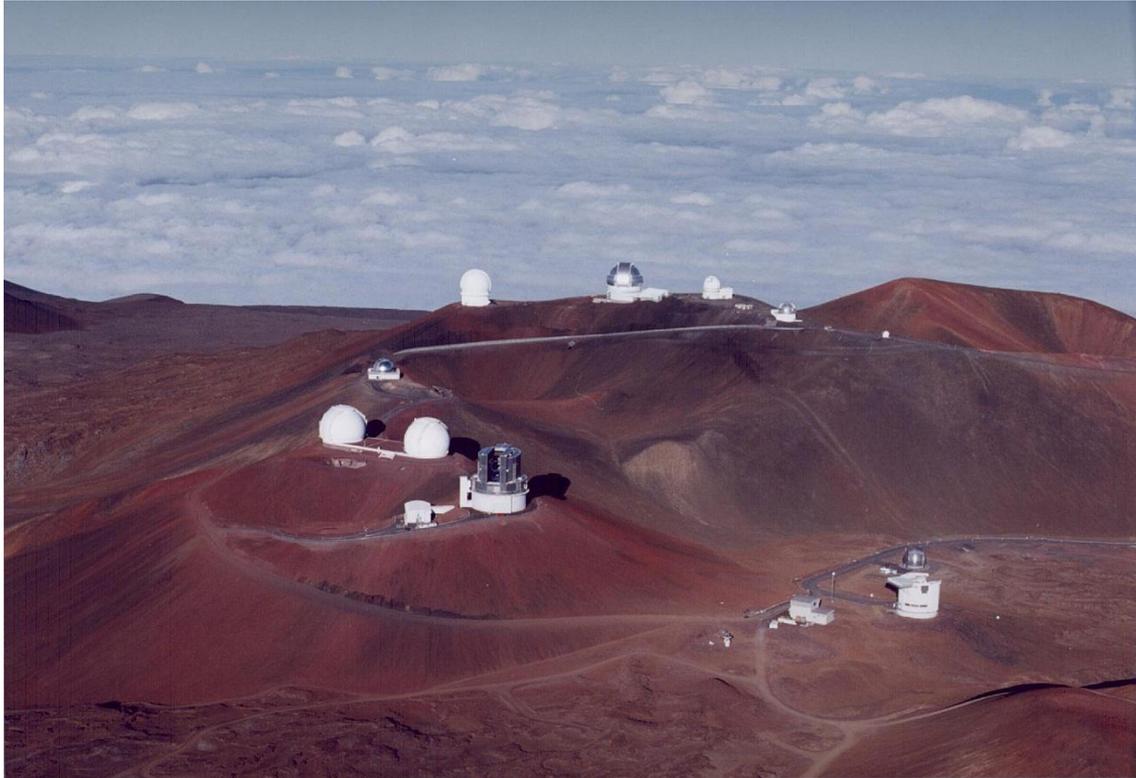


Subaru GLAO Simulation



Shin Oya (Subaru Telescope)

2012/10/16 @ Hilo

Outline

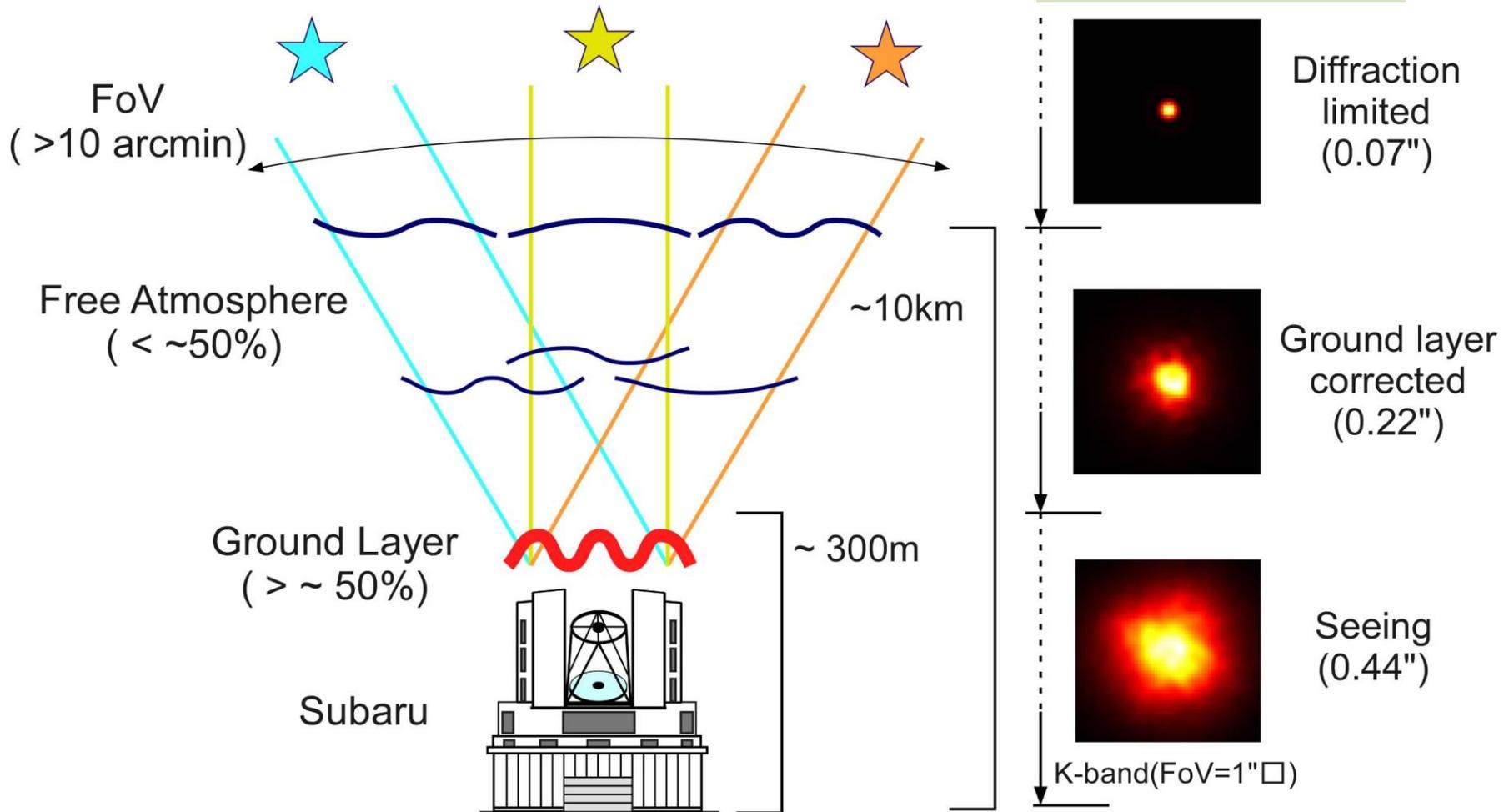
- What is Ground Layer Adaptive Optics (GLAO)?
 - a type of wide-field AO
 - Mauna Kea seeing (which determines GLAO performance)
- Simulation to evaluate performance
 - Seeing model, configuration
 - Correction
 - wavefront error (WFE)
 - profile (moffat FWHM; ensquared energy)
 - wavelength dependency, zenith angle dependency
 - Field-of-View
 - mechanical limit: $C_s 8.6' \phi \Rightarrow 20' \phi$ w/o ADC (cf. $N_s 4' \phi$)
 - constraint from performance?
- Adaptive Secondary Mirror (ASM) application

What is GLAO?

Wide-field AO (incl. GLAO) needs

Tomography

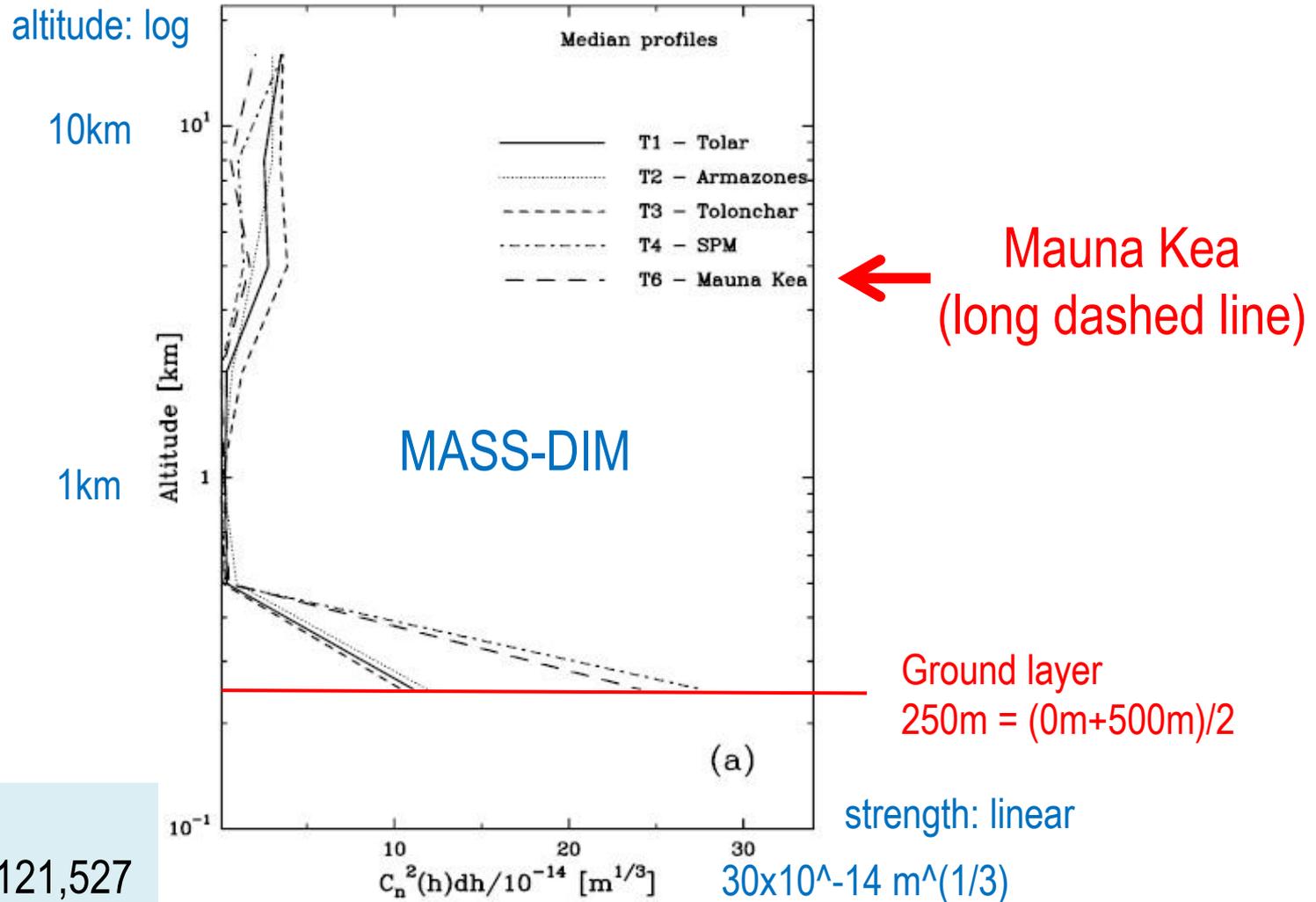
- Considering 3D structure of atmospheric turbulence
- Multiple guide stars



