小型屈折型補償光学装置CRAO: Onsky観測による性能評価結果

坂部健太　(京都産業大学大学院博士後期課程)

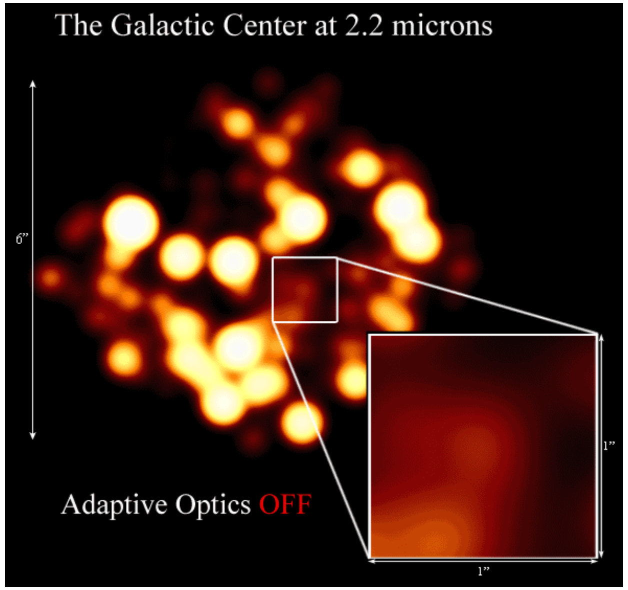
池田優二(フォトクロス)、大屋真(国立天文台)

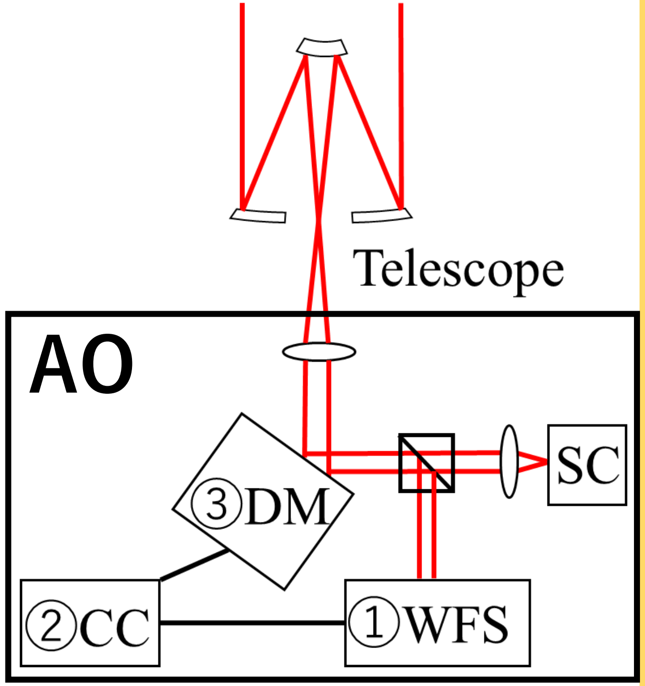
樽田順、河北秀世(京都産業大学)

Adaptive Optics(AO)

AO is now an essential technology for ground-based observations
Improved
- **Spatial resolution**
- **Limiting magnitude**

AO equipped Telescope
3-6m class：
ESO3.6m、CFHT、Palomer…
8-10m class ：
Subaru,Keck,VLT,Gemini…
1-2m class・・・





https://galacticcenter.astro.ucla.edu/adaptive-optics.html

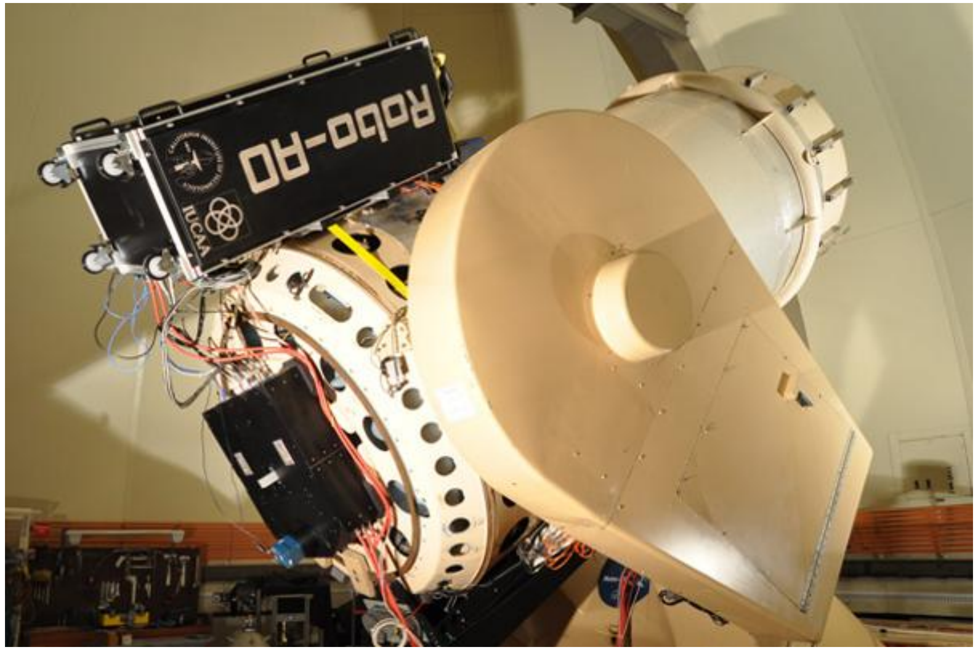
Adaptive Optics(AO)

Small-Aperture Telescope Characteristics and Potential with AO

Telescope time is easily occupied
•Long-term observations such as time-series astronomy and survey observations
•ToO observations

Example:RoboAO(Baranec et al., 2018)
- ✓ UH2.2m(2019~)
- ✓ λ400~1800nm
- ✓ 15W Rayleigh laser（LGSAO）
- ✓ Diffraction limit(λ400-800nm)
- ✓ Copy AO system:

  KAPAO(Severson et al., 2014),KalAO(Hagelberg et al., 2020)



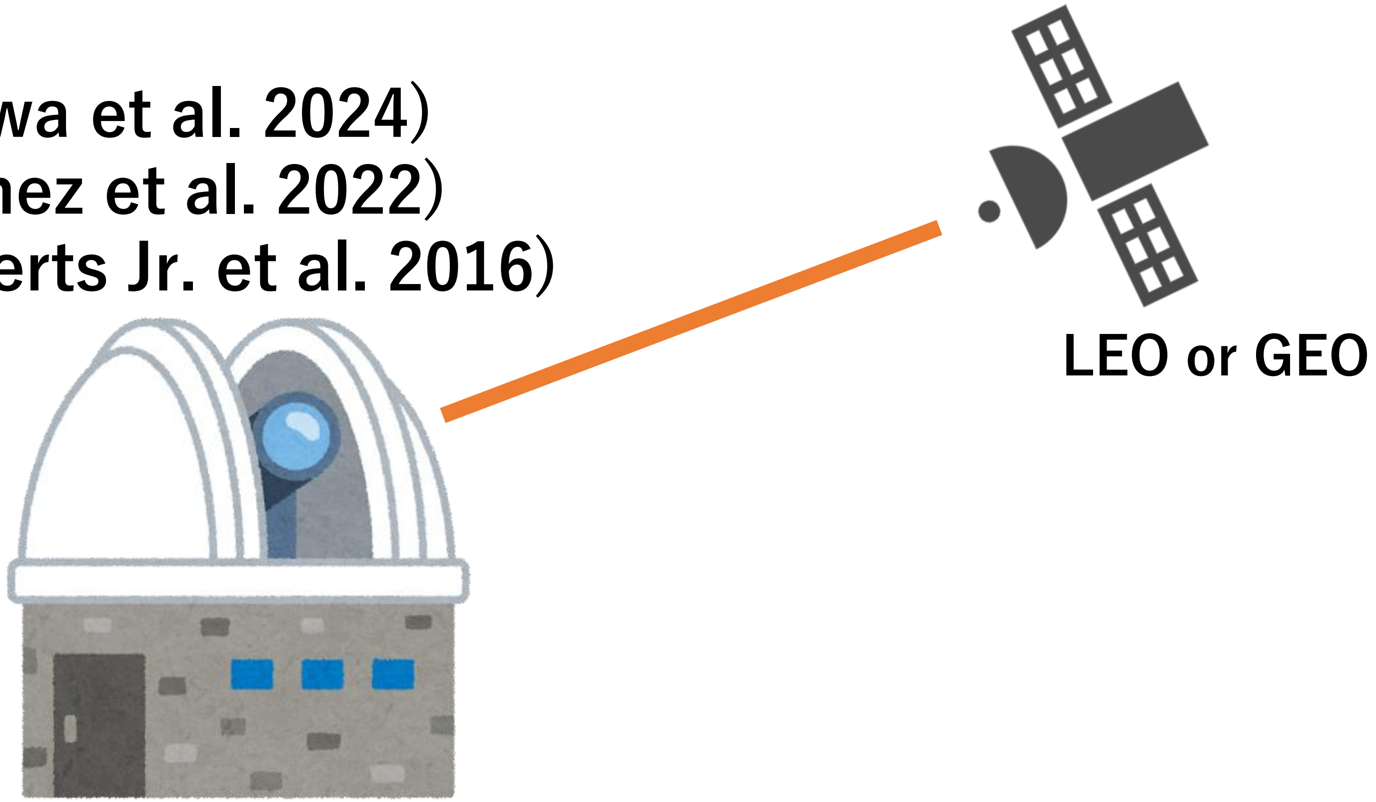
https://instru.iucaa.in/index.php/projects/16-ongoing-projects/9-robo-ao

