Shack-Hartmann光学系を用いた大気乱流分布測定 - すばる望遠鏡でのオンスカイ試験 -

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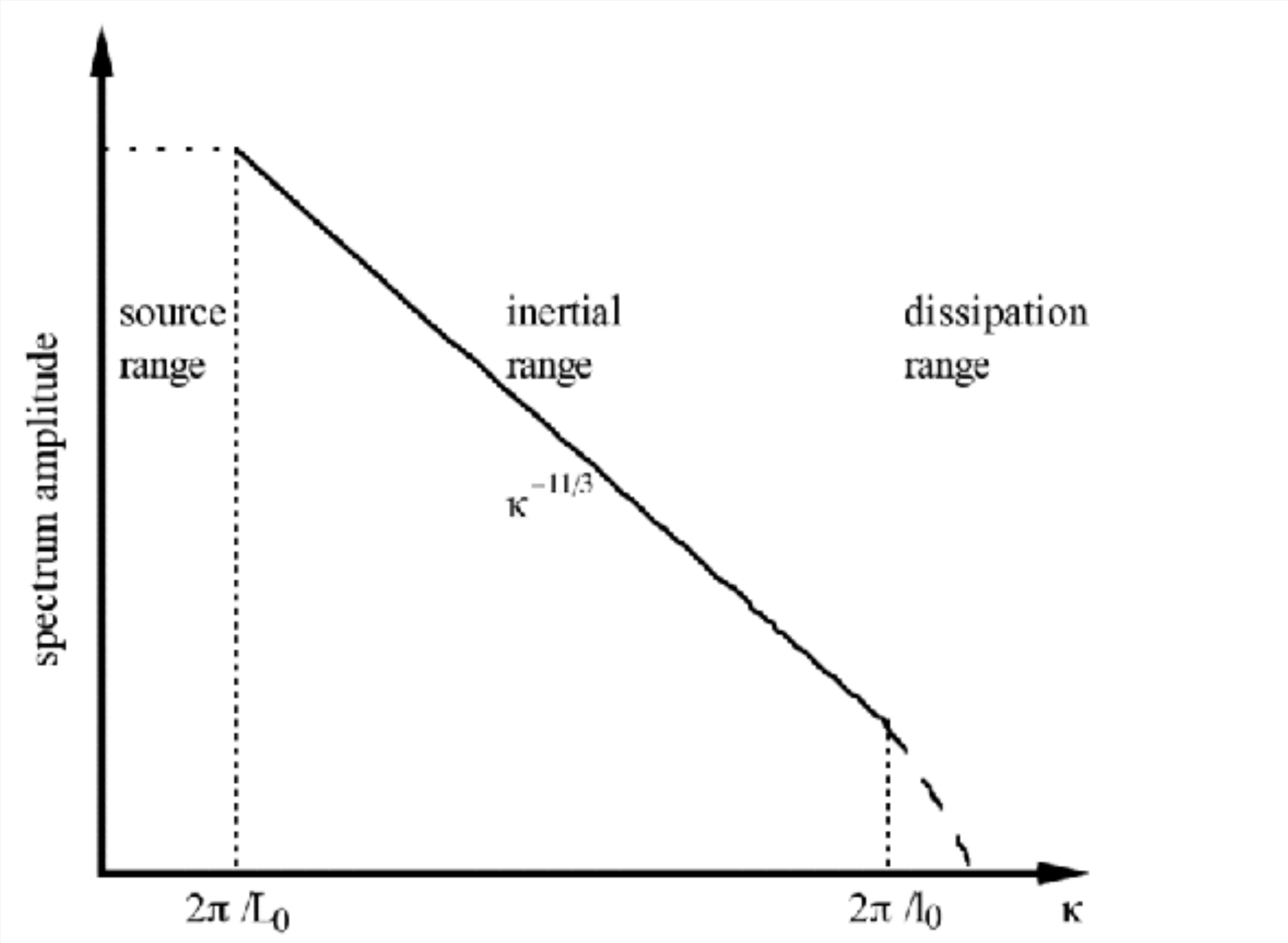
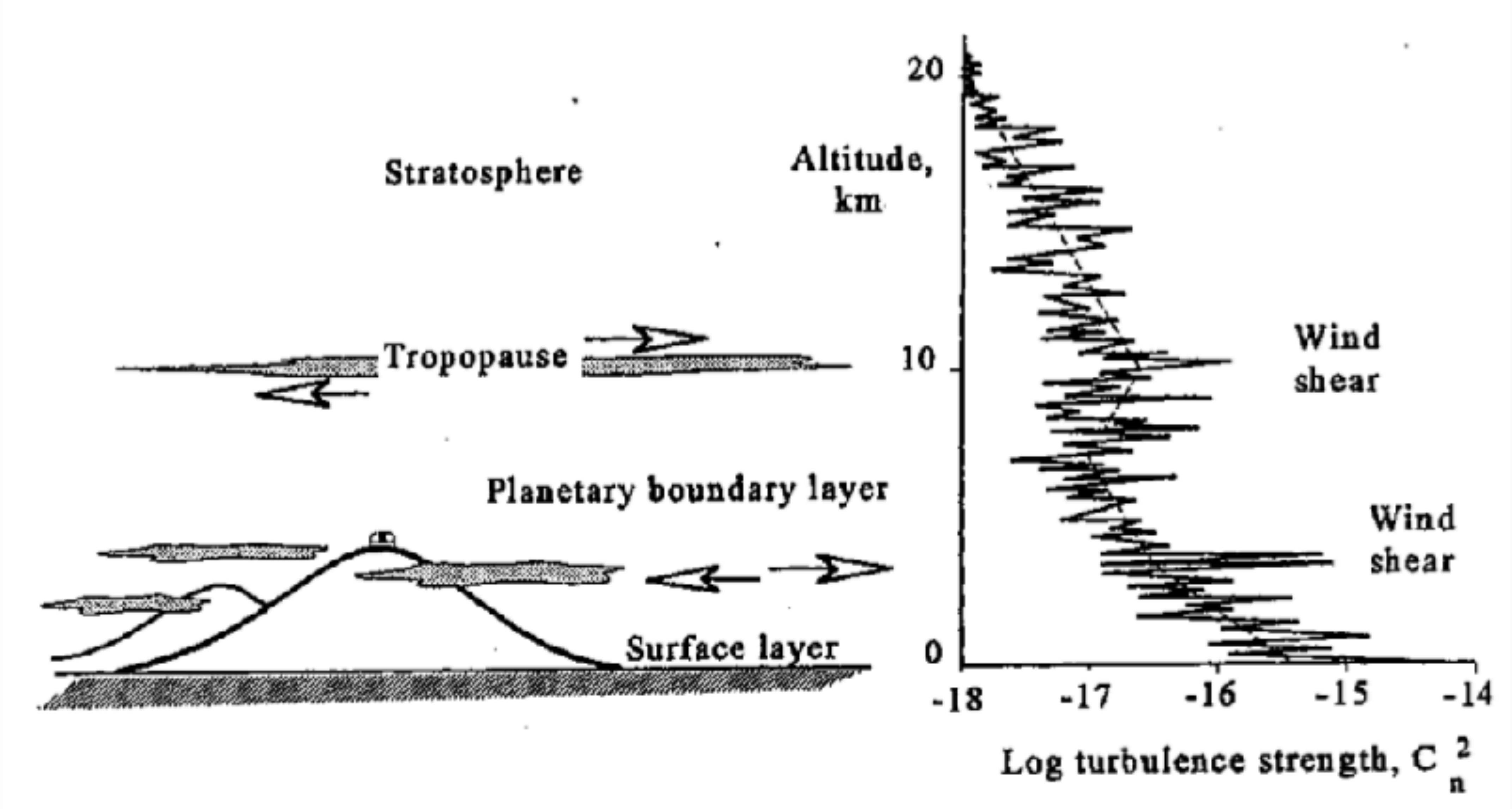
Power spectrum of atmospheric turbulence



Forssen et al. 2019
Hardy 1998



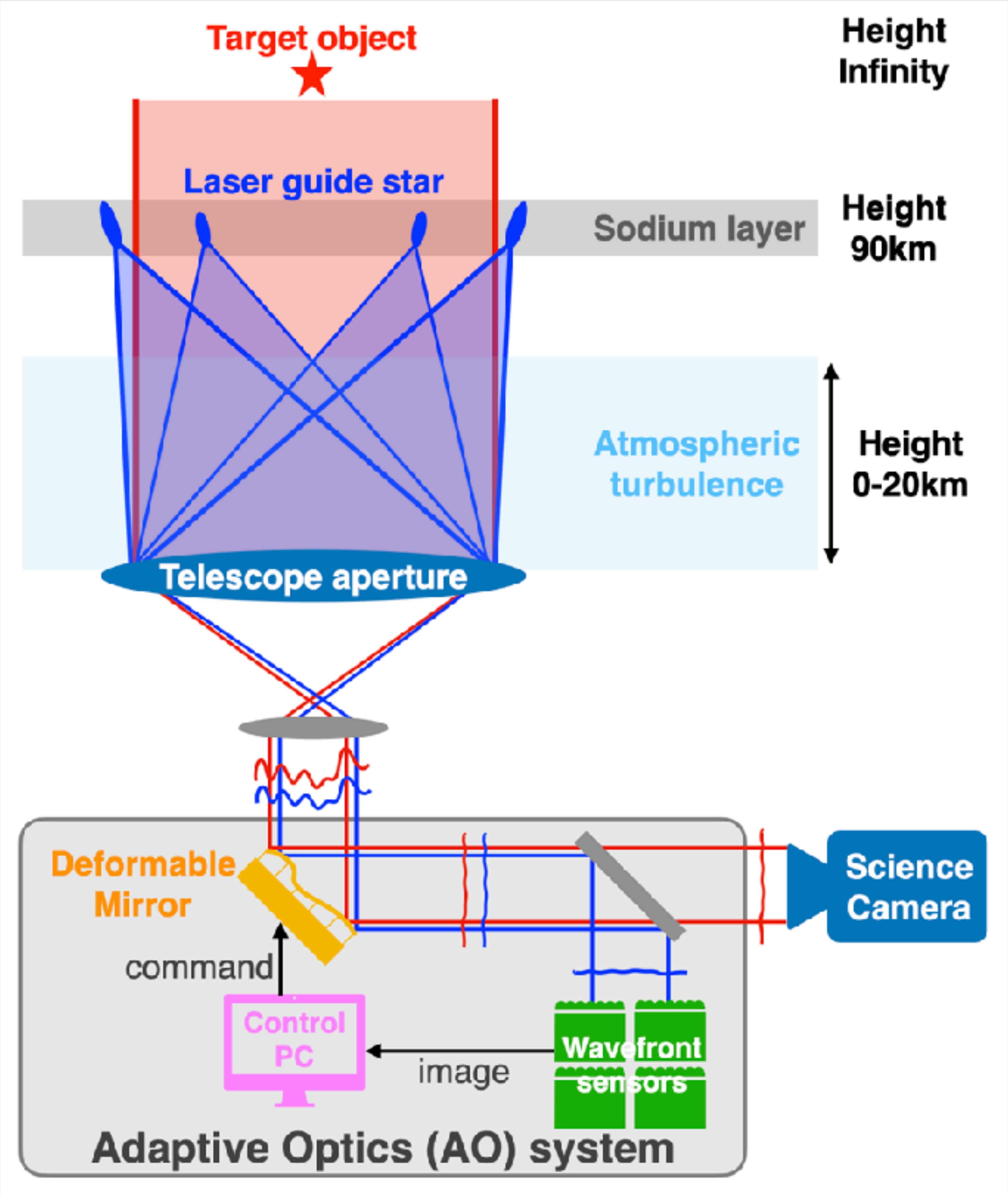
- Kolmogorov power spectrum

$$\Phi_N(f) = 9.7 \times 10^{-3} |f|^{-11/3} C_N^2 \ [\mathrm{m}^3]$$

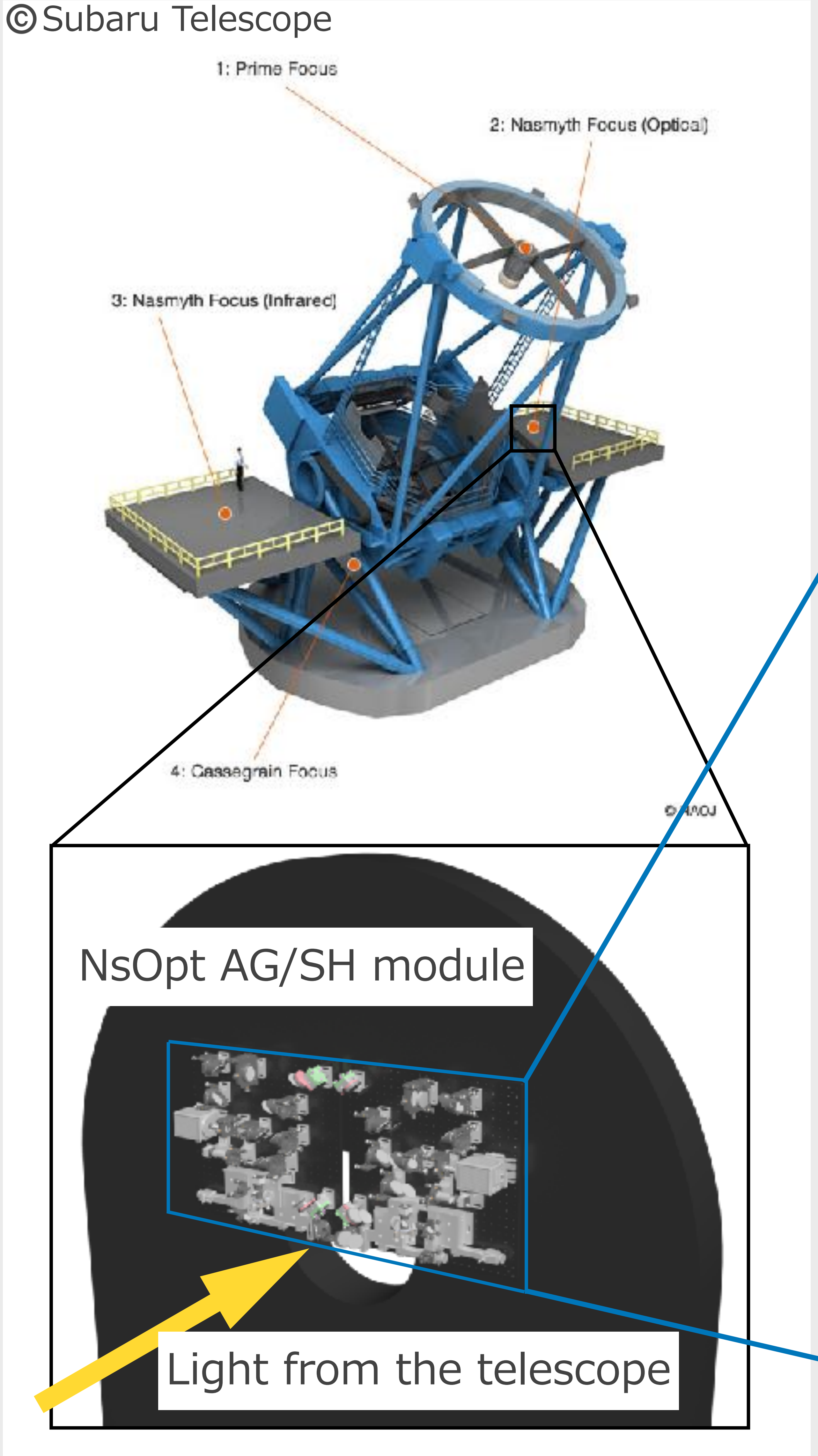
- $C_N^2(h)$: atmospheric turbulence profile
  - Site variation
  - Seasonal variation
  - Day-night variation
  - Tens-of-minutes variation

Turbulence profiling for AO w/ multiple GS

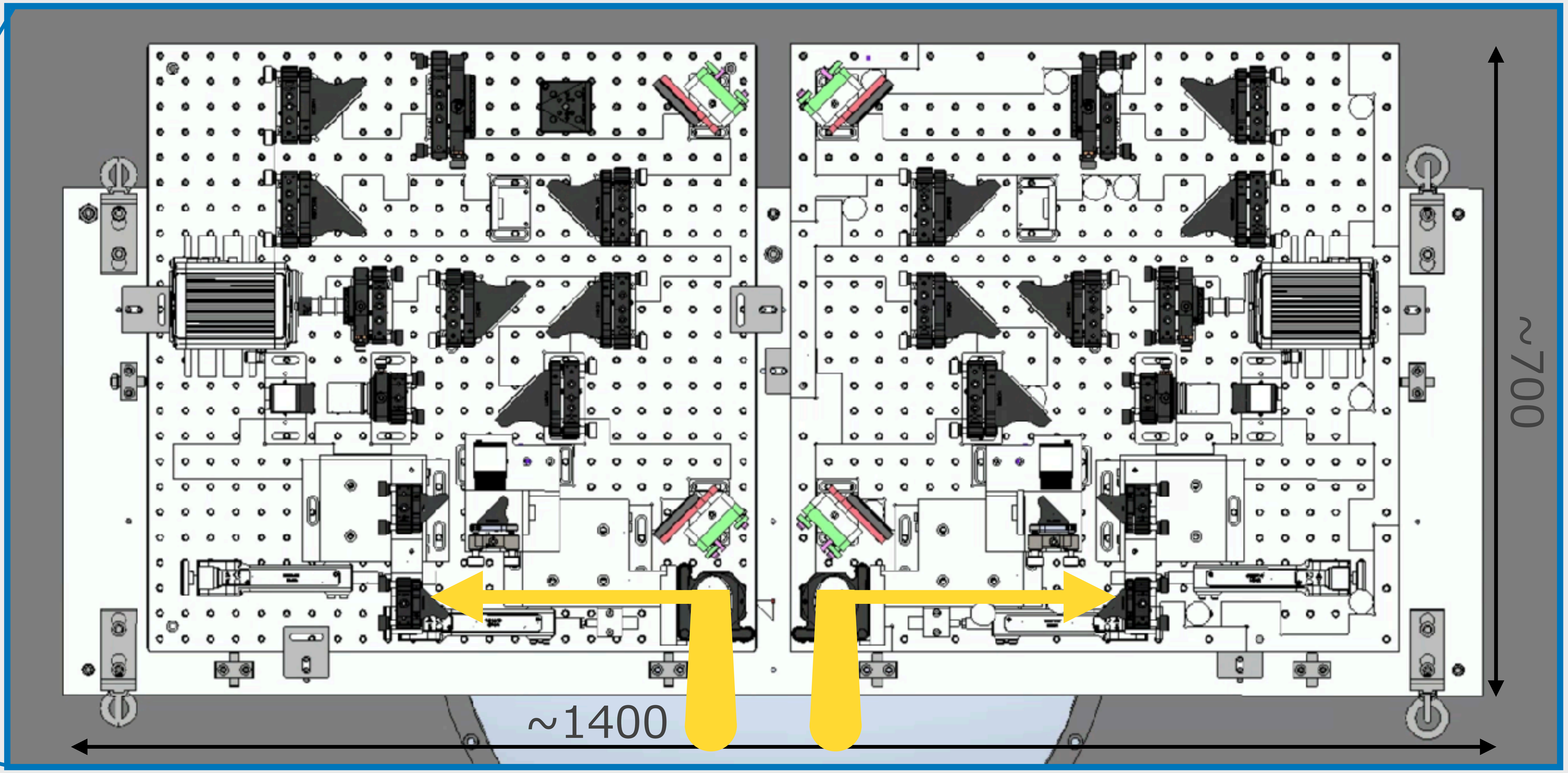
- Laser Tomographic AO (LTAO)
  - Multiple LGS measurement around target
  - Atmospheric tomography
    - A few, low-independent measurement
    - Turbulence profile as prior-information
- Ground Layer AO (GLAO)
  - Precise ground layer turbulence profile for performance simulation/evaluation