Mauna Kea seeing: overall profile

- Free atmosphere turbulence: weak
- Ground layer turbulence: strong

suitable for
GLAO



TMT 13N
Els+09, PASP, 121,527

Mauna Kea Seeing: ground layer

– Concentrated close to the surface

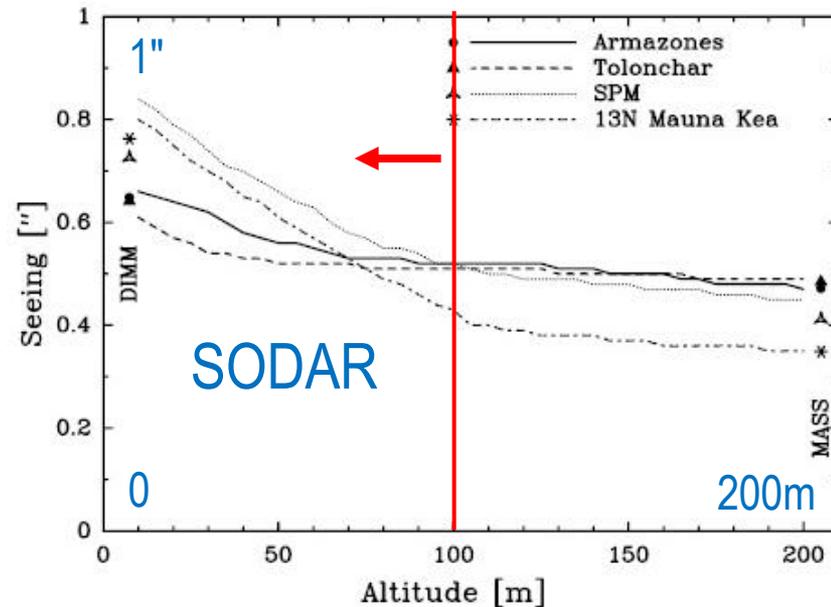
suitable for
GLAO

- Summit ridge (~70 m above Subaru)
 - Chun+09, MNRAS, 394, 1121
 - SLODAR (~2yr)
 - LORAS (~1yr)

- TMT site (~90m below Subaru)
 - Els+09, PASP, 121, 527
 - MASS-DIMM (~2yr)
 - SODAR (~2yr)

Altitude (m)	25 percentile	50 percentile	75 percentile
0.0	8.06E-14	1.04E-13	1.40E-13
15.0	3.31E-14	5.32E-14	8.56E-14
30.0	1.60E-15	1.41E-14	2.10E-14
45.0	0.00	6.34E-16	1.03E-14
80-160	5.20E-16	7.27E-15	2.43E-14
160-240	0.0	3.51E-15	1.01E-14
240-320	0.0	2.91E-15	9.01E-15
320-400	0.0	1.87E-15	6.91E-15
400-480	0.0	4.10E-16	4.97E-15
480-560	0.0	0.0	1.67E-15
560-640	0.0	0.0	0.0
FA	2.46e-13	1.57e-13	9.37e-14

ground layer < 80m



ground layer < 100m

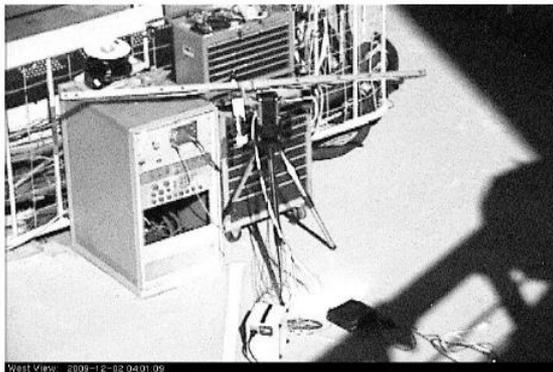
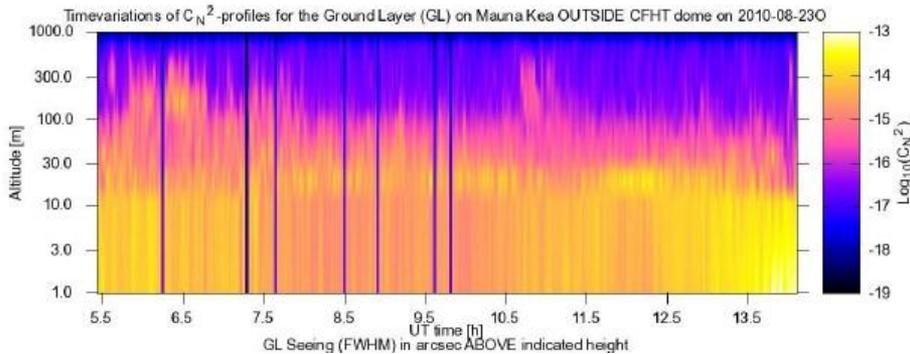
Seeing measurement plan at Subaru

Local ground-layer at Subaru?

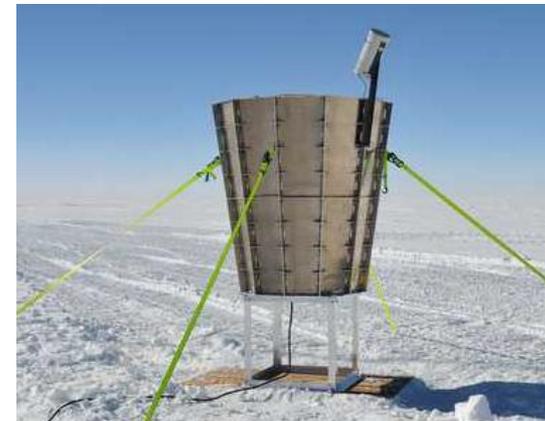
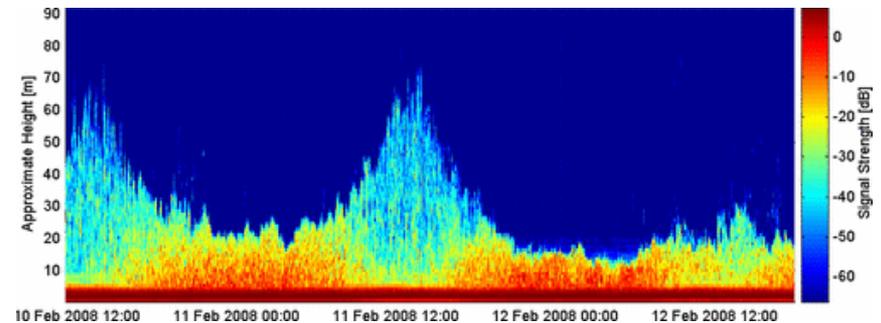
- 70m below and leeward of the ridge (laminar flow?)
- fine resolution data for more detailed simulation

Grant-in-Aid
(Houga)
from this FY

Luna Shabar (PTP) by Univ.BC
optical: 1 ~ 1000m



SNODAR by Univ. NSW
acoustic: 10 ~ 100m



RAVEN seeing model

D. Andersen+2012,PASP,124,469

- based on **TMT site testing profile** at 13N (Els+09,PASP,121,527)

- **IQ statistics difference** between 13N profile and Subaru is attributed to ground layer

Fractional Layer Strength

h km	seeing percentile		
	25%	50%	75%
r_0	19.4 cm	15.6 cm	12.1 cm
fwhm	0.53"	0.66"	0.85"
0	0.6823	0.5960	0.4971
0.5	0.0611	0.0963	0.1382
1	0.0212	0.0325	0.0577
2	0.0172	0.0372	0.0642
4	0.0757	0.0869	0.0833
8	0.0486	0.0684	0.0895
16	0.0939	0.0826	0.0700

increased to match
Subaru IQ statistics

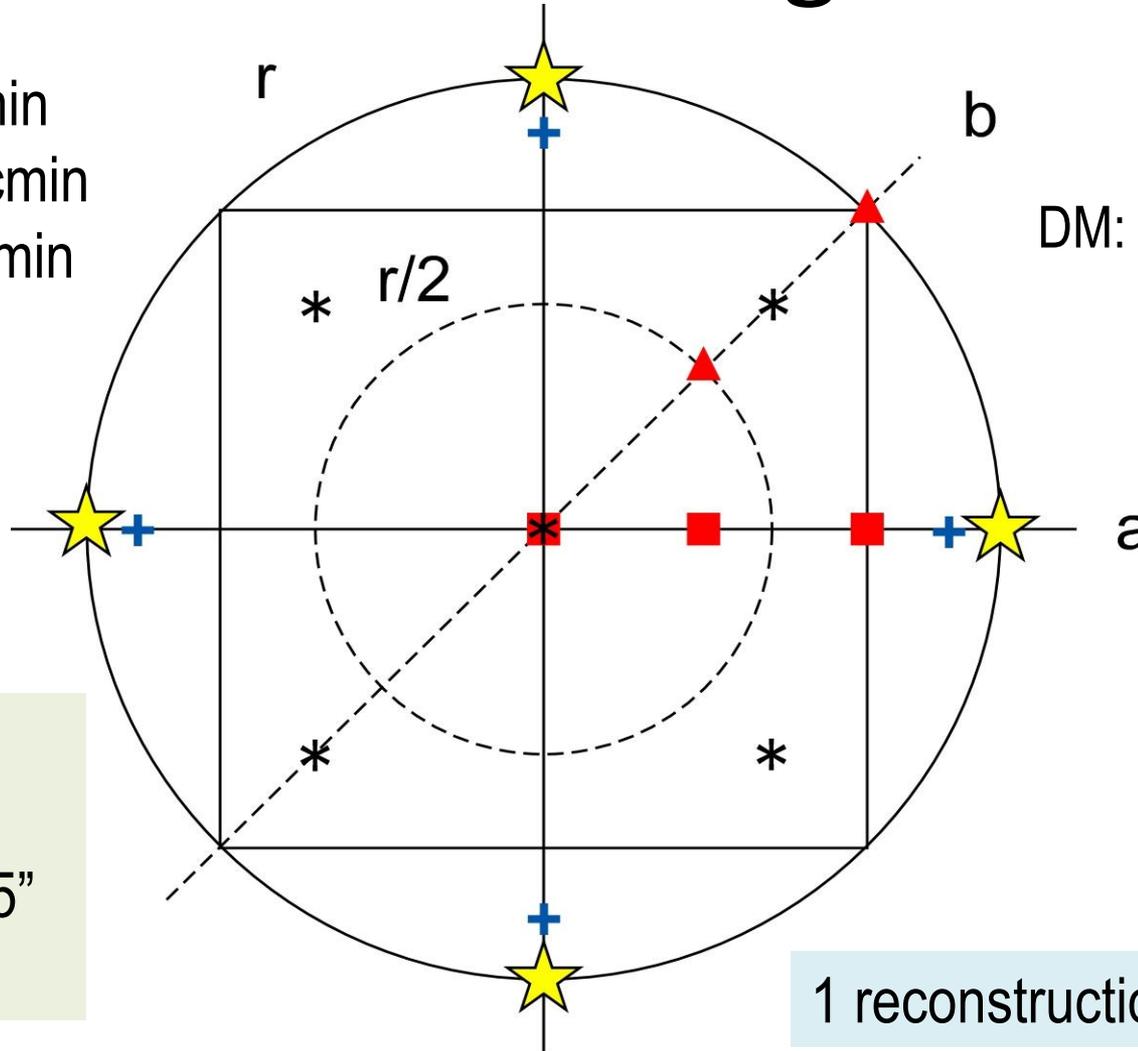
TMT site testing
profile ratio

Subaru GLAO configuration

tentative

$r = 5$ arcmin
7.5 arcmin
10 arcmin

DM: 32 act. Across
@ -80m



RAVEN seeing:

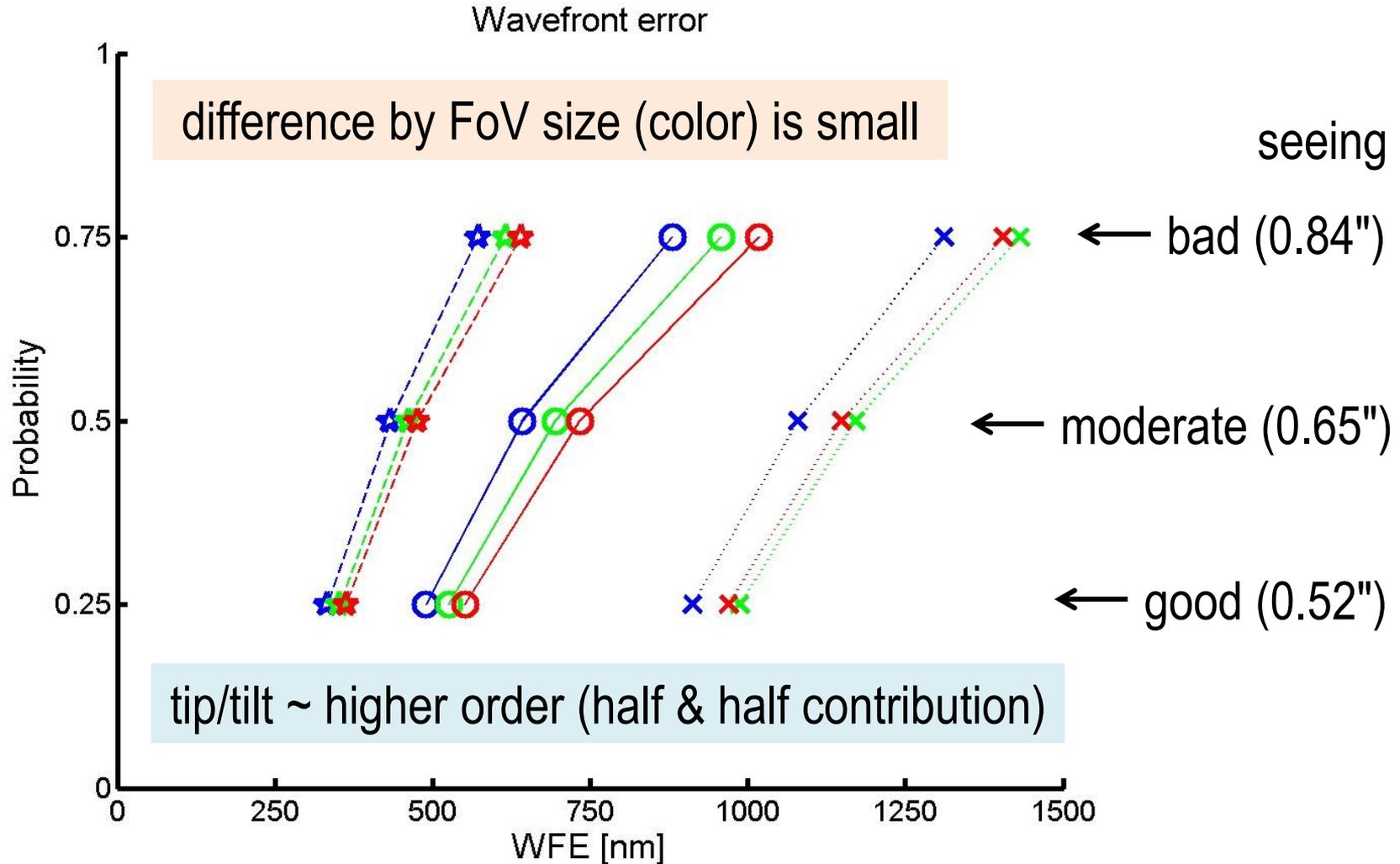
- good: 0.52"
- moderate: 0.65"
- bad: 0.84"

★: HoGS +: TTF-GS (50" inside of LGS)

■: PSF eval.(toward GS) ▲: (between GS)

* : DM fitting

Seeing dependence of WFE

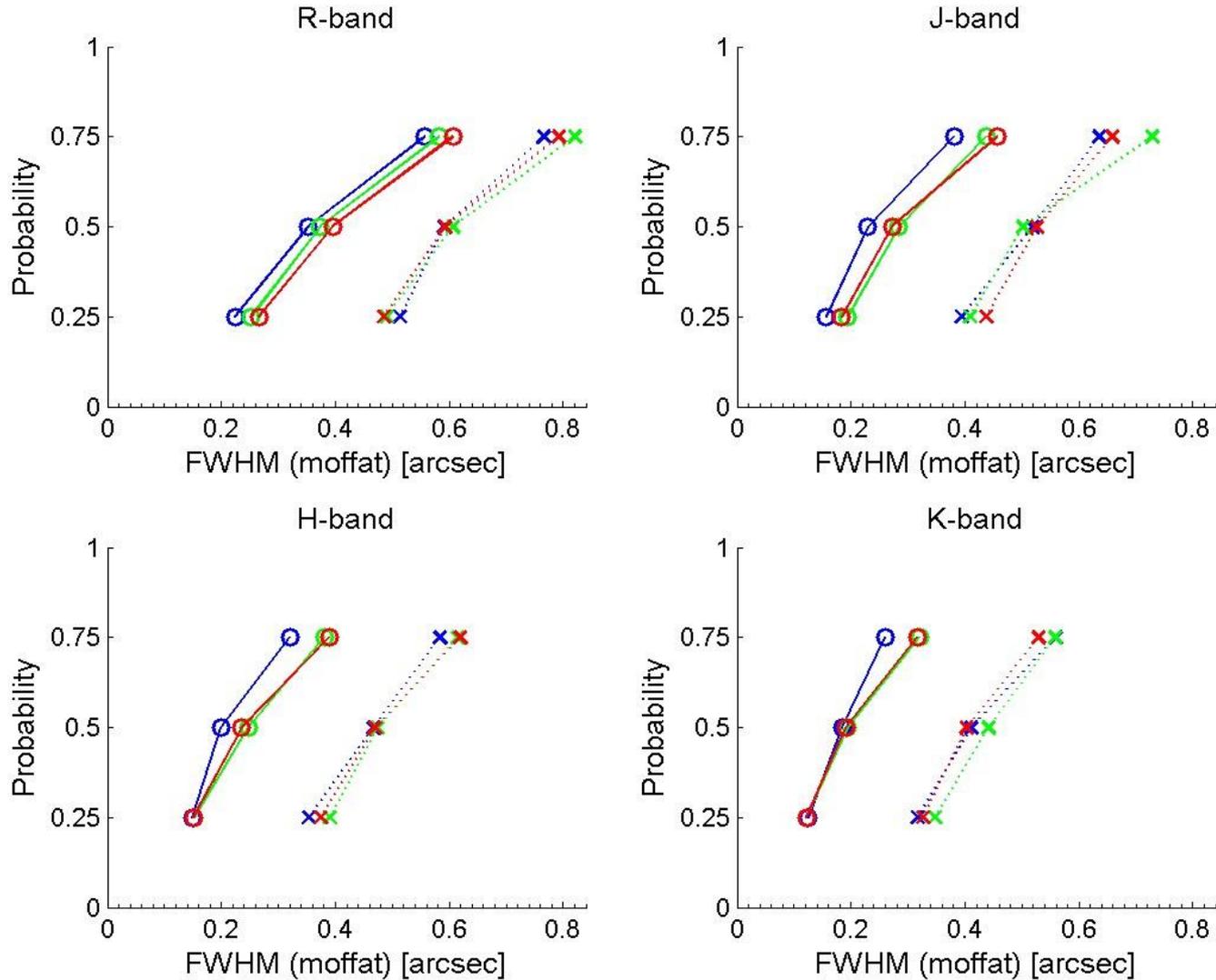


FOV: blue: $\varphi = 10\text{arcmin}$ 、green: $\varphi = 15\text{arcmin}$ 、red: $\varphi = 20\text{arcmin}$

WFE order: ○: all order、☆: tip/tilt removed = higher order

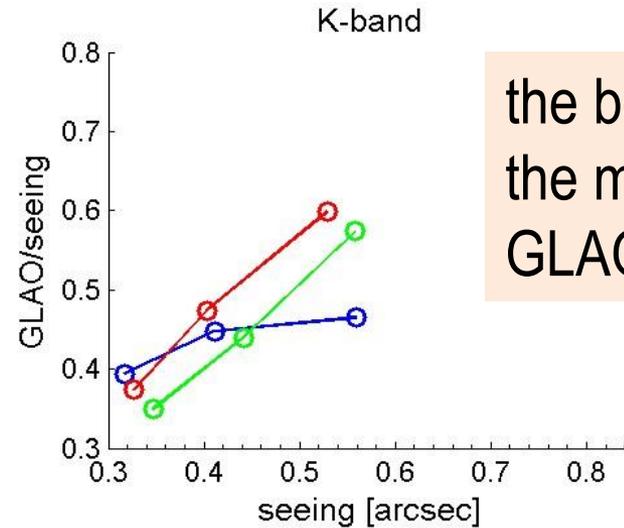
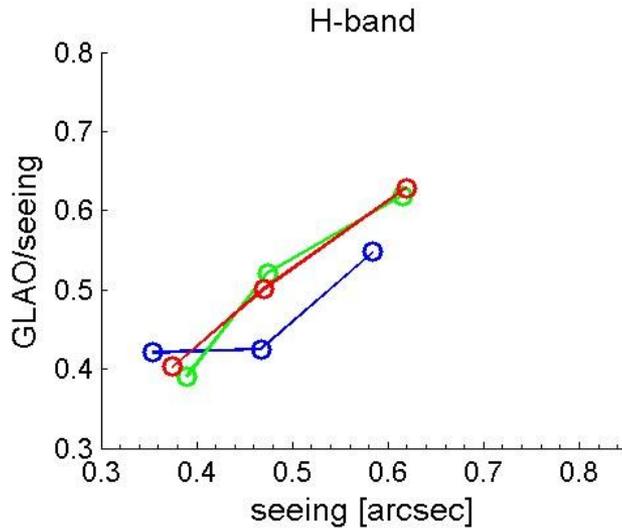
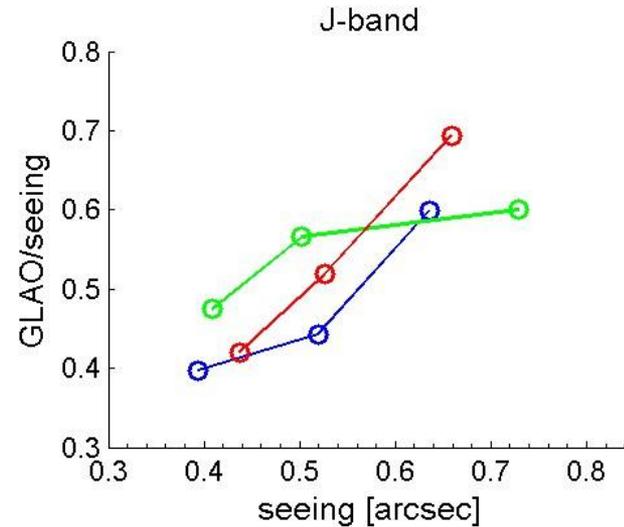
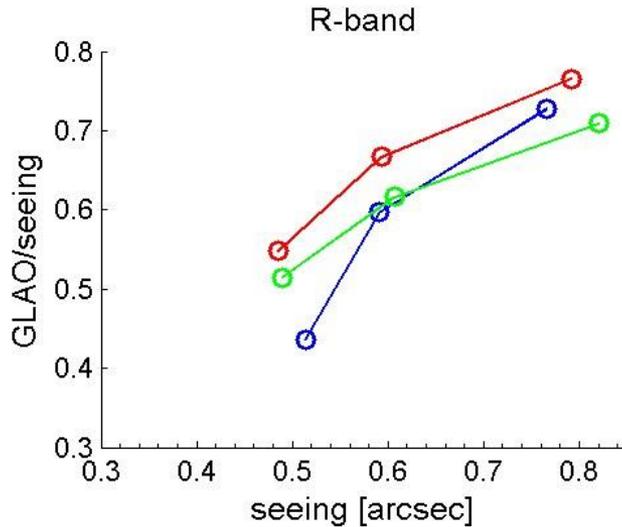
Seeing: ×