Adaptive Optics(AO)

AO in Free Space Optical Communications
Correction for atmospheric turbulence from satellites (λ1 - 1.5um), enables the establishment of communication links.

Project examples:

- **NICT D=1m (Y.Rokugawa et al. 2024)**
- **ANU D=0.7m (N. Martínez et al. 2022)**
- **NASA D=1m (L. C. Roberts Jr. et al. 2016)**



Adaptive Optics(AO)

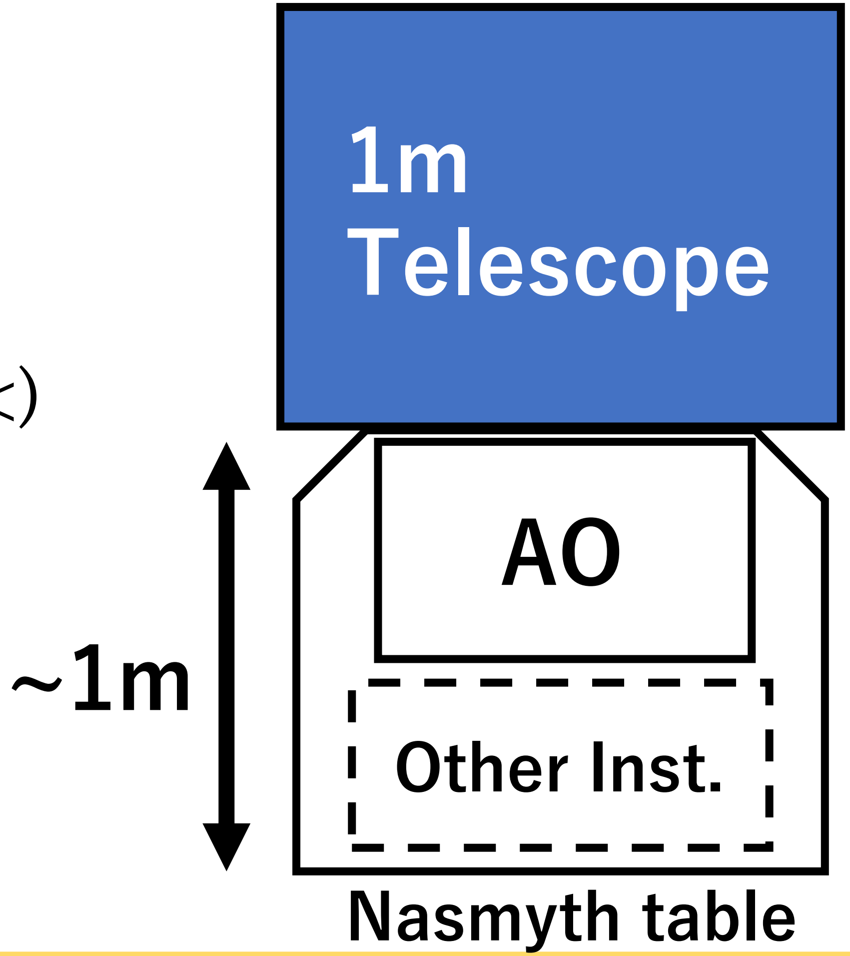
- RoboAO has a device size of 1m x 1m (weight 67kg).

→ Too large for installation on a small telescope with a Nasmyth table.

- Observations have been performed at Natural seeing ~1.0”

For the widespread adoption of AO systems on 1m telescopes

- The development of compact, Lightweight AO systems
- Correction even under poor natural seeing (2”<)

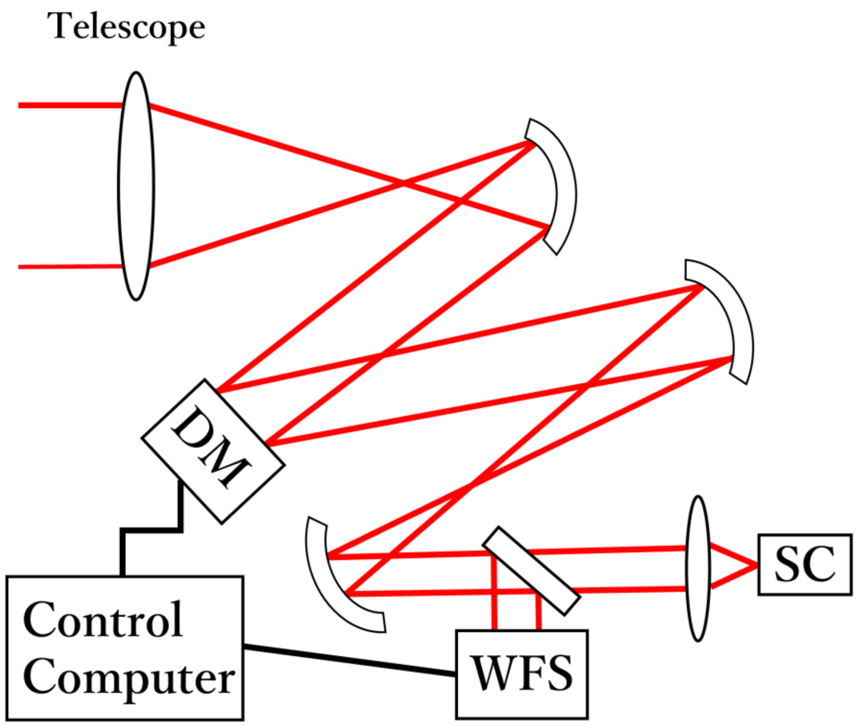


CRAO

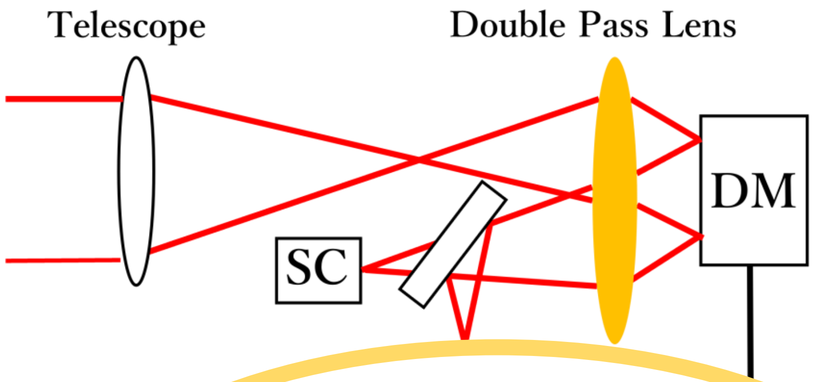
Compact Refractive Adaptive Optics (CRAO)

- Compact size achieved with refractive system
- Mounted on the 1.3m Araki Telescope (Typical seeing 2-3")

Reflective(w/mirror)



