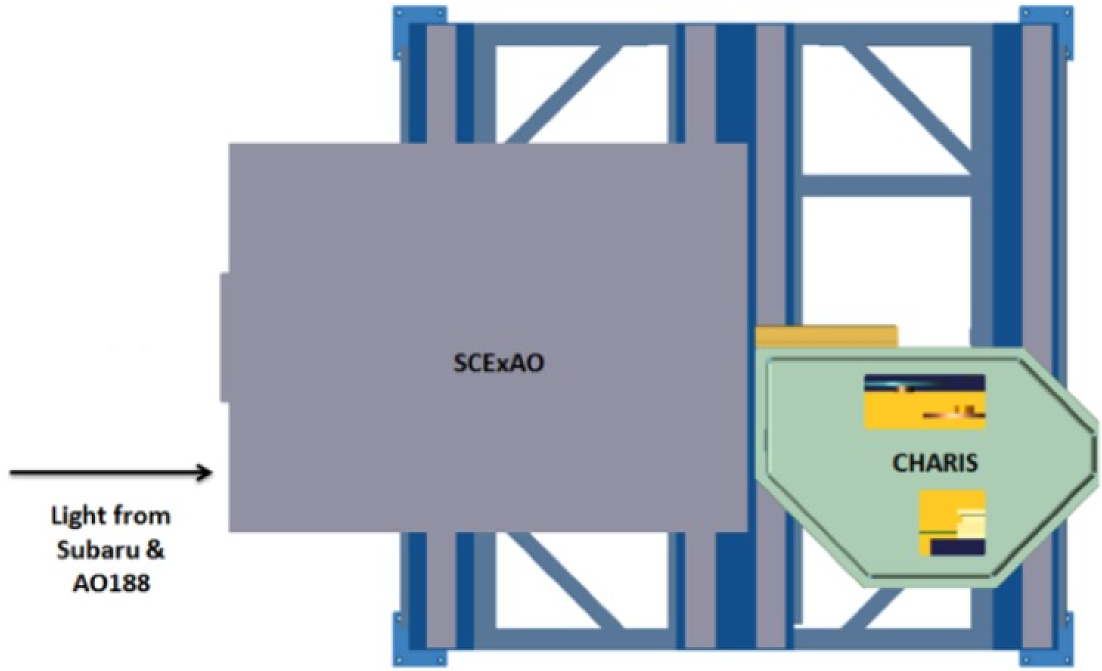


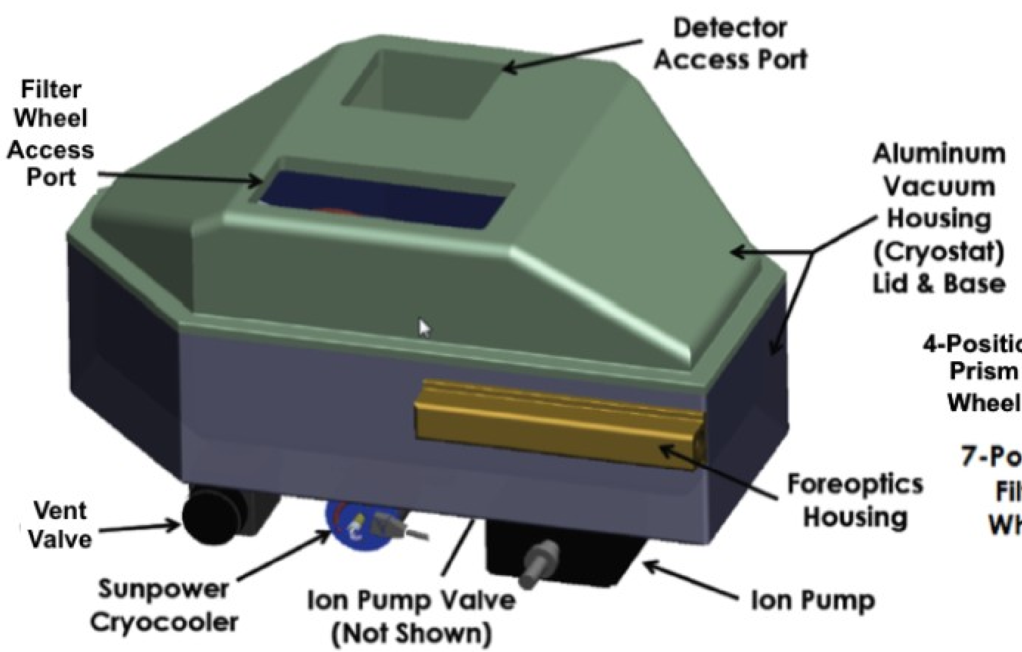
MKIDs image @ Palomar

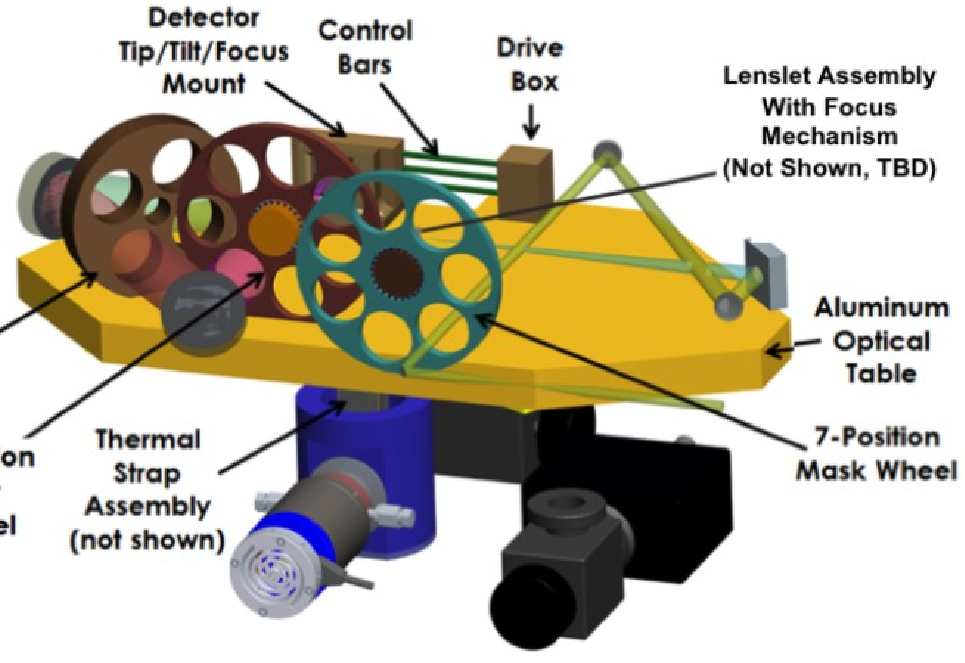


Exo-Earth targets within 20 pc
ELTs in near-IR (& visible ?)
~4m space telescope in visible light
Gl406
GJ65B
Gl551
Gl65AB
Gl905
Gl729
Gl699
Gl411
GJ244B
Gl559B
Gl559A
1.5pc
3pc
5pc
1e-06
1e-07
1e-08
1e-09
1e-10
1e-11
1e-12
Contrast
0.01
0.1
1
Angular Separation (arcsec)
B8
A5
F5
G5
K5
M0
M5
4.1
4
3.9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

CHARIS integral field spectrograph (NAOJ/Princeton)