Seeing dependence of FWHM



FOV: blue: $\phi = 10$ arcmin, green: $\phi = 15$ arcmin, red: $\phi = 20$ arcmin
GLAO: O, Seeing: x

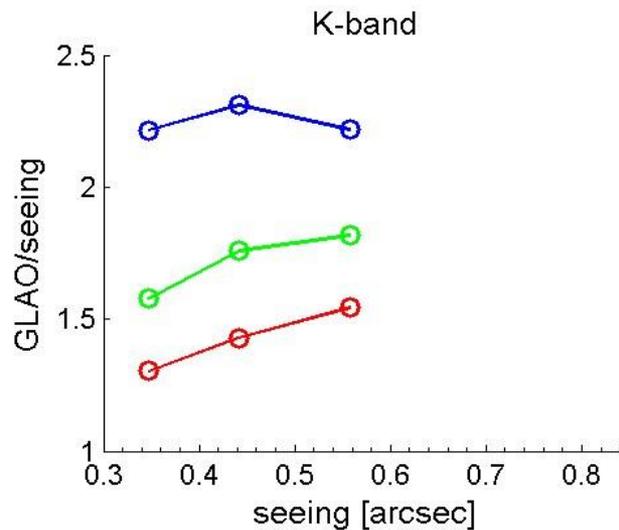
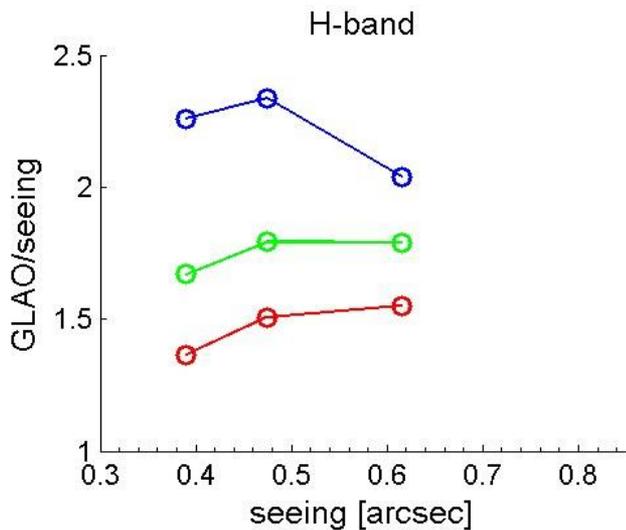
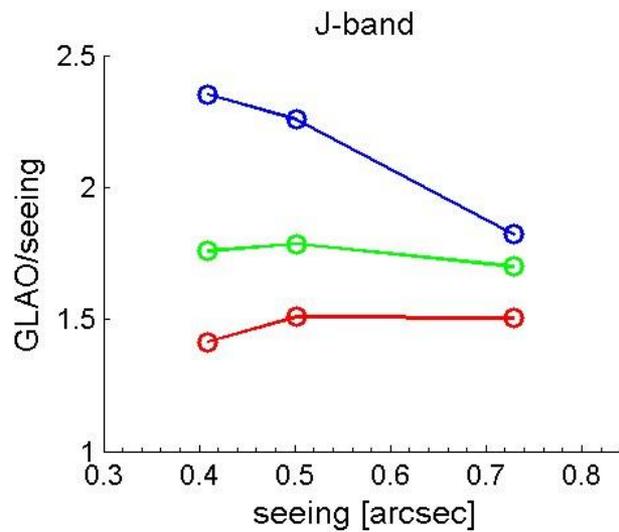
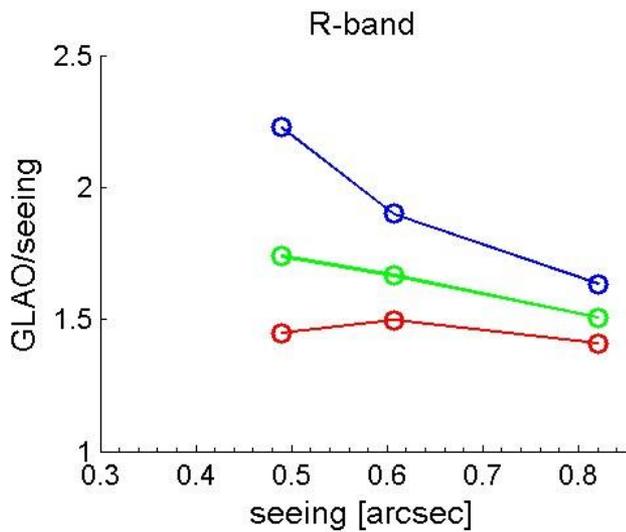
Seeing vs FWHM ratio (GLAO/seeing)



the better seeing is,
the more effective
GLAO correction is.

FOV: blue: $\phi = 10$ arcmin, green: $\phi = 15$ arcmin, red: $\phi = 20$ arcmin

Seeing vs EsqE ratio (GLAO/Seeing)



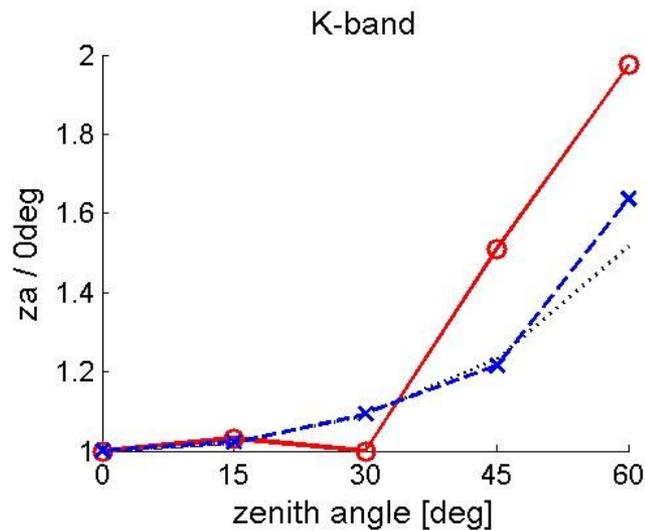
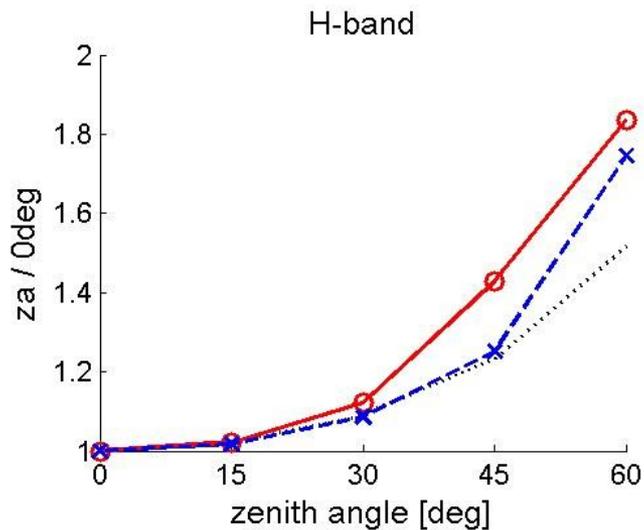
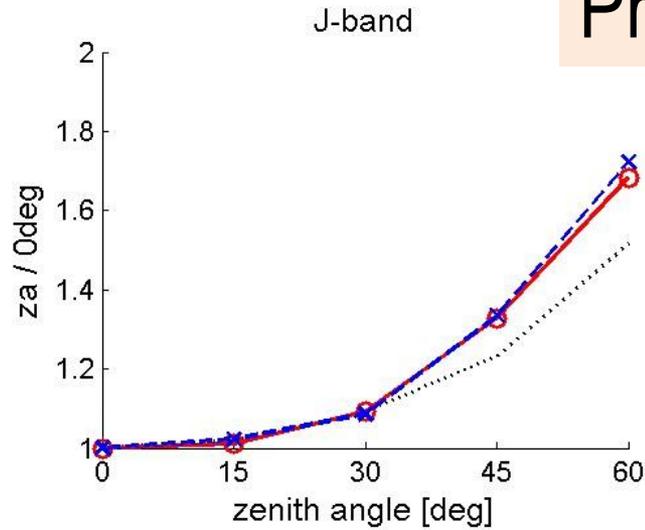
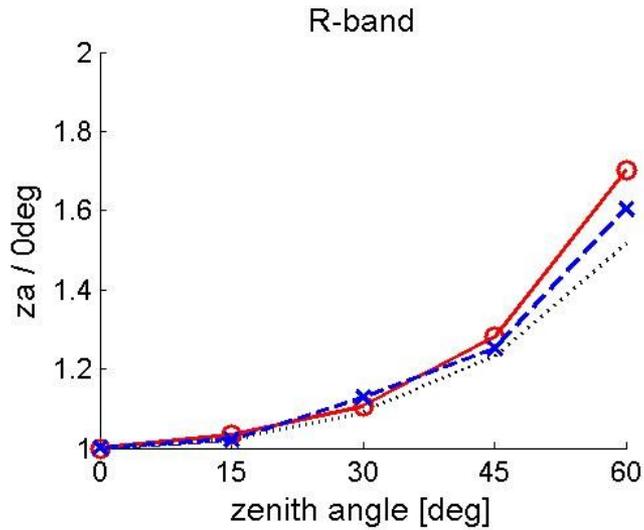
width: blue: 0.24"、green: 0.36"、red: 0.48"

FoV: 15' ϕ

Zenith angle dependence of FWHM

effective turbulence height increases

Preliminary!



theoretical
@ ZA<30

moderate
seeing
FoV: 15' ϕ

width: red solid-line: GLAO (center), blue dashed-line: Seeing
black dotted-line: theoretical (seeing)

Comments on the noise

Seeing: $\sigma_{\text{total}}^2 = \sigma_{\text{atm}}^{\text{FA}} + \sigma_{\text{atm}}^{\text{GL}}$

FA: free atmosphere
GL: ground layer



GLAO: $\sigma_{\text{WFE}}^2 = \underbrace{\sigma_{\text{atm}}^{\text{FA}}}_{\text{uncorrected (dominant) seeing determines performance}} + \underbrace{(\sigma_{\text{sense}}^2 + \sigma_{\text{fit}}^2 + \sigma_{\text{delay}}^2 + \sigma_{\text{etc}}^2)}_{\text{corrected (residual of AO system error) performance little change if } \sigma_{\text{each}} < \sigma_{\text{atm}}^{\text{FA}}}$

WFE (σ_{WFE}) increase

- limit mag (σ_{sensor}): 8% by R=18 (TTF, 10mag LGS), RN limit
- HoWFS order (σ_{fit}): ~0% by 8x8 R=15 \Leftrightarrow 32x32 R=13
- frame rate (σ_{delay}): 8% by 200Hz \Rightarrow 50Hz (gain=0.5)

Bright NGS vs Typical LGS

typical case: moderate seeing (0.66"), FoV 15'φ

WFE [nm]: Tot: **1274** ± 325, TT: 955 ± 395, Ho: 802 ± 129

- NGS sensor noise free (R=10)