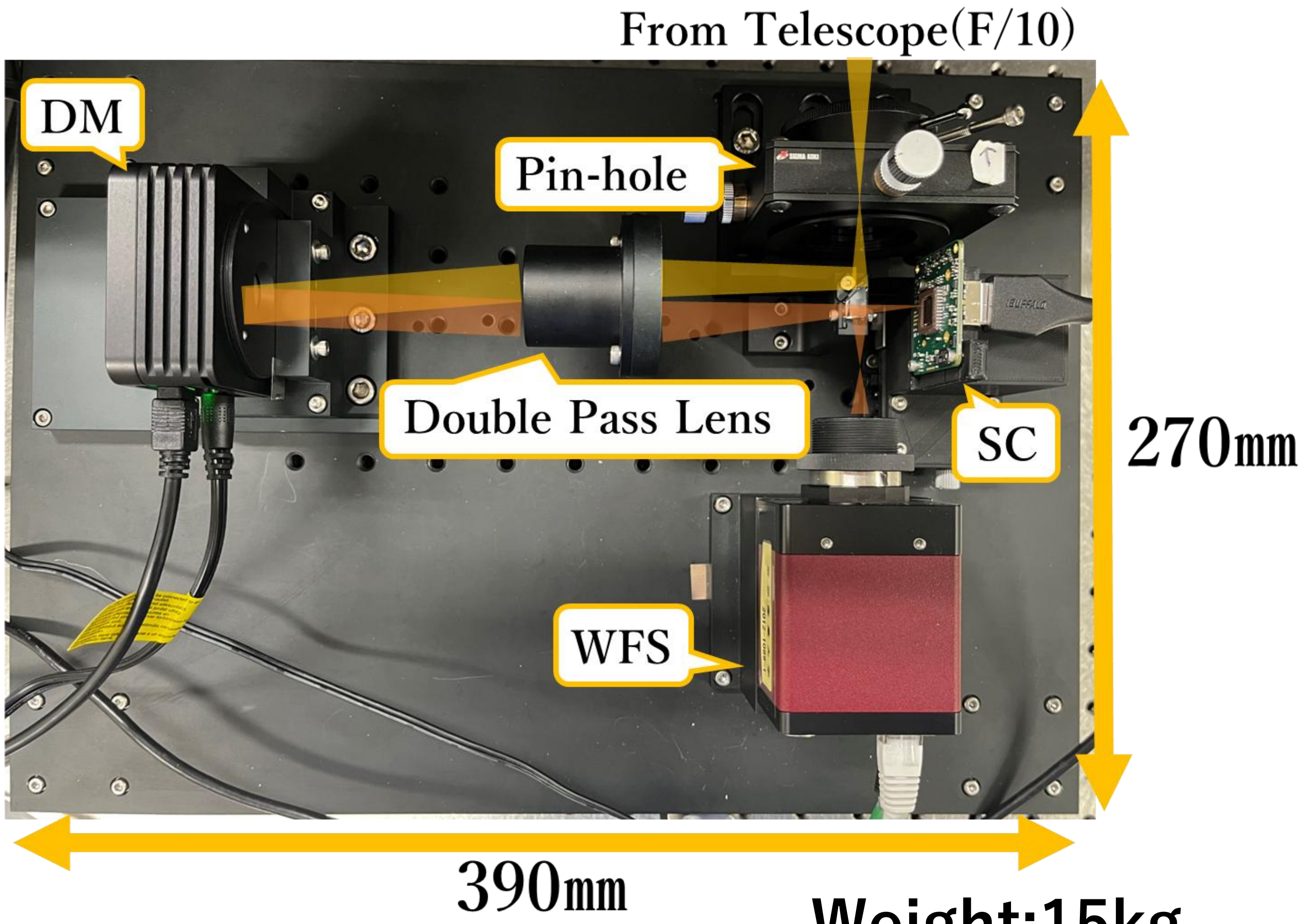
Refractive(w/lens)



In Kyoto
good sightseeing,
bad site-seeing

CRAO

Specification (Sakabe+ 2024)	
Optics	Refractive
Wavelength	400nm～700nm
AO type	SCAO
FoV	30”
WFS	12x12 SHWFS
DM	40 Piezo actuator
Loop freq.	<371Hz

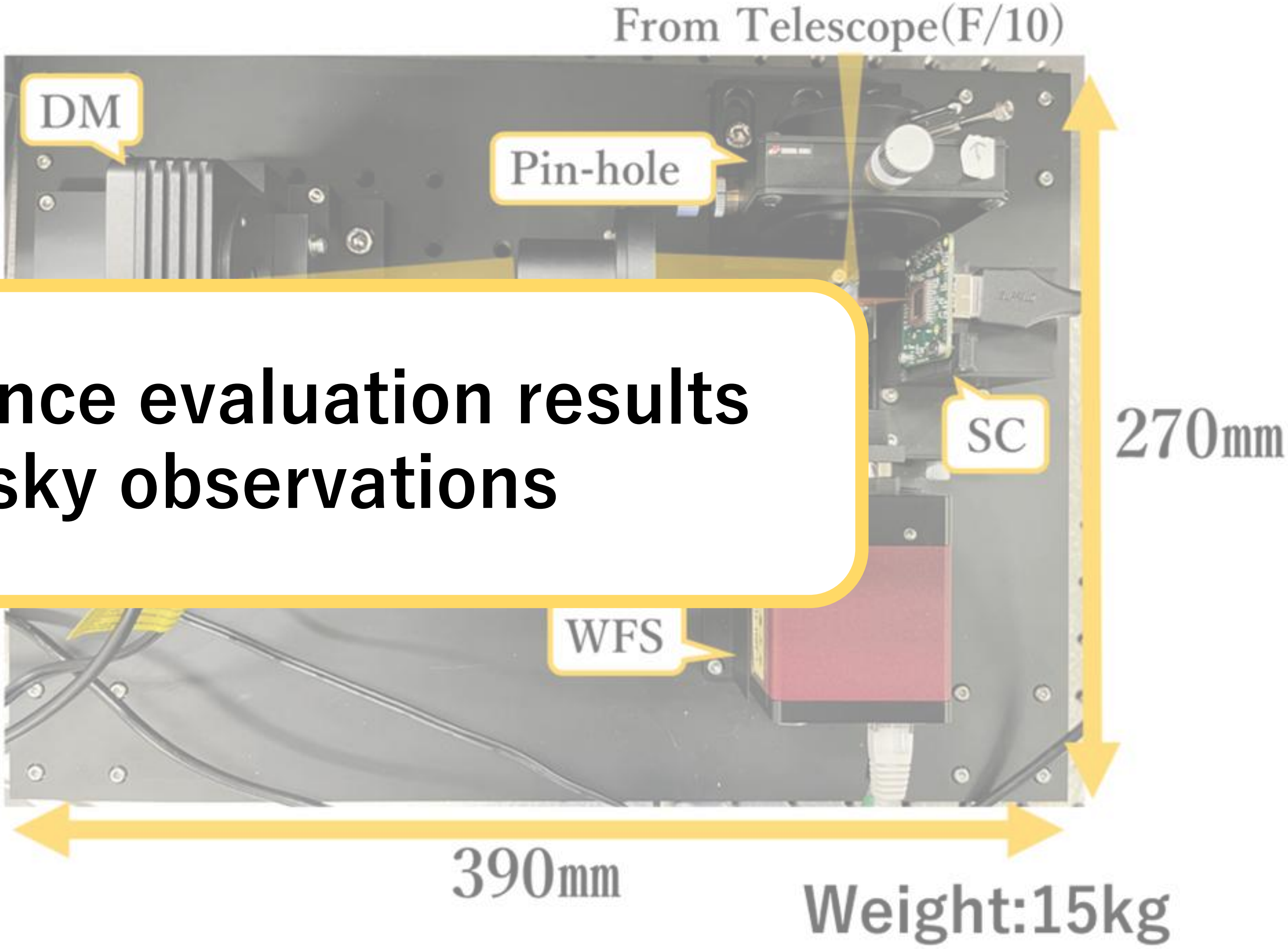


Weight:15kg

CRAO

Performance evaluation results from On-sky observations

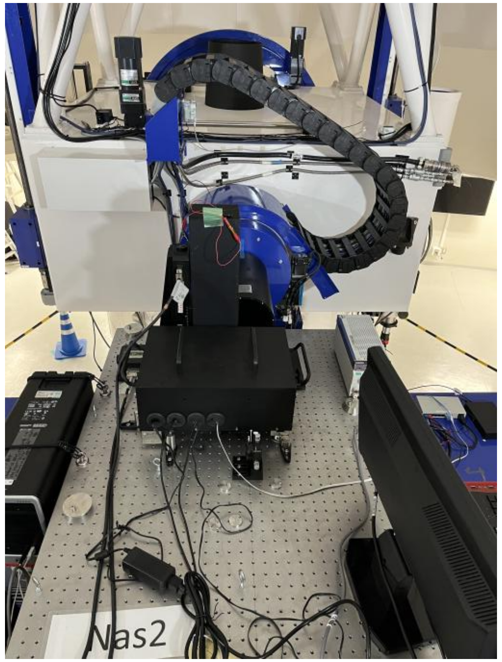
Specification (Sakabe+ 2024)	
Optics	Refractive
Wavelength	[illegible]
AO type	[illegible]
FoV	[illegible]
WFS	[illegible]
DM	40 Piezo actuator
Loop freq.	<371Hz