Turbulence profiling project



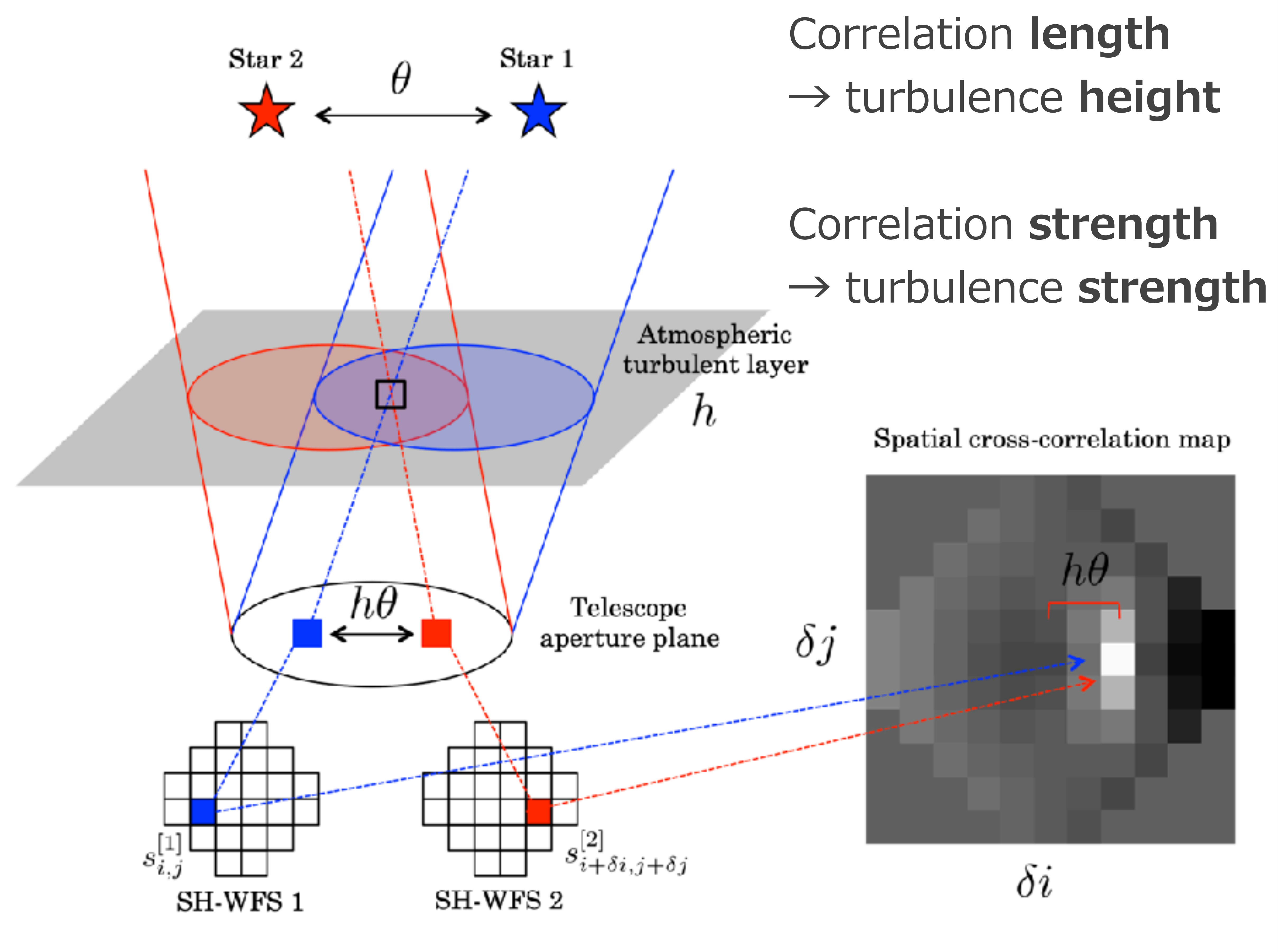
- Install on AG/SH module at Subaru Nasmyth-opt platform
- Consist of symmetric two Shack-Hartmann wavefront sensors



thickness~200mm, weight~100kg including baseplate

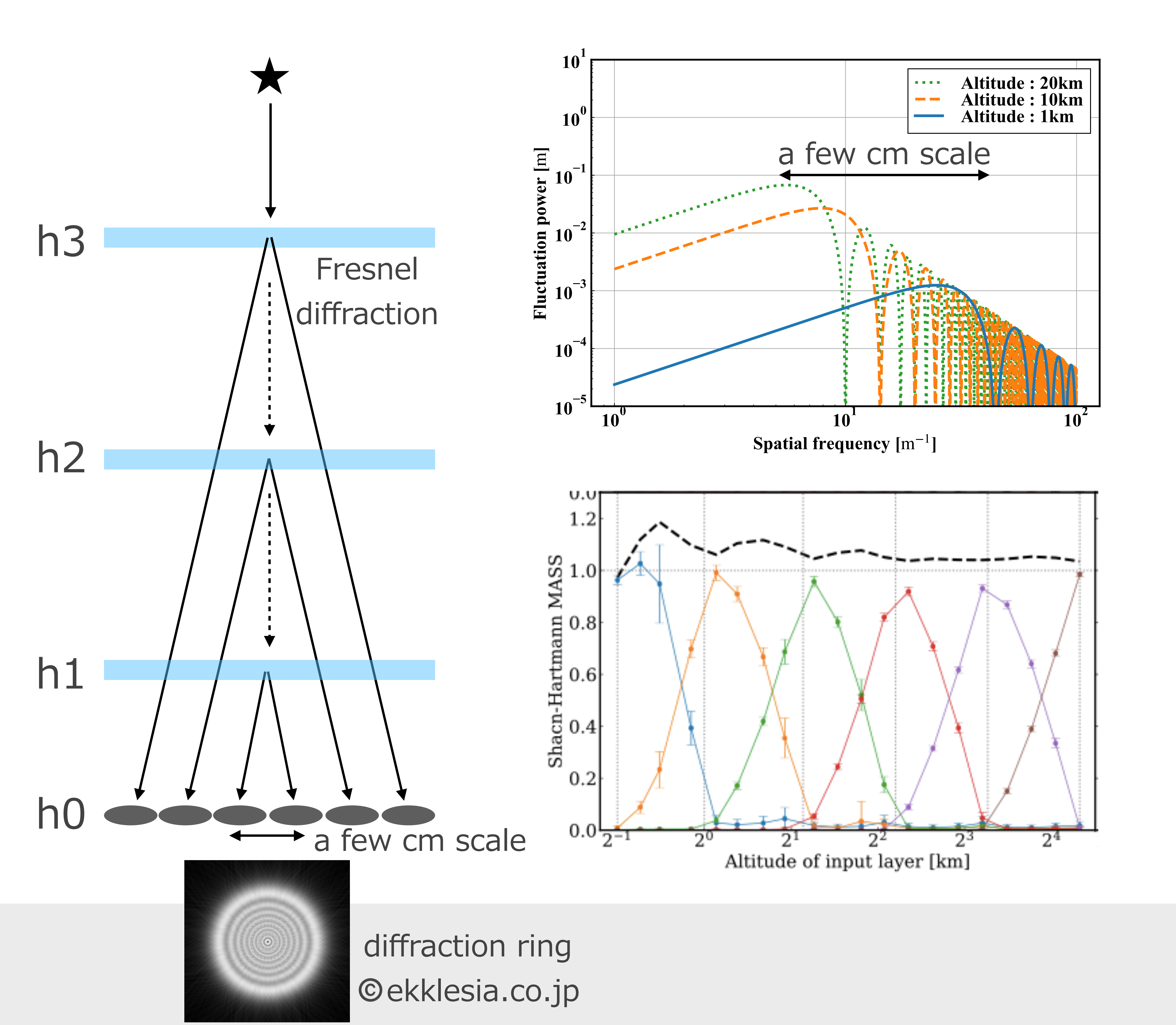
Ground layer profiling: SLODAR

- Slope detection and ranging (Wilson+2002)
- Principle
  - Common measurement of 2 WFSs
  - Measure spatial correlation of phase distortion between 2 stars
- Specification
  - Height resolution
    = subaperture size / star separation
  - Maximum hight
    = telescope size / star separation



Ono et al. 2016

Higher layer profiling: SH-MASS

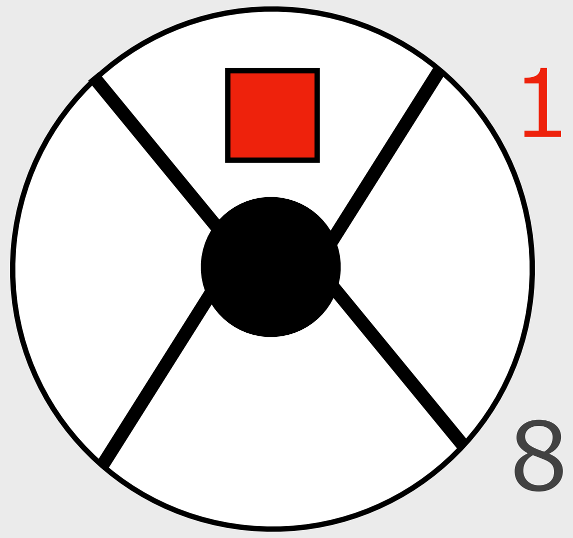


- Shack-Hartmann multi aperture scintillation sensor (Ogane+2021)
- Principle
  - Intensity pattern by Fresnel diffraction
  - Measure spatial correlation of intensity
- Specification
  - Height resolution ~ a few km
  - Minimum height ~ 0.5 km
- Limitation
  - Fine (~cm) spatial sampling is needed

Turbulence profiler design concept

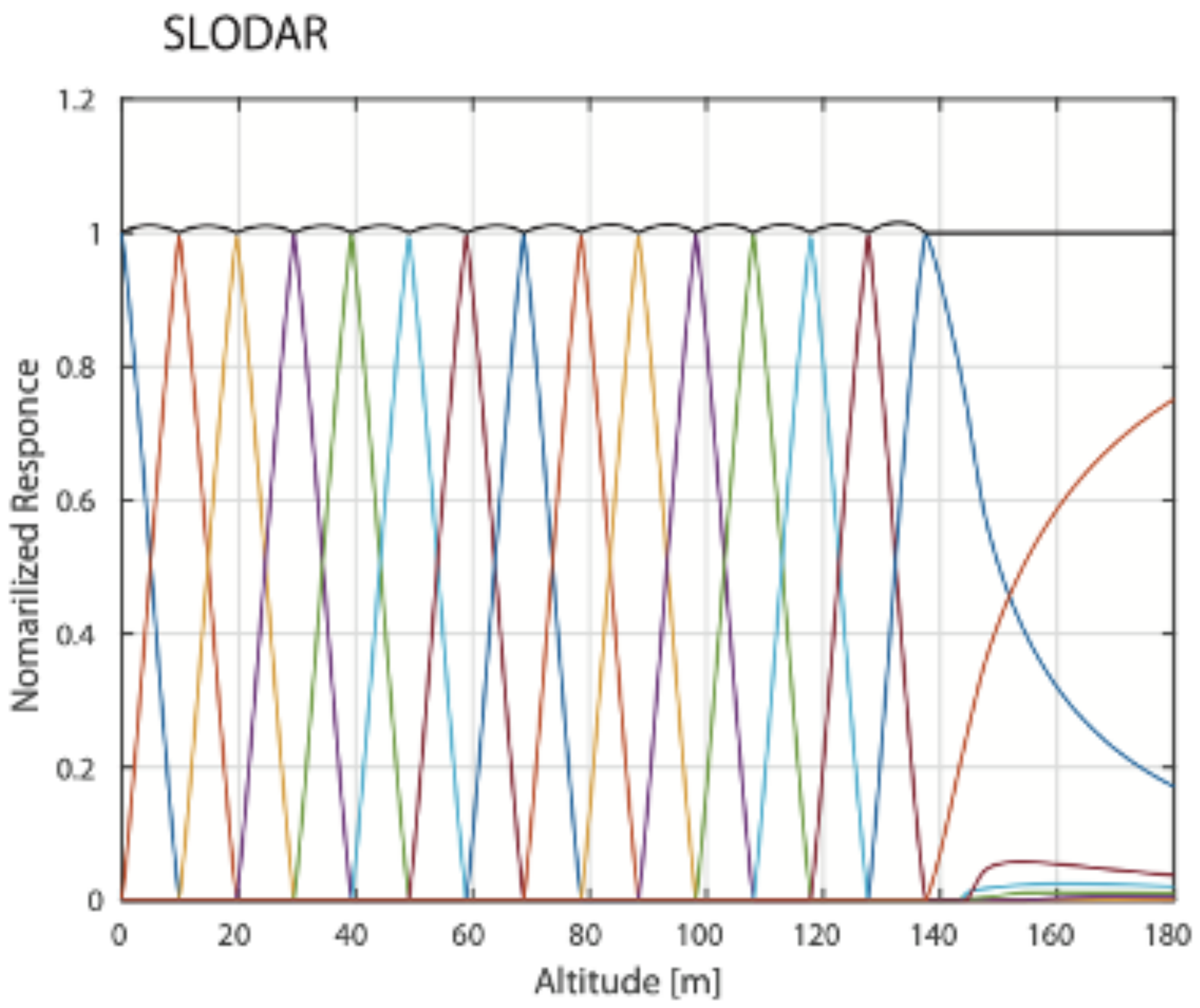
- Measurement condition
  - measurement SNR → larger than 5
  - separation of star pair → 3-5 arcmin
  - availability of star pair at any time

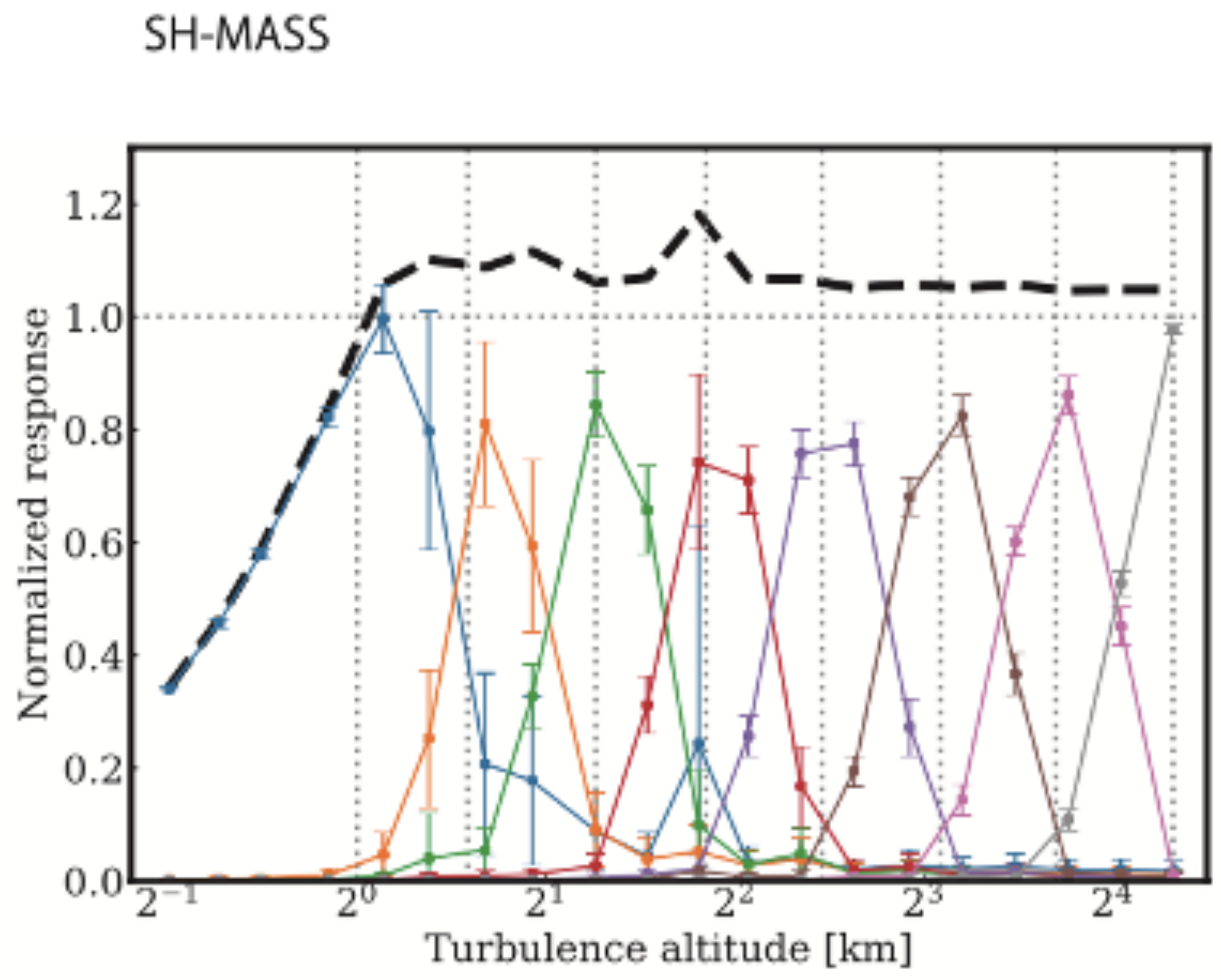
Optimal sub-aperture size is 2.0cm.
→ Only part of the Subaru's pupil is used.