WFE [nm]: Tot: **737** ± 95, TT: 515 ± 122, Ho: 519 ± 47

- LGS R=10, NGS(TTF) R=18mag

WFE [nm]: Tot: **783** ± 127, TT: 578 ± 161, Ho: 517 ± 47

WFS parameters: SH, 200Hz, gain=0.3, RN=0.1e-, 512x512pix

Possible observation modes by ASM

1. GLAO @ Cs

- seeing improvement over wide FoV

2. On-Source Single NGS @ Cs, Ns

- high SR for bright on-source NGS
- reduction of thermal background at $\lambda > 2\mu\text{m}$

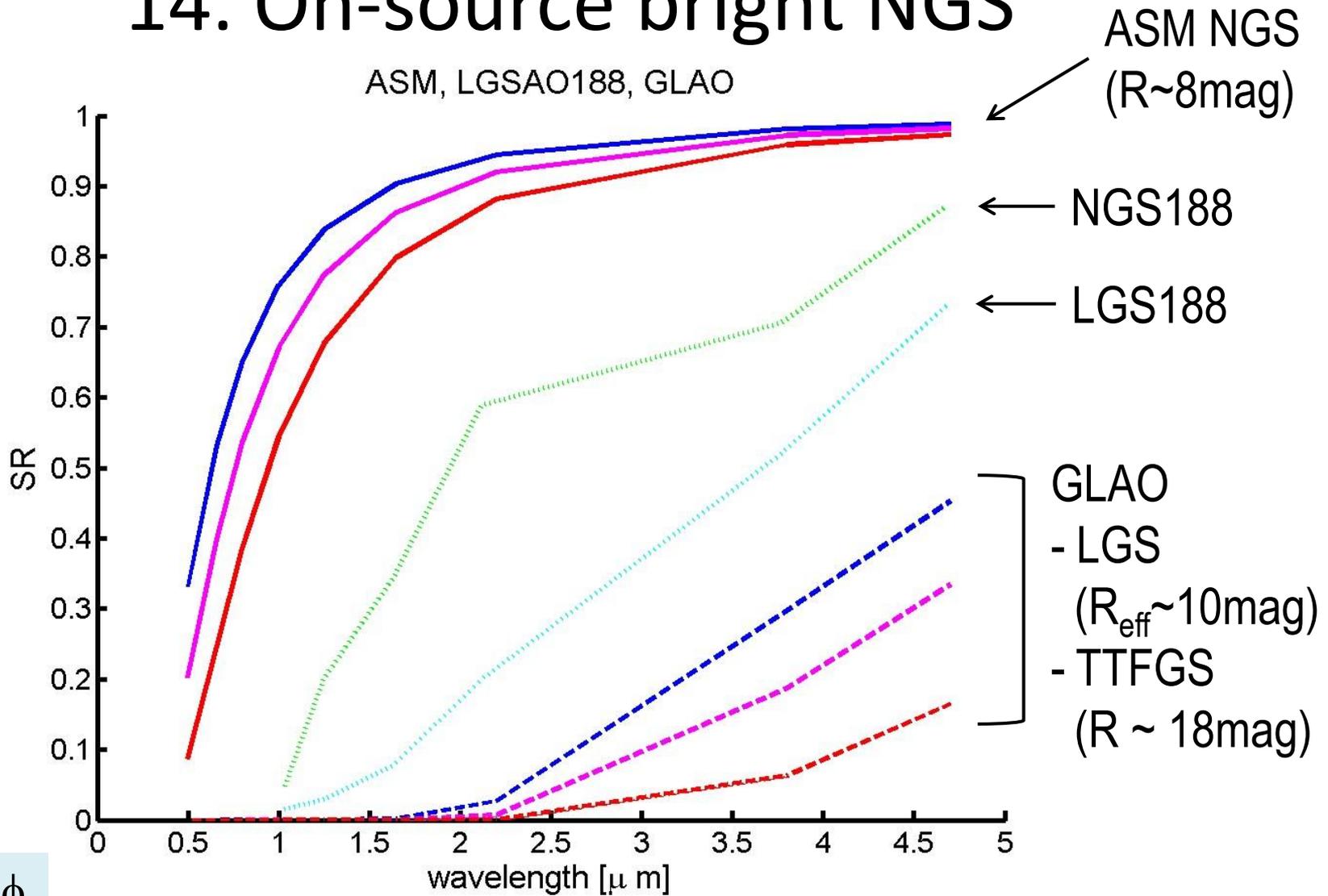
3. Single Conjugate Laser Tomography (SCLT) @ Cs, Ns

- better SR than on-source single LGS
- as close to on-source single NGS as possible

- Multi-Conjugate Laser Tomography (MCLT)?

- to increase FoV > 1 arcmin

14. On-source bright NGS



FoV: 15' ϕ

Seeing @ 0.5 μ m: good (0.52"), moderate (0.62"), bad (0.84")

System: solid: ASM, dashed: GLAO, LGSAO188: GLAO

Summary

- GLAO: Ground Layer Adaptive Optics
 - a wide-field AO correcting ground-layer turbulence only
 - Mauna Kea seeing is suitable for GLAO
- Expected performance of GLAO by MAOS simulation
 - Seeing model: TMT (13N) + GL to match Subaru IQ statistics
 - Parameters: 32 elem, 4GS (NGS or LGS+TTF), 200Hz, 0.1e-RN
 - Correction
 - FOV: $15' \Phi$, FWHM $< 0.2''$ @ K-band: 50%ile; $0.65'' @ 0.5\mu\text{m}$
 - Field-of-View
 - mechanical vignetting by the telescope & optical design of the instrument limit FoV (not GLAO performance)
- Other possible observation modes by ASM
 - On-source bright NGS
 - FOV: $1' \Phi$, SR ~ 0.9 @ K-band : 50%ile; $0.65'' @ 0.5\mu\text{m}$
 - Laser tomography
 - single conjugate (ASM only), multi conjugate (in future?)

Appendix

AO types

finer correction

(increasing the number of elements)



Correction
Performance

HiCIAO/SCEXAO

Wide field AO
(Subaru ngAO)

High Contrast
High Strehl

ExAO
extremely
high-order

LTAO
laser tomography
with IR-WFS

RAVEN

Diffraction Limited

Conventional
AO
single DM and WFS

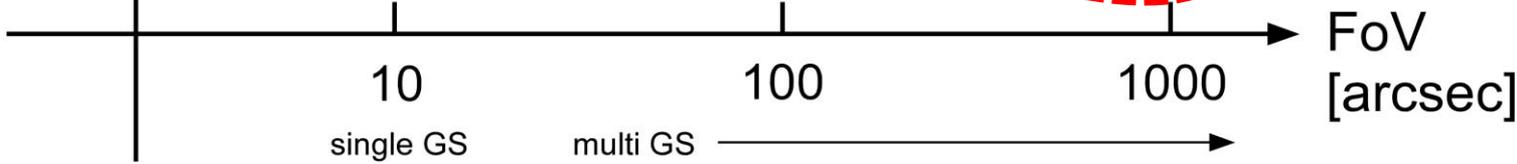
MCAO
multi DM
and WFS

MOAO
AO unit for
each target

Seeing Improvement

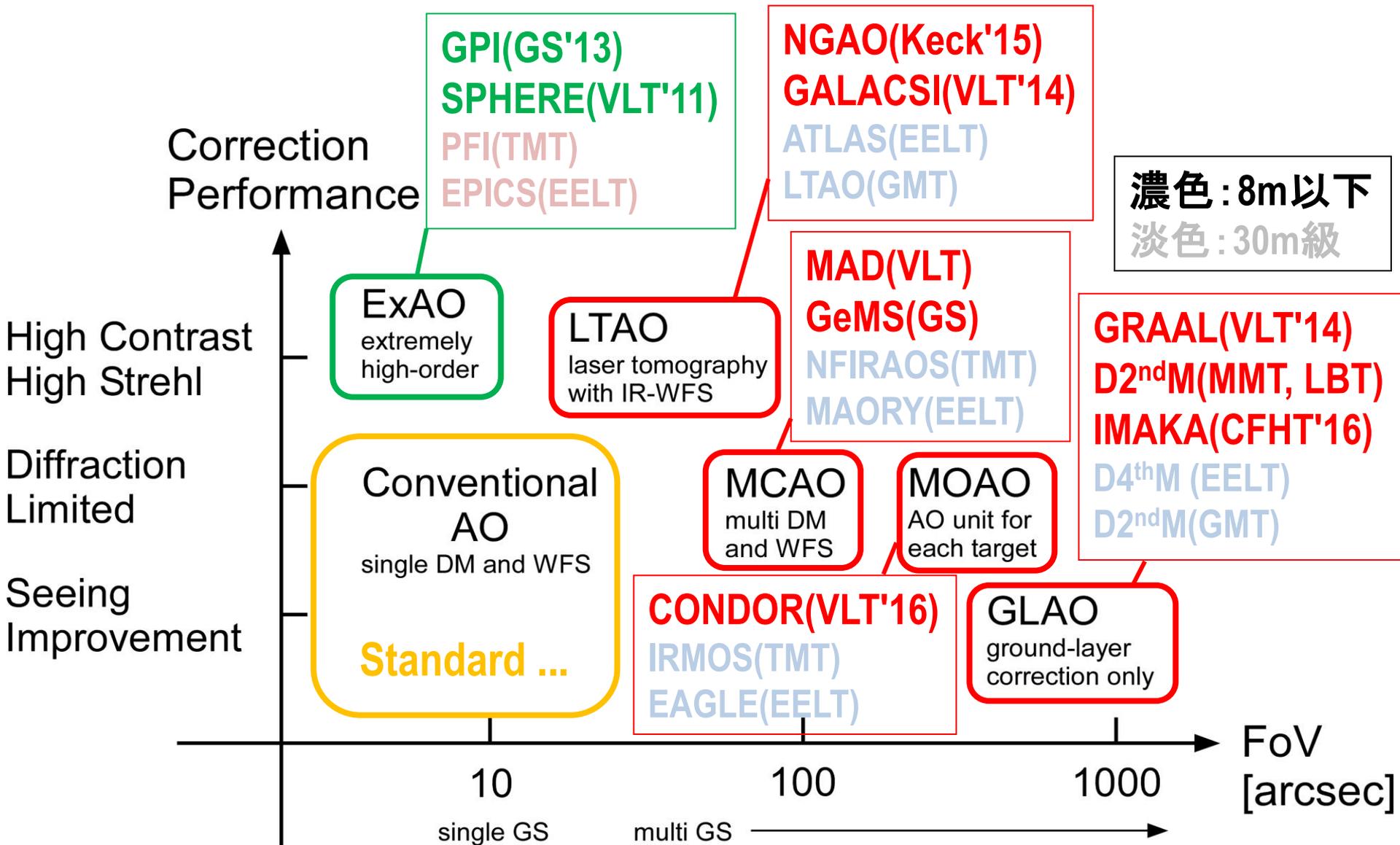
LGSAO188

GLAO
ground-layer
correction only



→ more layer correction
(increasing the number of DM & WFS)

世界のAOの分布



Comparison of simulation codes

Comparison with Gemini GLAO simulation (Appendix F1)

validation of MAOS configuration: compared with other

check influence of gray-zone: same seeing (0.6" @ 0.5um), but different height (300m, 500m, 900m) and strength of gray-zone

MAOS additional conditions

wind speed: 6.5m/s @ < 1km, 15m/s @ 2km, 30m/s @ 10km (IMAKA model) ; direction: random

DM fitting: 10' square 5 points: (0' ,0'), (+/-5', +/-5')