CRAO

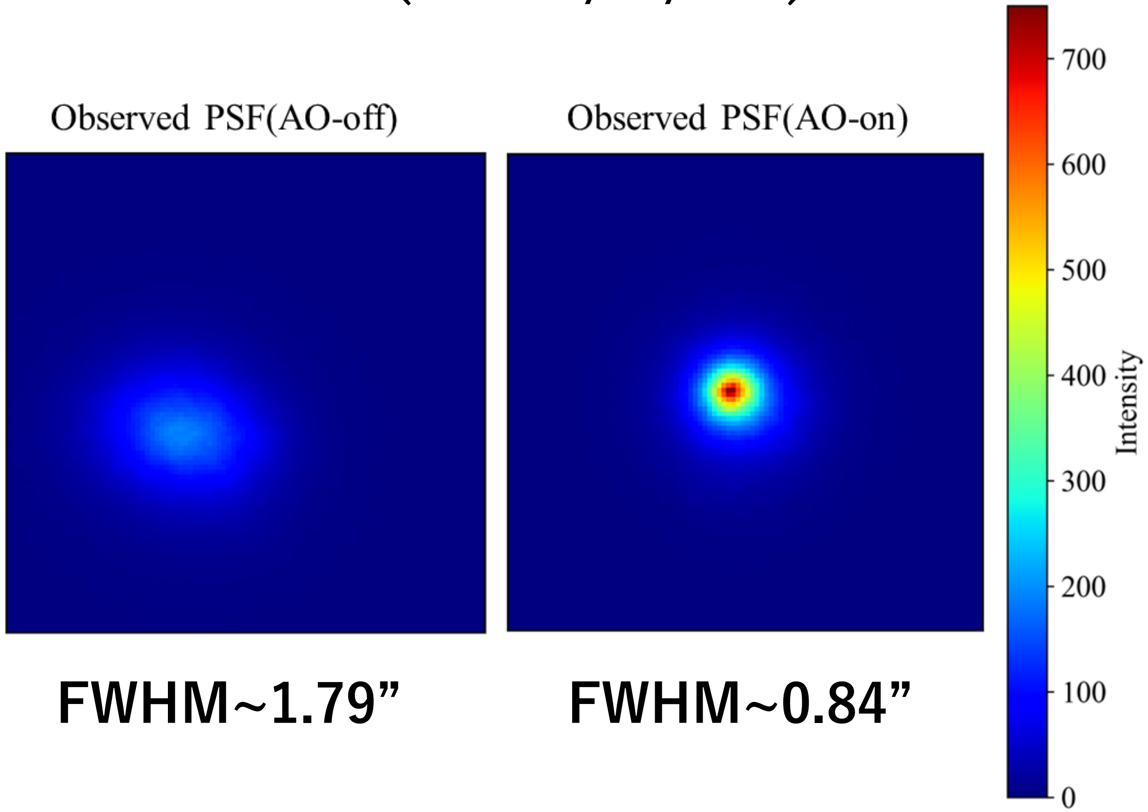
Observation log

Date	Object	Date	Object
2023/8/26	α Lyr , α Cyg	2024/1/24	α Boo , β Gem
2023/8/29	α Aql , α Cyg , α Lyr	2024/1/29	α Ori , β Gem , α Cma
2023/9/3	α Per , γ Cyg , α Lyr	2024/1/30	α Aur , α Uma , β Gem
2023/9/16	α Tau , α And , α Aur , α Cyg , β And , α Lyr	2024/2/12	α Boo , α Aur , β Gem , α Leo
2023/9/18	α Cyg	2024/2/13	α Boo , α Aur , α CMi , α Leo
2023/9/19	α Lyr	2024/3/10	α Boo , α Aur , α Uma , ϵ Leo , η Leo , ϵ Gem , η Boo , α Leo , ρ Boo
2023/9/25	α Cyg, α Umi, β And		
2023/10/2	α Cyg , β And		



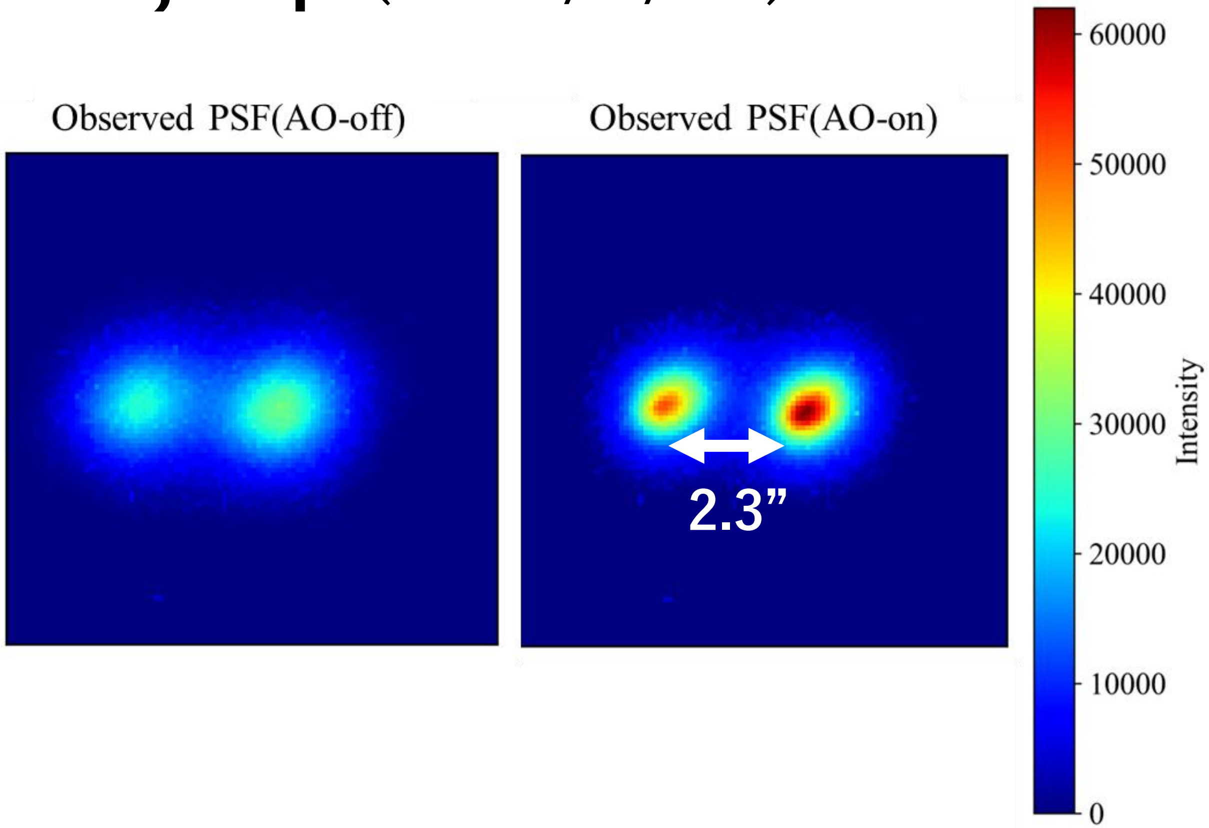
CRAO Observed PSF

α And (2023/9/16)



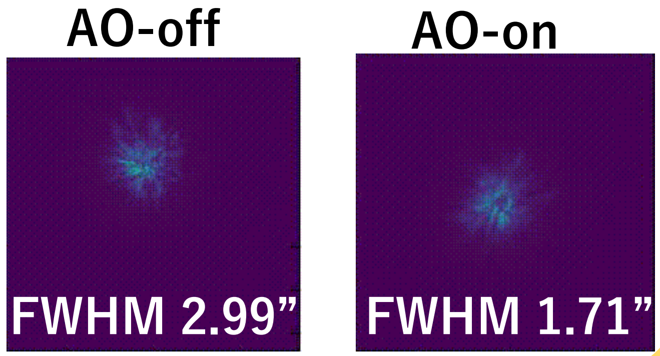
FWHM~1.79” **FWHM~0.84”**

ζ Aqr (2023/9/16)