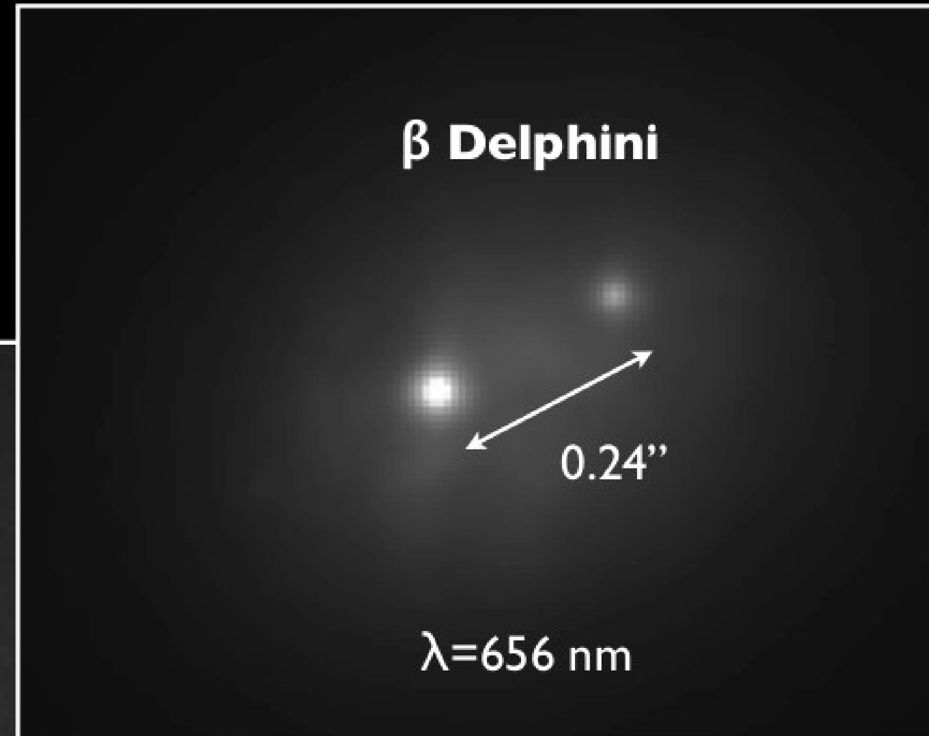


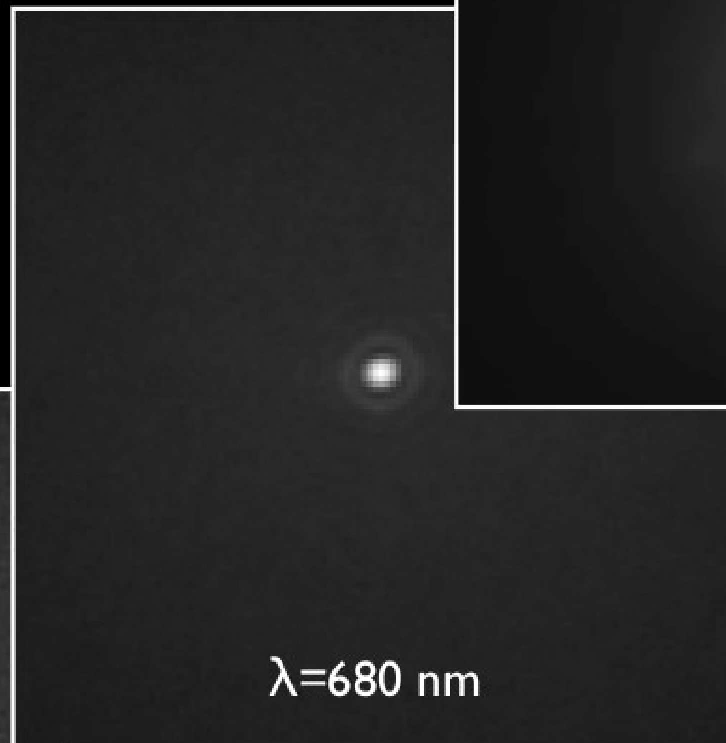


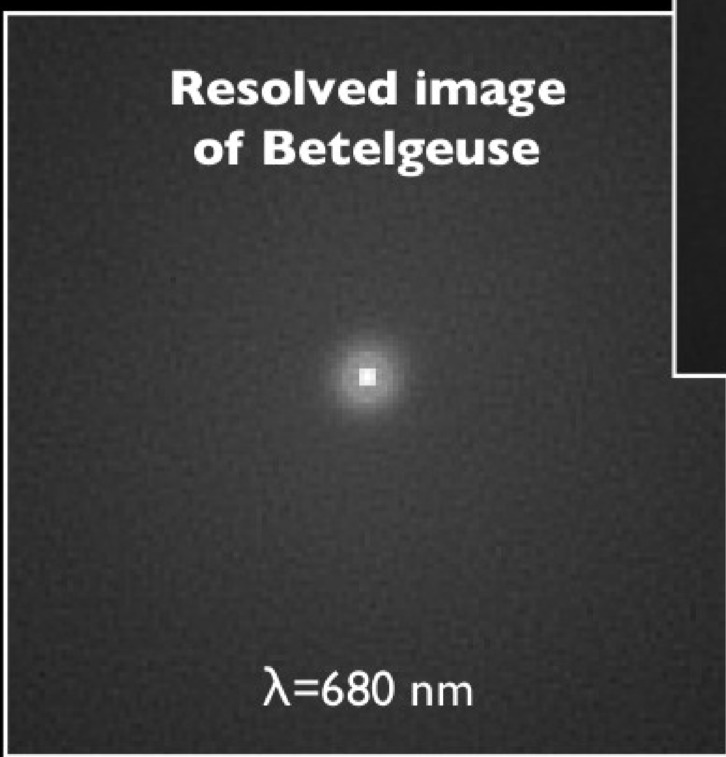


Visible imaging at diffraction limit (17 mas FWHM)

(fast frame imaging + Fourier Lucky)



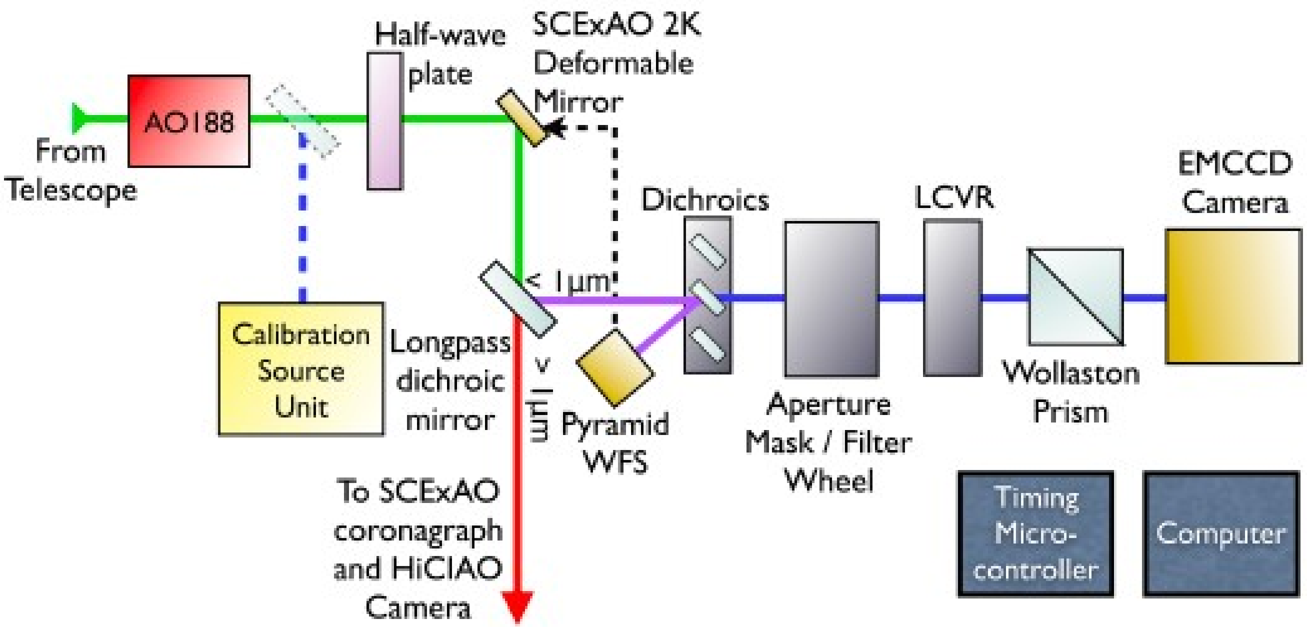


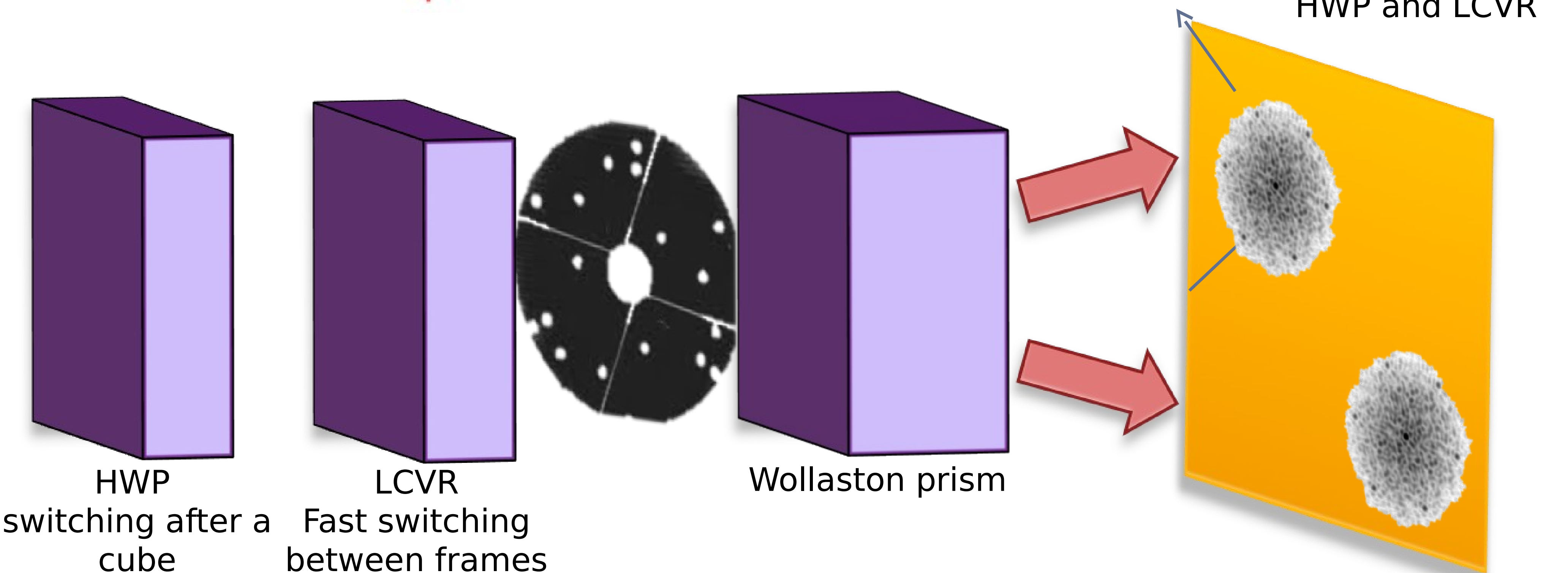


PhD dissertation by Vincent Garrel (Oct 2012)