Gain: 0.3

Noise free

MAOS

FWHM

Code	Star Pos.	UA code 1	UA code 1	UD code	PAOLA	CIBOLA			(Gauss)	(Moffat)	MAOS		
Profile	[arcmin]	[arcsec]	[arcsec]	[arcsec]	[arcsec]	[arcsec]	ave	std	[arcsec]	[arcsec]	beta	ave	std
Uncorrected		0.359	0.357	0.353	0.349		0.355	0.004	0.347	0.340	3.083	0.344	0.005

low gz

1	(0.0, 0.0)	0.258	0.224	0.235	0.221	0.220	0.235	0.017	0.215	0.209	1.70	0.212	0.004
1	(2.5, 0.0)	0.254	0.225	0.247	0.227	0.214	0.238	0.014	0.230	0.228	4.17	0.229	0.001
1	(5.0, 0.0)	0.256	0.228	0.252	0.230	0.214	0.242	0.015	0.234	0.227	1.62	0.231	0.005
1	(2.5, 2.5)	0.247	0.224	0.233	0.216	0.219	0.230	0.013	0.235	0.229	2.35	0.232	0.004
1	(5.0, 5.0)	0.263	0.222	0.253	0.235	0.230	0.243	0.018	0.250	0.246	2.66	0.248	0.003
ave		0.256	0.225	0.244	0.226	0.219	0.234		0.233	0.228	2.500	0.230	
std		0.006	0.002	0.009	0.007	0.007		0.015	0.013	0.013	1.031		0.012

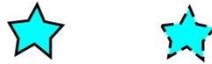
medium gz

2	(0.0, 0.0)	0.290	0.261	0.258	0.257	0.258	0.267	0.016	0.244	0.237	1.90	0.241	0.005
2	(2.5, 0.0)	0.282	0.260	0.263	0.261	0.252	0.267	0.010	0.262	0.259	5.77	0.261	0.002
2	(5.0, 0.0)	0.286	0.261	0.258	0.262	0.249	0.267	0.013	0.261	0.250	1.38	0.256	0.008
2	(2.5, 2.5)	0.282	0.257	0.258	0.251	0.255	0.262	0.014	0.243	0.243	1.80	0.243	0.000
2	(5.0, 5.0)	0.249	0.258	0.271	0.269	0.265	0.262	0.010	0.272	0.263	1.57	0.268	0.006
ave		0.278	0.259	0.262	0.260	0.256	0.263		0.256	0.250	2.484	0.253	
std		0.016	0.002	0.006	0.007	0.006		0.011	0.013	0.011	1.848		0.011

high gz

3	(0.0, 0.0)	0.350	0.314	0.307	0.309	0.312	0.320	0.020	0.291	0.287	4.34	0.289	0.003
3	(2.5, 0.0)	0.336	0.314	0.310	0.312	0.307	0.318	0.012	0.301	0.300	5.33	0.301	0.001
3	(5.0, 0.0)	0.322	0.307	0.305	0.306	0.294	0.310	0.008	0.326	0.322	4.85	0.324	0.003
3	(2.5, 2.5)	0.334	0.311	0.305	0.304	0.305	0.314	0.014	0.312	0.306	2.97	0.309	0.004
3	(5.0, 5.0)	0.334	0.308	0.303	0.314	0.307	0.315	0.014	0.300	0.283	1.24	0.292	0.012
ave		0.335	0.311	0.306	0.309	0.305	0.313		0.306	0.300	3.746	0.303	
std		0.010	0.003	0.003	0.004	0.007		0.013	0.013	0.016	1.656		0.014

広視野AO: MCAO



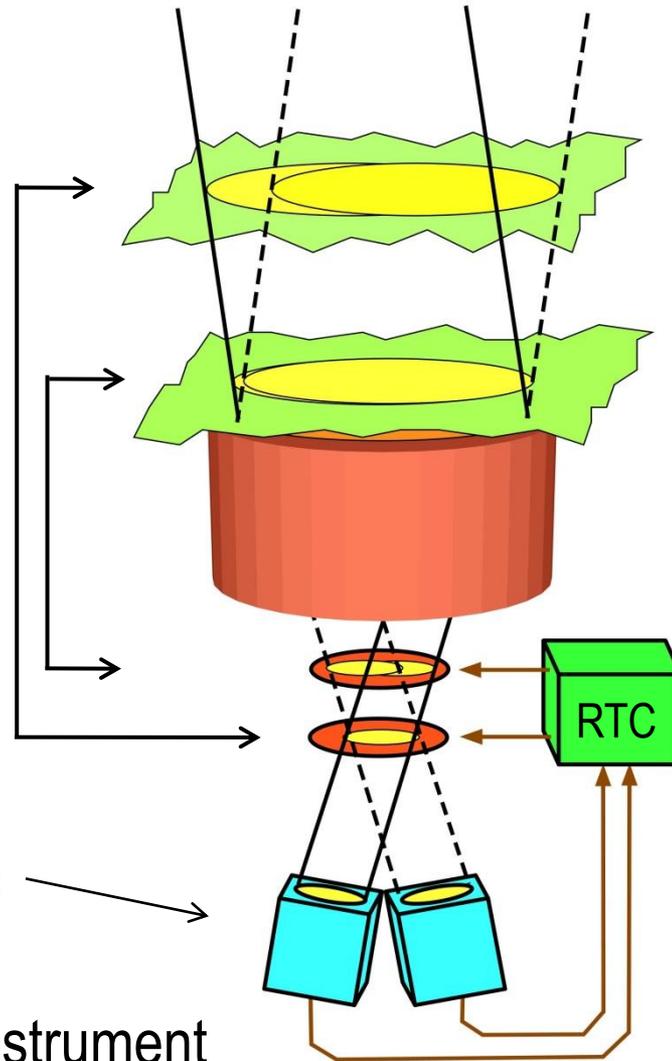
FoV: 2 arcmin
diffraction-limited
survey possible