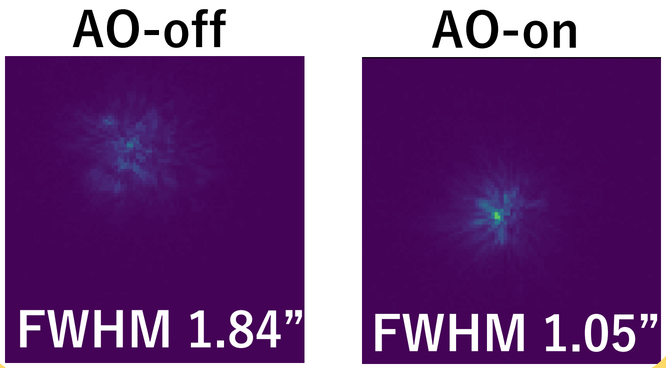


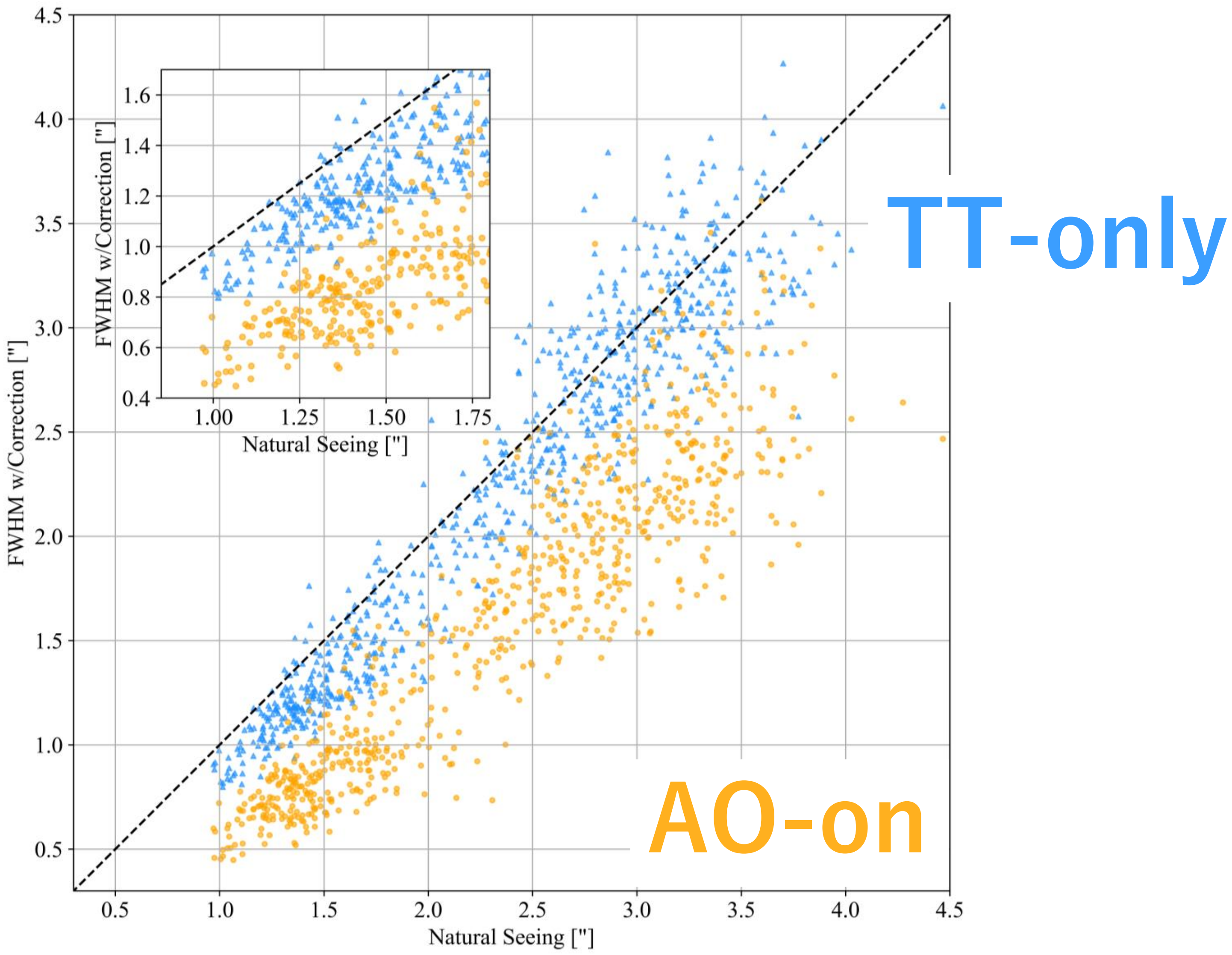
CRAO Correction result

2024/2/12 α Boo

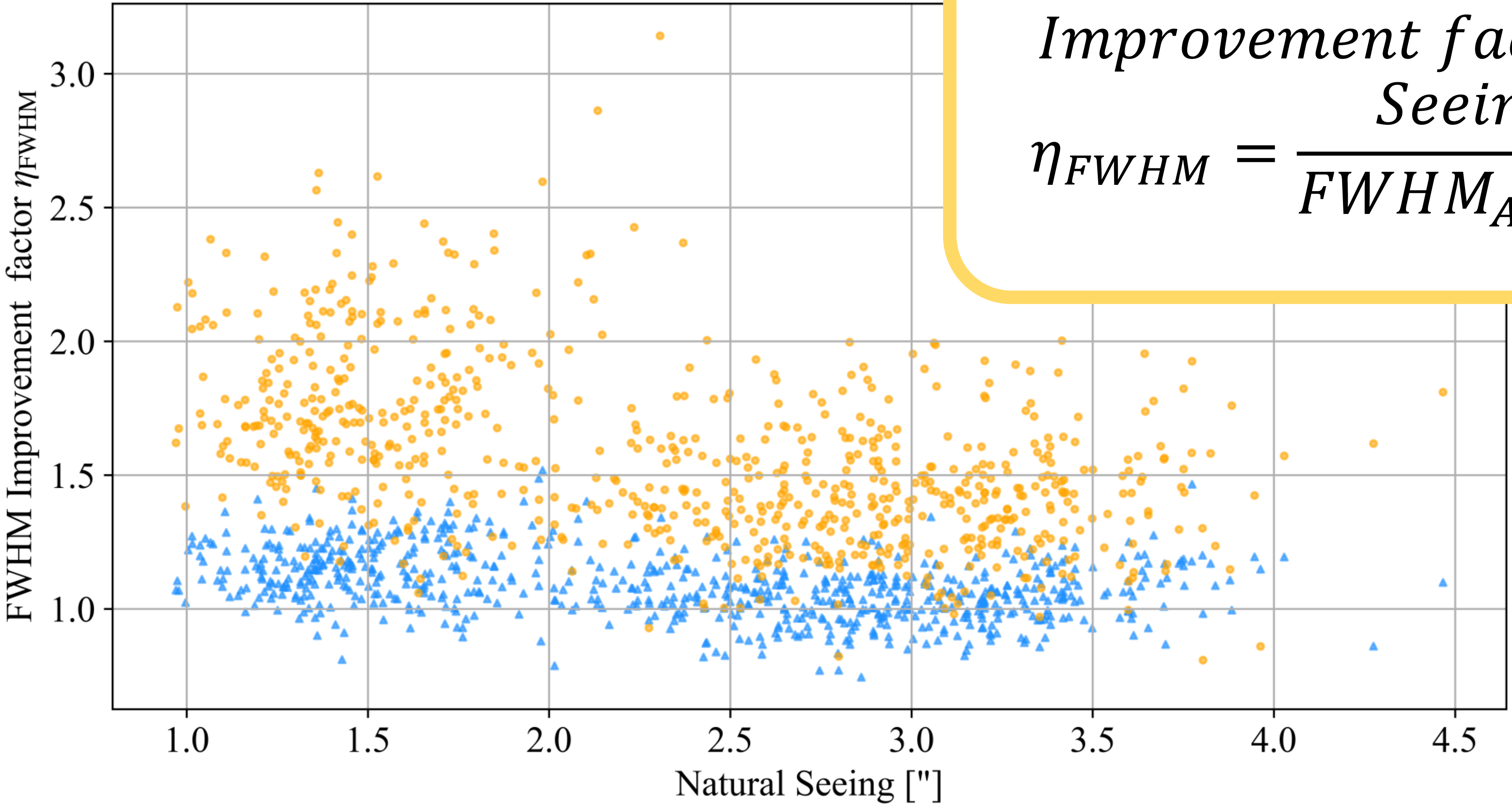


2023/8/26 α Lyr





CRAO Correction result



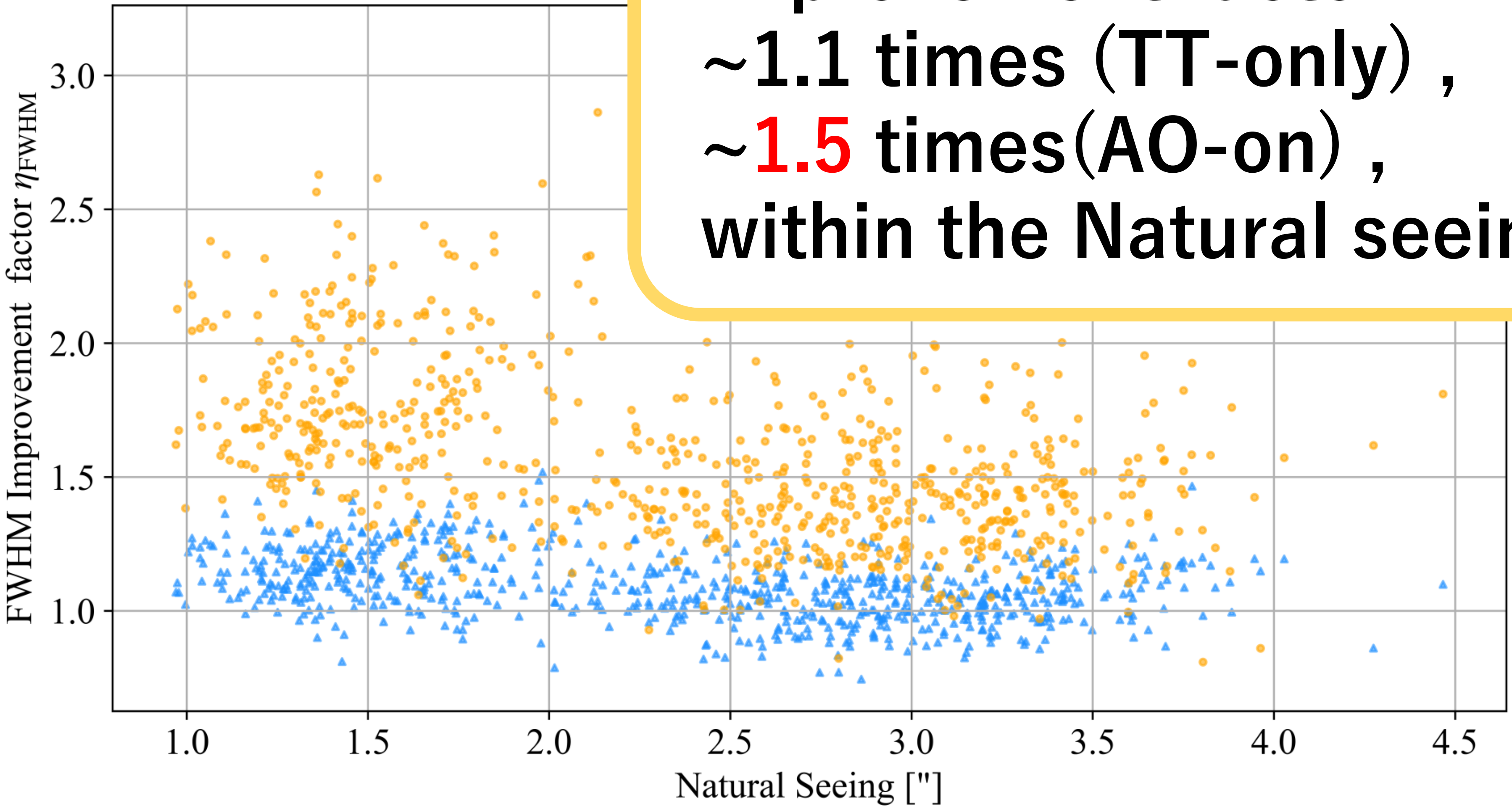
$$Improvement\ factor$$

$$\eta_{FWHM} = \frac{Seeing}{FWHM_{AO-on}}$$

AO-on

TT-only

CRAO Correction result



Improvement factor