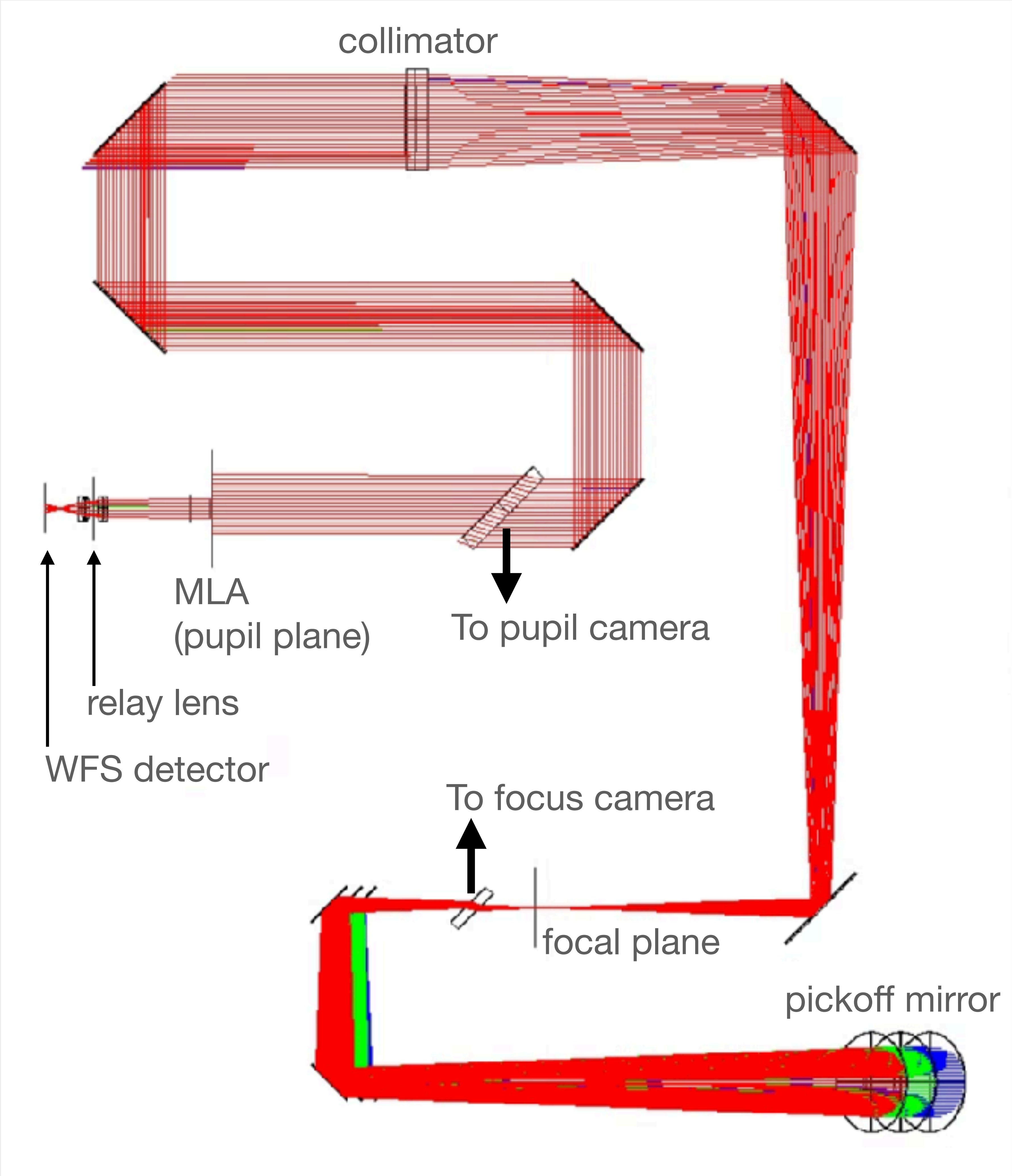
Turbulence profiler specification

	SLODAR	SH-MASS
Altitude range	<~300m	>~600m
Altitude resolution	~20m	a few km





Turbulence profiler optical design



Parameter	Design value	Note
Number of elements	66 x 66 (15 x 15)	when using all the lenslet
Subaperture size	2 cm	on primary mirror
Diffraction limit of subaperture	7.55 arcsec	at 600nm
Subaperture FoV	25 arcsec	
Pixel sampling	2.5 arcsec/pix	
Number of pixels per subaperture	10 pix	
Number of total pixels	660 pix (150 pix)	when using all the lenslet
Frame rate	200 fps (800 fps)	when reading 1k pix (256 pix)
Pixel size	6.5 um	*1
Read out noise	1.6 e/pixel	RMS value, *1
QE	82%	at 589nm, *1

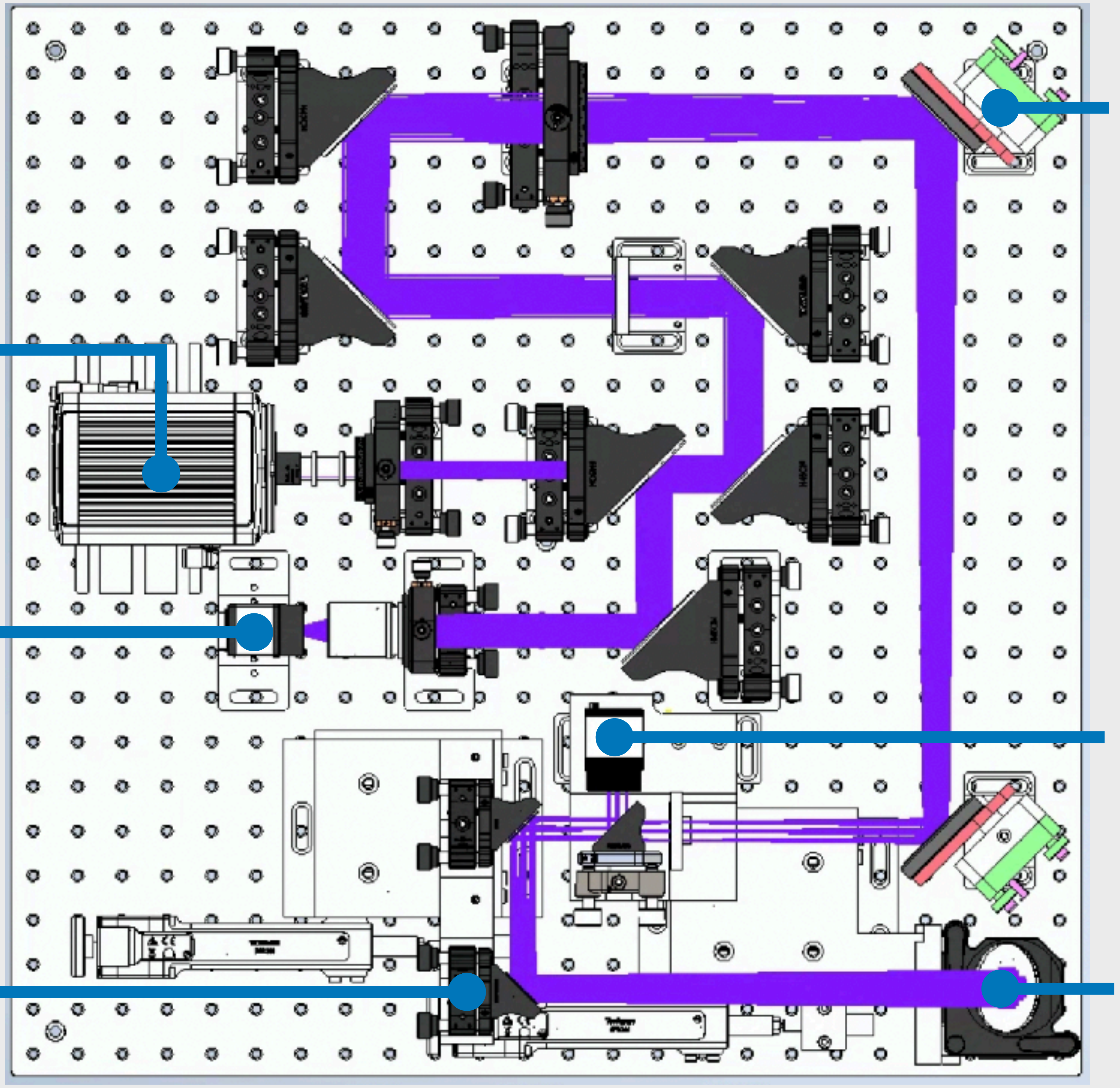
*1: Catalog value of Hamamatsu ORCA-Flash4.0 V2

Turbulence profiler mechanical design

Wavefront sensor: wavefront sensing of 1.4x1.4m pupil region with 66x66 division, 3pix/spot, 25arcsec/subap, 2kx2k pixels

Pupil camera: check pupil to match pupil between the two WFSs, Φ3m FoV, 2kx2k pixels

Focus adjustment mirror: adjust focusing of the target

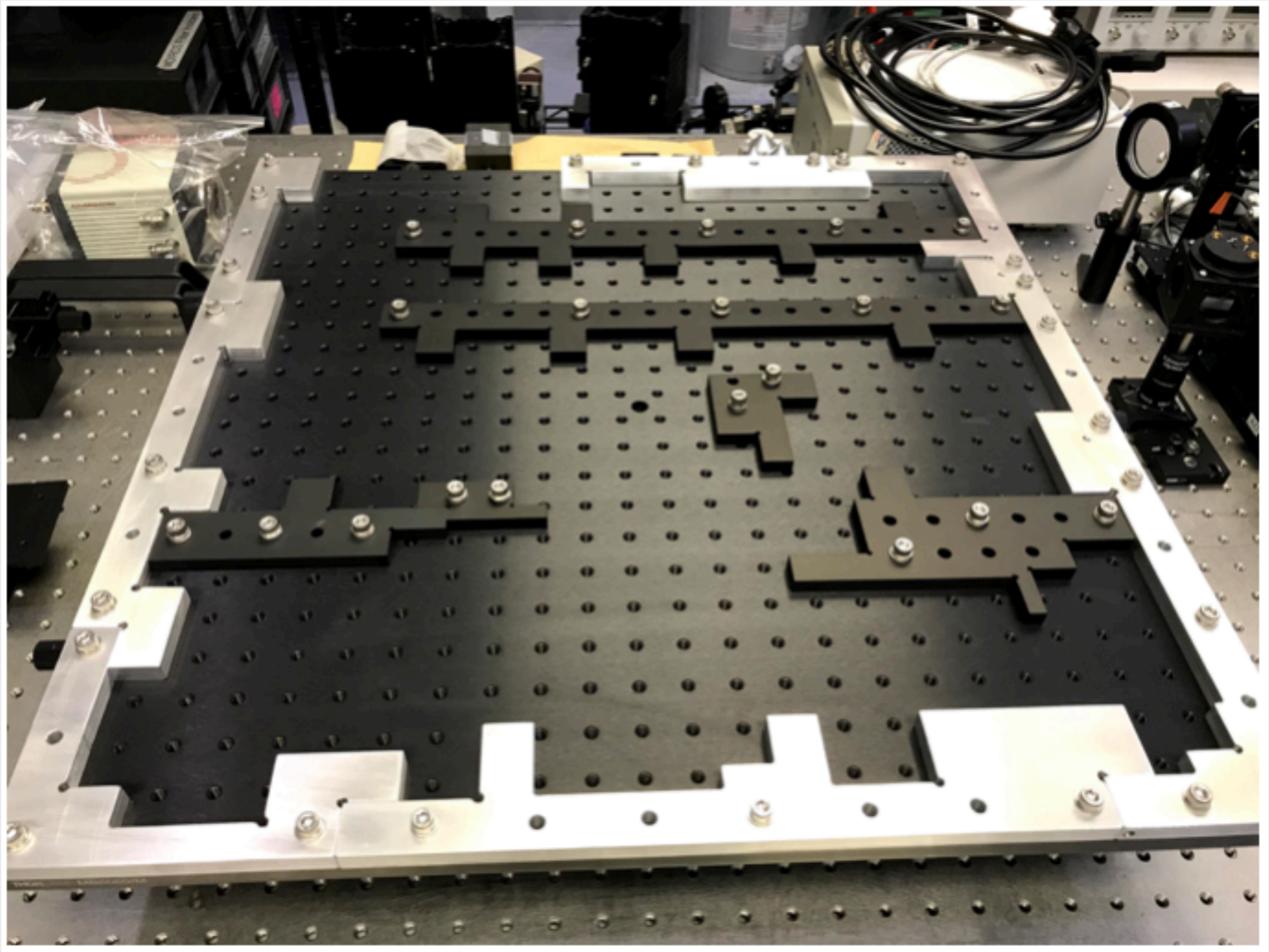


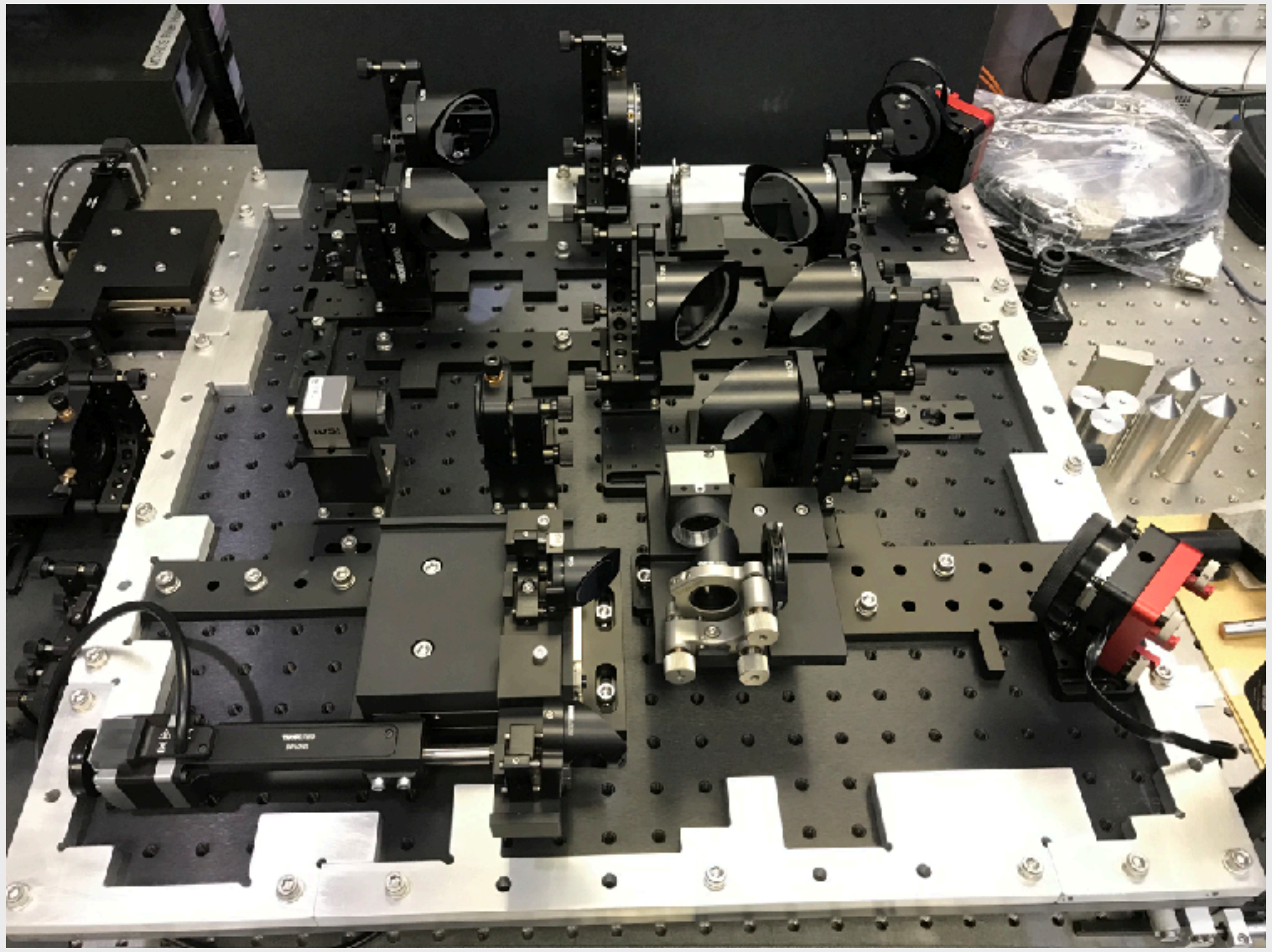
Pupil adjustment mirror pair: define Φ3m pupil to introduce collimator

Focus camera: check acquisition and focusing of the target, 10x10 arcsec FoV, 1kx1k pixels