VAMPIRES (Univ. of Sydney)

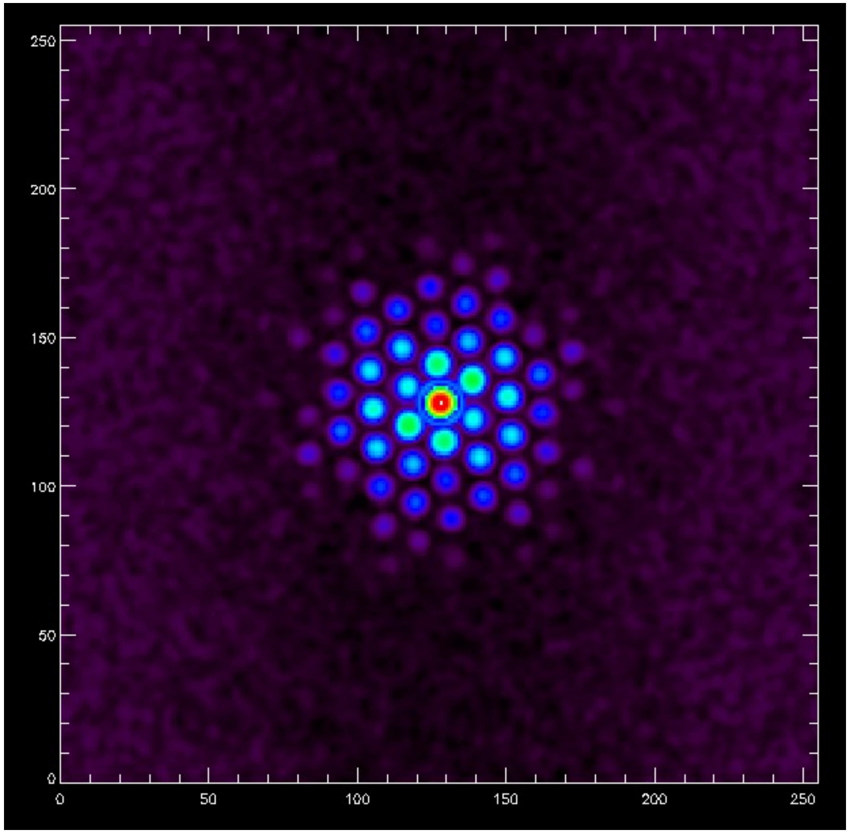
- Aperture masking interferometry for imaging *<1λ/D*
- 3 levels of polarization control in the visible
- Builds on work with NACO at VLT





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):

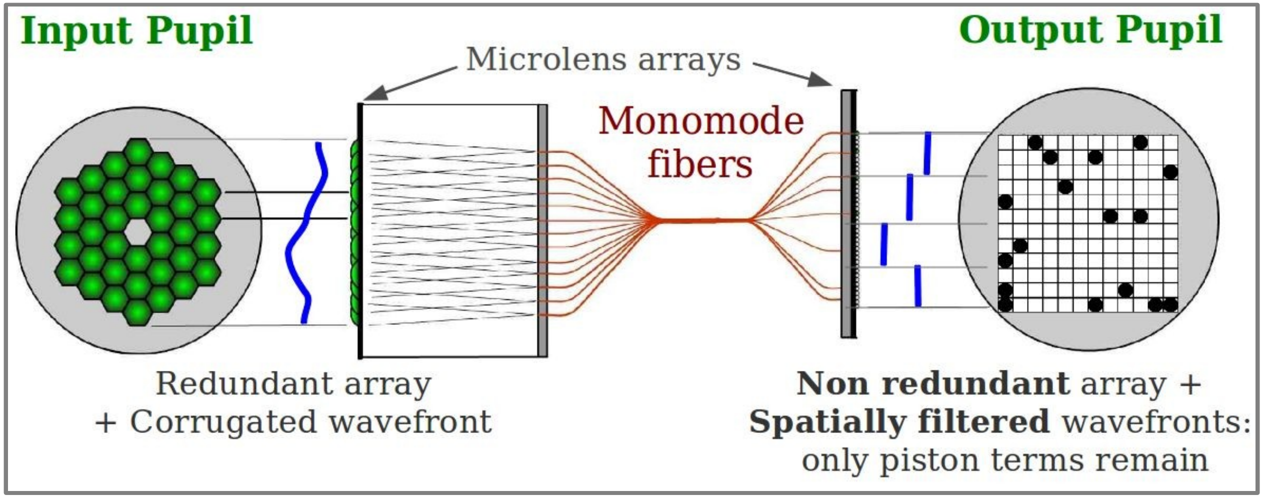
32.2 ± 0.13 mas (750 nm)

Literature Values
(U.D. Diameter):

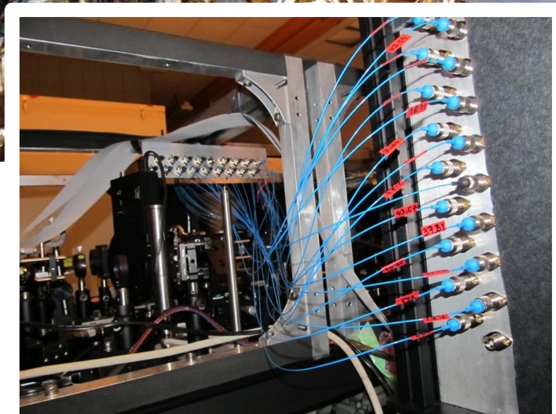
32.8 ± 4.10 mas (V band)