~1.1 times (TT-only) ,
~1.5 times(AO-on) ,
within the Natural seeing 1” to 4”

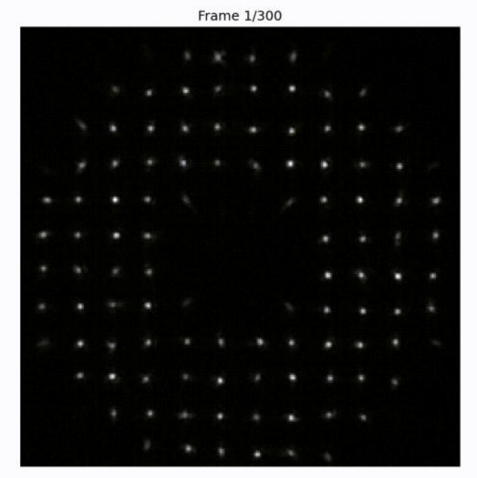
AO-on

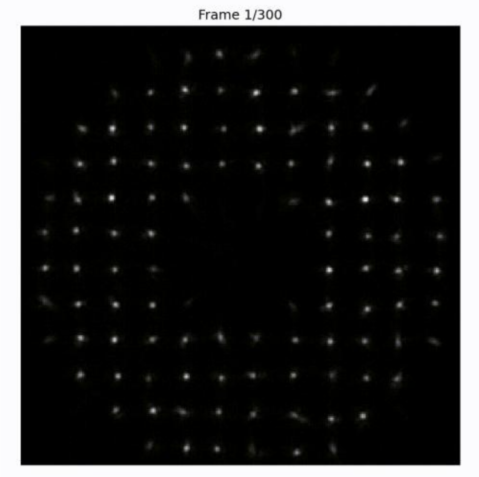
TT-only

CRAO Residual WFE

Wavefront Reconstruction from SHWFS Images

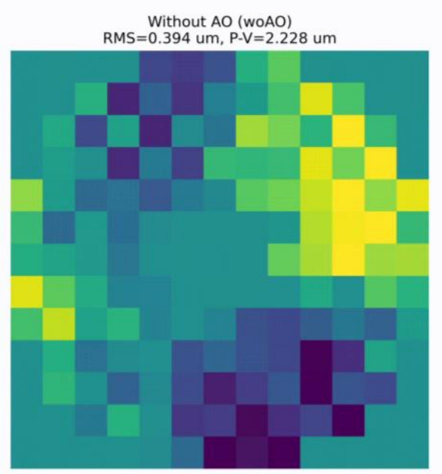
WFS-image

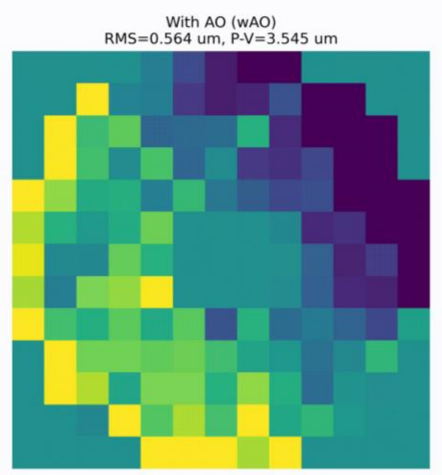




Conversion by Fried matrix (Fried, 1977)