Pickoff mirror: pickoff target at 1.5-2.5 arcmin from the telescope optical axis

Laboratory assembly



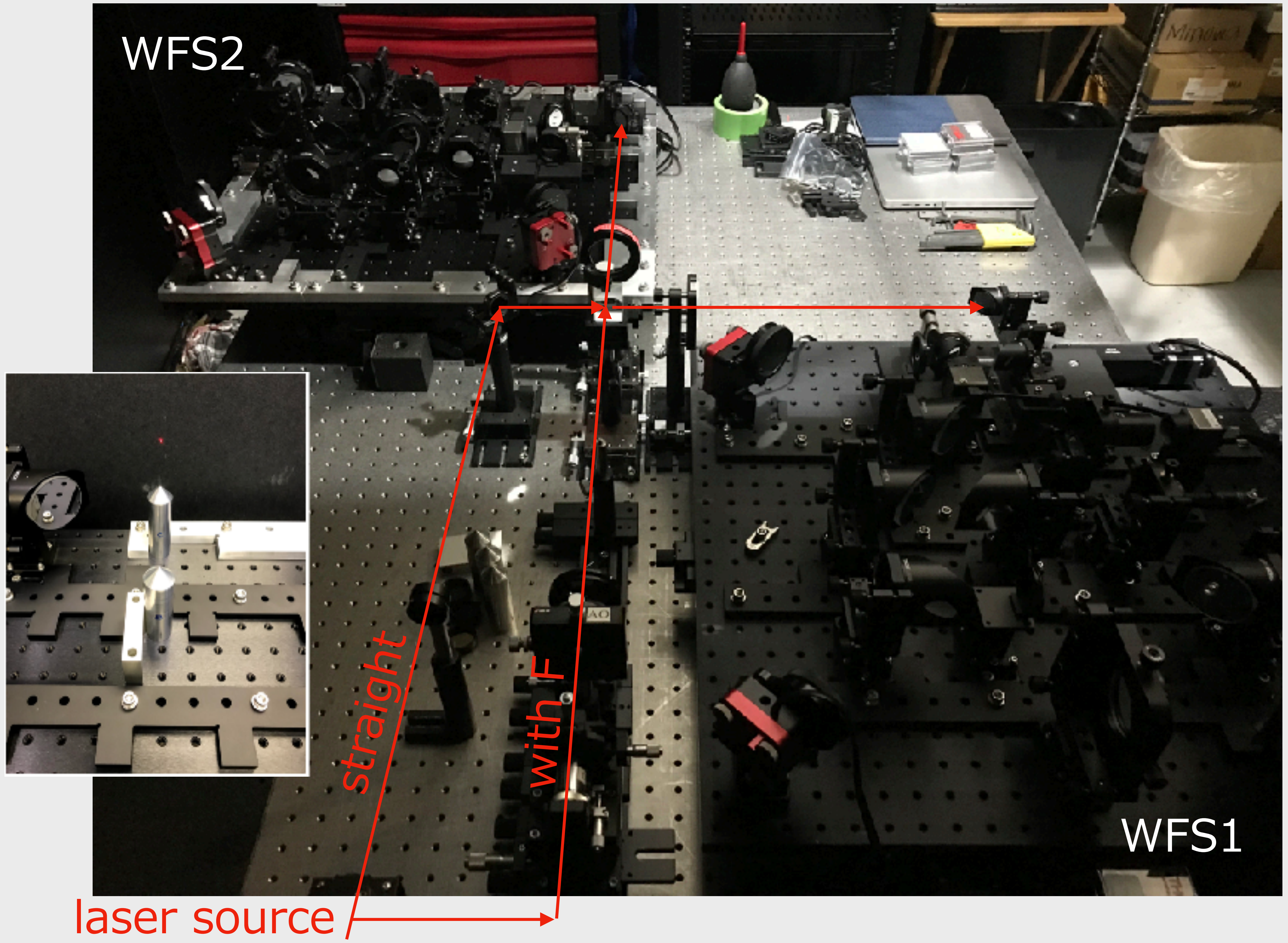


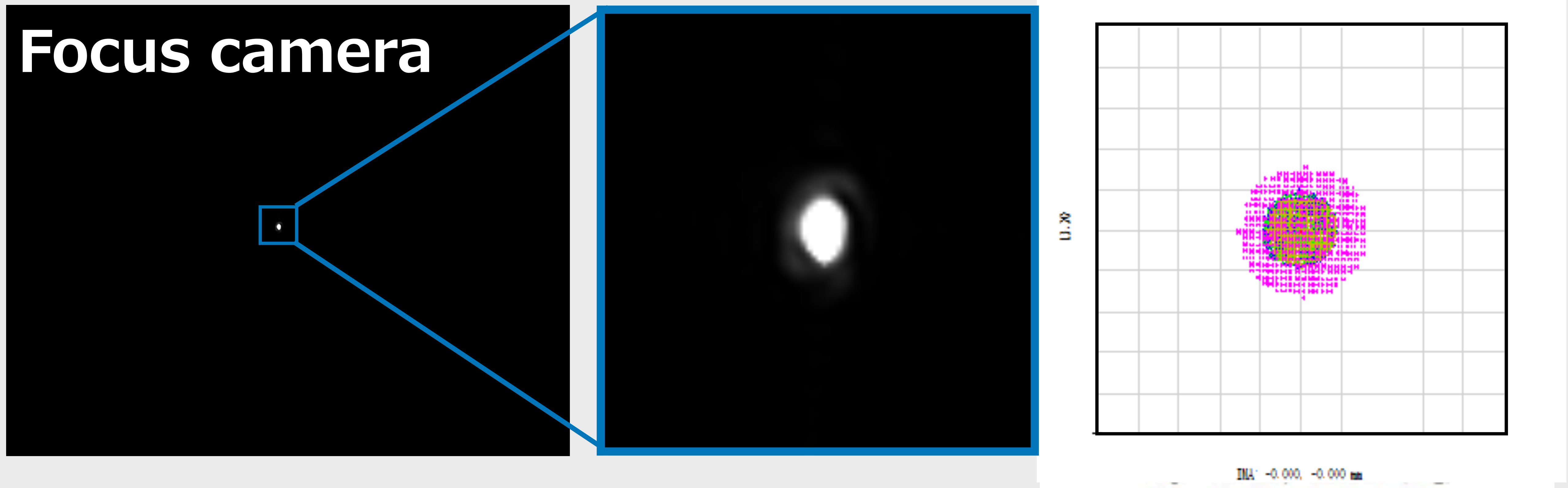
- Positioning jigs to place each mechanical component
- Base parts to match height of optical component
- Jigs and base parts are manufactured by Subaru machine shop and Misumi

Nov.2021-Apr.2022

Laboratory alignment

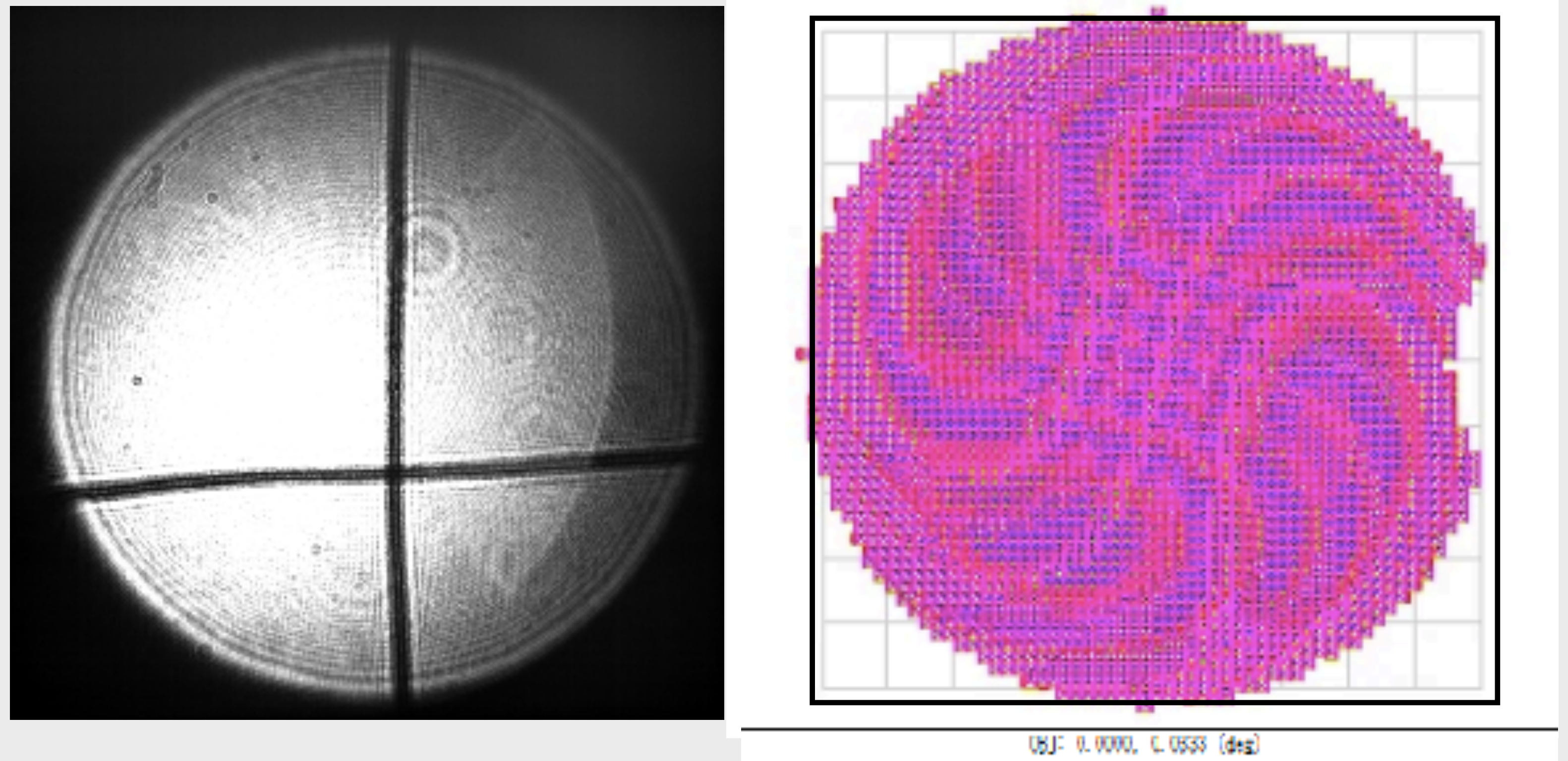
- Rough alignment with straight laser and alignment cones
- Precise alignment with detector image