CHARM Catalogue, Richichi et al. 2005

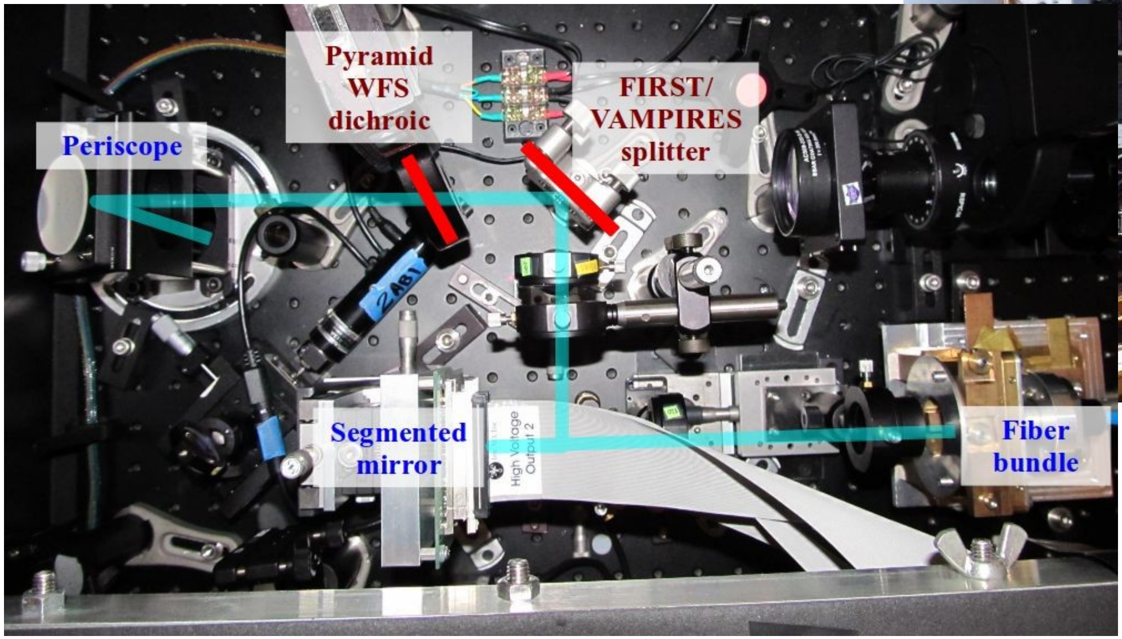
FIRST module on SCExAO visible bench



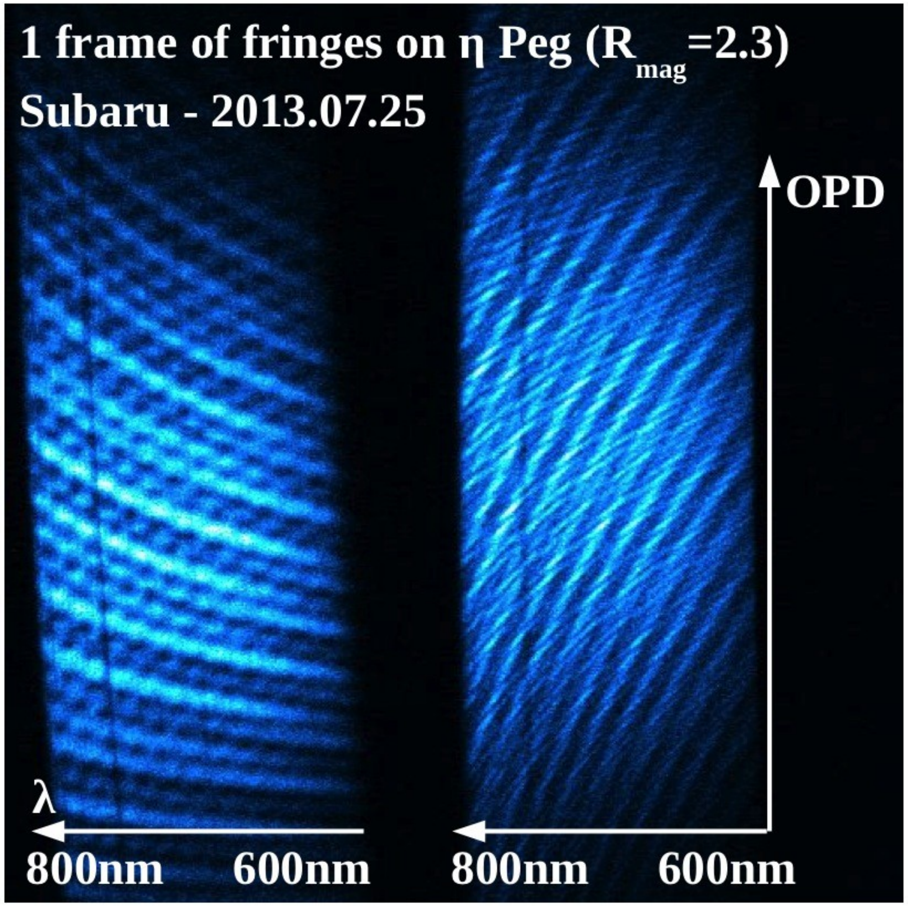
FIRST recombination bench



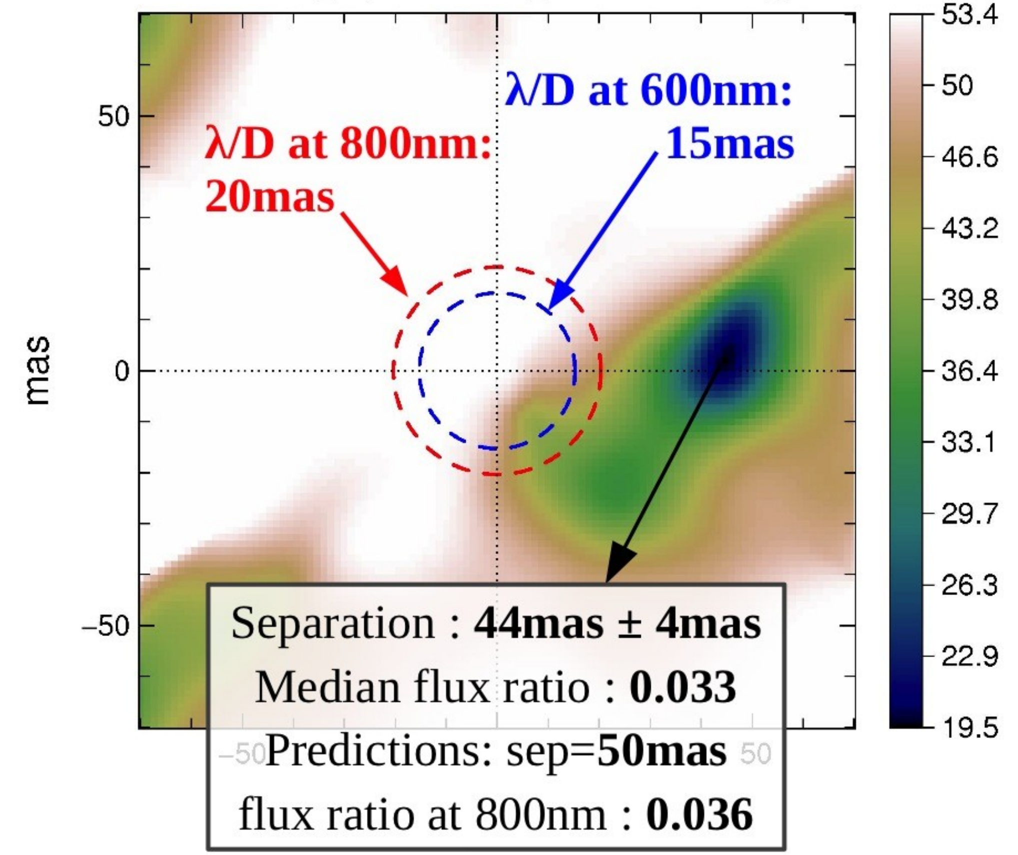
FIRST injection part



η Pegasi: Preliminary results



X^2 map (closure phase fitting)