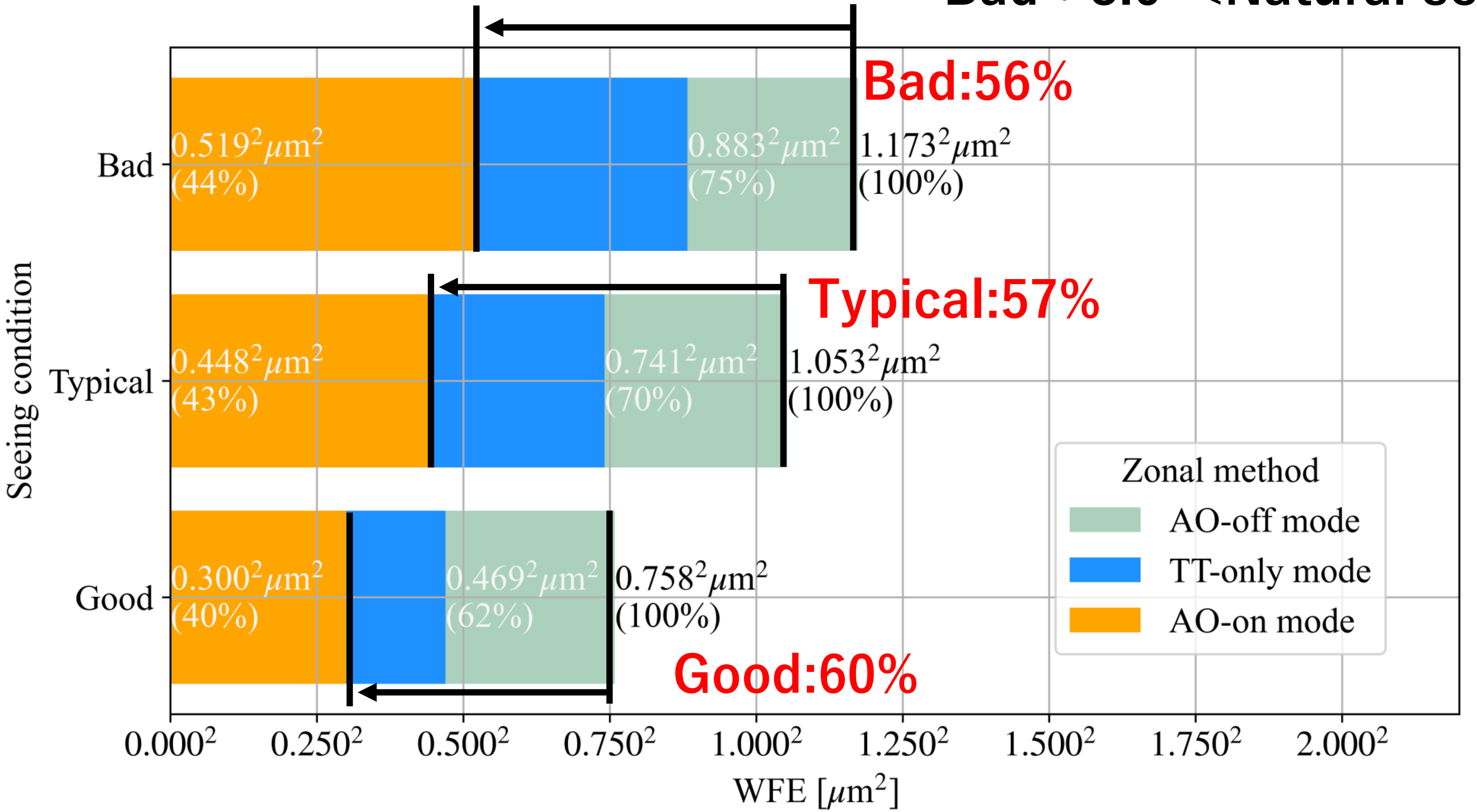
Reconstruct Wavefront





CRAO Residual WFE

Good : Natural seeing<=2.0”,
Typical：2.0”<Natural seeing<=3.0”,
Bad：3.0”<Natural seeing



CRAO Wavelength dependence

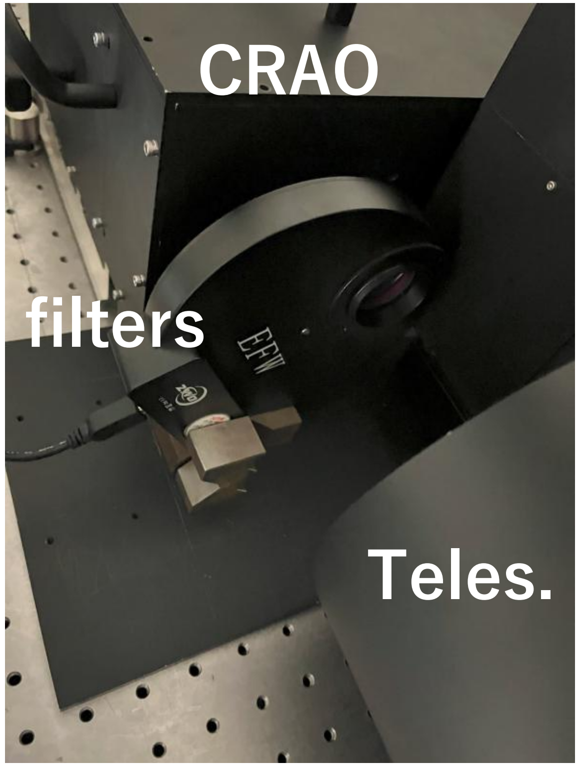
ZWO New LRGB Filters

*Measured with JASCO V670

	Minimum wavelength [nm]	Center wavelength [nm]	Maximum wavelength [nm]	Transmittance [%]
White	401.4	547.8	694.2	96.9
Red	596.8	646.2	695.6	97.6
Green	493.8	532.8	571.8	96.2
Blue	386.4	442.9	449.4	93.3

Observation object

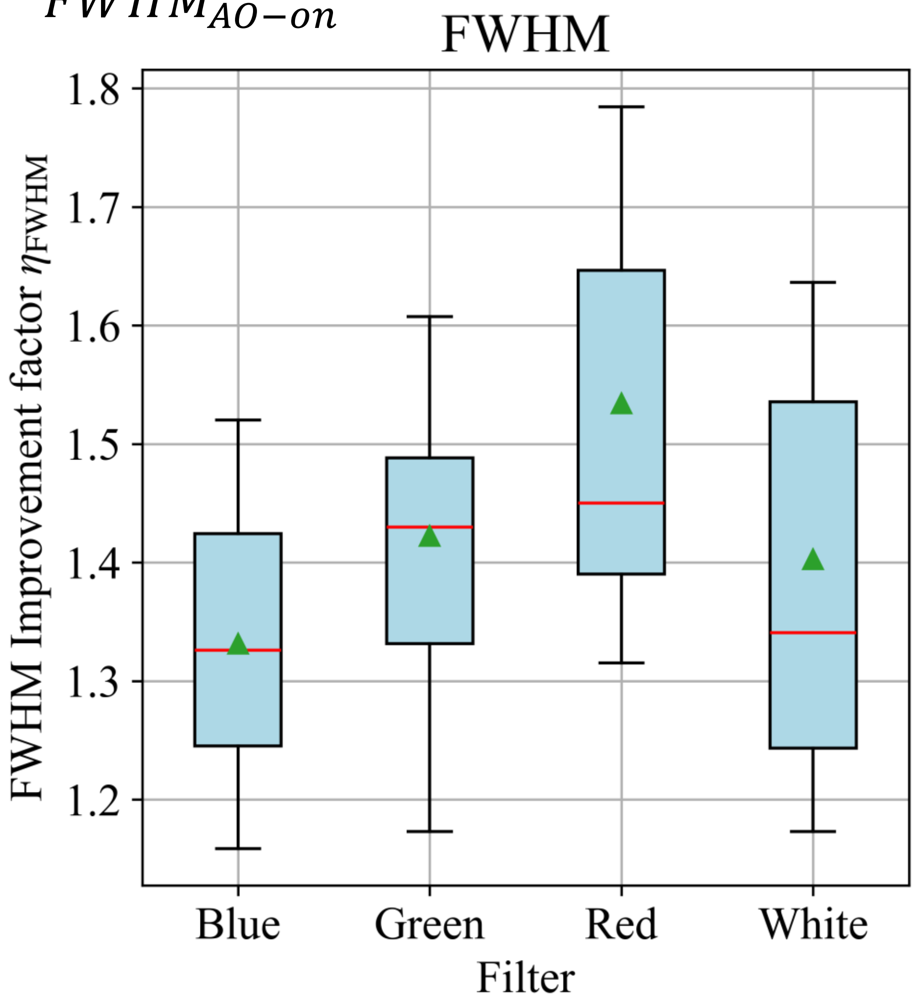
Date(UT)	Object	magnitude(m_V)	Spectral type	Elevation[°]
2024/2/12 9:53-12:08	α Aur	0.08	G3III	79-71
2024/2/12 15:30-17:49	α Leo	1.14	B8IV	67-52
2024/2/13 17:12-19:31	α Boo	-0.05	K1.5III	53-74