multiple layers
&
multiple correctors

conjugated

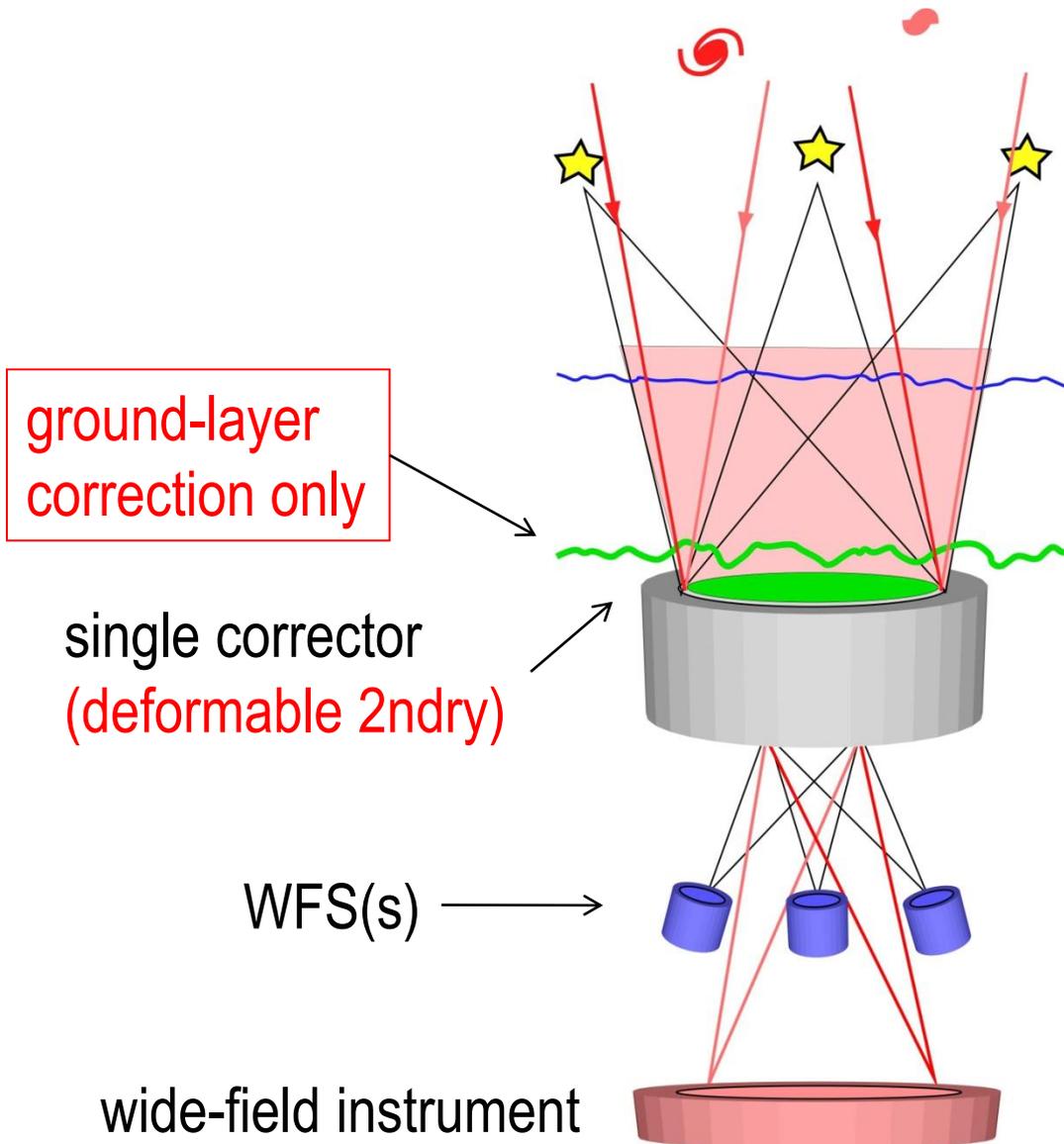
multiple WFSs

wide-field instrument

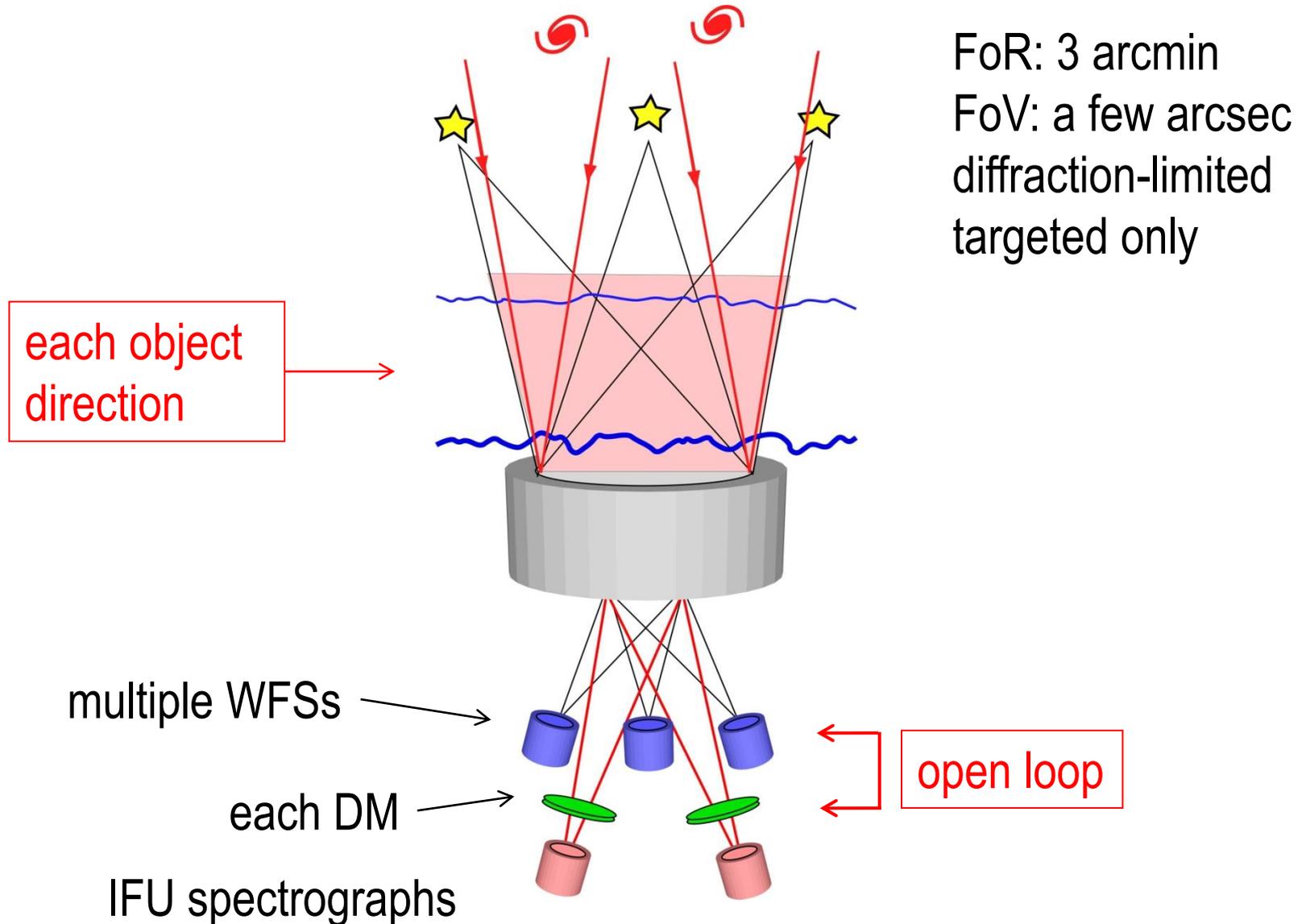


広視野: GLAO

FoV: 10 arcmin
fwhm: < 0.4 [arcsec]
survey possible



広視野AO: MOAO

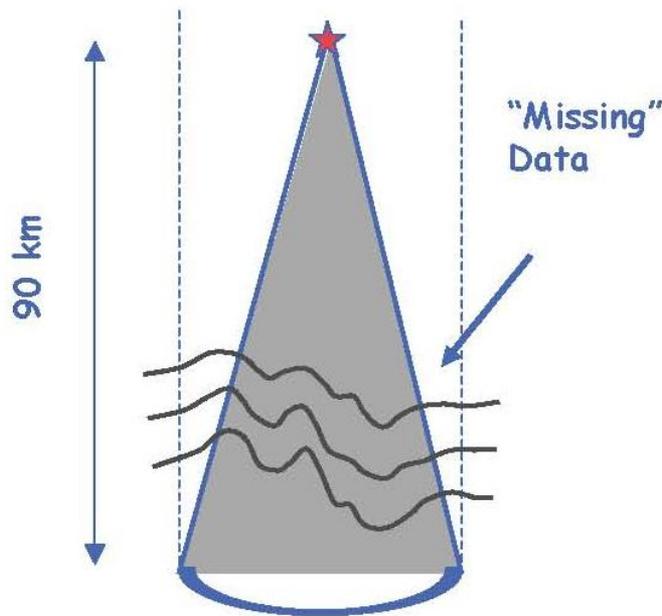


LGSコーン効果の低減: LTAO

AO tomography: measure turbulence and correct for “cone effect”

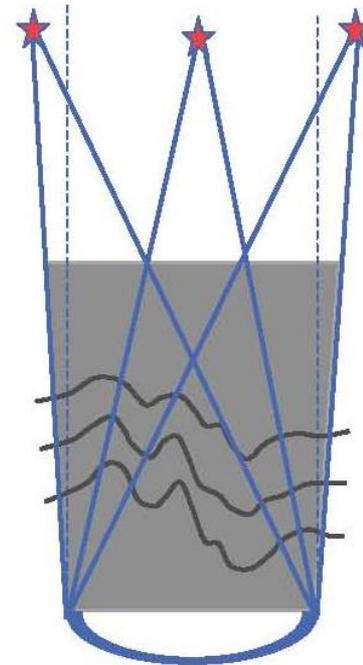


one laser guide star



Without tomography

multiple laser guide stars

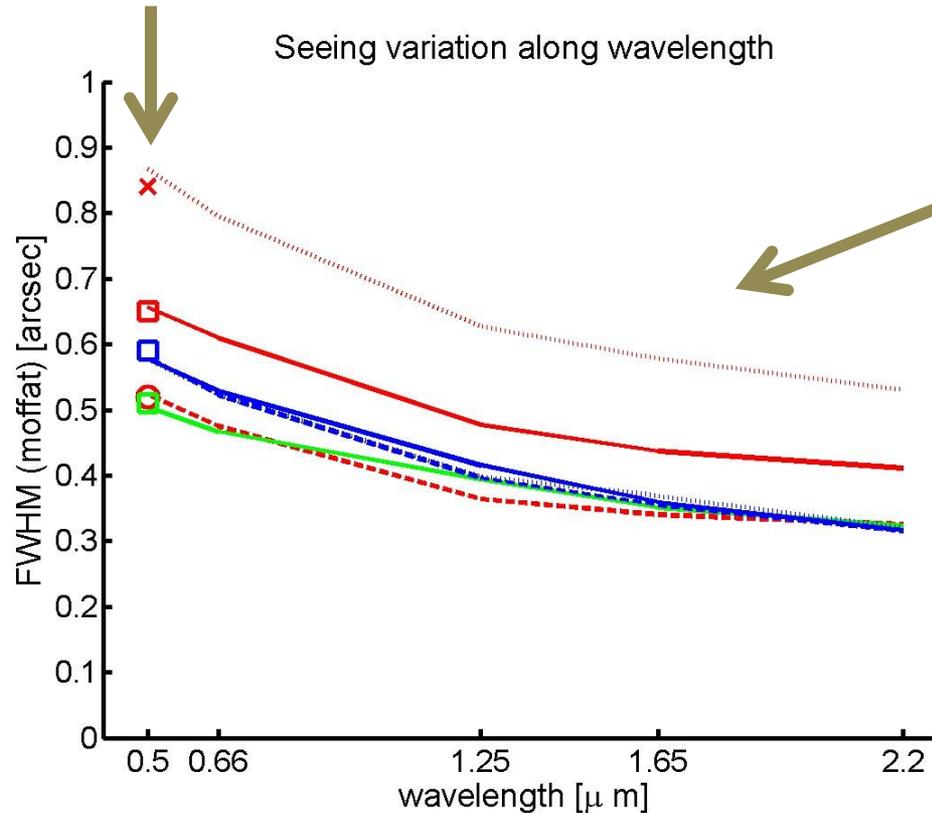


With tomography

With AO tomography, measure 3D distribution of turbulence above telescope

3. Seeing simulation

(1) MAOS calculation reproduces seeing @ 0.5 μm , if FWHM is scaled by 1.22

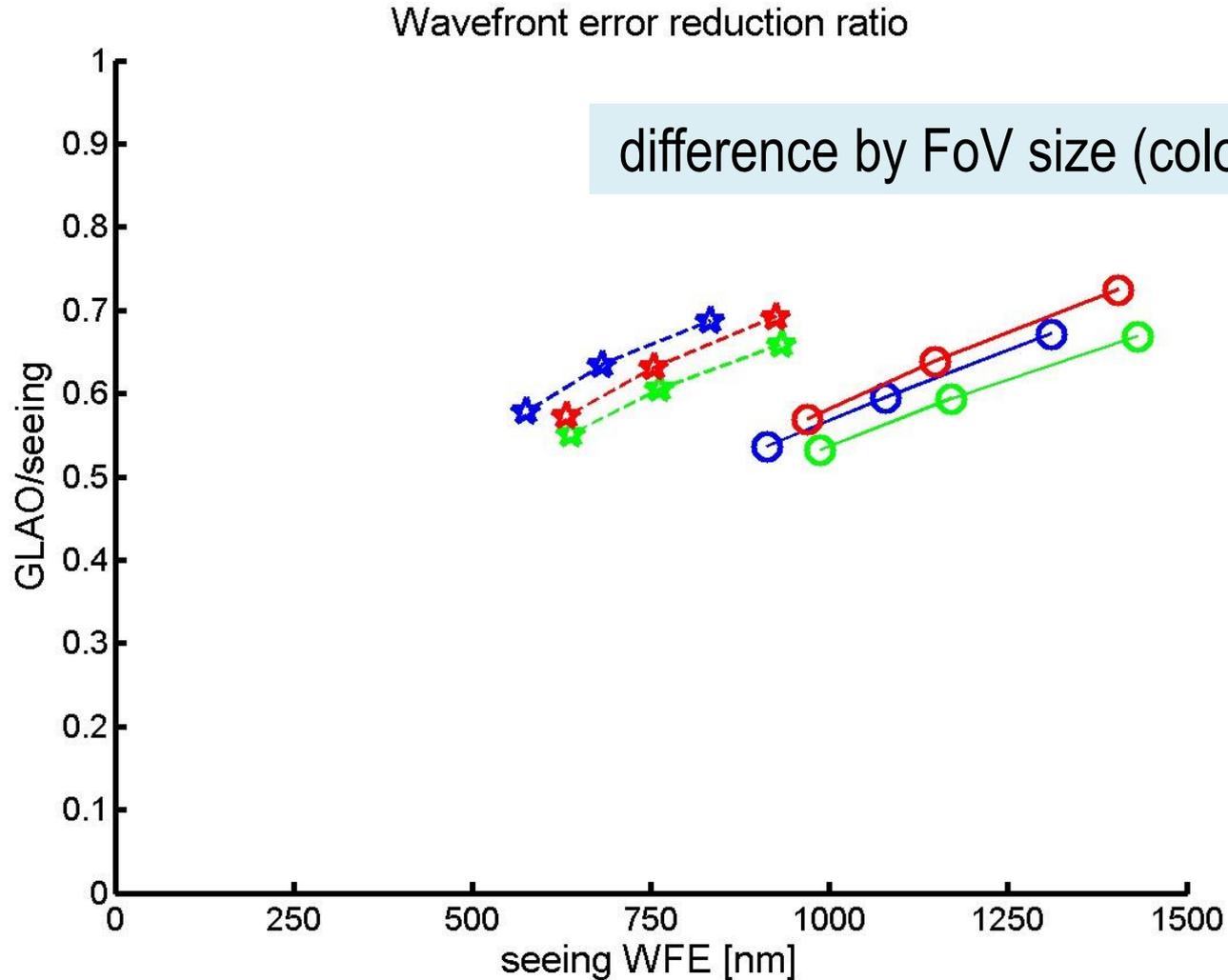


(2) λ dependence
seeing $\propto \lambda^{-0.2}$
fitting: $-0.3 \sim -0.4$
i.e., under estimate at longer wavelength

RAVEN is used for Subaru simulation

red: RAVEN: good(dashed; r0 \bigcirc), moderate(solid; r0 \square), bad(dotted; r0 \times)
blue: Gemini: low gray-zone(solid), mid gz(dashed), high gz(dotted); r0 \square
green: IMAKA: moderate(solid); r0 \square