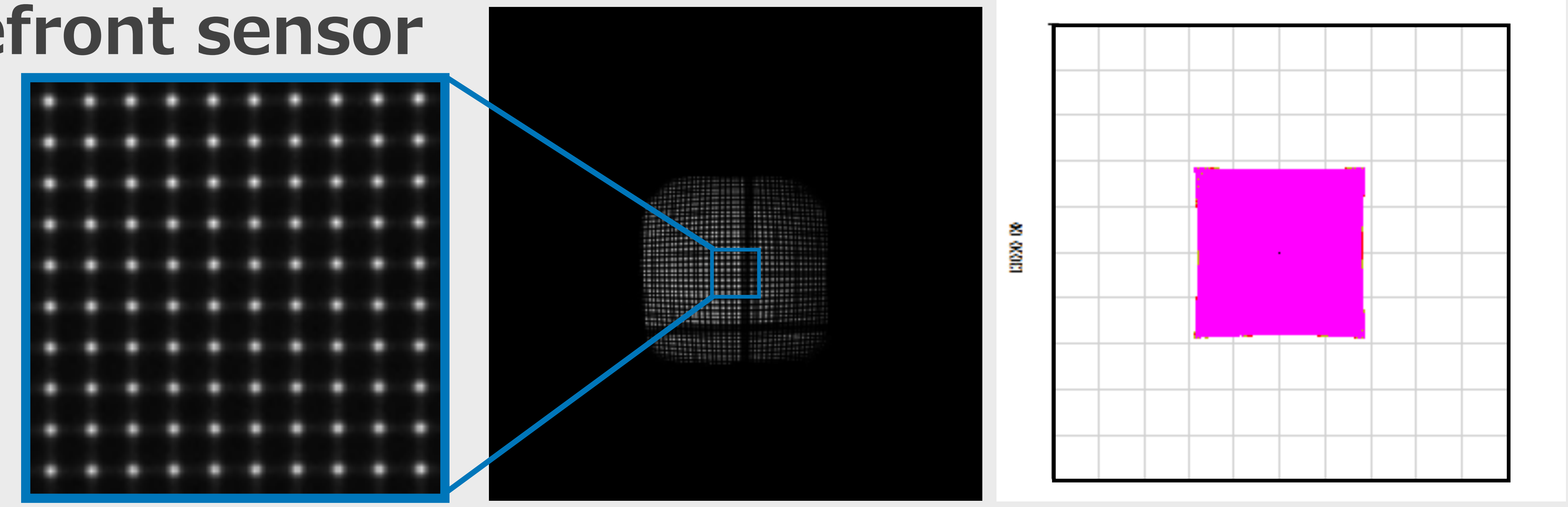


Pupil camera

*metal wire on pupil for simulating telescope spider



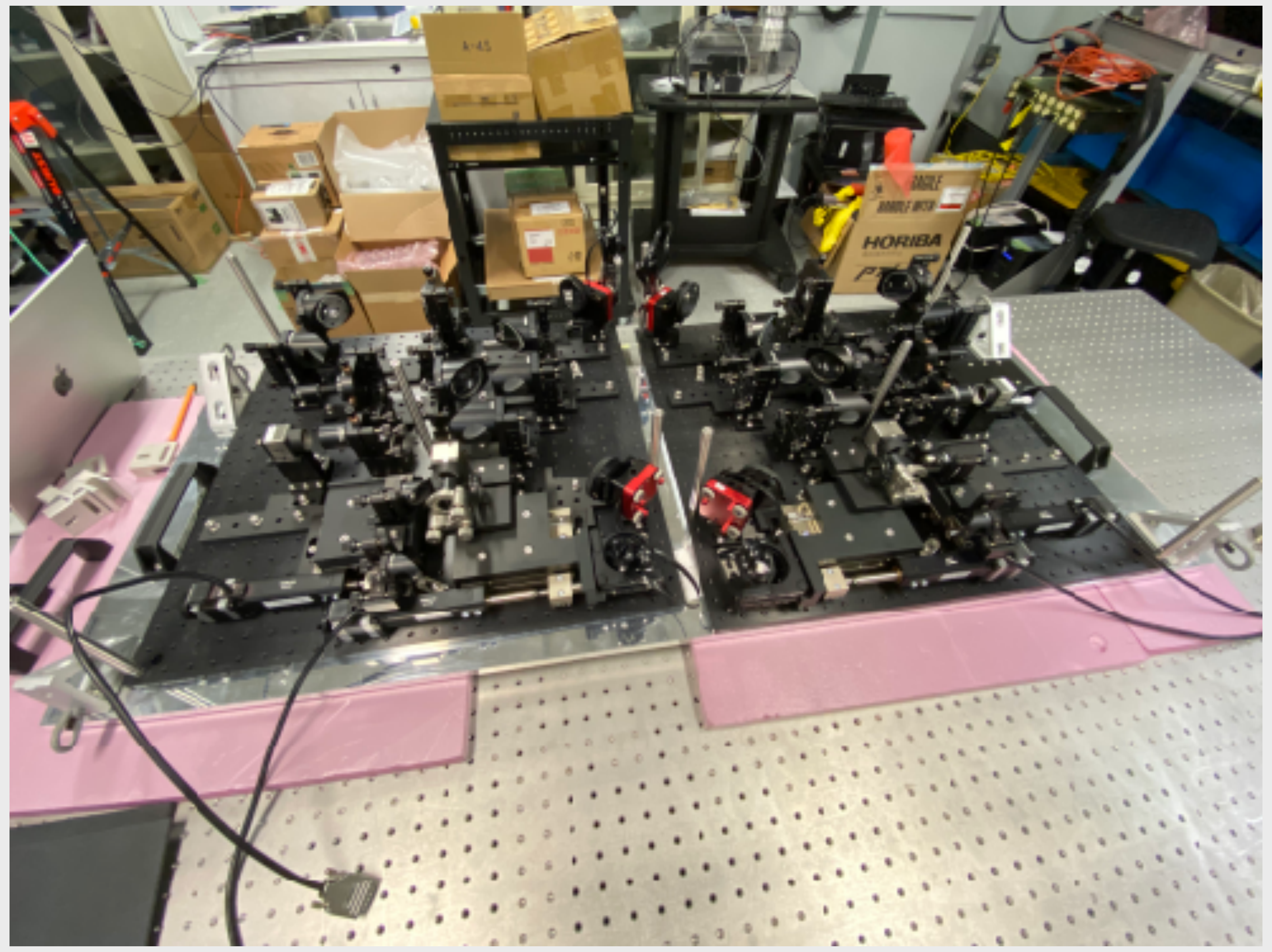
Wavefront sensor

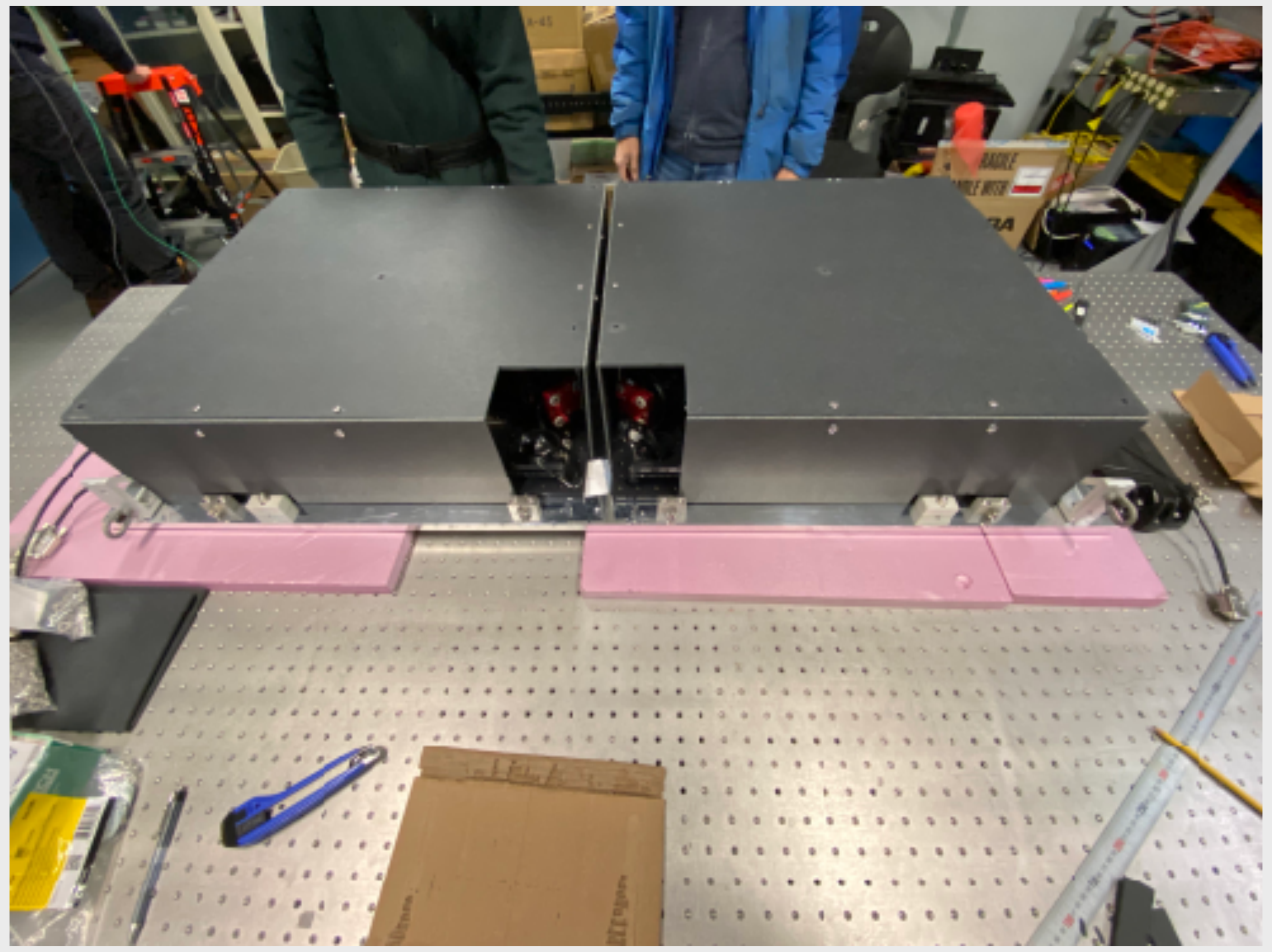


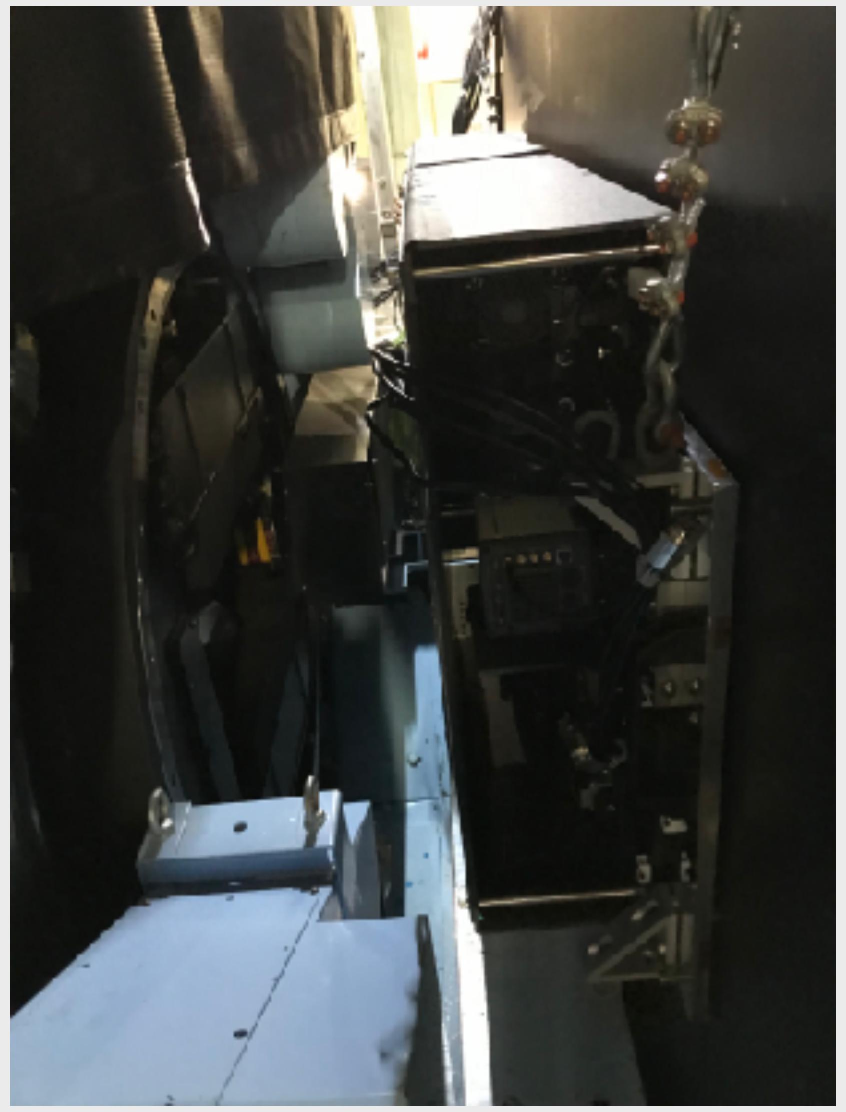
Jun,Nov 2022

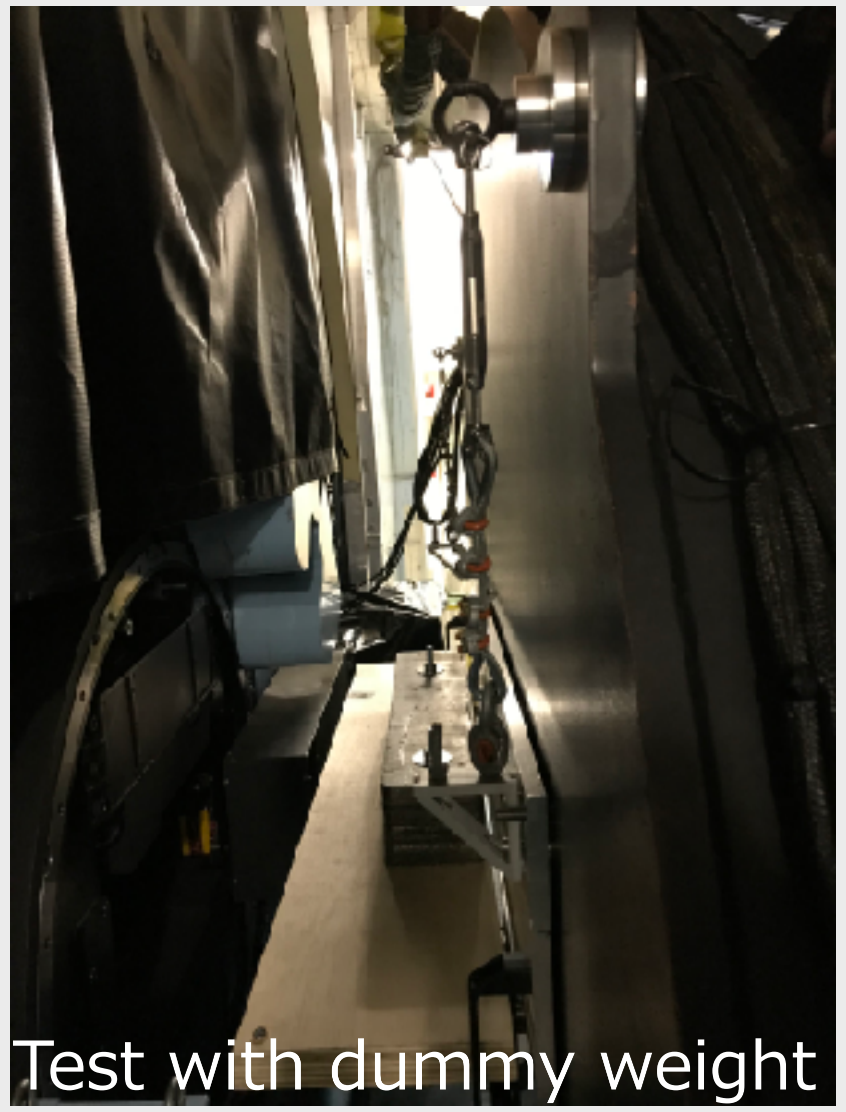
Installation to Subaru Telescope

- Align two WFSs on baseplate
- Attach pickoff mirror stages
- Crane the system to insert in front of the AG/SH layer
- Align to telescope optical axis with positioning pins
- Fix the system with metal wires and strong magnets





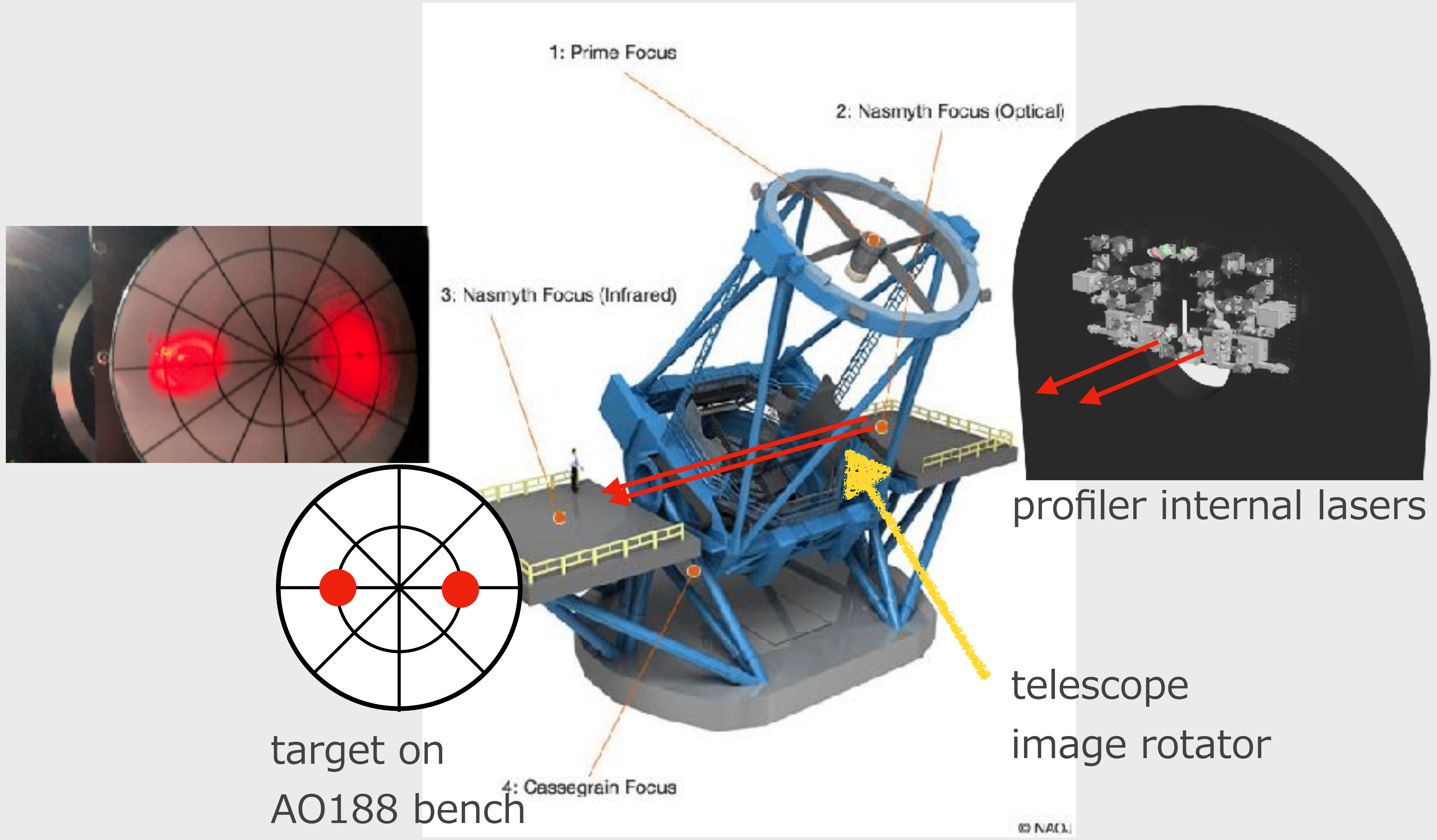




Test with dummy weight

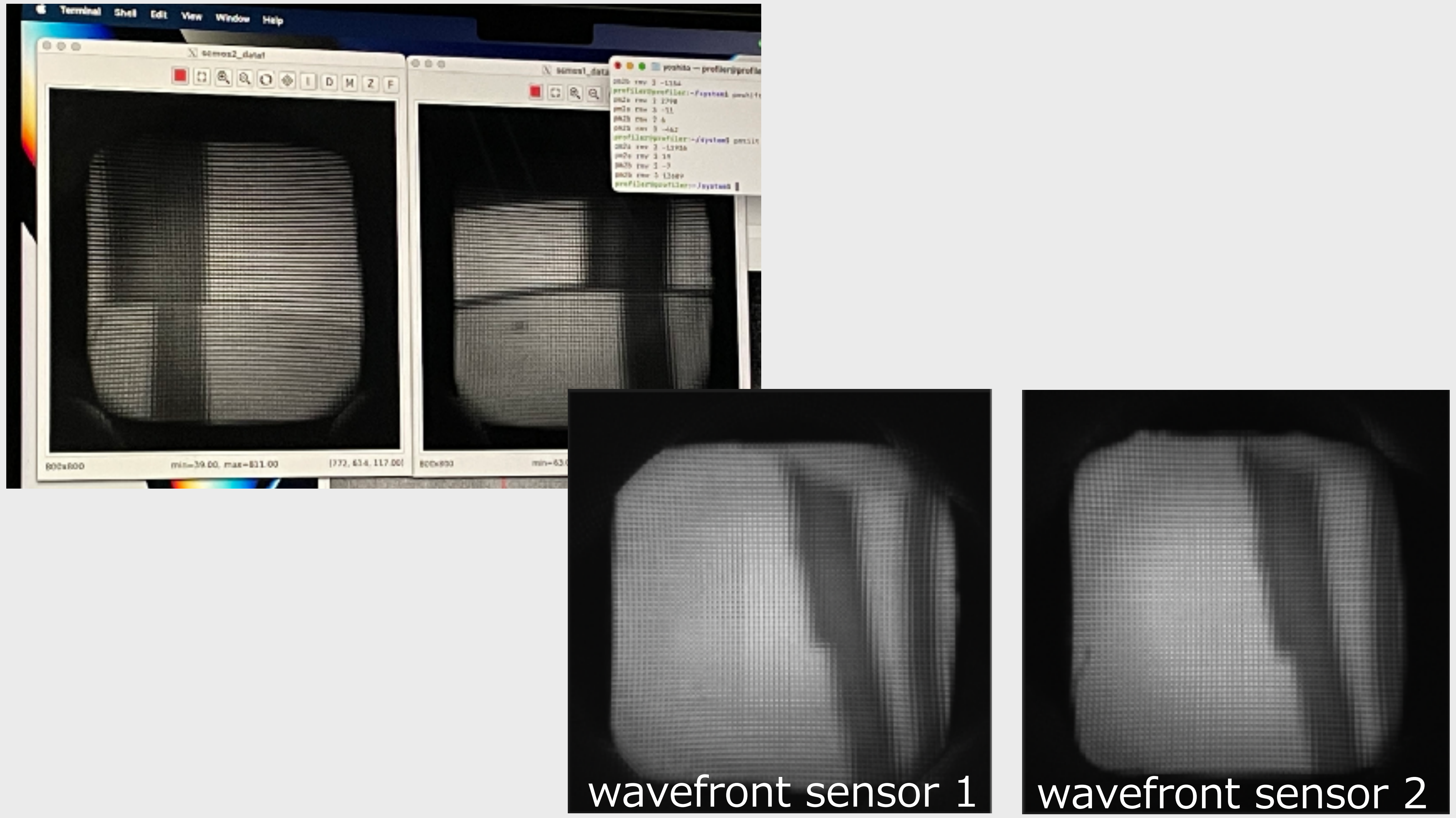
Alignment after installation

(1) Pickoff mirror



- Propagate laser beams from NsOpt to NsIR
- Rotate telescope image rotator
- Check two laser spots rotate along the circle.