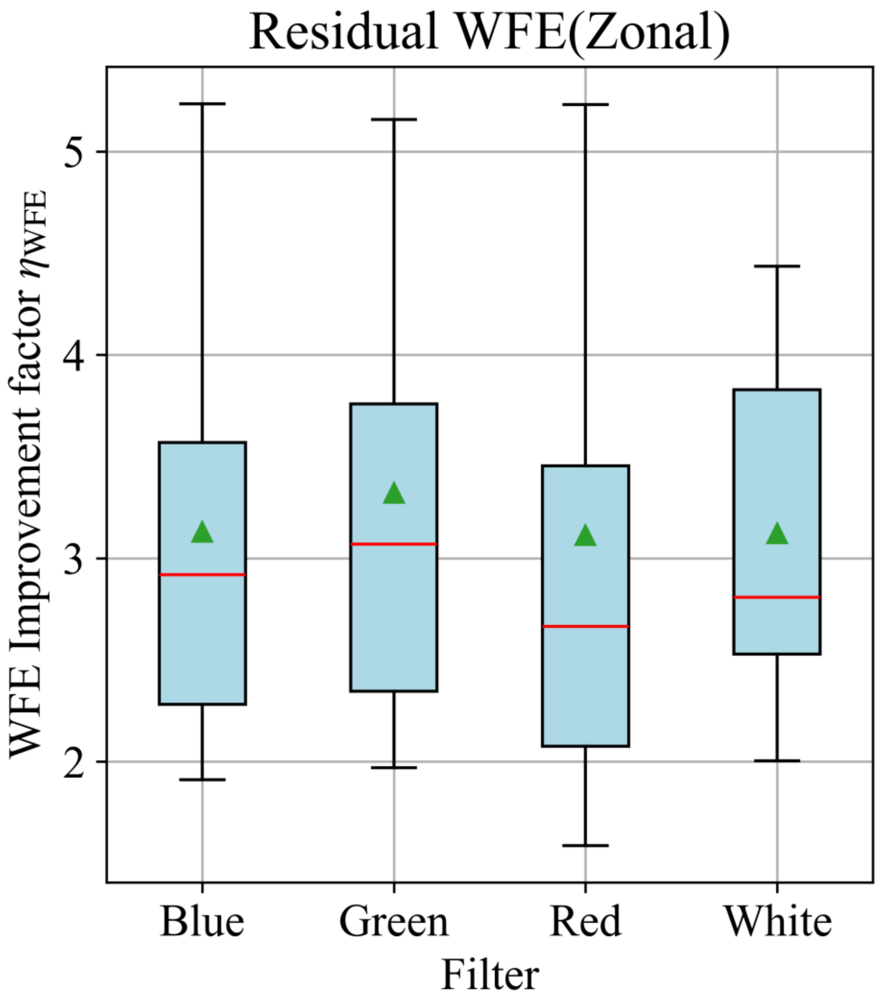


CRAO Wavelength dependence

$$\eta_{FWHM} = \frac{Seeing}{FWHM_{AO-on}}$$

$$\eta_{WFE} = \frac{Zonal\ WFE_{AO-off}}{Zonal\ WFE_{AO-on}}$$





-:Median
▲:Mean

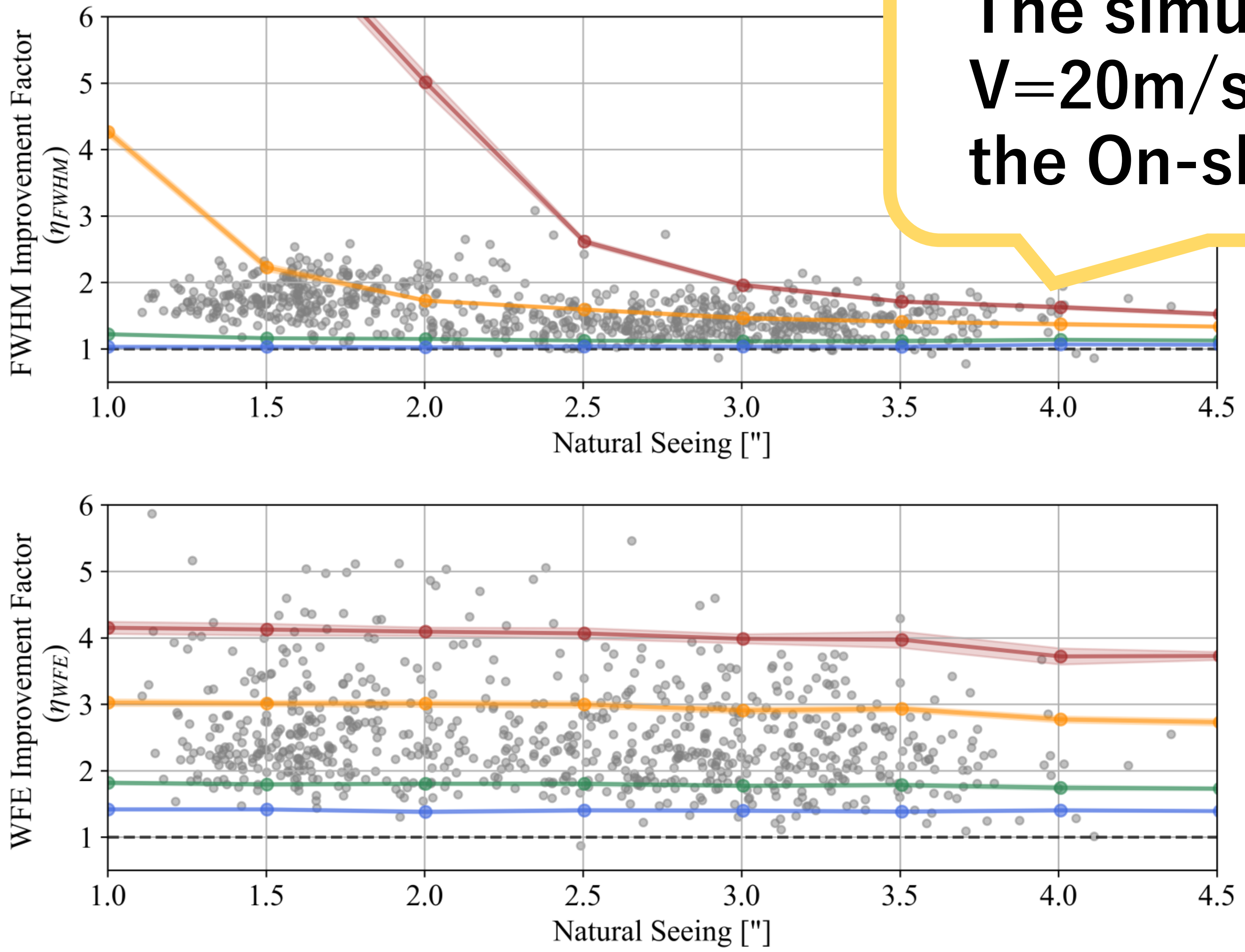
CRAO vs AO simulation

Verification of performance by AO simulation

COMPASS(F. Ferreira et al., 2018)

Parameter		Values
Atmosphere	Layers	1
	Fried parameter (r0)	3 cm
	Windspeed (V)	**10,20,45,70 m/s**
AO	WFS	12x12 Shack Hartmann
	DM	40 stacked actuator
	Loop freq.	200Hz

CRAO vs AO simulation



The simulation with V=20m/s matches the On-sky results

Windspeeds

V=10m/s

V=20m/s

V=45m/s

V=70m/s

Summary

- We developed the CRAO at the KAO of Kyoto Sangyo University
- Compact design achieved by using a double-pass lens
- On-sky observations performed in the 1.3m Araki Telescope
- Observed 14 nights between August 2023 and March 2024,
  and the following results were obtained:
  - ✓ Achieved ~1.5 times improvement in the Natural seeing 1-4"
  - ✓ Analysis of zonal WFE confirmed a reduction of approximately ~60%
  - ✓ No effect of chromatic aberration in On-sky observations using filters
  - ✓ Compared with the AO simulation,
    it was confirmed that the expected performance was achieved