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 : **R_{mag} < 3.5**

Preliminary analysis
of Subaru data taken on July 25th 2013

Median CP statistical error : **0.8°**

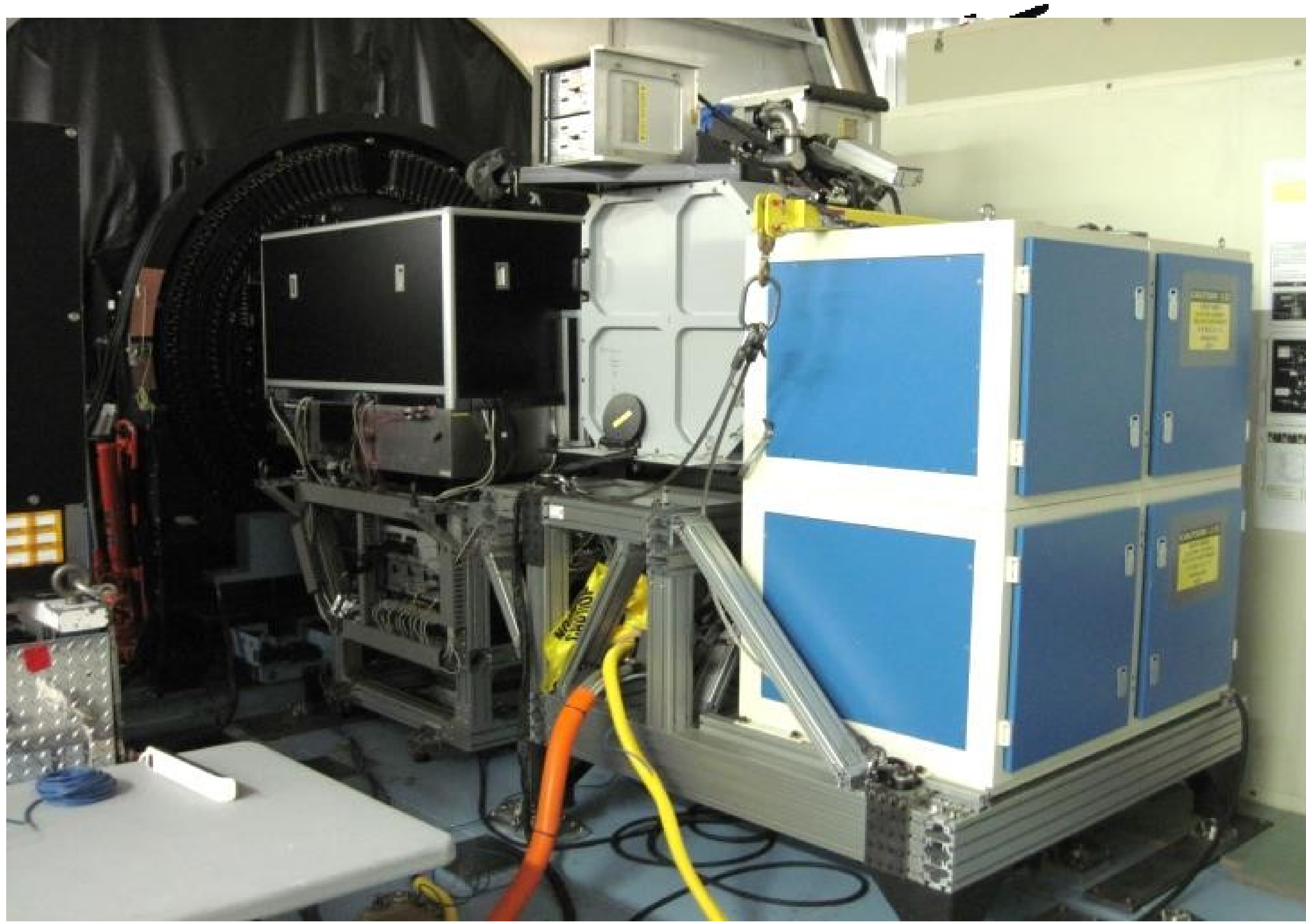
Median CP systematic error : **1.0°**

→ detection limit (4σ) : 240 at λ/D

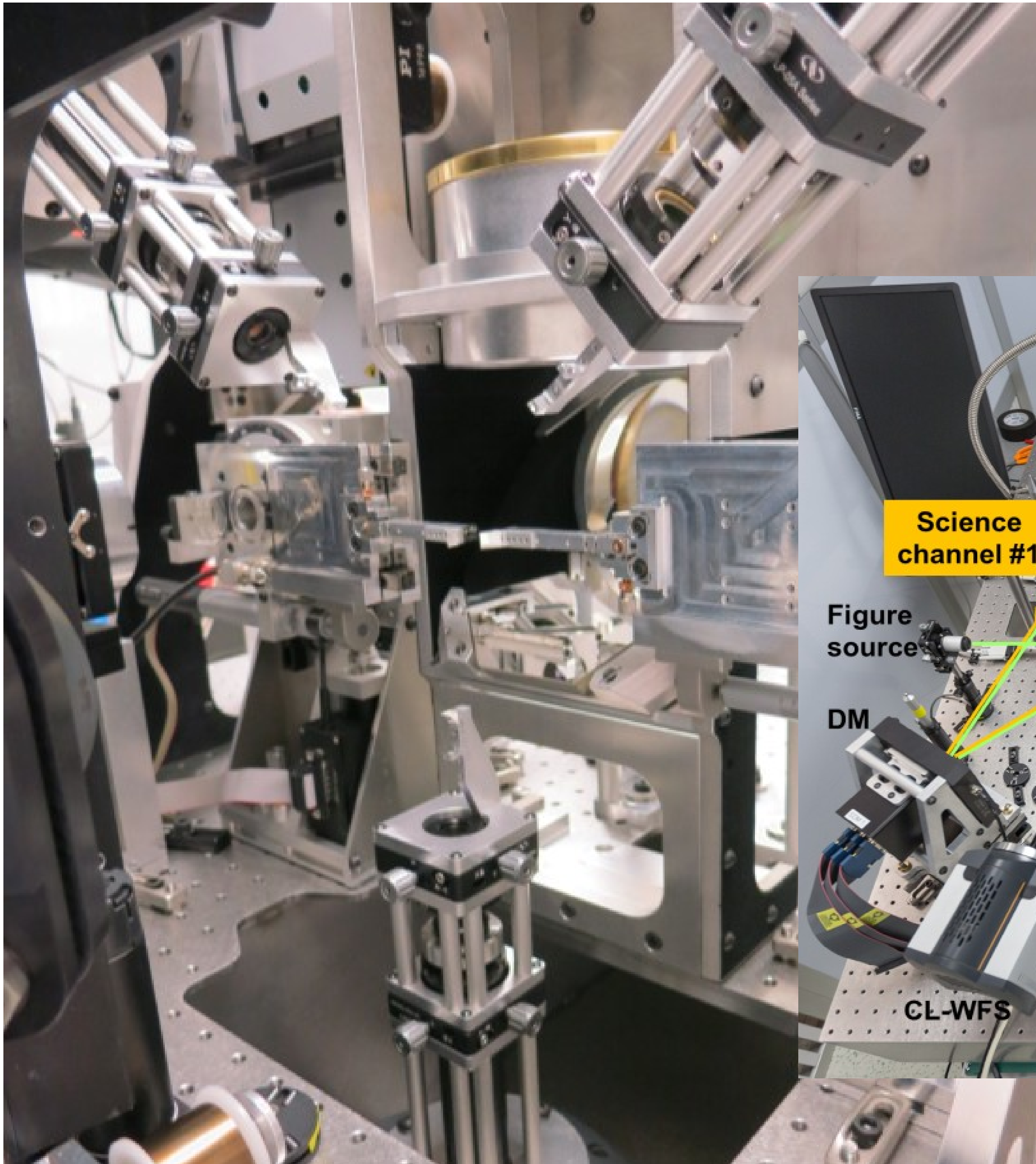
Sensitivity limit : **R_{mag} < 4.5**

RAVEN

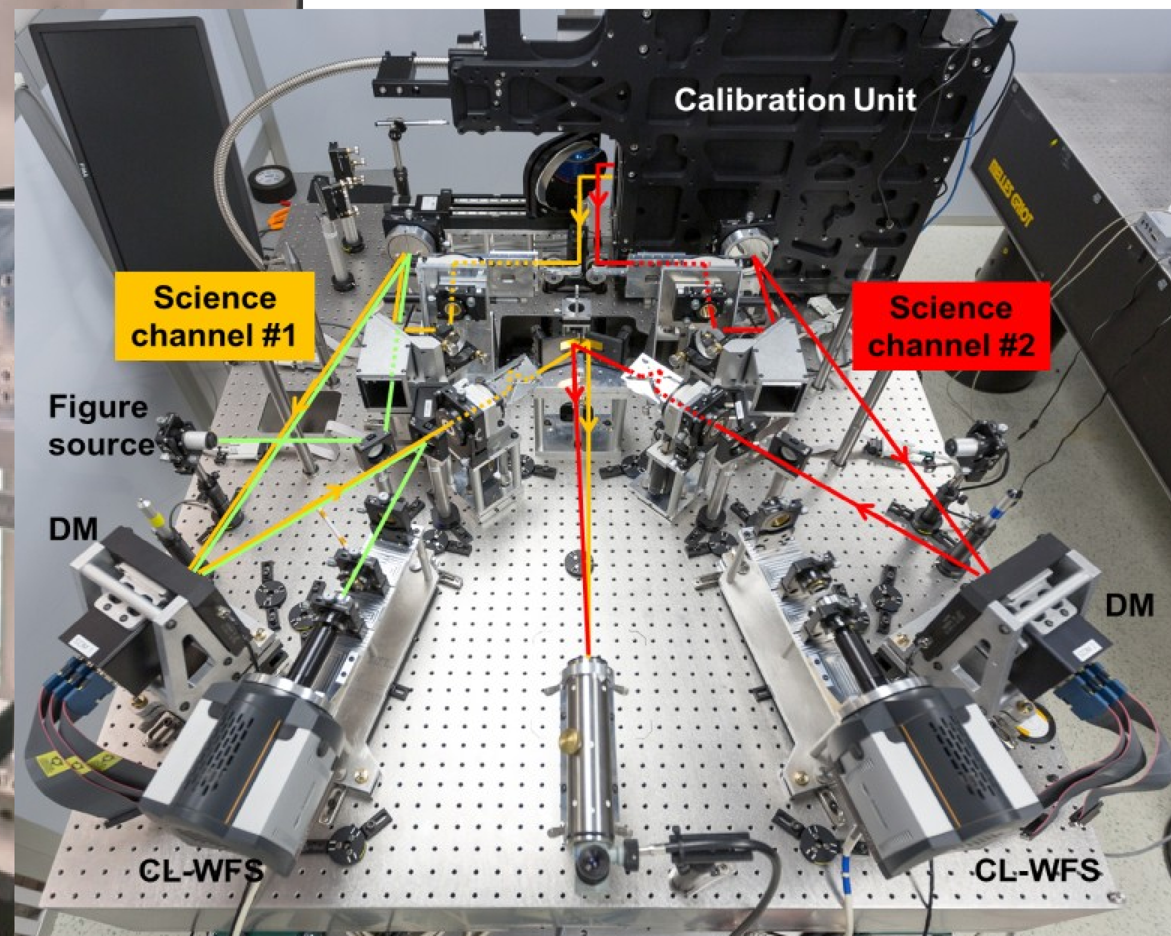
Olivier Lardière, Dave Andersen, Célia Blain, Colin Bradley, Darryl Gamroth, Kate Jackson, Reston Nash, Kim Venn, Jean-Pierre Véran, Carlos Correia, Shin Oya, Yutaka Hayano, Hiroshi Terada, Yoshito Ono, Masayuki Akiyama