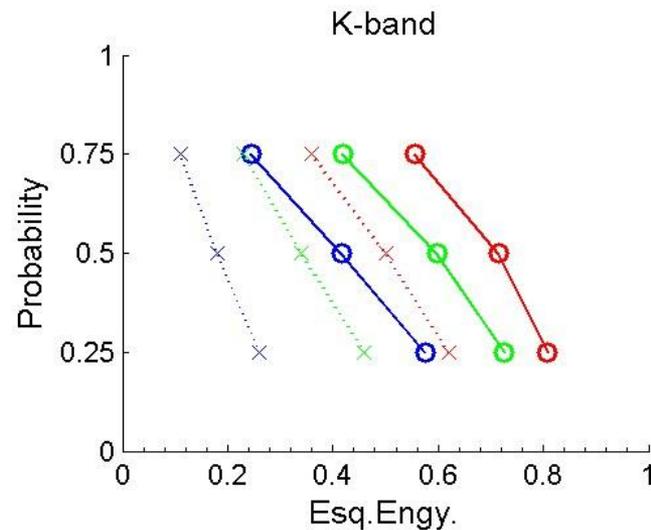
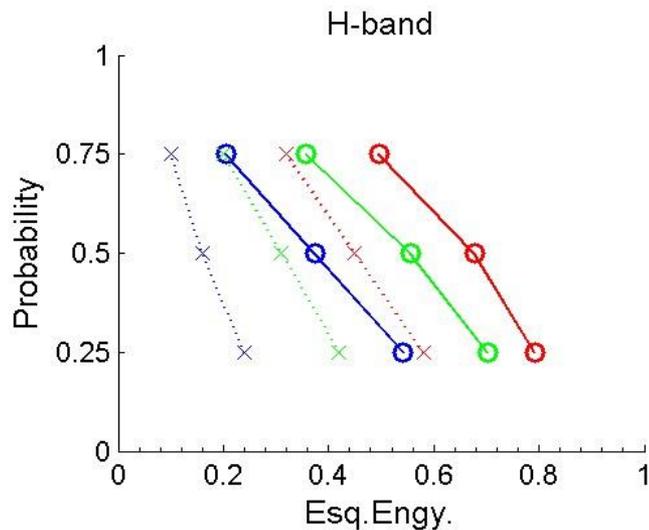
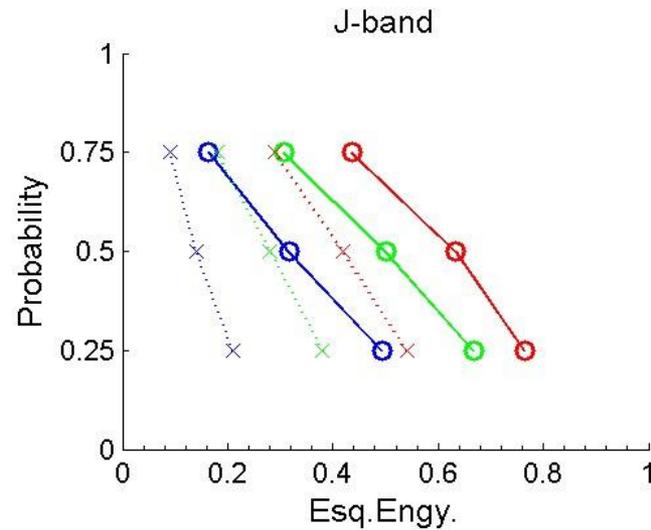
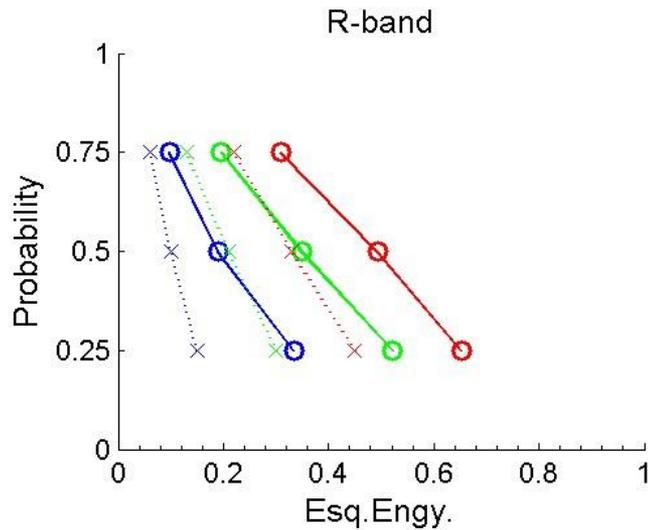
8. Seeing WFE vs WFE ratio (GLAO/Seeing)



FOV: blue: $\phi = 10$ arcmin, green: $\phi = 15$ arcmin, red: $\phi = 20$ arcmin

Order: \circ : all order, \star : piston/tip/tilt removed = higher order

7. Seeing dependence of EsqE



width: blue: 0.24"、green: 0.36"、red: 0.48"

GLAO: O、Seeing:

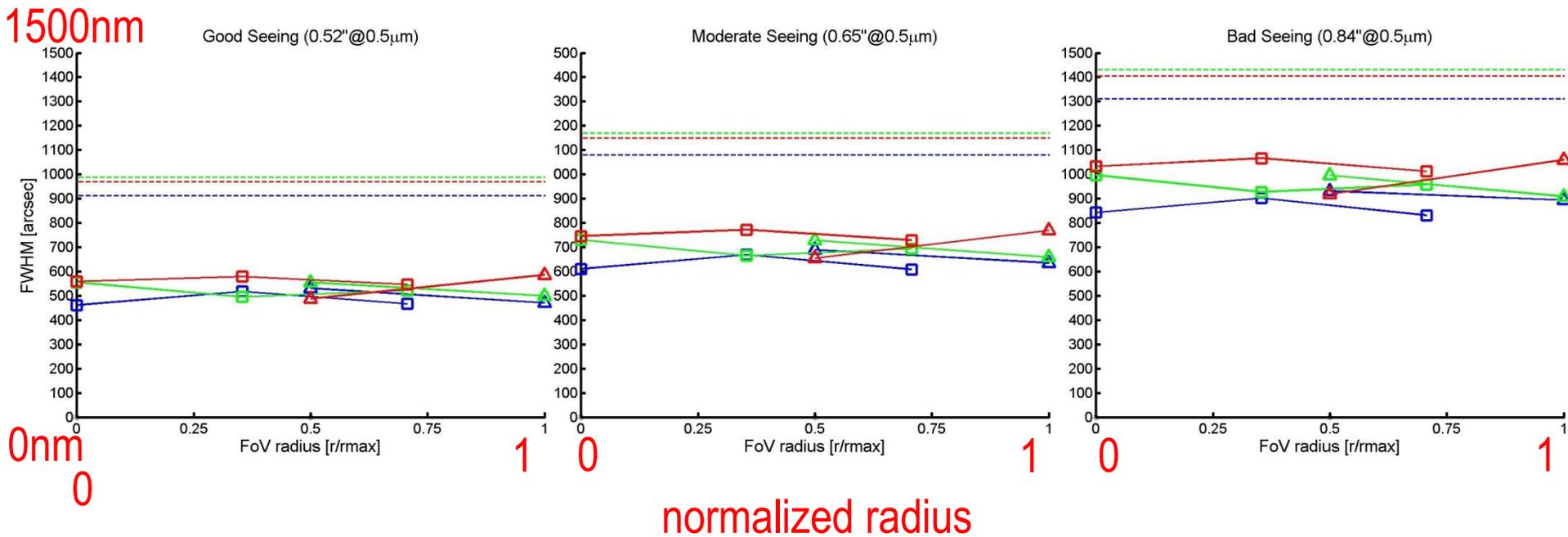
FoV: 15' ϕ

11. Field dependence of WFE

Good seeing (0.52")

Moderate seeing (0.62")

Bad seeing (0.84")



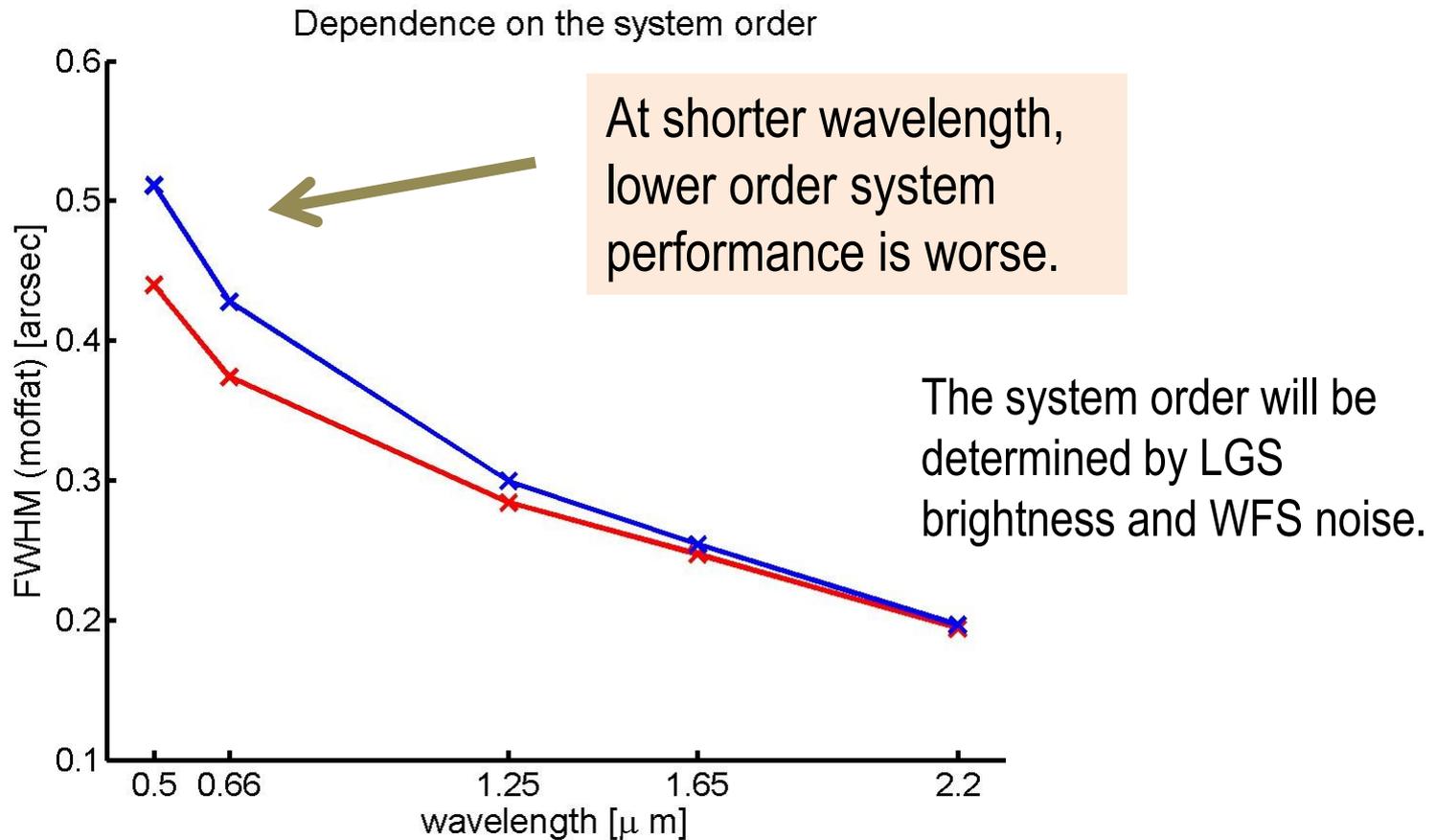
FoV: blue: 10' φ 、 green: 15' φ 、 red: 20' φ

direction: □: toward GS、△: between GS

GLAO: solid lines、seeing (uncorrected): dotted lines

12. Dependence on the system order

FoV: 15' ϕ
moderate
seeing



red: 32 act. across DM (& WFS)、blue: 10 act. across DM (& WFS)

Note that the result for the combination of high-order DM (32 act. across) and low-order WFS (10 act. across) is the same as 10 act. across DM (&WFS).