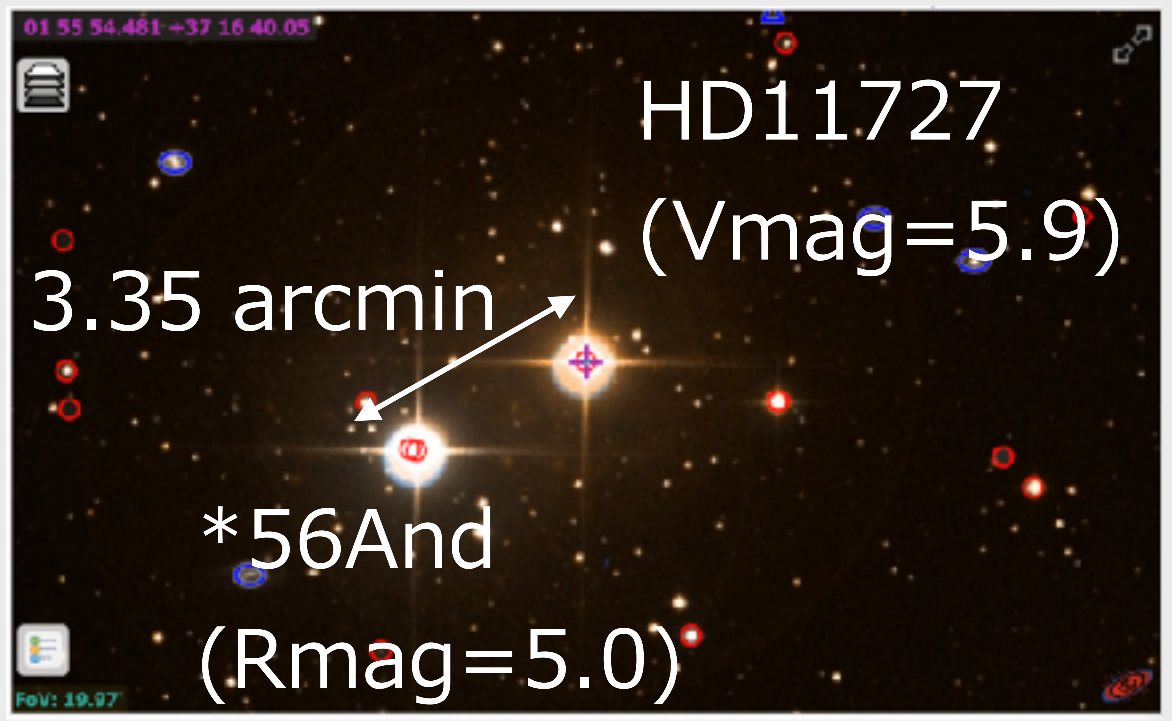
(2) Pupil adjustment mirror pair

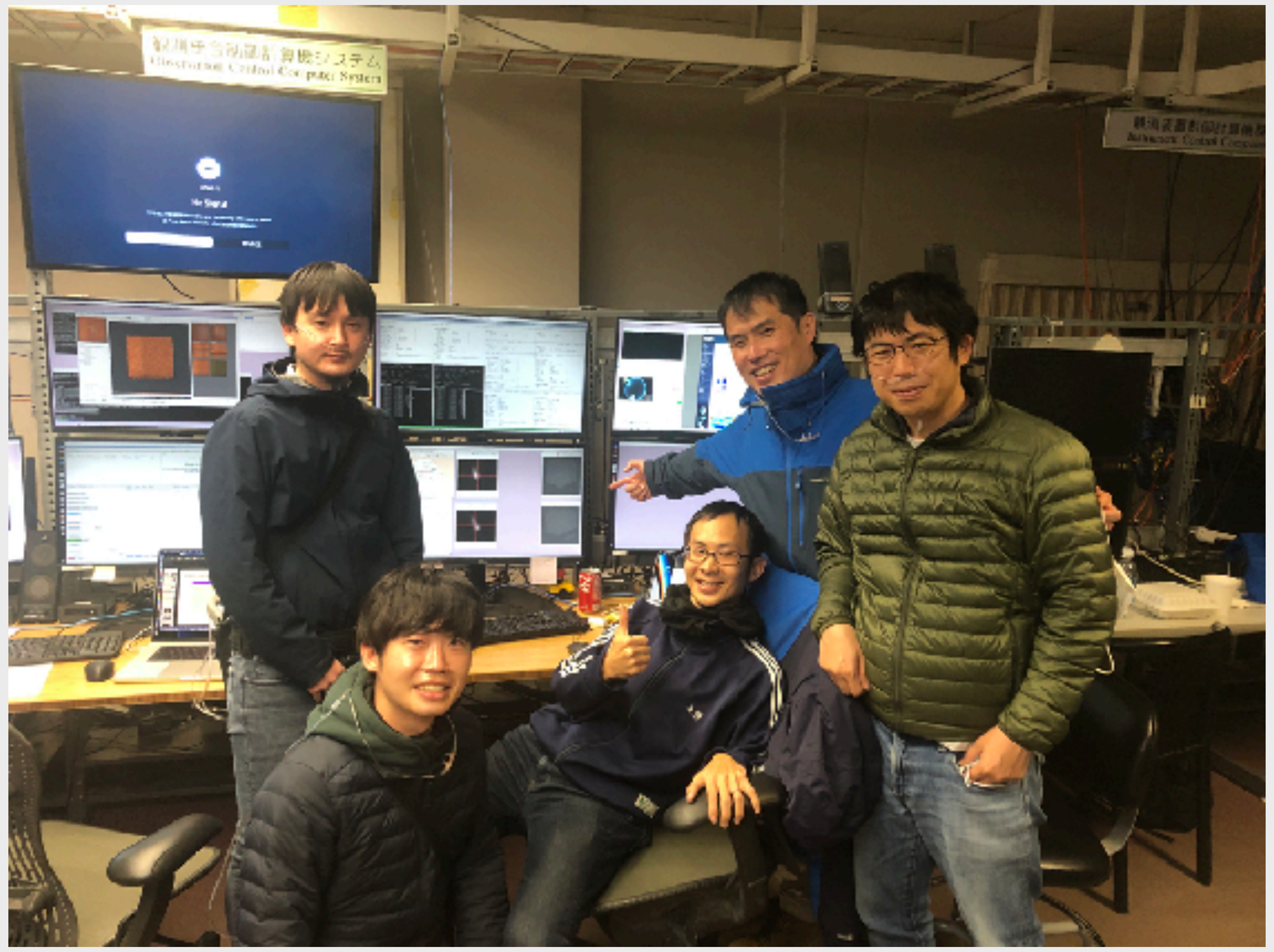


- Observe dome flat with pupil camera and wavefront sensor
- Telescope spider structure is observed
- Check two WFSs are observing with common telescope aperture.

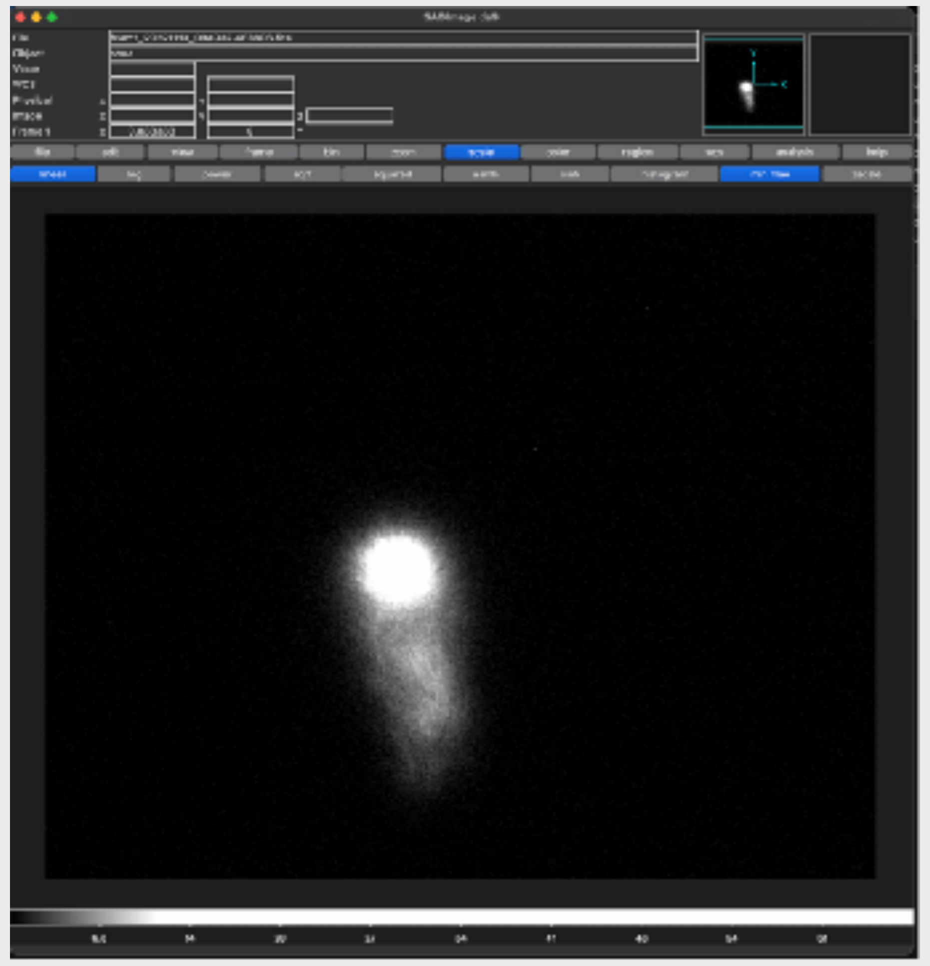
On-sky test with Subaru Telescope

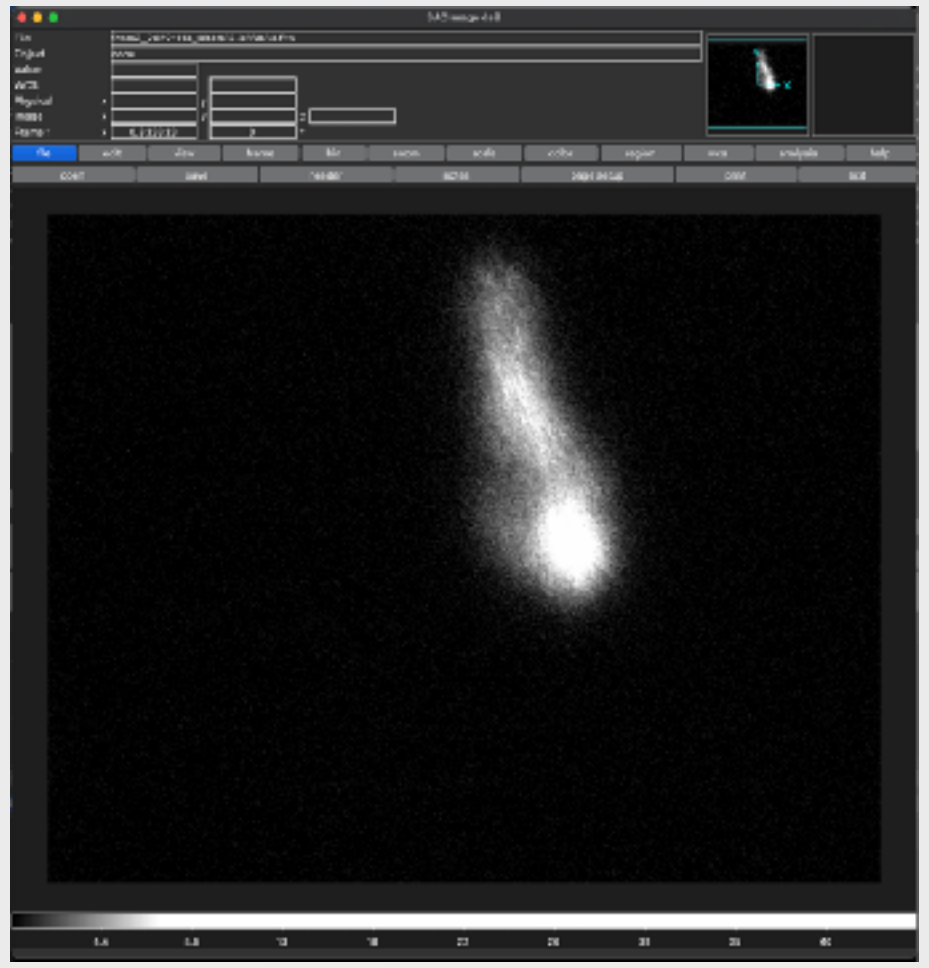
- November 12th, 2022 (First half night)
  - Object acquisition test
    - object: Altair (Rmag=0.6)
  - Profiling data acquisition
    - object: HD11727, *56And