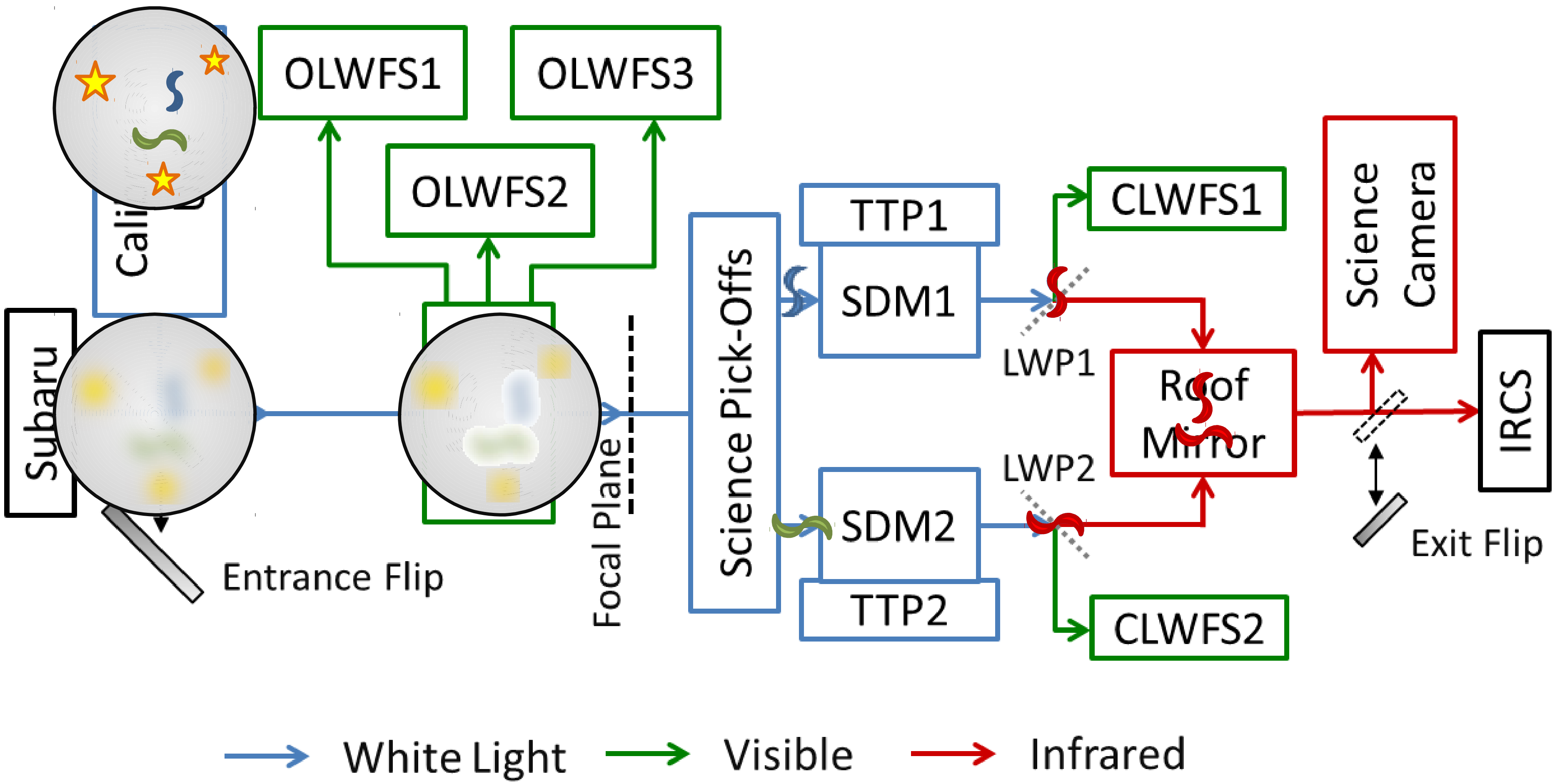
3 open loop WFSs



2 science channels



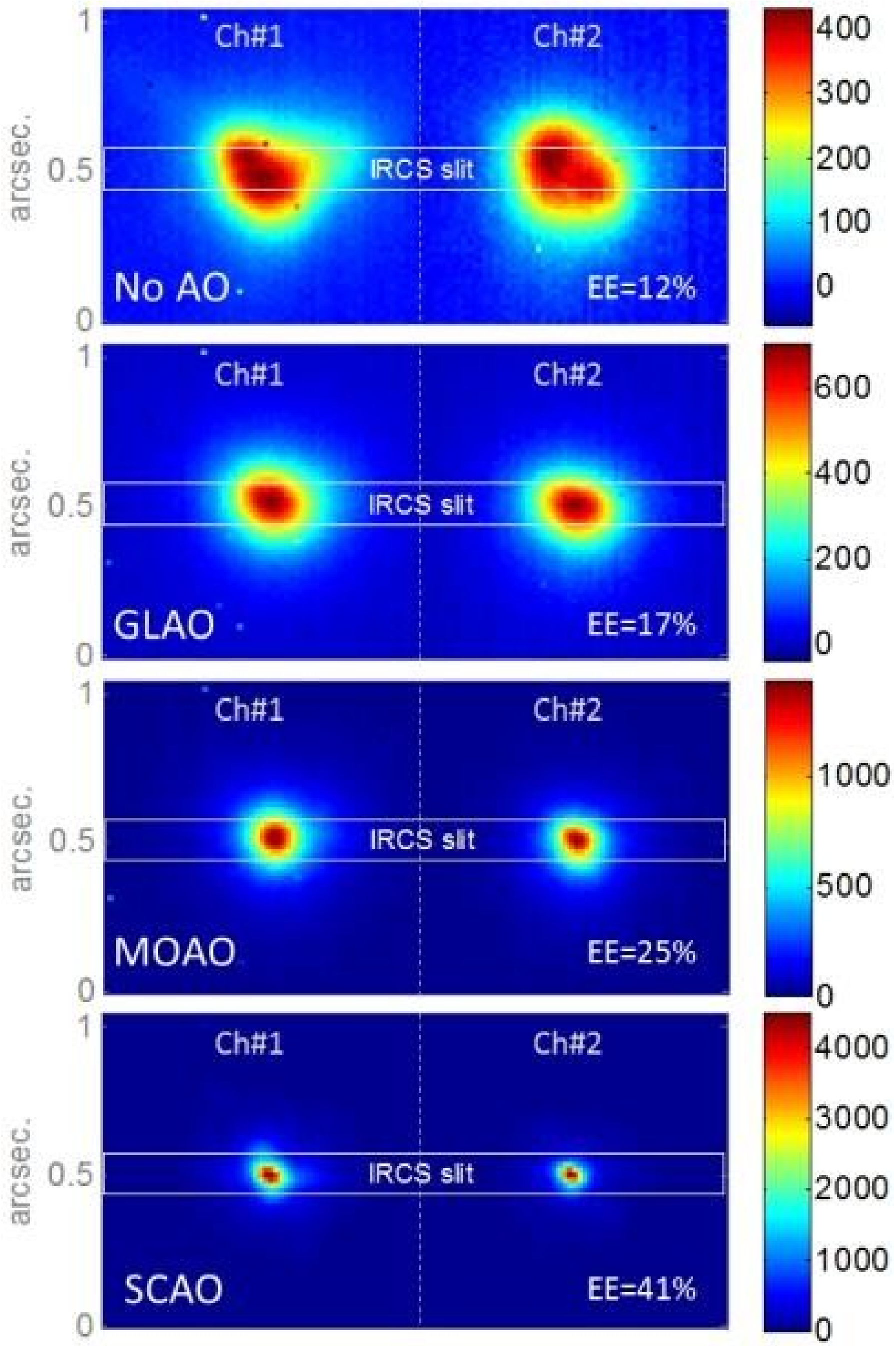
Raven Concept



- 10x10 0.4”pixel SH-WFS
- 13x13 (11x11 in pupil) actuator ALPAO DMs
- No derotator, no ADC in front of Raven

Slide from R. Nash

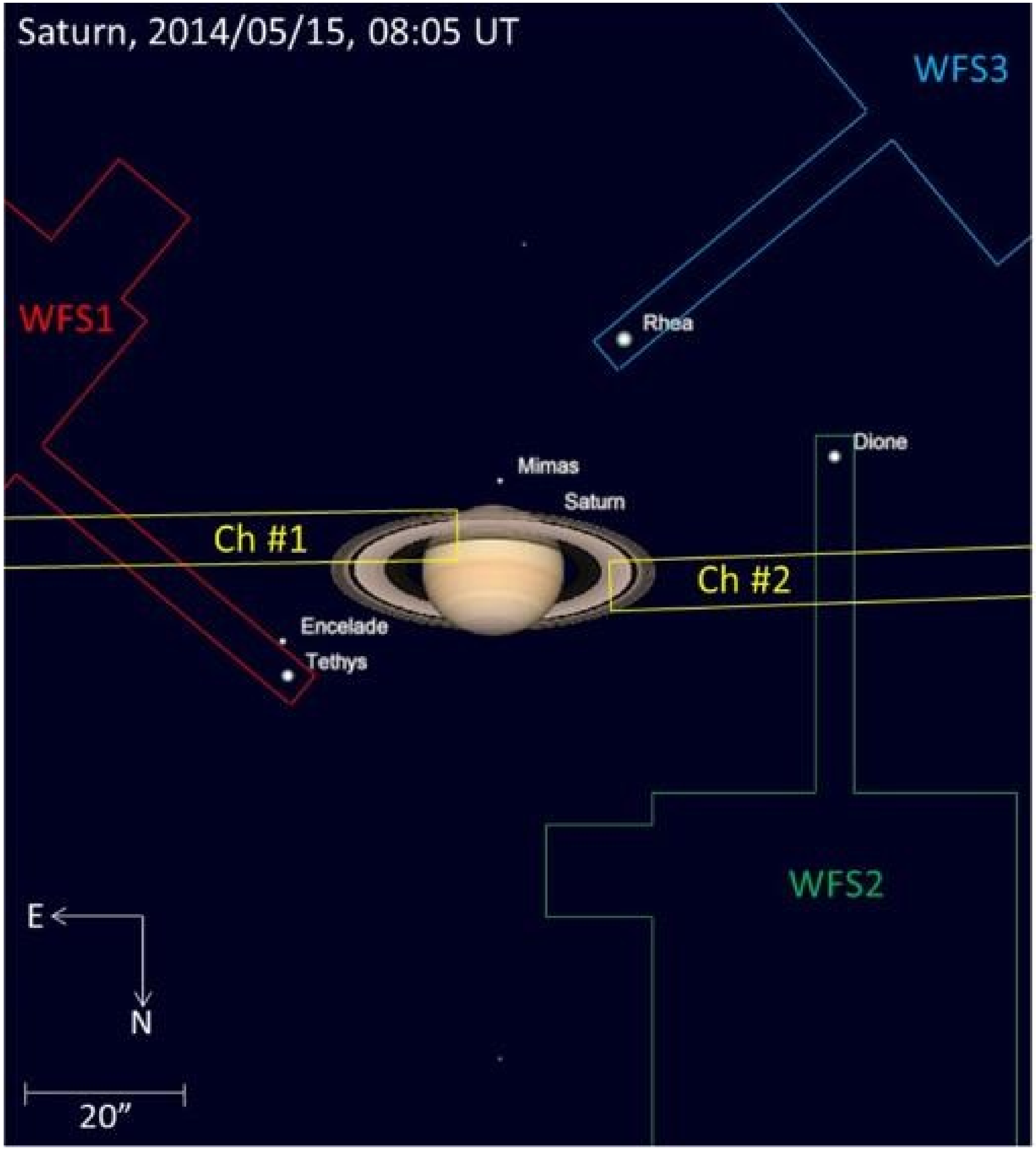
On-sky Preliminary Results

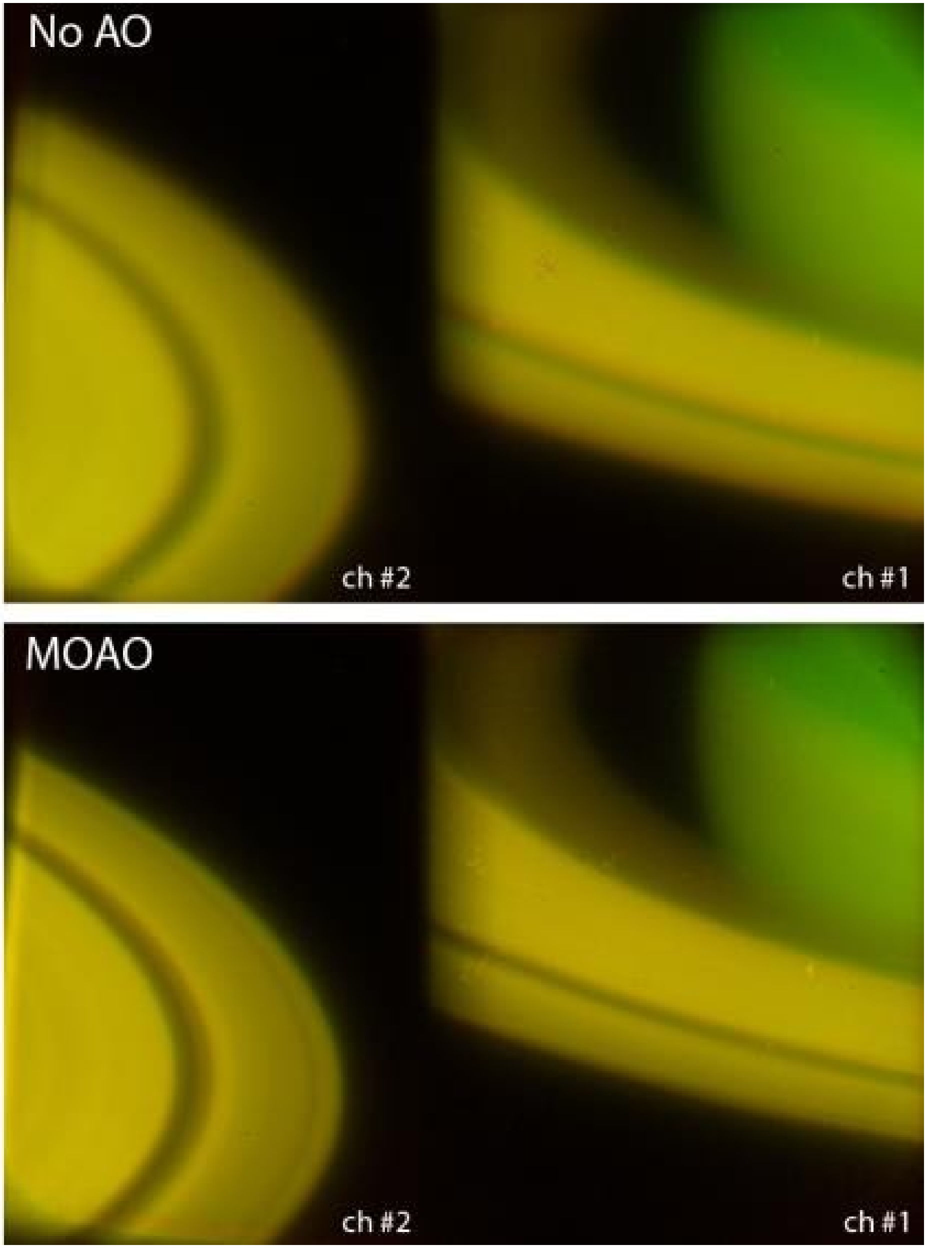


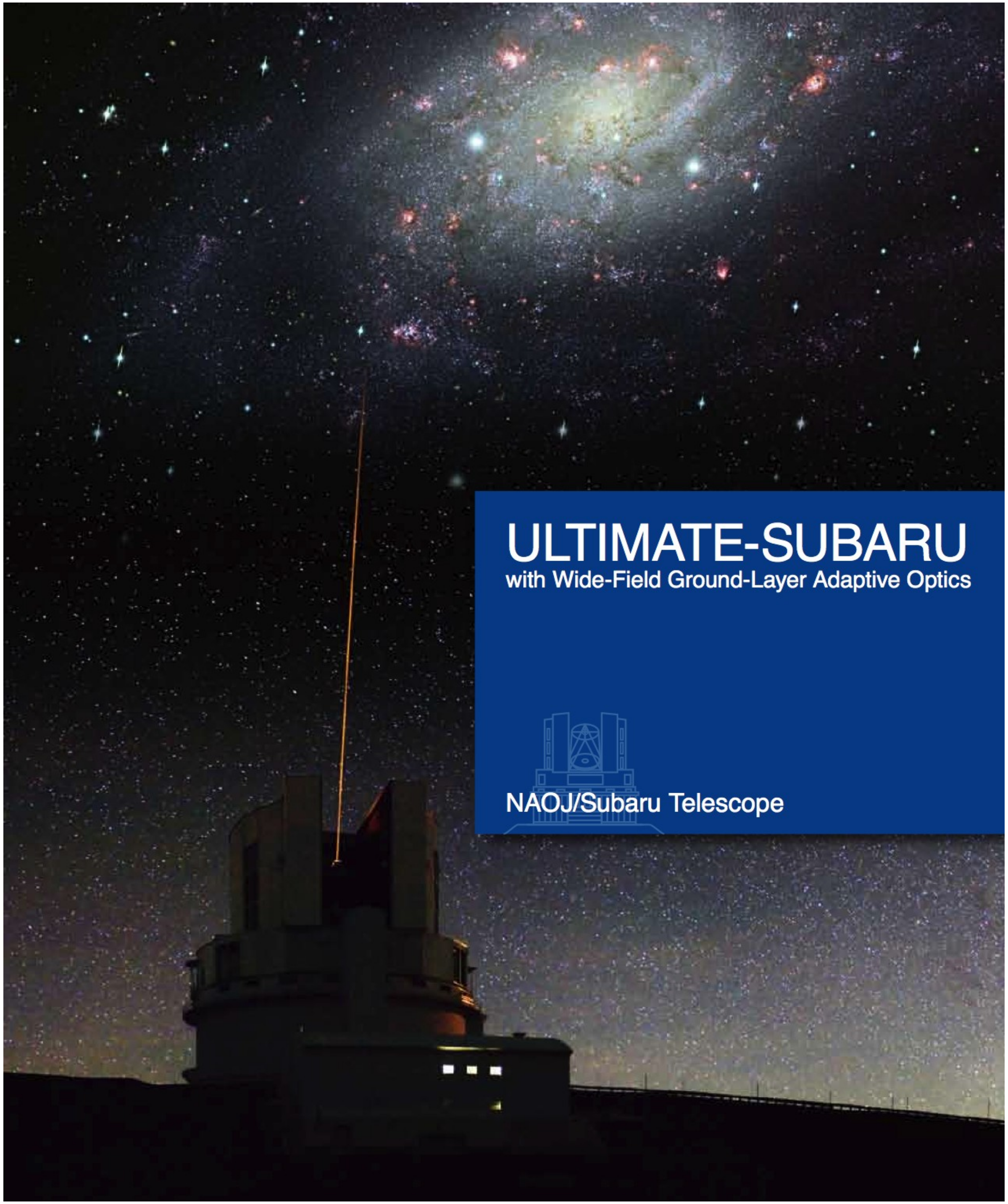
AO mode	On-sky Ch1	On-sky Ch2	In-Lab *Both ch.*	Simulation Ch1	Simulation Ch2
No AO	13.1	12	9.7	-	-
GLAO	15.6	17	17.9	-	-
model MOAO	22.9	25	29.0	28	34
L&A MOAO	23.2	30	-	28	34
SCAO	32.2	41	44.8	-	-

%EE in 140mas in J-band

MOAO Results on Saturn







Ultra-wide-field
Laser
Tomographic
Imager and
MOS with
AO for
Transcendent
Exploration by
SUBARU telescope.

Primary Investigator
Nobuo Arimito (NAOJ)
(Director of Subaru Telescope)

Project Scientist
Tadayuki Kodama (NAOJ)

Project Manager
Yutaka Hayano (NAOJ)

System overview

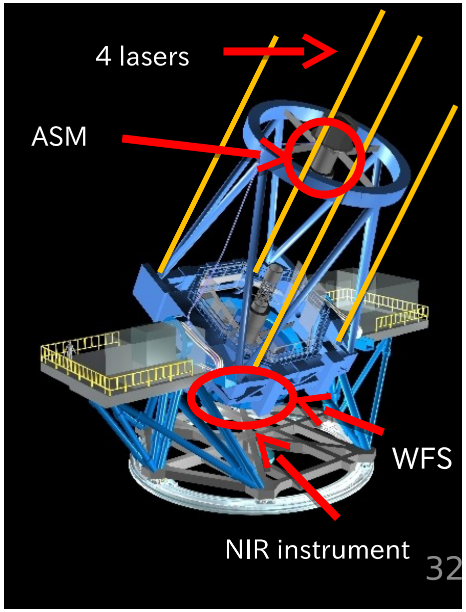
http://www.naoj.org/Projects/newdev/ngao/

1. Ground Layer AO with Adaptive Secondary Mirror (4 LGSs)
2. New Near-IR Instrument (Wide-field Imager + MOS)

→ Seeing Improvement (FWHM 0.4”→0.2”) over FOV >15’