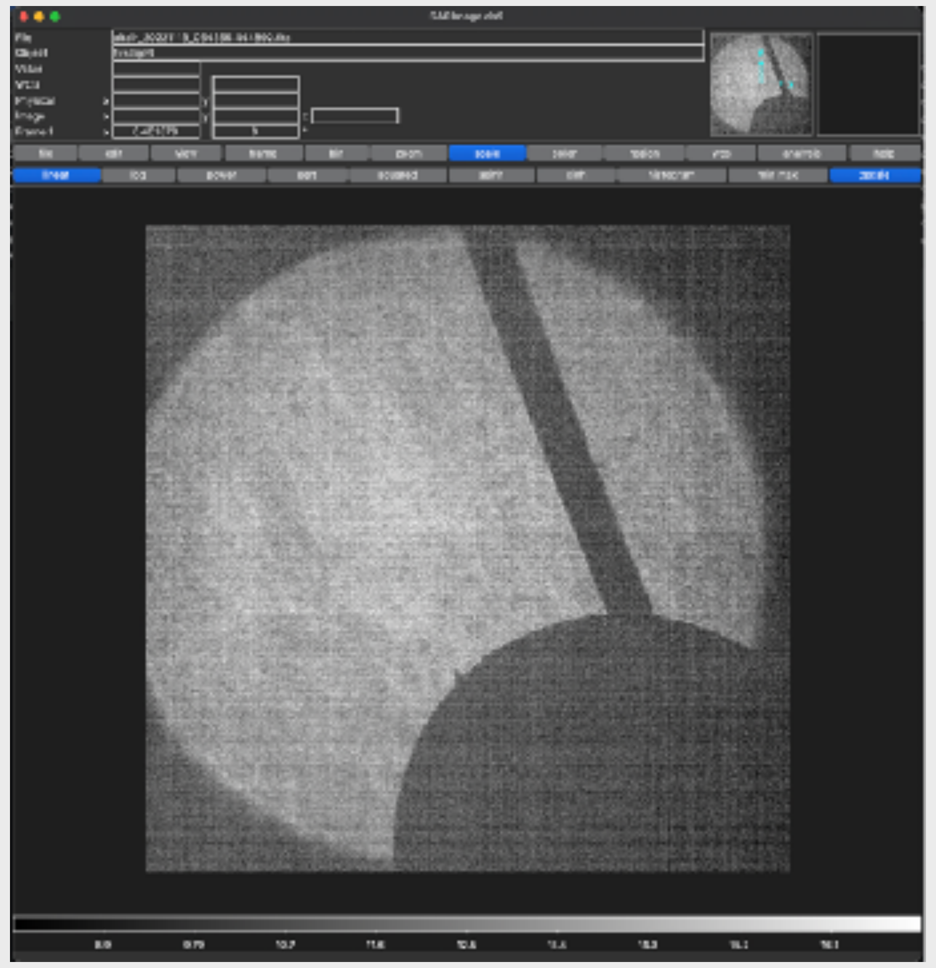


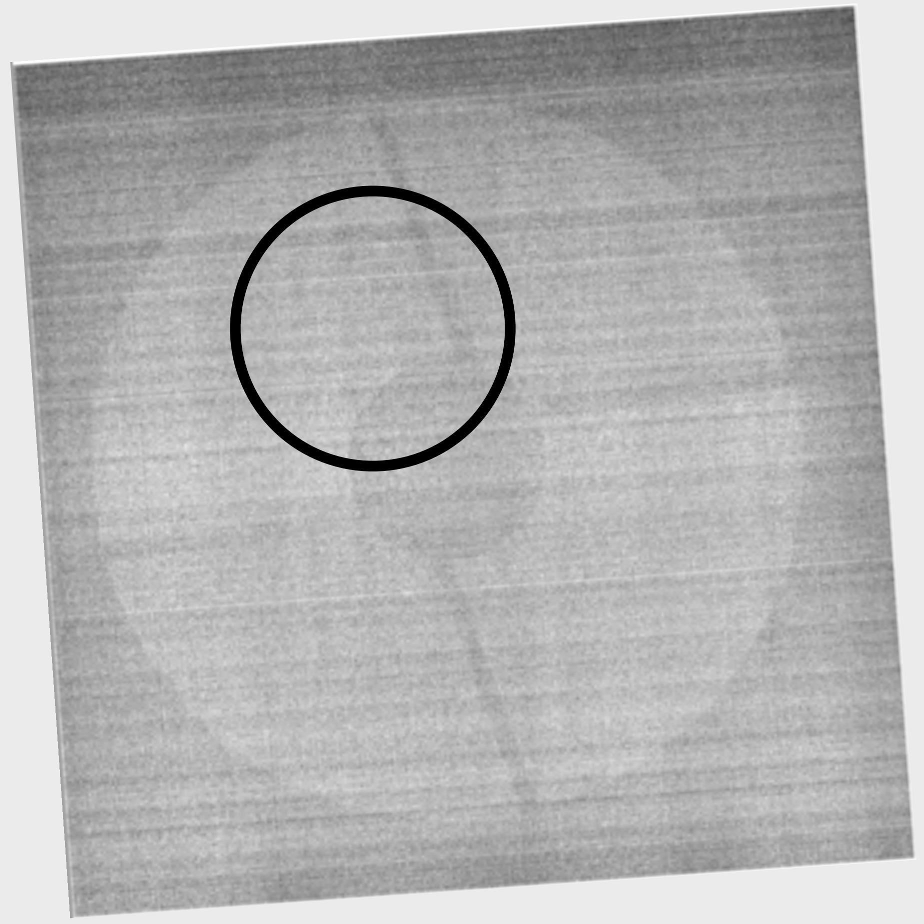
Focus camera





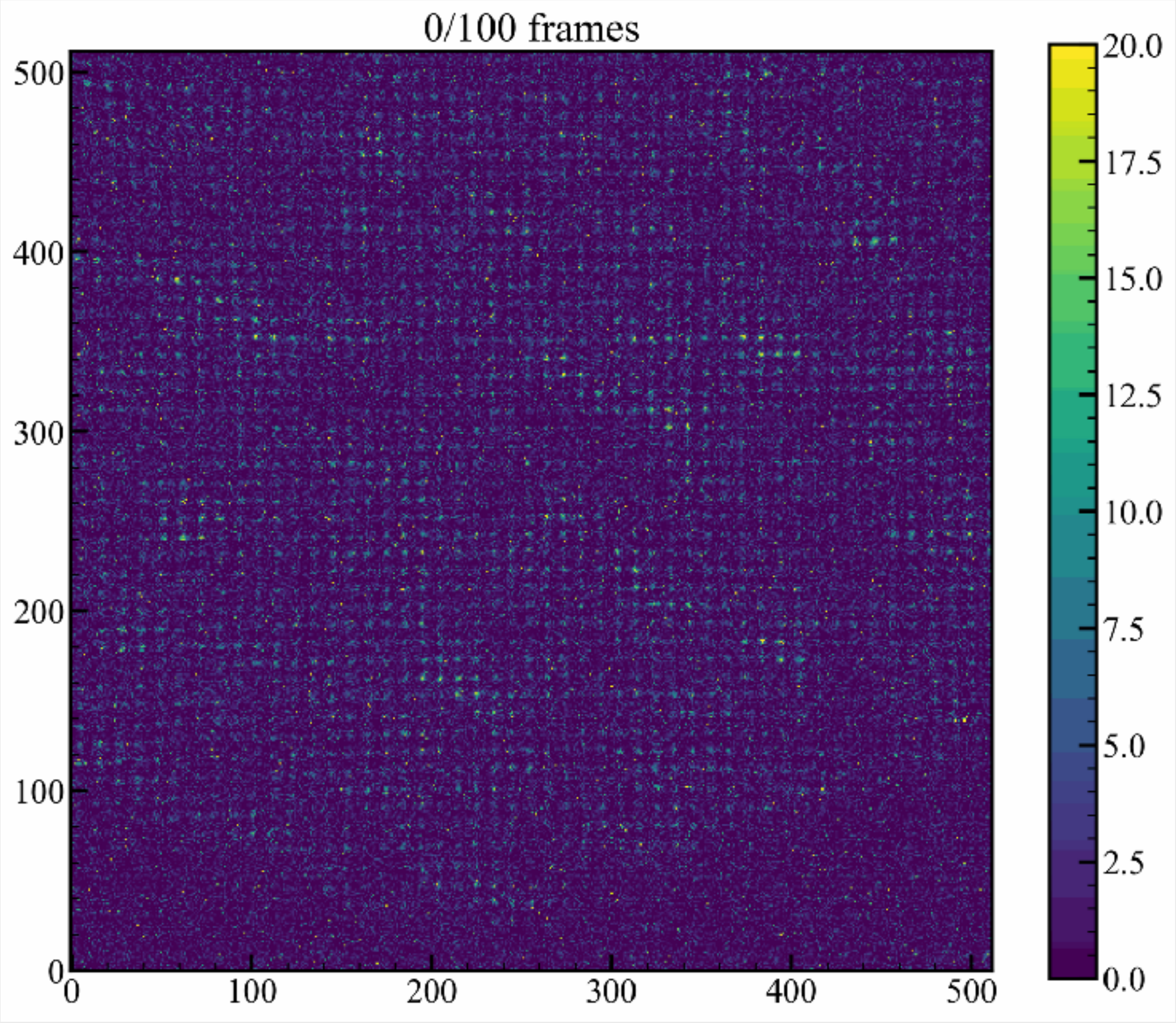
Pupil camera



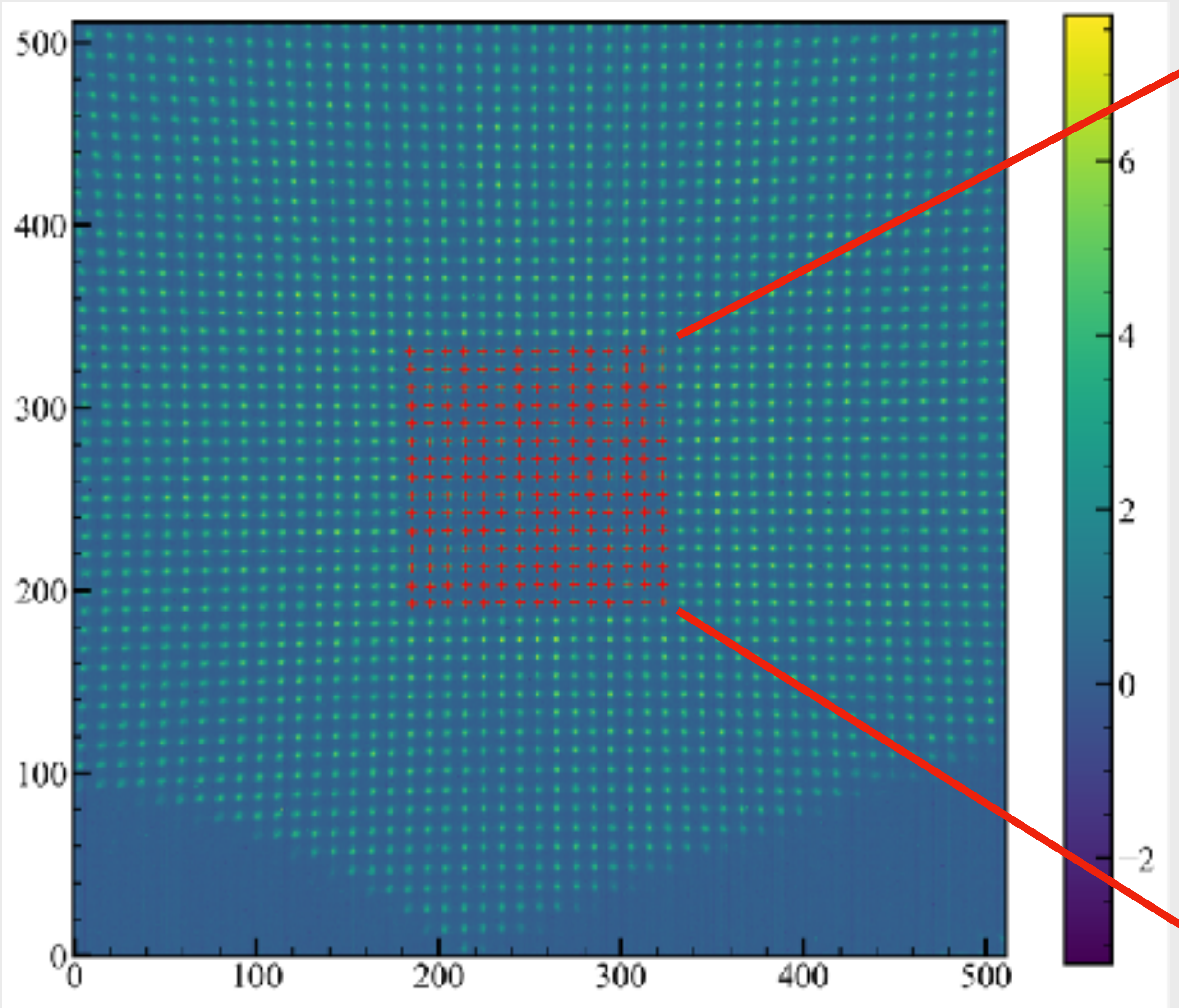


Obtained Shack-Hartmann data

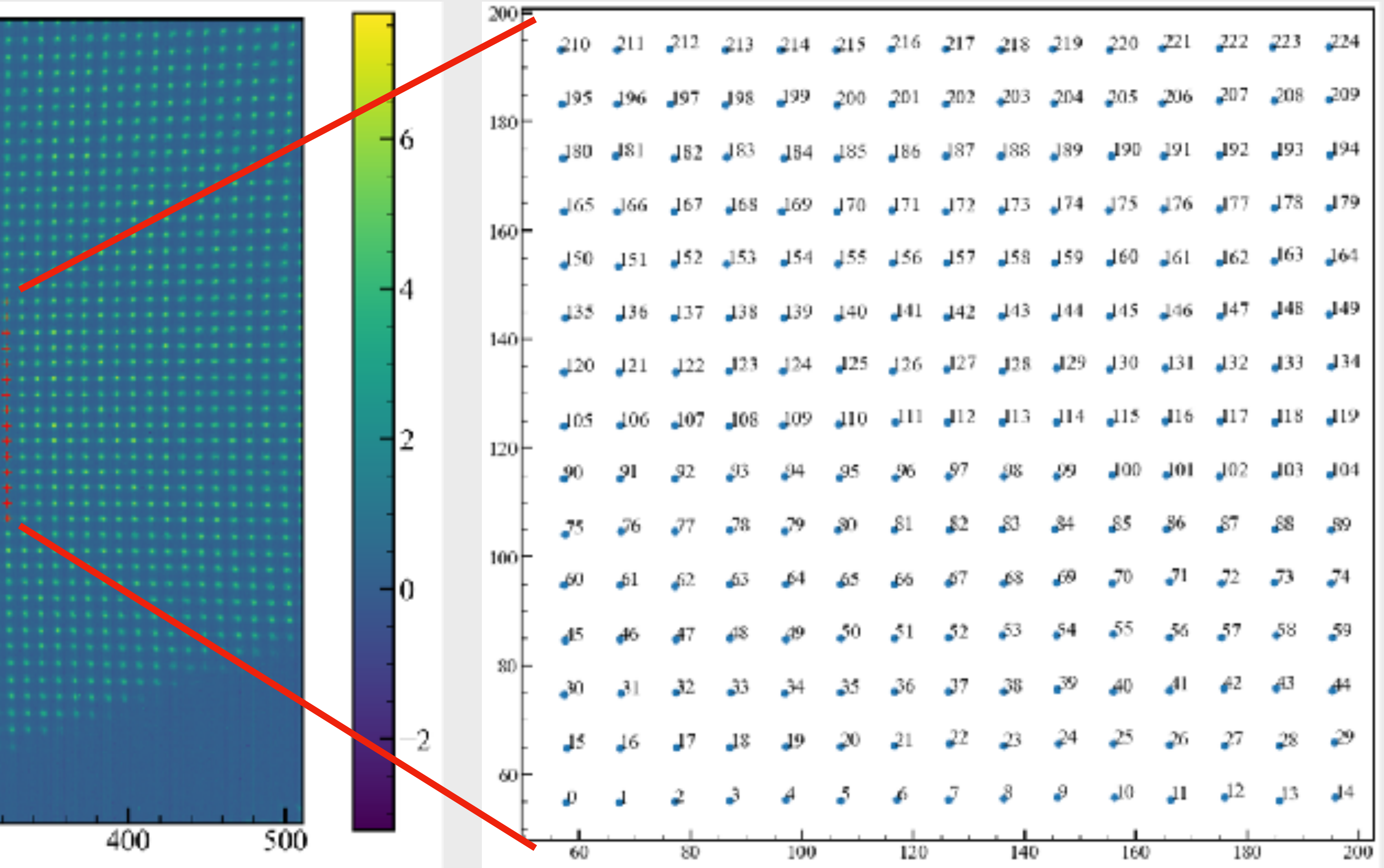
GIF animation of background-subtracted image



- 120-sec continuous image
  - 80Hz (800 x 800 readout)
  - 230Hz (512 x 512 readout)
  - 350Hz (256 x 256 readout)