- **High Spatial Resolution Competitive to HST at NIR**
- **Higher Sensitivity Equivalent to 2x Telescope Aperture*1**
- **6 Times Wider Field of View*2**

- Targeted to Start Operation in 2020

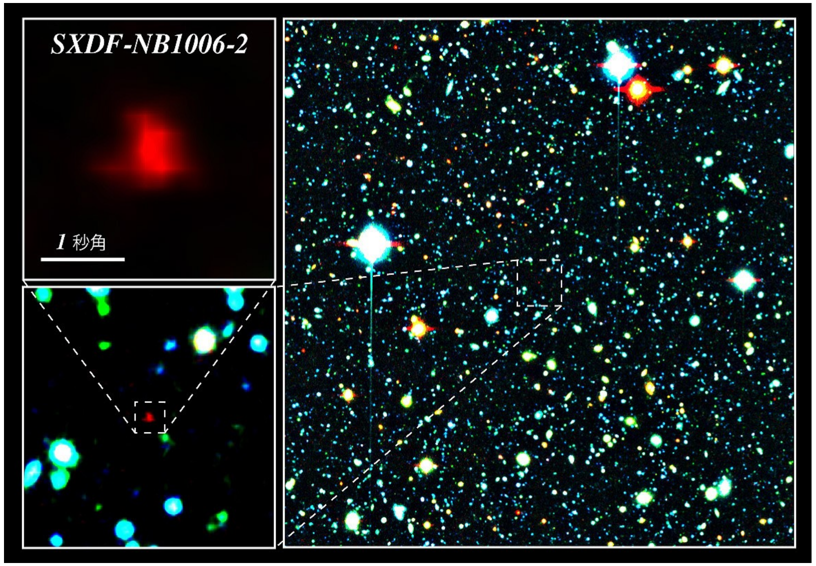


*1 For point sources.
*2 Relative to MOIRCS (seeing limited NIR instrument)

Key science goals

Discovery of the Most Distant Galaxies at z>7.5
Complete Census of the Galaxy Evolution

- Understand of the Cosmic Reionization
- NBF imaging survey (∽ 180 arcmin2), 100 galaxies.
- Target sample for TMT



z=7.215 Discovered by

Subaru/Suprime-Cam

(Shibuya+ 2012)

What are the key parameters to drive the galaxy evolution?
What determines morphologies of the galaxies?

- Large-Scale Near-IR Surveys (Imaging and spectroscopy) of about 5000 galaxies at z = 1 – 3.
- Morphological information (size, radial profiles, color distributions), star forming regions, large scale structure and environmental effect by wide-field imaging.
- Kinematics, Inflows and Outflows, SFR, Chemical compositions by multi-object spectrograph.

Prepared by T. Kodama

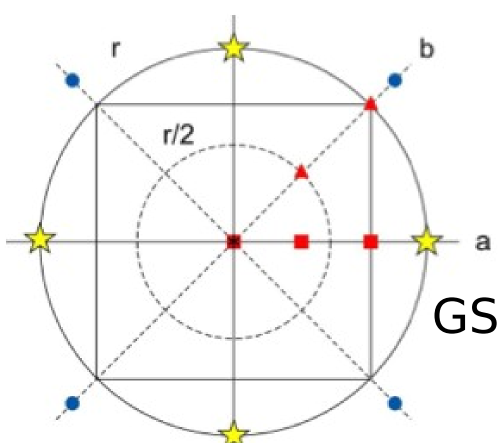
GLAO simulation

percentile	25%-ile	50%-ile	75%-ile
seeing	(good)	(moderate)	(bad)
height	fractional contribution		
0 km	0.4777	0.5507	0.5000
0.06 km	0.2055	0.1957	0.1872
0.5 km	0.0394	0.0605	0.0860
1 km	0.0137	0.0204	0.0359
2 km	0.1107	0.0234	0.0400
4 km	0.0488	0.0546	0.0518
8 km	0.0313	0.0429	0.0556
16 km	0.0731	0.0518	0.0435
$\int C_N^2 \times 10^{-13}\mathrm{m}^{1/3}$	3.5749	5.2736	8.1315
$r_0(0.5\mu\mathrm{m})$	14.9cm	11.8cm	9.1cm
fwhm(0.5μm)	0.56"	0.73"	0.97"
fwhm(AG)	0.49"	0.64"	0.84"

Add to match seeing statistics at Subaru.

TMT site test at 13N

Turbulence profile



★ : LGS (10mag)、● TTFGS (18mag)

GS asterism

FWHM

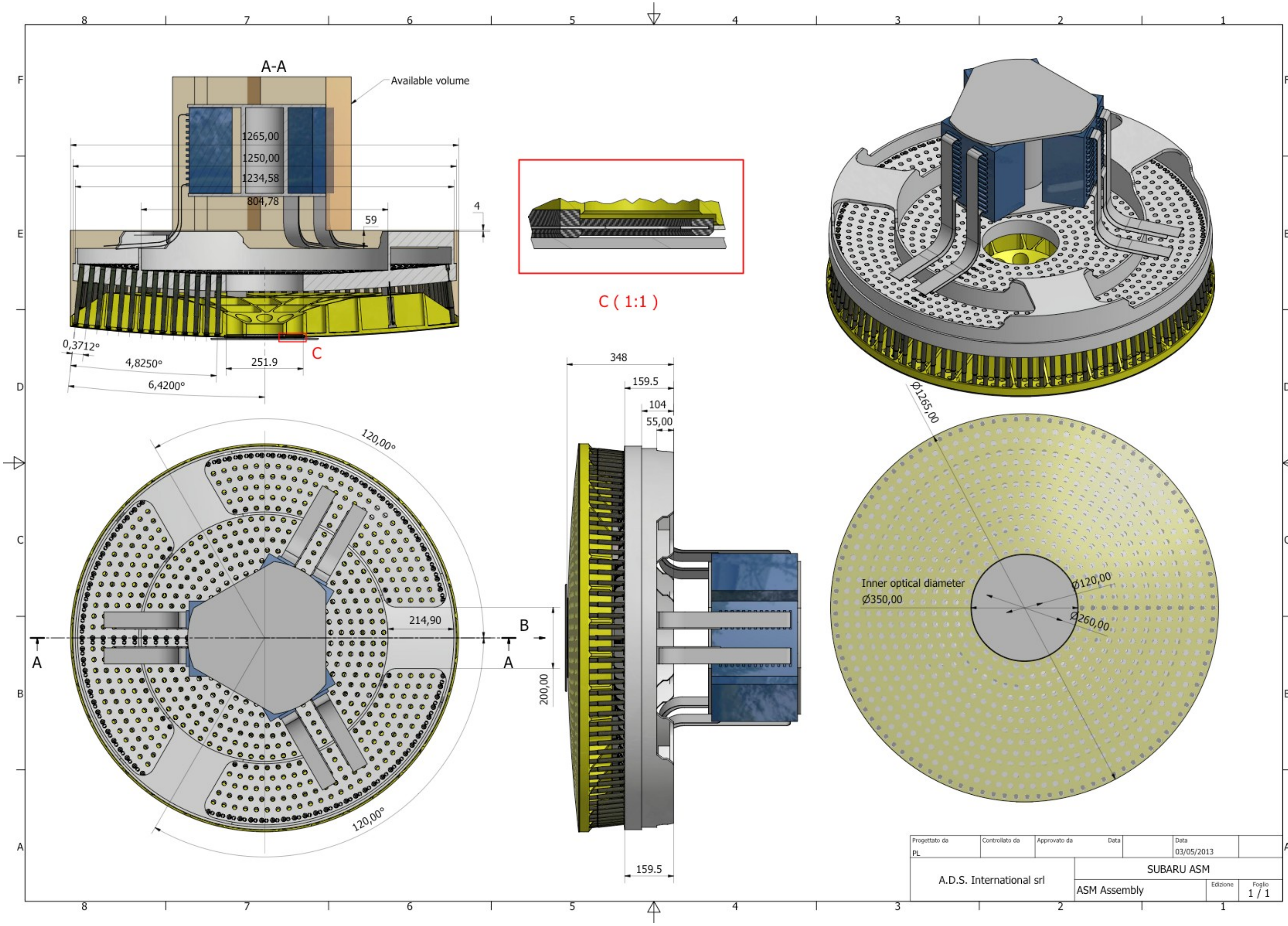
	R	J	H	K
Seeing	0.65"	0.51"	0.49"	0.44"
GLAO	0.41"	0.27"	0.23"	0.20"

Ensquared Energy (0.24"x0.24")

	R	J	H	K
Seeing	9%	12%	15%	17%
GLAO	16%	29%	36%	41%

S. Oya

Preliminary model for ASM



Mirror Dia: 1265mm

Actuators: 924
Spacing: ~ 35 mm

Center obscuration: 350mm

MICROGATE

ADS
A.D.S. International

Conclusions

Current capabilities:
AO188 facility AO (NGS+LGS)
High contrast imaging (HiCIAO, SCExAO)

Active ongoing development in extremeAO / exoplanets
(SCExAO + associated instruments/modules)

Future telescope upgrade to provide GLAO correction over ~>10' FOV
(ULTIMATE-Subaru)

AO development at Subaru prepares ELT era:
Subaru Telescope = prime wide field facility for large FOV work not possible on ELTs, including target identification for ELTs
ExAO development → direct imaging and spectroscopy of habitable planets on ELTs