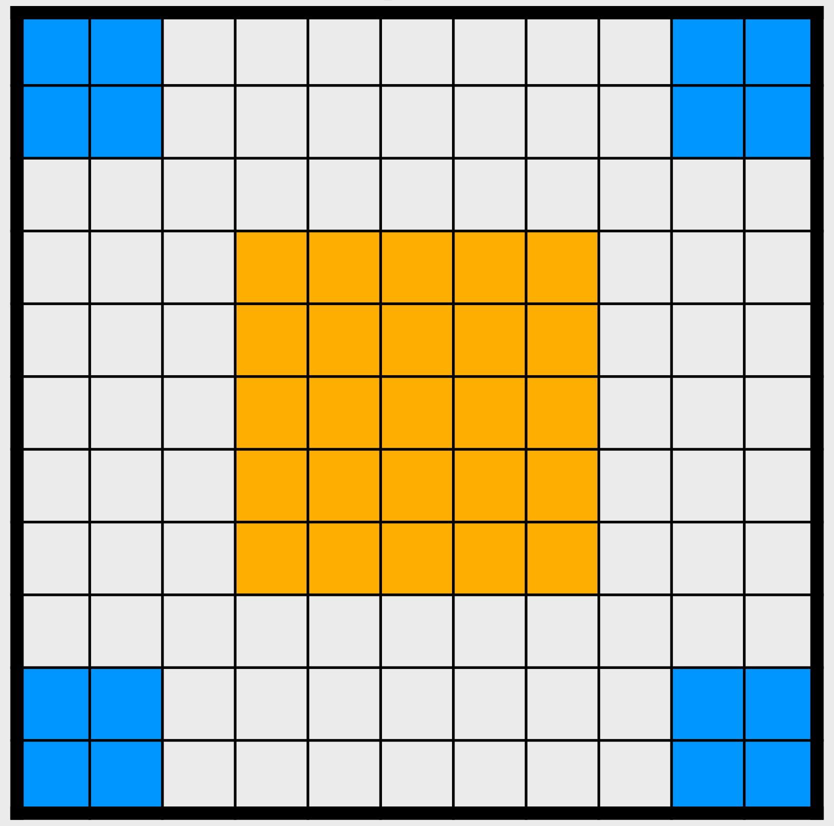
temporal mean



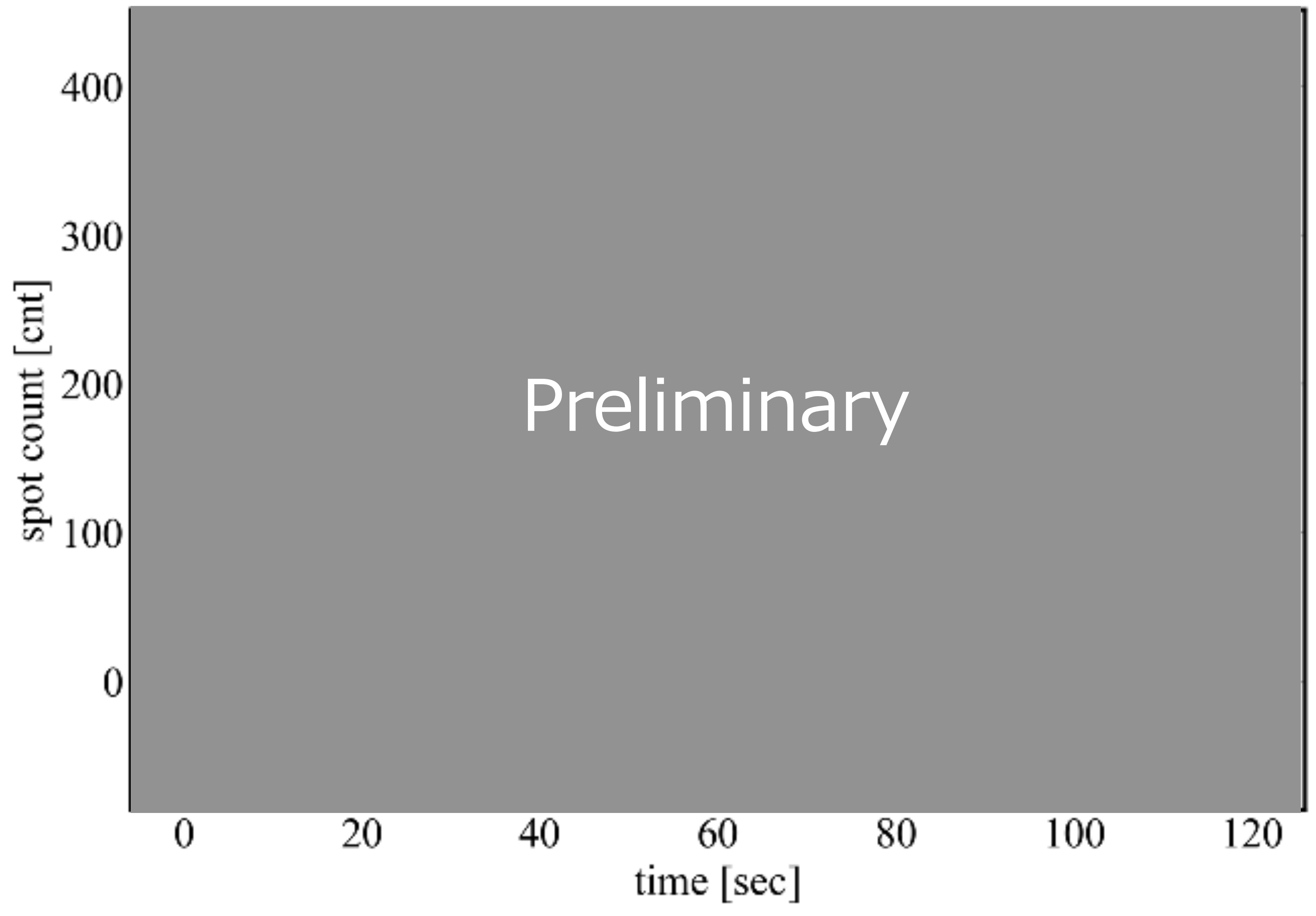
selected spots

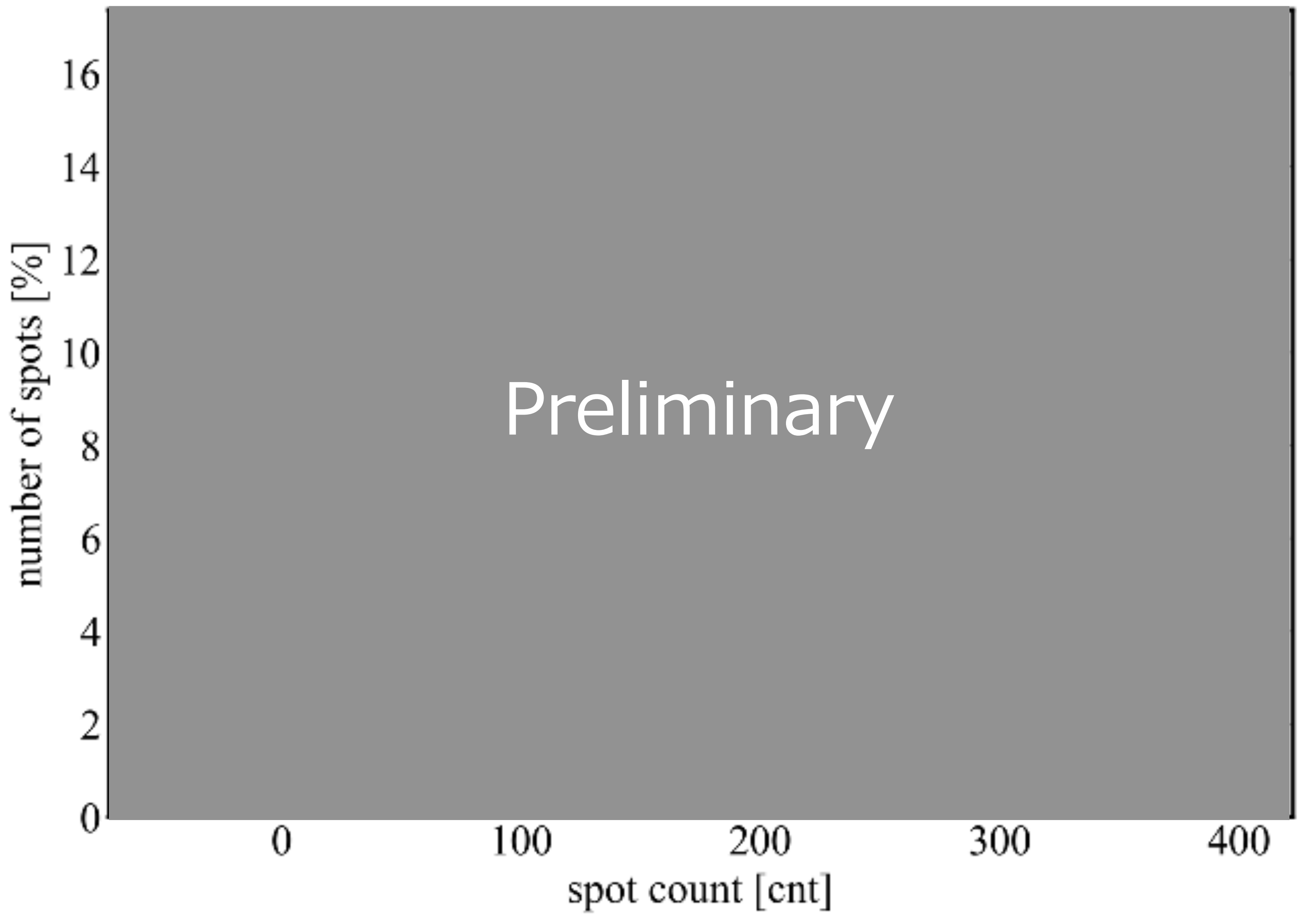
Temporal statistics of spot brightness

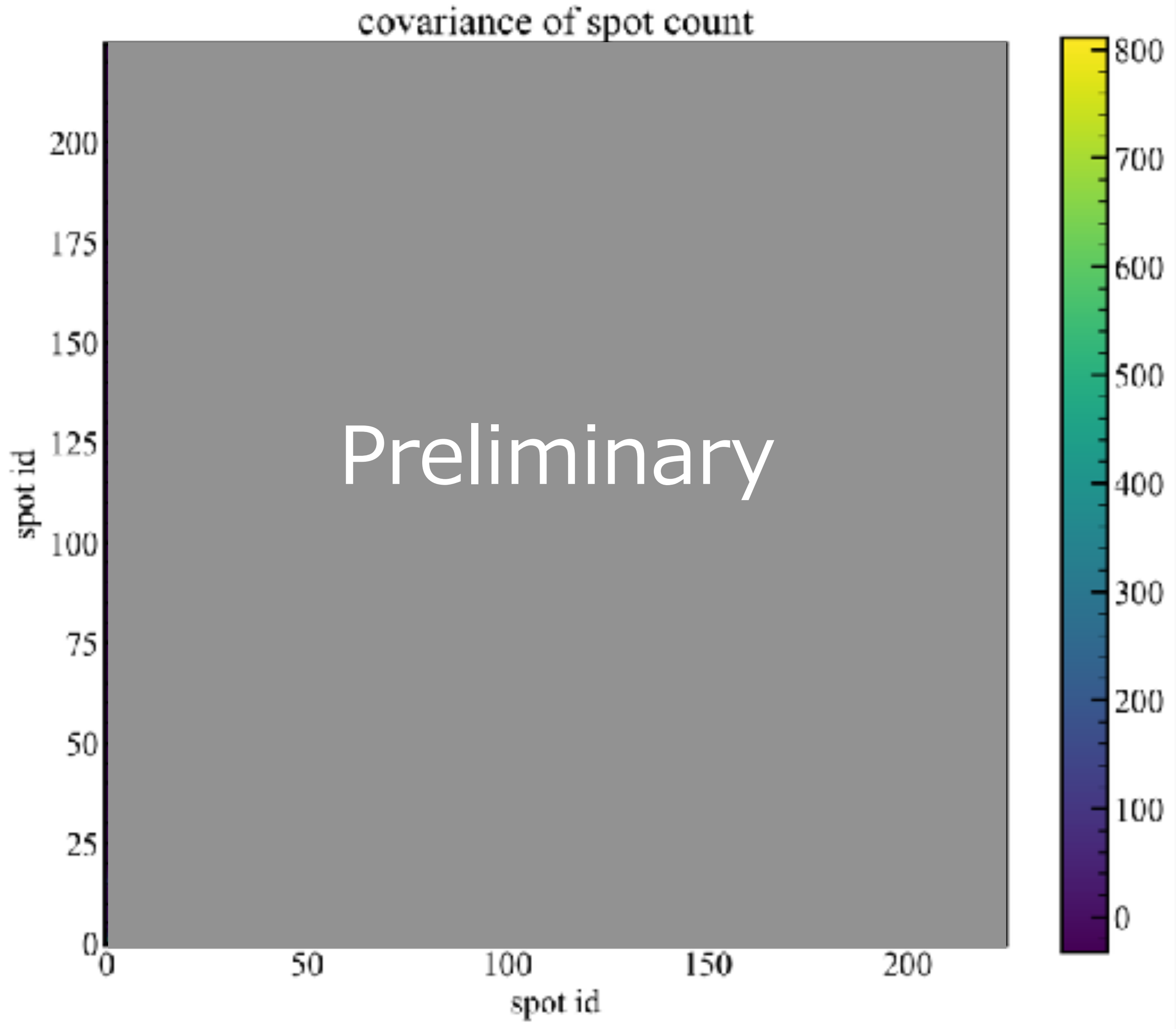
sub-aperture



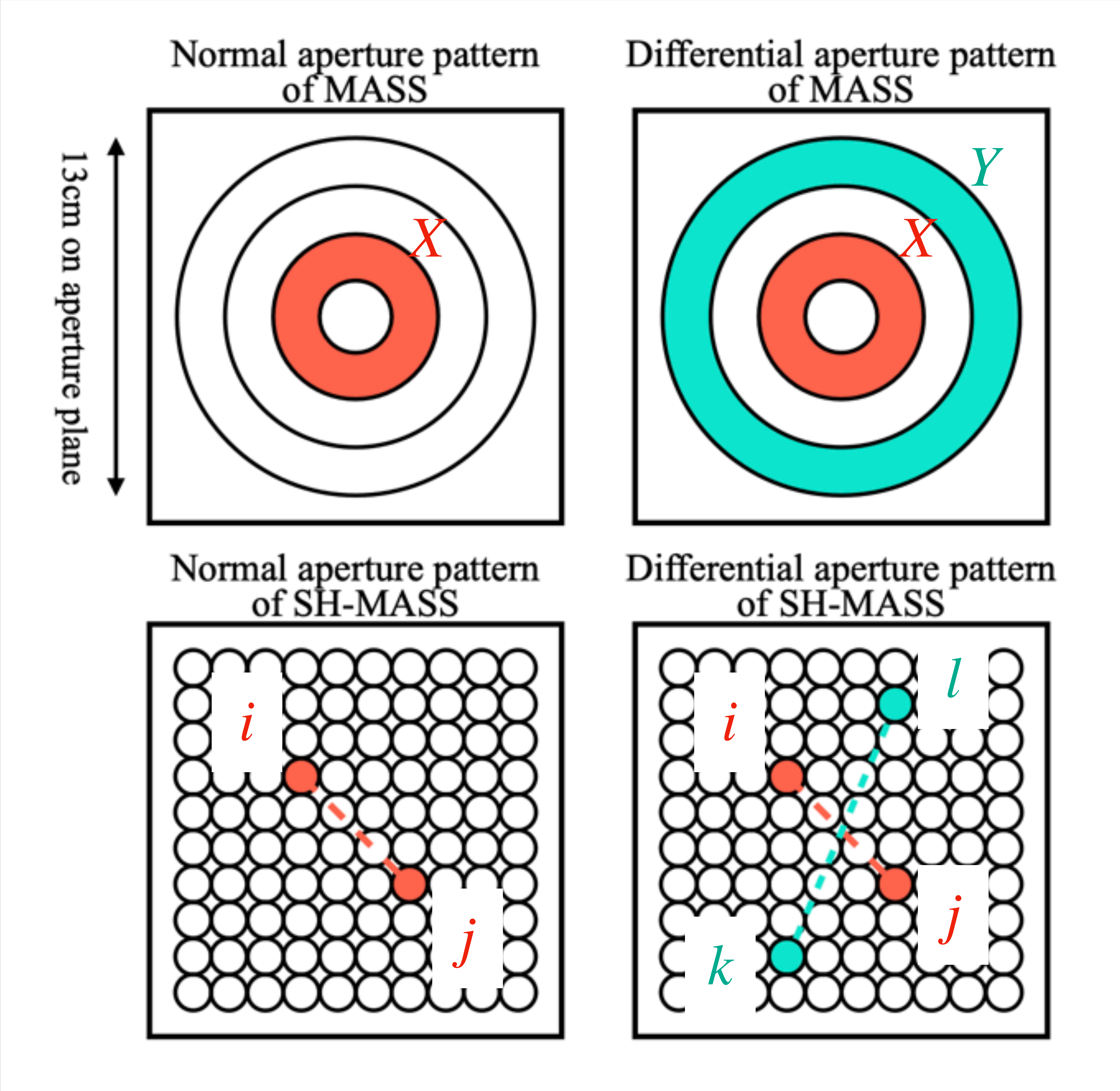
- Spot brightness defined as central 25x25 pixels in sub-aperture
- Spot brightness time series for 15x15 spots
- Temporal mean/variance/covariance calculated







Scintillation index

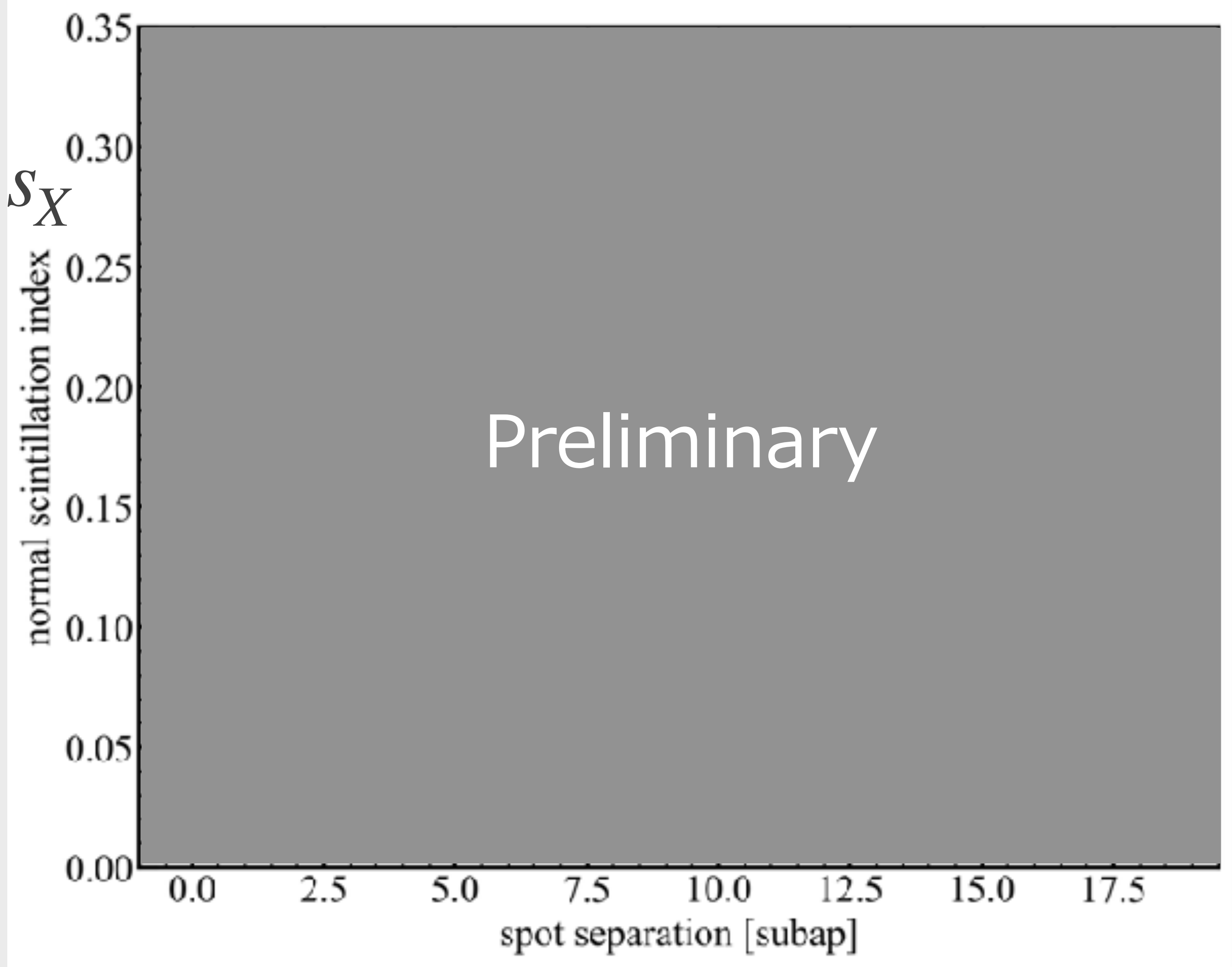


one spatial frequency

combination of two spatial frequencies

$$s_X = \mathrm{Var}\left[\frac{I_X}{\langle I_X\rangle}\right] = \frac{\mathrm{Var}[I_i] + \mathrm{Var}[I_j] + 2\mathrm{Cov}[I_i, I_j]}{(\langle I_i\rangle + \langle I_j\rangle)^2}$$

$$s_{XY} = \mathrm{Var}\left[\frac{I_X}{\langle I_X\rangle} - \frac{I_Y}{\langle I_Y\rangle}\right]$$
$$= s_X + s_Y - 2\frac{\mathrm{Cov}[I_i, I_k] + \mathrm{Cov}[I_j, I_k] + \mathrm{Cov}[I_i, I_l] + \mathrm{Cov}[I_j, I_l]}{(\langle I_i\rangle + \langle I_j\rangle)(\langle I_k\rangle + \langle I_l\rangle)}$$



Covariance up to ~5-10 cm scale

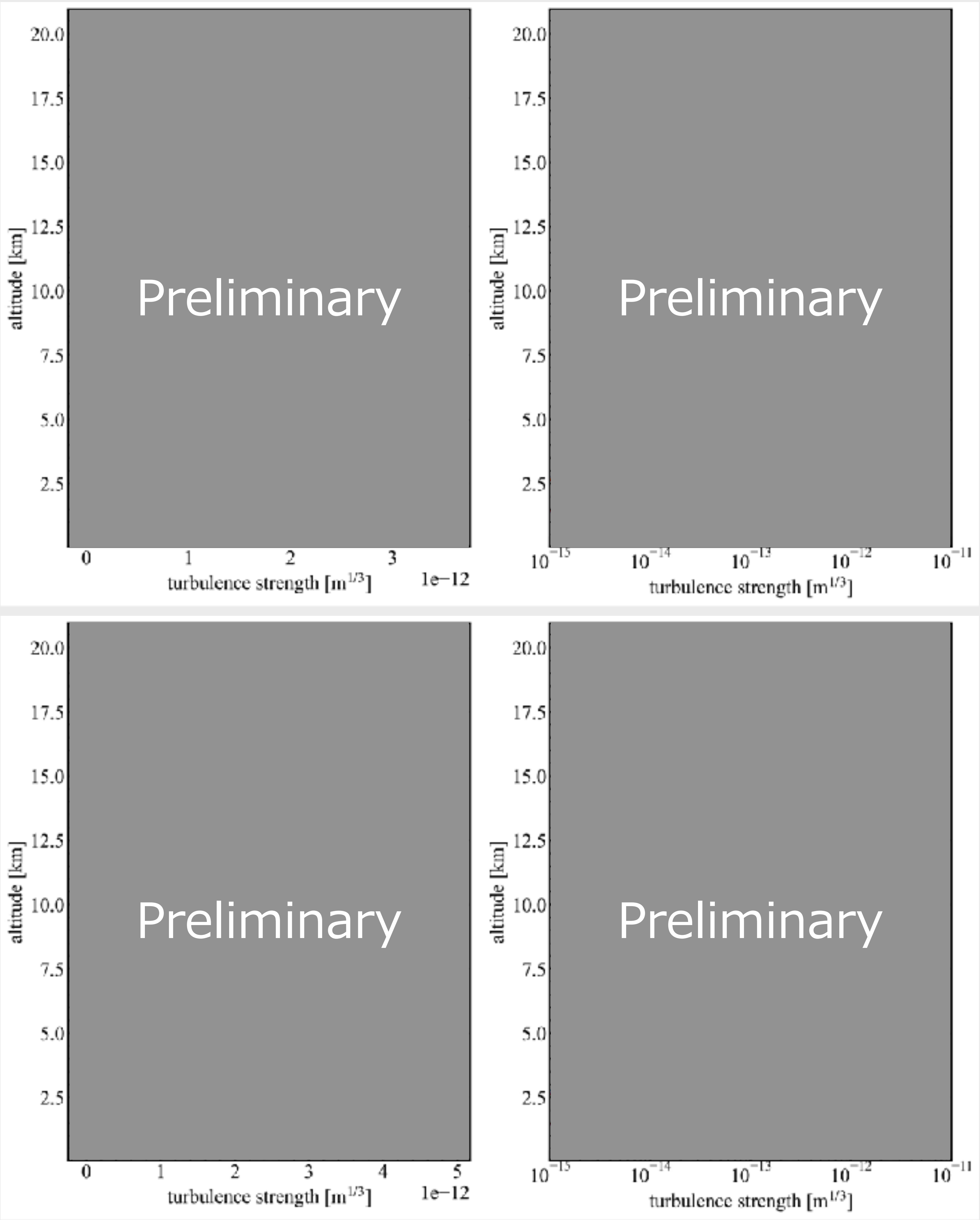
Overall scaling due to exposure time

Turbulence profile reconstruction

- Profile reconstruction by fitting model with 6-layer turbulence between 1km and 20km above
- Known
  - Observed spatial frequency pattern determined by normal/differential aperture
- Assumption
  - Kolmogorov turbulence
  - Weak perturbation
  - Fresnel propagation

WFS1

WFS2



consistent btw WFS1 & WFS2!

Discussion / Future work

- SH-MASS
  - Calibration with CFHT MASS-DIMM measurement
- SLODAR
  - For precise ground layer turbulence profile
- Report on the next ASJ meeting
- Next engineering observation
  - Mar. 8, 2023

Summary

- Purpose: Turbulence profile for future AO system at Subaru telescope
  - Prior information of atmospheric tomography in LTAO
  - Performance simulation/evaluation for GLAO
- Method: Development of new turbulence profiler
  - SH-MASS for high layer turbulence
  - SLODAR for ground layer turbulence
- Result
  - Development of turbulence profiler is done.
  - First light on November 12, 2022 (finally!)
  - Consistent SH-MASS result between dependent two wavefront sensors